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RESEARCH ARTICLE

Boreal bird abundance estimates within different energy sector disturbances vary with point count radius

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ABSTRACT

Responses of boreal birds to changes in forest structure and composition caused by construction of well pads, seismic lines, and pipelines are poorly understood. Bird species associated with older forests are predicted to experience larger population declines with increased disturbance compared with species associated with younger or open habitats; however, point count methods may influence apparent outcomes because the proportional area of disturbed vegetation and the magnitude, uncertainty, and detection of a disturbance response by birds vary as a function of sampling area. We analyzed point count data from 12 energy sector studies and measured how disturbance type and point count radius interacted to affect 531 impact ratios (mean abundance at point counts centered within disturbances relative to abundance at point counts within forest 150–400 m from the nearest edge bordering those disturbances [59 species*3 disturbance types*3 point count radii]). We observed larger disturbance effects (impact ratios) within larger-radius point counts at well pads (100-m and unlimited-distance) and pipelines (unlimited-distance) compared with 50-m point counts at seismic lines, and within 50-m point counts at well pads relative to 50-m point counts at seismic lines. Effect uncertainty was higher at well pads and pipelines than seismic lines, and lower within larger-radius point counts. The probability of detecting a disturbance response was greater for larger-radius point counts at pipelines than for 50-m point counts at seismic lines, and within 50-m point counts at well pads relative to 50-m point counts at seismic lines. On average, a species was more likely to increase in abundance near an energy sector disturbance if the species was not associated with older (>75 yr) forest stages. While the effects of disturbance varied by species and with disturbance type, the effects of pipelines and seismic lines were better detected by larger-radius point counts, while the effects of well pads were better detected by smaller-radius point counts.

Keywords: Boreal Avian Modelling Project, seismic line, well pad, pipeline, bird, boreal forest, anthropogenic impacts, habitat alteration

Les estimations de l'abondance des oiseaux boréaux dans les différentes perturbations du secteur de l'énergie varient avec le rayon des points d'écoute

RÉSUMÉ

Les réponses des oiseaux boréaux aux changements dans la structure et la composition des forêts, causés par la construction de plateformes d'exploitation, de lignes de sondage sismique et de pipelines, sont mal comprises. On prédit que les espèces d'oiseaux associées aux forêts anciennes déclinent davantage avec une augmentation des perturbations en comparaison des espèces associées aux habitats plus jeunes ou ouverts. Toutefois, les méthodes de points d'écoute peuvent influencer les résultats apparents car la superficie proportionnelle de la végétation perturbée, de même que l'amplitude, l'incertitude et la détection d'une réponse des oiseaux face aux perturbations varient en fonction de l'aire d'échantillonnage. Nous avons analysé des données de points d'écoute de 12 études du secteur de l'énergie et nous avons mesuré comment le type de perturbation et le rayon des points d'écoute interagissaient pour affecter 531 taux d'impact (abondance moyenne aux points d'écoute centrés sur les perturbations par rapport aux points d'écoute dans la forêt à 150-400 m de la bordure la plus proche de ces perturbations [59 espèces*3 types de

perturbations *3 rayons de points d'écoute]). Nous avons observé de plus grands effets des perturbations (taux d'impact) aux points d'écoute avec des rayons plus grands aux plateformes d'exploitation (100 m et distance illimitée) et aux pipelines (distance illimitée) en comparaison des points d'écoute de 50 m aux lignes de sondage sismique, et pour les points d'écoute de 50 m aux plateformes d'exploitation comparativement aux points d'écoute de 50 m aux lignes de sondage sismique. L'incertitude de l'effet était plus élevée aux plateformes d'exploitation et aux pipelines qu'aux lignes de sondage sismiques, et plus faible aux points d'écoute avec un plus grand rayon. La probabilité de détecter des réponses aux perturbations était plus élevée aux points d'écoute avec un plus grand rayon aux pipelines que pour les points d'écoute de 50 m aux lignes de sondage sismique, et aux points d'écoute de 50 m aux plateformes d'exploitation comparativement aux points d'écoute de 50 m aux lignes de sondage sismique. L'abondance des espèces était plus susceptible d'augmenter dans les habitats perturbés si celles-ci n'étaient pas associées aux stades de forêts plus avancés (> 75 ans). Alors que les effets des perturbations varient selon les espèces et le type de perturbation, les effets des pipelines et des lignes de forage sismique étaient plus facilement détectés par les points d'écoute avec des rayons plus grands. Les effets des plateformes d'exploitation étaient quant à eux plus facilement détectés par des points d'écoute avec de plus petits rayons.

Mots-clés: Projet de modélisation aviaire boréale, ligne de sondage sismique, plateforme d'exploitation, pipeline, oiseau, forêt boréale, impacts anthropiques, altération de l'habitat

INTRODUCTION

Disturbance associated with energy sector development of conventional oil and gas reserves (hereafter, "disturbance") is rapidly increasing in the boreal forest of western North America, potentially affecting wildlife through a combination of habitat alteration and habitat fragmentation (Schneider and Dyer 2006, Jordaan et al. 2009, Van Wilgenburg et al. 2013). Within the western boreal forest, habitat alteration and fragmentation caused by this disturbance is spatially extensive and results from: (1) seismic exploration that involves cutting narrow paths (seismic lines) tens to hundreds of kilometers long (width = 2–10 m, density = 1.5–10.0 km km^{-2}) to allow specialized vehicles to locate oil and gas deposits; (2) well pads drilled to test for and extract oil and gas (1–2 ha each); (3) pipelines and/or low use service roads connect-

ing well pads (width = 20–30 m); and (4) permanent gravel or paved access roads (width = 9–11 m [road] or 20–40 m [right-of-way], density = 1 km km^{-2}) to facilitate the maintenance of well pads and other facilities (Schneider and Dyer 2006, Jordaan et al. 2009, Van Wilgenburg et al. 2013). Well pads and pipelines result in greater amounts of habitat alteration per unit length than seismic lines, but, compared with other human activities such as forestry, the amount of habitat directly altered by such energy sector features is relatively small at a local scale. In contrast, the amount of edge created per unit area disturbed by energy sector activities is particularly large, especially for seismic lines (Schneider and Dyer 2006, Jordaan et al. 2009). Forest regeneration occurs in many energy sector disturbances; however, human use often keeps seismic lines and pipelines open (Figure 1). Soil compaction and mixing from construction and ground disturbance, as well as shading by surrounding vegetation, also inhibit tree regeneration (Lee and Boutin 2006, Lankau et al. 2013; but see Machtans 2006). Unlike forestry, where tree planting and natural regeneration result in rapid regrowth, changes in boreal forest bird habitat may persist for years in many types of energy sector disturbance (Lee and Boutin 2006, Lankau et al. 2013). Therefore, the energy sector creates a unique ecological footprint that is locally small, regionally extensive, and long lasting. These pervasive but indirect effects of energy development on birds can be especially challenging to assess (Smith and Dwyer 2016, Loss 2016).

Energy sector disturbances have only recently been studied for their effects on boreal birds (Bayne et al. 2005a, 2005b, Machtans 2006, Van Wilgenburg et al. 2013). Point counts are commonly used to examine how bird abundance in the boreal forest changes between disturbed habitats and the forest interior (e.g., Schmiegelow et al. 1997, Lankau et al. 2013). Differences in survey methods among studies may affect conclusions. One such difference

FIGURE 1. Seismic lines, pipelines, and well pads from oil and gas development in western Canada result in simultaneous conversion of boreal bird habitats (either loss or creation, depending on the species) and edge creation, providing the context for our boreal bird surveys in 2002–2014. Photo credit: Jeff Ball
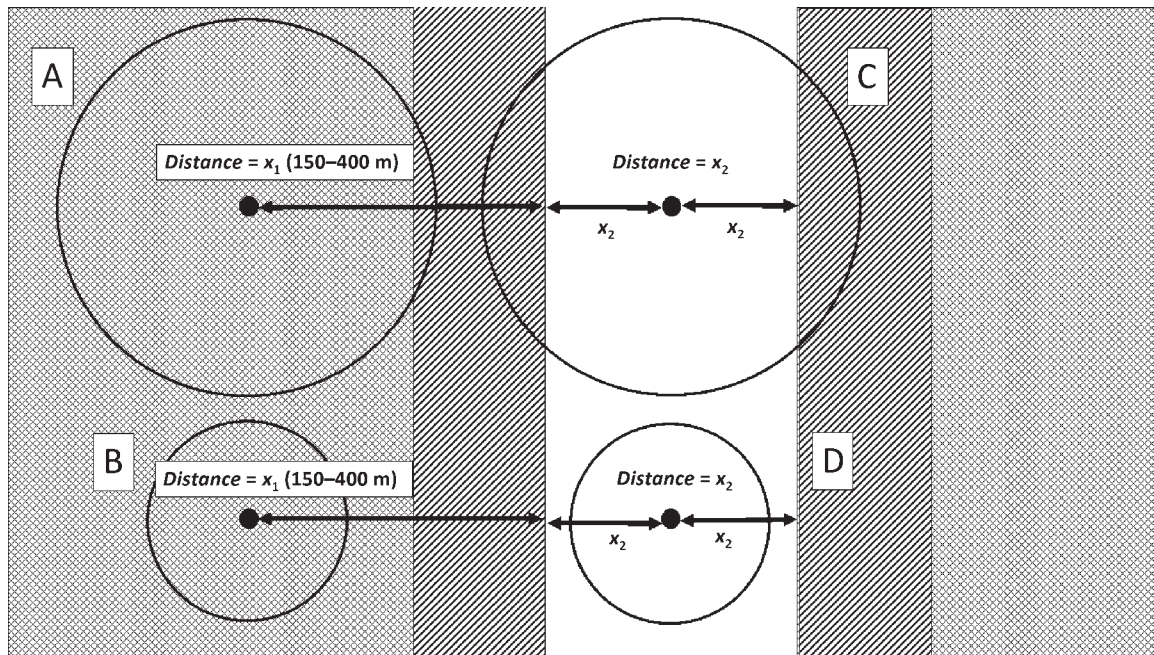
FIGURE 2. Point counts of different sizes in (**A**, **B**) forest interior and (**C**, **D**) near an edge between forest patches. Forest point counts A and B have their centers at the same distance ($x_1 \geq 150$ m) from the forest edge, but as point count A expands, it is increasingly likely to contact forest affected by edge habitat, making it less different from edge point count C. Edge point counts C and D have their centers at the same distance from a forest edge ($x_2 =$ from 3 m [some seismic lines] to 50 m [well pads]), but as point count C expands, it is increasing likely to contact the forest edge, making it less different from interior forest point count A. The smaller point counts B and D are more likely to be different from each other than the larger point counts A and C. Forest interior = crosshatched. Forest edge = diagonal shading. Unforested habitat = white.

is the radius of the survey area. In general, point count studies use either unlimited-distance point counts—in which all birds detected are recorded, regardless of the bird's distance from the observer—or limited-distance or fixed-radius point counts, in which only birds within a threshold distance are counted (Ralph et al. 1995, Thompson et al. 2002). Larger-radius point counts (e.g., 100-m or unlimited-distance) have a greater probability of detecting rare birds, reduced heterogeneity in abundance estimates (i.e. greater precision), and greater power to detect changes in abundance (Thompson et al. 2002); however, larger-radius point counts conducted in the forest interior (Figure 2A) are more likely to include disturbed or unforested habitats than smaller-radius point counts (Figure 2B). Similarly, larger-radius point counts located in or adjacent to a disturbance (Figure 2C) are more likely to contain forest interior habitat than smaller-radius point counts (Figure 2D). For a disturbance of a given area within a point count of radius r, the proportion of the point count occupied by that disturbance declines inversely with the square of r; thus, as the point count's radius is increased to $2r$, the proportion occupied by the disturbance within a point count of radius $2r$ is 0.25 times the original proportion. Thus, larger-radius point counts have an increasing probability of contaminating or diluting

the effects of different vegetation conditions on birds, reducing the magnitude of differences detected in the bird community among different vegetation types.

We assembled a novel collection of data from 12 studies of energy sector disturbances collated by the Boreal Avian Modelling Project (http://www.borealbirds.ca) between 2002 and 2014 in the boreal forests of western Canada, encompassing 1,852 point count survey locations. We used these data to determine: (1) which species displayed increased or decreased abundance at well pads, pipelines, and seismic lines; (2) how the amount of increase or decrease varied with disturbance type and point count radius; and (3) how the magnitude and (4) uncertainty of the estimated disturbance effect varied with point count survey radius (50-m, 100-m, and unlimited-distance). We predicted: (1) that species associated with older forest stages would be less abundant and species associated with younger forests, multiple forest stages, shrublands, or open lands would be more abundant in disturbed habitats relative to forest interiors (Schieck and Song 2006); (2) that there would be a smaller magnitude of response to seismic lines than to pipelines or well pads, due to smaller amounts of forest disturbed by seismic lines than either pipelines or well pads (Jordaan et al. 2009), and due to seismic lines having "softer" edges (Murcia 1995) (i.e. less
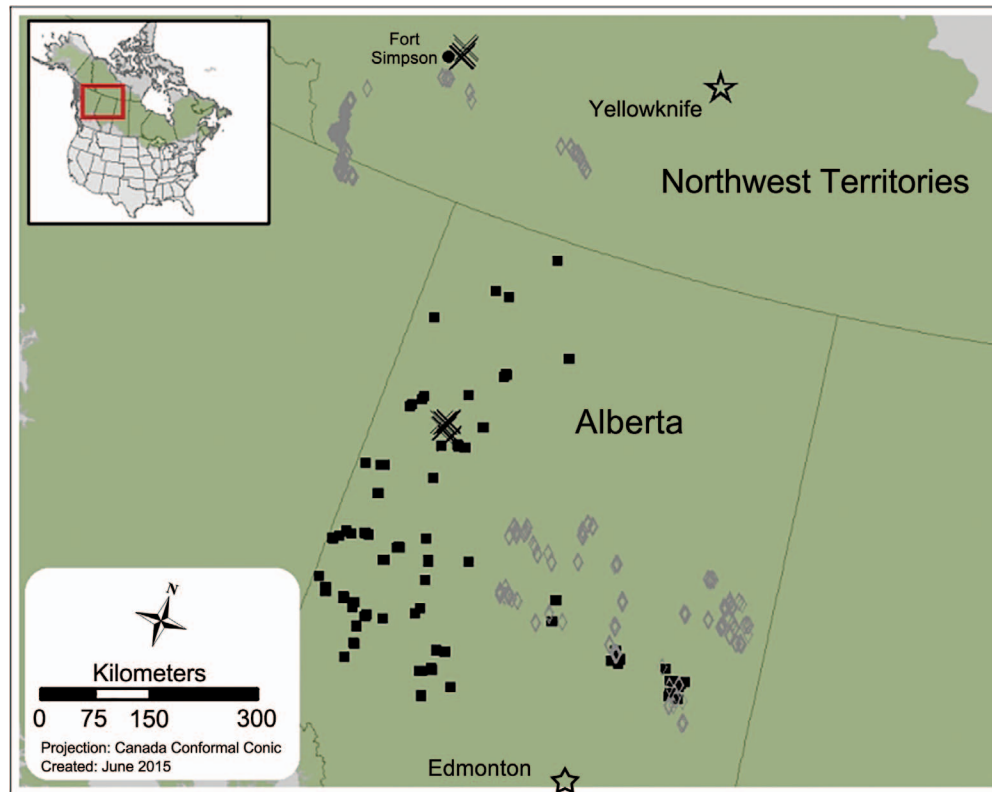
FIGURE 3. Study area examining the responses of boreal forest birds to energy sector disturbances using point counts of different radii in Alberta, northeastern British Columbia, and Northwest Territories, Canada, 2002–2014. Crosses = pipeline study sites. Diamonds = seismic line study sites. Squares = gas well pad study sites. Green = boreal and hemiboreal forest region (boreal zone map: Natural Resources Canada from Brandt [2009]).

extreme vegetation differences between surrounding forests and vegetation within seismic lines due to regeneration); (3) that the estimated magnitude of response would be greater within 50-m point counts than in 100-m or unlimited-distance point counts; and (4) that the uncertainty of the response would be higher in 50-m point counts due to higher variation in abundance estimates (Thompson et al. 2002).

METHODS

The 12 local-scale datasets (hereafter projects) used in this paper were collected by the authors between 2002 and 2014 using a common set of standard distance-sampling methods. Data were standardized for the combined analysis by assigning individual bird locations into 3 distance categories (0–50 m, 0–100 m, and 0–unlimited distance; Boreal Avian Modelling Project, http://www.borealbirds.ca). Each project included point count locations centered on an energy sector disturbance or in the forest interior. Disturbances included well pads (100 m × 100 m), seismic lines (width = 5–8 m), and pipelines (width = 25–40 m). The distance of interior forest points from

disturbed habitat differed among projects, but ranged from 150 m to 400 m from the disturbance edge. Similarly, the point counts located in the different disturbance types varied in both the proportion of disturbed habitat that they contained and the distance to the nearest forest edge, depending on the length and width of the disturbance. The general design was blocked, whereby point count stations were centered midway from forest edges within well pads, pipelines, and seismic lines, and were matched with 1 or 2 forest interior points 300–500 m away. The study area ranged from the southern edge of the boreal forest near Cold Lake, Alberta, Canada (54.4652°N, 110.1825°W), to Fort Simpson, Northwest Territories, Canada (61.8631°N, 121.3550°W). Each type of energy sector disturbance was studied in 2 or more spatially distinct locations (Figure 3).

We visited 1,852 unique point count locations, with 24% of the seismic line and 15% of the well pad point count locations visited twice per year. Forest interior point count locations were visited 1–2 times per year depending on the number of visits to the corresponding disturbed habitat point count locations. All pipeline point count locations and corresponding forest interior point count locations were visited once per year in 2 sequential years.

Preliminary analysis treating year as a random effect nested within station did not improve model fit (see below for description of analysis). In total, we included 2,516 point count visits in our analysis (202 at pipelines, 780 at seismic lines, 166 at well pads, and 1,368 in the forest interior).

Relative Abundance of Species at Energy Sector Disturbances and in the Forest Interior

We modeled raw estimates of relative abundance. There is currently considerable debate about the need to correct for detection error among study sites when estimating abundance (Anderson 2001, Johnson 2008, Welsh et al. 2013). We argue that methods that account for varying detectability of species carry their own statistical assumptions that are often violated by the data collected in field studies, and that there was little a priori reason to expect that detection rates would differ between our comparisons (Johnson 2008). We did not use mixture or occupancy models because many of our sites did not receive enough visits within or across seasons, and because many species had too few observations to generate reliable estimates of detectability given presence at sites (Welsh et al. 2013). Although point counts were conducted in our original studies using distance sampling methodology (Buckland et al. 2005), our primary interest was not in absolute differences in density, but rather in testing whether point counts of different radii revealed different relative patterns using a paired sampling design. We were also concerned that the mix of open and forested areas within our point counts centered on disturbed sites may have meant that declines in detections of open-land species with increasing distance were confounded with an absence of such species within forests at greater distances. A key requirement of distance sampling is that points are positioned independently of animals (uniformity assumption; Buckland et al. 2005). When points are placed in disturbed habitats contrasting with the forest interior, a bias is expected if animals are not uniformly distributed with respect to distance from the disturbance (Marques et al. 2010). Finally, we were interested in the effects of disturbance on the entire suite of boreal forest species in our study area, not just species common enough for distance sampling. Generally, 60–80 observations per stratum (e.g., habitat) are required for distance sampling (Buckland et al. 2005). Only 150 of 531 (~28%) combinations of species, disturbance type, and point count radius had at least 60 observations (Supplemental Material Table S1), and these observations were pooled across many types of habitat, within which effective detection radius can differ (e.g., open habitat [the disturbed areas] and closed habitat [surrounding forest types]). Had we replicated this analysis but used distance sampling to account for detection probability, we could have measured the effects of all disturbance types and point count radii for only 2 of 59 species (Ovenbird [*Seiurus aurocapilla*] and Tennessee Warbler [*Oreothlypis peregrina*]).

We treated the number of individuals observed per bird species as our response variable, while the independent variable of primary interest was disturbance type with 4 levels (pipeline, seismic line, well pad, and forest interior [reference level]). Disturbance type was evaluated using separate runs for each of the point count radii included in our data (0–50 m, 0–100 m, and 0–unlimited distance). Multiple models were considered, using combinations of latitude, longitude, time of day, time of year, canopy height of the adjacent forest, and vegetation composition, all of which were treated as nuisance covariates in our analyses. We obtained vegetation data from the Earth Observation for Sustainable Development of Forests raster layer (Natural Resources Canada, http://www.nrcan.gc.ca/forests/remote-sensing/13433) and the North American Land Cover Classification (NALC 2005). We collapsed vegetation definitions based on the availability of point counts within each vegetation type in each GIS layer (NALC 2005).

Analyses were performed using generalized linear mixed model regression with a Poisson distribution (Bolker et al. 2008) via the xtmepoisson command in Stata 11.2 (StataCorp, College Station, TX, USA). Each model contained disturbance type and nuisance covariates as fixed effects. Each model also contained 2 levels of nested random effects reflecting the hierarchical structure of the sampling design. We included site ($n = 287$) to account for the blocked nature of the point count locations with respect to the energy sector disturbance–forest interior comparison. Station ($n = 1,852$) was nested within site to account for the lack of independence among samples caused by visiting some of the same point count locations multiple times. Model results for disturbance type comparisons are presented as incident rate ratios (hereafter, impact ratios) for well pads, pipelines, and seismic lines. Impact ratios measure the expected difference in relative abundance of each species within each disturbance type relative to the adjacent forest interior within the same sampling radius after accounting for other fixed effects (e.g., vegetation). When impact ratios are back-transformed ($\exp[\beta]$), values >1 indicate that the average abundance of a species was higher in disturbed habitats, and values <1 indicate that the average abundance of a species was lower in disturbed habitats (Supplemental Material Table S2). Model fit was compared using Akaike's Information Criterion (AIC) and Akaike model weights (Burnham and Anderson 2002, Zuur et al. 2009). In subsequent analyses, we used the impact ratio for each edge type from the top model (lowest AIC, highest model weight) in each of the 3 analyses for each species.

Influence of Disturbance Type and Point Count Radius on the Magnitude and Uncertainty of Relative Abundance Estimates for Boreal Birds

The disturbance–forest interior analyses produced 3 impact ratios for each of the 59 species at each of the 3 sampling radii. We estimated the magnitude (absolute value or distance from 0) of the point estimate of each impact ratio, the uncertainty of that point estimate (measured as the breadth of the 90% confidence interval), and whether or not the point estimate, exp(β), was meaningfully different from 1 (i.e. 90% confidence interval excluded 1). Within each disturbance type, we used generalized linear models to analyze the effect of the point count radius on the magnitude of the impact ratio, uncertainty in the impact ratio estimate, and probability of detecting a disturbance effect. However, in the Poisson mixed-effects regression models that originally generated the impact ratios, the 3 impact ratios for each species within a given analysis were not independent of each other: they were each generated after accounting for other effects in the model, including the 2 other impact ratios. Thus, we also used an identifier for the species–point count radius (50-m, 100-m, or unlimited-distance) model run for each species as a random intercept effect (177 levels) in mixed-effects modeling using restricted maximum likelihood via the lmer function in the lme4 package of program R (Bates et al. 2015).

We evaluated the effects of point count radius (reference level = 50-m point count) and disturbance type (reference level = seismic line) as independent fixed factors to assess variation in: (1) the magnitude (absolute value) of the impact ratio for each species as a measure of change in the relative abundance in each different energy sector disturbance; (2) the uncertainty in the estimated value of each impact ratio (proportional to the breadth of the 90% confidence interval for each impact ratio coefficient = exp[$\beta \pm 2{*}1.645{*}\mathrm{SE}$ of β]); (3) whether or not any disturbance response was detected (i.e. whether 90% confidence intervals for exp[β] excluded 1); (4) whether or not a positive disturbance response was detected (i.e. whether the lower 90% confidence limit for exp[β] was >1); and (5) whether or not a negative disturbance response was detected (i.e. whether the upper 90% confidence limit for exp[β] was <1). We modeled magnitude and uncertainty with a normal error distribution and identity link function, and modeled detection of disturbance effects with a logit-link function. To reduce the influence of unusually large impact ratios with high estimate uncertainty on our modeling results, we weighted each observation by the inverse of the variance of each estimated impact ratio (i.e. SE of β^{-2}), so that impact ratios with greater uncertainty had less influence on the overall modeling results.

Magnitude and uncertainty were modeled as normally distributed, with uncertainty values log-transformed to approximate a normal distribution. As both metrics were based on impact ratios from a log-link function, we back-transformed these effect sizes after modeling ($= e^{\beta.\mathrm{magnitude}}$, $e^{\beta.90\% \ \mathrm{CI \ limits}}$) to calculate average relative differences in magnitude and uncertainty of edge response among disturbance types and point count radii as ratios. We also modeled whether any disturbance response was observed in each analysis (i.e. whether the 90% confidence intervals for exp[β] excluded 1: yes = 1, no = 0) using the glmer and logit-link functions in the lme4 package of program R (Bates et al. 2015). For each response variable, we tested 4 models: (1) point count radius alone; (2) disturbance type alone; (3) point count radius plus disturbance type without an interaction term; and (4) point count radius plus disturbance type with an interaction between these parameters. An example of model structure for a model including an interaction term is as follows:

(1) $\mathrm{Magnitude}(N_{ijk}) = \beta_0 + \beta_1{*}\mathrm{PCR}$
$$+ \beta_2{*}\mathrm{DT} + \beta_3{*}\mathrm{PCR}{*}\mathrm{DT}$$
$$+ \mathrm{normal \ error \ distribution}$$
$$/ \mathrm{identity \ link \ function};$$

(2) $\mathrm{Uncertainty}(N_{ijk}) = \beta_0 + \beta_1{*}\mathrm{PCR}$
$$+ \beta_2{*}\mathrm{DT} + \beta_3{*}\mathrm{PCR}{*}\mathrm{DT}$$
$$+ \mathrm{normal \ error \ distribution}$$
$$/ \mathrm{identity \ link \ function}$$
$$/ \mathrm{log\text{-}transformation \ of}$$
$$\mathrm{dependent \ variable; \ and}$$

(3) $\mathrm{logit}(P) = \beta_0 + \beta_1{*}\mathrm{PCR} + \beta_2{*}\mathrm{DT} + \beta_3{*}\mathrm{PCR}{*}\mathrm{DT},$

where P = probability of a nonzero response (detected = 1 or 0 for N_{ijk}), N_{ijk} represents the impact ratio coefficient for species i, disturbance type j, and point count radius k, PCR = point count radius, and DT = disturbance type.

We had a priori reason to expect that this interaction would be important, because within a given point count radius the disturbance type determines the proportion of the point count within disturbed habitat and the contrast of that habitat to the surrounding boreal forest. We ranked models by AIC value and generated estimates and 90% confidence intervals for the effects of point count radius and disturbance type (Burnham and Anderson 2002, Zuur et al. 2009).

We also modeled the probability that each impact ratio represented a positive or a negative response to disturbance (observed = 1, not observed = 0). For both response variables, we took the best model predicting the probability of observing a disturbance response (i.e. the interaction

FIGURE 4. Canada Warbler (*Cardellina canadensis*), associated with boreal old-growth forest, was on average 7–8× more abundant in boreal forest near pipelines compared with adjacent forest interior habitat during boreal bird surveys in the context of energy sector disturbances in western Canada, 2002–2014. Photo credit: Anjolene Hunt

model) and tested that model against models with additional effects:

(1) $\text{logit}(P) = \beta_0 + \beta_1 {}^*\text{PCR} + \beta_2 {}^*\text{DT} + \beta_3 {}^*\text{PCR} {}^*\text{DT};$

(2) $\text{logit}(P) = \beta_0 + \beta_1 {}^*\text{PCR} + \beta_2 {}^*\text{DT} + \beta_3 {}^*\text{PCR} {}^*\text{DT}$
$+ \beta_4 {}^*\text{HA}_{\text{old}};$

(3) $\text{logit}(P) = \beta_0 + \beta_1 {}^*\text{PCR} + \beta_2 {}^*\text{DT} + \beta_3 {}^*\text{PCR} {}^*\text{DT}$
$+ \beta_4 {}^*\text{HA}_{\text{old}} {}^*\text{DT};$

(4) $\text{logit}(P) = \beta_0 + \beta_1 {}^*\text{PCR} + \beta_2 {}^*\text{DT} + \beta_3 {}^*\text{PCR} {}^*\text{DT}$
$+ \beta_4 {}^*\text{HA}_{\text{young}};$

(5) $\text{logit}(P) = \beta_0 + \beta_1 {}^*\text{PCR} + \beta_2 {}^*\text{DT} + \beta_3 {}^*\text{PCR} {}^*\text{DT}$
$+ \beta_4 {}^*\text{HA}_{\text{young}} {}^*\text{DT};$

(6) $\text{logit}(P) = \beta_0 + \beta_1 {}^*\text{PCR} + \beta_2 {}^*\text{DT} + \beta_3 {}^*\text{PCR} {}^*\text{DT}$
$+ \beta_4 {}^*\text{HA}_{\text{mixed}}; \text{and}$

(7) $\text{logit}(P) = \beta_0 + \beta_1 {}^*\text{PCR} + \beta_2 {}^*\text{DT} + \beta_3 {}^*\text{PCR} {}^*\text{DT}$
$+ \beta_4 {}^*\text{HA}_{\text{mixed}} {}^*\text{DT},$

where P = probability of a positive (or negative) response (detected = 1 or 0 for N_{ijk}), N_{ijk} represents the impact ratio for species i, disturbance type j, and point count radius k, PCR = point count radius, DT = disturbance type, HA_{old} = whether or not species i is associated with old boreal forest stages (yes = 1, no = 0), HA_{young} = whether or not species i is associated with open lands, shrublands, or young forest stages, and HA_{mixed} = whether or not species i is a generalist that uses mixed habitats (Schieck and Song 2006).

We ranked models by AIC value and generated estimates and 90% confidence intervals for the effects of point count radius, disturbance type, and habitat association of each species (Burnham and Anderson 2002, Zuur et al. 2009).

RESULTS

Relative Abundance of Species at Energy Sector Disturbances and in the Forest Interior

The abundances of 35 of 59 species did not decrease within any energy sector disturbances relative to the forest interior, despite disturbance point count locations having less forested area than corresponding forest interior point count locations with the same radius. These 35 species showed only positive or neutral disturbance responses and included 4 generalist species inhabiting all forest stages, 11 species associated with shrublands, 1 open-land species, 4 species associated with parklands, 1 species associated with burns, and 4 species associated with aquatic boreal forest habitats (Schieck and Song 2006). However, 9 of the species (Bay-breasted Warbler [*Setophaga castanea*], Brown Creeper [*Certhia americana*], Canada Warbler [*Cardellina canadensis*; Figure 4], Cape May Warbler [*Setophaga tigrina*], Golden-crowned Kinglet [*Regulus satrapa*], Hairy Woodpecker [*Picoides villosus*], Warbling Vireo [*Vireo gilvus*], Winter Wren [*Troglodytes hiemalis*], and Yellow-bellied Sapsucker [*Sphyrapicus varius*; Figure 5]) that showed only positive or neutral responses were species that are typically associated with older forests >75 yr old (Schieck and Song 2006). These 9 species were more abundant along pipelines or seismic lines than in undisturbed boreal forests (Supplemental Material Table S1).

The 24 species that decreased within 1 or more type of disturbance included 4 generalist forest species, 6 species associated with shrublands or young forests, and 14 species associated with older forests (Schieck and Song 2006). For example, depending on the sampling radius considered, Red-eyed Vireos (*Vireo olivaceus*; Figure 6) were 14–35% less abundant along seismic lines, 26–31% less abundant along pipelines, and 21–66% less abundant at well pads compared with adjacent forest interior. Ovenbirds were 2–19% less abundant

FIGURE 5. Yellow-bellied Sapsucker (*Sphyrapicus varius*), associated with boreal old-growth forest, was on average 5–7× more abundant in boreal forest near pipelines compared with adjacent forest interior habitat during boreal bird surveys in the context of energy sector disturbances in western Canada, 2002–2014. Photo credit: Jeff Ball

FIGURE 6. Red-eyed Vireo (*Vireo olivaceus*), a forest generalist, was on average 14–35% less abundant along seismic lines, 26–31% less abundant along pipelines, and 21–66% less abundant at well pads compared with adjacent forest interior habitat during boreal bird surveys in the context of energy sector disturbances in western Canada, 2002–2014. Photo credit: Jeff Ball

along seismic lines, 2–24% less abundant along pipelines, and 11–69% less abundant at well pads compared with adjacent forest interior (Supplemental Material Table S2).

Fourteen species exhibited mixed positive and negative responses to different disturbances. Most of these species are associated with older forests (Schieck and Song 2006). For example, in 50-m point counts, Boreal Chickadees (*Poecile hudsonicus*) were from 71% less abundant to 19% more abundant along pipelines and were from 25% to 98% less abundant at well pads, but were from 21% to 122% more abundant along seismic lines, than in interior forest. In 100-m point counts, Boreal Chickadees were from 64% less abundant to 24% more abundant along pipelines and from 88% less abundant to 3% more abundant at well pads, but were 9–92% more abundant along seismic lines, than in interior forest. In 50-m point counts, Ruby-crowned Kinglets (*Regulus calendula*) were 7–67% less abundant at well pads and 2–73% less abundant along pipelines, but were 6–51% more abundant along seismic lines, than in interior forest. In 100-m point counts, Ruby-crowned Kinglets were from 36% less abundant to 19% more abundant along pipelines, but were 3–35% more abundant along seismic lines, than in interior forest (Supplemental Material Table S2).

Influence of Disturbance Type and Point Count Radius on the Magnitude and Uncertainty of Relative Abundance Estimates for Boreal Birds

When disturbance types were analyzed separately, within all disturbance types the magnitude of impact ratios declined with increasing point count radius relative to 50-m-radius point counts (i.e. β_{100m}, $\beta_{unlimited} < 0$, both 90% CI limits < 0). Similarly, the log-transformed uncertainty in each impact ratio's estimate also declined with increasing point count radius. However, the probability of detecting a disturbance effect of seismic lines increased within 100-m and unlimited-distance point counts relative to 50-m point counts, while the probability of detecting a disturbance effect of well pads or pipelines decreased within 100-m and unlimited-distance point counts relative to 50-m point counts (Figure 7).

Within mixed-effects models ($n = 509$ [although our habitat models generated 531 impact ratios across all combinations of species, disturbance type, and point count radius, we discarded 22 impact ratios because a few species were absent from some disturbance types]), there was very strong support (>99% of the model weight; Table 1) for an interaction between disturbance type and point count radius on the magnitude of the impact ratio. Averaged across species, the magnitude of response was ~37–39% lower for 100-m and unlimited-distance point counts at well pads than for 50-m point counts at seismic lines ($\beta_{well\ pad*100m} = -0.49$, 90% CL $= -0.62$, -0.35; $\beta_{well\ pad*unlimited} = -0.46$, 90% CL $= -0.59$, -0.33), and 14% higher for unlimited-distance point counts at pipelines than for 50-m point counts at seismic lines ($\beta_{pipeline*unlimited} = 0.13$, 90% CL $= 0.01$, 0.25; Table 1). Averaged across species, the magnitude of the disturbance response was approximately twice as high within
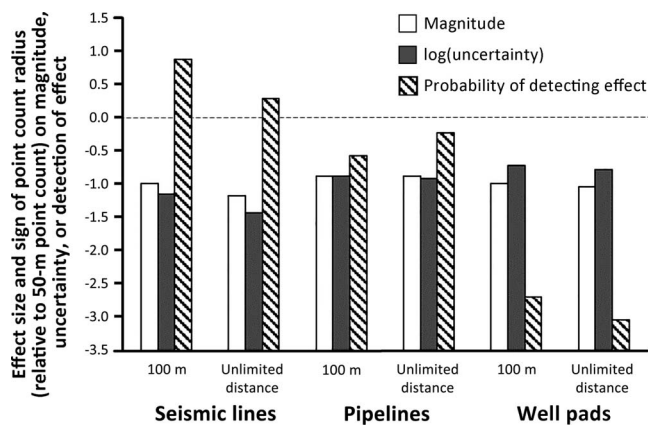
FIGURE 7. Bar plot where bars indicate the coefficient size and sign associated with the effect of point count radius (100 m relative to 50 m, unlimited distance relative to 50 m) on magnitude of impact ratios, log(uncertainty in point estimate of impact ratios), and probability of detecting a disturbance effect (both 90% confidence interval limits of impact ratio estimate were either negative or positive) of energy sector disturbances on boreal forest bird abundance in western Canada, 2002–2014, when impact ratios were analyzed separately by disturbance type: seismic lines ($n = 176$); pipelines ($n = 163$); wellpads ($n = 170$). The dashed line at $y = 0$ indicates where the effect size of point count radius would not result in a difference in magnitude, uncertainty, or probability of detecting a disturbance effect, relative to a 50-m point count. Magnitude of and log-transformed uncertainty in each impact ratio's estimate declined on 100-m and unlimited distance point counts relative to 50-m point counts for all disturbance types. Probability of detecting a disturbance effect of seismic lines increased while probability of detecting a disturbance effect of wellpads or pipelines decreased on 100-m and unlimited distance point counts relative to 50-m point counts.

50-m point counts at well pads as it was within any point count radius at seismic lines and pipelines, or within 100-m or unlimited-distance point counts at well pads.

There was strong support (∼85% of the model weight; Table 2) for additive effects of both disturbance type and

point count radius on the uncertainty in the estimate of relative abundance of boreal forest birds within disturbed and forest interior habitats. After back-transforming parameter estimates and averaging across species, uncertainty in the estimate was 62% higher for well pads than for seismic lines ($\beta = 0.48$, 90% CL = 0.43, 0.53) and 48% higher for pipelines than for seismic lines ($\beta = 0.39$, 90% CL = 0.35, 0.43). Uncertainty in estimates was 30% lower for 100-m radius point counts ($\beta = -0.35$, 90% CL = −0.56, −0.15) than for 50-m point counts, and was 34% lower for unlimited-distance point counts ($\beta = -0.42$, 90% CL = −0.62, −0.21) than for 50-m point counts (Table 2).

There was very strong support (>99% of the model weight; Table 3) for an interaction between disturbance type and point count radius in determining whether or not the estimated relative abundance within disturbed and forest interior habitats differed from zero. Averaged across species, differences in relative abundance between disturbed habitats and forest interior habitats were more likely to be detected by 100-m and unlimited-distance point counts at pipelines than by 50-m point counts at seismic lines, but were less likely to be detected by 100-m and unlimited-distance point counts at well pads than by 50-m point counts at seismic lines (Table 3). The probability of detecting a nonzero effect of disturbance was approximately twice as high for 50-m point counts at well pads as it was for 50-m point counts at seismic lines.

Interactions between point count radius and disturbance type and between disturbance type and a species' habitat association strongly predicted whether or not a positive disturbance response (relative abundance higher within disturbed habitats than the forest interior) was observed. In the model with the highest Akaike weight, higher abundance in disturbed habitats relative to the forest interior was more likely to be detected with 100-m and unlimited-distance point counts at both well pads and pipelines than with 50-m point counts at seismic lines (Table 4). Higher abundance in disturbed habitats relative

TABLE 1. Model weights and top-model parameter estimates (disturbance type [DT] relative to seismic lines, point count radius [PCR] relative to 50 m) for predicting the magnitude of relative abundance estimates of boreal forest birds in forest interior habitats and habitats affected by energy sector disturbances in western Canada, 2002–2014. Parameter estimates were derived from the model with the highest Akaike weight (w_i). Models were ranked by the difference in Akaike's Information Criterion (ΔAIC) from the top model. K is the number of model parameters, and $-2\ln L$ is the maximized log-likelihood.

Model	K	ΔAIC	$-2\ln L$	w_i	Parameter	Effect size	Lower 90% CL	Upper 90% CL
DT*PCR	9	0.00 [a]	906.38	>0.99	100-m radius	−0.17	−0.33	0.00
DT + PCR	5	48.22	962.91	0.00	Unlimited distance	−0.25	−0.41	−0.09
DT	3	56.20	974.99	0.00	Pipeline	0.00	−0.10	0.11
PCR	3	75.38	994.17	0.00	Well pad	0.54	0.44	0.64
					100-m radius*Pipeline	0.08	−0.05	0.20
					Unlimited distance*Pipeline	0.13	0.01	0.25
					100-m radius*Well pad	−0.49	−0.62	−0.35
					Unlimited distance*Well pad	−0.46	−0.59	−0.33

[a] The AIC of the top model = 928.9.

TABLE 2. Model weights and top-model parameter estimates (disturbance type [DT] relative to seismic lines, point count radius [PCR] relative to 50 m) for predicting the uncertainty of the numeric edge response estimate of boreal forest birds to energy sector disturbances in western Canada, 2002–2014. Parameter estimates were derived from the model with the highest Akaike weight (w_i). Models were ranked by the difference in Akaike's Information Criterion (ΔAIC) from the top model. K is the number of model parameters, and $-2\ln L$ is the maximized log-likelihood.

Model	K	ΔAIC	$-2\ln L$	w_i	Parameter	Effect size	Lower 90% CL	Upper 90% CL
DT + PCR	5	0.00 [a]	945.92	0.85	100-m radius	−0.35	−0.56	−0.15
DT	3	3.45	953.47	0.15	Unlimited distance	−0.42	−0.62	−0.21
DT*PCR	9	13.51	951.12	0.00	Pipeline	0.39	0.35	0.43
PCR	3	224.45	1174.47	0.00	Well pad	0.48	0.43	0.53

[a] The AIC of the top model = 960.1.

to the forest interior was less likely to be detected for generalist species using mixed habitats within well pads than within seismic lines, but was more likely to be detected for such species within pipelines than within seismic lines (Table 4). Interaction models in which the habitat association that was tested consisted of open lands, shrublands, or younger forest stands (second-highest model weight; Table 4) or mature boreal forest stands (third-highest model weight; Table 4) exhibited similar effects of point count radius interacting with disturbance type. A positive effect was less likely to be observed for species associated with mature forest stages within well pads or pipelines than within seismic lines, but was more likely to be observed within well pads or pipelines than within seismic lines for species associated with younger or open habitats. These models had negligible Akaike weights, but are reported here to show how birds of different habitat associations responded to energy sector disturbances.

Interactions between point count radius and disturbance type and between disturbance type and a species' habitat association strongly predicted whether or not a negative disturbance response (lower relative abundance within disturbed habitats than the forest interior) was

observed. The model with the highest Akaike weight predicted that lower abundance in disturbed habitats relative to the forest interior was less likely to be detected by 100-m and unlimited-distance point counts at well pads than by 50-m point counts at seismic lines, but was more likely to be detected with larger-radius point counts at pipelines than with 50-m point counts at seismic lines (Table 5). Lower abundance in disturbed habitats relative to the forest interior was also less likely to be detected for species associated with open lands, shrublands, or younger forests within well pads than within seismic lines, but was more likely to be detected for such species within pipelines than within seismic lines (Table 5). Interaction models in which the habitat association that was tested consisted of mature boreal forest stands (second-highest model; Table 5) or mixed habitats (third-highest model; Table 5) exhibited similar effects of point count radius interacting with disturbance type. A negative effect was more likely to be observed for species within well pads or pipelines than within seismic lines for species associated with mature forest stages, and was less likely to be observed within well pads or pipelines than within seismic lines for generalist species that used mixed habitats. These models had negligible Akaike weights, but again are reported here to

TABLE 3. Model weights and top-model parameter estimates (disturbance type [DT], point count radius [PCR]) for predicting a nonzero disturbance response—that is a difference in relative abundance between disturbed and forest interior habitats (detected = 1, not detected = 0) for boreal forest birds affected by energy sector disturbances in western Canada, 2002–2014. Parameter estimates were derived from the model with the highest Akaike weight (w_i). Models were ranked by the difference in Akaike's Information Criterion (ΔAIC) from the top model. K is the number of model parameters, and $-2\ln L$ is the maximized log-likelihood.

Model	K	ΔAIC	$-2\ln L$	w_i	Parameter	Effect size	Lower 90% CL	Upper 90% CL
DT*PCR	9	0.00 [a]	12465.3	>0.99	100-m radius	0.65	−1.05	2.34
DT	3	2720.13	15197.8	0.00	Unlimited distance	−0.14	−1.82	1.54
DT + PCR	5	2723.92	15197.5	0.00	Pipeline	−0.60	−0.80	−0.40
PCR	3	3764.41	16242.1	0.00	Well pad	2.93	2.72	3.14
					100-m radius*Pipeline	2.18	1.92	2.44
					Unlimited distance*Pipeline	3.62	3.36	3.88
					100-m radius*Well pad	−4.23	−4.53	−3.94
					Unlimited distance*Well pad	−4.12	−4.42	−3.82

[a] The AIC of the top model = 12,485.7.

TABLE 4. Model weights and top-model parameter estimates (disturbance type [DT], point count radius [PCR], habitat association [HA]) for predicting a positive disturbance response—that is a higher mean abundance in disturbed habitats relative to forest interior (detected = 1, not detected = 0) of boreal forest birds to energy sector disturbances in western Canada, 2002–2014. HA_{mature} = whether a species was associated with mature forest stages. HA_{young} = whether a species was associated with shrublands, open lands, or younger forest stages. HA_{mixed} = whether a species was a generalist using mixed habitats. Parameter estimates were derived from the model with the highest Akaike weight (w_i). Models were ranked by the difference in Akaike's Information Criterion (ΔAIC) from the top model. K is the number of model parameters, and $-2\ln L$ is the maximized log-likelihood.

Model	K	ΔAIC	$-2\ln L$	w_i	Parameter	Effect size	Lower 90% CL	Upper 90% CL
DT*PCR + DT*HA$_{mixed}$	12	0.00 [a]	5340.0	>0.99	HA$_{mixed}$ (yes = 1)	−2.53	−4.97	−0.09
DT*PCR + DT*HA$_{young}$	12	59.31	5399.4	0.00	100-m radius	−0.12	−2.56	2.32
DT*PCR + DT*HA$_{mature}$	12	248.96	5589.0	0.00	Unlimited distance	−1.90	−4.34	0.55
DT*PCR + HA$_{young}$	10	829.37	6173.6	0.00	Pipeline	−2.08	−2.42	−1.74
DT*PCR + HA$_{mature}$	10	833.41	6177.8	0.00	Well pad	−5.68	−6.36	−5.00
DT*PCR	9	833.47	6179.8	0.00	100-m radius*Pipeline	1.24	0.83	1.65
DT*PCR + HA$_{mixed}$	10	835.66	6180.0	0.00	Unlimited distance*Pipeline	3.80	3.38	4.22
					100-m radius*Well pad	4.43	3.69	5.16
					Unlimited distance*Well pad	5.31	4.56	6.06
					HA$_{mixed}$*Pipeline	10.28	8.36	12.21
					HA$_{mixed}$*Well pad	−5.47	−6.26	−4.69

[a] The AIC of the top model = 5366.8.

DISCUSSION

Relative Abundance of Species at Energy Sector Disturbances and in the Forest Interior

We found that, overall, relatively few species in our study were less abundant within disturbed habitats associated with oil and gas development than in adjacent boreal forest >150 m from a disturbance edge, while some species actually had higher abundance within these disturbed habitats. Like Schieck and Song (2006), we found that birds associated with forests >75 yr old were more likely to be less abundant within disturbed habitats than in the forest interior, especially at well pads and pipelines relative to seismic lines. The declines of mature forest birds within disturbed habitats associated with energy infrastructure are consistent with observed negative effects of forest fragmentation on and loss of Ovenbirds in logged or agricultural landscapes (Bayne and Hobson 2001, 2002, Mazerolle and Hobson 2004) and on species associated with older boreal forests that have been disturbed by fires or harvesting (Schieck and Song 2006). Some species associated with older forests were less abundant within one kind of energy sector disturbance but were more

TABLE 5. Model weights and top-model parameter estimates (disturbance type [DT], point count radius [PCR], habitat association [HA]) for predicting a negative disturbance response—that is a lower mean abundance in disturbed habitats relative to forest interior (detected = 1, not detected = 0) of boreal forest birds to energy sector disturbances in western Canada, 2002–2014. HA_{mature} = whether a species was associated with mature forest stages. HA_{young} = whether a species was associated with shrublands, open lands, or younger forest stages. HA_{mixed} = whether a species was a generalist using mixed habitats. Parameter estimates were derived from the model with the highest Akaike weight (w_i). Models were ranked by the difference in Akaike's Information Criterion (ΔAIC) from the top model. K is the number of model parameters, and $-2\ln L$ is the maximized log-likelihood.

Model	K	ΔAIC	$-2\ln L$	w_i	Parameter	Effect size	Lower 90% CL	Upper 90% CL
DT*PCR + DT*HA$_{young}$	12	0.00	6745.0	>0.99	HA$_{young}$ (yes = 1)	−1.60	−4.35	1.16
DT*PCR + DT*HA$_{mature}$	12	98.96	6843.9	0.00	100-m radius	1.57	−2.21	5.35
DT*PCR + DT*HA$_{mixed}$	12	250.43	6995.4	0.00	Unlimited distance	1.47	−2.29	5.22
DT*PCR	9	645.60	7396.9	0.00	Pipeline	0.73	0.41	1.06
DT*PCR + HA$_{mixed}$	10	652.99	7402.2	0.00	Well pad	9.16	8.54	9.77
DT*PCR + HA$_{mature}$	10	654.26	7403.4	0.00	100-m radius*Pipeline	2.46	2.07	2.85
DT*PCR + HA$_{young}$	10	4711.46	7403.5	0.00	Unlimited distance*Pipeline	2.57	2.19	2.95
					100-m radius*Well pad	−8.79	−9.46	−8.11
					Unlimited distance*Well pad	−8.36	−9.01	−7.71
					HA$_{young}$*Pipeline	0.50	0.09	0.91
					HA$_{young}$*Well pad	−7.81	−8.52	−7.11

[a] The AIC of the top model = 6,771.7.

abundant within other kinds of disturbance (pipelines and/ or seismic lines) relative to interior forest habitat. While inconsistent responses to differing disturbance types could be a reflection of some local scale difference or sampling bias related to where particular disturbances and species co-occurred, these results are consistent with abundance varying with both the contrast along edges between disturbances and undisturbed forests (Murcia 1995) and with the area of disturbed habitat, which is greater along pipelines and at well pads than along seismic lines. Interspecific variation in the response to disturbance by boreal forest birds parallels interspecific variation by grassland birds responding to energy infrastructure (Ludlow et al. 2015, Mahoney and Chalfoun 2016).

Influence of Disturbance Type and Point Count Radius on the Magnitude and Uncertainty of Relative Abundance Estimates for Boreal Birds

In general, we confirmed our prediction that absolute differences in bird abundances between disturbed habitats and forest interiors were greater for well pads and pipelines than for seismic lines, likely due to the relatively larger amount of altered habitat associated with well pads and pipelines within point count locations (Jordaan et al. 2009). Alternatively, this response magnitude may have been caused by a greater contrast between forested and unforested areas associated with well pads and pipelines than seismic lines (Murcia 1995), because forest regeneration is more likely along seismic lines. Despite the greater uncertainty in disturbance response estimates for pipelines, edge contrast may explain the higher probability of detecting both nonzero differences and positive responses by species to pipelines relative to seismic lines.

Decreasing the sampling area of point counts increased the magnitude and the uncertainty of the disturbance response at well pads, which affected the probability of detecting differences in abundance between disturbed and undisturbed habitats, which we predicted would be the case based on previous studies of point count radius effects (Ralph et al. 1996, Thompson et al. 2002). Although the uncertainty of the estimated disturbance response was greater for smaller-radius point counts, birds were most likely to exhibit a disturbance response within 50-m point counts at well pads, probably due to habitat conversion within the disturbance rather than to greater edge contrast between well pads and the adjacent forests than for pipelines or seismic lines with boreal forests. The 1-ha well pads in our study were more likely to be dominated by nonwoody vegetation than were the other disturbance types that we examined, and the disturbed area of the well pad covered the entire area within a 50-m-radius point count centered on the well pad.

Point count radius affected the detection of a biologically meaningful disturbance response, which is important when estimating zones of impact for energy sector activities. Zone-of-impact measurements are often used in environmental impact assessments, but there has been little consistency in how these measures are calculated. While the width of a zone of impact is often determined by estimating how the effect size changes with point distance from an effect source (Hansen et al. 2001, Ewers and Didham 2007), the width can also be generated by comparing relative effect size within a specified distance of a disturbance compared with points for the same survey area farther from that source. For example, a comparison of the relative abundance of a bird species within 50 m of well pads with that within 50-m-radius forest interior point counts can be used to calculate the effect of well pads on species abundance within a 50-m zone of impact around well pads. Using small point count radii results in the assigment of small zones of impact, but is more likely to detect a larger magnitude of effect for some disturbance types. Our results show that deciding the size of the radius over which to estimate the impact of a particular energy activity for birds requires making a tradeoff between effect size and precision. Smaller-radius point counts have a greater probability of detecting birds that are present within the point count radius and result in smaller errors in distance estimates to individual birds (Buckland et al. 2005, Alldredge et al. 2007). The magnitude and greater likelihood of nonzero responses to well pads within 50-m point counts in our study also suggest that 50-m zones of impact should be used to model potential disturbance effects where there is high contrast between disturbed and undisturbed habitats. A larger number of smaller-radius point counts could be situated within a given study area or sampled in a given amount of time, to increase statistical power. However, reducing the point count radius reduces the number of individuals detected (Supplemental Material Table S1), which increased point count variability in a previous study (Thompson et al. 2002) and within all disturbance types in our study, and which reduced the power to detect the effects on bird abundance by Thompson et al. (2002) and along seismic lines in our study. The greater likelihood of detecting disturbance effects of seismic lines with 100-m point counts than with 50-m point counts, and the greater uncertainty in estimated disturbance responses in 50-m point counts in general, suggests that 100-m zones of impact should be used to model disturbance effects along seismic lines.

Potential Issues with Testing for Disturbances Effects at the Scale of Point Counts

One advantage of point count data over other methods for assessing the effects of energy sector disturbances is that point counts can be collected with relatively little effort compared with spot-mapping, radio-telemetry, or nest searches (Bart and Earnst 2002). This makes it easier to

obtain large sample sizes and increased statistical power to detect disturbance effects. However, as demonstrated here and elsewhere, point counts are a rather blunt tool for detecting differences in abundance in disturbed and undisturbed habitats when these disturbances are smaller than the areas sampled by the point counts (Ralph et al. 1995, Thompson et al. 2002, Alldredge et al. 2007). If point count data from different studies and study areas are collected using the same methods over many years and can be adjusted to a common standard, they may be analyzed together to make inferences about disturbance effects over larger areas, recognizing that the differences observed will depend on the analytical standard (Sólymos et al. 2013, Matsuoka et al. 2014). Further, the disturbance response measured using point counts captures primarily singing behavior; for example, point counts may detect fewer birds near disturbed habitats at dawn, but will most likely not detect birds engaging in nonforaging activities near disturbances later in the day (Mazerolle and Hobson 2003). The detection of changes in bird abundance within disturbed habitats also depends on the spatial scale of analysis, and some authors argue that disturbance effects analyzed at smaller scales, such as point counts, cannot be used to predict the population responses of birds at larger spatial scales (e.g., landscapes with ≥ 2 habitat patches of interest; Stephens et al. 2003). Finally, greater abundance within a particular habitat does not always indicate better habitat quality as measured by reproductive success (Gates and Gysel 1978, Van Horne 1983), which may decline for some species in the presence of oil and gas development (Ludlow et al. 2015). Thus, we argue that to test whether the local disturbance effects that we observed have any meaningful population impacts, the effects still need to be validated by studies that measure the behavior of birds relative to the disturbances (e.g., Mazerolle and Hobson 2003, Winder et al. 2015) and by landscape-scale analyses of bird abundance and reproductive success at differing levels of overall energy sector disturbance (Loss 2016, Smith and Dwyer 2016).

In previous boreal bird studies, any effects of habitat fragmentation were attributed purely to habitat loss rather than to edge effects, unless habitat alteration (dominated by forestry) was extensive (Schmiegelow et al. 1997, Schmiegelow and Mönkkönen 2002). However, our studies occurred in landscapes that, in contrast, have incurred relatively little habitat loss, but rather have experienced very large increases in forest edge due to energy sector disturbances (Schneider and Dyer 2006, Jordaan et al. 2009, Van Wilgenburg et al. 2013). The creation of forest edge results in potential changes in abiotic or biotic processes ("edge effects") that may extend from tens to hundreds of meters into adjoining habitat (Paton 1994, Murcia 1995, Laurance et al. 2002, Mascarúa López et al. 2006). Bird abundance may increase with increased food

resources and nesting sites along forest edges (Yahner 1988, Ries et al. 2004), or may decline if there are increases in competitors, predators, or parasitism, or reductions in food, in or near forest edges (Ries et al. 2004). We did not distinguish between disturbance effects due to habitat alteration from these effects due to the increase in forest edge, because our study was not designed to separate the effects. In our study, disturbances that resulted in greater habitat conversion (i.e. well pads and pipelines) were associated with "harder" edges bordering disturbed habitats (i.e. forest edges with greater physical or structural contrast to the disturbed habitat), which influences resource levels (Murcia 1995, Ries et al. 2004, Bayne and Hobson 1997). The boreal forest birds in our study that also use resources in shrublands, open lands, and mixed habitats might have benefited from the creation of forest edges associated with energy sector disturbances, or they might have benefited from the creation of new vegetation structure and composition (Schieck and Song 2006). Similarly, species associated with older forest stages might have responded more negatively to pipelines and well pads relative to seismic lines due to the greater amount of habitat alteration, or the "harder" edges associated with well pads and pipelines (Schieck and Song 2006).

Conclusion

Using individual point counts as samples, we found that boreal forest birds displayed different numeric responses to disturbed habitats associated with energy sector development. Averaged across species, birds associated with open lands, shrublands, young forest stages, or mixed habitats were more likely to be more abundant in disturbed habitats, or to show neutral responses, while birds associated with older forest stages were less likely to be more abundant in disturbed habitats, compared with the forest interior. Both disturbance type and point count radius affected the magnitude of bird species' responses to the various disturbances, the uncertainty of the estimated response, and the actual detection of a disturbance response. Even if the disturbance effects for a species are small, the creation of hundreds of thousands of kilometers of linear oil and gas infrastructure is cumulative habitat change that may result in large population changes over regional extents, and must be accounted for in future modeling studies and environmental impact assessments.

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