

## RESEARCH ARTICLE

# Impacts of oil well drilling and operating noise on abundance and productivity of grassland songbirds

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**Handling Editor:** Matt Hayward**Abstract**

1. Anthropogenic noise from natural resource extraction may negatively impact many species, particularly those reliant on acoustic communication. To compare the impacts of several types of noise resulting from oil extraction operations on habitat use and productivity of grassland songbirds, we designed and implemented a novel large-scale, spatially and temporally replicated experiment.
2. We recreated soundscapes produced by drilling and operating oil well noise, and compared impacts of noise-producing and quiet playback infrastructure, in twenty-nine 64.7-ha native prairie sites in Alberta, Canada, from 2013 to 2015. Drilling noise recordings played 24 hr/day for 10 days, twice during each breeding season, while oil well operating noise played continuously, 24 hr/day, throughout each ~90-day breeding season.
3. Despite the much shorter duration of drilling noise playbacks, drilling noise negatively impacted three of our four focal species, and had a much greater impact on habitat use and productivity than did well operating noise. Infrastructure also impacted Vesper Sparrows and Sprague's Pipits, even in the absence of noise.
4. *Synthesis and applications.* Acute oil drilling noise had a greater negative impact on breeding migratory birds when compared to chronic oil well noise, perhaps because drilling noise is unpredictable. While this study demonstrates that noise alone can negatively impact habitat use, nesting success and nestling quality, it is also clear that effective mitigation strategies require both noise and above-ground infrastructure management to reduce impacts on wildlife.

**KEYWORDS**

anthropogenic noise, avian abundance, energy extraction, grassland songbirds, nesting success, noise playback, soundscape ecology

## 1 | INTRODUCTION

The increasing encroachment of anthropogenic noise into natural environments is a source of significant concern for wildlife conservation (Shannon, McKenna, et al., 2016), and both spatial extent and complexity of anthropogenic noise from activities related to natural resource extraction are expected to rise as development increases across the world. This noise pollution may increase risks to species reliant on acoustic communication that are already experiencing

significant population declines (Barber et al., 2010), such as grassland birds (Rosenberg et al., 2019; Sauer et al., 2017). Anthropogenic noise may reduce the abundance of sensitive species (Francis et al., 2011), affect predator-prey dynamics (Francis et al., 2009; Shannon et al., 2016), interfere with acoustic communication (Warren et al., 2006) and act as a physiological stressor (Blickley, Blackwood, et al., 2012; Blickley, Word, et al., 2012), all of which can lead to fitness consequences at impacted sites (Barber et al., 2010).

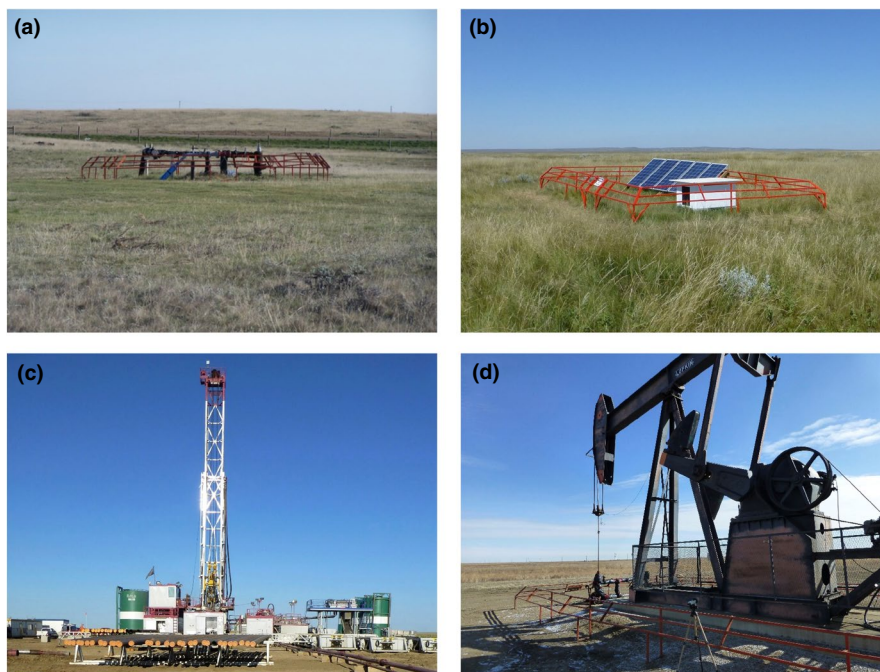
Hence, noise pollution results in functional habitat loss and degradation (Francis, 2015), decreased habitat quality and has a particularly large footprint due to the propagation of noise far beyond the perimeter of the built environment (Francis, Paritsis, et al., 2011).

Research on anthropogenic noise, however, is constantly challenged by difficulties in isolating effects of noise from potentially confounding factors associated with the anthropic source (e.g. roads and other above-ground features, chemical pollution; see Shannon, McKenna, et al., 2016). Surprisingly, even noiseless, roadless, 1-m tall shallow-gas wells impact abundances of grassland songbirds (Figure 1a; Rodger & Koper, 2017), demonstrating that even small structures might explain some effects of the built environment that could erroneously be attributed to noise. Thus, controlled playback experiments that isolate effects of noise from confounding factors at spatial scales relevant to conservation and land management are pivotal to help us understand responses to anthropogenic noise and to develop effective conservation strategies (Shannon, McKenna, et al., 2016). Recent large-scale playback studies have demonstrated that noise alone can affect passerine abundance and weight gain (McClure et al., 2013; Ware et al., 2015), clutch size and nestling body condition (Injaian et al., 2018), and lek attendance by Greater Sage-Grouse (*Centrocercus urophasianus*; Blickley, Blackwood, et al., 2012), greatly improving our appreciation for effects of noise in real-world conditions. While previous research has demonstrated negative impacts of broadcast energy sector noise on ground-nesting songbirds (Cinto Mejia et al., 2019), we know of no equivalent research assessing effects of the different types of operational oil noise across their breeding grounds.

Anthropogenic noise is tremendously variable in amplitude, frequency and pattern, and it is likely that impacts of noise vary strongly with its acoustic characteristics (Francis & Barber, 2013). Acute or erratic sounds may be perceived by wildlife as immediate

threats, and may also be difficult to adapt to if sounds are unpredictable (Blickley, Blackwood, et al., 2012; Francis & Barber, 2013). In contrast, continuous noise may mask vocalizations or important environmental cues, such as approaching predators, but is less likely to distract individuals from critical tasks such as foraging and caring for young (Leek et al., 1991; Wright et al., 2007). Despite this, we know of no long-term, landscape-scale playback studies that have tested whether different types of anthropogenic noise vary in their impacts on abundance and productivity of wildlife. Further research on this in the context of conservation is critical, as environmental noise regulations generally limit noise amplitudes but ignore other sound characteristics (e.g. Environment & Climate Change Canada, 2019; Federal Register, 2015). A better understanding of the relative ecological impacts of different types of industrial noises under real-world conditions is necessary to assess whether our current approaches to noise regulation are adequate.

Oil extraction provides an opportunity for an anthropogenic noise study of both practical and theoretical interest. Determining whether oil extraction influences wildlife because of the impacts of well construction, operating noise or because of the presence of above-ground infrastructure is essential to developing effective mitigation strategies. Noise produced by drilling rigs (Figure 1c) is acute, intermittent and inconsistent, with frequent and irregular changes in frequency and amplitude. In contrast, operating noise of oil wells is chronic, rhythmic and encompasses a wide range of frequencies (i.e. pumpjacks; Figure 1d). Furthermore, while some wells are powered via their connection to the provincial power grid, others are generator-powered and are thus much louder (Rosa & Koper, 2018), suggesting that their ecological footprint might also be larger. Hence, oil infrastructure provides a diverse suite of anthropogenic sounds, all distributed across a relatively homogeneous prairie landscape, allowing us to explore impacts of various anthropogenic sounds



**FIGURE 1** (a) Shallow-gas well pads, which are abundant across this region, have a very similar footprint (average 23.1 m<sup>2</sup>) and height (1.44 m; Rodger & Koper, 2017) to (b) playback units designed for the present study (footprint: 35.8 m<sup>2</sup>, height: 1.25 m; Rosa et al., 2015), and are composed of some of the same materials (i.e. identical technical fencing). Both are diminutive in comparison with (c) oil well drilling rigs (height: 24 m) and (d) pumpjacks (height: 4.5 m)

within a replicated design and at the landscape scale relevant to conservation and natural resources management.

To evaluate the impacts of noise from different oil infrastructure sources on relative abundance and productivity of migratory birds, we conducted a large-scale, multi-year field playback experiment where we recreated the soundscape produced by energy infrastructure by playing high-fidelity recordings of operating noise from two types of oil wells, and also of well drilling operations, at sites without oil infrastructure. We focused on four grassland songbird species experiencing population declines across their North American range (Sauer et al., 2017), including two federally threatened species (Government of Canada, 2018): Chestnut-collared Longspur *Calcarius ornatus* and Sprague's Pipit *Anthus spragueii*, and two non-listed species: Savannah Sparrow *Passerculus sandwichensis* and Vesper Sparrow *Poocetes gramineus*. These species were all abundant enough for us to evaluate impacts of noise on both abundance and nesting success while also encompassing the range of habitat preferences expressed by birds of this guild, from short (Chestnut-collared Longspur) to tall (Sprague's Pipit) grassland vegetation.

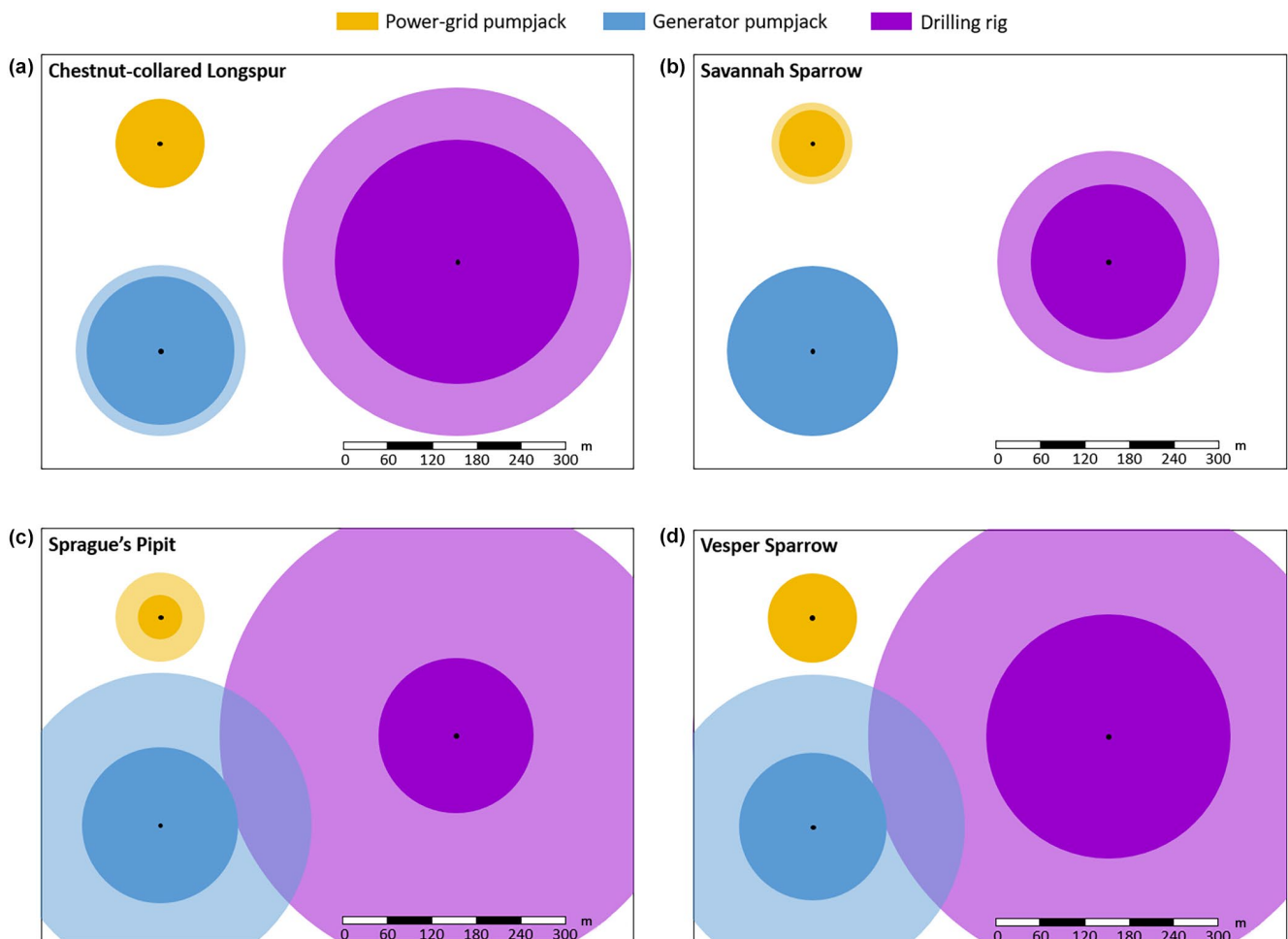
Vocalizations of these species also vary from relatively low to high frequencies such that the spatial extent of habitat potentially influenced by drilling and other industrial noise differs among species (Figure 2; see also Rosa & Koper, 2018), suggesting that we should expect a range of potential responses to noise from these species.

## 2 | MATERIALS AND METHODS

Experiments were conducted under University of Manitoba animal care protocol F15-005, Canadian Wildlife Service permit #11-MB/SKL/AB-SC007, and Alberta Environment and Sustainable Research Development Research Permit #56016.

### 2.1 | Study sites and treatments

We monitored bird abundance and nests in twenty-nine 64.7-ha (i.e. quarter section) mixed-grass prairie sites during three



**FIGURE 2** Acoustic footprint of drilling rig (purple) and pumpjack operating (yellow and blue) noise for (a) Chestnut-collared Longspur, (b) Savannah Sparrow, (c) Sprague's Pipit and (d) Vesper Sparrow. Inner circles indicate surface area where noise can energetically mask signals (noise levels within peak frequency exceed ambient levels). Outer circles represent surface area where noise can interfere with signal transmission (noise levels within frequency range of vocalization exceed ambient levels; see methods in Rosa & Koper, 2018; Appendix S1)

breeding seasons from early May to early August 2013–2015. Sites were located within 100 km of Brooks, County of Newell, Alberta (50°33'51"N; 111°53'56"W), a region with one of the highest densities of oil development in Canada (Government of Alberta, 2014); however, none of our study sites for this project contained oil infrastructure. We recorded real energy infrastructure and then broadcasted high-fidelity recordings by means of solar-powered playback systems. One playback system was placed at the centre of each of our native prairie quarter-section sites, except controls (for playback design details and fidelity tests; see Rosa et al., 2015).

Treatments included (a) drilling playbacks ( $n = 6$  sites;  $88 \pm 4.0$  dB(C)); (b) generator-powered pumpjack playbacks ( $n = 6$ ;  $73 \pm 5.2$  dB(C)); (c) power-grid pumpjack playbacks ( $n = 6$ ;  $62 \pm 2.8$  dB(C)); (d) infrastructure-only playbacks that look identical to the other playbacks, but emit no sound, to control for effects driven by the presence of the playback units ( $n = 6$ ); and (e) controls, with neither playback infrastructure nor real oil wells ( $n = 17$ ; Table 1). Infrastructure-only playbacks were very similar in dimension and materials in comparison with the shallow-gas wells that are abundant across this landscape (Figure 1a,b). Noise playback and infrastructure-only treatments were rotated among sites randomly between 2014 and 2015 to ensure that differences among treatments were not caused by differences among sites, resulting in 41 replicates in total.

We made recordings of three generator-powered pumpjacks, three power-grid pumpjacks (Rosa et al., 2015) and three different drilling rigs (Appendix S1). Active oil wells and drilling rigs were recorded at three different locations for a minimum of 65 min, in winds  $<7$  km/hr, using Zoom H4N handheld recorders. Microphones were setup approximately 1.5–6 m from the loudest noise source at pumpjacks (Rosa et al., 2015) and up to 50 m for drilling rig operations due to safety and logistical constraints (Appendix S1). We took sound pressure level (SPL) measurements along transects radiating in four cardinal directions using a Brüel and Kjær 2250 SPL meter/frequency analyser (Brüel and Kjær, Denmark) at active generator and power-grid pumpjacks, and drilling rig operations and at all playbacks sites. We measured  $LC_{eq}$  (C-weighted time-averaged values of SPL in decibels) for broadband sound because it is a flatter frequency filter, with less emphasis on frequencies biased towards human hearing when compared to A-weighting (Pater et al., 2009; see Rosa et al., 2015 and Appendix S1). We then compared sound characteristics of broadcast stimuli to real pumpjack noise (Rosa et al., 2015) and drilling rig noise (Appendix S1) and found we were

able to accurately reproduce the noise stimuli across the landscape (see Rosa et al., 2015 and Appendix S1 for detailed analyses).

Each recording was emitted from a different playback broadcasting unit. Pumpjack operating noise was broadcasted 24 hr/day for approximately 90 days each year, corresponding with the duration of the breeding season. Pumpjacks produce noise across a wide range of frequencies and within a predictable and consistent cycle (Figure 1d; Curry et al., 2018). Real pumpjacks are either powered through connection to the power grid ('power-grid pumpjacks') or powered by generators, which add noise ('generator pumpjacks'), so we compared effects of recordings of wells with both power sources. In contrast, for the drilling noise treatment, recordings of drilling rigs were broadcasted 24 hr/day during two 10-day periods within each breeding season, corresponding with the average duration of drilling operations for one well in this region (V. Dyck, Cenovus Energy, pers. comm.), separated by at least 15 days between the two 10-day broadcast periods. In addition to being played only 20 days/year, drilling noise differed from operating well noise in that drilling noise was inconsistent, erratic and changed throughout the recording and over the duration of the playback period (Figure 1c). Drilling noises, such as loud clanking of pipes, powering of different generators, intercom systems and trucks, all have sudden onsets that are highly variable and unpredictable. The start of the drilling playback periods was staggered by 3 days among the different replicates to allow us to distinguish effects of date and drilling noise.

## 2.2 | Field surveys

We conducted avian abundance surveys at each study site along transects radiating away from the playback structure, or centre of controls, in opposite directions (i.e. two 400 m  $\times$  200 m survey areas/site). We recorded all individuals and nests encountered, but only used data from our four focal species for this study. Each transect was surveyed twice each year from mid-May to early July, between sunrise and 10:00, on days without rain or winds  $>20$  km/hr (Ralph et al., 1993). We conducted 24–34 1-m<sup>2</sup> vegetation survey plots overlapping with abundance transects at each study site each year to account for potential confounding effects related to vegetation structure and composition (Fisher & Davis, 2011; for extended methods and vegetation results see Rosa, 2019). Nests were found by flushing adults off nests by dragging a weighted 25-m rope, as this method is recommended to minimize bias and facilitate

Site type	Noise type	$LC_{eq}$	Playback period (days) per year
Drilling activity	Intermittent	$88 \pm 4.0$	$10 \pm 0.6 \times 2$ periods
Generator pumpjack	Chronic	$73 \pm 5.2$	$95 \pm 11.0$
Power-grid pumpjack	Chronic	$62 \pm 2.8$	$87 \pm 11.9$
Infrastructure-only	Natural ambient	$51 \pm 3.3^*$	N/A
Control	Natural ambient	$51 \pm 3.3^*$	N/A

**TABLE 1** Site and noise type, C-weighted time-averaged sound pressure level for broadband noise ( $LC_{eq}$ ) 10 m from playback unit, and duration of playback periods per year for each treatment ( $\pm$  SD for both). Asterisks (\*) indicate that  $LC_{eq}$  for infrastructure-only and control sites were estimated from background noise level measurements

systematic nest searches in grasslands (Conkling et al., 2015). We searched 32 ha in 2013, 28 ha in 2014 and 56 ha in 2015, per site, from late May to mid-June, twice each year. No nests were damaged or affected by the ropes as the grass lifts the rope above the eggs or nestlings (Winter et al., 2003). Nests were marked and monitored every 2–4 days until broods fledged or were destroyed (Winter et al., 2003), at which point a 1-m<sup>2</sup> vegetation survey plot was also conducted at the nest.

The outcome of a nest was determined by observing development of nestlings for approximately 10 days after hatching (Ehrlich et al., 1988), and by noting disturbances indicative of predation (e.g. empty damaged nest at early nest age). A nest was considered successful if a minimum of one juvenile fledged. As we focused on effects of noise on nest predation, nests that were abandoned ( $n = 36$ ) or were unsuccessful due to unfavourable weather conditions ( $n = 9$ ) were excluded from statistical analyses. Clutch size consisted of the final number of eggs laid by the female. If nests were found after hatching, we used number of nestlings as an estimate of clutch size.

We also took morphometric measurements of the nestlings of two species for which we had the most nests; we had insufficient data to do so for our other two focal species. We measured Savannah Sparrow and Chestnut-collared Longspur nestlings at approximately day 5. Nestlings were weighed individually in holding bags using a Pesola micro-line spring scale (model #20030; 30 g capacity  $\times$  0.25 g resolution;  $\pm 0.3\%$  accuracy). We measured the length of the left tarsometatarsal bone (i.e. tarsus length) from the notch of the intertarsal joint to the top of the bent foot using a SPI dial calliper (model #31-415-3; 0.1 mm graduation;  $\pm 0.0015$  mm accuracy).

### 2.3 | Statistical analyses

We compared the drilling rig, generator pumpjack and power-grid pumpjack treatments to both the control and infrastructure-only treatments. We used unadjusted counts of birds as indices of relative abundance because our previous studies in this region indicate that these focal species are highly perceptible (Leston et al., 2015) and that song detection and distance estimates by human observers are not hindered by oil well noise (Koper et al., 2016). We ran generalized linear mixed models for each individual species (PROC GLIMMIX; SAS 9.4) to analyse bird abundance, body condition (i.e. scaled mass index: Peig & Green, 2009) and clutch size, and logistic-exposure models (PROC NLMIXED; SAS 9.4) to analyse nesting success (Shaffer, 2004). We used diagnostic graphs, deviance/df ratios and correlation tables to ensure assumptions of tests were met and that independent variables were not highly correlated.

We conducted all analyses at two spatial scales. Site-scale analyses were conducted at the scale of our quarter-section sites (i.e. 64.7 ha), at which management actions are typically implemented in this region. Site-scale analyses included treatment as a fixed variable, plus any vegetation variables that had an impact on the response variable according to preliminary analyses that we ran

prior to analysing effects of treatments (for vegetation results, see Rosa, 2019). Local-scale analyses (0–400 m) allowed us to determine whether impacts of noise and infrastructure were greatest closer to the disturbance, and thus whether effects of noise might be amplitude dependant. Local-scale models included treatment, distance to playback unit or site centre (for controls) and an interaction term between treatment and distance, as well as required vegetation variables. We included random variables to control for multiple samples within sites or nests and among years. We included site as a random variable for models with abundance and clutch size, and nest\_ID for body condition to control for measurements of siblings within nests.

## 3 | RESULTS

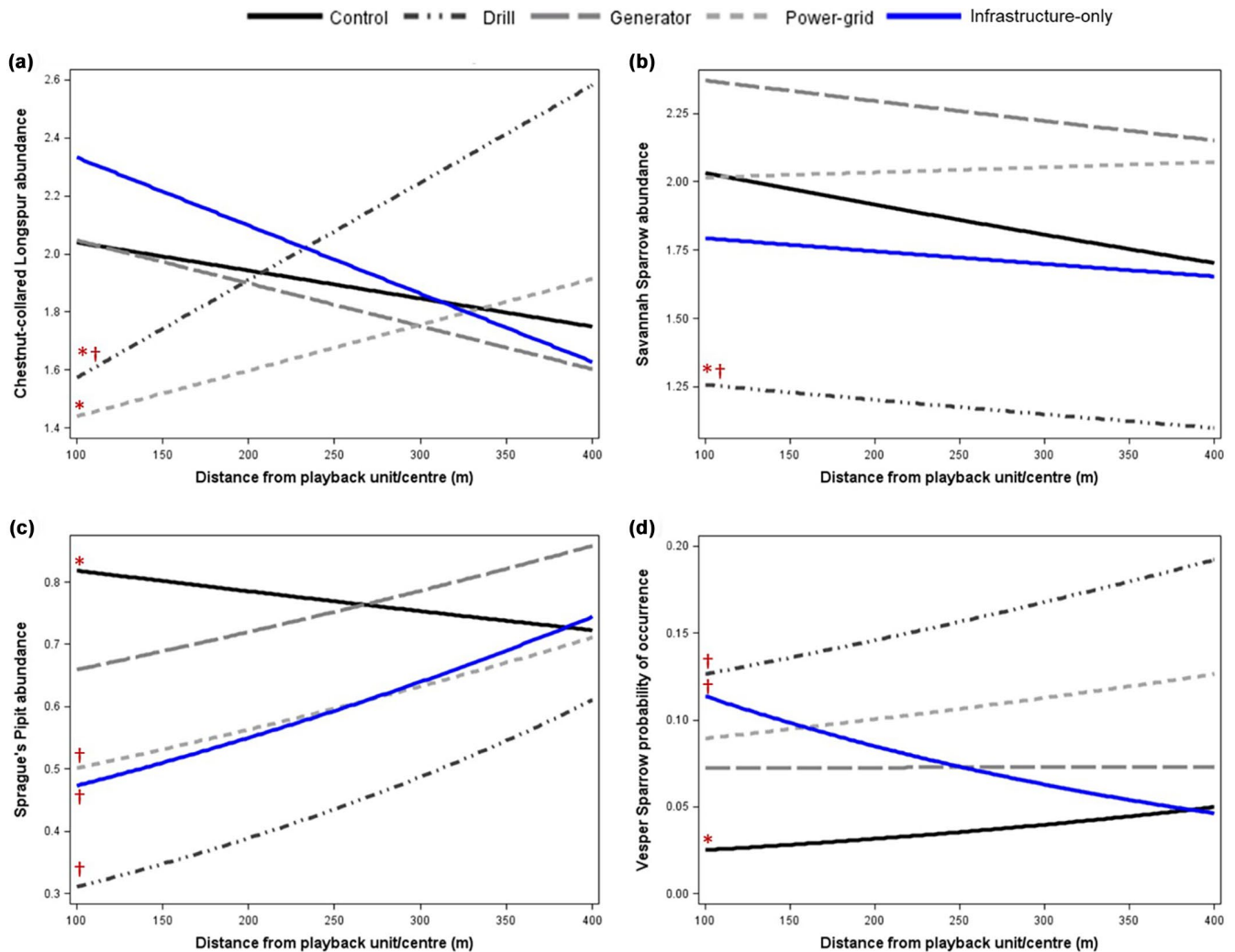
We used a post-hoc power analysis to ensure we achieved adequate power with our design. We estimated we could achieve power of 0.78 to detect a moderate effect size (6% change) with  $\alpha = 0.1$  with our 41 replicates (G\*Power 3.1.9.4). We concluded that this was close to the typical goal of achieving power of 0.8 in ecological studies, and thus that power to detect effects was sufficient. Practical limitations prevented us from having equal numbers of controls and treatment sites, but we were able to balance sample sizes among noise and infrastructure-only treatments.

### 3.1 | Avian abundance

We observed 2,982 Savannah Sparrows ( $\text{mean}_{\text{treatment}} = 596.4$ ;  $SD_{\text{treatment}} = 277.22$ ), 1,439 Chestnut-collared Longspurs ( $\text{mean}_{\text{treatment}} = 287.8$ ;  $SD_{\text{treatment}} = 272.95$ ), 1,022 Sprague's Pipits ( $\text{mean}_{\text{treatment}} = 204.4$ ;  $SD_{\text{treatment}} = 132.78$ ) and 239 Vesper Sparrows ( $\text{mean}_{\text{treatment}} = 47.8$ ;  $SD_{\text{treatment}} = 28.74$ ) during our surveys. Savannah Sparrows were our most abundant species in all treatments. Drilling noise negatively impacted relative abundance of more focal species than did pumpjack operating noise. At the local scale, we detected fewer Chestnut-collared Longspurs at both drilling and power-grid pumpjack playback treatments. This effect increased with proximity to noise (Figure 3a; Appendix S2, Table S2.8) such that adjacent to the playback infrastructure, relative abundance declined more than 30% compared with the infrastructure-only treatment. Although Chestnut-collared Longspurs avoided the drilling playbacks, which were associated with the greatest surface area of acoustic disturbance, they also avoided the power-grid pumpjacks, which had the smallest surface area of impact (Figure 2a). We did not detect significant effects of noise on Chestnut-collared Longspurs at the site scale ( $p \geq 0.44$ ; Table S2.9), suggesting that longspurs only avoid playbacks in the immediate vicinity of playbacks. At both the local and site scales, Savannah Sparrows avoided drilling noise (Figure 3b; Tables S2.8 and S2.9), where their relative abundance declined by close to 30%.

Two species' abundances were affected by the above-ground infrastructure rather than noise. At the local scale, Sprague's Pipits





**FIGURE 3** Effects of drilling rig, generator and power-grid pumpjack playback noise and of presence of the playback unit at the local scale on abundance of four species of grassland songbirds for each experimental treatment, from 2013 to 2015, in Alberta, Canada. All treatments were compared to both infrastructure-only (blue line) and control treatments (solid black line). Significant differences ( $p < 0.1$ ) compared to infrastructure-only treatment are indicated by \* and compared to control by †, for each species: (a) Chestnut-collared Longspur, (b) Savannah Sparrow, (c) Sprague's Pipit and (d) Vesper Sparrow (probability of occurrence, i.e. presence or absence). To facilitate interpretation of graphs, 90% confidence intervals were omitted from this figure (for statistical results and confidence intervals, see Appendix S2)

were more abundant at controls compared with all treatments with structures present, except for generator pumpjack playbacks (Figure 3c; Table S2.8). Adjacent to the infrastructure, their relative abundance declined by 40%–60% compared with controls (Figure 3c). Sprague's Pipit abundance was independent of treatment at the site scale ( $p \geq 0.36$ ; Table S2.9). Conversely, Vesper Sparrows were less abundant at controls compared to infrastructure-only and drilling playback sites at both the local ( $p = 0.02$ ; Figure 3d) and site scales ( $p < 0.05$ ; Table S2.9).

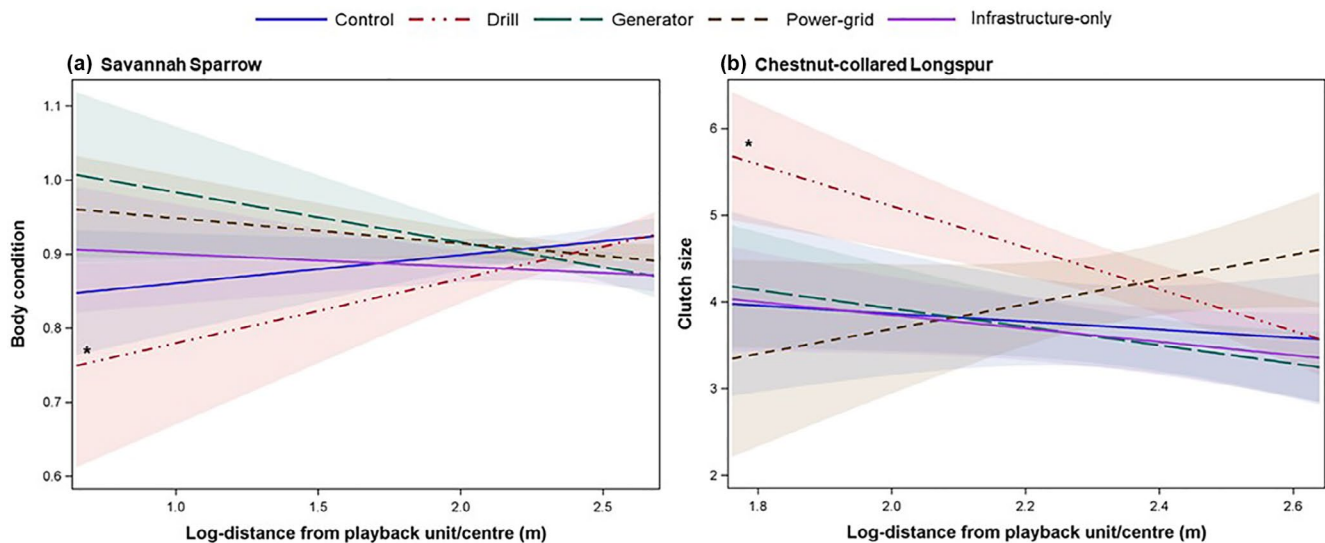
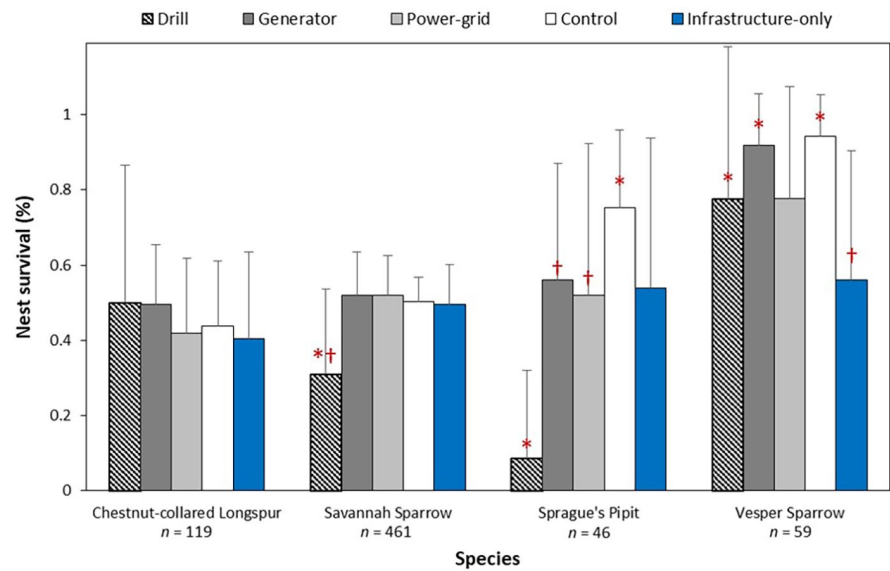
### 3.2 | Nesting success

We found and monitored 685 nests (i.e. 461 Savannah Sparrow, 119 Chestnut-collared Longspur, 46 Sprague's Pipit, and 59 Vesper

Sparrow nests). At the site scale, drilling playback noise resulted in approximately 35% decline in nesting success of Savannah Sparrows, and 85% decline in nesting success of Sprague's Pipits (Figure 4; Table S2.10). Hence, drilling noise had a much greater impact on nesting success than did pumpjack noise. Sprague's Pipits also had greater nesting success at controls compared to pumpjack playback sites and the infrastructure-only treatment. Nesting success of Vesper Sparrow was significantly lower at the infrastructure-only treatment compared to both the control and two of the noise treatments (Figure 4). We detected no significant effect of treatments on nesting success of Chestnut-collared Longspurs (Figure 4).

We did not detect impacts on nesting success at the local scale for Chestnut-collared Longspur ( $p \geq 0.12$ ) or Savannah Sparrow ( $p \geq 0.24$ ), indicating that impacts of noise reduced nesting success throughout the sites, regardless of distance to noise. Local-scale

**FIGURE 4** Effects of drilling rig and operating generator- and power-grid pumpjack noise playbacks, and of presence of playback unit, at the site scale on overall probability of nest survival (%) for four species of grassland songbirds at each experimental treatment, from 2013 to 2015, in Alberta, Canada. Noise-producing treatments were compared both to infrastructure-only (blue) and control (white) treatment. Significant differences ( $p < 0.1$ ) compared to infrastructure-only treatment are indicated by \* and compared to control by †. Errors bars indicate 90% confidence intervals



**FIGURE 5** Significant effects of noise on (a) nestling body condition of Savannah Sparrow and (b) clutch size of Chestnut-collared Longspur as a function of log-transformed distance from playback unit (or centre point at control treatments). Significant local-scale effects ( $p < 0.1$ ) are denoted by an asterisk (\*; see figures denoting non-significant effects in Appendix S2)

models including distance to infrastructure did not converge for Sprague's Pipits or Vesper Sparrows, perhaps because of their smaller sample sizes, suggesting that the added distance variable overparameterized models.

### 3.3 | Nestling body condition and clutch size

We measured Savannah Sparrow ( $n = 650$  from 182 nests) and Chestnut-collared Longspur ( $n = 219$  from 61 nests) nestlings at approximately day 5 (mean age = 5.04;  $SD \pm 0.43$ ). We did not detect significant effects of noise or infrastructure on body condition of nestling Savannah Sparrows at the site scale ( $p > 0.114$ ), but at the

local scale, nestlings had lower body condition near drilling noise (Figure 5a). Chestnut-collared Longspurs had significantly increased body condition at all noisy sites and the infrastructure-only treatment compared with controls ( $\beta = 0.869$ ;  $SE = 0.165$ ;  $p = 0.008$ ), but this effect was independent of distance to infrastructure ( $p > 0.940$ ).

Clutch sizes of Savannah Sparrow ( $n = 182$ ; mean = 4.17 eggs per nest;  $SD \pm 0.72$ ) were independent of noise or infrastructure at the site ( $p > 0.153$ ) and local scales ( $p > 0.226$ ). At the site scale, Chestnut-collared Longspur ( $n = 61$ ; mean = 3.89 eggs per nest;  $SD \pm 0.82$ ) produced larger clutches in both treatments that they avoided: drilling playbacks ( $\beta = 4.269$ ;  $SE = 1.838$ ;  $p = 0.012$ ) and power-grid pumpjack playbacks ( $\beta = 4.2268$ ;  $SE = 1.884$ ;  $p = 0.051$ ). At the local scale, Chestnut-collared Longspur clutch sizes were

larger at drilling playbacks ( $p < 0.069$ ), particularly close to the playback unit ( $p < 0.051$ ; Figure 5b), where clutch sizes averaged 5.5 eggs compared with 4 eggs at control and infrastructure-only sites.

## 4 | DISCUSSION

We found surprisingly few impacts of operating noise of wells despite the high amplitude of the noise they emit. In contrast, drilling noise negatively impacted three of our four focal species, which is particularly remarkable given that drilling noise played for only 22% of the time. Clearly, of the sounds we compared, drilling has the greatest potential for negatively impacting migratory songbirds during their breeding season. Although industry is constrained by setback buffers for drilling activities during peak breeding periods, in Canada these buffer zones are only limited to 100–200 m for listed species and 5–50 m for unlisted migratory songbirds (Canadian Energy Pipeline Association, 2013; Environment & Climate Change Canada, 2019), which is insufficient to mitigate many of the effects we observed, particularly on nesting success. However, three of our four focal species seemed able to adapt to chronic well operating noise, suggesting fewer conservation implications of operating noise. Nonetheless, limiting operating noise from oil wells would benefit Chestnut-collared Longspurs, and this has important regulatory implications as this species is Threatened in Canada (Government of Canada, 2018).

Drilling noise may have greater ecological impacts than oil well operating noise because the sudden onset and frequent shifts in frequency and amplitude of drilling noise can be alarming, threatening or distracting (e.g. Francis & Barber, 2013), or because drilling noise had a larger acoustic footprint than did operating noise (Figure 2). In contrast, chronic noise such as rhythmic oil well operating noise may be more conducive to acclimatization (Wright et al., 2007), and its predictability may allow birds to adopt effective behavioural coping mechanisms (Francis & Barber, 2013). Interestingly, Blickley, Blackwood, et al. (2012) found that chronic road noise had a greater impact on Greater Sage-Grouse than did natural gas well drilling noise and concluded that this may be because road noise was less predictable than drilling noise in their study. Similarly, Injaian, Poon, et al. (2018) found decreased productivity of tree swallows *Tachycineta bicolor* exposed to road noise. In our study system, drilling noise may reduce Savannah Sparrow nestling body condition because noise decreases feeding rates of adults, as a result of distraction or increased vigilance in noisy environments (Campbell et al., 2019; Ware et al., 2015), or perhaps because nestlings or parents exposed to noise experience altered corticosterone levels (Injaian, Taff, et al., 2018). We note that there are likely to be numerous other ecological interactions that are disrupted by drilling noise, but which we could not measure in our study, such as interspecific competition and other heterospecific interactions (e.g. Francis et al., 2009), and future studies should explore these interactions further.

To our surprise, generator-powered well noise did not have a greater impact on abundance and productivity than did power-grid

well noise, even though the acoustic footprint of generator-powered wells is significantly larger due to its higher amplitude (Figure 2). Chestnut-collared Longspurs and Sprague's pipits both showed greater avoidance of power grid than generator-powered well noise, suggesting that effects of noise may result, in part, from its acoustic structure, rather than simply amplitude (see also Blickley, Blackwood, et al., 2012; Rosa & Koper, 2018). While Kleist et al. (2018) found effects of noise amplitude on productivity and nestling development in some cavity-nesting species, some of these effects were strongly nonlinear, suggesting complex impacts of noise on physiology. Although settlement and egg-laying dates of tree swallows varied with noise amplitude, Injaian, Poon, et al. (2018) found that other measures of productivity were sensitive to the presence but not amplitude of noise. Cumulatively, these results are inconsistent with legal regulations of noise in North America, where amplitude and duration of anthropogenic noise and buffer distances around noisy industrial activities are regulated, while other characteristics of noise, such as frequency and predictability, are not considered (e.g. Environment & Climate Change Canada, 2019; Federal Register, 2015). In contrast to the assumptions behind these regulations, our results emphasize that making industrial infrastructure quieter will not always decrease its ecological impacts.

Our results also demonstrate that even diminutive above-ground infrastructure can affect species abundance and productivity. Abundance and nesting success of two of our focal species, Sprague's Pipits and Vesper Sparrows, were influenced by the presence of playback infrastructure, rather than its noise. This is particularly notable because the infrastructure to which these species responded, just like the shallow-gas wells that the infrastructure mimics, was silent, independent of roads, was only a metre high, and produced no air pollutants, and thus it lacks many of the characteristics often assumed to explain negative impacts of human development. Sprague's Pipits avoid and Vesper Sparrows are attracted to shrubs and other natural perch sites, probably explaining their responses to infrastructure (Rodgers & Koper, 2017). Although Vesper Sparrows often use anthropogenic habitat as perch sites for territorial display and thus may respond positively to the presence of anthropogenic structures (e.g. Rodgers & Koper, 2017), anthropogenic structures may also attract predators that use structures as perch sites (e.g. Ferruginous Hawks *Buteo regalis*; Wallace et al., 2016), or may use the presence of structures as visual cues indicating the presence of anthropogenically supplemented food sources, perhaps explaining the lower nesting success in these sites. The presence of above-ground infrastructure may result in an ecological trap for species that are attracted to infrastructure despite its negative impacts on productivity (Schlaepfer et al., 2002), such as Vesper Sparrows. Decreased productivity might occur where abundance is higher if competition for resources is correlated with abundance, or if predators are attracted to sites with high nest densities, although the latter is considered unlikely to influence predation risk of ground-nesting grassland songbirds as many depredation events are incidental in this system (Vickery et al., 1992). Regardless, recognizing



the impacts of the presence of above-ground infrastructure is critical to developing effective mitigation strategies, as minimizing industrial noise will not protect species that are affected by the infrastructure itself.

The noise from infrastructure, on the other hand, may result in a different type of trap for Chestnut-collared Longspurs, which avoided noise even though they experienced no negative impacts from it; in fact, they had higher productivity near noise types they avoided. Patten and Kelly (2010) named avoidance of suitable habitat a 'perceptual trap'. This results in functional loss of habitat and is particularly problematic for species whose population declines are attributed primarily to habitat loss, such as Chestnut-collared Longspurs (Environment & Climate Change Canada, 2017). Chestnut-collared Longspurs might be particularly sensitive to noise for two reasons: first, their vocalizations are relatively low, resulting in greater overlap with low-frequency oil infrastructure noise and thus a greater risk of energetic masking (Rosa & Koper, 2018; see also Francis et al., 2011), and second, they prefer short vegetation, which is more likely to occur in sites disturbed by oil activity, where anthropogenic noise is loudest. Of our four focal species, only Savannah Sparrows consistently selected habitats in which they also had high productivity. Savannah Sparrows are habitat generalists that have successfully adapted to many anthropogenically modified landscapes, and perhaps their ability to accurately identify lower risk breeding sites has contributed to their relative success (e.g. Clavel et al., 2011; Futuyma & Moreno, 1988; Kassen, 2002).

Mitigating both anthropogenic noise and above-ground infrastructure associated with the oil industry is necessary to reduce impacts on migratory grassland songbirds. Reducing noise amplitude at the source (e.g. mufflers, sound dampening walls or curtains) or shifting the timing of drilling activities away from the breeding period would reduce some, but not all, impacts of oil infrastructure on grassland songbirds (see also Francis, Ortega, et al., 2011). Noise reduction technology is frequently employed in human-populated areas (e.g. Habib et al., 2007), demonstrating that noise mitigation strategies are immediately and commercially available. Reducing the presence of above-ground infrastructure by drilling horizontally from centralized wells pads with noise barriers (see Francis, Ortega, et al., 2011) would reduce the extent of above-ground infrastructure, and is necessary to help to conserve other species, including Sprague's Pipits and Vesper Sparrows. Since our results show that Chestnut-collared Longspurs are sensitive to noise, whereas Sprague's Pipits are sensitive to above-ground infrastructure, both noise and the presence of oil well infrastructure must be reduced to conserve species at risk in this area.

We also note the gap between science and legislation regarding our understanding of the impacts of anthropogenic noise on birds. While most oil activities produce noise that constitutes a high-risk sensory disturbance according to federal regulations (e.g. 10 dB above ambient levels or noise levels higher than 50 dB; Environment & Climate Change Canada, 2017), energy associations argue that migratory birds inhabiting these areas are likely habituated to the noise

(e.g. Canadian Energy Pipeline Association, 2013), and thus are at little risk from it. However, our results demonstrate that apparent habituation to noise or the presence of species in noisy areas does not imply a lack of impact, as noise and the presence of infrastructure often have different impacts on abundance and productivity. Government and industry noise regulations should be revised to recognize that, and to reflect the fact that best management practices are dependent on the type of noise to which wildlife are exposed (see also Blickley, Blackwood, et al., 2012; Dooling & Popper, 2007).

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## CONFLICT OF INTEREST

Despite providing partial funding for this research to N.K. and P.R., Cenovus Energy had no input in the study design, data analysis, results interpretation or written work submitted for review. Their contributions consisted of providing safety training and assisting in logistics related to locating potential study sites. To maintain integrity, they were not consulted on this manuscript.

## AUTHORS' CONTRIBUTIONS

P.R. and N.K. designed the experiment; P.R. collected and analysed the field data and led the writing of the manuscript; N.K. supervised all work and the overall research programme. All authors contributed critically to drafts and gave final approval for publication.

## DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository <https://doi.org/10.5061/dryad.3j9kd51jz> (Rosa & Koper, 2021).

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## SUPPORTING INFORMATION

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