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Keeping birds away from food using sonic technology: a potential for protecting crops

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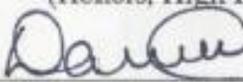
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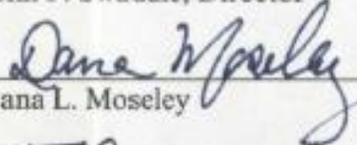
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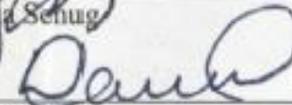
by

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Accepted for __Honors__
(Honors, High Honors, Highest Honors)

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Williamsburg, VA
April 22, 2016

Abstract

Pest birds cause billions of dollars in damages in the agricultural (crop loss) and aviation (collision with aircraft) industries annually in the US. Current methods to control problem birds are often ineffective. A new solution: A broadband spatially-controlled noise (termed a "sonic net") will prevent birds from hearing each other and hearing predators, rendering an area unsuitable and making birds go elsewhere. The goal of the current project is to evaluate whether a sonic net is an effective way to deter wild songbirds from food sources. We recorded the behavior and inter-species interactions of birds at feeders located at two sites. The sonic net was deployed at one feeder at each site, while the other feeder served as a control without additional noise. Overall, birds spent approximately 35% less time at the sonic net feeders compared to control feeders. Dominant species' duration per visit did not vary significantly (1.4%), while subordinate species were largely affected by noise (51.3%). Additionally, we assessed the inter-species interactions underneath noise and food manipulation (less access to food on control feeder). Socially dominant species spent only 4.45% less time at the sonic net feeder as compared to subordinate species (33.5%). This suggests that the sonic net may affect species differently depending on dominance hierarchy and vocal ranges, meaning that protection of food crops may depend on the species present in the area. Nonetheless, the sonic net is a potential solution to reduce crop loss caused by pest birds from farms over long periods of time.

Introduction

Anthropogenic noise (i.e., noise produced by human development) affects terrestrial and aquatic environments, inducing changes in behavioral and physiological traits of numerous taxa (Holt and Johnston, 2015; Francis et al., 2009; McClure et al., 2013; Ware et al., 2015). As a result of changes in noisy areas, these habitats have low species diversity, with high densities of specific species, especially among avian populations (Anderies et al. 2007). To understand these changes in avian communities, it is important to recognize the mechanisms by which noise affects interactions among bird species.

Anthropogenic noise is characterized by low frequencies and high amplitudes (McClure et al., 2013; Ware et al., 2015; Francis et al., 2009). Previous studies have shown correlations between the negative effects of noise on species composition and disruption of acoustic communication (Francis et al. 2009; Francis, 2011; Goodwin and Shriver, 2010; Mahjoub et al., 2015). Acoustic communication is crucial to many aspects of avian life history, including mating, foraging, and territoriality (Catchpole and Slater, 2008; McMullen et al., 2013). For example, flocking bird species, like the European starling (*Sturnus vulgaris*), rely on acoustic communication to indicate the location of food and roosting areas, and warn of nearby predators (Mahjoub et al., 2015). Evolutionarily, singing in some bird species is used in sexual selection in which the quality of song (length and complexity) can attract mates or deter conspecifics (Goodwin and Podos, 2012; McMullen et al., 2013; Swaddle et al., 2015). In addition to visual signals, auditory information is used to convey and maintain inter- and intra-species hierarchies within avian communities. In order for successful communication to occur, a signaler must

transmit information to a receiver and a receiver must be able to interpret and respond appropriately to the perceived signal (McMullen et al., 2013).

Acoustic signals are particularly sensitive to changes in acoustic environments in which noise may overlap with the signal. Disruption of acoustic communication can occur when auditory signals are produced within the amplitude and frequency ranges of noise. If auditory communication is disrupted, species-specific behaviors such as antipredator responses are adapted to noise presence. For example, breeding female house sparrows (*Passer domesticus)* exposed to noise are more likely to flush more quickly as compared to control house sparrows (Meillère et al., 2015). Additionally, a common consequence of auditory communication disruption is movement of species to new areas. Gray flycatchers (*Empidonax wrightii*), gray vireos (*Vireo vicinior*), and spotted towhees (*Piplio maculatus*) were observed to nest farther away than other species in areas adjacent to noisy gas wells (Francis et al., 2009).

Natural habitats exposed to constant anthropogenic noise showed reduction in both species abundance and richness (Francis et al., 2009, McClure et al. 2013). These findings suggests acoustic tolerance varies among avian species. For example, species that vocalize within the frequency range of traffic noise (less than 3 kHz) are more effected, as opposed to species that vocalize outside of the range, and are less likely to visit noisy areas (Goodwin and Shriver, 2010). Species living in noisy environments have also been shown to adapt their songs to increase their likelihood of successful communication (Grace and Anderson, 2014). Certain song elements of the Carolina chickadee (Poecile carolinensis) are produced successfully within high noise areas, suggesting that songs incorporating these elements are effectively detected by conspecifics (Grace and Anderson, 2014). In addition to this acoustic masking effect, foraging behaviors effected in the presence of noise are characteristic of disruption within avian

communities (Francis, 2015; Ware et al., 2015). Species that rely on animal based diets or omnivorous diets were deterred frequently by noise, possibly as interference with detection of prey as compared to species with a plant based diet (Francis, 2015). However, disruption of foraging/vigilance tradeoff system may occur as a result of acoustic masking (Ware et al., 2015). Under noise exposure, birds have been shown to alter the frequency of behaviors to reduce the possibility of depredation (Ware et al. 2015). Furthermore, perception of increased risk of depredation may develop and as a consequence, birds in the presence of noise may disproportionately increase vigilance behaviors compared to foraging behaviors (Mahjoub et al., 2015; Ware et al., 2015). Decreased foraging behaviors suggest lower likelihood of providing food to chicks, reducing overall fitness for the next generation (Ware et al., 2015). Thus, a disruption in auditory communication may result in changes within community structure and dominant and subordinate species interactions (community hierarchy).

It is clear that acoustic disruption of species specific behaviors can alter species abundance and community structure. As species abundance decreases within noisy areas, the species that remain interact with each other in different ways as compared to the pre-noise population. Additionally, specific behaviors, such as agonistic, vigilance, and foraging behaviors may be reduced or enhanced in order to moderate the effects of noise. Hence, in order to adapt to noise, behavior should change to accommodate the loss in acoustic information. If an individual cannot do so without increasing its depredation risk, only noise deprived areas provide acoustically suitable habitats.

Though unintended noise introduction can influence an area's ecology via disruption of species specific occupancy, purposeful introduction of noise into an area can incur economic benefits. For instance, pest birds cost an estimated 1.2 billion dollars annually via damages to

agricultural and aviation industries (Pimentel et al., 2000). Our research group has shown that several songbird species can be displaced from target areas by loud (80 dB SPL) and broad-frequency (2-10 kHz) continuous noise (Mahjoub et al. 2015; Swaddle et al. 2016). If the noise is delivered through highly directional speakers we can produce a spatially-contained sound beam, termed a "sonic net", which can exclude approximately 80% of all individuals from areas for at least four weeks continuously (Swaddle et al. 2016). Groups of birds that remain in noise exposed food sources are subject to increased interspecies competition via competitive exclusion. The effect of noise on community hierarchy around food sources may also influence interspecific behavioral interaction and subsequent species specific access to food. Though studies suggest noise disproportionately impacts foraging/vigilance tradeoffs, interspecies competition under noise effect needs further evaluation.

The primary goal of this thesis was to determine whether a sonic net deterred wild birds from experimentally-controlled food sources, in nature. As the sonic net likely masks acoustic communication, we hypothesized that birds should be deterred from the affected feeders because birds may have reduced abilities to hear predator and alarm calls within the sound field. Specifically, we predicted that birds will eat less food from the sound-treated feeders and birds will spend less time on the affected feeders. Further, we hypothesized that birds will alter their behavior when exposed to the sonic net. We predicted that vigilance behaviors will increase across all species in the presence of the sonic net and that self-maintenance and feeding behaviors will decrease.

We also hypothesized that there will be inter-species differences in response to the sonic net and, further, that inter-species dominance interactions will play a role in competitive exclusion associated with access to the preferred (control compared with sonic net) feeders.

Accordingly, we predicted that there will be a greater proportion of the more dominant/competitive species (i.e., species that can displace other species from the feeders) on the control feeder compared with the sonic net feeder. As dominant species might be able to maintain exclusive access to the control feeder, agonistic behaviors between less dominant birds will increase on the sonic net feeder. Further, we predicted that this species distribution (more of the dominant species on the control feeder and more of the subordinate species on the sonic net feeder) will become more accentuated when food accessibility is decreased at the control feeder, as the benefits of competitive exclusion will be increased.

Methods

Subjects, sites, and bird feeders

We studied free-living songbirds from December 2014 to June 2015 at two sites on the campus of the College of William and Mary: at the Keck Environmental Field Laboratory and at the campus greenhouse located off South Henry Street, Williamsburg, Virginia. The two sites were approximately 1.94km apart and therefore considered independent of each other. The species we studied included the Carolina chickadee (*Poecile carolinensis*), tufted titmouse (*Baeolophus bicolor*), white-throated sparrow (*Zonotrichia albicollis*), white-breasted nuthatch (*Sitta carolinensis*), dark-eyed junco (*Junco hyemalis*), and the northern cardinal (*Cardinalis cardinalis*) (Figure 5 in Appendix).

At each study site we erected two bird feeders, which were approximately 25m apart. Each bird feeder was a plastic cylinder that could hold up to 8L of bird seed which equates to roughly 1700g (Squirrel Buster Plus, Brome Bird Care) and had 6 feeding holes at which birds could perch on a small plastic dowel and access the seed. Each feeder was suspended between

1.3m and 1.4m from the ground from a metal mounting pole that had a squirrel-proof guard on it to prevent rodents and snakes from either consuming seed or directly accessing the birds while they were feeding. All feeders were inspected at least 3 to 5 times a week.

We mounted two closed-circuit digital video cameras (Lorex LH020 Eco Blackbox2 series) in proximity to each feeder so that one focused tightly on the bird feeder and allowed us to record detailed behaviors and the other was focused more broadly at a 97m^2 area around the feeder so we could notate which birds were generally in the area adjacent to the feeder. The videos were recorded onto LaCie Rugged Mini Disks (USB 3.0 - 500GB, 301558), Seagate Expansion drives (3TB, USB 3.0, STBV3000100), and WD Elements External hard drives (WDBUZG0010BBK-NESN) at 960H (960x480) resolution.

Noise manipulation

We erected a Holosonics audiospotlight (0.61 X 0.61m) speaker at each site so that the narrow beam of sound emitted from this speaker was pointed directly at one of the feeders. The speaker was also arranged so that the sound emitted was barely audible to the human ear at the other feeder at each site. Hence, we designated the effected bird feeder as the "noise" feeder and the other as the "control" feeder, at each site. Throughout the study, as appropriate (see below), we played a 2-10kHz "pink" noise that reached an amplitude of 73.3 dB SPL (Keck) and 84.6 dB SPL (Greenhouse) at the "noise" feeder. We used this frequency range and amplitude because it was known to displace birds from food sources in captivity (Mahjoub et al., 2015) and in an open field trial (Swaddle et al., 2016). The sound file was created on a .wav file and played

back through each speaker's built-in audio player and calibrated with a handheld decibel meter (Extech Instruments, 407727).

Noise experiment

To acclimate the birds to the feeders, all feeders were filled with seed and left at each site without artificial noise exposure for two weeks (from 12/09/14 to 03/09/15 (Keck) and from 12/09/14 to 03/27/15 (Greenhouse)) prior to experimental trials. During that time we recorded digital video at each feeder between 0600 and 1000 every day. We also calculated the mass of the seed removed from each feeder by subtracting the mass of seed remaining after 2-3 days from the mass of seed that was initially put into the feeder. Seed mass was recorded on an Ohaus electronic scale to 0.001g precision (Keck) and a Mettler Toledo PJ6000 electronic scale to 0.001g precision (Greenhouse). Observations around the feeders indicated that there was spillage of seed, that was later consumed by ground-feeding animals (e.g., birds and squirrels), but we feel that the amount of seed removed is still a good indicator of overall feeding activity at each feeder even if it does not capture precisely the mass of seed eaten by birds that visited each feeder.

Immediately following the acclimation period we presented the 2-10 kHz noise through the speaker at each site for two weeks continuously, while continuing with the video recordings and collection of seed-mass data as described above.

Food accessibility experiment

Immediately following the two weeks of noise exposure we turned off the speakers and observed birds for a period of seven days. Following this control period, we manipulated the

accessibility to food on each feeder by taping over some of the food access holes. Specifically, we taped over 4 of the 6 feeding holes on the "control" feeders and 2 out of 6 on the "noise" feeders. Hence, there were twice as many open feeding holes available on the "noise" feeders, though no artificial noise was played through the speakers during this initial two week period. We assessed the mass of seed removed from the feeders and recorded videos as before.

After two weeks of the manipulation of food accessibility we turned on the speakers to play the 2-10 kHz noise, as in the noise experiment. We did not alter food accessibility further, hence the feeder receiving the noise treatment had twice the theoretical food accessibility as the feeder that did not receive the noise treatment. After two weeks, we kept the manipulation of food accessibility but we turned off the speakers. After two more weeks, we removed all tape from the feeders.

Behavioral video analysis

We subsampled all videos for the occurrence of behaviors. Specifically, we documented every occurrence and duration of vigilance behaviors (which could co-occur with other behaviors, such as feeding or locomotion) and non-vigilant feeding and self-maintenance (e.g. preening, bill wiping) behaviors during 1 min out of every 10 mins of video. Vigilance was defined as a bird facing away from the seed access hole and/or having its head up and appearing to be looking away from the feeder. Non-vigilant behavior was defined as an instance when the bird appeared to be visually focused on the food access hole or was occupied in a self-maintenance behavior. We also recorded the total time that birds (identified to species-level) spent feeding at each feeder. Behaviors were recorded only if a bird was on the feeder for at least 1 second.

In total, we recorded the occurrence and durations of feeding, vigilant, and non-vigilant behaviors for each feeder for 1 minute every 10 minutes for two hours. These two hour samples were taken in the morning between 06:00 to 10:00. The start time of each two hour segment depended on video availability (due to recording errors). The set time for observation was designated between 7:00 to 9:00am; however, due to recording errors on specific dates, the time range fluctuated to gather adequate amounts of data. From the same videos, we also recorded all agonistic interactions among individuals, noting the apparent "winner" and "loser" of these interactions and whether birds were displaced. We used these observations to construct an among-species competitive dominance hierarchy matrix of "wins" and "losses", from which we generated a linear competitive hierarchy across four species that occurred at sufficient frequency on the videos (Carolina chickadee, tufted titmouse, white-throated sparrow, northern cardinal).

Statistical analyses

We identified four species that were present at both sites and throughout the sound manipulation experiment, visited the feeders frequently, and interacted with each other at least five times on the videos. These species were the northern cardinal, tufted titmouse, white-throated sparrow, and Carolina chickadee. We constructed an inter-species social dominance matrix by notating all of the active displacements (i.e., one bird interacts with another and the recipient of the behavior is displaced) and passive displacements (i.e., one bird leaves the feeder as another one arrives without direct behavioral interaction between the two) among these four focal species. We assigned relative dominance based on the number of active displacement

interactions that were won or lost. If we could not assign dominance rank based on this information we used the outcomes of passive displacement interactions to assign rank.

To explore the effects of the sonic net on the amount of time birds spent on the feeders, we calculated the percent difference between the sum of duration of birds' visits to the sonic net feeder compared to the average sum of durations to both the sonic net and control feeders (sum of duration at sonic net / ½ x (sum of duration at sonic net + sum of duration at control) x 100). We termed this metric the "*% preference for sonic net feeder*". A positive value in this metric indicated that birds spent relatively more time at the sonic net feeder compared with the control feeder at the same site.

To test whether the sound field affected the amount of time birds spent on the feeders, we compared the "*% preference for sonic net feeder*" at times when the speaker was turned on versus the times when the speaker was turned off, using an ANOVA model with the sound manipulation as a fixed effect and site as a random effect. We performed these analyses relative to the sum of durations for all birds together and then separately for our four focal species (northern cardinal, tufted titmouse, white-throated sparrow, Carolina chickadee). From these tests we generated estimated marginal means, 95% confidence intervals, and partial eta-squared values as a measure of effect size.

To test whether the restricted food accessibility on the control feeders (achieved by taping over the feeding holes) influenced the effect of the sonic net on the time birds spent on the feeders, we analyzed the "*% preference for sonic net feeder*" data at times when the speaker was turned on and compared the periods before the feed holes were taped to when the holes were occluded, using an ANOVA model with the food accessibility manipulation as a fixed effect and site as a random effect. We analyzed the data for the northern cardinal, tufted titmouse, and

Carolina chickadee separately. We could not perform the analysis for the white-throated sparrow as it is a migrant and had left our study sites by the time the food accessibility manipulation occurred. As before, we report and interpret estimated marginal means, 95% confidence intervals, and effect sizes.

We also examined whether the time spent by all species (pooled) in vigilance behaviors was affected by the sound field. Similar to above we calculated the "*% time more vigilant on sonic net feeder*" as the sum of duration of vigilance behaviors at sonic net / ½ x (sum of duration of vigilance behaviors at sonic net + sum of vigilance durations at control) x 100. A positive value in this metric indicated that birds spent more time in vigilance behaviors at the sonic net feeder. We compared the "*% time more vigilant on sonic net feeder*" at times when the speaker was activated or not, using an ANOVA model with the sound manipulation as a fixed effect and site as a random effect. We report and interpret estimated marginal means, 95% confidence intervals, and effect sizes.

We could not analyze similar information concerning non-vigilant feeding behaviors and self-maintenance behaviors as these occurred too infrequently on the videos. All statistical analyses were performed with IBM SPSS Statistics v23, employing two-tailed tests of probability. We interpreted the effects of treatment groups by inspecting the overlap of 95% confidence intervals with estimated marginal means, and by examining effect sizes.

Results

When all species data were pooled, birds spent less time on feeders affected by the sound field compared with controls ($F_{1,9} = 4.76$, $P = 0.057$, effect size = 0.347; Figure 1). As the estimated marginal mean for the "*% preference for sonic net feeder*" when the speaker was on

lay outside the 95% confidence interval for the same metric when the speaker was off, and the

effect size was moderate (0.347), we interpret this to be a moderate reduction in the amount of

time birds spent on the feeders that were affected by the sonic net.

Outcomes of active displacement interactions rendered a linear inter-species social

dominance hierarchy, where the northern cardinal was dominant over the tufted titmouse, which

was dominant over the white-throated sparrow, which was dominant over the Carolina chickadee

(Tables 1 and 2). Specifically, the northern cardinals won all of their interactions and never lost.

The tufted titmouse won 7 and lost 1, all to the white-throated sparrow, indicating consistent

social dominance with a single inversion of the hierarchy. The white-throated sparrows lost all of

their interactions with the northern cardinals and all but one with the tufted titmouse individuals

but won all three interactions with the Carolina chickadees. The Carolina chickadees did not win

any interactions, losing all of their contests with the white-throated sparrows.

Table 1. A matrix of active displacement interactions among four species (NOCA = northern
cardinal, TUTI = tufted titmouse, WTSP = white-throated sparrow, CACH = Carolina chickadee.
The data in rows indicate the number of interactions won by that species. The numbers in
columns indicated the number of interactions lost by that species.

Winning	Losing species				
species	NOCA	TUTI	WTSP	CACH	# wins
NOCA	X	0	27	0	27
TUTI	0	X	7	0	7
WTSP	0	1	X	3	4
CACH	0	0	0	X	0
# losses	0	1	34	3	

Each of our four focal species was affected differently by the sound field. The northern

cardinal did not alter the amount of time it spent on affected feeders ($F_{1,9} = 0.003$, $P = 0.954$,

effect size < 0.001; Figure 2), neither did the tufted titmouse ($F_{1,9} = 0.253$, $P = 0.627$, effect size

= 0.027; Figure 2). However, the white-throated sparrows were greatly affected by the sonic net ($F_{1,9}$ = 22.24, P = 0.001, effect size = 0.712; Figure 2) and very largely deterred from the noisy feeders relative to their presence on the control feeder. The effect size was quite large (0.712) and the 95% confidence intervals for the treatment groups did not overlap with each other (Figure 2), indicating a robust effect of the sonic net on this species. Carolina chickadees were also deterred by the sound field, but not as strongly as the white-throated sparrows ($F_{1,9}$ = 4.12, P = 0.073, effect size = 0.314; Figure 2d). Confidence intervals and estimated marginal means from opposing treatments did not overlap with each other and the effect size indicated a moderate effect size (0.396). Comparing the four species, we find that the most socially dominant species, northern cardinal and tufted titmouse, were not notably affected by the sonic net. However, the two more-subordinate species—Carolina chickadee and white-throated sparrow—were displaced from the sonic net feeder by the presence of the sound field.

With the speaker on throughout, there was no influence of manipulating food accessibility (lowering it at the control feeder relative to the sonic net feeder) on the visit durations of all bird species pooled together ($F_{1,9}$ = 1.06, P = 0.330, effect size = 0.105). Additionally, the two most dominant species were not affected by this manipulation of food accessibility (northern cardinal: $F_{1,9}$ = 0.219, P = 0.651, effect size = 0.024; tufted titmouse: $F_{1,9}$ = 0.389, P = 0.549, effect size = 0.041; Figure 3). However, the Carolina chickadee was affected by the food accessibility manipulation ($F_{1,9}$ = 4.59, P = 0.061, effect size = 0.338; Figure 3). The 95% confidence intervals did not overlap with the estimated marginal mean from the other treatment group, indicating a relative increase in presence at the sonic net feeder when food access is restricted at the control feeder.

Presence of the sonic net sound field did not appear to influence the amount of time birds (all species pooled together) spent occupied in vigilance behaviors ($F_{1,9} = 0.166$, $P = 0.693$, effect size = 0.018; Figure 4).

Figure 1. Estimated marginal means of "*% preference for sonic net feeder*" before the speaker was turned on (no sound) and when the speaker was turned on (sound on), using data from all birds pooled together. Error bars represent upper and lower 95% confidence intervals.
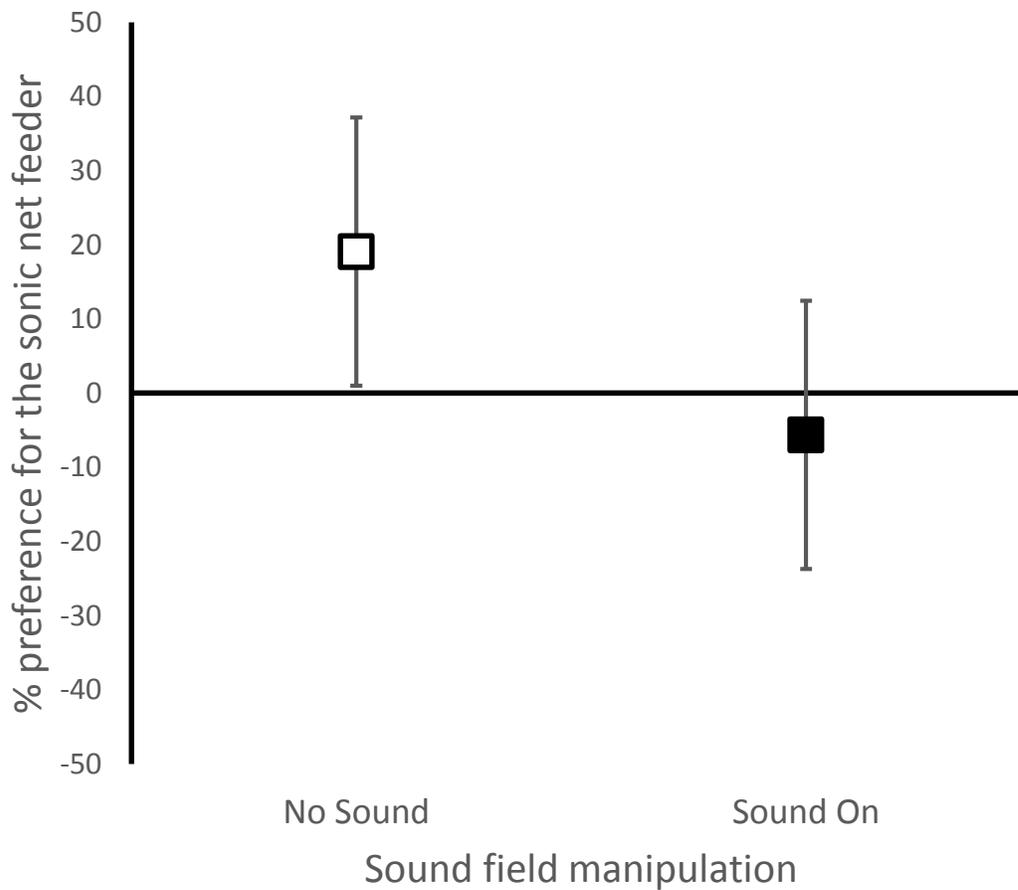

Figure 1

Figure 2. Estimated marginal means of "*% preference for sonic net feeder*" before the speaker was turned on (no sound) and when the speaker was turned on (sound on), using data from the northern cardinal (NOCA), tufted titmouse (TUTI), white-throated sparrow (WTSP), and Carolina chickadee (CACH) separately. Error bars represent upper and lower 95% confidence intervals.
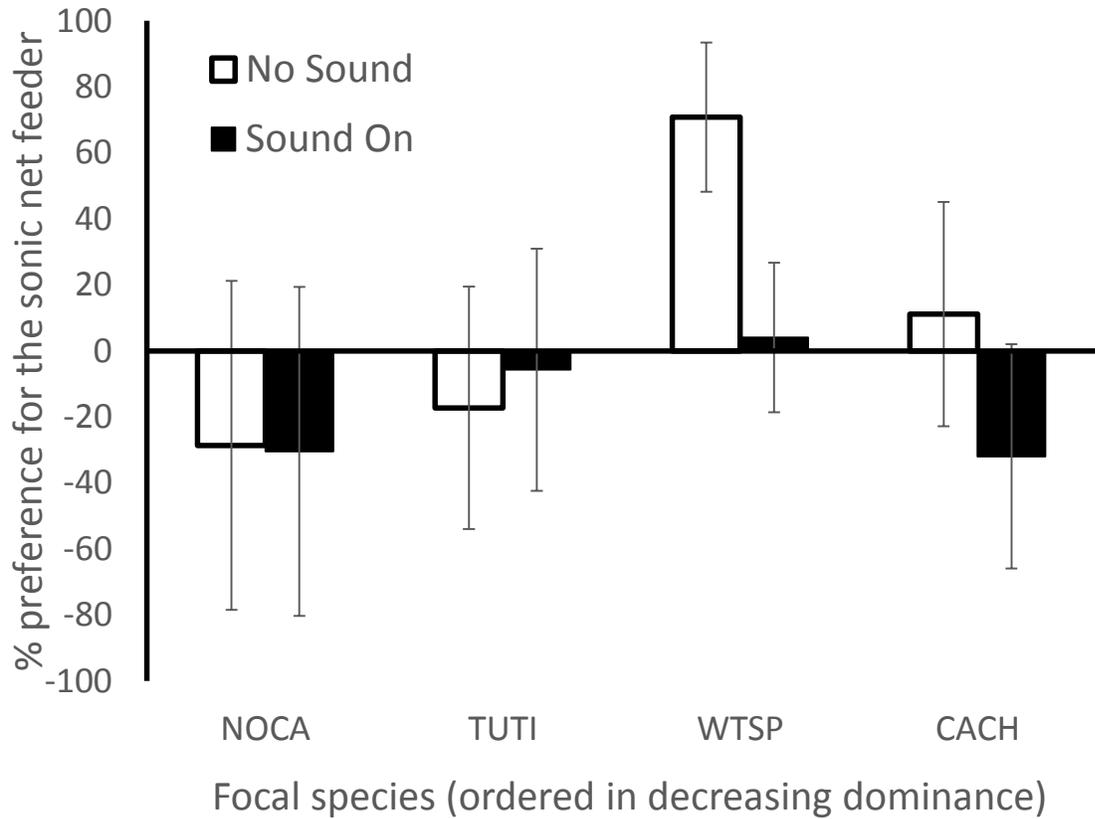

Figure 2

Figure 3. Estimated marginal means of "*% preference for sonic net feeder*" before the food accessibility was restricted at the control feeder (equal food access) and food access holes were more restricted at the control feeder compared with the sonic net feeder (less food access at Control), using data from the northern cardinal (NOCA), tufted titmouse (TUTI), and Carolina chickadee (CACH) separately. Error bars represent upper and lower 95% confidence intervals.
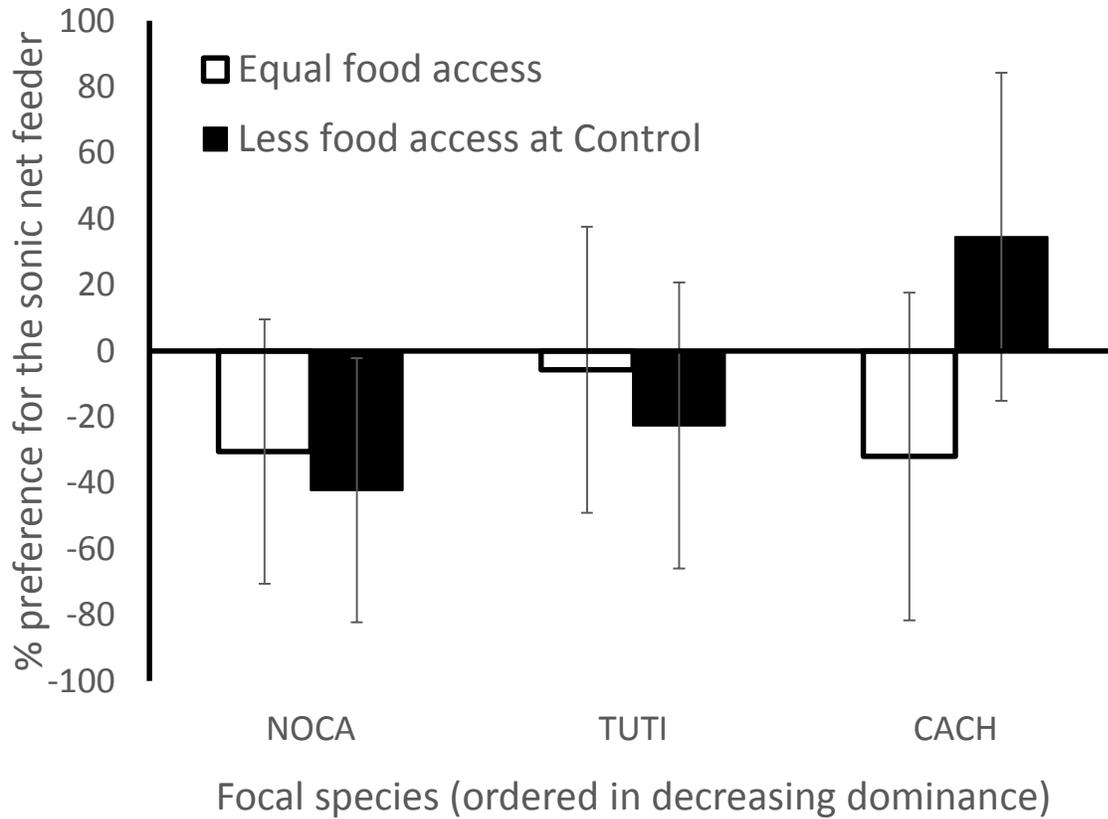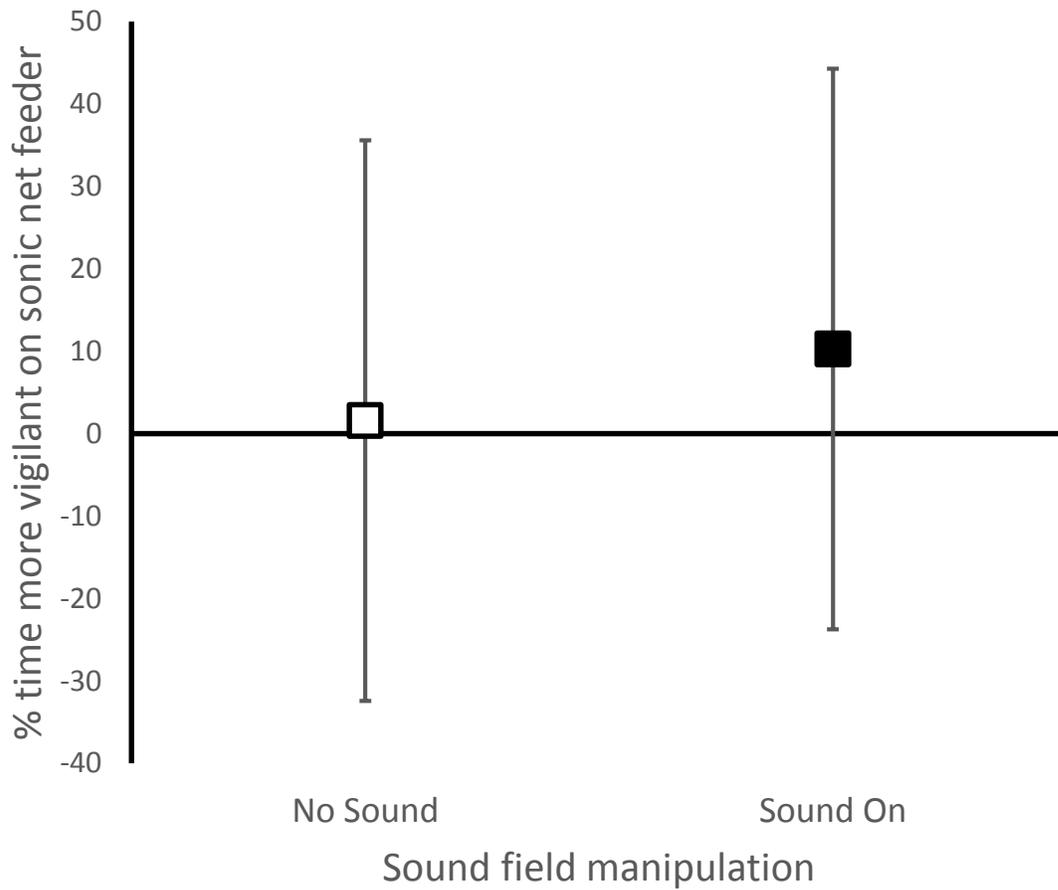

Figure 3

Figure 4. Estimated marginal means of "*% time more vigilant on sonic net feeder*" before the speaker was turned on (no sound) and when the speaker was turned on (sound on), using data from all birds pooled together. Error bars represent upper and lower 95% confidence intervals.

Figure 4

Discussion

Overall, we find that birds visited the sonic net-affected feeders for 35% less time than the control feeders. This effect size is slightly smaller than our previous studies of food-exclusion in captive European starlings (45%, Mahjoub et al. 2015) and much smaller than a summertime field study of songbirds (82%, Swaddle et al. 2016). One potential explanation of our smaller effect size is that much of our study was performed in the early spring where food availability may be lower than our previous summer study (Swaddle et al. 2016). Plentiful food sources, such as our feeders, during the early spring may offer a higher value food source and thus may be more attractive feeding sites than either feeders in captivity (Mahjoub et al. 2015) or summertime fields (Swaddle et al. 2016). Hence, it might be more difficult to displace birds from the feeders in this study, which would diminish the effect of manipulating the acoustics around one of the feeders at our sites. In addition, the two feeders (sonic net vs control) were reasonably close to each other at each site, hence the manipulation of sound at the sonic net feeder may have also displaced birds from the control feeder, which would have reduced the apparent effect size of the sonic net manipulation.

The displacement of birds from the sonic net feeder has broad implications and applications in agriculture. Here, we have shown that a rich food source, such as might be experienced in an agricultural setting, can be partially protected by a sound field that overlaps with avian acoustic communication channels. Importantly, birds in our study had a "control" feeder to go to as an alternate food source. This implies that one method of crop protection may be to offer pest birds an alternate food source away from the protected area. This could be artificial feeders or could be a lower-value crop area. To explore these ideas further, we manipulated food access at the control feeders to render the sonic net feeders even more

attractive. Even in those situations, the birds were displaced from the sonic net feeder, although to a lesser extent (10.5%).

We are not the first to show that anthropogenic noise alters occupancy and duration of visits of avian species (Francis et al. 2009; Francis et al. 2011; Swaddle et al., 2016). The dominant species (northern cardinals and tufted titmice) most frequently occupied the control feeders both before and after sound treatment. Considering these occupancy patterns, it is likely that the control feeders may have been located by chance in higher quality habitat. As suggested by Francis et al. (2011), larger birds with lower acoustic frequencies are most likely to be subject to the effects of noise. However, this is not what we observed. The most important factor is likely the frequencies at which species communicate rather than size of an individual. Our results also suggest that these most socially-dominant species were not significantly affected by the sonic net manipulation. The frequency and amplitude ranges of the species' vocalizations may play a key role in these results. It is possible that the northern cardinal and the tufted titmouse have elements within their communication that are easily detected in the presence of noise. The *chirr* component of the northern cardinal's song, for example, has a broad frequency bandwidth and the songs of the tufted titmouse can vary in rate and amplitude depending on the season (Grubb and Pravasudov, 1994; Halkin and Linville, 1999). Interestingly, the white-throated sparrow and the Carolina chickadee were most deterred by the sound field focused on the sonic net. This is the opposite pattern to what we predicted if inter-species dominance influences the presence of particular species at the feeders.

We hypothesized that inter-species differences would determine which bird species are most affected by the sonic net. We predicted inter-species dominance interaction would play a role in competitive exclusion associated with access to feeder treatment (control as compared to

the sonic net). Moreover, a greater proportion of dominant species would have longer visit durations on the control feeder (compared to the sonic net feeder). Since dominant species might maintain exclusive access to the control feeder, we also predicted that an increase of agonistic behaviors would occur between less dominant species on the sonic net feeder. We observed a linear dominance hierarchy among four species: The northern cardinal was dominant over the tufted titmouse, which was dominant over the white-throated sparrow, which was dominant over the Carolina chickadee. The two least-dominant species were most affected by the sonic net: the white-throated sparrow was most strongly displaced by the sound field, followed by the Carolina chickadee. Conversely, the two most dominant were least affected: the northern cardinal and tufted titmouse were not substantially affected by the sonic net and held a preference for the control feeder throughout the noise experiment (Figure 2). The most subordinate species are presumably more easily displaced from feeders, as we commonly observed, hence these subordinate species should be more likely to feed at the less preferred (i.e. sonic net) feeder. However, we observed the opposite, where the subordinate species (Carolina chickadee and white-throated sparrow) were less likely to be observed at the sonic net feeder under noise exposure. These inter-species differences in response to the sonic net were not consistent with our interpretations of how interspecies dominance might influence species presence at the sonic net feeder. Additionally, the northern cardinal and white-throated sparrow have similar diets, consisting of nuts, berries, and insects, while the tufted titmouse and Carolina chickadee primarily feed on insects (Grubb and Pravasudov, 1994; Halkin and Linville, 1999; Mostrom et al., 2002; Falls and Kopachena, 2004). Since our results showed that the Carolina chickadee and the white throated sparrow were deterred most by the sonic net, diet should not be used exclusively to determine the extent to which a species is deterred.

We originally predicted that this dominance-related distribution of species would become more pronounced when food accessibility was decreased on the control feeder. Notwithstanding the inter-species patterns observed when there was equal food access at the sonic net versus the control feeder, when food access was limited at the control feeder we observed inter-species differences that supported our hypothesis in which inter-species competition might affect the presence of birds at the feeders. Specifically, when some of the food holes were taped-over on the control feeder, presumably making it a less favorable food source, we saw that the Carolina chickadee switched feeder preference toward the sonic net feeder, which is consistent with our competitive exclusion hypothesis. Here, the least dominant species (i.e., Carolina chickadee) shifted their feeding toward the less preferable feeder (i.e., the sonic net feeder) perhaps because the more dominant species (i.e., northern cardinal and tufted titmouse) could better control food access at the control feeder, where there was greater food availability (Figure 3). Interestingly, Carolina chickadees initially preferred the sonic net feeder before treatment then decreased preference to the sonic net feeder by 86%. Its presence on the sonic net feeder suggests that the Carolina chickadee managed to compete with competitive exclusion and gain access to the control feeder during sound treatments.

It is important to understand the mechanisms by which the 2 to 10 kHz sound reduced duration of visits. Avian species often rely on acoustic signaling as an indication of fitness, protecting a territory, or notifying other birds to food or predators (Francis et al. 2009; Mahjoub et al. 2015; Swaddle et al. 2015). Birds that are unable to detect predatory cues have especially high predation risks, in which the risk of depredation increases among those individuals. Across all species, however, the frequency of vigilance behaviors did not vary across the sonic net and control treatments. This does not support our reasoning behind the mechanism of deterrence by

sound. In instances in which bird species cannot communicate acoustically, we predicted an increase in vigilance behaviors across all individuals on the sonic net feeder. It is possible that the dominant species have less foraging competition and predation risk, which in this case, noise has less of an effect on vigilance frequency. Subordinate species, however, have a higher foraging competition (with other subordinate species and dominant species) and have a higher predation risk. Thus lower frequencies of visits may be attributed to lower preference for the sonic net feeder with less active visitation to the sonic net feeder overall and so, vigilance behaviors were not observed.

Noise pollution is an increasingly prevalent problem across the globe (Slabberkorn and Ripmeester, 2008; Swaddle et al., 2015). The results from this study help us better understand mechanisms by which wild avian populations are altered by anthropogenic noise pollution. Studies of birds living within cities are good models to study species specific tolerance levels to noise. With rapid change in avian communities in city landscapes, acoustic adaptations may also be used as a marker for evolutionary change (Swaddle et al. 2015). To determine the extent by which sound or dominance hierarchy influences community structure, frequency range variation within the frequency range of the sonic net needs to be explored. Additional studies during migratory months are needed, as birds are actively seeking more food for migration. We would predict that migrating birds would be less successful in gathering food in noisy areas as the vigilance/ foraging tradeoff would be disrupted. Migratory birds in the presence of noise are particularly at risk if they cannot stock up adequate amounts of food at stopover sites (McClure et al. 2013). Identifying species that are especially sensitive to anthropogenic noise may aid in conservation efforts for endangered species (Francis and Barber, 2013). Considering this information, analysis of species-specific sensitivities of the northern cardinal, tufted titmouse,

white-throated sparrow, and Carolina chickadee may need further investigation into consequences of noise on avian populations.

Our results suggest that the sonic net decreased the duration of birds' visits to the feeders, indicating that a broad-frequency sound field can protect a rich food source from damage by wild birds. Rich food sources, such as farms, are especially vulnerable to crop damage and loss. So, deploying the sonic net around crops has potential to protect farms over a long period of time. Thus, it may be a promising method of deterring pest birds from agriculturally important areas. However, in this case because some species still visit areas exposed to sound, it may be recommended that farmers deploy the sonic net on the most valuable crops and possibly designated a small portion of the least valuable crop to birds.

Acknowledgements

Appendix

Figure 5. List of Species Observed at Feeders

Common Name	Scientific Name	Four-letter code
Northern Cardinal	*Cardinalis cardinalis*	NOCA
Tufted Titmouse	*Baeolophus bicolor*	TUTI
Carolina Chickadee	*Poecile carolinensis*	CACH
White-throated Sparrow	*Zonotrichia albicollis*	WTSP
Brown-headed Cowbird	*Molothrus ater*	BHCO
Wood Thrush	*Hylocichla mustelina*	WOTH
White-breasted Nuthatch	*Sitta carolinensis*	WBNU
Mourning Dove	*Zenaida macroura*	MODO
Chipping Sparrow	*Spizella passerina*	CHSP
Field Sparrow	*Spizella pusilla*	FISP
Red-bellied woodpecker	*Melanerpes carolinus*	RBWO
Downy Woodpecker	*Picoides pubescens*	DOWO
American Goldfinch	*Spinus tristis*	AMGO
House Finch	*Haemorhous mexicanus*	HOFI
Carolina Wren	*Thryothorus ludovicianus*	CARW
Song Sparrow	*Melospiza melodia*	SOSP
Dark-eyed Junco	*Junco hyemalis*	DEJU
Brown Thrasher	*Toxostoma rufum*	BRTH

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