



From evidence to protection: A critical review and original analysis of the implementation gap in managing oil and gas impacts on biodiversity

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Abstract. Oil and gas development alters habitat in some of the world's most biodiverse regions, and the ecological mechanisms behind these impacts are now well described. Recent syntheses argue that the binding constraint on better outcomes is no longer ecological knowledge but the translation of that knowledge into enforceable and durable protection. This claim has rarely been tested with data. We combine a critical review of the literature through mid-2026 with four original analyses of openly published datasets. First, using 1,169 listing and recovery documents for 608 Canadian species at risk (CAN-SAR database), we find that oil and gas drilling is identified as a threat for 18.9% of species (95% CI 15.7–22.5%), rising to 41.5% for mammals and 33.3% for birds. Recognition depends strongly on assessment protocol: reports that used the standardized IUCN-CMP threats calculator were 4.6 times more likely to record the threat (95% CI 2.3–9.1), which fully explains its apparent rise over time. The severity of this threat was scored as unknown less often (13.0%) than for other threats (17.8%). Second, only 5 of 313 recovery strategies (1.6%) met the statutory deadline, and strategies for oil-and-gas-exposed species were more than twice as likely to leave critical habitat unidentified (35.5% versus 18.2%; odds ratio 2.48, 95% CI 1.34–4.56), a difference explained largely by the wide-ranging vertebrates that dominate this group. Third, propagating the national boreal caribou demography model shows that the expected growth rate falls below replacement at about 8.5% anthropogenic disturbance when fire is negligible, and that the probability of a stable or growing population at the policy benchmark of 35% disturbance is about 0.14. Fourth, the U.S. protections governing three indicator species changed direction at least once between 2023 and 2026, with federal listings lasting 2.1–2.4 years. Together these results show that knowledge of oil and gas threats is adequate for action, and that losses accumulate in the steps that follow: planning, threshold setting, and the durability of protection. We close with recommendations aimed at each of these steps.

1 Introduction

Oil and gas development reaches into some of the most biodiverse and least disturbed places on Earth, including the sagebrush steppe of the western United States, the boreal forests and peatlands of Canada, the lowland forests of the western Amazon, the Niger Delta, the Potohar Plateau of northern Pakistan, and continental shelves from the Gulf of Mexico to the Arctic



(Finer et al., 2008; Butt et al., 2013; Harfoot et al., 2018). Its footprint is rarely dramatic at the scale of a single site. A well pad occupies a few hectares, and a seismic line is often only a few meters wide. The ecological consequence comes from accumulation: pads, access roads, pipelines, compressor stations, and survey lines added over decades until an entire landscape is reorganized, a process that ecologists describe as energy sprawl (Northrup and Wittemyer, 2013; Jones et al., 2015). Between 2000 and 2012, the drilling of roughly 50,000 new wells each year removed vegetation from about 3 million hectares of central North America (Allred et al., 2015), and energy development has been identified as the largest single driver of land-use change projected for the United States (Trainor et al., 2016).

Two decades of research have turned these observations into a detailed account of mechanisms and, for several indicator species, into quantitative thresholds. Greater sage-grouse (*Centrocercus urophasianus*) leks decline with well density in the surrounding few kilometers (Walker et al., 2007; Green et al., 2017); boreal caribou (*Rangifer tarandus caribou*) recruitment falls as linear features give wolves faster access to caribou range (Dickie et al., 2017; Johnson et al., 2020); mule deer (*Odocoileus hemionus*) avoid active well pads and, in one intensively studied Wyoming field, declined by about 36% over 15 years without evidence of habituation (Sawyer et al., 2009, 2017). Such thresholds matter for policy because a threshold, unlike a qualitative finding, can be written into a permit condition or a recovery target. Wyoming's sage-grouse core area strategy and Canada's boreal caribou recovery strategy are examples of this translation (Environment Canada, 2012; Wyoming Governor, 2019).

However, it has become increasingly clear that knowing a threshold and holding a landscape below it are separate achievements. Six years after the Canadian caribou strategy set a 65% undisturbed-habitat target, 30 of 51 ranges remained below it and total disturbance had increased in 30 ranges (ECCC, 2024). Biodiversity offsets, the stage of the mitigation hierarchy most often invoked to reconcile continued extraction with conservation, have achieved no net loss in only about a third of documented cases (zu Ermgassen et al., 2019; Maron et al., 2025). In the United States, the federal protection of several species that overlap oil and gas basins has been granted, vacated, and reconsidered within a few years (FWS, 2024, 2026; Texas Attorney General, 2026). These observations have led several authors, including the earlier version of this synthesis, to argue that the binding constraint on better outcomes is now implementation rather than ecological knowledge.

That argument is plausible, but it has mostly been made by assembling examples, and examples can be chosen to fit. A stronger test requires data that follow the same set of species from the recognition of a threat, through the planning of protection, to the durability of that protection over time. In this work, we combine a critical review of the literature with four original analyses built entirely on openly published data, so that each step of the chain from evidence to protection can be examined quantitatively (Fig. 1). Analysis 1 uses the CAN-SAR database of Canadian species-at-risk documents (Naujokaitis-Lewis et al., 2022) to measure how often, and how confidently, oil and gas drilling is recognized as a threat. Analysis 2 uses the same records to ask whether recovery planning for oil-and-gas-exposed species is timely and spatially explicit. Analysis 3 propagates the national boreal caribou demography–disturbance model (Johnson et al., 2020) to ask whether the disturbance benchmark used in policy is consistent with population stability. Analysis 4 reconstructs the legal history of four U.S. decisions to measure how long protection lasts relative to the projects it governs. We set these results against global production data to show where development is concentrated and where it is growing, and against the empirical record of each stage of the mitigation hierarchy.

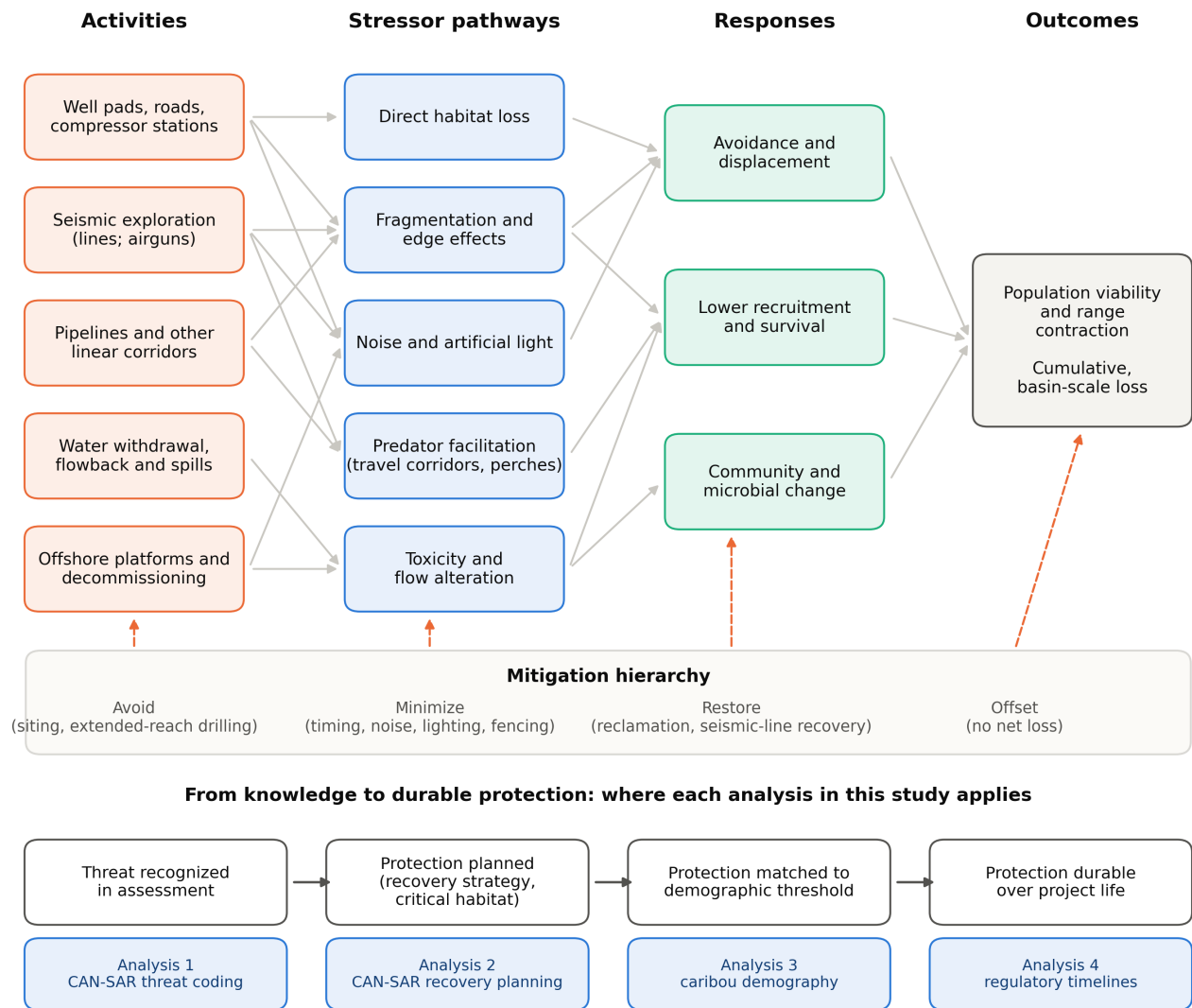


Figure 1. Conceptual framework of this study. Oil and gas activities (left) act on biodiversity through five stressor pathways that produce behavioral, demographic, and community responses, which accumulate into population-level and basin-scale outcomes. The four stages of the mitigation hierarchy intervene at different points in this chain (dashed arrows). The lower panel shows the sequence from threat recognition to durable protection and the step at which each original analysis in this study applies.

The rest of the paper is organized as follows. Section 2 describes the review scope and the four analyses. Section 3 synthesizes the evidence on impact pathways. Section 4 reports the original analyses. Section 5 evaluates the mitigation hierarchy against its track record. Section 6 discusses where the gap between evidence and protection actually sits, what this implies for under-studied basins such as the Potohar Plateau, and which interventions follow from the results. Section 7 concludes.



Table 1. Representative search term combinations used in the literature search. Each industry term was combined with each ecological term in its row, and searches were repeated with the terms in the right-hand column as a check on coverage.

Industry term	Ecological term	Example combined query
oil and gas; unconventional; shale	biodiversity; habitat fragmentation	“unconventional oil and gas” AND “habitat fragmentation”
seismic line; linear feature; pipeline	caribou; wolf; predation	“seismic line*” AND caribou AND predation
well pad; well density	sage-grouse; lek; mule deer	“well density” AND (lek OR “mule deer”)
compressor station; industrial noise	songbird; owl; acoustic	“compressor station” AND noise AND bird*
flowback; produced water; spill	aquatic toxicity; fish; invertebrate	“produced water” AND toxicity AND fish
seismic survey; airgun	marine mammal; zooplankton; invertebrate	“air gun” AND (zooplankton OR “marine mammal”)
decommissioning; rigs-to-reefs	artificial reef; fish production	decommissioning AND “artificial reef”
mitigation hierarchy; offset; reclamation	no net loss; restoration outcome	“biodiversity offset*” AND “no net loss”

2 Materials and methods

2.1 Scope and structure of the review

This is a critical review supported by original data analysis, not a systematic review or meta-analysis. We searched Scopus, Web of Science, and Google Scholar for literature published between January 2013 (the year of the last broad synthesis of energy development impacts on wildlife; Northrup and Wittemyer, 2013) and June 2026, using combinations of industry and ecological terms (Table 1). Earlier studies are cited where they remain the primary source of a threshold or mechanism. We supplemented the peer-reviewed literature with primary regulatory sources (Federal Register notices, Bureau of Land Management records of decision, Canadian recovery documents, and court filings as reported by the parties), because regulatory status changed repeatedly during the review period and secondary reporting of these events is often imprecise. Inclusion favored studies that reported a quantitative dose–response relationship, a threshold, or a measured outcome of a mitigation measure. We followed the transparency principles of the ROSES reporting standard (Haddaway et al., 2018) in documenting search terms and sources, but we did not perform formal critical appraisal or quantitative pooling of the reviewed studies.

2.2 Analyses 1 and 2: threat recognition and recovery planning for Canadian species at risk

CAN-SAR is an open database that extracts standardized information from the listing and recovery documents of species protected under Canada’s *Species at Risk Act* (SARA) (Naujokaitis-Lewis et al., 2022). Each document is coded for the threats



it identifies, using the IUCN–Conservation Measures Partnership (IUCN-CMP) classification (Salafsky et al., 2008). Where a document includes a threats calculator, the impact, scope, severity, and timing of each threat are also recorded on ordinal scales. Recovery strategies are additionally coded for whether critical habitat is fully identified, partially identified, or not identified.

80 We used the development version of the database at a fixed commit (608 species, 1,169 documents published up to March 2021), which extends the published release of 594 species and 1,146 documents.

We classed a species as exposed to oil and gas if any of its documents identified IUCN-CMP threat 3.1 (oil and gas drilling). This category covers exploration, drilling, and production infrastructure, while pipelines (4.2) and spills from industrial sources (9.2) are coded separately and are shared with other sectors. Our exposure measure is therefore conservative. For Analysis 1,

85 we calculated the share of species whose most recent COSEWIC status report identified threat 3.1, overall and by taxonomic group, with Wilson 95% confidence intervals, and tested for heterogeneity among groups with a chi-square test. To separate a genuine change in threat prevalence from a change in how threats are documented, we fitted logistic regressions of threat 3.1 identification in all 502 status reports with a coded threat section against publication year, with and without an indicator for use of the threats calculator (adopted by COSEWIC in the early 2010s) and taxonomic group. We then compared the share
 90 of identified threats whose severity was scored “unknown” for threat 3.1 against all other level-2 threats pooled, as a direct measure of whether the severity of oil and gas impacts is poorly understood.

For Analysis 2, we took the first final recovery strategy for each species (excluding amendments) and calculated the time from the species’ addition to SARA Schedule 1 to the publication of that strategy. Section 42 of SARA requires a proposed strategy within one year of listing for endangered and extirpated species and within two years for threatened species. We compared lags
 95 between exposed and unexposed species with a Mann–Whitney test and with linear models of log-transformed lag that adjusted for listing year and taxonomic group, because a large cohort of species listed at SARA’s inception in 2003 carries long lags regardless of exposure. We modeled the probability that critical habitat was not identified with logistic regressions including exposure, publication year, and taxonomic group. Two strategies with negative lags, caused by mismatched population units, were excluded from the lag analysis.

100 2.3 Analysis 3: demographic thresholds for boreal caribou

The boreal caribou recovery strategy defines critical habitat partly through a benchmark of 65% undisturbed habitat, equivalent to 35% total disturbance, derived from a 2011 meta-analysis of recruitment across 24 ranges and chosen to give a 60% probability that a local population is self-sustaining (Environment Canada, 2011, 2012). Johnson et al. (2020) later refitted national models of recruitment and adult female survival using a larger demographic dataset. We used their model M4 for both vital
 105 rates, in which recruitment R (calves per cow) and adult female survival S are log-linear functions of buffered anthropogenic disturbance A and fire F (both in percent of range area):

$$R = \exp(\beta_0 + \beta_A A + \beta_F F), \quad S = \frac{46 \exp(\gamma_0 + \gamma_A A + \gamma_F F) - 0.5}{45}, \quad (1)$$

where the transformation of S is the small-sample correction applied in the `caribouMetrics` package (Hughes et al., 2025). Following the same package, the expected population growth rate is $\lambda = S(1 + 0.5R)$, assuming an equal calf sex ratio.



110 Coefficients and their 95% confidence intervals were taken from the coefficient table distributed with `caribouMetrics`
 (Table S1). We propagated parameter uncertainty by drawing 40,000 coefficient sets from normal distributions matched to the
 published intervals, and we represented variation among ranges by drawing vital rates from beta distributions parameterized
 by the published precision terms. For each draw we recorded the anthropogenic disturbance at which the expected λ first fell
 below 1, and for each disturbance level we calculated the probability that $\lambda \geq 1$ after adding among-range variation. Because
 115 the coefficients were drawn independently, the intervals we report are wider than those from the joint posterior, which is not
 publicly available.

2.4 Analysis 4: durability of regulatory protection

We reconstructed the legal status, from 2012 to August 2026, of four U.S. federal decisions that govern oil and gas activity in the
 habitat of indicator species: the Endangered Species Act (ESA) listing of the dunes sagebrush lizard (*Sceloporus arenicolus*) in
 120 the Permian Basin, the ESA listing of the lesser prairie-chicken (*Tympanuchus pallidicinctus*), the Bureau of Land Management
 (BLM) land-use plans for greater sage-grouse, and Cook Inlet Lease Sale 258 in the range of the endangered Cook Inlet beluga
 (*Delphinapterus leucas*). Each event was dated from the Federal Register, BLM records of decision, or statements by the parties
 to litigation (FWS, 2015, 2022, 2024, 2026; BLM, 2025; Earthjustice, 2024; BOEM, 2025; Texas Attorney General, 2026). We
 measured the duration of each period of protection or operative decision and compared it with the operating life of the projects
 125 it governs.

2.5 Production geography and land-use intensity

We placed these analyses in a global context using country-level oil and gas production for 2010 and 2024 from the Energy
 Institute Statistical Review of World Energy, as compiled by Our World in Data (EI, 2025; Our World in Data, 2025). We
 compared land-use intensity across electricity sources using the harmonized medians of Lovering et al. (2022).

130 2.6 Statistical software and reproducibility

All analyses were run in Python 3 (NumPy, pandas, SciPy, statsmodels, matplotlib). Every figure is generated by a stand-
 alone script that downloads its input data from a version-pinned public repository, so the complete analysis can be reproduced
 in Google Colab without local files. The scripts also print every statistic reported in Section 4. Code and derived tables are
 provided as Supplementary Material.

135 3 Pathways of impact: synthesis of the evidence

3.1 Surface footprint, fragmentation, and linear features

The shift from single vertical wells to multi-well pads with horizontal laterals has changed the shape of the oil and gas footprint
 more than its total size. A single pad can now drain a resource that once required many separate wells, each with its own pad



and road, so consolidation can reduce road density per unit of production. However, individual pads are larger, and field development still adds gathering pipelines, compressor stations, water-handling facilities, and traffic. Direct loss is compounded by edge effects, because roads and cleared corridors change microclimate, soil moisture, and light well beyond the cleared footprint and provide entry points for invasive plants. In sagebrush steppe, cheatgrass (*Bromus tectorum*) invasion along disturbed edges shortens fire-return intervals and can convert shrubland to annual grassland, which turns a temporary disturbance into a persistent change of state.

Linear features act as barriers and conduits in ways that are separable from habitat loss. Seismic lines cleared through boreal forest remove little habitat by area, yet wolves travel faster and farther along them, which increases encounter rates with caribou (Dickie et al., 2017). Recovery of these lines is slow. On many legacy lines in Alberta's oil sands region, tree regeneration remains inadequate decades after clearing, especially on wet, lowland sites (van Rensen et al., 2015; Dabros et al., 2018). As a result, linear disturbance can accumulate faster than it dissipates over the life of a field. For migratory ungulates, the combined effect of roads, fences, and pads within a migration corridor matters more than any single feature, which is why corridor mapping has become a central tool for siting (Kauffman et al., 2021).

3.2 Sensory disturbance

Compressor stations and other continuous sources produce chronic low-frequency noise that changes the use of habitat well beyond the physical footprint. In the boreal forest of Alberta, songbird densities were lower near noisy compressor stations than near comparable but quiet well pads, which isolates the effect of noise from that of habitat loss (Bayne et al., 2008). In New Mexico, noise from gas-well compressors reorganized nesting bird communities and even reduced nest predation by displacing a key predator (Francis et al., 2009), showing that noise effects propagate through species interactions. Experimental playback isolates the mechanism. Northern saw-whet owls (*Aegolius acadicus*) hunting under compressor noise recorded 50–800 m from a station (46–73 dB(A)) had 8% lower odds of hunting success for each additional decibel (Mason et al., 2016). Because this is a dose–response relationship rather than a threshold, a fixed setback distance cannot capture the effect; exposure has to be managed as a continuous quantity. Artificial light from flares and facilities disrupts nocturnal behavior and migratory orientation, and although down-shielded lighting is inexpensive, it remains inconsistently required.

3.3 Water, effluents, and spills

Hydraulic fracturing withdraws large volumes of freshwater over short periods, which can stress small streams in basins where water is already allocated to agriculture and municipalities. The wastewater that returns to the surface varies far more between basins than the surface footprint does: a continental analysis found that flowback and produced water per well and per unit of energy produced differed by one to two orders of magnitude among North American plays (Zolfaghari et al., 2024). Consequently, two basins with similar well densities can present very different contamination risks. Flowback and produced water is acutely and chronically toxic to freshwater invertebrates and fish, and its toxicity is not explained by salinity alone; organic constituents, metals, and their interaction contribute substantially (Folkerts et al., 2020). Crude oil spills add a separate pathway. After the *Deepwater Horizon* spill, embryonic exposure of pelagic fishes to crude oil caused cardiac defects



(Incardona et al., 2014) and lasting impairment of swimming performance in mahi-mahi (*Coryphaena hippurus*) (Mager et al., 2014).

3.4 Marine and offshore systems

175 Seismic surveys with airgun arrays are among the loudest anthropogenic sources in the ocean. Beyond the well-documented behavioral responses and risk of hearing threshold shifts in marine mammals, which are reflected in current exposure criteria (Southall et al., 2019), recent experiments show effects at the base of the food web. A single airgun increased zooplankton mortality two- to threefold up to 1.2 km from the source (McCauley et al., 2017), and exposure of commercial scallops caused physiological harm and impaired behavior (Day et al., 2017). These results imply that the ecological footprint of a survey
 180 extends well beyond the area in which marine mammal mitigation zones are enforced.

Platforms themselves create hard substrate that can support productive fish assemblages. Platforms off California support some of the highest secondary fish production per unit area measured in any marine habitat (Claisse et al., 2014). This evidence underlies interest in “rigs-to-reefs” decommissioning, in which part of a structure is left in place. However, a 2026 global systematic review found that almost all empirical work concerns reefing options, while only three studies addressed the effects
 185 of full removal, too few to support firm conclusions either way (Lemasson and Knights, 2026). Because partial removal is typically cheaper for operators than full removal, the current evidence base is thinnest precisely for the option that lacks a financial advocate.

3.5 Taxon-specific synthesis

Table 2 summarizes the mechanisms, responses, and quantitative evidence for the taxa with the strongest records. Two features
 190 stand out. First, the dominant mechanism differs among taxa even within the same landscape: predator facilitation for caribou, direct avoidance and energetic cost for mule deer, lek abandonment for sage-grouse, and specialized habitat loss for the dunes sagebrush lizard. Mitigation designed for one indicator species therefore does not automatically protect others. Second, quantitative thresholds exist for only a handful of species, almost all of them in North America.

4 Results of the original analyses

195 4.1 Where oil and gas are produced and where production is growing

World oil and gas production rose from 77,684 TWh in 2010 to 94,076 TWh in 2024, an increase of 21.1% (Fig. 2). The growth was highly concentrated. The United States more than doubled its output, from 9,626 to 20,307 TWh, and accounted for 65% of the global net increase; together with Canada (+1,950 TWh), North America accounted for 77%. Ten countries produced 71.0% of the 2024 total. Declines were concentrated in Venezuela, Mexico, the North Sea producers, Angola, and Nigeria.
 200 Pakistan’s combined output fell by 34%, from 396 to 261 TWh, while new frontier producers emerged, most visibly Guyana, which went from no production in 2010 to 358 TWh in 2024.



Table 2. Taxon-specific synthesis of oil and gas impacts. Thresholds are study- and region-specific rather than universal.

Taxon	Main mechanism	Measured response	Quantitative evidence
Boreal caribou	Linear features facilitate wolf movement; early-seral forage supports alternate prey	Lower calf recruitment; weaker effect on adult survival	Recruitment declines about 1.7% per 1% anthropogenic disturbance (Johnson et al., 2020); 30 of 51 ranges below the 65% undisturbed target (ECCC, 2024)
Greater sage-grouse	Well density and traffic near leks; habitat loss	Lower lek attendance and persistence, with time lags	Negative effects of well density within several km of leks (Walker et al., 2007; Green et al., 2017)
Mule deer	Avoidance of active pads; loss of winter range	Displacement; long-term abundance decline	About 36% decline over 15 years in a Wyoming gas field, with no habituation (Sawyer et al., 2017)
Sagebrush songbirds	Habitat loss; noise masking	Lower density near development	Declines with well density in Wyoming (Gilbert and Chalfoun, 2011)
Boreal and dryland birds	Chronic compressor noise	Lower density; altered nesting communities	Lower density at noisy sites (Bayne et al., 2008); community change (Francis et al., 2009)
Owls	Noise masking of prey sounds	Lower hunting success	Odds of success fall 8% per dB (Mason et al., 2016)
Dunes sagebrush lizard	Loss of shinnery-oak dune blowouts	Local extirpation; habitat not restorable on policy timescales	Listed endangered 2024; listing vacated 2026 (FWS, 2024; Texas Attorney General, 2026)
Freshwater biota	Flowback and produced water spills	Acute and sublethal toxicity	Toxicity not explained by salinity alone (Folkerts et al., 2020)
Zooplankton and scallops	Seismic airgun exposure	Mortality; physiological harm	Two- to threefold zooplankton mortality to 1.2 km (McCauley et al., 2017; Day et al., 2017)
Cook Inlet beluga	Vessel and industrial noise; cumulative stressors	Population failed to recover after harvest ended	331 whales in 2022 (95% range 290–386), versus about 1,300 in 1979 (Goetz et al., 2023; NOAA Fisheries, 2023)



This pattern carries an implication that is easy to miss. Because recent growth has occurred mostly in the United States and Canada, it has occurred where the ecological evidence base is densest and where threshold research for sage-grouse, caribou, and mule deer is most advanced. If the implementation gap were simply a matter of missing knowledge, the North American record would be the place where outcomes should be best. The analyses that follow ask whether it is.

4.2 Analysis 1: recognition of oil and gas threats in Canadian species-at-risk assessments

Of the 608 species in the database, 130 (21.4%) had oil and gas drilling identified as a threat in at least one listing or recovery document. In the most recent status report for each species, the threat was identified for 95 of 503 species with a coded threat section (18.9%; 95% CI 15.7–22.5%). Prevalence differed strongly among taxonomic groups ($\chi^2 = 45.5$, $df = 6$, $p < 10^{-7}$; Fig. 3a). It was highest for mammals (41.5%, 22 of 53; 95% CI 29.3–54.9%) and birds (33.3%, 26 of 78; 23.9–44.4%), intermediate for invertebrates (21.4%), reptiles (18.2%), amphibians (15.0%), and fishes (14.1%), and lowest for plants and lichens (7.3%, 13 of 178; 4.3–12.1%). The ranking is consistent with the mechanisms in Section 3: wide-ranging vertebrates encounter more of a basin's cumulative footprint than narrowly distributed plants do.

The share of status reports identifying the threat increased with publication year (odds ratio 1.12 per year; 95% CI 1.06–1.18). At first sight, this suggests that oil and gas pressure on Canadian species intensified over the period. The data do not support that reading. When use of the IUCN-CMP threats calculator is added to the model, the year effect disappears (odds ratio 0.98 per year; 0.91–1.07; $p = 0.68$), whereas reports that used the calculator were 4.6 times more likely to record the threat (95% CI 2.3–9.1). Adjusting further for taxonomic group strengthens this effect (odds ratio 7.0; 3.2–15.2). As shown in Fig. 3b, only 10.4% of narrative reports (32 of 307) identified oil and gas drilling, compared with 32.3% of calculator-based reports (63 of 195), and this difference persists within each publication period. The apparent trend is therefore an artifact of how threats are documented. It also means that species last assessed before the calculator was adopted are likely to have oil and gas threats under-recorded in their official documents.

When the threat was identified and scored, its severity was rarely treated as unknown. Only 9 of 69 scored instances of threat 3.1 (13.0%) had severity recorded as unknown, compared with 653 of 3,664 instances (17.8%) for all other threats pooled (Fisher's exact test, odds ratio 0.69, $p = 0.34$; Fig. 3c). Oil and gas drilling sits among the better-characterized threats, well below climate-driven habitat shift (53.7% unknown), drought (48.1%), and industrial effluents (34.2%). The profile of the scored threat is also informative. Of the 63 instances with a known impact score, 50 (79%) were rated negligible or low, yet 46 of 77 instances with a known timing score (60%) were rated as continuing. In other words, the assessments describe oil and gas drilling as an individually small but persistent pressure, which is precisely the profile that project-by-project review is least able to control.

4.3 Analysis 2: recovery planning for oil-and-gas-exposed species

Recovery planning lagged far behind the statutory schedule for all species. Across 313 first recovery strategies with a valid listing date, the median time from listing to publication was 7.7 years (interquartile range 4.3–11.5 years), and only 5 strategies (1.6%) appeared within the one- or two-year period set by SARA (Fig. 4a). Much of this delay reflects the backlog of species

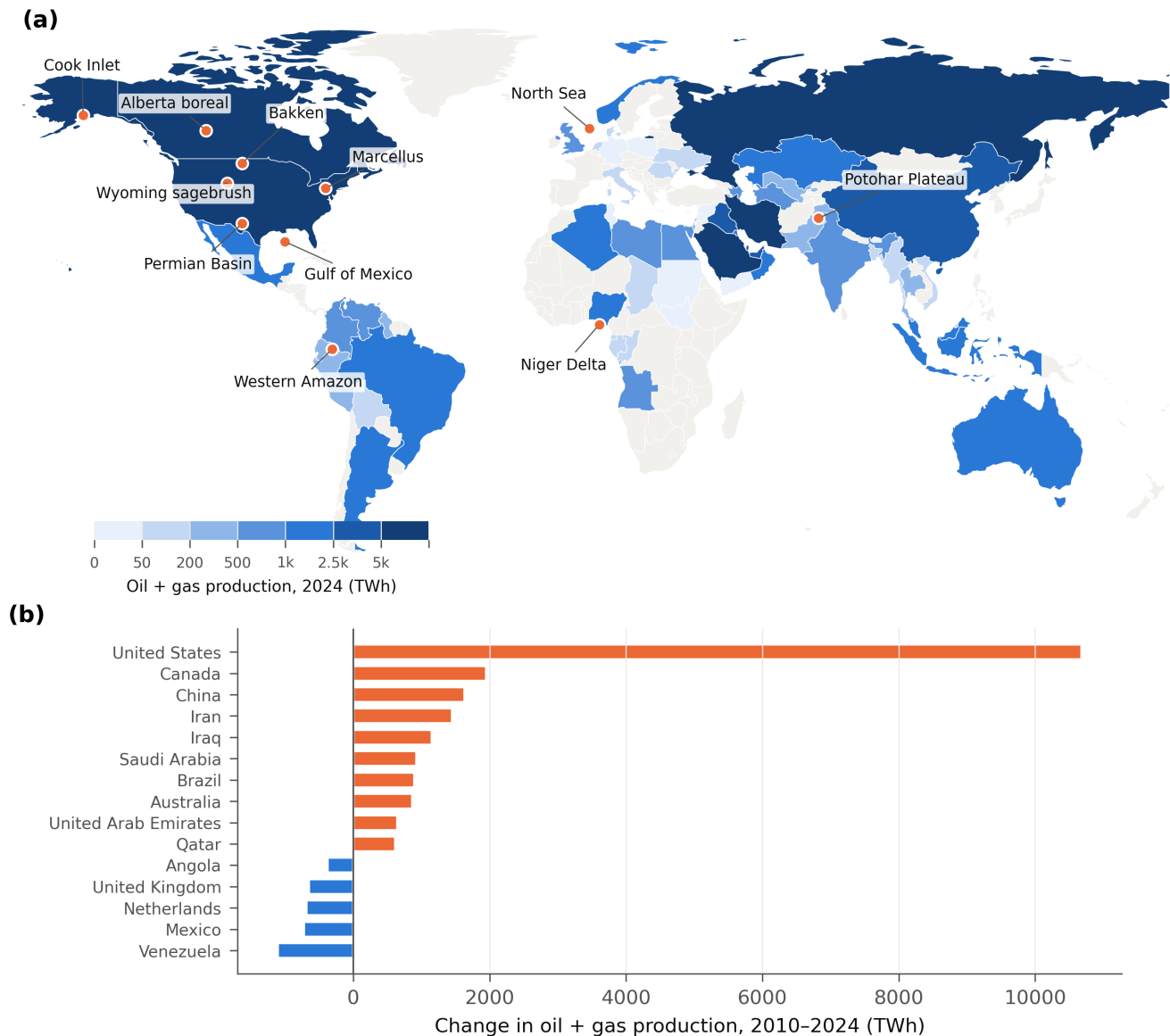


Figure 2. Geography of oil and gas production. (a) Combined oil and gas production in 2024 (TWh of primary energy) by country, with the basins and regions discussed in this review marked. Countries in light grey are not reported individually in the source dataset. (b) Change in combined production between 2010 and 2024 for the ten largest increases and five largest decreases. Data: Energy Institute Statistical Review of World Energy via Our World in Data (EI, 2025; Our World in Data, 2025); country outlines from Natural Earth.

235 listed when the Act came into force: the median lag was 10.2 years for species listed in 2003–2004, 7.2 years for those listed in 2005–2010, and 3.6 years for those listed after 2010. Strategies for oil-and-gas-exposed species appeared somewhat sooner (median 6.1 versus 8.0 years; Mann–Whitney $p = 0.004$), but this difference is explained by listing cohort and taxonomic group



(adjusted ratio of lags 0.88; 95% CI 0.75–1.03). Exposure to oil and gas therefore neither accelerated nor delayed planning once these factors are considered.

240 The spatial content of the strategies differed more clearly. Critical habitat was not identified in 35.5% of strategies for exposed species (22 of 62), compared with 18.2% for unexposed species (46 of 253), and was fully identified in 27.4% versus 37.5% (Fig. 4b). The odds of critical habitat being left unidentified were 2.48 times higher for exposed species (95% CI 1.34–4.56; $p = 0.004$), and the difference remained after adjusting for publication year (odds ratio 2.16; 1.11–4.23). However, it was no longer significant once taxonomic group was added (odds ratio 1.30; 0.61–2.78). This attenuation is itself informative. The species most exposed to oil and gas are wide-ranging birds and mammals, whose critical habitat is hardest to delineate, and these are exactly the species for which spatially explicit protection is most needed. The contrast is sharpest for birds: critical habitat was not identified in 9 of 14 strategies for exposed species and was fully identified in none of them, compared with 6 and 5 of 24, respectively, for unexposed birds (Fig. 4c).

4.4 Analysis 3: demographic thresholds for boreal caribou

250 Propagating the national model shows that recruitment is the vital rate that responds most to disturbance (Fig. 5a). Expected recruitment falls from 36 calves per 100 cows in an undisturbed range to 20 at 35% anthropogenic disturbance, while adult female survival declines only from 0.87 to 0.85. The expected growth rate in an undisturbed, unburned range is only slightly above replacement ($\lambda = 1.027$; 95% interval 0.998–1.058), which leaves little margin for disturbance (Fig. 5b). Expected λ falls below 1 at a median of 8.5% anthropogenic disturbance (95% interval 0–18.0%) when fire is negligible, at 5.5% when 10% of the range has burned, and at 1.5% when 25% has burned. At the 35% disturbance benchmark, the expected growth rate is 0.930 (0.904–0.957) in the absence of fire, which corresponds to a decline of about 7% per year.

Once variation among ranges is included, the probability that a range has $\lambda \geq 1$ is 0.65 without disturbance, 0.47 at 10%, 0.31 at 20%, and 0.14 at 35% anthropogenic disturbance (Fig. 5c). The 60% probability that underpinned the policy benchmark is maintained only up to about 2.5% anthropogenic disturbance in an unburned range, and is not reached at any level of anthropogenic disturbance once 10% of the range has burned. These numbers should not be read as a new threshold, because they rest on national averages, on independent coefficient draws, and on a simplified growth model without density dependence. They do show that the most recent national model, taken at face value, is not consistent with the 35% benchmark delivering a 60% probability of population stability. Many ranges exceed even that benchmark (ECCC, 2024), so the gap between the demographic evidence and the protected state of the landscape is larger than the policy target alone suggests.

265 4.5 Analysis 4: durability of regulatory protection

Table 3 and Fig. 6 reconstruct the four U.S. decisions. The dunes sagebrush lizard, which is restricted to shinnery-oak dune blowouts in the Permian Basin, was listed as endangered effective 20 June 2024 after its proposed listing had been withdrawn in 2012 (FWS, 2024). The listing was vacated through a settlement between Texas and the federal government in July 2026, with a new status review to follow (Texas Attorney General, 2026). The lesser prairie-chicken listing took effect on 27 March 2023, was vacated by the U.S. District Court for the Western District of Texas on 12 August 2025, and was formally removed



Table 3. Selected U.S. decisions governing oil and gas activity in the habitat of indicator species, 2012–2026.

Species or decision	Status timeline	Relevance to oil and gas
Dunes sagebrush lizard	Proposed listing withdrawn 2012; listed endangered, effective June 2024; listing vacated by settlement, July 2026	Frac-sand mining and well pads in the Permian Basin (FWS, 2024; Texas Attorney General, 2026)
Lesser prairie-chicken	Listed 2022, effective March 2023; vacated August 2025 (W.D. Tex.); removal rule February 2026	Well pads, roads, and vertical structures in the southern Great Plains (FWS, 2022, 2026)
Greater sage-grouse	ESA listing not warranted and BLM plans 2015; amended 2019; range-wide plans January 2025; replaced December 2025 (about 65 million acres)	Well-density and disturbance limits on federal land in the West (FWS, 2015; BLM, 2025)
Cook Inlet Lease Sale 258	Sale held December 2022; court finds analysis inadequate, July 2024; sale reaffirmed December 2025	Offshore leasing in the range of an endangered beluga population (Earthjustice, 2024; BOEM, 2025)

from the list on 26 February 2026 (FWS, 2022, 2026). Federal protection therefore lasted 2.1 years for the lizard and 2.4 years for the prairie-chicken. BLM sage-grouse plans were adopted in 2015, amended in 2019, replaced by range-wide records of decision in January 2025, and replaced again in December 2025 by plans covering about 65 million acres of sagebrush habitat that make more land available for development than the 2015 plans (FWS, 2015; BLM, 2025). Cook Inlet Lease Sale 258, held in December 2022, was found by a federal court in July 2024 to rest on an inadequate analysis of cumulative effects and vessel noise on belugas; the lease was suspended, and the sale was reaffirmed in December 2025 after a supplemental environmental impact statement (Earthjustice, 2024; BOEM, 2025).

In none of these cases did the reversal follow new ecological evidence. The Cook Inlet beluga population remains at roughly a quarter of its 1979 size (331 whales in 2022 versus about 1,300) (NOAA Fisheries, 2023), and the dune habitat of the sagebrush lizard cannot be recreated on any policy-relevant timescale. What changed was litigation and administration. The consequence for mitigation is concrete. Oil and gas leases, wells, and associated infrastructure operate for decades, whereas the protections examined here lasted roughly one to four years before they were reversed or replaced. A mitigation commitment negotiated under one legal status cannot be assumed to remain in force for the life of the project it was designed to offset.

5 The mitigation hierarchy against its track record

5.1 Avoidance and minimization

Avoidance remains the most effective stage of the hierarchy because it prevents impacts that later stages can only partly repair. Extended-reach horizontal drilling allows a resource to be developed from surface locations several kilometers away, which makes it technically possible to keep infrastructure out of leks, calving grounds, and migration corridors. Whether this happens



depends on siting rules rather than on technology. Minimization measures such as seasonal restrictions, noise attenuation at
290 compressor stations, shielded lighting, wildlife-friendly fencing, and shared access roads are individually well documented,
but our Analysis 1 shows why they are hard to enforce: the threat they address is usually scored as small at the level of a single
project, so the cumulative benefit of minimization is rarely visible in any one permit decision.

5.2 Restoration and monitoring

Reclamation science has advanced faster than the criteria regulators use to judge it. Inoculation with native soil biota and the
295 use of nitrogen-fixing pioneer plants can accelerate recovery of degraded dryland sites (Guo et al., 2024), and silvicultural
treatment of seismic lines can shorten the decades that natural regeneration requires on wet sites (van Rensen et al., 2015;
Dabros et al., 2018). Monitoring has improved even more rapidly. UAV-based LiDAR and multispectral surveys combined
with deep learning can now characterize individual trees on reclaimed well sites across seasons (Movchan et al., 2025), which
makes it feasible to release reclamation bonds on the basis of measured ecological recovery rather than elapsed time or simple
300 vegetation cover. Environmental DNA is following a similar path from research method toward operational monitoring around
offshore infrastructure. The constraint is institutional: bond-release criteria in most jurisdictions have not been updated to
require what these tools can verify.

5.3 Offsets and no net loss

Offsetting is the weakest stage of the hierarchy empirically. A global review found that only about a third of no-net-loss policies
305 and individual offsets reported achieving their goal, mostly in wetlands; none of four studies in forested systems demonstrated
no net loss, and there was no evidence that avoided-loss offsets achieved it (zu Ermgassen et al., 2019). A more recent review
concludes that offsets generally underperform but, because they carry explicit quantitative targets, are more auditable than
many alternative mechanisms (Maron et al., 2025). Our Analysis 4 adds a failure mode that these reviews do not address. An
offset agreement is typically negotiated under a particular legal status of the affected species. If that status is reversed within
310 two or three years, as it was for the dunes sagebrush lizard and the lesser prairie-chicken, the legal basis for enforcing the offset
can lapse long before the offset matures. For habitat that cannot be recreated, such as shinnery-oak dunes, offsetting cannot
deliver equivalence at all.

5.4 Decommissioning

For offshore infrastructure, the evidence favors retaining structures only in the narrow sense that reefing options have been
315 studied and full removal has not (Lemasson and Knights, 2026). Reefed structures can support diverse and productive assem-
blages, and structures with higher vertical relief appear to offer more ecological value than toppled ones. However, the lack of
empirical studies of removal, together with the cost advantage of partial removal for operators, means that decisions are being
made with evidence that is systematically incomplete. Closing this gap requires studies of removal outcomes, not additional
studies of reefing.



320 5.5 Land-use intensity compared with other energy sources

A comparison with other energy sources is needed to keep the oil and gas footprint in proportion (Fig. 7). The median land-use intensity of natural gas electricity is 410 ha per TWh per year for the direct footprint and 1,900 ha when the spacing between wells is included, compared with 2,000 ha for ground-mounted solar photovoltaics, 130 ha for the direct footprint of wind and 12,000 ha with turbine spacing, and 58,000 ha for dedicated biomass (Lovering et al., 2022). Fossil gas is therefore
 325 not land-intensive by this measure. Its biodiversity impact arises from where development occurs and from the pathways, including noise, linear features, and wastewater, that area-based metrics do not capture. The renewable build-out carries its own biodiversity cost: land occupation by renewable infrastructure is estimated to have caused a global biodiversity loss equivalent to 1.9×10^{-3} global potentially disappeared fraction of species in 2015, with cumulative losses projected to rise substantially by 2060 (Wang et al., 2025). For both sectors, siting and cumulative-effects assessment determine most of the outcome, and
 330 the institutional failures documented here for oil and gas are likely to recur for renewables unless they are addressed directly.

6 Discussion

6.1 Where the gap between evidence and protection sits

The four analyses allow a more precise statement of the implementation gap than the literature has so far offered. The ecological knowledge is adequate for action. When Canadian assessments examine oil and gas drilling with a structured protocol, they
 335 identify it for a third of species and score its severity with more confidence than most other threats (Analysis 1). The national caribou model quantifies how disturbance translates into population growth with enough precision to show that the current benchmark is permissive (Analysis 3). The losses accumulate in the steps that follow. Recovery strategies appear years after the statutory deadline, and for the wide-ranging vertebrates most exposed to oil and gas they frequently leave critical habitat undefined (Analysis 2). Where protection is defined, it can be reversed within the first few years of a project's multi-decade
 340 life (Analysis 4).

Analysis 1 also qualifies the simple distinction between knowledge and implementation. Whether the threat is recognized depends on the assessment protocol more than on the passage of time. Recognition is thus itself partly an implementation outcome: an institution that adopts a structured assessment tool learns more about the threats its species face than one that does not. The practical consequence is that the official record understates oil and gas threats for species last assessed before
 345 the calculator was adopted, and reassessing those species with the current protocol is an inexpensive way to correct the record.

The threat profile recorded for oil and gas, which is individually small but continuing, explains why the gap persists. Project-level review is designed to evaluate impacts one at a time, so each new well or road is judged against a baseline already degraded by its predecessors. The caribou analysis shows the demographic result of this process: the expected growth rate falls below replacement at a level of anthropogenic disturbance that most individual projects would never approach on their own.
 350 Cumulative effects assessment at the scale of a basin or a range, with binding limits on total disturbance, is the only approach that matches the scale at which the impact occurs.



6.2 Evidence geography and the Potohar Plateau

The empirical base reviewed here is concentrated in North America and, for marine systems, in the North Sea and the Gulf of Mexico. The production data show that this concentration is reasonable for recent growth, which has occurred mostly in the United States and Canada, but it leaves large producing regions with almost no species-specific evidence. Northern Punjab illustrates the problem. The Potohar Plateau has produced oil since the early twentieth century and remains one of Pakistan's principal onshore oil provinces, and it overlaps the Salt Range and Kala Chitta hills that support the Punjab urial (*Ovis vignei punjabiensis*) as well as wetlands used by migratory waterfowl. Seismic surveying there involves vegetation clearance and shot-hole detonation, an acute form of disturbance with little analogue in the chronic-noise studies that dominate the North American literature. Environmental assessment is required under the Pakistan and Punjab Environmental Protection Acts, but we found no published, taxon-specific disturbance threshold research for the region comparable to that available for sage-grouse or caribou.

Our results suggest how to prioritize research in such basins. The North American record shows that thresholds alone do not secure outcomes, so new research in basins like Potohar should be designed from the outset to feed a binding cumulative limit. The methods required are established and inexpensive relative to the value of the resource: GPS telemetry and camera trapping of a focal ungulate such as the urial, combined with mapped disturbance density, would allow a first dose–response relationship to be estimated within a few years. Pakistan's declining production also creates an opportunity, because decommissioning and reclamation of mature fields could be designed around measured ecological recovery from the start.

6.3 Recommendations

The results point to interventions at each step of the chain in Fig. 1. At the stage of recognition, species whose most recent assessment predates standardized threat calculators should be reassessed with the current protocol, starting with wide-ranging mammals and birds in producing regions, because our analysis shows that the older narrative format records oil and gas threats about three times less often (odds ratio 4.6–7.0 in favor of the calculator). At the stage of planning, statutory deadlines for recovery strategies need an enforcement mechanism, and when critical habitat cannot be fully identified for wide-ranging species, interim protection should be based on range-level disturbance limits rather than left undefined. At the stage of threshold setting, disturbance benchmarks should be re-evaluated whenever the underlying demographic models are updated. For boreal caribou, the national model implies that the 35% benchmark provides much less than a 60% probability of population stability, and the risk tolerance built into the benchmark should be made explicit and revisited. At the stage of durability, mitigation and offset agreements should include financial assurance or conservation easements that remain in force if the listing that motivated them is withdrawn. Across all stages, reclamation bonds should be released on the basis of measured ecological recovery, which UAV-LiDAR and environmental DNA now make verifiable, and passive acoustic monitoring should replace fixed setback distances as the standard for compressor stations and offshore seismic surveys, because noise effects follow a dose–response relationship rather than a threshold.



6.4 Limitations

385 Several limitations qualify these results. The review is critical rather than systematic, so the literature synthesis may reflect the
selection of well-known studies, although the four original analyses do not depend on that selection. The CAN-SAR data end
in March 2021 and reflect what documents record rather than the true distribution of threats; coding threat 3.1 alone excludes
pipelines and spills, so our exposure estimates are conservative. Critical habitat status refers to the first strategy for each species
and does not capture later amendments. The caribou analysis uses national average relationships and independent coefficient
390 draws, and its growth model omits density dependence and local adjustments, so it should be read as an evaluation of the
benchmark rather than as a prediction for any single range. The regulatory analysis covers four U.S. decisions selected for their
relevance to oil and gas and is not a random sample of environmental decisions; several of these matters remained subject to
litigation at the time of writing, and readers should confirm their current status before relying on them for regulatory purposes.
Finally, the production data measure output rather than footprint, and national totals conceal the location of development within
395 countries.

7 Conclusions

Oil and gas development imposes measurable costs on biodiversity, and for the best-studied species these costs are quantified
with considerable precision. In this work, we tested the widely repeated claim that the binding constraint on better outcomes
is implementation rather than knowledge, using four analyses of openly published data. The evidence supports the claim and
400 locates the losses more precisely. Canadian assessments identify oil and gas drilling as a threat for 18.9% of species at risk and
for 41.5% of mammals, and they score its severity with more confidence than most threats, but whether the threat is recorded at
all depends on the assessment protocol. Recovery strategies met the statutory deadline in only 1.6% of cases and, for exposed
species, left critical habitat unidentified twice as often. The national caribou model implies that population growth falls below
replacement at about 8.5% anthropogenic disturbance, far below the 35% benchmark used in policy. In the United States,
405 protections for three indicator species of oil and gas landscapes changed direction within two to three years.

These findings suggest that further research on impact mechanisms, while still valuable in under-studied regions, is not
where the largest return now lies in well-studied basins. The larger return lies in structured reassessment of threats, enforceable
planning deadlines, periodic re-evaluation of disturbance benchmarks against updated demographic models, and mitigation
instruments designed to outlast changes in legal status. Looking ahead, the reproducible approach used here can be extended
410 to other national species-at-risk databases, to the U.S. ESA recovery-plan record, and to producing regions such as the Potohar
Plateau as field data become available, so that the distance between evidence and protection can be tracked over time rather
than asserted.

Data availability. All data used in this study are openly available. The CAN-SAR database is available from the Open Science Frame-
work (<https://osf.io/e4a58/>) and from the LandSciTech/CANSARD GitHub repository; national caribou coefficients are distributed with the



415 *caribouMetrics* R package (LandSciTech/caribouMetrics); production data are from the Our World in Data energy dataset (owid/energy-data).

Appendix A

Table A1. Coefficients of the national boreal caribou demography models used in Analysis 3 (model M4 of Johnson et al., 2020, as distributed with *caribouMetrics*). Disturbance covariates are in percent of range area.

Vital rate	Term	Estimate	95% CI
Recruitment	Intercept	−1.023	−1.143 to −0.903
	Anthropogenic disturbance	−0.0170	−0.0200 to −0.0140
	Fire (excluding overlap)	−0.0081	−0.0120 to −0.0040
	Precision	19.86	–
Adult female survival	Intercept	−0.148	−0.170 to −0.126
	Anthropogenic disturbance	−0.0008	−0.0010 to −0.0004
	Fire (excluding overlap)	0.0002	−0.0004 to 0.0008
	Precision	63.73	–

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420 *Competing interests.* The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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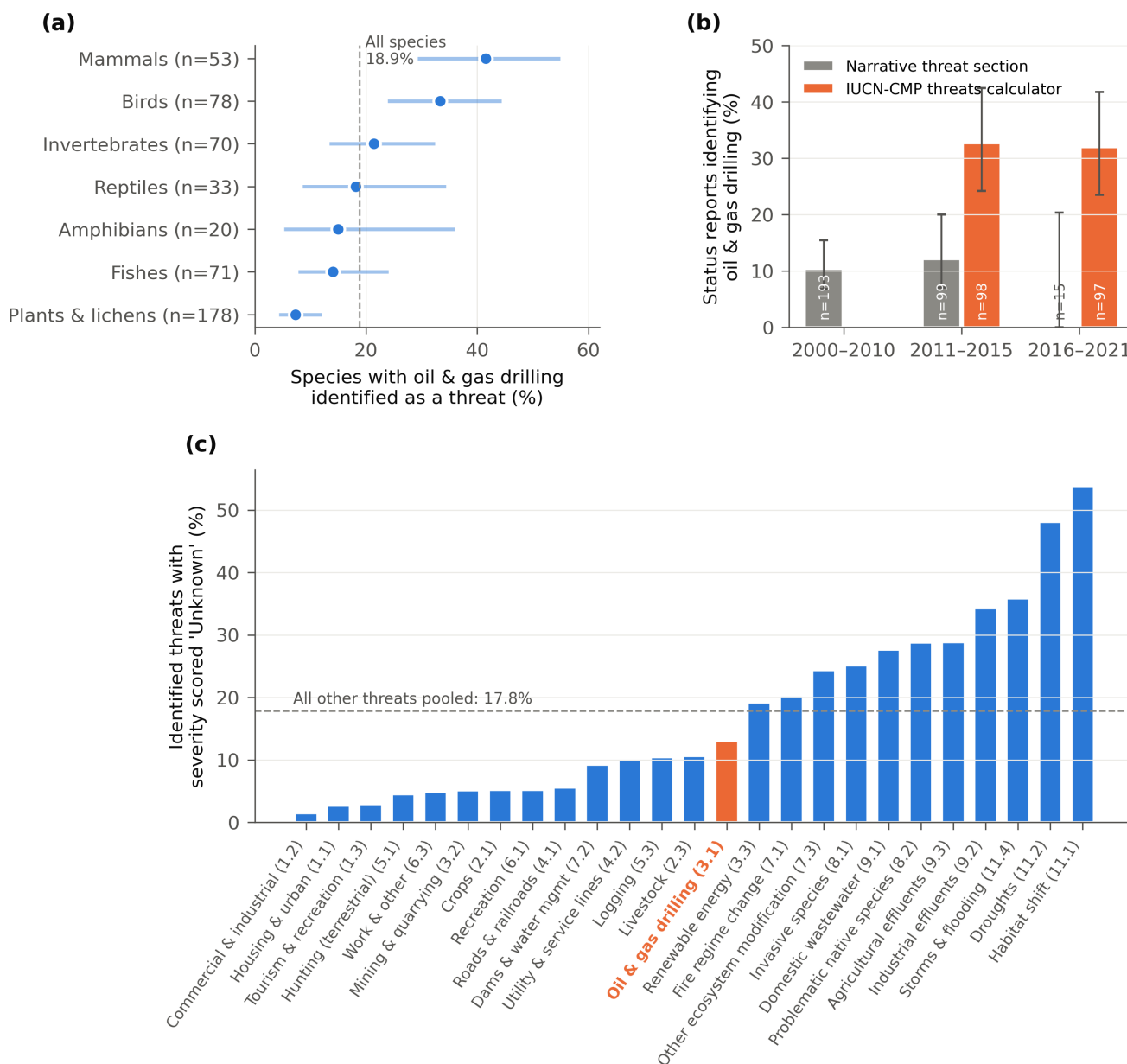


Figure 3. Recognition of oil and gas threats for Canadian species at risk (Analysis 1). (a) Share of species whose most recent COSEWIC status report identifies IUCN-CMP threat 3.1 (oil and gas drilling), by taxonomic group, with 95% Wilson confidence intervals; the dashed line shows the value for all species. (b) Share of status reports identifying the threat by publication period and assessment protocol (narrative threat section versus the standardized IUCN-CMP threats calculator); bars show 95% confidence intervals and bar labels give sample sizes. (c) Share of identified threats whose severity was scored as unknown in calculator-based documents, for the 25 most frequently scored threats; the dashed line shows the pooled value for all threats other than 3.1. Data: CAN-SAR (Naujokaitis-Lewis et al., 2022).

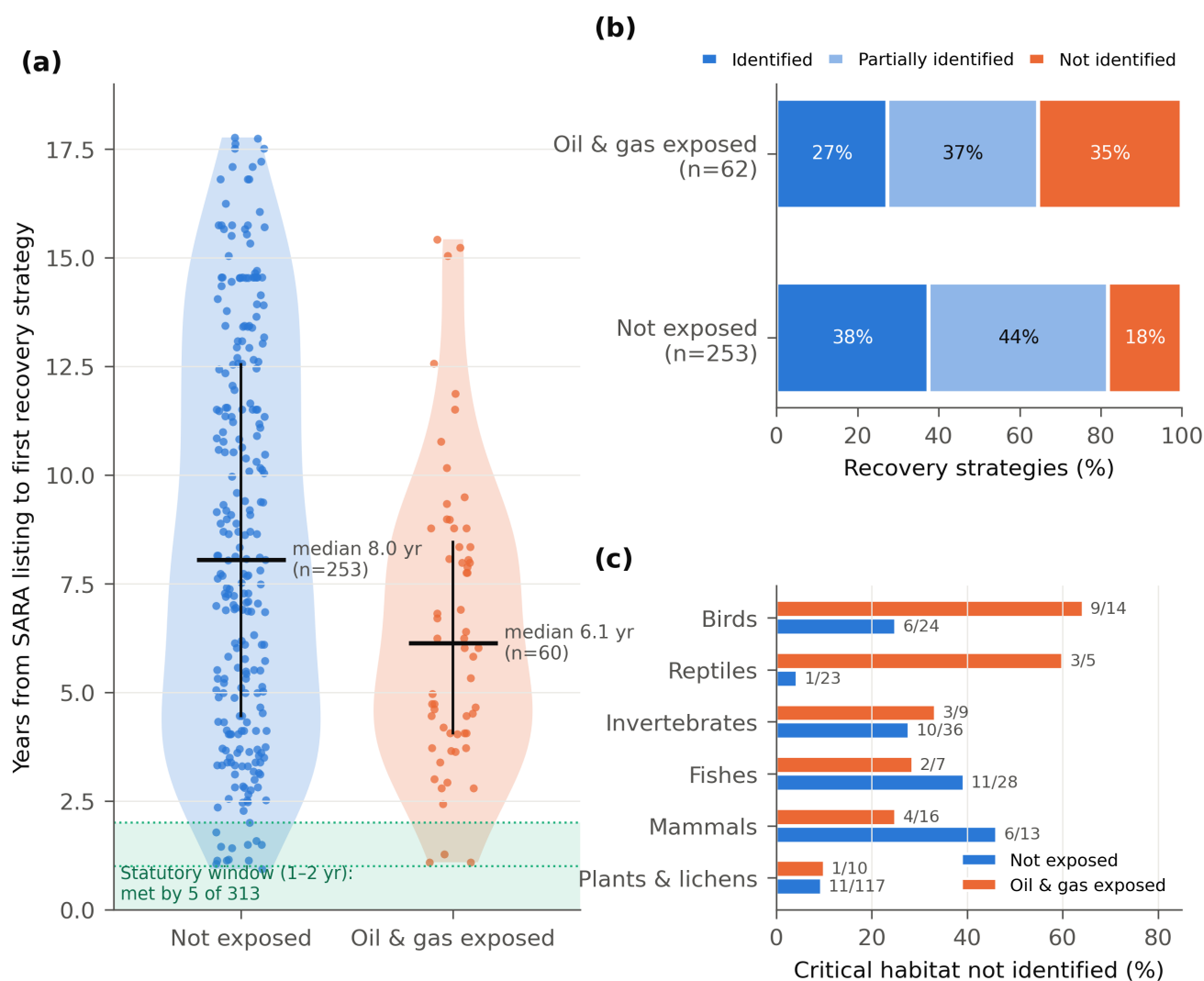


Figure 4. Recovery planning for Canadian species at risk (Analysis 2). (a) Years from listing on SARA Schedule 1 to publication of the first recovery strategy for species with and without oil and gas drilling recorded as a threat; horizontal bars show medians and vertical bars interquartile ranges, and the shaded band marks the statutory period of one to two years. (b) Critical habitat status in the first recovery strategy, by exposure. (c) Share of strategies in which critical habitat was not identified, by taxonomic group; labels give counts. Groups with fewer than five exposed species are omitted from (c). Data: CAN-SAR (Naujokaitis-Lewis et al., 2022).

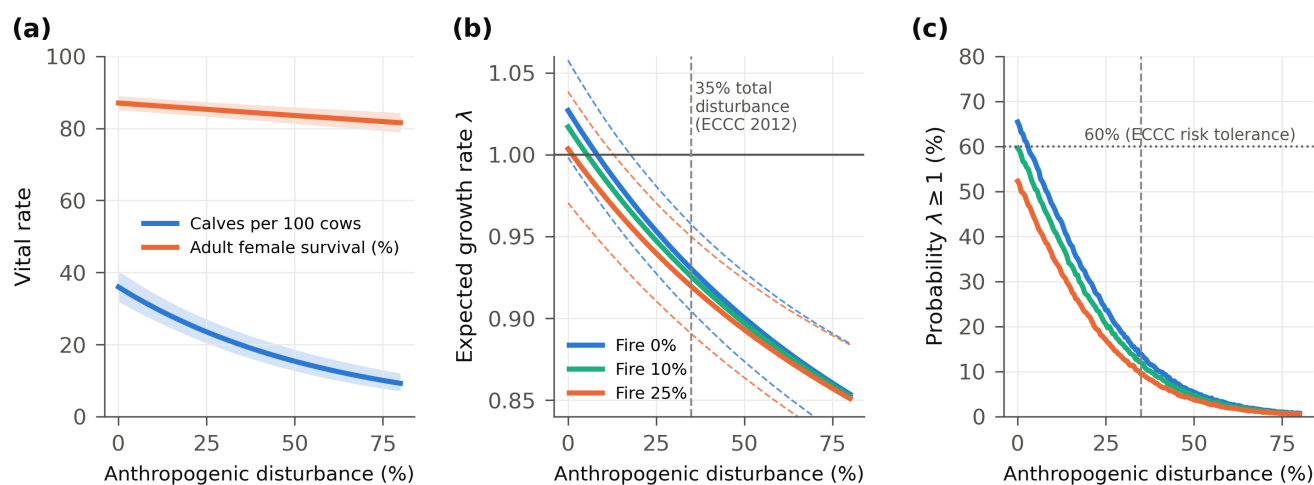


Figure 5. Boreal caribou demography implied by the national disturbance model of Johnson et al. (2020) (Analysis 3). (a) Expected recruitment (calves per 100 cows) and adult female survival against anthropogenic disturbance, with fire set to zero; shading shows 95% intervals from parameter uncertainty. (b) Expected population growth rate λ for three levels of fire; dashed lines show 95% intervals for 0% and 25% fire. (c) Probability that $\lambda \geq 1$ after adding variation among ranges; the dotted line marks the 60% probability used to set the policy benchmark, and the vertical dashed line marks 35% total disturbance (Environment Canada, 2012).

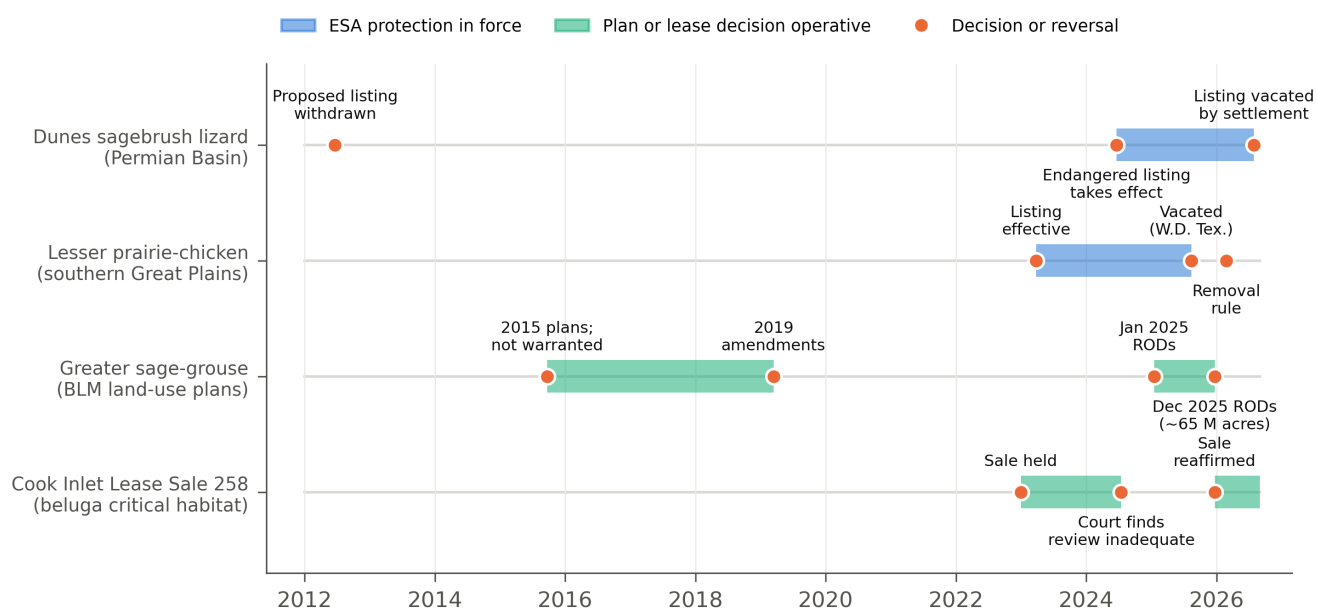


Figure 6. Legal status of four U.S. decisions governing oil and gas activity in the habitat of indicator species (Analysis 4). Blue bars show periods in which ESA protection was in force; green bars show periods in which a land-use plan or lease decision was operative; circles mark decisions or reversals, dated to the month from the sources in Table 3.

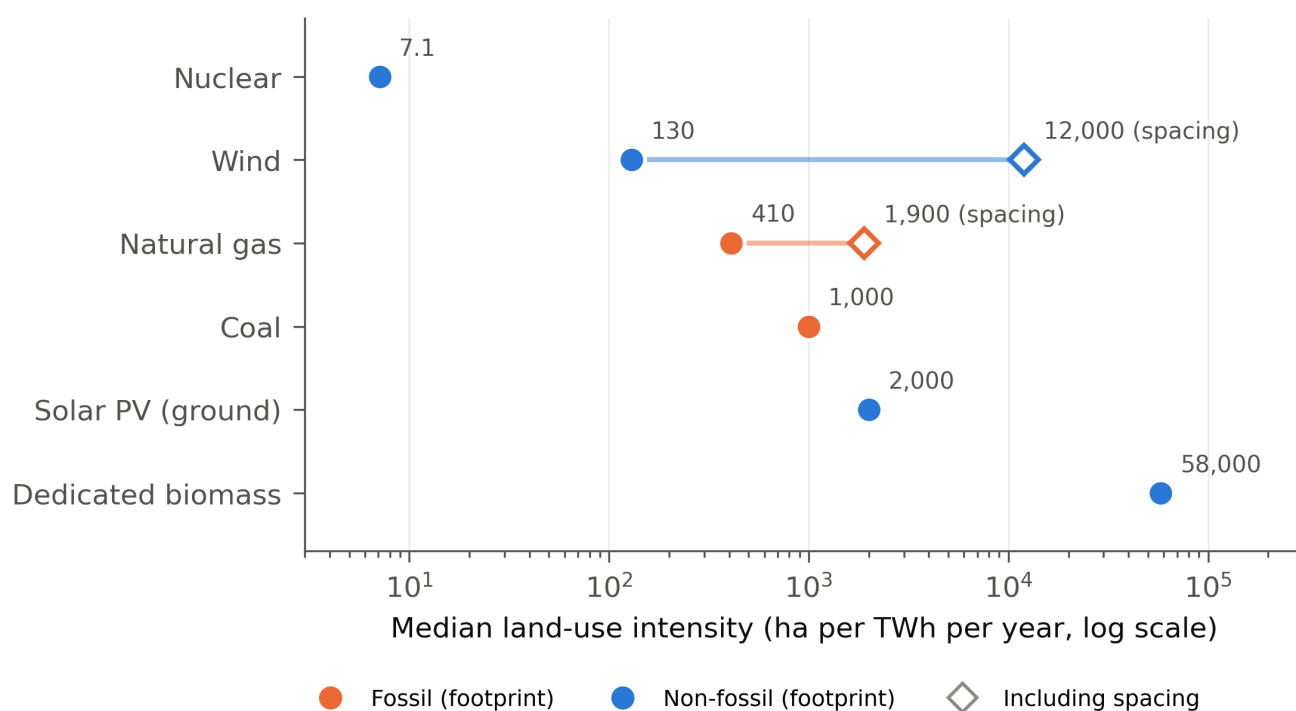


Figure 7. Median land-use intensity of electricity by source (ha per TWh per year, log scale). Circles show the direct footprint; open diamonds include the land enclosed by the spacing between wind turbines or gas wells. Data: Lovering et al. (2022).