Environmental noise influences song frequency of Yellow Warblers (*Dendroica petechia*) in Grand Teton National Park

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Abstract We explored how Yellow Warblers (*Dendroica petechia*) alter their songs when encountering noise in Grand Teton National Park. Different strategies for avoiding signal masking are used by other species of birds, yet there is a lack of information of birds' responses to higher noise levels – above 65 dB; such levels are often found in National Parks that have many visitors. In this study, we investigated singing behavior of Yellow Warblers when facing noise that ranged from 30 dB to 80 dB. In these preliminary results, we found that some features of Yellow Warblers did not appear to change with background noise level, including mean minimum frequency, bandwidth and song length. Other song features we studied did show small but statistically significant changes with higher background noise, including the peak frequency and the mean minimum frequency, both of which were significantly negatively correlated with the level of background noise. This result is different from the positive correlations that are typically observed. We speculate that this difference is due to the very high dB levels of background noise that we observed.

Introduction

Noise has long been considered an important constraint on avian acoustic signal design (Ryan and Brenowitz, 1985; Brumm and Slabbekoorn, 2005; reviewed by Brumm, 2013). Background noise can influence both the transmission and reception of avian acoustic signals by decreasing the signal to noise ratios, thereby reducing the distance over which a signal can be identified (Marten et al., 1977). Birds that need to transmit signals in a noisy environment must compete for acoustic space with other noises in their environment. Such potent signal masking may be avoided by species that sing in ways that minimize disruption by noise; this is expected to give them higher fitness. Here we report on our studies of how background noise affects some features of the songs of Yellow Warblers (*Dendroica petechia*) in Grand Teton National Park (GTNP).

Background noise will vary according to its source and proximity. Sources of background noise include: abiotic noise, such as wind or running water; biotic noise, such as insects, frogs, heterospecific birds or even conspecifics; and anthropogenic noise, produced by humans, including traffic. Traffic noise is of special interest in national parks which are charged with supporting visitors while mitigating their potential effects on wildlife. Noise levels in urban areas or close to motorways can be very high, often reaching levels of 65 dB or more (Barrigon et al., 2002; Zannin et al., 2002; Tsai et al., 2009). Such high levels have been recorded in Grand Teton National Park and may affect the acoustic environment of resident songbirds. Traffic noise is usually low-pitched with its main energy typically below 1 kHz (Can et al., 2010; Bocharov et al., 2012).

A variety of bird species respond to anthropogenic

noise by raising the signal to noise ratio (S/NR). Brumm and Zollinger (2013) have summarized findings from 14 such species. The strategies used by birds can be separated into two categories: (1) reducing the experienced background noise level by choosing when or where to sing; and (2) increasing the signal level of songs. To reduce background noise levels they experience, birds may adjust the timing of signaling, thereby reducing the masking effect. For example, Lengagne and Slater (2002) found that Tawny Owls (*Strix aluco*) stopped calling during noisy rainy periods. Similarly, European Robins (*Erithacus rubecula*) challenged by background noise may sing more at night when traffic noise is lower (Fuller et al., 2007). Bewick's Wren (*Thryomanes bewickii*) and Wrentit (*Chamaea fasciata*) adjusted the timing of their peak song output to avoid the peak song activity of heterospecific neighbors (Cody and Brown, 1969; Ficken et al., 1974). Some birds may adjust the timing of their signaling on an even finer scale. For example, Common Nightingales (*Luscinia megarhynchos*) time the onset of their songs to fall between the songs of other species to avoid potential masking of their own signals (Brumm, 2006).

Birds may also increase signal level. It is frequently observed that birds sing more loudly when there is background noise, a response termed the Lombard effect (Brumm and Zollinger, 2011). For example, nightingales in areas with higher levels of traffic noise sang louder than those in quieter areas (Brumm and Todt, 2002). Similar results were also found in male Blue-throated Hummingbirds (*Lampornis clemenciae*; Pytte et al., 2003) and Noisy Miners (*Manorina melanocephala*; Lowry et al., 2012). Birds may also increase signal redundancy by repeating the same syllable or song type in noisy environments – e.g. Japanese Quail (*Coturnix japonica*; Potash, 1972), King Penguins (*Apenodytes patagonicus*; Lengagne et al., 1999) and Common Chaffinches (*Phylloscopus collybita*; Verzijden et al., 2010). Another way of increasing signal redundancy is by singing more hurriedly in noisy places – Blackbirds (*Turdus merula*) in Vienna (Nemeth and H, 2009), Great Tits (*Parus major*; Slabbekoorn and den Boer-Visser, 2006) and Black-capped Chickadees (*Poecile atricapillus*; Proppe et al., 2011). Some birds have

been found to extend their signal duration, which presumably increases signal levels, in noisy environments. For example, Budgerigars (*Melopsittacus undulatus*) increased the duration of their contact calls significantly with increasing levels of environmental noise (Osmanski and Dooling, 2009). Nestling Tree Swallows (*Tachycineta bicolour*) increased the duration of their begging calls in response to noise playback in nest boxes in the field (Leonard and Horn, 2005).

Birds can also improve the S/NR of their song by shifting the frequency of the signal away from the frequency band of noise or by switching the song type to another with higher minimum frequency. Shifts in signal frequency in noisy environments have been reported for Great Tits (Slabbekoorn and Peet, 2003), Common Chiffchaff (*Phylloscopus collybita*; Verzijden et al., 2010), European Robin (*Erithacus rubecula*; Montague et al., 2012), House Finch (*Carpodacus mexicanus*; Bermudez-Cuamatzin et al., 2011), Reed Bunting (*Emberiza schoeniclus*; Gross et al., 2010), and Red Wattlebirds (*Anthochaera carunculata*; Hu and Cardoso, 2010). These studies found a positive relationship between the minimum frequency of the bird's song and the level of environmental noise. Related to this, some birds appear to improve the S/NR of their songs by emphasizing song types that are less masked by the environmental noise (e.g., Great Tits; Halfwerk and Slabbekoorn, 2009).

The signal intensity of bird song is highly non-linear with frequency (Nemeth et al., 2013). This is also true for amplitude, and is likely true for response to background noise. In previous studies, the environmental noise levels range from approximately 30 dB to 65 dB, while for birds living near the road at GTNP the noise level can easily reach 80 dB. There are few studies of responses of birds when facing high levels of noise. Because higher noise levels are frequent at GTNP, they may affect the birds there differently. We focused our efforts on Yellow Warblers, which are common residents in GTNP.

Yellow Warblers are widespread and distributed throughout most of North America, and down to northern South America, where they are found in
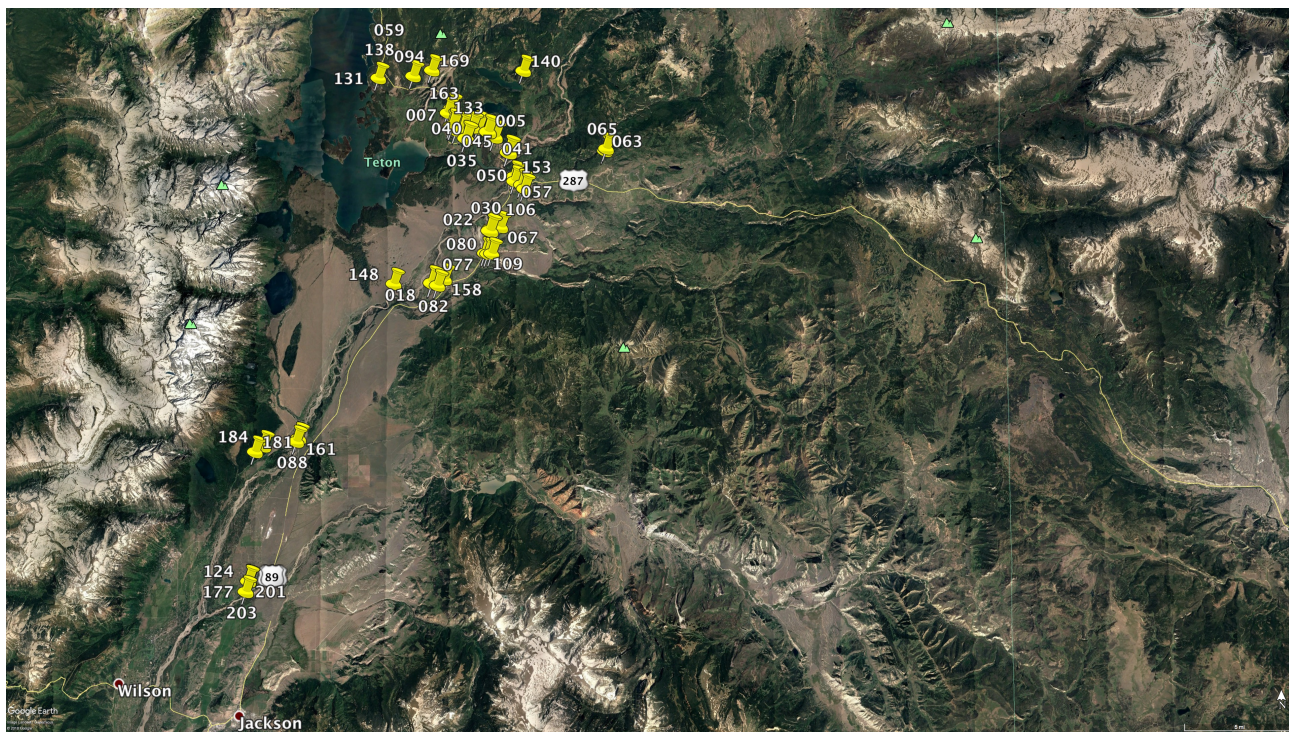
Figure 1. Locations where we recorded Yellow Warbler songs for this study. Details for numbered sites can be found in Supplementary Data Table 1. Most recordings were from the area between the Moran Junction in the north and Moose Entrance Station of Grand Teton National Park. Scale and direction are in the lower right. For orientation, Wilson and Jackson are located toward the bottom of the figure.

mangrove habitat. They are long-distance migrants, which breed across central and northern North America, and they spend winters in Central America and northern South America. They breed primarily in shrubby thickets and damp woods, particularly along watercourses and in wetlands. Woodland breeding habitat is commonly composed of willows, alders, and cottonwoods across North America and up to about 9,000 feet in the West (Lowther et al., 1999). Although Yellow Warblers are widespread in North America, their populations decreased by 25% between 1966 and 2014 (Sauer et al., 2017).

In GTNP, Yellow Warblers are often found among willows but also live in cottonwood woodlands and in brush near water. The populations of Yellow Warblers are spread widely and evenly across GTNP. Accordingly, we were able to measure their response in the same breeding stages, and the climate and geographic conditions were therefore similar in noisy and quiet environments.

Yellow Warbler songs consist of short sequences of varied phrases. There are commonly 7-12 syllables, grouped into a few phrases, to compose a song of 1-1.5 seconds in length.

Methods

Field data collection

Recordings of Yellow Warblers were made throughout the day between June 18 and July 4, 2017. Most recordings were made near highways 26, 191 or 89, near their junction in Moran, Wyoming, in GTNP. The times and locations of each recording are listed in Supplementary Table 1 with file numbers corresponding to pin labels in Figure 1.

All songs were recorded with a Sennheiser omnidirectional microphone with a parabolic reflector and Marantz digital recorder with a 44.1 kHz sampling rate, 16-bit, and WAV file type. A GPS (Garmin

GPSmap76) was used to record the location of each individual at the beginning of its recorded file. At least one clear song was recorded from each of 42 birds; typically there were more songs, up to 47, with an average of 15.3 songs/singer (see details of recordings in Supplementary Table 1). The distance between the focal individual and the recorder was classified as < 5 m, 5 − 10 m, 10 − 15 m, or > 15 m. To ensure that different individuals were recorded in each file, the locations of recorded birds were separated from those of any other recording by at least 200 meters.

Noise levels were measured with an Extech 407736 sound level meter. Derryberry's method (Derryberry et al., 2016) was used to measure background noise levels at each site, following the methods described by Brumm (2004). Noise levels at each location were measured for one minute in each of four orthogonal directions. The maximum value of sound level in each direction within the one-minute period was recorded. The four measurements were then averaged for further analysis.

Analysis

Background noise and the distance of the singer from the recorder varied widely. This poses methodological challenges to the measurement of song frequencies. Most previous studies of bird song in noisy environments relied on visual inspection of spectrograms to identify minimum and maximum frequencies of each song. This approach is sensitive to background noise, a measurement bias that may lead to false-positive associations (Zollinger et al., 2012). The problems with this "measurement-by-eye" method have been established in recent years, and an alternative power spectrum threshold method has been proposed (Brumm et al., 2017; Rios-Chelén et al., 2017).

Accordingly, we used the power spectrum threshold approach to measure song frequency, as described by Zollinger et al. (2012) and illustrated in Figure 2. We first used *Praat* software (Boersma and Weenink, 2016) to annotate the start and end time of each syllable and song. We then used Matlab (version R2016b; The Mathworks Inc., 2005) for parameter measurements.
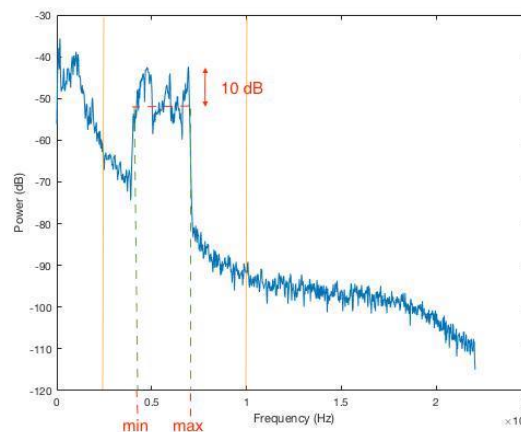

Figure 2. The power spectrum of one song syllable of a Yellow Warbler, with power (in dB) plotted against frequency (in Hz). The Yellow Warbler's song spans frequencies from 2.2 to 10 kHz (orange vertical lines, so frequencies outside this range were ignored in estimation of minimum and maximum frequency where power was 10 dB below the maximum decibel threshold.

ter measurements. For frequency measurements, we obtained the power spectrum for each syllable, plotting the power (in dB) of the recording at each frequency. We then we found the maximum and minimum frequencies of each syllable as described by Zollinger et al. (2012). That is to say, the minimum intensity difference between signal and noise in the power spectrum of each syllable was observed to be approximately 10 dB, so we set the decibel level lower than 10 dB from the maximum decibel as the intensity threshold delineating signal from noise – providing estimates of minimum frequency and maximum frequency for that syllable (see Figure 2).

Measurements were restricted to the frequency range of the Yellow Warbler's song (2.2 to 10 kHz). We measured minimum and maximum frequency for each syllable as described above. We subsequently determined the minimum and maximum frequencies of each song by selecting the minimum and maximum frequencies, respectively, of all the syllables from that song. The parameters measured for each song included: (1) minimum frequency (Min_Freq); (2) maximum frequency (Max_Freq); (3) peak frequency (the frequency with highest amplitude in the

Variable	Correlation with dB	Pearson probability		Multiple R^2	Spearman Rho with dB	probability
Min_Freq	-0.35	0.022	*	0.1243	-0.29	0.058
Max_Freq	-0.29	0.065		0.0823	-0.23	0.14
Bandwidth	0.04	0.796		0.0017	0.04	0.826
Peak_Freq	-0.39	0.01	**	0.1555	-0.28	0.071
Song_Length	-0.06	0.729		0.003	-0.05	0.732
Complexity	0.07	0.651		0.0052	0.03	0.841

Table 1. Correlations between measured song variables of Yellow Warblers and background noise (dB) in Grand Teton National Park.

power spectrum) (Peak_Freq); (4) bandwidth (maximum − minimum frequency) (Bandwidth); (5) song length (Song_Length, seconds); and (6) complexity (bandwidth divided by song length). We analyzed a total of 42 recording files. Supplemental Table 1 reports these values together with the date, starting time, location, background dB measure, and number of songs analyzed for each file.

Preliminary Results

The objective of this study was to determine whether certain features of Yellow Warblers' songs changed in association with variation in background noise. Observed correlations are listed in Table 1, measured with parametric (Pearson's correlation coefficient) and non-parametric (Spearman's Rho) models. Small but statistically significant negative correlations were observed in the parametric model between background noise (dB) and minimum (Min_Freq, -0.35) and peak song frequency (Peak_Freq, -0.39), suggesting that higher background noise was associated with slightly lower-pitched songs. The association was not especially strong, as the R^2 was 0.12 for Min_Freq and 0.16 for Peak_Freq. The associations for these variables are shown in Figures 3 and 4. No other correlations were statistically significant.

The finding that peak and the mean minimum frequencies were significantly negatively correlated with background noise is contrary to our expectation

based on previous research. This unexpected result could be due to the new low-bias measurement method used here, but this does not seem likely. More importantly, we suggest that we encountered a much larger range of sound intensity than included in most earlier studies, and in particular we recorded bird songs from areas with much higher noise levels (65 to 80 dB) than other studies.

Most other studies have reported a positive correlation between dB and Frequency (reviewed by Brumm and Zollinger, 2013), and have suggested that an increase in song frequency helps to separate the high-frequency song from low-frequency anthropogenic background noise, but this relationship need not be linear. Nemeth et al. (2013) noted that frequency should have little effect on the signal to noise ratio, but rather that amplitude should have a major effect due to the Lombard effect. The Lombard effect is common in humans and has been observed in nearly all bird studies in which it has been possible to measure song amplitude in the presence of background noise. They postulate that the positive correlation is due to an inherent relationship between frequency and amplitude in the production of bird song.

This relationship in song production is, however, non-linear, with the correlation actually being negative at higher frequencies. We postulate that there may be some limit to the extent to which birds can expend extra energy to modify their songs, call it E_{max}. The
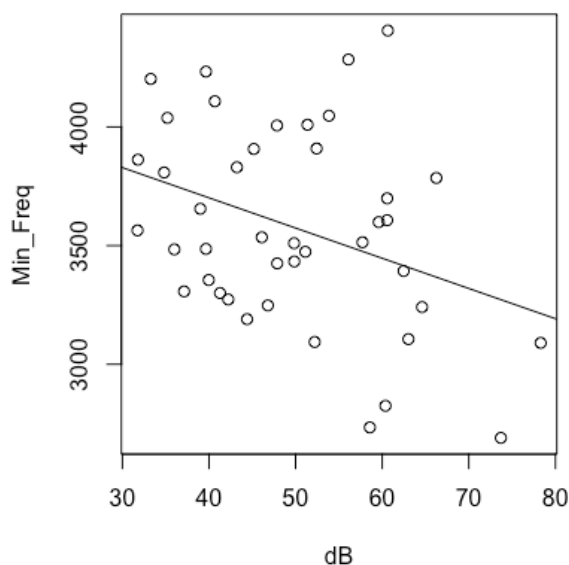
Figure 3. Minimum song frequency (Min_Freq) recorded from Yellow Warblers in different background sound environments (dB) in Grand Teton National Park (Pearson's r=-0.35, p<0.05.
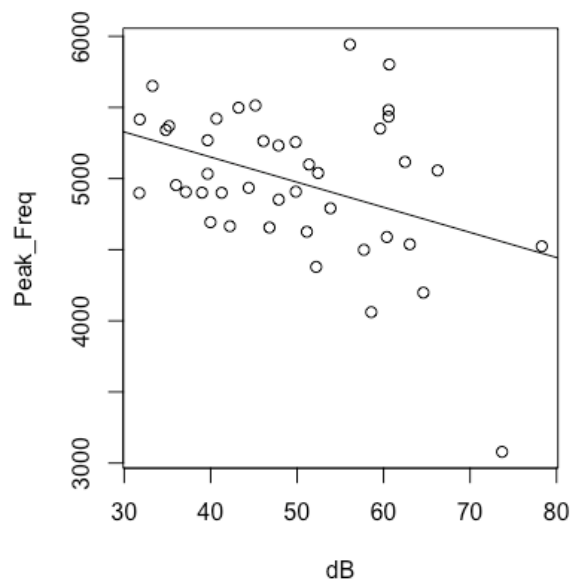
Figure 4. Peak song frequency (Peak_Freq) recorded from Yellow Warblers in different background sound environments (dB) in Grand Teton National Park (Pearson's r=-0.39, p=0.01.

mechanics of sound production in birds can be quite complex (Suthers, 2009), and the song features of many birds are apparently modified in response to demands by the environment (Marten et al., 1977). To a first approximation, however, we can consider a physical description of a simple harmonic oscillator for sound production. In such a model, the time rate at which energy (E) is expended is proportional to the product of frequency of that sound (f) times its amplitude (Am), all squared ($E \sim (f * Am)^2$); this is to say that the total energy required is a product of amplitude and frequency (see e.g. Serway, 1990). That energy must be bounded by something similar to E_{max}, meaning there should be a fall off of amplitude at higher frequencies because that will matter more than frequency for the signal to noise ratio in conditions of greater noise. If this speculation is correct, there should be a premium for amplitudes at the higher dB levels, with a corresponding decline in frequency. This would mean we would see a positive relationship between song frequency measures and

noise at dB lower than E_{max}, but a negative relationship at higher dB. That is, in fact, what was observed for Min_Freq and Peak_Freq (see Figure 5). The relation between amplitude and power was positive at low dB, but negative at higher values. We note, however, that an ANOVA to compare the first order and second order polynomial regressions was not statistically significant. Clearly this merits further analysis.

Conclusions

Anthropogenic noise in GTNP has the potential to disrupt communication between animals that live there. We studied some ways that Yellow Warblers that breed in the area around Moran might adapt to minimize such disruption. We recorded background noise in sites that had low (30 dB) to high (80 db) levels of background noise and then measured select features of the Yellow Warblers' songs recorded at these sites. Some features of the songs, including minimum frequency and peak frequency,
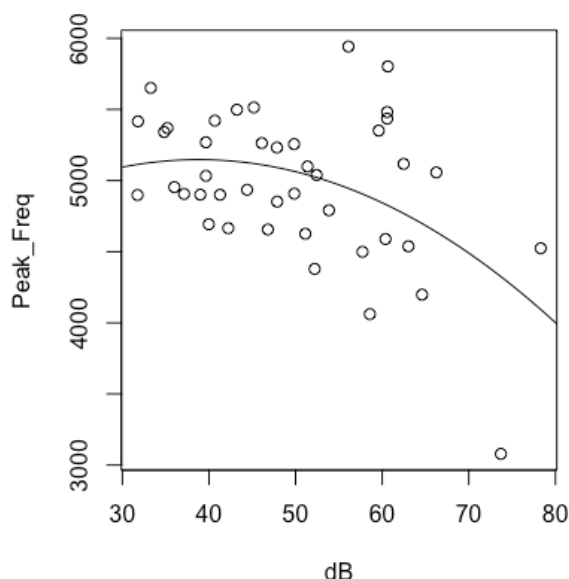
Figure 5. Peak song frequency (Peak_Freq) varied non-linearly with background noise levels in Grand Teton National Park (quadratic fit: Peak_Freq = 3286.9 + 24.7*dB - 0.36*dB^2.

showed a small but negative and statistically significant correlation between song frequency and background noise level. Other features, including bandwidth, song length and one measure of complexity (bandwidth/song length) showed no such correlation. Some song features, including amplitude, redundancy and timing have been reported as adaptive features in other species of birds, but we were not able to observe them directly in this study. These remain as objects for future studies, as do the fitness effects as measured by increased energetic costs that such disturbances might cause.

We chose Yellow Warblers for this study because they possess a rich variety of songs and a flexibility of singing behavior. In our small study of 42 recordings from the area around Moran, we readily distinguished more than 31 different phrases and 38 syllable types. Each phrase type was comprised of 2 to 4 different types of syllables. While each syllable type had a different frequency range, the variety of songs showed the high flexibility of the Yellow Warbler's singing be-

havior in different environments. However, we did not have sufficient quality recordings to compare song types among environments, across the time of day, or in response to other bird songs.

Future Work

Birds are known to use a variety of adaptations to overcome disturbance by anthropogenic noise. Adaptations we could not include in our study included selective use of phrase types, periods of singing, overlap with other species, and adaptations by amplitude, with the Lombard effect, where song amplitude increases with background noise level. These would be interesting areas for future work.

We observed small but statistically significant negative correlations between song frequency (note that this term refers to the pitch of the song, not the frequency with which songs are iterated) and level of background noise. While not unheard of, this is different from the large majority of similar studies in other species of birds. We postulated that this might be related to nonlinear relations between the energy required for song and maximizing S/NR at high noise levels. When we fit a quadratic relation of song frequency at different noise levels, from low to quite high, we did observe a nonlinear response – with an increase in frequency at lower noise levels and then a decrease at higher noise levels. Our sample size was inadequate to clearly establish that relationship as a test of our hypothesis. Future work should repeat the observations to ensure that the relations we observed here are indeed general, and then address what the explanation might be.

Acknowledgements

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File	Date:Time	Location X	Location Y	Sample Size	Distance	dB	Min Freq	Max Freq	Bandwidth	Peak Freq	Song Length	Complexity
CL005	6/18/17, 3:19 PM	43.8634	-110.53851	7	1	52.425	3909	6977	3068	5039	1.28	2392.24
CL007	6/18/17, 4:14 PM	43.86752	-110.57192	20	10	63.025	3106	6268	3162	4538	1.48	2143.57
CL014	6/19/17, 8:38 AM	43.86503	-110.56199	9	10	46.08	3535	6882	3347	5263	1.44	2324.09
CL018	6/19/17, 9:03 AM	43.65746	-110.71126	13	10	43.225	3830	7446	3616	5498	1.55	2336.35
CL022	6/19/17, 1:13 PM	43.79559	-110.53652	4	15	56.1	4284	7261	2977	5942	1.56	1914.17
CL030	6/19/17, 3:40 PM	43.79658	-110.53599	13	10	51.375	4009	6766	2756	5099	1.24	2225.1
CL035	6/20/17, 7:12 AM	43.85899	-110.55913	16	15	31.8	3862	7454	3592	5416	1.18	3035.1
CL040	6/20/17, 8:23 AM	43.866	-110.54793	6	15	53.85	4047	6917	2870	4791	1.13	2547.45
CL041	6/21/17, 5:37 AM	43.85994	-110.53233	18	5	57.725	3514	6967	3453	4499	1.25	2756.65
CL045	6/21/17, 6:13 AM	43.84915	-110.51896	20	20	73.7	2690	5415	2725	3079	1.16	2352.6
CL050	6/21/17, 7:27 AM	43.82783	-110.50614	8	5	33.275	4202	7146	2944	5651	1.55	1897.81
CL057	6/21/17, 9:16 AM	43.83025	-110.51297	19	7.5	60.575	3607	7107	3501	5435	1.18	2961.96
CL059	6/21/17, 10:57 AM	43.93821	-110.64234	47	5	36	3484	6599	3115	4954	1.35	2299.95
CL063	6/22/17, 5:00 AM	43.8508	-110.42741	12	20	37.125	3307	6864	3557	4906	1.33	2665.36
CL065	6/22/17, 5:59 AM	43.85228	-110.42629	18	15	35.2	4038	7317	3278	5369	1.12	2926.13
CL067	6/22/17, 7:31 AM	43.79902	-110.52609	15	5	59.6	3599	7475	3877	5351	1.63	2384.78

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File	Date:Time	Location X	Location Y	Sample Size	Distance	dB	Min Freq	Max Freq	Bandwidth	Peak Freq	Song Length	Complexity
CL077	6/23/17, 5:32 PM	43.78066	-110.53778	8	10	39.65	4233	7283	3050	5269	1.41	2164.53
CL080	6/23/17, 7:01 PM	43.7809	-110.53427	9	7.5	40.675	4108	7016	2908	5421	1.39	2093.91
CL082	6/24/17, 8:33 AM	43.75942	-110.58522	45	5	39.65	3486	6767	3281	5033	1.29	2548.28
CL088	6/25/17, 7:54 AM	43.65403	-110.71651	8	15	49.825	3510	7698	4188	5256	1.32	3177.67
CL094	6/26/17, 5:36 AM	43.90301	-110.609	28	10	60.65	4406	7360	2954	5802	1.21	2449.52
CL099	6/26/17, 7:14 AM	43.86525	-110.56811	19	7.5	64.6	3241	6455	3214	4198	1.2	2687.13
CL106	6/26/17, 2:52 PM	43.82514	-110.50355	28	5	31.75	3564	6839	3275	4898	1.18	2786.09
CL109	6/27/17, 7:26 AM	43.78112	-110.54051	1	5	46.8	3248	6712	3464	4656	1.18	2946.35
CL124	6/27/17, 5:33 PM	43.56062	-110.75941	23	10	39.975	3355	6112	2757	4693	1.29	2138.75
CL131	6/28/17, 8:12 AM	43.90182	-110.64203	10	15	44.4	3190	6690	3500	4935	1.26	2787.43
CL133	6/28/17, 3:05 PM	43.86738	-110.55278	9	15	66.25	3785	6836	3051	5057	1.2	2547.75
CL138	6/29/17, 7:51 AM	43.93159	-110.63705	21	15	34.825	3808	7053	3245	5341	1.09	2966.69
CL140	6/29/17, 8:34 AM	43.90624	-110.64697	14	10	42.225	3273	6922	3648	4665	1.22	2980.98
CL148	6/30/17, 8:01 AM	43.7606	-110.62632	24	5	49.85	3433	7759	4326	4908	1.46	2963.55
CL153	6/30/17, 3:18 PM	43.83358	-110.51334	1	10	78.3	3090	6788	3698	4524	1.25	2961.38
CL158	6/30/17, 4:27 PM	43.76368	-110.57889	8	10	51.125	3474	6366	2892	4626	1.41	2052.58

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File	Date:Time	Location X	Location Y	Sample Size	Distance	dB	Min Freq	Max Freq	Bandwidth	Peak Freq	Song Length	Complexity
CL161	6/30/17, 5:54 PM	43.65611	-110.71449	12	15	41.275	3300	6466	3166	4900	1.18	2691.42
CL163	7/2/17, 7:13 AM	43.87747	-110.57618	21	5	52.2	3094	6425	3331	4379	1.17	2848.44
CL165	7/2/17, 7:39 AM	43.88062	-110.57272	38	5	60.575	3699	7259	3560	5482	1.41	2531.25
CL169	7/2/17, 4:55 PM	43.90691	-110.59122	7	7.5	39	3655	6796	3140	4901	1.27	2469.06
CL171	7/3/17, 8:41 AM	43.86854	-110.57317	4	15	60.375	2825	6391	3566	4589	1.29	2759.21
CL177	7/3/17, 11:23 AM	43.56042	-110.75988	15	5	47.875	3425	6708	3283	4852	1.1	2996.88
CL181	7/3/17, 1:33 PM	43.64715	-110.75483	4	15	62.475	3393	6669	3276	5117	1	3273.08
CL184	7/3/17, 2:01 PM	43.65086	-110.74709	1	10	58.575	2734	6384	3649	4061	1.22	2998.71
CL201	7/4/17, 10:09 AM	43.56055	-110.75998	31	5	45.175	3907	7553	3645	5514	1.35	2696.42
CL203	7/4/17, 10:27 AM	43.55342	-110.76214	6	10	47.85	4006	7024	3018	5232	1.11	2708.44

Supplementary Table 1. File and collection information for recordings of Yellow Warblers' songs in Grand Teton National Park (see Figure 1 for a map of recording locations, with pin labels matching file numbers here)