Assessing the relationship between anthropogenic nightlight, noise, and avian contributions to ecosystem services

By

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Abstract

Anthropogenic sensory pollutants, especially anthropogenic nightlight and noise (ANLN), are well-known agents of habitat degradation for many bird species. Studies show that ANLN can also induce physiological stress, affect habitat selection, and reduce the reproductive success of birds, but the large-scale effects of ANLN on the ecosystem services birds provide have not been examined. I categorized 60 bird species based on the services they provide and used mixed effects models to predict their probability of occurrence within the contiguous United States during their breeding season. I then spatially modeled species' occurrence rates based on the partial dependence effects of each pollutant separately and summed the rates by service category to produce predicted service maps.

Of the 60 species, night light and noise showed significant effects on occurrence for 8% (n=5) and 22% (n=13) of species, respectively. Nightlight was negatively correlated to seed dispersal and invertebrate pest control, and noise positively or negatively correlated with these services, dependent on species. Though many species' occurrence was not drastically affected by ANLN levels, over certain thresholds, many occurrence rates dropped to zero (n=40 and n=53 species, for nightlight and noise, respectively). This largely explains the >50% predicted reduction of urban area services; however, why some areas, such as the Mojave Desert, saw similar reductions due to noise is unclear. Given ANLN's lack of consistent effects in >75% of models, these results suggest ANLN may not inevitably decrease all avian services. Further research is needed to examine the nuances of ecosystem service and avian species' resilience across the ANLN gradient.

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Chapter 1: Introduction

As the world's population continues to grow and human disturbance creeps outward from urban and suburban centers[1], anthropogenic forces will likely continue to decrease high-quality habitat available to wildlife. In addition to habitat loss, anthropogenic habitat modification, such as increased noise, night light, and chemical pollution, is expected to alter behaviors[2,3], increase physiological stress[4,5], and increase mortality rates[6,7] of wildlife, including birds.

Many of these drivers of mortality have been the targets of mitigation efforts, from pollution reduction[7,8] to lights out initiatives[9,10]. Anthropogenic nightlight's myriad effects on birds are broadly studied, with evidence that nightlight affects use of habitat[11] and navigation[12] during migration, foraging patterns[13,14], timing of clutch initiation[15], chick body condition[5,16], sleep quality[17], and susceptibility to malarial infection[18,19]. While these effects generally decrease fitness, nightlight also may provide advantages, such as increased foraging opportunities[2,14,20] and safety from predators[2].

Anthropogenic noise, however, remains a largely overlooked aspect of habitat modification. In the United States, human activities have markedly increased noise levels over the past 50 years[20]; this trend is associated with myriad consequences for birds, influencing stress hormone levels[1,5,22], breeding site selection[23,24], mating and reproductive success[23,25], and even birdsong frequency[26]. These effects are wide-ranging, occurring across urban-rural gradients[27], but there is unexplained variation in the impacts of noise among species[24,28,29]. For example, noise does not significantly impact nest box selection[22] or the reproductive success[25] of western bluebirds (*Sialia mexicana*), but increasing noise drives reductions in reproductive success in the closely related eastern bluebird (*Sialia sialis*)[30].

Distinguishing between the short- and long-term effects of noise and other anthropogenic pollutants on species fitness and choice of habitat will be crucial to prioritizing conservation interventions as the human footprint continues to expand.

Beyond their direct effects on bird mortality and fitness, anthropogenic sensory pollutants (here anthropogenic night light and noise, ANLN) may have broad indirect effects on the environment. Birds contribute to supporting, provisioning, and cultural ecosystem services[31], and these contributions can be altered by the impacts of sensory pollutants on bird behaviors, distributions, and population sizes. Many of the regulating and supporting services birds provide derive from their foraging or hunting activities[31,32]. For instance, through consumption of invertebrates, insectivorous bird species regulate pests and prevent disease outbreaks[33] for a wide variety of agricultural[31,32,34] and natural ecosystems[31]. Pollination, seed dispersal, and waste disposal are other regulating services birds provide on a large scale[31]. Nest construction is a supporting service, with cavities excavated by woodpeckers often used by secondary cavity nesting birds and other cavity nesting animals[35]. Numerous bird species are hunted as game[36], or kept as domesticated livestock for eggs and/or meat around the world, a source of provisioning services. In their interactions with people, birds also provide cultural services: millions of people worldwide engage in hunting and birding[37], which generate significant economic value, are culturally important, and provide positive psychological benefits[38]. The services birds provide can have staggering economic value; for example, a single species – the Clark’s nutcracker (*Nucifraga columbiana*) – generates an estimated value of $11-$14 billion per year in the United States through the dispersal of Whitebark pine seeds[34]. The valuation of bird-derived ecosystem services is challenging[32,39,40], and the impacts that large scale anthropogenic night light and noise will have on bird mediated ecosystem services remains an open question.

To address this question, I modeled the potential effects of ANLN on bird ecosystem services across the continental United States (CONUS). I obtained measures of nightlight and noise across the continental US and integrated them into models of bird occupancy to determine species' sensitivity to these sensory pollutants. I summarized the model results across bird species according to the main ecosystem services they provide, including seed dispersal, invertebrate pest control, nutrient cycling, pollination, and carrion disposal. This enabled me to estimate how nightlight and noise may diminish avian services across the continental US.

Chapter 2: Methods

Categorizing Ecosystem Services

I used the ecosystem services framework outlined by Şekercioğlu *et al.* (2016)[41] to define ecosystem service categories. I chose to examine services birds provide that are directly connected to human well-being: seed dispersal, invertebrate pest control, nutrient cycling, pollination, and carrion removal.

I reviewed all of the literature cited in Şekercioğlu *et al.* (2016)[41] that corresponded to any of these five services; for each study, focal genus and species was determined from the abstract, and studies with the words “ecosystem service” and that named a focal category of service were included. I also examined reviews and meta-analyses for relevant observational and experimental studies. If a paper did not record individual species as providing a service, it was excluded. I categorized a species as providing an ecosystem service if a study reported a quantitative measure of the species performing it. For example, in an experimental exclosure study of hummingbirds from a flowering shrub (*Penstemon pseudospectabilis*), the seed set of the plants visited by both insects and Black-chinned or Broad-tailed hummingbirds was twice that of plants only visited by insects[42]. Thus, these two hummingbird species were added to the pollination service category. Species could be categorized into more than one ecosystem service category.

One service category, carrion disposal, was treated differently from the other four: although many bird species consume carrion, most do so opportunistically and are classified as facultative scavengers. An exclosure study in South Carolina[43] found that avian facultative scavengers visited carcasses rarely and did not consume enough carrion to functionally replace Black vultures (*Coragyps atratus*) and Turkey vultures (*Cathartes aura*), the only two obligate avian scavengers found in the continental US. For the purposes of this study, only these two obligate scavengers were assigned to carrion disposal; facultative scavengers were not assigned to this service category.

Species sensitivity models

To model bird species sensitivity to nightlight and noise, I combined bird occurrence data with maps of nightlight and noise, while controlling for other anthropogenic impacts on the landscape. Bird occurrence data was extracted from the United States Geological Survey's (USGS) annual survey of bird species that breed in the United States, Mexico, and Canada (the Breeding Bird Survey, or BBS)[44] for years 2007-2012. Noise data was obtained from the National Parks Soundscape model[45], and nightlight data from and the New World Atlas of Artificial Sky Brightness[46,47]. The National Parks Soundscape dataset is a comprehensive noise model that accounts for topography in sound propagation and removes natural background sounds (e.g. seismic activity, wind) from total observed sound, creating a strictly anthropogenic noise dataset. This dataset provides the L50 noise exceedance (the noise level exceeded 50% of the time on a 'normal' summer day). The New World Atlas similarly removes natural background night light (e.g. moonlight, starlight, and volcanoes), and is able to detect and represent blue light more accurately than other available night light datasets[46] (e.g. from Visible Infrared Imaging Radiometer Suite, or VIIRS).

General linear mixed effects models were used to determine individual bird species sensitivity to nightlight and noise. A separate logistic regression (binomial/logit function) model was fit for each species using the fitme function from the R package spaMM[48], with a random intercept and random slopes estimated for noise and nightlight. To control for other anthropogenic effects, human population density and percent of impervious surface were included as covariates. Year, latitude/longitude, and BBS route were included as random effects. The model structure is as follows:

Species occurrence ~ intercept + Anthropogenic noise + Anthropogenic light + scaled night length + scaled square root of human population + scaled impervious surface + scaled Julian date + (1/latitude longitude coordinates) + (1/year) + (1/BBS route)

Species whose coefficient for noise or night light did not cross zero were considered to have a consistent response to that pollutant. The models were constructed and run in R v.3.6.1[49] using the R packages spaMM[48], car[50], DHARMa[51], and lme4[52].

Ecosystem Service Total Species & Density Maps

To estimate the likelihood of an ecosystem service being robust or vulnerable to the effects of anthropogenic sensory pollutants, I compared the species richness of that service based on species breeding range maps to the predicted species richness of that service based on ANLN’s effects on species occurrence. Per the findings of Philpott *et al.* (2009)[53] that performance of the service of arthropod reduction was significantly positively correlated with species richness, I argue that ecosystem services will be more robust to decline if services in a particular geographic area are provided by multiple species. Thus, I calculated species richness using the breeding ranges[54] of all species in a service category across the continental United States, and considered richness to be an index of the level of service that birds provide in a particular location.

To calculate the effects of ANLN on the potential provision of ecosystem services and construct the ES ‘density maps’, species’ breeding ranges were used to crop the nightlight and noise datasets, resulting in a nightlight raster and noise raster for each species (see red box in

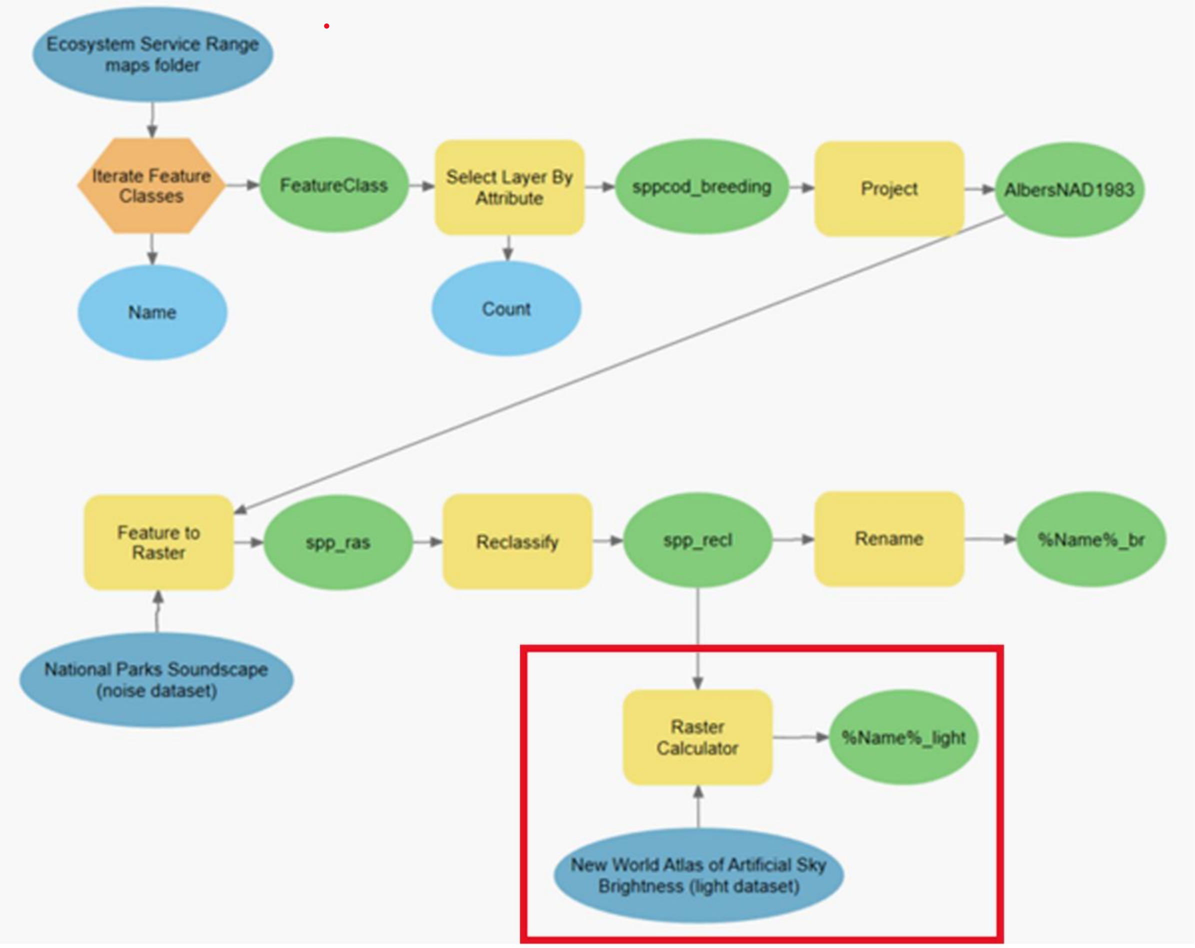


Figure 1). Species that demonstrated consistently positive or negative effects

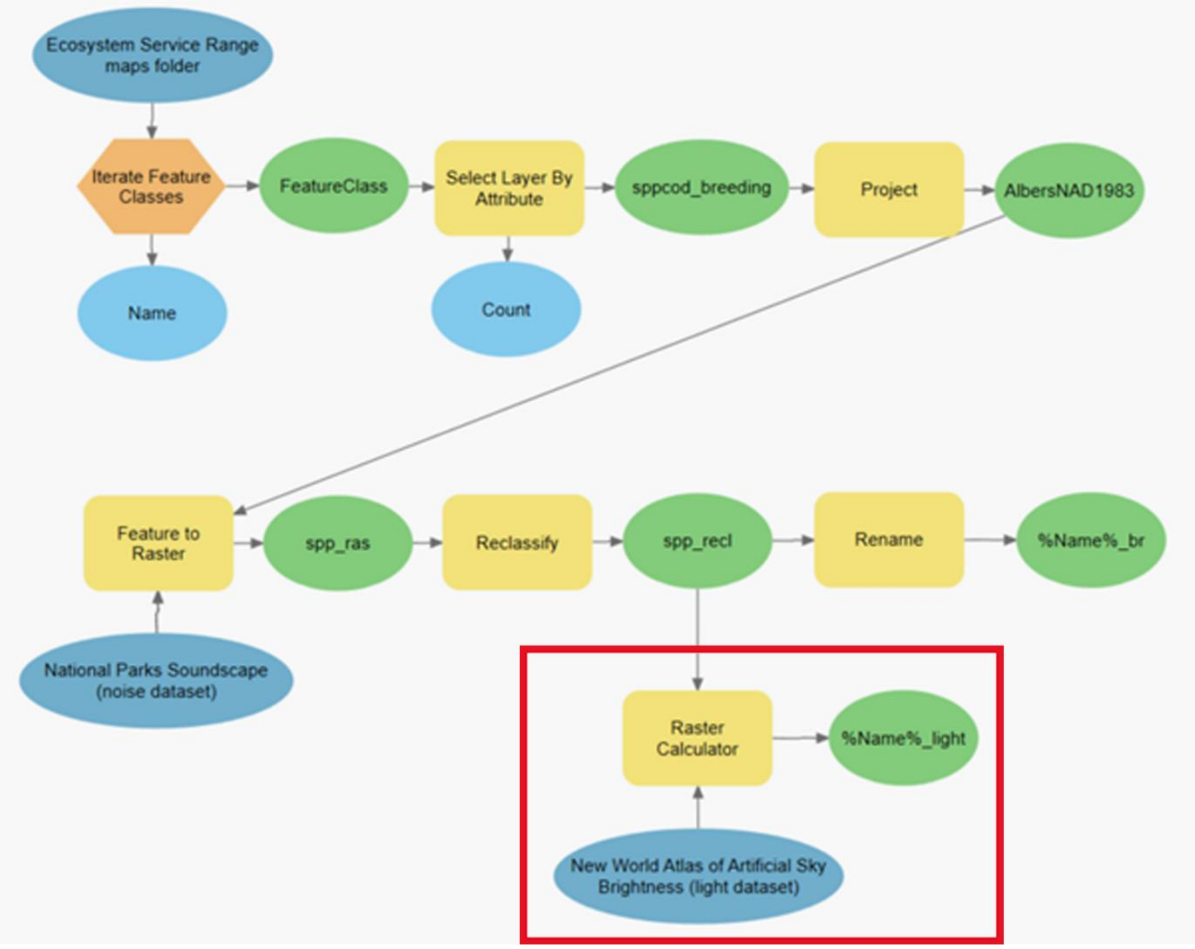


Figure 1: ArcGIS workflow converting migratory species breeding polygons to pollutant rasters (here species_light rasters). In raster files, %Name% is the eBird species code. %Name%_insurance are rasters of zeros and ones representing a species breeding range, and %Name%_light are rasters of the light dataset clipped to species range. A slightly modified workflow exists for noise, with the noise dataset replacing the light dataset input into the raster calculator.

for one or both pollutants within the mixed effects model (‘sensitive’ species) were separated from species without strong pollutant effects. Then, the sensitive species’ species-pollutant raster(s) were converted to estimates of occurrence. This was accomplished by calculating the partial dependence effects of the pollutant on occurrence with the pdep_effects function from the spaMM package[48]. For each service, the occurrence rasters of species sensitive to night light were summed with the insensitive species’ breeding rasters to estimate the effects of night light on that service. The same process was repeated with noise, resulting in two rasters for each service, each estimating the effects of the respective pollutant.

To estimate the effects of ANLN on specific ecoregions of the contiguous United States, I calculated zonal statistics in ArcGIS Pro, using US Environmental Protection Agency level 1 and level 2 ecoregion shapefiles[55,56] (**Figure 2**). I examined the mean effect size for each pollutant-service combination over both ecoregion levels.

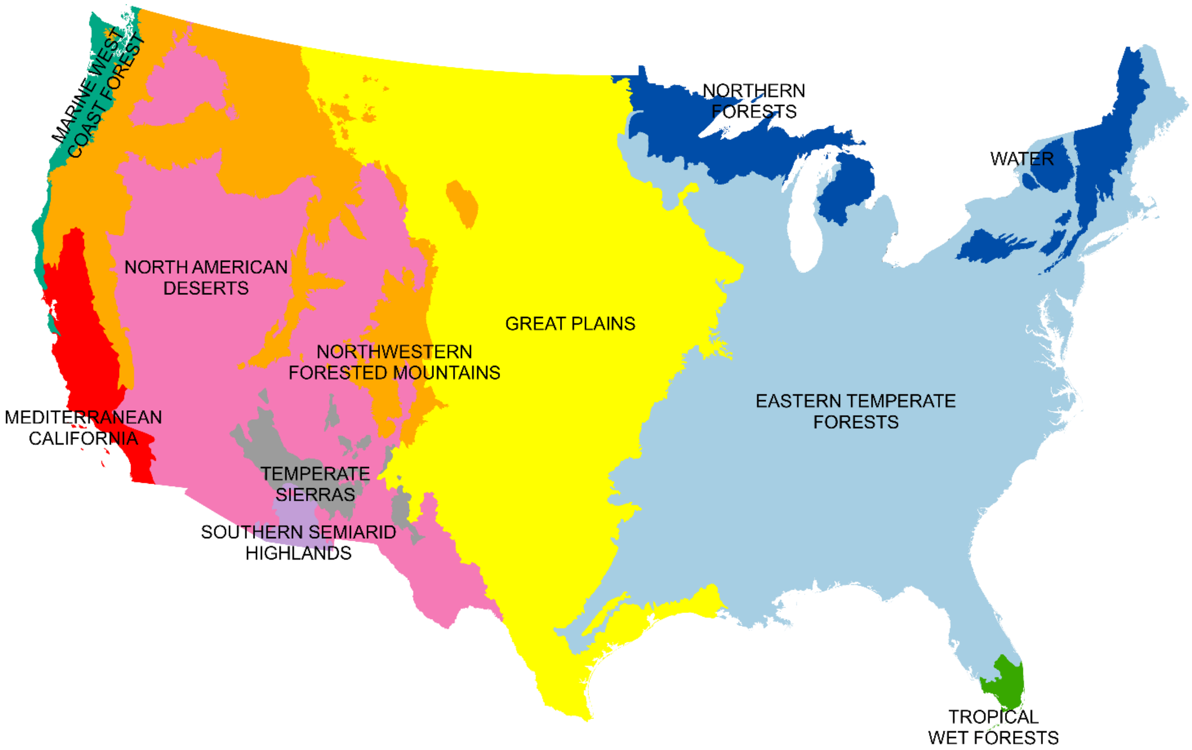


Figure 2: EPA Level 1 (top) and Level 2 (bottom)

Chapter 3: Results

Bird species Ecosystem Service categorization

I reviewed 165 studies and placed 60 species into the five ecosystem service categories. More than two thirds of species were placed into these two categories, with more than 20 species each. A few species were placed into more than one category, as the literature documented they provide each of those services. These species include red-bellied woodpecker, red-winged blackbird, and ring-billed gull.

Species sensitivity to ANLN

Of the 60 species modeled, 5 had consistently negative relationships between night light and occurrence probability, and 13 had consistent relationships between noise and their occurrence probability. These affected species fell into two ecosystem service categories, seed dispersal and invertebrate pest control.

Many species' occurrence was not significantly affected by anthropogenic pollutants across the range of covariates within the model, most species' occurrence rates dropped off beyond certain pollutant thresholds. This maximum threshold of night light or noise varied by species, which is illustrated by the effects of night light on select species in **Figure 3** (for all modeled species, see **Appendix A: Species Pollutant Level Thresholds**). threshold. More species exclude themselves from areas of high noise (n = 52) than areas of high night light (n = 39).

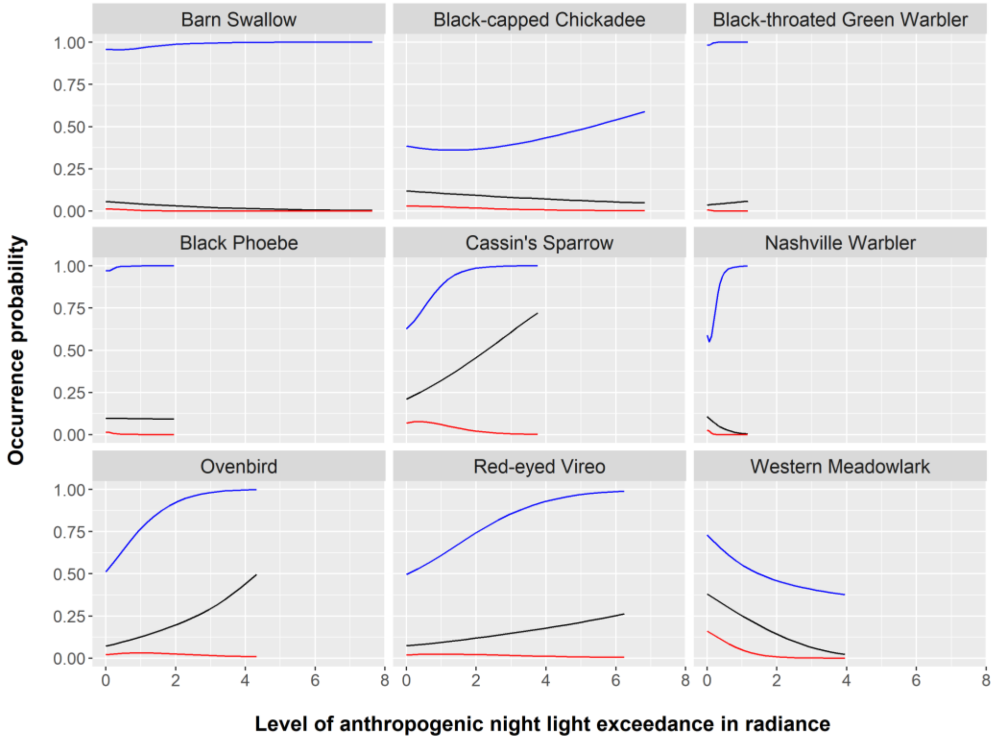


Figure 3: Predicted occurrence of select Invertebrate Pest Control species by partial dependence effects of night light

ANLN effects on Ecosystem Services

Of the five ecosystem services studied, three – seed dispersal, invertebrate pest control, and nutrient cycling – are provided by species whose occurrence was impacted by night light or noise across pollutant levels in the mixed effects models (**Figure 4** and **Figure 5**). Only one species that provides nutrient cycling, the red-winged blackbird, was impacted across the range of ANLN levels. None of the species that provide carrion disposal or pollination showed ANLN impacts in the models.

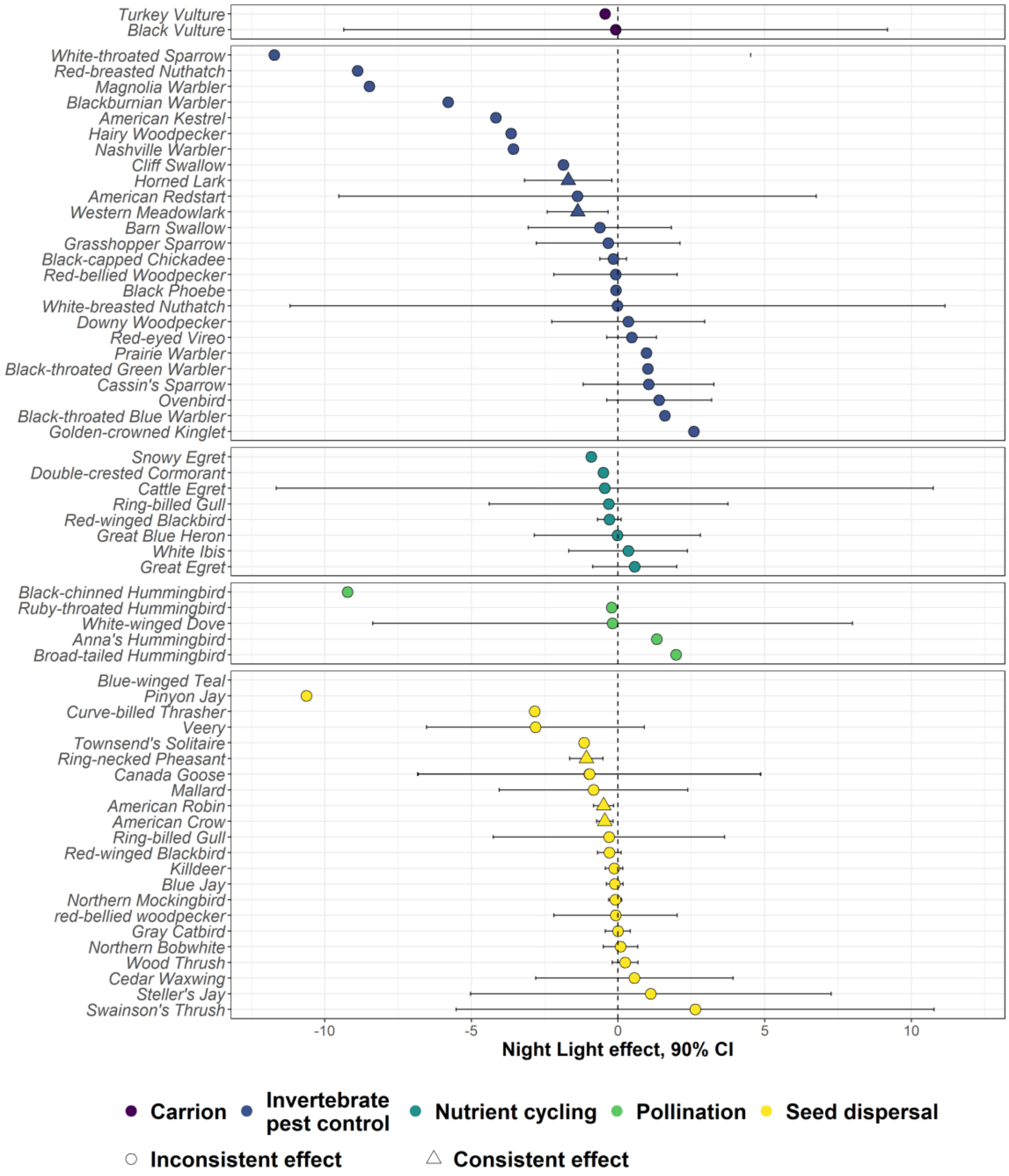


Figure 4: Night light effects on occurrence for each species mixed effects model. Night light was measured as the ratio of brightness above natural skyglow (as described in Falchi et al. 2016[33]). Each subplot displays species by service (point color). Those species whose coefficient's 90% confidence interval (CI) does not cross zero are symbolized by a triangle, and those species whose CI does cross zero are represented by circles. Circes without error bars have CI which exceed the x-axis limits. The blue-winged teal's night light coefficient fell well beyond the plot limits and was not included.

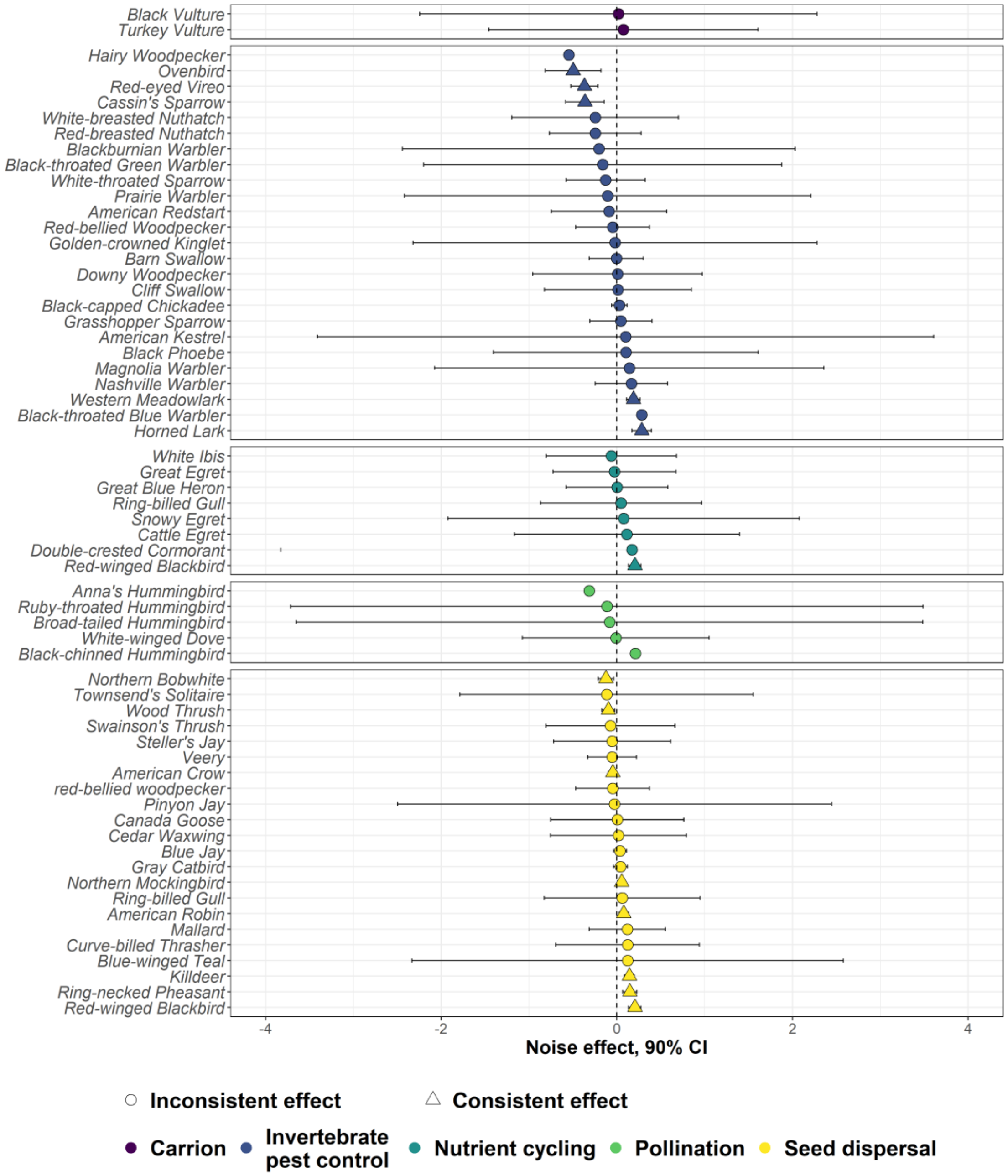


Figure 5: Noise effects on occurrence for each species mixed effect model. Noise coefficients are the effect on occurrence for every decibel above natural background. Each subplot displays species by service (point color). Those species whose coefficient's 90% confidence interval (CI) does not cross zero are symbolized by a triangle, *and t*hose species whose CI does cross zero are represented by circles. Circes without error bars have CI which exceed the x-axis limits.

Seed Dispersal

The potential effects of nightlight and the potential effects of noise on the number of species likely to inhabit an area and provide seed dispersal are varied. Nightlight has less of a negative effect across the continental United States (CONUS), with most areas predicted to lose less than 20% of seed dispersal services, and the desert southwest and areas within the Rocky mountains losing 6% or less (**Figure 6**). The exceptions are in and around areas of high nightlight pollution, such as Los Angeles, Chicago, Miami, New York City, etc.

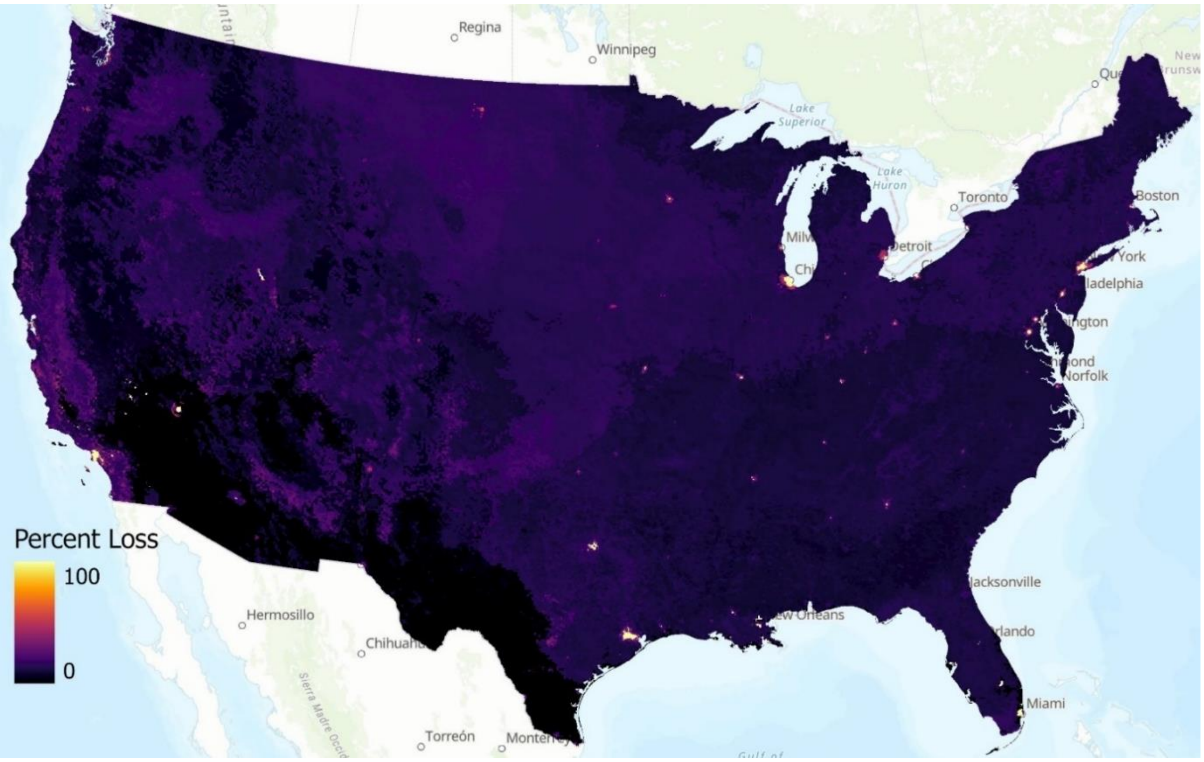


Figure 6: Nightlight effects on Seed Dispersal

Noise, on the other hand, appears to lead to a decrease in species providing seed dispersal across a much wider geographical range of CONUS (**Figure 7**). Like night light, noise leads to potential decreases in seed dispersal in and around large cities; however, its negative influence extends into areas of the desert southwest, areas of southern and central Texas, and the coastal range of California (see cutouts).

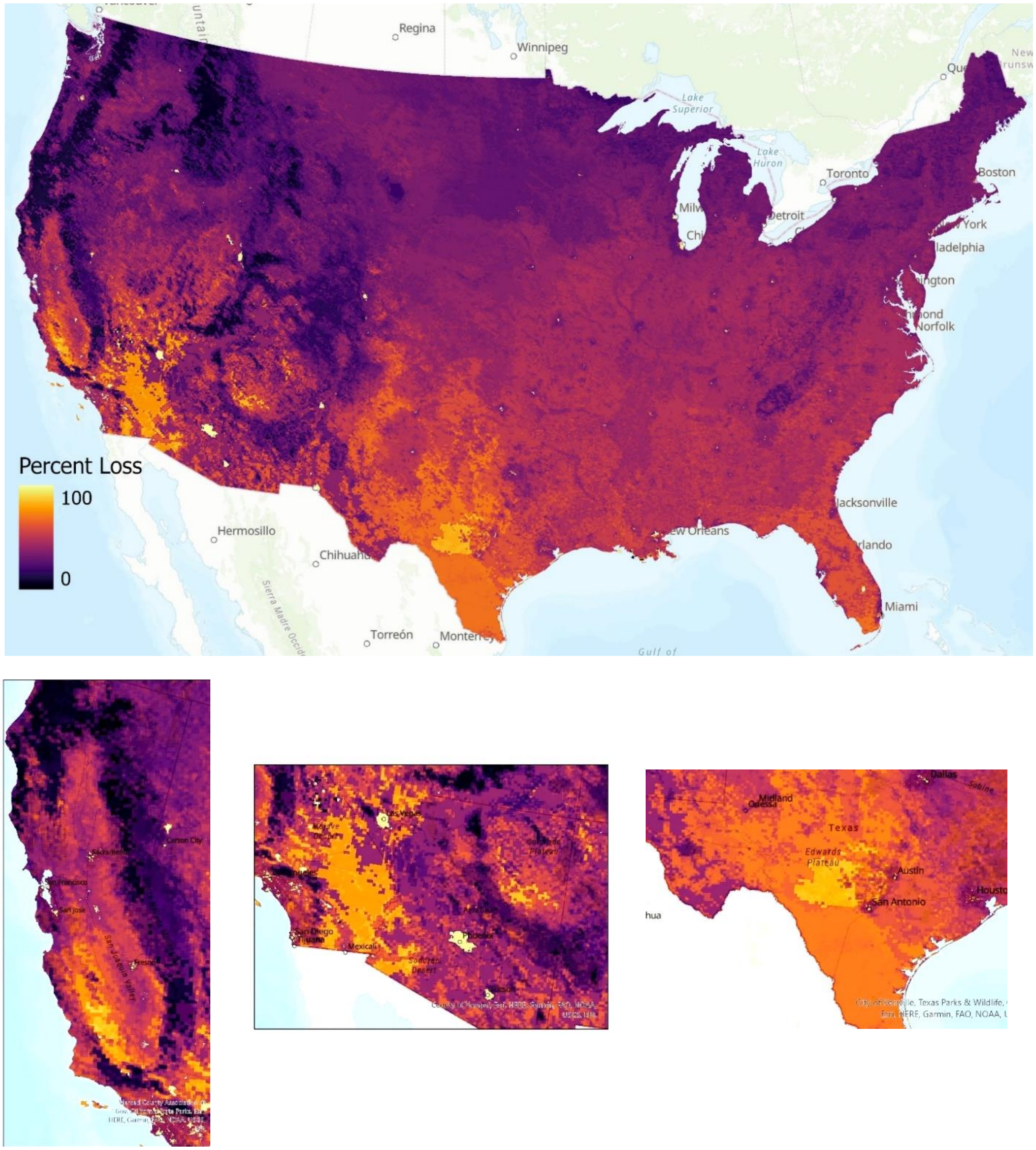


Figure 7: Noise effects on Seed Dispersal

Invertebrate Pest Control

The effect of nightlight on invertebrate pest control is most pronounced in large cities, with Los Angeles, Las Vegas, Chicago, and New York predicted to have less than one third of their service potential. However, most of the southeast, Midwest, and the northwest lose less than 20% of services when considering night light (**Figure 8**). Noise seems to follow a similar pattern as light for these species, with large metropolitan areas most affected. Invertebrate pest control sees greater declines due to noise than light, especially when considering the eastern portions of Maryland, North Carolina and South Carolina, and areas of the Great Plains (**Figure 9**). Nevertheless, almost the entire continental United States retains more than 60% of its service potential.

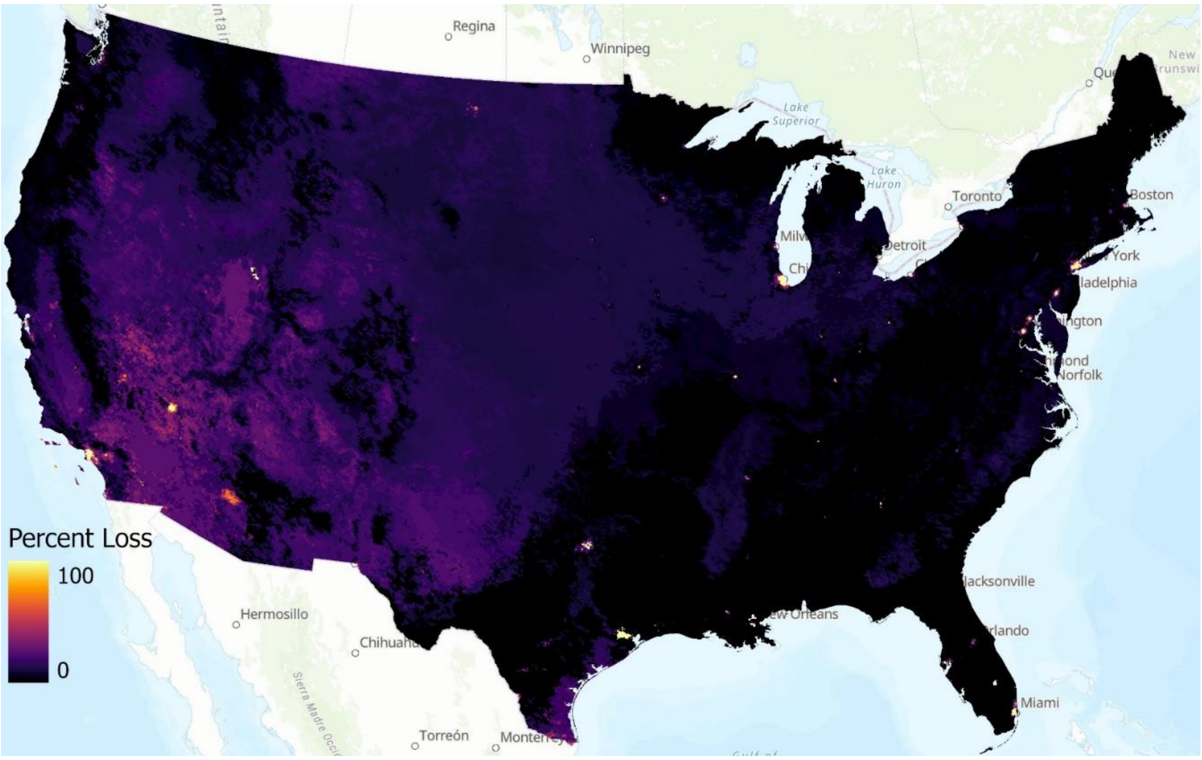


Figure 8: Night light effects on Invertebrate Pest Control

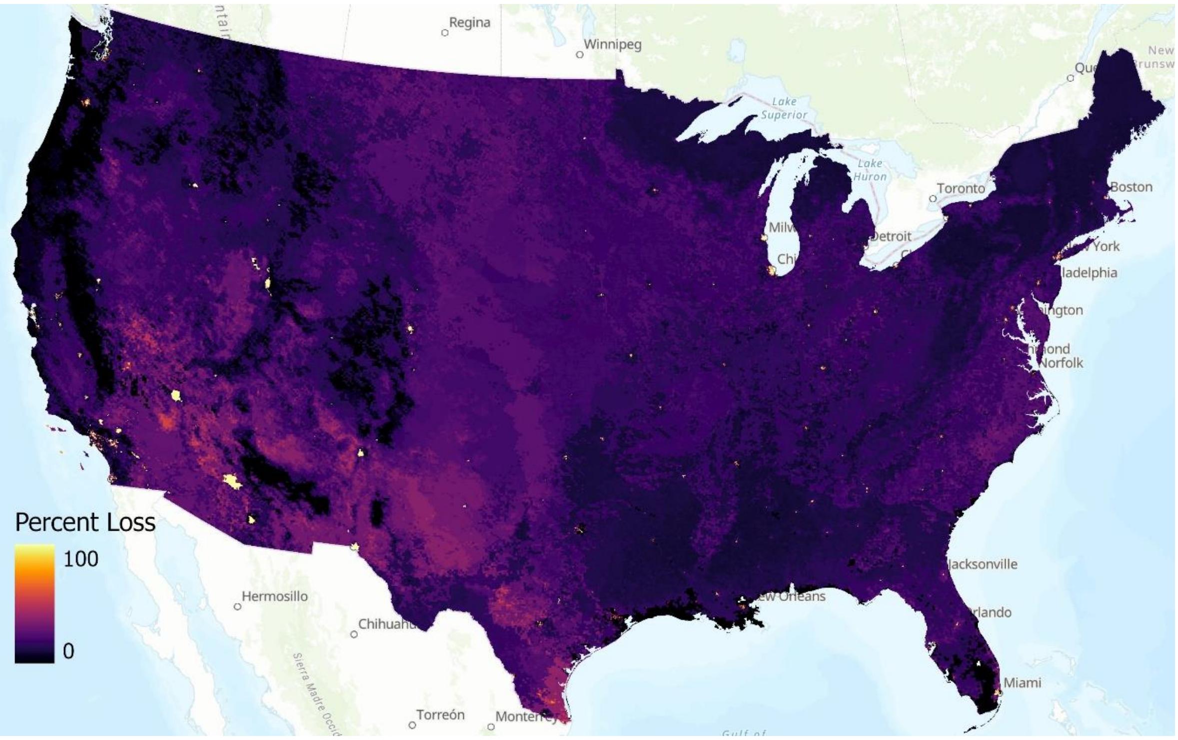


Figure 9: Noise effects on Invertebrate Pest Control

Nutrient Cycling

Night light did not have many strong effects on nutrient cycling outside of metropolitan areas. This makes sense, as these species did not demonstrate high sensitivity to night light or noise in the mixed models, and most also have high maximum light and noise thresholds, as can be seen in **Appendix A: Species Pollutant Level Thresholds**. Of the species categorized as providing nutrient cycling, only one, the red-winged blackbird, had a consistent effect, a positive relationship with noise. Additionally, it is the only species within the nutrient cycling group with a breeding range that spans the contiguous United States, with some areas in the west only covered by this species, and other areas not accounted for at all (see **Appendix B: Additional figures** for maps demonstrating areas not covered). Due to these factors, not only did the red-winged blackbird have a disproportionate impact in my spatial models in the west, southwest, and the Appalachian Mountains, but there may be unexpected effects of ANLN in mountainous areas we did not capture. Thus, I am not confident in the accuracy of the present results for this service. The categorization of more species that provide this service will likely address the challenge of assessing ANLN's impact.

Pollination & Carrion Disposal

The largest effects of night light and noise on pollination and carrion disposal were seen in and around metropolitan areas, as species providing these services were not found to be sensitive to night light or noise (see Figures 10-13 **Figure *10***: Night light effects on Pollination), though some pollinators were found to have relatively low night light thresholds (see **Appendix A: Species Pollutant Level Thresholds**). Although a small number of species were analyzed for these two services, the unique evolutionary traits required to effectively pollinate plants and dispose of carrion restrict the species capable of providing these services to a smaller subset of species than the other services discussed. This contrasts with nutrient cycling above, which is likely provided by many more species than were included in this analysis. Thus, I have higher confidence in the results for these services and present them here.

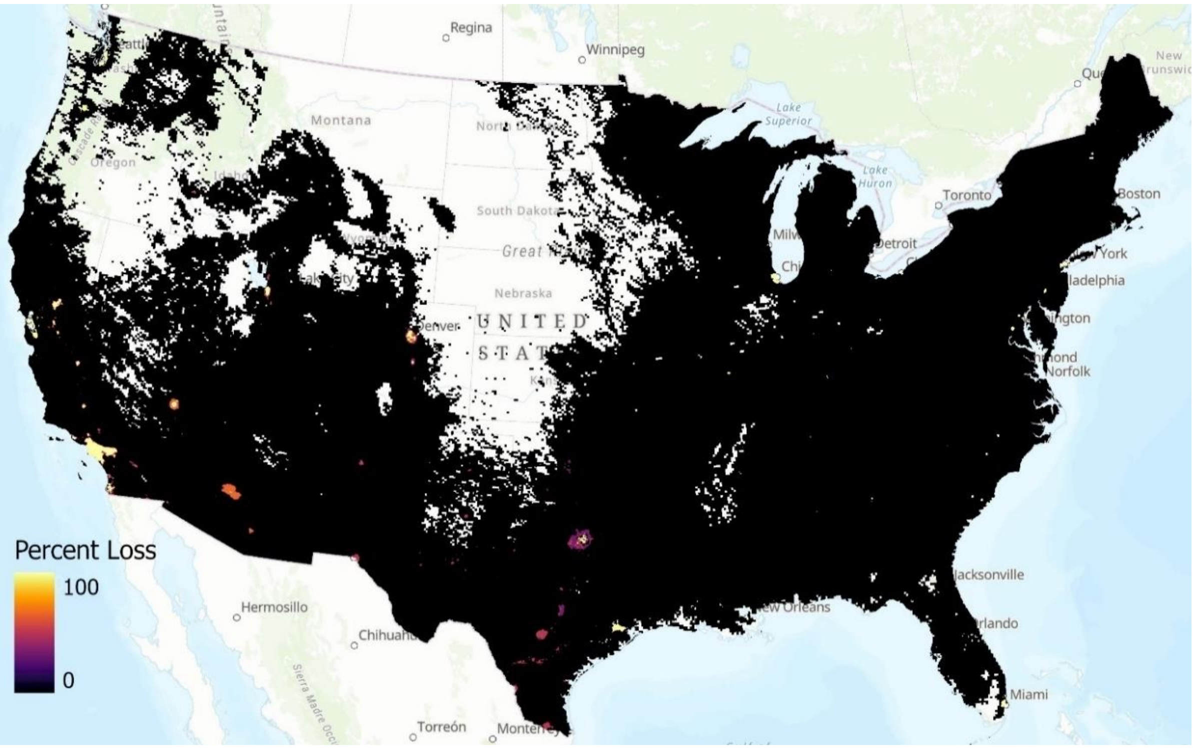


Figure 10: Night light effects on Pollination

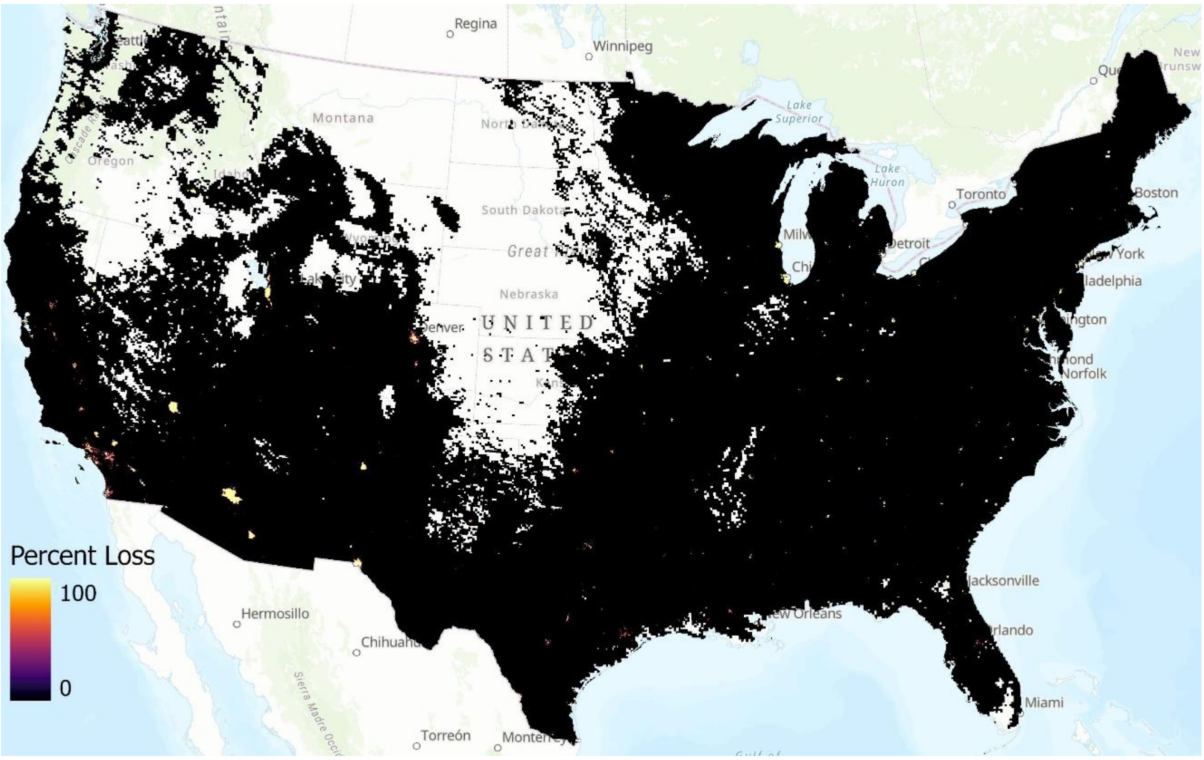


Figure 11: Noise effects on Pollination

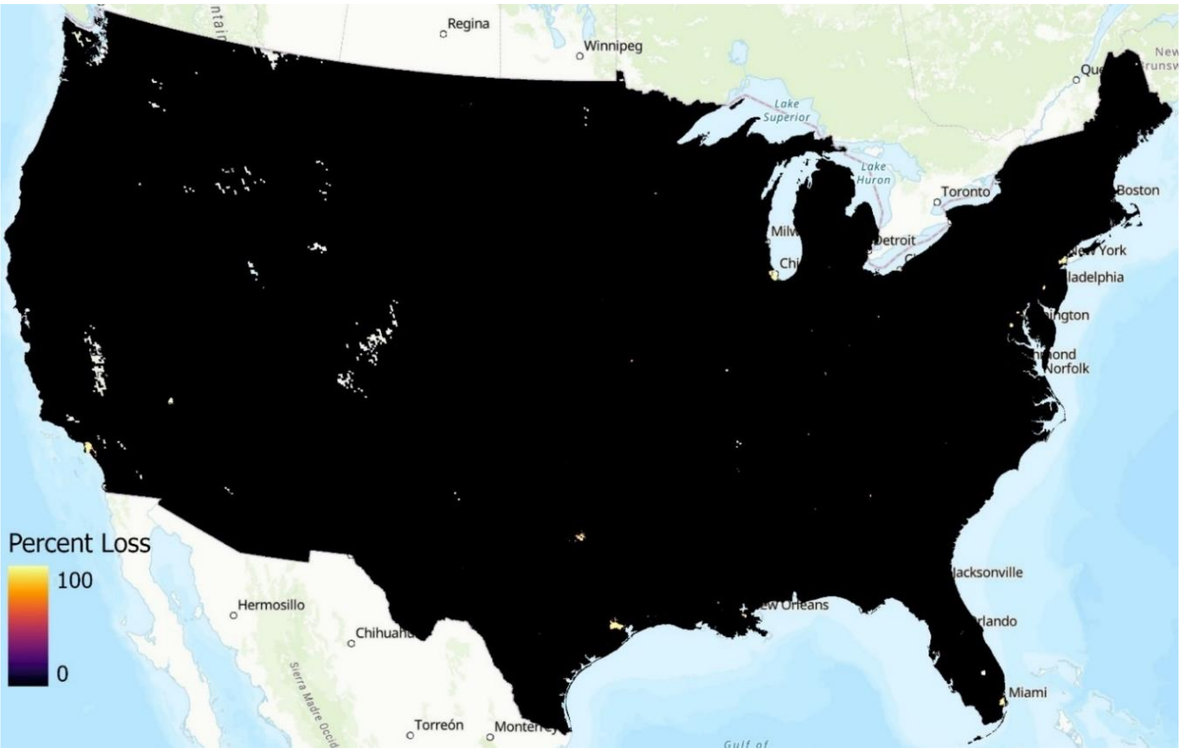


Figure 12: Night light effects on Carrion Disposal

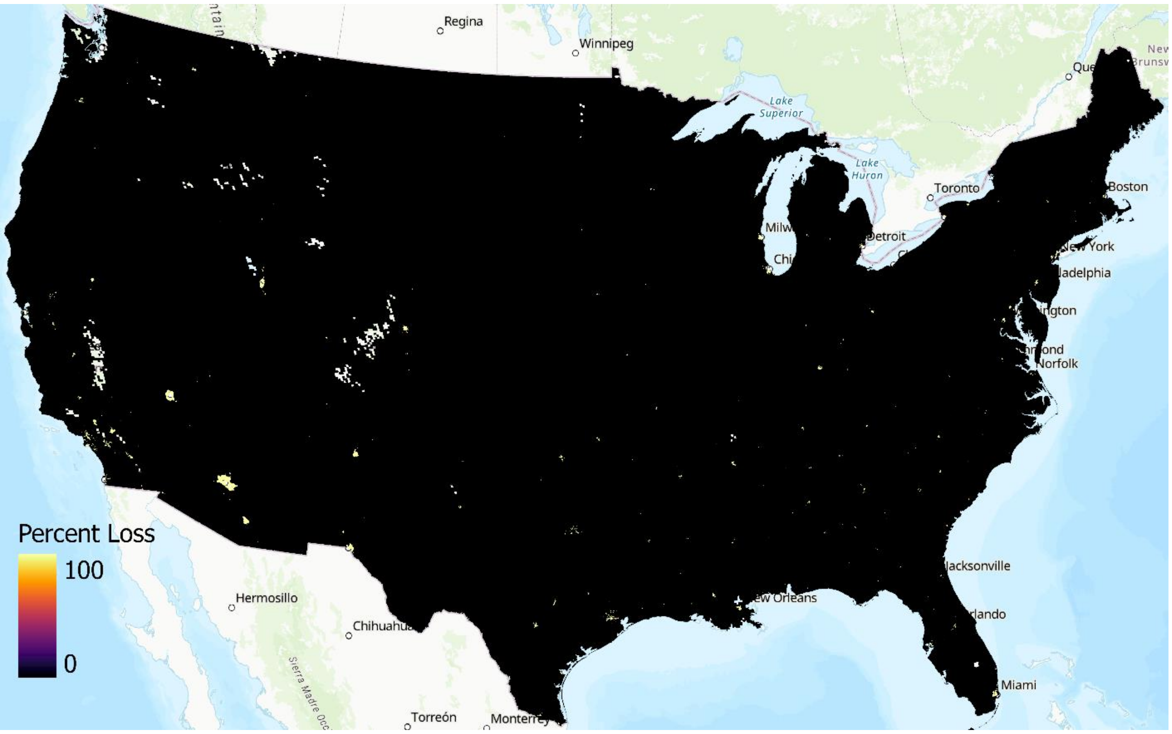


Figure 13: Noise effects on Carrion Disposal

Ecoregions & Ecosystem Services

The average predicted effects of pollutants on ecosystem service loss vary across ecoregions (see **Figure 2** and **Table 1** below for level 1 ecoregions and their associated level 2 regions). In US EPA level 1 ecoregions, both night light and noise have greatest potential affects across services in the Tropical Wet Forests, Mediterranean California, and North American Deserts, with light also affecting Marine West Coast Forests, and noise the Southern Semiarid Highlands. In level 2 ecoregions the strongest effects of both light and noise are in the Everglades, Mediterranean California, Warm Deserts and semiarid regions, with the most affected semiarid regions differentiating by pollutant (light highly influencing West-Central Semiarid Prairies, and noise influencing the South-Central Semiarid Prairies and the Tamaulipas-Texas Semiarid Plain).

Table 1: EPA Level 1 Ecoregions and Associated Level 2 Ecoregions

Level 1 Ecoregion	**Level 2 Ecoregions**
Eastern Temperate Forests	Central USA Plains Mixed Wood Plains Ozark/Ouachita-Appalachian Forests Southeastern USA Plains Mississippi Alluvial and Southeast USA Coastal Plains
Northern Forests	Mixed Wood Shield Atlantic Highlands
Tropical Wet Forests	Everglades
Great Plains	Temperate Prairies West-central Semiarid Prairies South Central Semiarid Prairies Tamaulipas-Texas Semiarid Plain Texas-Louisiana Coastal Plain

North American deserts	Cold Deserts Warm Deserts
Northwestern forested mountains	Western Cordillera
Temperate Sierras	Upper Gila Mountains
Southern Semiarid Highlands	Western Sierra Madre Piedmont
Marine West Coast Forest	Marine West Coast Forest
Mediterranean California	Mediterranean California

Seed dispersal follows the trend described above when considering level 1 ecoregions (see **Figure 14**), with average loss due to noise in the Tropical Wet Forests exceeding 50%, and the lowest average loss in mountainous west ecoregions, including the Northwestern Forested Mountains and the Marine West Coast Forest at approximately 20% and 26%, respectively. The average predicted loss of seed dispersal due to light was much lower, with

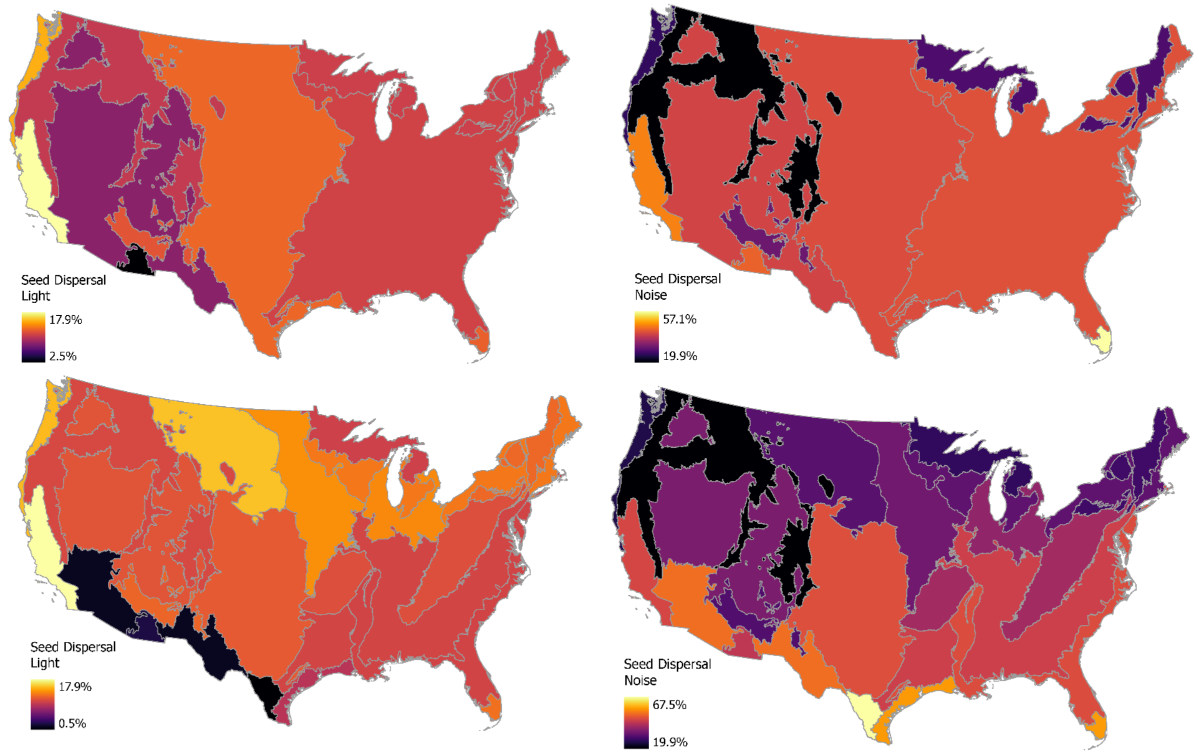


Figure 14: Average Loss of Seed Dispersal by pollutant in Level 1 and Level 2 Ecoregions

the highest loss at 18% in the Mediterranean California ecoregion, the lowest area of loss in the Southern Semiarid Highlands region at less than 3%, and most other ecoregions losing 10%-13% of potential seed dispersal.

When we consider level 2 ecoregions, we see seed dispersal loss due to noise greatest in the southernmost ecoregions, including the Everglades and Texas-Louisiana coastal plain at 57%, and highest loss in the Tamaulipas-Texas semiarid plain at 68%. The level 2 coregions most robust to seed dispersal loss due to noise are the same areas as level 1 regions, the Northwestern Forested Mountains and Marine West Coast. Of note, the highest losses due to light are predicted occur in west coast ecoregions such as the Marine West Coast Forest, Mediterranean California, and the West-Central Semiarid Prairies (all between 15% and 18% loss), and the lowest losses occur in the desert southwest, with the Tamaulipas-Texas Semiarid Plain, the Warm Deserts, and the Western Sierra Madre Piedmont losing less than 3%.

Invertebrate pest control also sees smaller losses due to light than noise (see **Figure 15**), but the difference is much smaller than for seed dispersal. The range of pest control loss due to noise is 5% - 21% for level 1 ecoregions, with highest loss occurring in the North American Deserts, Southern Semiarid Highlands, and the Great Plains, and lowest loss in some forested ecoregions, with Marine West Coast Forest, Northwestern Forested Mountains, and Tropical Wet Forests all losing <10%. Pest control loss due to light ranged from <1% - 18%, with the North American Deserts and Mediterranean California sustaining the highest loss, and Northern, Eastern Temperate, and Marine West Coast Forests all losing <3%. Level 2 ecoregions saw a 5% - 26% loss in pest control due to noise, with arid and semiarid regions tending to incur higher loss, and wetter areas (Marine West Coast Forest,

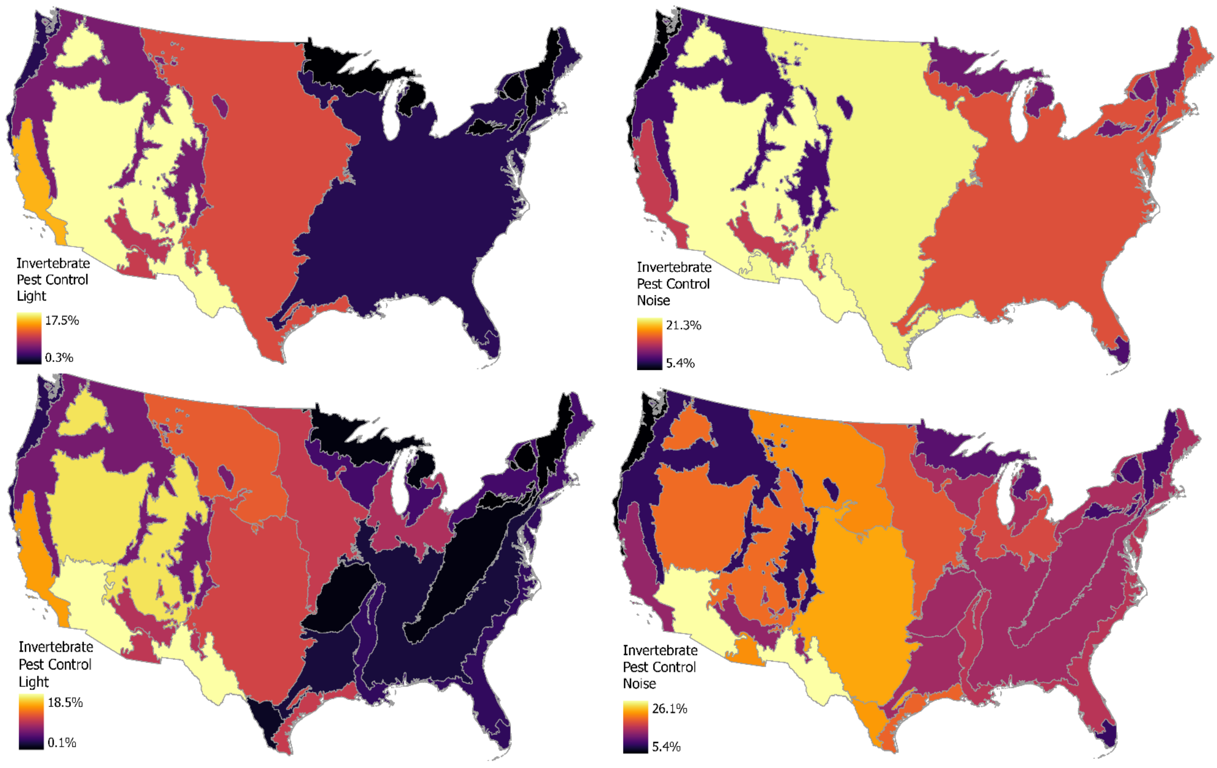


Figure 15: Average Loss of Invertebrate Pest Control by Pollutant in Level 1 and Level 2 Ecoregions

Everglades, Atlantic Highlands) tending to experience lower predicted loss. Invertebrate pest control loss due to light at level 2 ecoregions, with losses of >1%-18.5%, followed level 1 regions fairly closely, with highest losses occurring in the arid and semiarid regions of the west, and the smallest losses occurring across the eastern half of the country at ≤ 3%.

Pollination generally was minimally affected by night light and noise, though in contrast to the services discussed thus far, light's effects were greater (see **Figure 16**). Maximum predicted loss due to night light was calculated at 6%, and noise at >2%, with Mediterranean California predicted to experience the highest loss across both pollutants and ecoregion levels. The Northern Forests, Temperate Sierras, and Southern Semiarid Highlands are the level one ecoregions at lowest risk of loss due to light and noise, with the level 2 subregions Atlantic Highlands, Mixed Wood Shield, and West-Central Semiarid Prairies experiencing the smallest losses due to light and noise (all >0.05%).

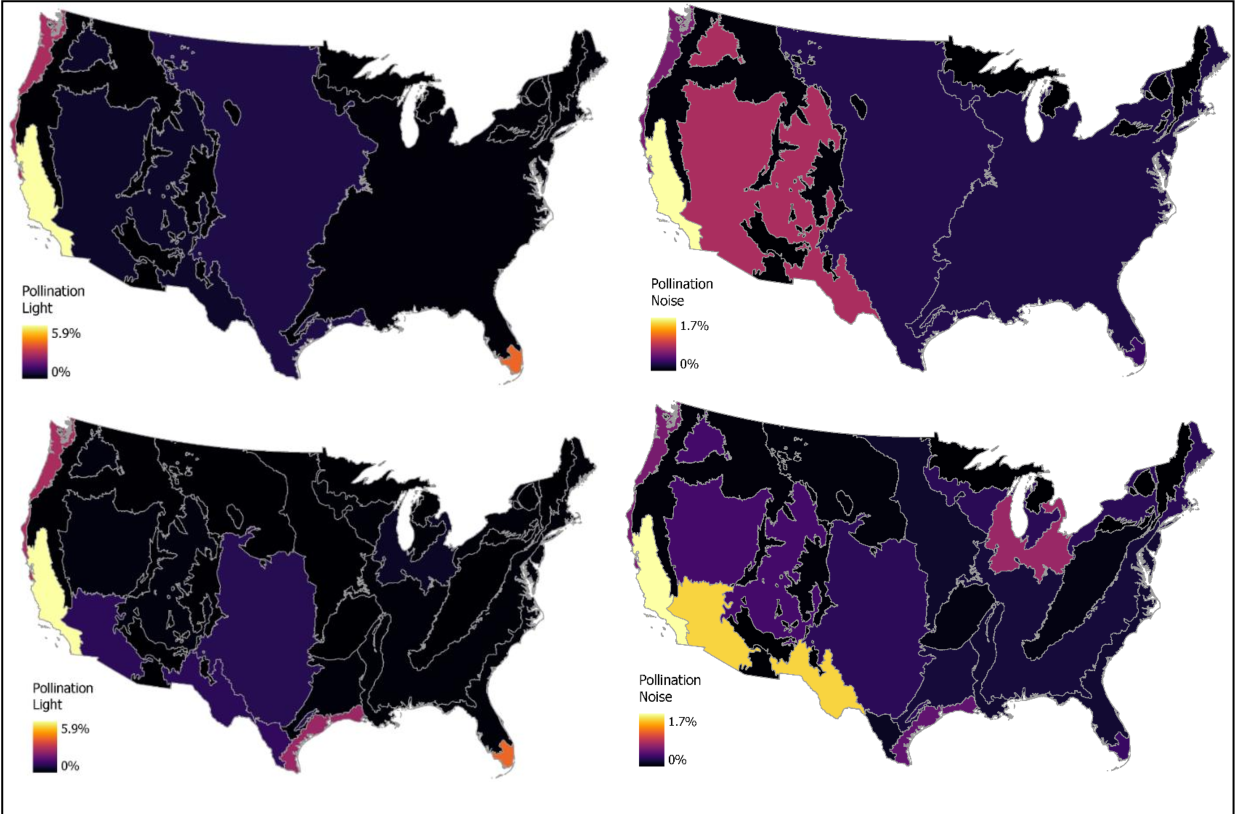


Figure 16: Average Loss of Pollination by Pollutant in Level 1 and Level 2 Ecoregions

Carrion disposal is also predicted to be minimally affected by night light and noise across ecoregions, with average maximum losses at approximately 2% due to light and 1% due to noise (see **Figure 17**). The Tropical Wet Forests/Everglades and the Texas-Louisiana Coast Plain are the only ecoregions predicted to lose >1% of carrion disposal due to light, and in addition to these regions, noise also affects level 2 Warm Deserts at just over 1% loss.

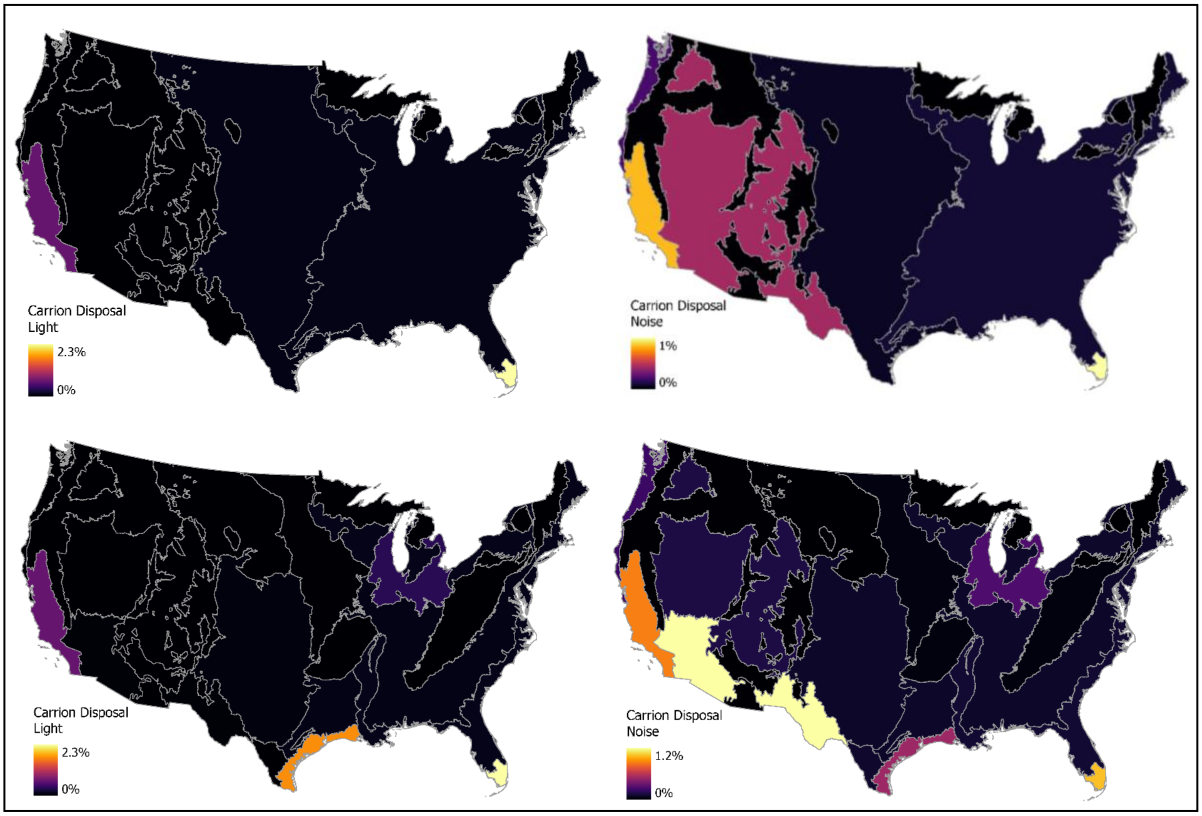


Figure 17: Average Loss of Carrion Disposal by Pollutant in Level 1 and Level 2 Ecoregions

Chapter 4: Discussion

Urbanization and the increasing ANLN pollution associated with this most extreme form of human disturbance will likely impact ecosystem services provided by birds. These impacts will vary across the services, with seed dispersal likely to decrease the most, followed by invertebrate pest control; the highest losses concentrate in the arid and semiarid ecoregions of the Southwest. Compared to seed dispersal and pest control, carrion disposal and pollination are predicted to be relatively unaffected by ANLN. I also found that noise is more pertinent than night light, and over a wider spatial scale, indicating anthropogenic noise may have greater influence on avian ecosystem services. All services are predicted to be severely diminished within large urban areas, such as Los Angeles, Chicago, and New York City, tracking with my finding that a majority of the 60 species are intolerant to high levels of one or both sensory pollutants, levels almost certain to be encountered in tandem in large urban centers. One third of the continental US is experiencing diminished services due to nightlight and noise.

Noise had much stronger effects on bird occurrence and ecosystem services than nightlight. Given the tendency of anthropogenic noise to be sound of low frequencies, it may propagate further through certain environments, such as dense forests, that light is less able to penetrate, and thus may have further reaching effects. However, despite these potential limitations, my findings are supported by efforts to assess the independent roles of noise and light[57]. In contrast to migration, when many nocturnal migrants are exposed and particularly vulnerable to high levels of night light[58,59,60], during the breeding season many species of birds resume a more typical sleep-wake cycle. Birds demonstrate many adaptations to night light: great tits (*Parus major*) alter their roosting behaviors within brightly lit environments to avoid high light levels[61], other bird species seem to prefer certain levels of night light over total darkness[62,20], and migratory species seem to alter their association with urban areas during the breeding season, while resident species do not[63].

I found that seed dispersal and invertebrate pest control are more impacted than the other three services, and that the Southwest is at higher risk than other regions. My review of the literature yielded 22 species that perform seed dispersal and 25 species that perform invertebrate pest control, compared to only a handful of species confirmed to provide nutrient cycling, pollination, and carrion disposal (n = 8, n = 5 and n = 2, respectively). Of the species in these three services, only one was found to be particularly sensitive to ANLN, and had a disproportionate impact due to its wide geographic range. If analyses of these three services are run with a larger number of species included, a more nuanced or alternative picture of the effects of ANLN may emerge. The identity and number of species included in my analysis likely also influences the high impacts of ANLN in the Southwest. The rural portions of these arid and semiarid areas do not experience extremely high pollutant levels (based on the nightlight[46,47] and noise[45] datasets used), but generally have a lower total number of species providing seed dispersal and invertebrate pest control. Thus, loss in these areas could be driven by a few highly affected species.

Limitations

This research is limited by current gaps in our scientific knowledge of ecosystem services provided by fauna and the effects of community alterations on service provision. The research available regarding individual bird species' ecosystem service provision is sparse, particularly when considering studies that quantitatively measure a service. Thus, many species that provide the five ecosystem services studied no doubt were left out of these analyses. This could be remedied by assuming species provide services according to their foraging guilds; however, as several of the studies reviewed for this research demonstrate[43,64-67], eating a certain food does not necessarily equate to effectively providing a service. Furthermore, in my review of the literature I only came across a few studies[20,68,69] examining the effects of ANLN on bird community assemblages, or the effects of community changes on service provision in a particular area. Though the ecosystem function literature supports the idea of the redundancy hypothesis, it is unclear what the species richness ‘tipping point’ is beyond which a service will decline. This area of study is critical when considering species changes in abundance and/or extirpation due to human disturbance.

This research is also limited by the shortcomings of statistical and spatial models. As mentioned in the methods section, an interaction factor between night light and noise was not incorporated into the species ANLN models, as it significantly increased each model’s computation time. My findings of the opposing effects of night light and noise on some species are in line with previous research detailing the complex and nuanced relationships between these pollutants, habitat type/traits, and community assemblages[57,20,70]. Including this factor may help give a clearer picture of ANLN’s cumulative effects on ecosystem services, and perhaps explain some of the large differences in predicted service loss between pollutants. Due to computational and time constraints, I also was unable to include a level of nuance of ecosystem service provision that might be desired by other researchers or natural resource managers. Scientists or conservation professionals may be interested in a very particular aspect of a service, such as when nutrient peak nutrient cycling occurs, or when/where nutrient cycling may occur in excess, such that it becomes a disservice. Due to use of occurrence rather than abundance data, and a focus on broad service categories, this research is unable to answer such questions. Furthermore, the ‘seasonality’ of service provision – the shift of species’ diets toward invertebrates before and while raising young, and back toward their ‘nonbreeding’ diet – was not accounted for in these models, and the variation in species’ breeding season lengths (and thus a measure of how much they may contribute to a service within their breeding) also was not included. The species range maps used did not parse the breeding range into chick rearing areas and non-breeding (but still summer) areas. This could be accomplished in the future with a different eBird Status and Trends product, in combination with temporally finer breeding season information.

Potential Applications

The datasets generated by this research will be useful for natural resource managers, planners, and ecologists concerned with preserving ecosystem services from human disturbance within certain habitats. While ecoregion data is given as averages of level 1 and level 2 ecoregions, conservation professionals may find homing in on more specific local ecoregions (EPA levels 3 or 4) more useful to examine potential effects of ANLN on specific areas of concern. This is easily accomplished in GIS software with these datasets and the appropriate EPA ecoregion datasets. While these data may not be easily used within typical conservation decision tools (such as cost-benefit analyses), they could be useful to demonstrate the potential effects of ANLN to the public, government, and nonprofit or for-profit companies. The ANLN species models may be used in their own right, if the effects of ANLN on that species are of concern in a particular area or the species’ entire range.

Literature Cited

1. Venter, O. *et al.* Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. *Nat. Commun.* 7, 1–11 (2016).
2. Ditmer, M. A. *et al.* Artificial nightlight alters the predator–prey dynamics of an apex carnivore. *Ecography (Cop.).* 44, 149–161 (2021).
3. Winger, B. M. *et al.* Nocturnal flight-calling behaviour predicts vulnerability to artificial light in migratory birds. *Proc. R. Soc. B Biol. Sci.* **286**, (2019).
4. Blickley, J. L. *et al.* Experimental Chronic Noise Is Related to Elevated Fecal Corticosteroid Metabolites in Lekking Male Greater Sage-Grouse (Centrocercus urophasianus). *PloS One* **7**, (2012).
5. Grunst, M. L. *et al.* Early-life exposure to artificial light at night elevates physiological stress in free-living songbirds. *Environ. Pollut.* **259**, (2020).
6. van Doren, B. M. *et al.* Drivers of fatal bird collisions in an urban center. *Proc. Natl. Acad. Sci. U. S. A.* **118**, 1–8 (2021).
7. Grier, J. W. Ban of DDT and subsequent recovery of reproduction in bald eagles. *Science (80-.).* **218**, 1232–1234 (1982).
8. Kelly, T. R. & Johnson, C. K. Lead exposure in free-flying Turkey vultures is associated with big game hunting in California. *PLoS One* **6**, (2011).
9. Van Doren, B. M. *et al.* High-intensity urban light installation dramatically alters nocturnal bird migration. *Proc. Natl. Acad. Sci. U. S. A.* **114**, 11175–11180 (2017).
10. Evans Ogden, Lesley J., "Summary Report on the Bird Friendly Building Program: Effect of Light Reduction on Collision of Migratory Birds." (2002). Fatal Light Awareness Program (FLAP). 5. https://digitalcommons.unl.edu/flap/5

11. McLaren, J. D. *et al.* Artificial light at night confounds broad-scale habitat use by migrating birds. *Ecol. Lett.* **21**, 356–364 (2018).
12. Wiltschko, W. & Wiltschko, R. Migratory orientation of European Robins is affected by the wavelength of light as well as by magnetic pulse. *J Comp Physiol A* **177**, 363–369 (1995).
13. Titulaer, M., Spoelstra, K., Lange, C. Y. M. J. G. & Visser, M. E. Activity Patterns during Food Provisioning Are Affected by Artificial Light in Free Living Great Tits (Parus major). *PLoS One* **7**, 37377 (2012).
14. Santos, C. D. *et al.* Effects of artificial illumination on the nocturnal foraging of waders. *Acta Oecologica* **36**, 166–172 (2010).
15. Senzaki, M. *et al.* Sensory pollutants alter bird phenology and fitness across a continent. *Nature* 587, 605–609 (2020).
16. Ferraro, D. M., Le, M. L. T. & Francis, C. D. Combined effect of anthropogenic noise and artificial night lighting negatively affect Western Bluebird chick development. *Condor* **122**, 1–12 (2020).
17. Aulsebrook, A. E. *et al.* White and Amber Light at Night Disrupt Sleep Physiology in Birds. *Curr. Biol.* **30**, 3657-3663.e5 (2020).
18. Ouyang, J. Q. *et al.* Restless roosts: Light pollution affects behavior, sleep, and physiology in a free-living songbird. *Glob. Chang. Biol.* **23**, 4987–4994 (2017).
19. Becker, D. J. *et al.* Artificial light at night amplifies seasonal relapse of haemosporidian parasites in a widespread songbird: ALAN and parasite relapse. *Proc. R. Soc. B Biol. Sci.* **287**, (2020).
20. Willems, J. S., Phillips, J. N. & Francis, C. D. Artificial light at night and anthropogenic noise alter the foraging activity and structure of vertebrate communities. *Sci. Total Environ.* **805**, 150223 (2022).

21. Barber, J. R., Crooks, K. R. & Fristrup, K. M. The costs of chronic noise exposure for terrestrial organisms. *Trends Ecol. Evol.* **25**, 180–189 (2010).
22. Kleist, N. J., Guralnick, R. P., Cruz, A., Lowry, C. A. & Francis, C. D. Chronic anthropogenic noise disrupts glucocorticoid signaling and has multiple effects on fitness in an avian community. *Proc. Natl. Acad. Sci. U. S. A.* **115**, E648–E657 (2018).
23. Habib, L., Bayne, E. M. & Boutin, S. Chronic industrial noise affects pairing success and age structure of ovenbirds Seiurus aurocapilla*. J. Appl. Ecol.* **44**, 176–184 (2007).
24. Kleist, N. J., Guralnick, R. P., Cruz, A. & Francis, C. D. Sound settlement: Noise surpasses land cover in explaining breeding habitat selection of secondary cavity-nesting birds: Noise. *Ecol. Appl.* **27**, 260–273 (2017).
25. Mulholland, T. I. *et al.* Effects of Experimental Anthropogenic Noise Exposure on the Reproductive Success of Secondary Cavity Nesting Birds. *Integr. Comp. Biol.* **58**, 967–976 (2018).
26. Dowling, J. L., Luther, D. A. & Marra, P. P. Comparative effects of urban development and anthropogenic noise on bird songs. *Behav. Ecol.* **23**, 201–209 (2012).
27. Barber, J. R. *et al.* Anthropogenic noise exposure in protected natural areas: Estimating the scale of ecological consequences. *Landsc. Ecol.* **26**, 1281–1295 (2011).
28. Bayne, E. M., Habib, L. & Boutin, S. Impacts of chronic anthropogenic noise from energy-sector activity on abundance of songbirds in the boreal forest. *Conserv. Biol.* **22**, 1186–1193 (2008).
29. Shannon, G. *et al.* A synthesis of two decades of research documenting the effects of noise on wildlife. *Biol. Rev.* **91**, 982–1005 (2016).

30. Kight, C. R., Saha, M. S. & Swaddle, J. P. Anthropogenic noise is associated with reductions in the productivity of breeding Eastern Bluebirds (Sialia sialis). *Ecol. Appl.* **22**, 1989–1996 (2012).
31. Whelan, C. J., Wenny, D. G. & Marquis, R. J. Ecosystem services provided by birds. *Ann. N. Y. Acad. Sci.* **1134**, 25–60 (2008).
32. Whelan, C. J., Şekercioğlu, Ç. H. & Wenny, D. G. Why birds matter: from economic ornithology to ecosystem services. *Journal of Ornithology* vol. 156 227–238 (2015).
33. Bruns, H. The economic importance of birds in forests. *Bird Study* **7**, 193–208 (1960).
34. Şekercioğlu, Ç. H. Analysis: The Economic Value of Birds. *Living Bird* https://www.allaboutbirds.org/news/analysis-the-economic-value-of-birds/ (2017).
35. Aitken, K. E. H., Wiebe, K. L. & Martin, K. Nest-site reuse patterns for a cavity-nesting bird community in interior British Columbia. *Auk* **119**, 391–402 (2002).
36. Bennett, J. & S. Whitten. Duck hunting and wet- land conservation: compromise or synergy? *Canad. J. Agric. Econ.* **51**, 161-173 (2003).
37. Kjølsrød, L. & Kjølsrød, L. in *Leisure as Source of Knowledge, Social Resilience and Public Commitment* 145–168 (Palgrave Macmillan UK, 2019). Doi:10.1057/978-1-137-46287-9_7
38. Methorst, J., Arbieu, U., Bonn, A., Böhning-Gaese, K. & Müller, T. Non-material contributions of wildlife to human well-being: A systematic review. *Environ. Res. Lett.* **15**, (2020).
39. Şekercioğlu, Ç. H., Daily, G. C. & Ehrlich, P. R. Ecosystem consequences of bird declines. *Proc. Natl. Acad. Sci. U. S. A.* **101**, 18042–18047 (2004).
40. Boerema, A., Rebelo, A. J., Bodi, M. B., Esler, K. J. & Meire, P. Are ecosystem services adequately quantified? *J. Appl. Ecol.* **54**, 358–370 (2017) doi:10.1111/1365-2664.12696.

41. Why Birds Matter: Avian Ecological Function and Ecosystem Services. University of Chicago Press (2016).
42. Lange, R. S. & Scott, P. E. Hummingbird and Bee Pollination of Penstemon pseudospectabilis. *J. Torrey Bot. Soc.* **126**, 99–106 (1999).
43. Hill, J. E., DeVault, T. L., Beasley, J. C., Rhodes, O. E. & Belant, J. L. Effects of vulture exclusion on carrion consumption by facultative scavengers. *Ecol. Evol.* **8**, 2518–2526 (2018).
44. Pardieck, K.L., Ziolkowski Jr., D.J., Lutmerding, M., Aponte, V.I., and Hudson, M-A.R., 2020, North American Breeding Bird Survey Dataset 1966 – 2019: U.S. Geological Survey data release, https://doi.org/10.5066/P9J6QUF6.
45. Mennitt, D. J., Sherrill, K. & Fristrup, K. A geospatial model of ambient sound pressure levels in the contiguous United States. **135**, (2015).
46. Falchi F, Cinzano P, Duriscoe D, Kyba CC, Elvidge CD, Baugh K, Portnov BA, Rybnikova NA, Furgoni R. The new world atlas of artificial night sky brightness. *Sci. Adv.* **2**, (2016).
47. Falchi, Fabio; Cinzano, Pierantonio; Duriscoe, Dan; Kyba, Christopher C. M.; Elvidge, Christopher D.; Baugh, Kimberly; Portnov, Boris; Rybnikova, Nataliya A.; Furgoni, Riccardo (2016): Supplement to: The New World Atlas of Artificial Night Sky Brightness. GFZ Data Services. http://doi.org/10.5880/GFZ.1.4.2016.001
48. Rousset F, Ferdy J (2014). “Testing environmental and genetic effects in the presence of spatial autocorrelation.” *Ecography*, **37**(8), 781-790. http://dx.doi.org/10.1111/ecog.00566.
49. R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.
50. Fox J, Weisberg S (2019). *An R Companion to Applied Regression*, Third edition. Sage, Thousand Oaks CA. https://socialsciences.mcmaster.ca/jfox/Books/Companion/

51. Florian Hartig (2022). DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models. R package version 0.4.5. https://CRAN.R-project.org/package=DHARMa
52. Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models Usinglme4. *Journal of Statistical Software*, *67*(1). https://doi.org/10.18637/jss.v067.i01
53. Philpott, S. M. *et al.* (2009). Functional richness and ecosystem services: Bird predation on arthropods in tropical agroecosystems. *Ecol. Appl.* **19**, 1858–1867 (2009).
54. Fink, D., T. Auer, A. Johnston, M. Strimas-Mackey, O. Robinson, S. Ligocki, W. Hochachka, C. Wood, I. Davies, M. Iliff, L. Seitz. 2020. eBird Status and Trends, Data Version: 2019; Released: 2020. Cornell Lab of Ornithology, Ithaca, New York. https://doi.org/10.2173/ebirdst.2019
55. U.S. Environmental Protection Agency. NA_Eco_Level1 dataset. U.S. EPA Office of Research & Development (ORD) - National Health and Environmental Effects Research Laboratory (NHEERL), Corvallis, Oregon (2010). https://www.epa.gov/eco-research/ecoregions-north-america
56. U.S. Environmental Protection Agency. NA_CEC_Eco_Level2 dataset. U.S. EPA Office of Research & Development (ORD) - National Health and Environmental Effects Research Laboratory (NHEERL), Corvallis, Oregon (2010). https://www.epa.gov/eco-research/ecoregions-north-america
57. Wilson, A. A. *et al.* Artificial night light and anthropogenic noise interact to influence bird abundance over a continental scale. *Glob. Chang. Biol.* **27**, 3987–4004 (2021).

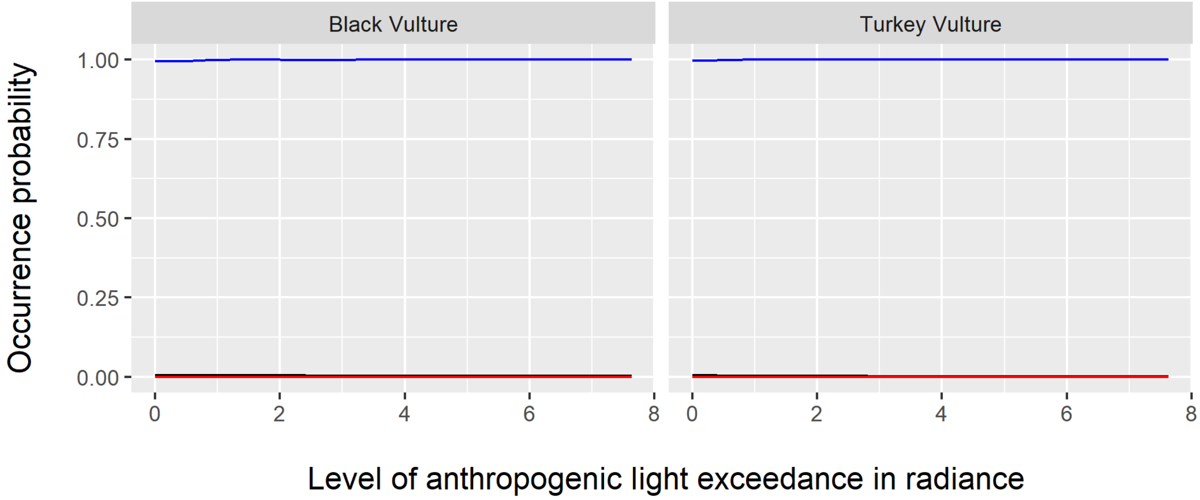
58. La Sorte, F. A., Fink, D., Buler, J. J., Farnsworth, A. & Cabrera-Cruz, S. A. Seasonal associations with urban light pollution for nocturnally migrating bird populations. *Glob. Chang. Biol.* **23**, 4609–4619 (2017).
59. Horton, K. G. *et al.* Bright lights in the big cities: migratory birds' exposure to artificial light. *Front. Ecol. Environ.* **17**, 209–214 (2019).
60. Cabrera-Cruz, S. A., Smolinsky, J. A. & Buler, J. J. Light pollution is greatest within migration passage areas for nocturnally-migrating birds around the world. *Sci. Rep.* **8**, 4–11 (2018).
61. De Jong, M., Ouyang, J. Q., Van Grunsven, R. H. A., Visser, M. E. & Spoelstra, K. Do wild great tits avoid exposure to light at night? *PLoS One* **11**, 1–8 (2016).
62. Meerlo, P. *et al.* The preference and costs of sleeping under light at night in forest and urban great tits. (2019).
63. Callaghan, C. T., Cornwell, W. K., Poore, A. G. B., Benedetti, Y. & Morelli, F. Urban tolerance of birds changes throughout the full annual cycle. 1503–1517 (2021) doi:10.1111/jbi.14093
64. Jennings, D. E., Gould, J. R., Vandenberg, J. D., Duan, J. J. & Shrewsbury, P. M. Quantifying the impact of woodpecker predation on population dynamics of the emerald ash borer (Agrilus planipennis). *PLoS One* **8**, (2013).
65. Traveset, A. Effect of seed passage through vertebrate frugivores' guts on germination: A review. *Perspect. Plant Ecol. Evol. Syst.* **1**, 151–190 (1998).
66. Hamilton, D. J., Ankney, C. D. & Bailey, R. C. Predation of Zebra Mussels by Diving Ducks: An Exclosure Study. *Ecology* **75**, 521–531 (1994).
67. Powers, K. D, Noble, R. E. & Chabreck, R. H. Seed Distribution by Waterfowl in Southwestern Louisiana. *J. Wildl. Manage.* **42**, 598–605 (1978).

68. Fröhlich, A. & Ciach, M. Nocturnal noise and habitat homogeneity limit species richness of owls in an urban environment. *Environ. Sci. Pollut. Res.* **26**, 17284–17291 (2019).
69. Phillips, J. N., Termondt, S. E., Francis, C. D. & Phillips, J. N. Long-term noise pollution affects seedling recruitment and community composition, with negative effects persisting after removal. (2021).
70. Dominoni, D., Smit, J. A. H., Visser, M. E. & Halfwerk, W. Multisensory pollution: Artificial light at night and anthropogenic noise have interactive effects on activity patterns of great tits (Parus major). *Environ. Pollut.* **256**, 113314 (2020).

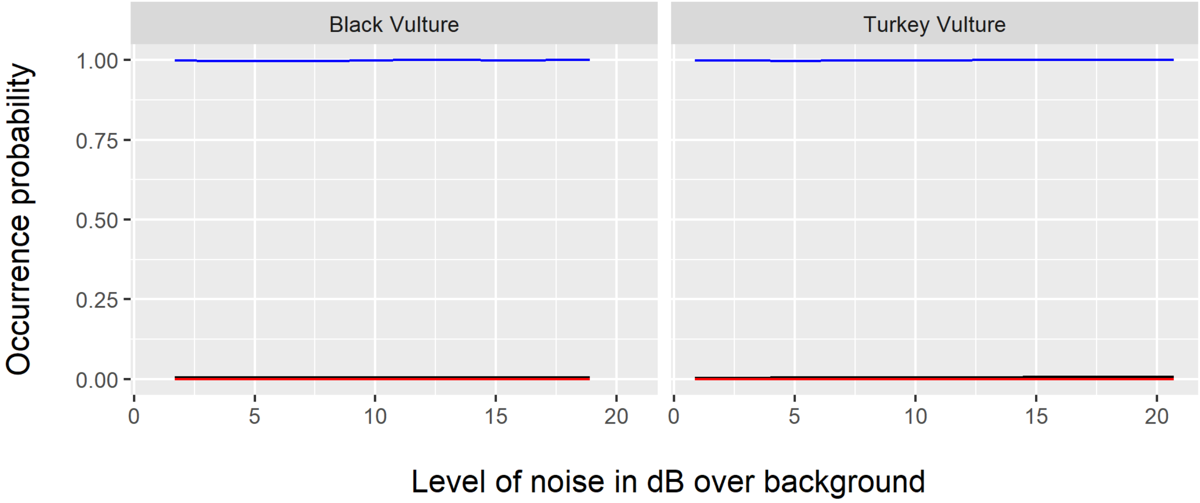
Appendix A: Species Pollutant Level Thresholds

This appendix contains plots of species predicted occurrence by partial dependence effects of pollutant, grouped by ecosystem service. Black lines represent the average predicted occurrence rate, red lines represent the lower confidence interval (2.5%) and blue lines the upper confidence interval (97.5%) of predicted occurrence. Many occurrence predictions drop off after a certain pollutant level, indicating that the species was not observed along Breeding Bird Survey routes with night light or noise at or above that level.

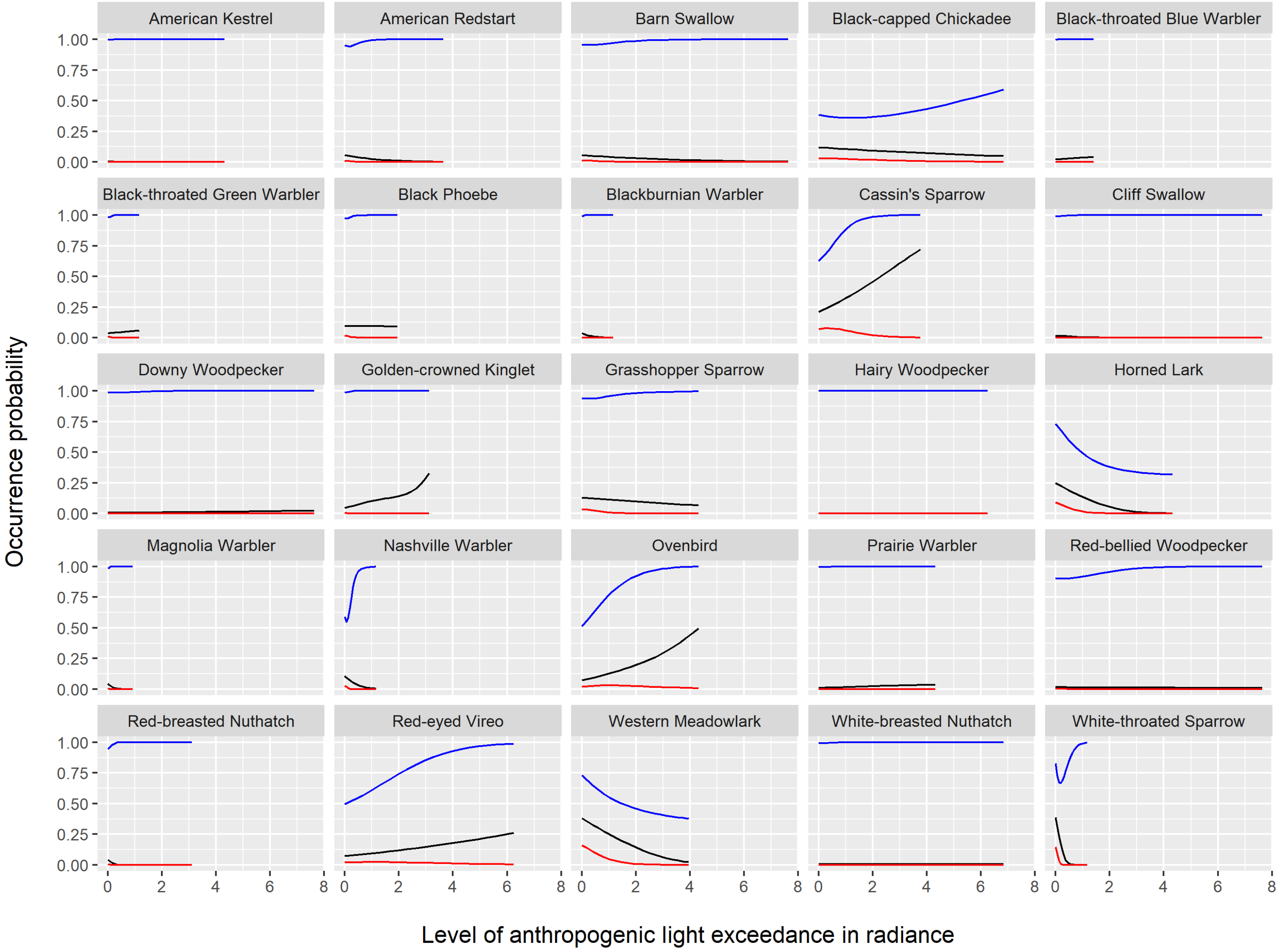
Carrion Disposal, Night Light



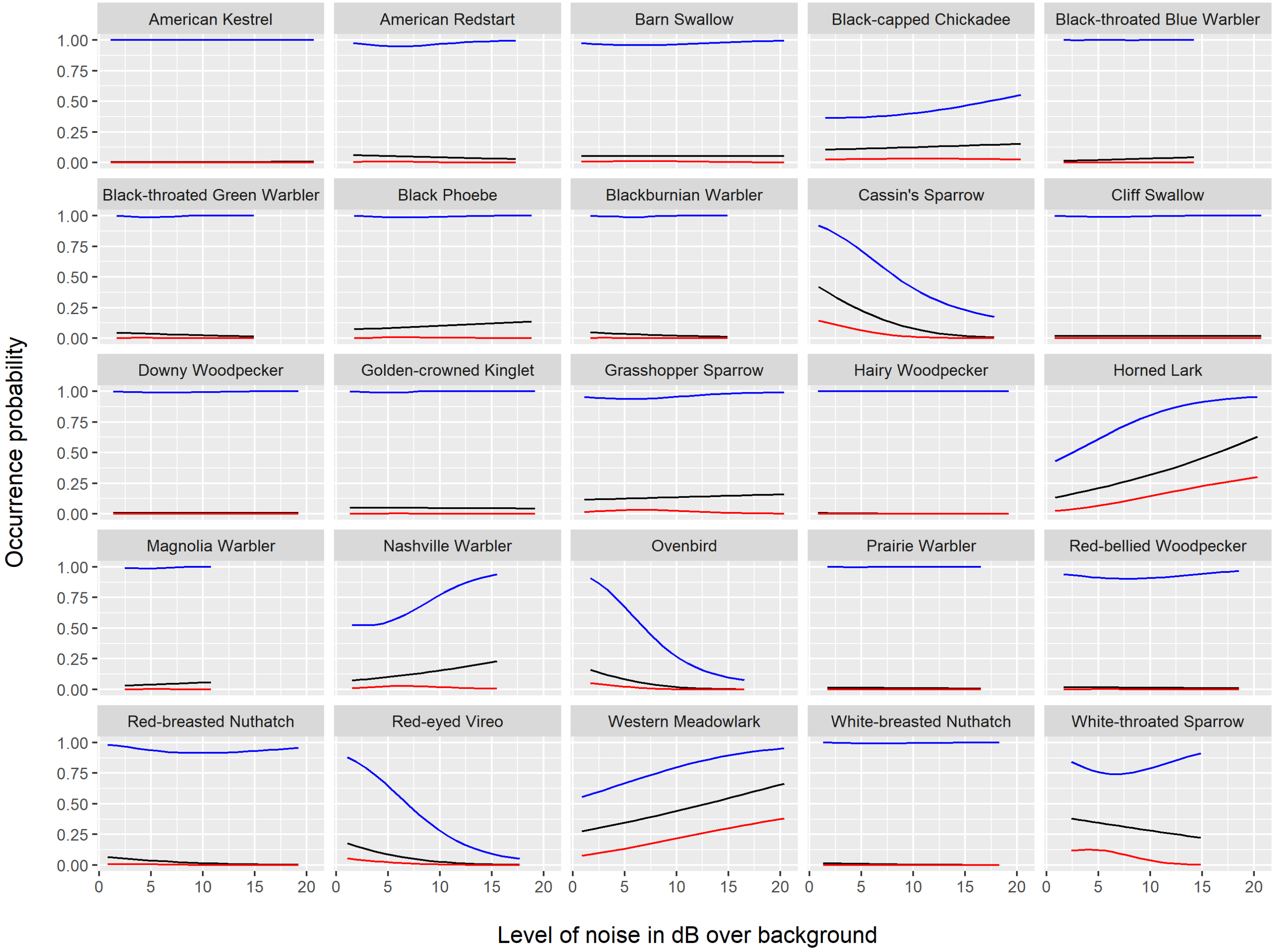
Carrion Disposal, Noise



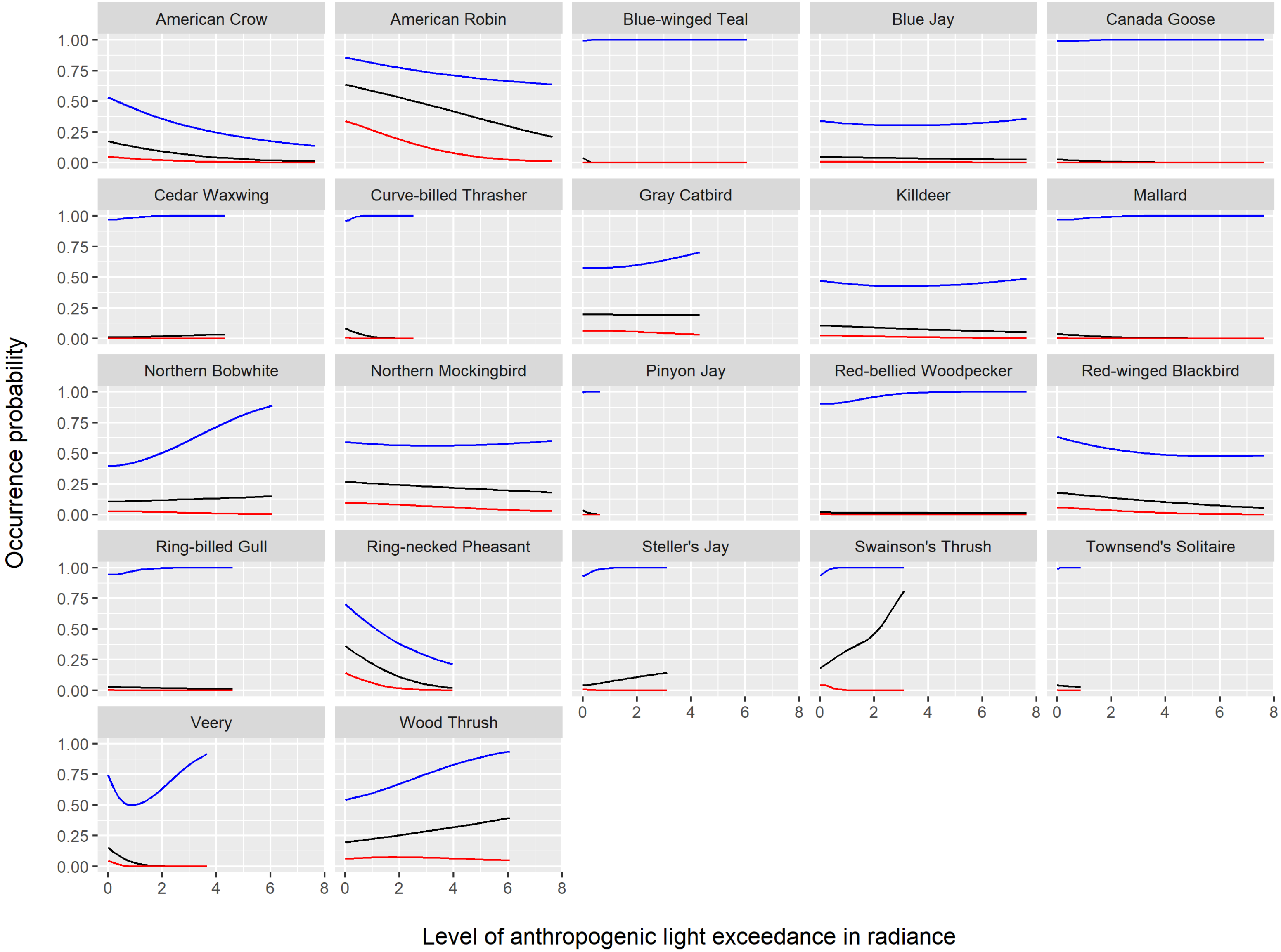
Invertebrate Pest Control, Night Light



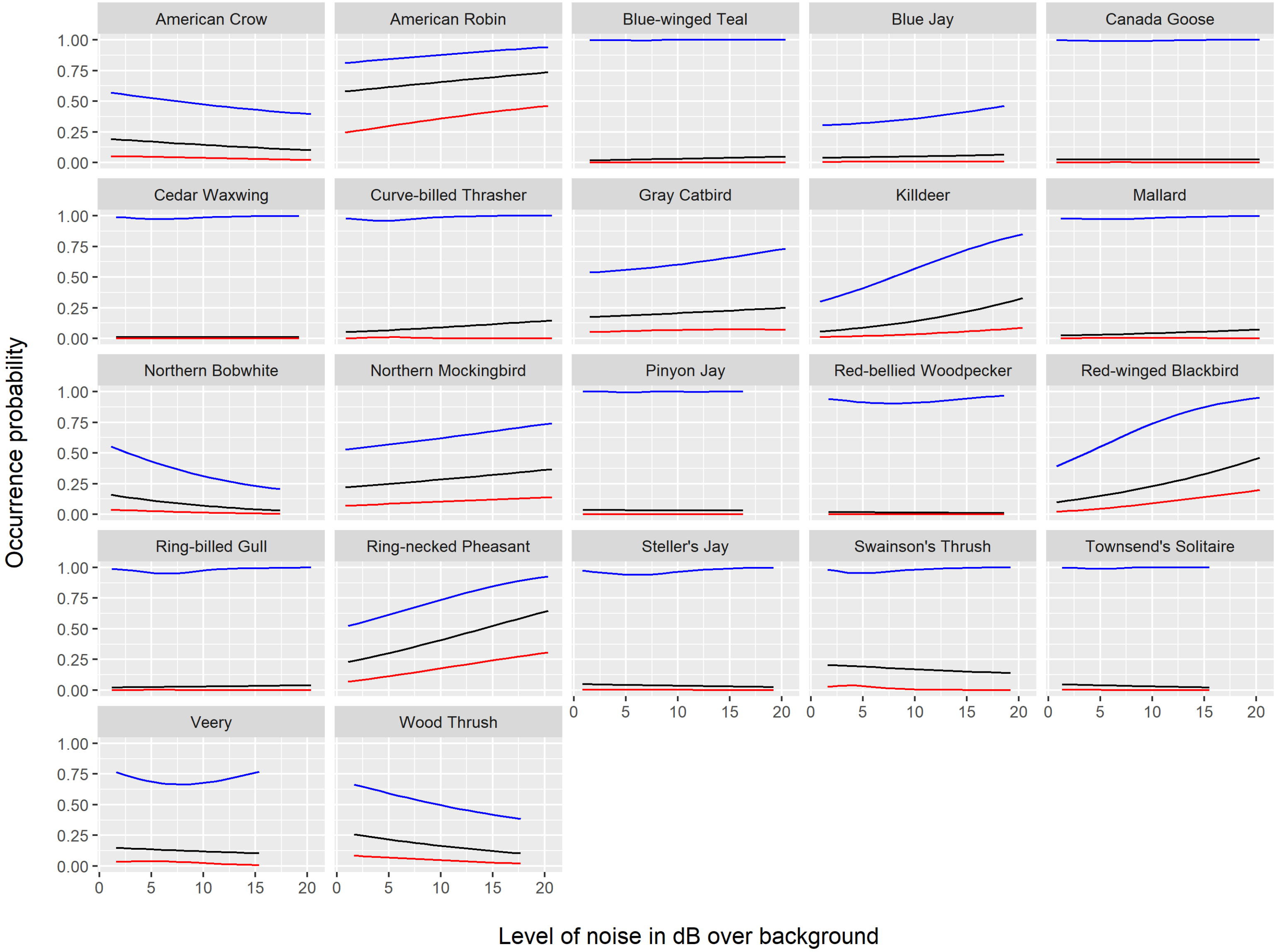
Invertebrate Pest Control, Noise



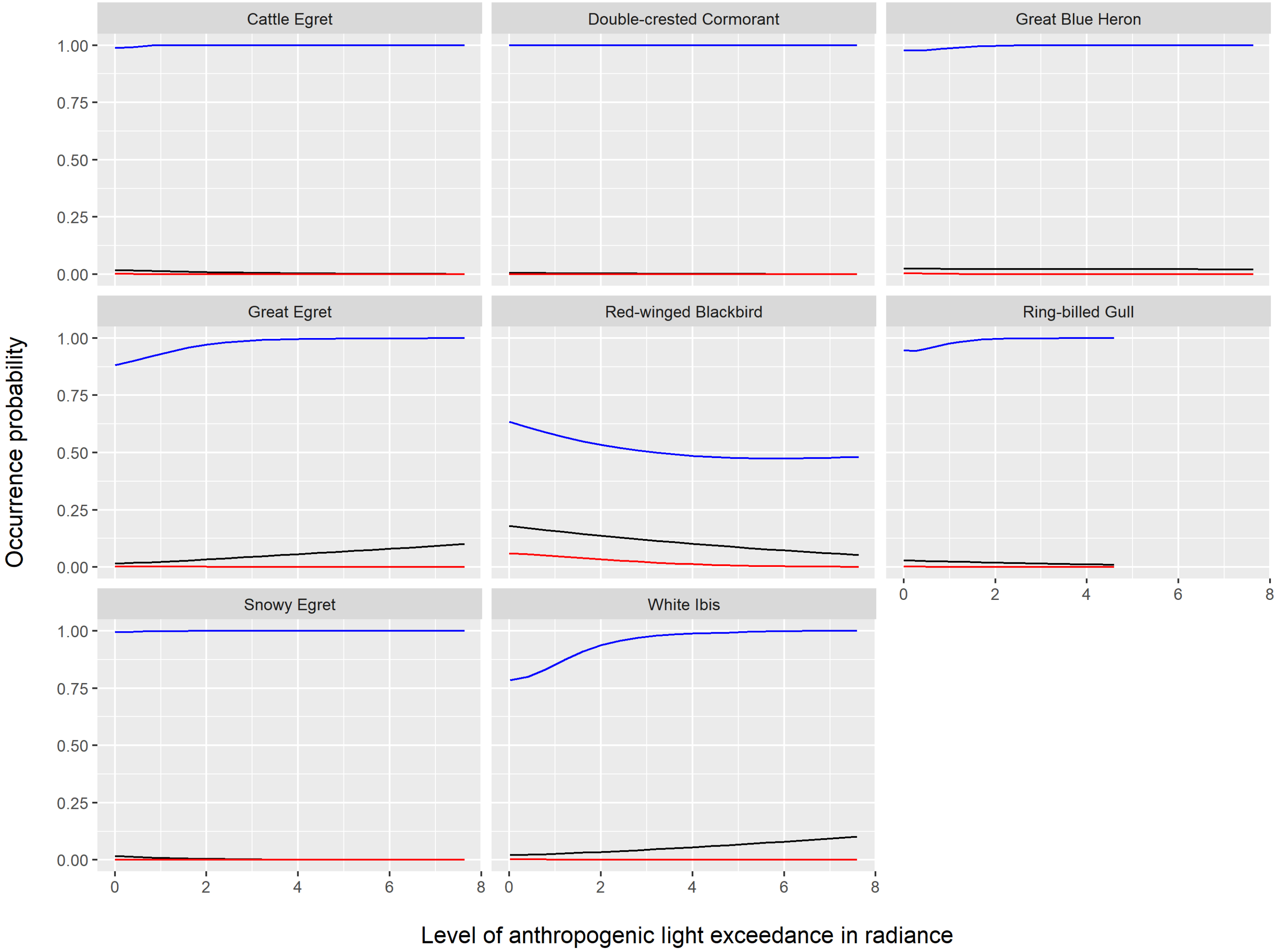
Seed Dispersal, Night Light



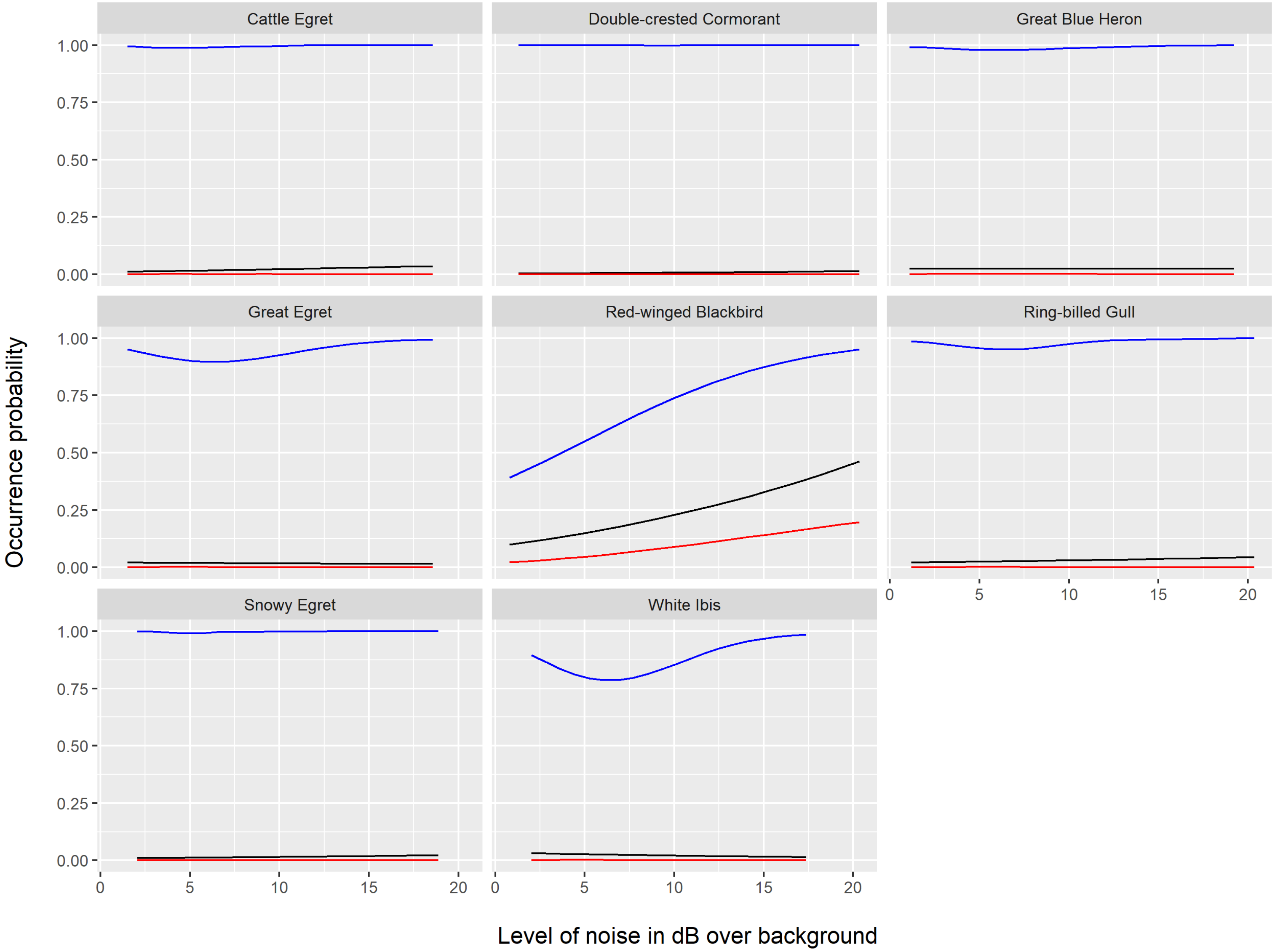
Seed Dispersal, Noise



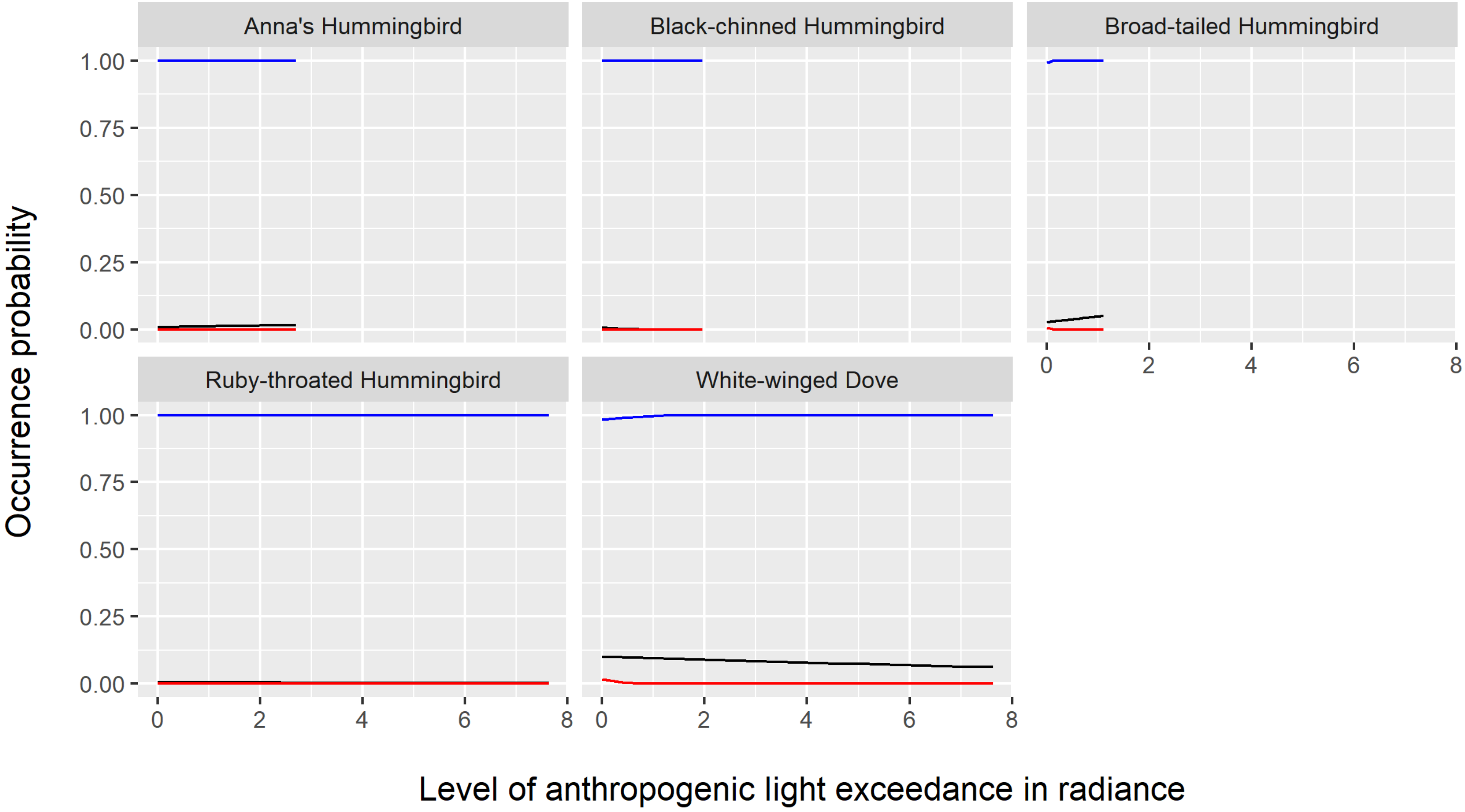
Nutrient Cycling, Night Light



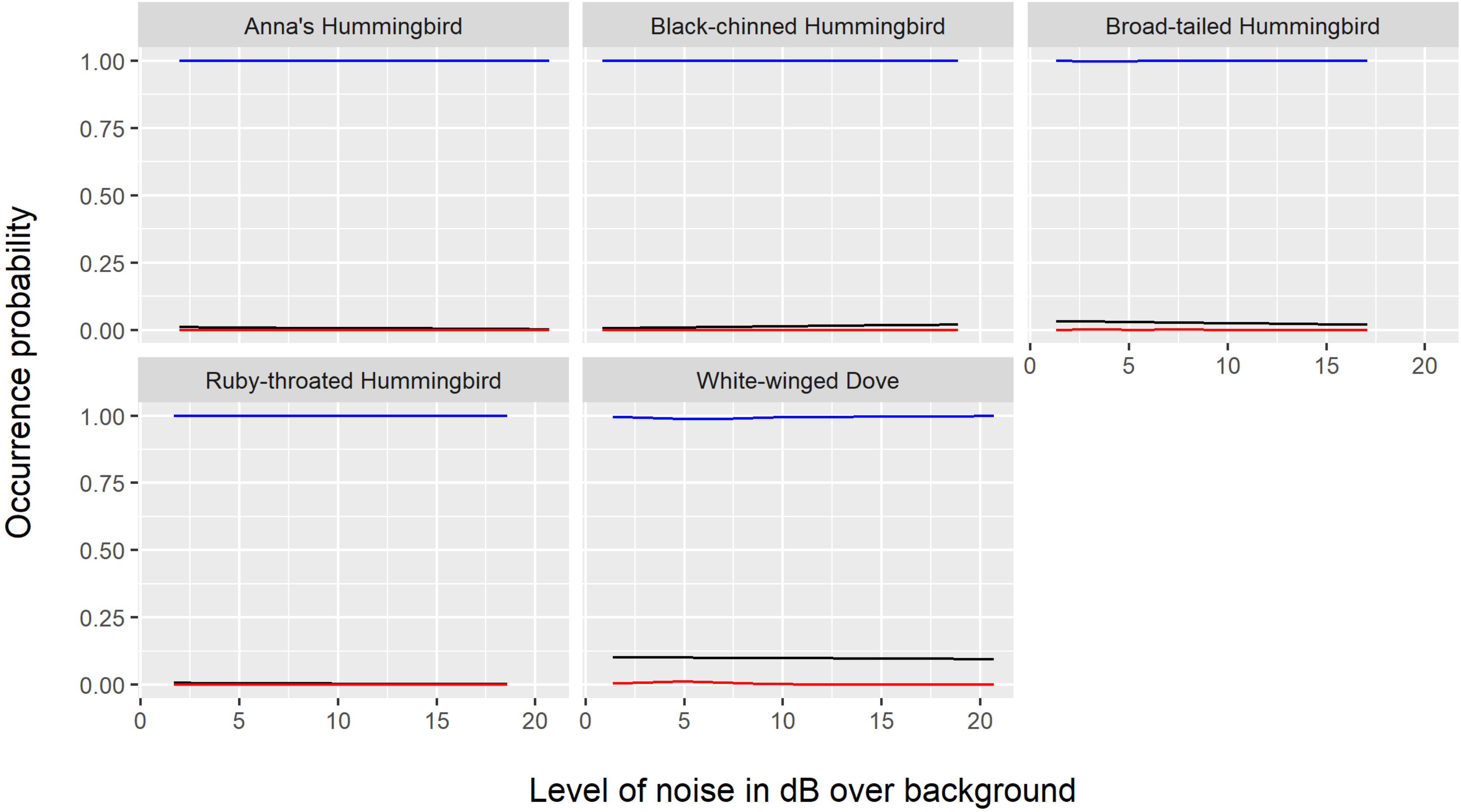
Nutrient Cycling, Noise



Pollination, Night Light

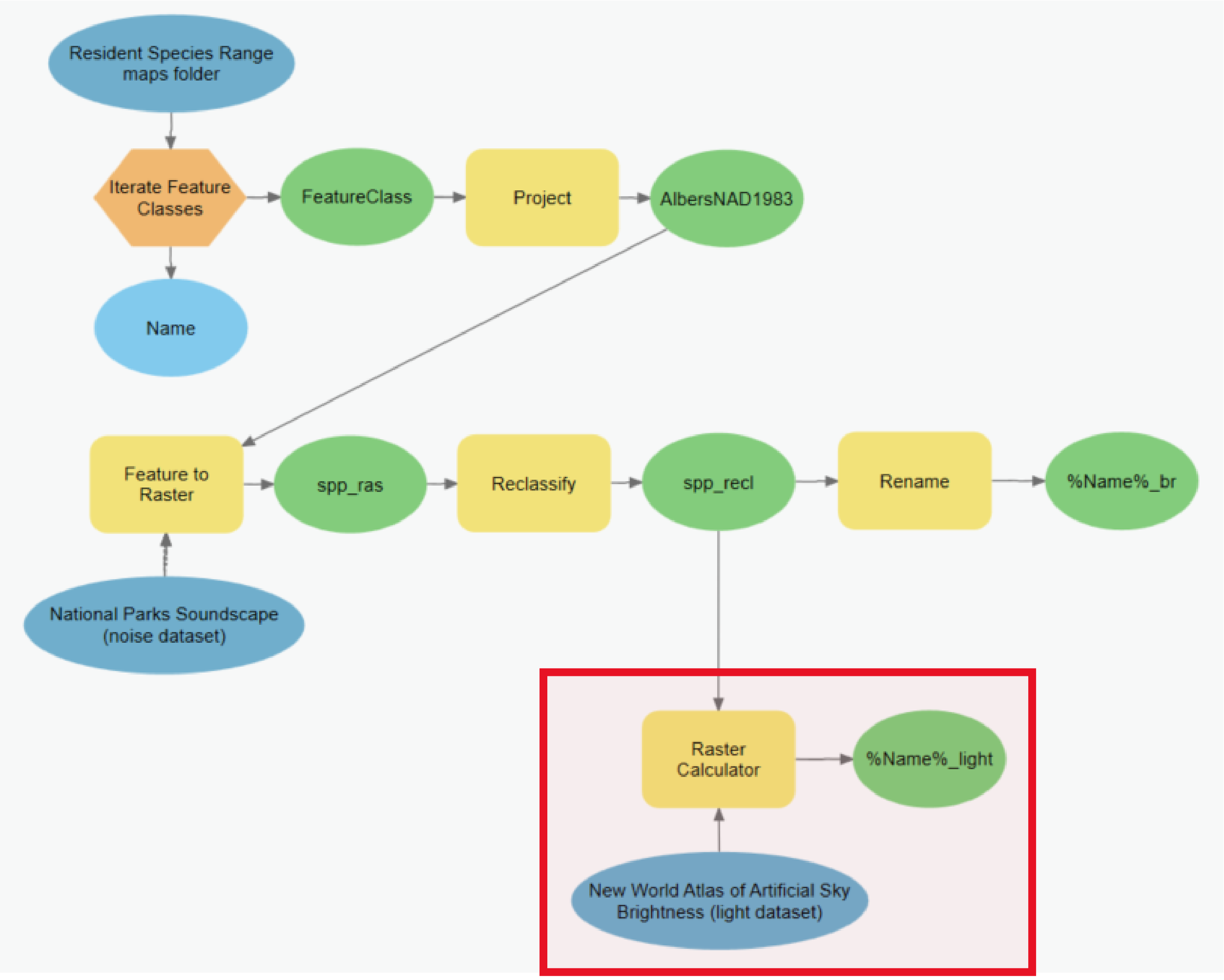


Pollination, Noise



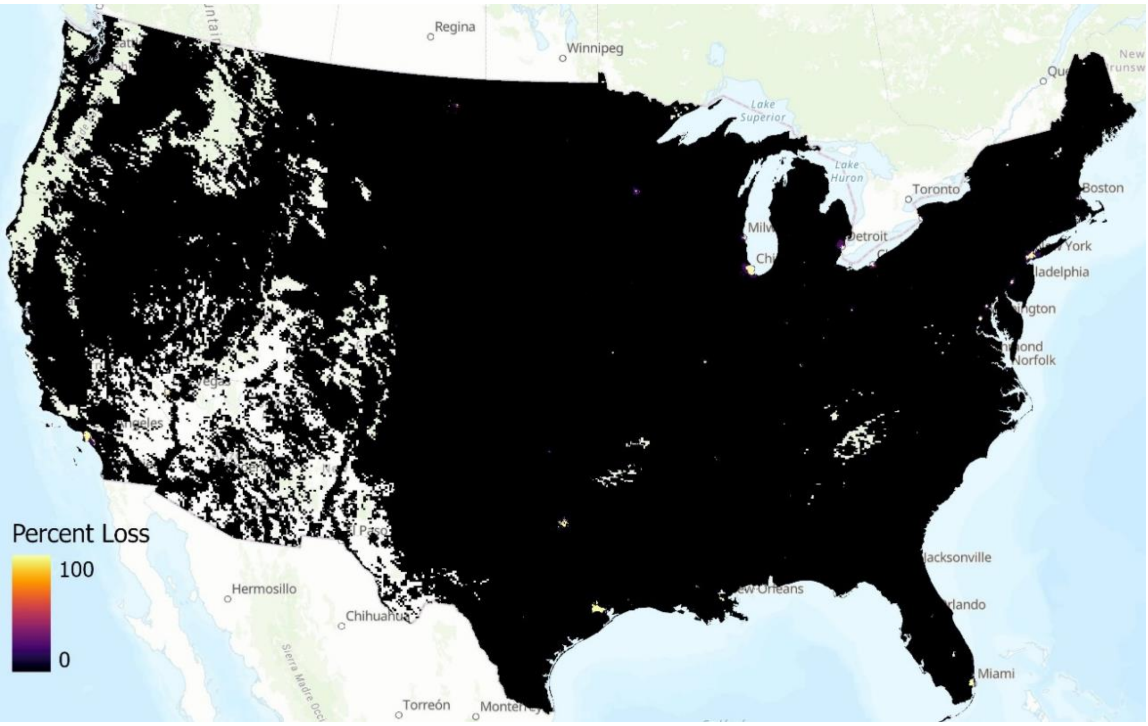
Appendix B: Additional figures

ArcGIS workflow converting resident species polygons to rasters

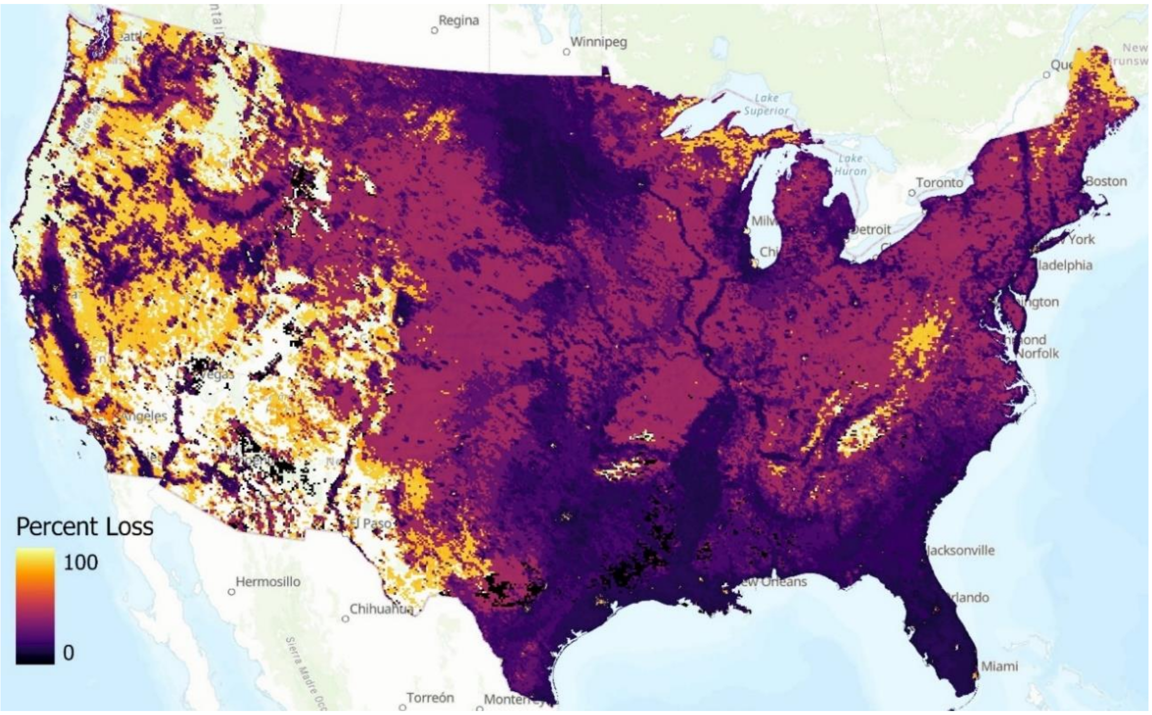


ArcGIS workflow for converting resident species breeding polygons to ES total species rasters and light pollutant species rasters.

Night light effects on Nutrient Cycling



Noise effects on Nutrient Cycling



Note the areas of the West, Southwest, and small patches along the Appalachian mountains which both maps are white, a color not in the percent loss color scale. These are areas that fall outside of the ranges of the eight species categorized as providing nutrient cycling. In the map below, areas of high loss in the West, Southwest, Northeast, Appalachia, and the Upper Midwest are all due to the effects of one species, the red-winged blackbird.