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Canadian prairies wetland stressors and indicators: a systematic review to inform monitoring and management

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Prairie pothole wetlands in the Canadian Prairies Ecozone support ecosystem services such as biodiversity conservation, migratory bird habitat, water purification, and flooy -30d and drought mitigation. They are shaped by natural drivers such as climate and landscape factors, while human activities, including agriculture and urban development, impose pressures such as drainage, contamination, and vegetation alteration. To inform wetland monitoring activities, we systematically reviewed peer-reviewed research on Canadian Prairies Ecozone wetlands and organized empirical relationships using the Driver-Pressure-State framework. We synthesized research scope, identified dominant stressor-response pathways, and evaluated candidate indicators. We compiled 376 studies and extracted 4,379 pairwise relationships among drivers, pressures, abiotic states, and biotic states. Weather and climate, landscape factors such as topography, and agriculture were the most frequently studied drivers, with agriculture representing the dominant anthropogenic driver. Several drivers and pressures were poorly represented, including urbanization, recreation, water flow alterations, vegetation removal, and biological invasion. Abiotic research was concentrated on surface water chemistry and hydrology, while biotic research prioritized organismal metrics such as abundance, biomass, and vital rates over biodiversity metrics such as richness or community composition. The pathway with the highest number of statistical tests linked agriculture to contaminants, surface water chemistry, and biotic responses. Birds were the most frequently studied taxon and had consistent empirical support demonstrating their responses to agriculture, hydrology, wetland extent, and weather and climate, supporting bird abundance and vital rates as candidate indicators in agricultural landscapes. Plants were assessed less often, but existing statistical tests showed a high frequency of significant effects from agriculture, hydrology, substrate physicochemical conditions, and water chemistry, supporting plant abundance as a candidate indicator. Research effort was uneven across taxa, and research coverage did not consistently match the proportional distribution of human footprints to wetlands. This review identifies useful candidate indicators for wetland monitoring while highlighting where additional research is needed to reduce bias and inform conservation and monitoring. We also present an interactive web dashboard that allows readers to query the extracted Driver-Pressure-State relationships and explore the complete evidence base.

KEYWORDS

driver-pressure-state, environmental monitoring, evidence synthesis, human footprint (HF), waterfowl

1 Introduction

Prairie pothole wetlands function as vital socioecological systems that face unprecedented pressure from anthropogenic activities. Within the Canadian Prairies Ecozone, which includes southern Alberta, Manitoba, and Saskatchewan (Figure 1), wetlands mostly comprise marshes and shallow ponds, which provide habitat for diverse life, such as plant communities and migratory waterfowl (Doherty et al., 2015; Tangen et al., 2022). Wetlands also provide essential ecosystem services, including water purification, flood and drought mitigation, carbon storage, the support of rich biodiversity, and outdoor recreational value (Badiou et al., 2011; Craft and Casey, 2000; Crumpton and Goldsborough, 1998; Dunne et al., 2007; Lane et al., 2015; Reddy et al., 1999; Serran and Creed, 2016). Despite their critical value to people and wildlife, wetlands in the Canadian Prairies Ecozone (Watmough et al., 2017; Whitfield et al., 2024) and wetlands globally (Davidson, 2014) continue to be underprioritized in policy (Ramsar Convention on Wetlands, 2018), degraded, and lost, undermining both regional biodiversity and the provisioning of essential ecosystem services.

Prior to widespread human development, wild bison grazing and wildfire were the primary natural drivers of environmental change across these prairie landscapes (Paterson et al., 2024), along with long-term climate drying cycles that ultimately transitioned the region from forest to open grasslands (Schneider, 2013). Currently, this post-glacial ecozone contains numerous shallow depressions commonly called sloughs or potholes, which lack a naturally integrated surface drainage network (Hayashi et al., 2016; Zarrinabadi et al., 2023). The regional climate is dry, with mean annual potential evaporation consistently exceeding precipitation (Hayashi et al., 2016; Hogg, 1994). Consequently, these wetlands have highly fluctuating water levels and frequently dry out, relying primarily on spring snowmelt runoff over frozen ground to replenish surface water (Hayashi et al., 2016). Restricted surface outflow leads to the retention of nutrients and dissolved ions, often resulting in high biological productivity and seasonal variability in water chemistry (Hayashi et al., 2016; Miranda and Whitfield, 2024). While seasonal drying cycles make prairie wetlands particularly difficult to monitor (Clare and Creed, 2014), they remain among the ecosystems most heavily impacted by anthropogenic activities (Bartzen et al., 2010; Baulch et al., 2021; Serran and Creed, 2016) and are the focus of this systematic review.

Among stressors impacting wetlands in the Canadian Prairies Ecozone, the conversion of land for agriculture and urban development is a leading cause of wetland loss (Bartzen et al., 2010; Baulch et al., 2021; Serran and Creed, 2016), consistent with

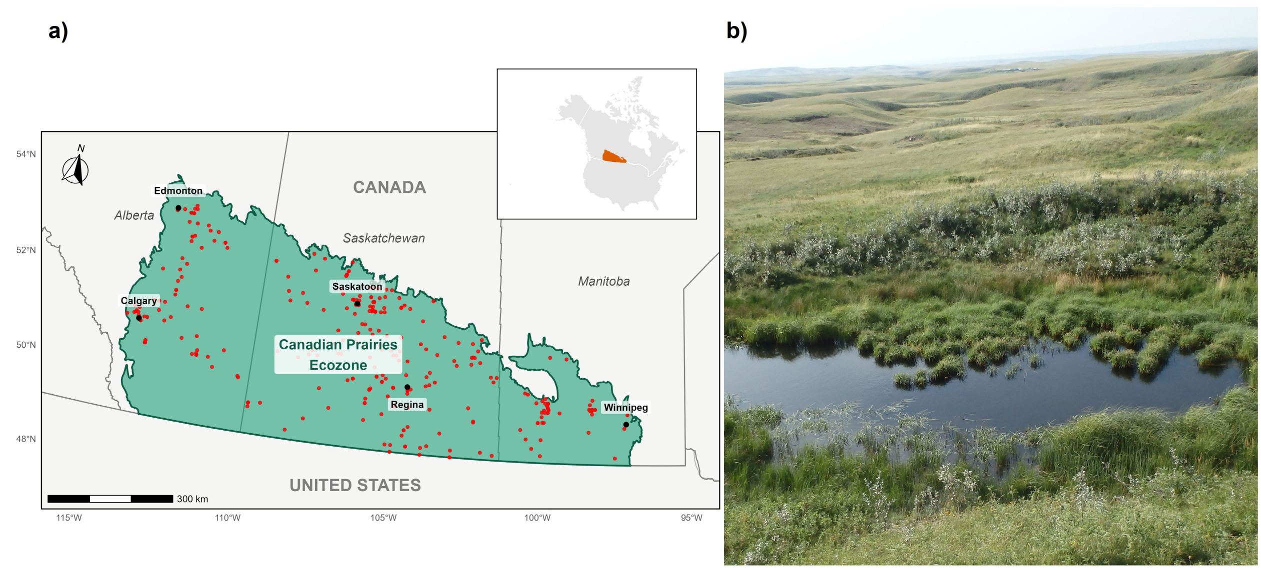

FIGURE 1
(a) Map of the Canadian Prairies Ecozone showing the overlapping Canadian provinces and major cities. Red points represent the centroid of the wetland study location for each study selected for this literature review. The top-right inset map displays the United States and Canada, highlighting the location of the Canadian Prairies Ecozone. **(b)** An example of a typical wetland situated in the Canadian Prairies Ecozone. Photo credit: Rebecca Rooney.

primary drivers of wetland clearing worldwide (Fluet-Chouinard et al., 2023). The most visible impact of agriculture is the permanent conversion of shallow wetlands into viable cropland via surface ditching, thereby eliminating their natural hydrological and ecological functions (Cortus et al., 2011; Pattison-Williams et al., 2018; Rideout et al., 2022). For the remaining wetlands, agricultural practices create highly modified hydrological states; increased irrigation withdrawals lower water levels, while soil compaction impairs infiltration and increases surface runoff (Hayashi et al., 2016; Vonderbank et al., 2025). These ecosystems also experience erosion, nutrient loading from fertilizers, pesticide contamination, and reduced riparian vegetation from grazing (Bartzen et al., 2010; Cade-Menun et al., 2013; Environment Canada, 2013a; Main et al., 2014; Zarrinabadi et al., 2023, 2025). Additionally, these disturbances can indirectly promote the establishment of invasive wetland species (Roy et al., 2019). In urban regions, development causes significant impacts to the abiotic and biotic aspects of wetlands (Rooney et al., 2015; Sizo et al., 2015). In Alberta, permanent wetland loss occurs disproportionately close to urban centers (Rooney et al., 2022), while projections showed that previous conservation measures in Saskatchewan could not compensate for historical wetland losses (Sizo et al., 2015). Additionally, climate change presents an ongoing threat to the region (Kulshreshtha, 2011; Schindler and Donahue, 2006), which faces the highest projected temperature increases in southern Canada (Kulshreshtha, 2011). While extreme events like droughts and floods are becoming more frequent, water scarcity remains the most critical climate change threat to wetlands (Sauchyn and Kulshreshtha, 2008; Schindler and Donahue, 2006). Ultimately, this reduction in water availability compounds with agricultural irrigation demands (Sauchyn and Kulshreshtha, 2008; Schindler and Donahue, 2006), providing one example of how these various stressors simultaneously affect regional wetlands.

Across the Canadian Prairies Ecozone, ongoing wetland alterations have demonstrated negative effects on biodiversity. For instance, agricultural practices cause a drop in plant biodiversity at wetland edges (Kirk et al., 2024). Climate-driven hydrological shifts also lower the diversity of aquatic macroinvertebrates and waterbirds, and ongoing declines in hydroperiod dynamics shift wetland vegetation to terrestrial species (Daniel and Rooney, 2024). Bird communities have received specific research focus due to their high wetland dependence, as these habitats provide critical nesting, foraging, and migratory environments for priority species (Environment Canada, 2013b). Consequently, the loss of grasslands and wetlands correlates with declining wetland-dependent bird populations across this landscape (Bartzen et al., 2010; Olimb and Robinson, 2019; Paterson et al., 2024; Watmough et al., 2017). Because natural habitat availability is the primary predictor of biodiversity in the region (Paterson et al., 2024), conservation efforts are required to maintain wetland-dependent taxa.

The preceding examples highlight how various stressors, including agricultural nutrient loading (Cade-Menun et al., 2013; Main et al., 2014), climate-driven hydrological shifts (Sauchyn and Kulshreshtha, 2008; Kulshreshtha, 2011), and habitat loss (Bartzen et al., 2010; Paterson et al., 2024), impact Canadian Prairies Ecozone wetlands. Yet, to successfully manage and conserve these habitats, we must synthesize this broad literature to understand how these various stressors collectively affect the region, as information overload and fragmented research frequently hinder environmental decision-making (Pullin et al., 2020). To our knowledge, no systematic literature review has yet addressed this need. Because ecological knowledge advances by integrating accumulated evidence to support informed decisions (Nichols et al., 2019), a systematic review provides an opportunity to synthesize available knowledge, identify research gaps (Bangdiwala, 2024), evaluate the compound effects of overlapping threats, identify research gaps, and establish a framework for assessing overall wetland ecosystem vulnerability.

To structure ecological data from systematic literature reviews, the Driver-Pressure-State-Impact-Response (DPSIR) framework organizes empirical linkages between human systems and the environment, an approach widely adopted by international agencies (Patrício et al., 2016). Recent applications map how socioeconomic and natural stressors affect wetlands while identifying reliable indicators for conservation monitoring. In the Alberta Oil Sands, a literature review identified chemical contaminants as a primary pressure and highlighted wetland plants as key indicators (Ficken et al., 2022), informing monitoring research that verified water quality, benthic invertebrates, and vegetation as reliable metrics (Mahoney et al., 2023). In the Global South, DPSIR-based assessments show that rapid population growth and expanding economic activities drive severe pressures like vegetation clearing, pollution, and water diversions, culminating in degraded hydrology and toxic accumulations that cause wetland biodiversity loss (El Behja et al., 2024; Wantzen et al., 2019). In China, a spatial DPSIR study on wetlands established that mining pressures cause land subsidence and habitat fragmentation (Li et al., 2025). Collectively, these studies demonstrate that DPSIR successfully maps cause-effect relationships from concurrent wetland stressors, providing a diagnostic foundation for management decisions.

Aligning with this need for evidence-based management decisions in response to the severe loss of Canadian Prairies Ecozone wetlands, the Government of Alberta implemented the updated Alberta Wetland Policy in 2015 (Alberta Environment and Parks, 2015; Government of Alberta, 2013), which replaced an interim no-net-loss policy that had been active in the Settled Area since 1998. To support this policy, we undertook a literature review to understand the key stressors and wetland responses that are impacting Canadian Prairies Ecozone wetlands based on wetland research to date. We assessed the papers using the DPS elements from the DPSIR framework to develop an evidence-based state of knowledge wetland conceptual model for the region, which could be used to guide wetland monitoring, evaluation and reporting activities. Our primary objective was to provide this conceptual model by systematically reviewing and compiling empirical data on wetland responses to environmental variations, identifying candidate indicators potentially responsive to both specific (e.g., Ficken et al., 2022; Roach and Walker, 2017) and multiple co-occurring stressors (e.g., Ficken et al., 2022; Gosselin et al., 2010; Squires et al., 2010). To achieve this, we focused exclusively on the Drivers, Pressures, and State (DPS) portions of the DPSIR framework, establishing a quantitative synthesis to support consensus building (Carnohan et al., 2023) and enable policymakers to identify subsequent impacts and formulate responses. We systematically reviewed regional literature to map research effort, evaluate empirical support for driver-pressure-state relationships, and identify candidate indicators for wetland monitoring.

2 Methods

Our systematic literature review evaluated natural and human-induced wetland stressors across the Canadian Prairies Ecozone, a geographic scope chosen because neighboring provinces share comparable climates, topography, soils, and biota with Alberta (Ecological Stratification Working Group, 1996). The project adhered to best practices for systematic reviews (Page et al., 2021) and stakeholder co-development (Collaboration for Environmental Evidence, 2022) to meet the practical needs of monitoring programs. We categorized extracted metadata and pairwise relationships using the conceptual definitions established by Oesterwind et al. (2016). Following their criteria, Drivers represent overarching socioeconomic or environmental forces (e.g., agriculture or regional climate trends), Pressures are the specific mechanisms altering wetlands (e.g., water diversions or contamination), and States encompass the measurable physical, chemical, and biological conditions of the ecosystem (e.g., hydrology, nutrient concentrations, and plant community composition). We based our initial classification categories on a previous application of this framework developed for Boreal Alberta wetlands (Ficken et al., 2022), and iteratively updated these categories as new components emerged during data extraction. Ultimately, identifying these relationships highlights variables that can serve as early warning indicators in long-term regional monitoring frameworks (Cairns et al., 1993; Ficken et al., 2022).

3 Search and inclusion criteria

We searched the Web of Science Core Collection database. In consultation with government stakeholders (Collaboration for Environmental Evidence, 2022), we developed a Topic search query combining regional geography and wetland characteristics. Specifically, we used geographic and location keywords including "Prairies Ecozone", "Prairie Pothole Region", "Palliser Triangle", "Aspen Parkland", "Mixed Grassland", "Fescue Grassland", "Cypress Hills", "Missouri Coteau", "Great Plains", "Saskatchewan River", "Red River Basin", "Assiniboine River", "Qu'Appelle River", "Souris River", "Bow River", "Oldman River", "Red Deer River", "Milk River", "Battle River", "Old Wives Lake", "Chaplin Lake", "The Quill Lakes", "Lake Diefenbaker", "Last Mountain Lake", and "Swift Current Creek", which we paired with the regional modifiers (Canad* OR Alberta OR Saskatchewan OR Manitoba). We also targeted broader regional papers by pairing "Alberta", "Saskatchewan", "Manitoba", or "prairie" with explicit wetland terms, using the search string (wetland OR pothole OR slough* OR swamp* OR marsh* OR fen OR fens OR meadow* OR lake* OR kettle* OR coulee* OR bog* OR pond* OR peatland*). Finally, we captured these wetland terms when they appeared within one word of specific descriptive attributes, including wet, alkali, intermittent, alkaline, saline, subsaline, "low-prairie", shallow, deep, permanent, ephemeral, temporary, seasonal, semipermanent, "semi-permanent", or brackish.

To complement our literature search, we conducted a targeted, AI-assisted step to capture recently published literature or relevant studies not captured in our Web of Science search due to differences in database indexing systems. On June 2, 2026, using the Google Scholar Labs feature, we queried the platform for original research papers focused on the Canadian Prairies Ecozone that featured wetland-related response variables. We provided the platform with our pre-compiled list of Web of Science selected papers. This reference list served to establish a baseline of eligible studies to align the AI's selection with our inclusion criteria. We explicitly instructed the platform to exclude these records from the new results to minimize duplicate occurrences and focus exclusively on unique literature. From this pool, we excluded ineligible and duplicate records already captured via the Web of Science database.

4 Selection criteria and screening protocol

Following the initial database search, and in accordance with PRISMA guidelines (Page et al., 2021), we tracked study selection in a two-phase process consisting of an initial title and abstract screening to remove irrelevant records. We then conducted a full-text review of the retained articles, excluding remaining ineligible studies to produce the final dataset. For the abstract screening phase, we automated the process within a Google Spreadsheet using the built-in =AI() function powered by Google 3.5 Gemini (Flash model tier). We evaluated each study against four sequential inclusion criteria. First, a geolocation filter verified whether the study area was located within the Canadian Prairies Ecozone (studies with data aggregated at a broader regional scale were excluded). Second, a wetland focus filter identified papers measuring wetland components by looking at synonyms of wetland types or abiotic or biotic descriptors. Third, a water depth filter excluded deep-water bodies, large reservoirs, and terminal lakes while ensuring shallow wetland environments and shorelines were retained. Fourth, a methodological filter discarded technical and methodological papers, ensuring the final selection was restricted to peer-reviewed original research articles documenting an ecological response or an observational relationship between explanatory variables and wetland state measures. Papers meeting all four criteria were automatically selected for full review.

To validate the automated screening process, we used a hybrid verification approach combining a full manual audit of all records included by the AI with a 10% representative random sample of the excluded records. This sampling strategy allowed us to calculate performance metrics for positive classifications and extrapolate error rates for exclusions (Stewart-Evans et al., 2025; You et al., 2025). Based on this validation subset, we evaluated the screening automation using sensitivity to measure the proportion of relevant studies correctly identified; specificity to measure the proportion of irrelevant studies correctly excluded; and precision to assess the proportion of AI-included studies that were truly relevant.

5 Data extraction and classification

Data extraction and classification of pairwise variables and study information were performed with the enterprise version of Microsoft 365 Copilot (GPT-5.5 tier, extended reasoning mode). We first developed a data extraction and categorization prompt iteratively by reviewing initial outputs and refining the instructions until the results were satisfactory (provided in Supplemental Material 1). We then refined the prompt iteratively by benchmarking the AI outputs against the data extraction and categorization from an expert-compiled DPS literature review of the Oil Sands region (Ficken et al., 2022). Subsequently, we used this prompt to extract general study information and pairs of variables (Appendix 1). Due to context window limits, we uploaded each article individually to maximize output completeness. As an initial quality control step to filter out ineligible papers missed during the automated screening phase, we verified that the response variables directly measured a wetland component in the Canadian Prairies Ecozone and further excluded ineligible studies.

Following selection, we systematically classified the broad study characteristics for each included article (see Appendix 2 for complete list of categories and definitions). We categorized the wetland classes following the Canadian Wetland Classification System (National Wetlands Working Group, 1997) as bog, fen, general peatland, marsh, swamp, shallow open water, or multiple. We recorded the wetland status as natural, artificial, or a combination of both. We categorized the study design into experimental studies, defined by the manipulation of variables in either a controlled laboratory setting or a natural field environment; observational approaches were differentiated into field surveys, which involved one-time or short-term data collection across a wide area or landscape gradient; field monitoring, which focused on tracking changes over time using field measurements without experimental manipulation; and remote sensing, which relied on satellite or aerial imagery. We also identified modelling studies used to predict ecological outcomes, and paleo reconstructions of past environments using proxy data. Furthermore, we noted if the measurement approach was a one-time event or repeated over time. We recorded the spatial scale, ranging from controlled microcosms to regional assessments, along with the temporal scale of the measurements taken. We assigned up to two relevant wetland condition and function buckets to each study, covering hydrological condition, water quality improvement, biodiversity, human use, and carbon sink capacity. Most of these categories were adopted from the Alberta Wetland Policy (Government of Alberta, 2013), where hydrologic function consists of storing runoff to reduce flooding and soil erosion, water quality improvement includes filtering pollutants and facilitating sedimentation, human uses describe activities of cultural significance, recreation, and education, and biodiversity represents the contribution of wetlands to biodiversity and ecological health. We also included carbon sink capacity as an additional category to reflect its recent prioritization by policymakers.

For included studies, we classified pairs of variables extracted from the main manuscript text, tables, and figures (excluding supplemental material) into drivers, pressures, and/or wetland states following a Driver-Pressure-State (DPS) framework. Across all papers, data extraction was limited to wetland variables used to test hypotheses or fulfill stated objectives. For quantitative studies, we extracted as many applicable variables as possible, structuring the dataset so that each row represented a single statistical test of one link (two variables). Conversely, for exploratory or descriptive studies, each row captured one specific result or variable per study objective. Additionally, for papers presenting several candidate models, we extracted data just for the first selected model. We then classified relationships as significant if $p<0.05$ or other inferential criteria, whereas descriptive studies lacking inferential statistics were noted as having no formal statistical test; these were used to assess weight of effort rather than strength of evidence. We did not include directionality, as identifying a statistically significant effect adequately indicates importance for environmental monitoring. We focused exclusively on primary relationships and main effects, excluding interaction effects and *post-hoc* analyses. We also classified all biotic state variables by their specific taxonomic group (e.g., plants, invertebrates, birds, amphibians, microbes). We also categorized them into specific metric classes (Appendix 2) and then grouped them into broader categories to prevent excessive fragmentation in our visualizations. For example, we aggregated population size changes (abundance, occurrence, density) under “abundance” and combined accumulation or growth measures (growth rate, mortality) into “biomass and vital rates.” Individual metric classes remain accessible through our interactive dashboard. Each extracted link included a direct quote from the source text for manual verification. Finally, we compiled each variable pair extracted through this AI-assisted approach into a systematic review dataset, manually verifying and recategorizing entries where necessary.

As a final step, following environmental evidence synthesis guidelines for stakeholder engagement and data validation (Collaboration for Environmental Evidence, 2022), we validated the DPS categorization in collaboration with wetland experts from the Government of Alberta. This peer review served a dual purpose: to refine the conceptual categorizations and to validate the AI-assisted extraction and categorization approach. We randomly selected around 10% of the papers and compared the classifications of the primary data extractor against those of the experts. We then held calibration discussions to resolve discrepancies and reach a consensus on the most accurate categorization methods. Finally, we reviewed and adjusted the dataset where needed to ensure entries conformed to the consolidated rules established during this peer-review process.

6 Data analysis

For the data analysis, we evaluated the weight of effort and the strength of evidence using an interactive visual user interface created as an online dashboard that can be interrogated by the reader (https://shiny.math.uwaterloo.ca/dpsir_wetland_dashboard_prairies). To assess the weight of effort, we summarized general study characteristics across the compiled literature by generating frequency bar plots of the temporal and spatial scales and calculating the total number of studies per wetland type. We also mapped the geographic distribution of drivers and pressures by plotting each study on a Prairies Ecozone map using the centroid of the study area. Additionally, we constructed a Sankey diagram to visualize the pathways and volume of connections, represented by the total number of variable pairs captured in the literature, moving sequentially from drivers to pressures, abiotic states, and biotic states (e.g., Ficken et al., 2022). To evaluate the strength of evidence, we analyzed the frequency of significant statistical relationships between environmental variables and biotic or abiotic wetland measures. For example, a high frequency of significant tests linking hydrological alteration to plant abundance indicates that plants are potential candidate indicators of hydrological change. Conversely, a high proportion of non-significant tests suggests a lack of responsiveness, mixed results reflect disagreement within the literature, and an absence of tests highlights knowledge gaps.

7 Results

7.1 Literature retrieval and validation of the DPS framework

The initial Web of Science search on January 9, 2026, yielded 1,286 results. The AI-automated abstract screening initially selected 606 papers for full-text review. Based on the manual verification of all AI-included records (n=606) and a sample of AI-excluded records (n=78), the automated selection achieved 95% sensitivity (successfully capturing relevant studies) and 75% specificity (effectively filtering records that did not meet inclusion criteria). During the full-text review, we excluded 12 studies because the full text was irretrievable through institutional or public databases and an additional 229 studies that did not meet the inclusion criteria, leaving a dataset of 365 studies. Because over one-third of the initially included abstracts lacked the required metrics at the full-text level, the final AI-automated precision was 60.2%. The supplementary Google Scholar Labs search identified 50 matches. After removing 16 duplicates and excluding 23 ineligible records, we added 11 studies, bringing the final dataset to 376 included papers (Figure 2).

We validated our categorization approach across 39 papers (approximately 10% of the dataset), refining the framework through weekly consensus meetings. Our discussions typically addressed discrepancies in variable inclusion eligibility and DPS classifications. For example, we debated variable eligibility in mixed studies, leading us to extract strictly wetland-related variables and exclude upland variables. We also discussed how to distinguish immediate pressures from broader drivers. In one instance, we resolved to classify grazing as a specific pressure (vegetation removal) rather than a driver (agriculture), and we added a "root cause" category to capture underlying economic activities. We continuously updated the main dataset based on these weekly discussions to ensure standardized classification.

The core findings from all included studies are accessible via an interactive online Shiny app (https://shiny.math.uwaterloo.ca/dpsir_wetland_dashboard_prairies), where users may filter the literature by study categories, dynamically visualize the maps and research effort and evidence graphs presented in this section, hover over visual elements to view specific study counts, and access the corresponding bibliographic references.

7.2 Geographic, chronological, and ecological scope of studies

Publication years ranged from 1928 to 2025, with a median of 2010. Studies published prior to 1970 constitute only 0.8% (n=3) of

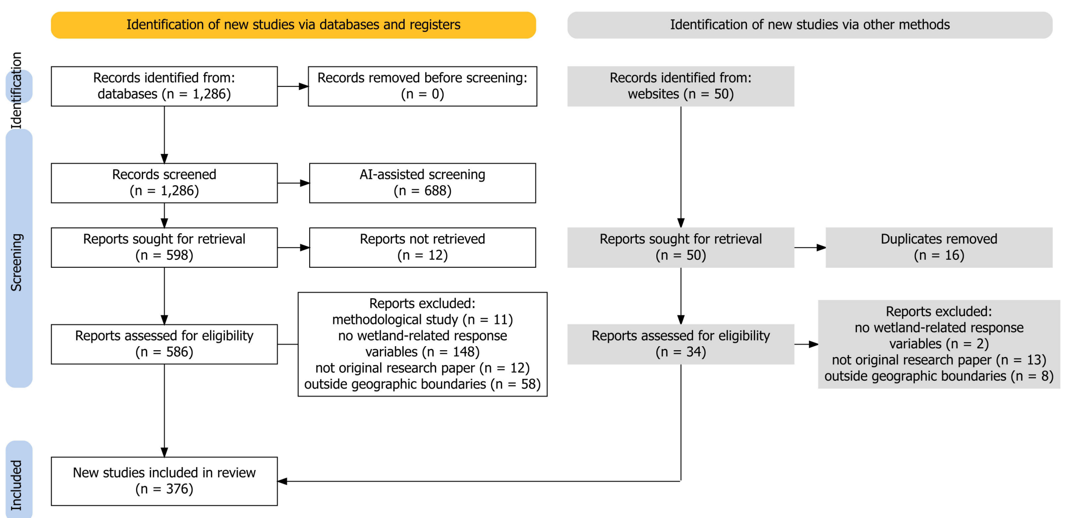

FIGURE 2
PRISMA flow diagram detailing the literature search and study selection process (adapted from Page et al., 2021). The diagram tracks the progression of database and website records through an AI-assisted screening, full-text review, and exclusion phases.

our total dataset, meaning that historical contexts do not heavily skew the overall tallying or modern take-home messages. Regarding spatial scales (Figure 3a), most research consisted of multi-site studies (148 studies, 39%) and regional-scale evaluations (135 studies, 36%), while the remaining studies were conducted at single-site, mesocosm, or microcosm scales (93 studies, 25%). For study designs (Figure 3b), the majority were field surveys (143 studies, 38%) and field monitoring (112 studies, 30%), followed by field experiments (44 studies, 12%), modeling (38 studies, 10%), and paleoenvironmental research (26 studies, 7%). We found very few laboratory experiments (8 studies, 2%) and remote sensing studies (5 studies, 1%). In terms of temporal scales (Figure 3c), the largest proportion of studies spanned 1 to 5 years (156 studies, 41%), followed by long-term dynamics exceeding 10 years (111 studies,

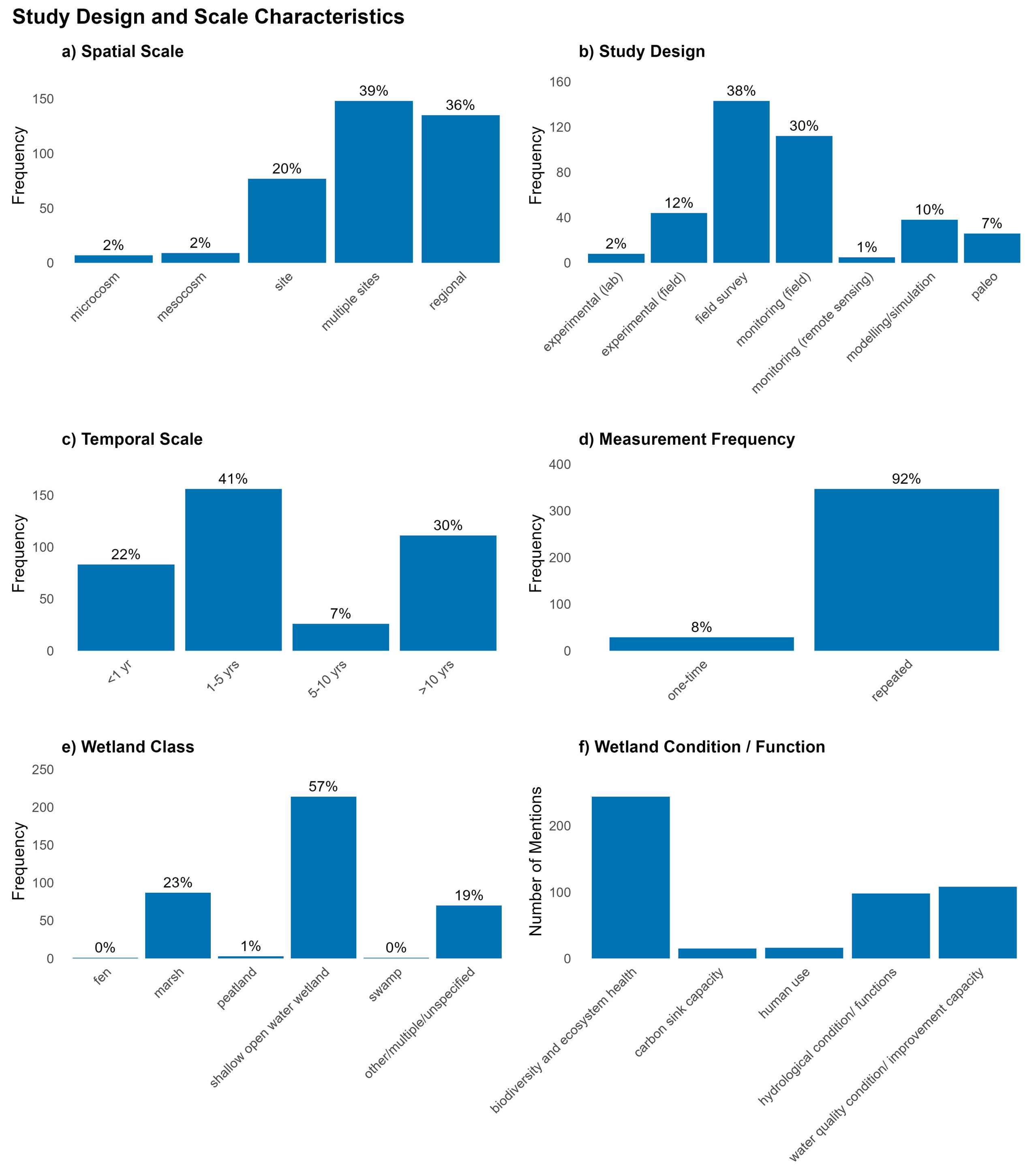

FIGURE 3
Study design and scale characteristics of the 376 included studies (see Appendix 2 for complete list of categories and definitions). **(a–e)** display the frequency of studies categorized by spatial scale, study design, temporal scale, measurement frequency, and wetland class. **(f)** shows the number of mentions for wetland condition and function categories, where each individual study may have up to two mentions per category.

30%), while shorter-term investigations (<1 year) and mid-term assessments (5 to 10 years) accounted for the remainder (109 studies, 29%). Across the compiled literature, most studies focused on shallow open water wetlands (214 studies, 57%) and marshes (87 studies, 23%) (Figure 3e). The remaining 75 studies (20%) examined other wetland types, including peatlands, fens, bogs, swamps, and multiple or unspecified wetlands. When considering the study focus on our predefined wetland function categories (limited to a maximum of two per study) (Figure 3f), biodiversity and ecosystem health received the most mentions (244), closely followed by water quality condition/improvement capacity (108) and hydrological condition/functions (98). Conversely, we found very few studies addressing carbon sink capacity (15 mentions) and human use (16 mentions) (Figure 3f).

7.3 Research effort on anthropogenic drivers and pressures affecting wetlands

Our systematic review dataset compiled a total of 4,379 pairwise variable links representing individual statistical and descriptive tests. These links comprised a total of 43 individual variables classified into 10 driver classes, 14 types of pressures, 7 abiotic states, and 12 biotic state classes. To contextualize the relative focus of the literature, percentages for individual variables reflect their proportional representation within their respective categories. Among the overarching phenomena initiating wetland change, the most frequently evaluated drivers were weather and climate (596 tests, 37.7%), landscape factors (495 tests, 31.3%), and agriculture (379 tests, 23.9%). Other drivers such as urban, transportation, recreation, energy/mining, fire, and forestry were not common, collectively accounting for 7.1% of the dataset. This analysis incorporates all reported relationships, which could allow data-rich studies to disproportionately drive the results. To evaluate this, a sensitivity analysis restricting the dataset to one unique variable pair per study yielded an 80% overall proportional overlap in network weighting, indicating consistent patterns across the literature rather than the influence of unequal study weighting (see Appendix 3 for full details).

For direct mechanisms resulting from anthropogenic activities, the most highly studied pressures were conservation intervention (274 tests, 32.1%), contaminants (205 tests, 24%), and wetland restoration (139 tests, 16.3%). The least researched pressures included water flow alterations, grazing, fertilization, biological invasion, vegetation removal, fishing, soil disturbances, accounting for 27.6%. Within wetland ecosystem states, the predominant abiotic states researched were surface water chemistry (602 tests, 33.3%), hydrology (547 tests, 30.3%), and wetland extent (328 tests, 18.2%). The remaining abiotic tests consisted of less researched categories such as substrate physico-chemical properties, micrometeorological conditions, and groundwater chemistry (18.2%). The biotic states literature was dominated by abundance (992 tests, 40.4%), biomass & vital rates (561 tests, 22.8%), and dominance (239 tests, 9.7%), leaving 27.1% distributed among scattered tests on nutrient cycling, richness, behavior, physiology & tissue chemistry, trophic interactions, morphology, population structure, and ecosystem engineering (the latter would require a biotic-to-abiotic pathway in our DPS framework), and aggregated metrics.

The sequential pathways visualized via the Sankey diagram highlight the most frequently tested and inferred connections in the literature (Figure 4, plotting linkages with >15 documented tests, n=3,058 variable pairs). When examining stressor cascades, the two most heavily documented links between a driver and a pressure occurred between agriculture and contaminants (168 inferred tests, 28.1% of all tests), and agriculture and conservation intervention (86 inferred tests, 14.3% of all tests). Further along the stressor-response pathway, the top two pressure-to-state connections linked contaminants to surface water chemistry (82 tests, 27.2% of all tests) and water flow alterations to hydrology (40 tests, 13.2% of all tests). Finally, the dominant abiotic-to-biotic links connected wetland extent to abundance (167 tests, 18.3% of all tests) and hydrology to abundance (98 tests, 10.7% of all tests). Additionally, drivers frequently showed direct connectivity to biotic responses without an intermediate pressure or abiotic state mapped, led by agriculture influencing abundance (152 tests, 16.1% of all tests) and landscape factors influencing abundance (127 tests, 13.5% of all tests).

When tracing the most frequent continuous full-system pathways from drivers through intermediate pressures and abiotic states to biotic responses, determined by the minimum number of continuous tests linking the entire chain, a single highly documented route emerged. This primary pathway flowed from agriculture to contaminants to surface water chemistry, which then cascaded into three distinct biotic responses: abundance (82 continuous tests), biomass & vital rates (79 tests), and nutrient cycling (50 tests). If intermediate pressures are excluded from the cascade, the two most prevalent remaining sequences flow from landscape factors to hydrology to abundance (98 continuous tests), and from weather and climate to hydrology to abundance (98 tests).

Conversely, pathways falling below the visualization threshold (15 or fewer tests) reveal research gaps across the DPS framework. For driver-to-pressure relationships, 21 distinct pathways were rarely tested (e.g., urban and water flow alterations). Similarly, 23 pressure-to-abiotic state connections (e.g., grazing and substrate physico-chemical properties, water flow alterations and hydrology) and 29 abiotic-to-biotic connections (e.g., substrate physico-chemical properties and biomass & vital rates, hydrology and nutrient cycling) returned sparse results.

Geographic mapping of study centroids across the Canadian Prairies Ecozone showed that overall, most research effort is concentrated in Saskatchewan, followed by Alberta, with the least number of studies in Manitoba, a distribution that remains unchanged even when excluding the ~5% of studies that span multiple provinces (Figure 5). Research regarding agriculture, weather and climate, and landscape factors is broadly distributed across the ecozone. Other categories, including recreation, urban development, energy and mining, and transportation, demonstrate limited, scattered research effort. Notably, studies regarding biological invasion as an explanatory variable are geographically restricted, appearing as a singular cluster within Manitoba.

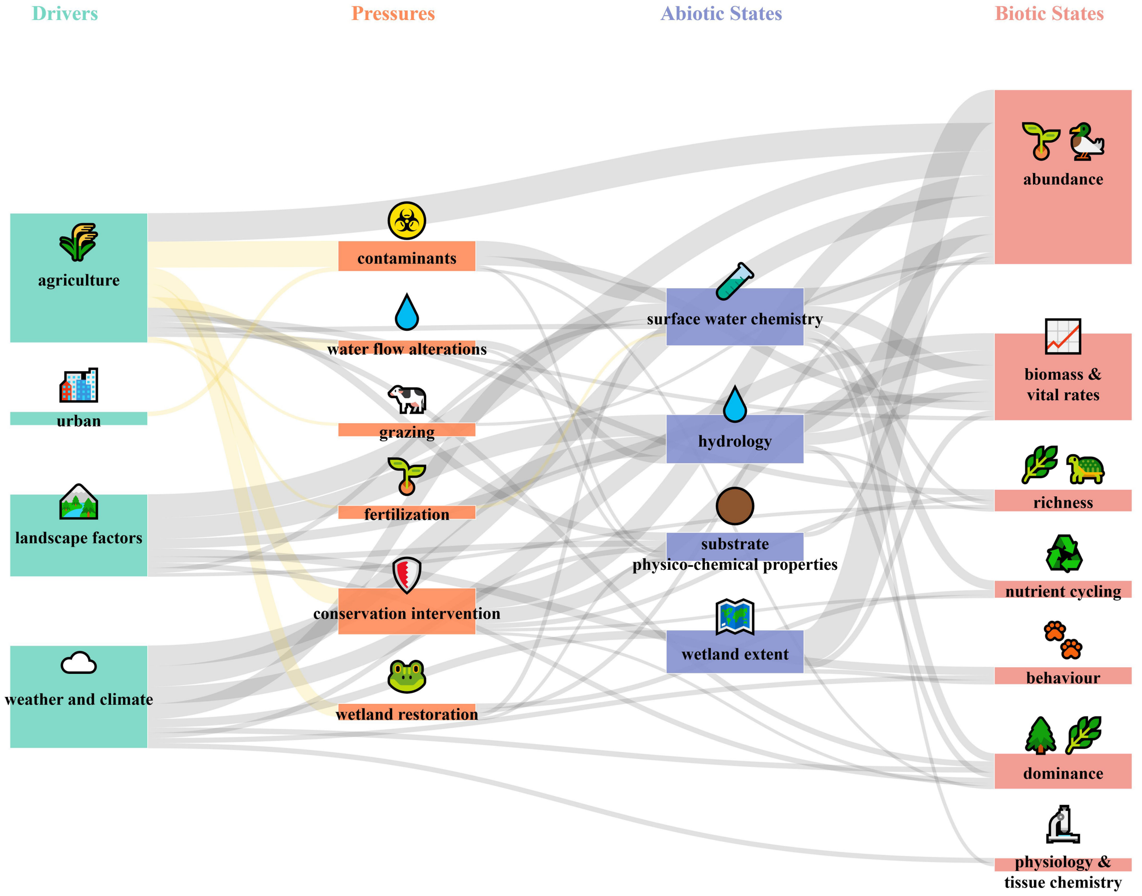

FIGURE 4
Canadian prairies ecozone: research effort across DPSIR pathways. This Sankey diagram illustrates the relationships between drivers, pressures, abiotic States, and biotic states occurring 15 or more times in the selected literature. See Appendix 2 for a complete list of categories and definitions.

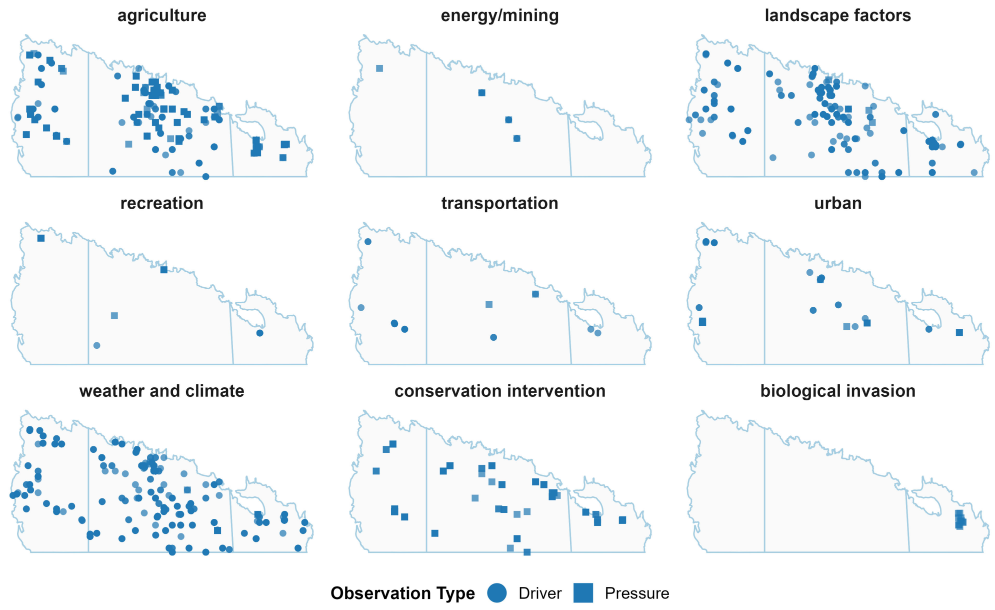

FIGURE 5
Spatial distribution of research effort for drivers and pressures across the Canadian Prairies Ecozone, demonstrating the geographic spread of studies for each category of drivers or pressures (note: wetland restoration is grouped under conservation intervention in this visualization; pressures that are not plotted on their own are included in the maps of their associated drivers).

7.4 Strength of empirical evidence supporting candidate indicators

The abiotic ecosystem response map displays 619 unique tests (Figure 6), representing 79.6% of the total abiotic evidence available in the dataset (n=778). The evidence is concentrated in surface water chemistry, which accounts for 316 tests and spans the widest breadth of stressors. In contrast, research into wetland extent is significantly more restricted, contributing only 28 tests and appearing largely limited to impacts from weather and climate. Beyond this threshold, we identified 42 unique pairs of variables that were excluded due to sparse reporting (<15 tests). These links occupy a long tail of the literature, characterized by varying degrees of data scarcity. The moderate portion of this tail (n=2 to 14 tests) includes combinations such as vegetation removal-substrate physico-chemical properties and wetland extent-surface water chemistry. At the extreme end of the tail (n=1), evidence is highly fragmented, exemplified by pairs such as agriculture-micrometeorological conditions and conservation intervention-hydrology.

For tests involving biotic states, the volume of empirical literature varied across the taxonomic groups: birds were the most studied taxon with 1157 tests across 26 explanatory categories spanning drivers, pressures, and abiotic states, followed by plants (471 tests, 29 categories), invertebrates (283 tests, 24 categories), microbes (268 tests, 18 categories), algae (187 tests, 19 categories), multiple taxa (114 tests, 16 categories), amphibians (82 tests, 17 categories), mammals (74 tests, 14 categories), and fish (31 tests, 11 categories).

Because birds and plants were the most well-studied wetland biotic groups in the region, we analyzed the frequency of statistical significance to wetland stressors for these taxa, isolating specific biotic responses (e.g., abundance, biomass, richness) across a range of explanatory variables (Figure 7). We restricted our reporting to explanatory categories with more than 15 tests to improve visualization of results. Out of the range of drivers, pressures and states represented in Figure 3, this limited our review to the drivers 1) landscape factors, 2) weather and climate, and 3) agriculture. It also restricted pressures to conservation intervention. Finally, it limited the abiotic states to 1) hydrology, 2) substrate physico-chemical properties, 3) surface water chemistry, and 4) wetland extent.

Birds metrics showed consistent empirical support in response to several drivers, defined as having a high proportion of significant results, demonstrating a high frequency of significance to agriculture (118/163, 72%; mostly abundance and biomass & vital rates) and weather and climate (85/117, 73%; mostly abundance and biomass & vital rates), a moderate frequency to landscape factors (86/148, 58%; mostly abundance and biomass & vital rates), and a low frequency to transportation (5/19, 26%; mostly abundance and biomass & vital rates). Pressures on bird metrics include a high frequency of significance for wetland restoration (16/21, 76%; mostly abundance and dominance), but a low frequency for conservation intervention (55/166, 33%; mostly abundance and biomass & vital rates). Regarding abiotic states, bird metrics showed a high frequency of significant results to hydrology (44/47, 94%; mostly abundance and behavior) and a moderate frequency to wetland extent (107/201, 53%; mostly abundance and biomass & vital rates) and (Figure 7).

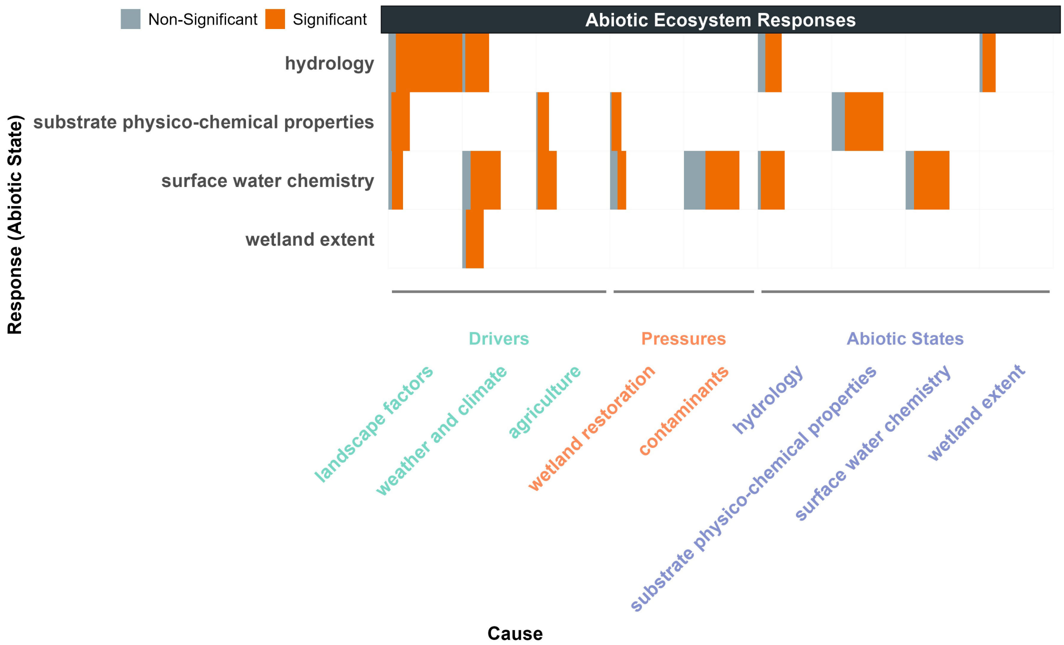

FIGURE 6
Wetland abiotic responses to drivers, pressures, and abiotic states in the Canadian Prairies Ecozone, including relationships that were identified 15 or more times across the reviewed studies. Within the grid, the horizontal width of the colored bands represents the frequency of statistical tests between a given driver, pressure, or explanatory abiotic state and a responding abiotic state. Orange segments highlight significant outcomes (indicating sensitivity), while gray segments indicate non-significant results. Note that it is possible that the same category is tested as explanatory and its respective response variable (e.g., pond water depth as an explanatory variable and infiltration rate as a response variable are both abiotic hydrological states).

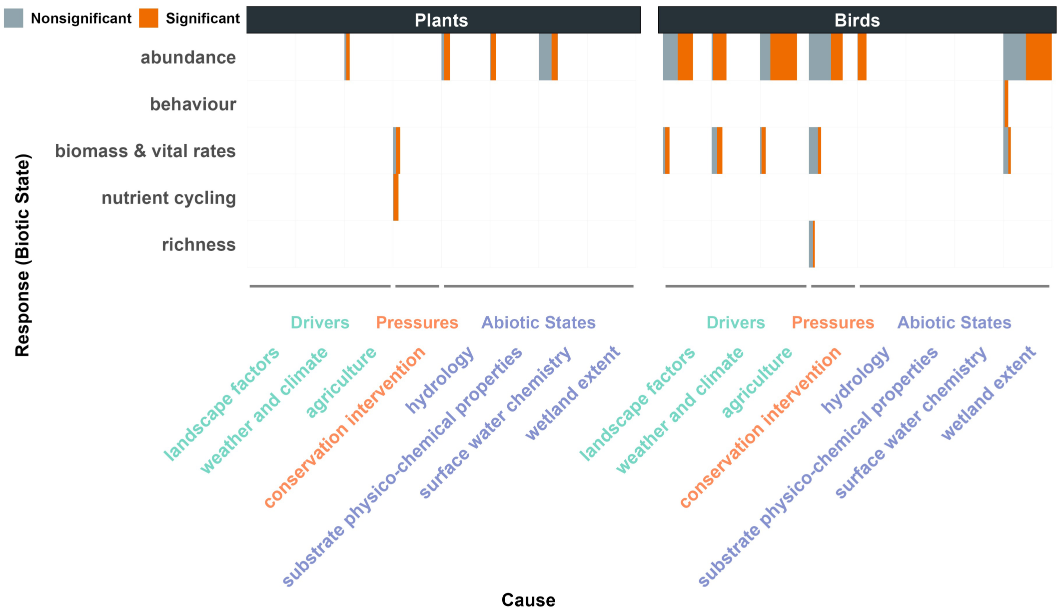

FIGURE 7
Wetland biotic responses to drivers, pressures, and abiotic states in the Canadian Prairies Ecozone, including relationships that were identified 15 or more times across the reviewed studies. Within the grid, the horizontal width of the colored bands represents the frequency of statistical tests between a given driver, pressure, or abiotic state and a wetland biotic state. Orange segments highlight significant outcomes (indicating sensitivity), while *gray* segments represent non-significant results.

For plants, we found a high frequency of significant tests to agriculture (30/38, 79%; mostly abundance and richness) and weather and climate (14/18, 78%; mostly biomass & vital rates and abundance), and a moderate frequency for landscape factors (24/46, 52%; mostly biomass & vital rates and abundance). Pressures on plant communities included a high frequency of significant tests for water flow alterations (26/30, 87%; mostly biomass & vital rates and abundance) and wetland restoration (15/19, 79%; mostly abundance and physiology & tissue chemistry), and a moderate frequency for conservation intervention (41/63, 65%; mostly biomass & vital rates and nutrient cycling), and vegetation removal (13/29, 45%; mostly biomass & vital rates and abundance). Abiotic variables affecting plants included a high frequency of significant tests for substrate physico-chemical properties (20/22, 91%; mostly abundance and biomass & vital rates), hydrology (32/44, 73%; mostly abundance and biomass & vital rates), and a moderate frequency for surface water chemistry (34/76, 45%; mostly abundance and biomass & vital rates),(Figure 7).

For several biotic relationships across taxa, the low frequency of statistical tests limits our ability to evaluate consistent empirical support (e.g., n~15). For instance, we captured limited tests of richness for conservation intervention (n=18, 1.4%, for birds), nutrient cycling for conservation intervention (n=17, 1.3%, for plants), and behavior for wetland extent (n=16, 1.2%, for birds) (Figure 7). Furthermore, 476 relationships (35.8% of the total biotic evidence) are very rarely tested in the literature. For example, biotic metrics such as biochemistry, dominance, population structure, morphology, tissue content, physiology, and trophic interactions were either entirely absent from stressor-response relationships or tested very rarely (<15 times).

Based on statistical test frequency plotted in the Sankey diagram (Figure 4), the most frequently tested pathway links agriculture (driver) to contamination (pressure), which subsequently alters surface water chemistry (abiotic state) and various biotic metrics. However, as our evidence maps above indicate, this specific pathway lacks data for birds and provides little evidence regarding plant responses. Consequently, we expanded our investigation to evaluate the responses of the remaining taxa to surface water chemistry, independent of the specific biotic metric measured (Figure 8). Our results highlight a high frequency of empirical support for microbial responses to water quality changes (62 tests, 72.1%), and when considering all taxa together, the overall evidence of significant effects remains fair (184 tests, 68.4%). Within the microbial tests demonstrating significance, herbicides were the most frequently evaluated contaminant (15 tests, 88.2%), while sulfate was the most commonly measured surface water chemistry parameter (10 tests, 19.2%). Finally, the most frequent biotic metric used to assess microbial responses to water chemistry was nutrient cycling (14 tests, 26.9%).

8 Discussion

Our systematic literature review provides a regional synthesis of wetland stressors affecting abiotic and biotic wetland states across the Canadian Prairies Ecozone, with implications for wetland monitoring and conservation in landscapes that support people, biodiversity, and migratory birds. Focusing exclusively on the Canadian context, we first synthesize stressor-response

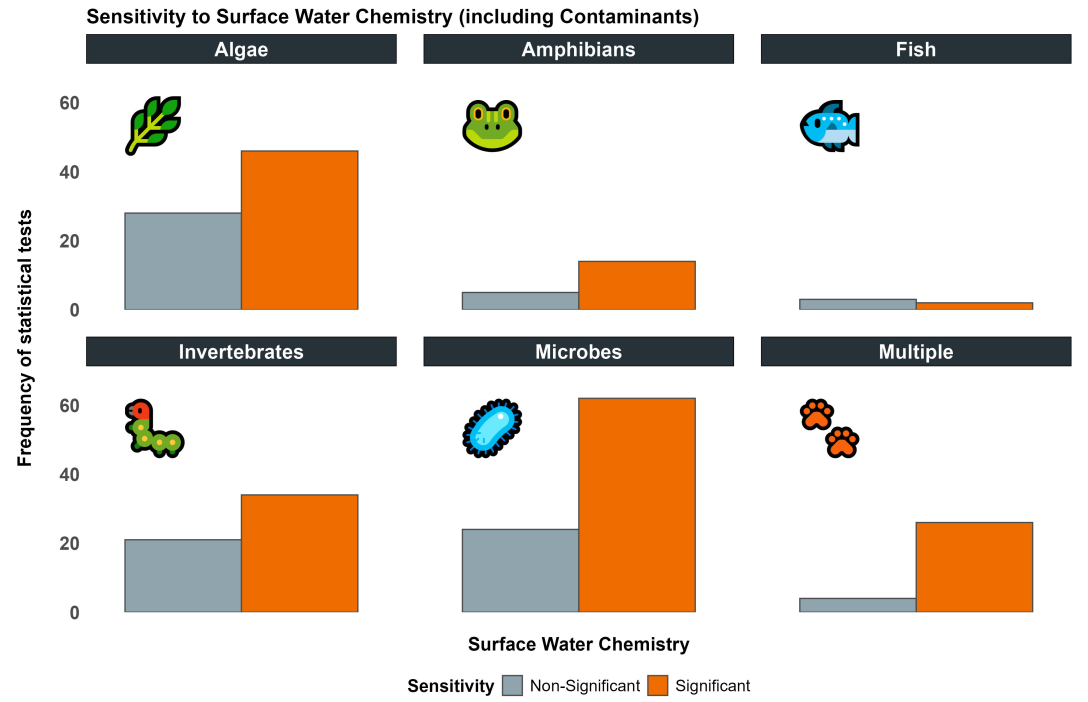

FIGURE 8
Taxon-specific sensitivity to alterations in surface water chemistry. The bars represent the total frequency of statistical tests for each taxonomic group. Unlike previous figures, the y-axis aggregates all types of biotic responses together. Orange bars denote significant outcomes (indicating sensitivity to changes in surface water chemistry), while *gray* bars represent non-significant results.

relationships based on their test frequency and the proportion of significant results. This approach allows us to identify potential monitoring indicators and management priorities, while also highlighting poorly studied stressors, abiotic states, and taxa. We then compare the Canadian Prairies Ecozone DPS framework with boreal wetland research to highlight shared pressures, regional differences, and transferable indicators. Finally, we examine how research effort aligns with regional economic drivers and taxon-specific funding, before discussing methodological limitations related to literature review design and large language model-assisted data extraction.

8.1 Synthesis of stressor-response relationships and implications to wetland monitoring and management

Supported by a high volume of statistical tests and consistently significant results, our findings demonstrate that agriculture, when measured as a driver through factors like the proportion of surrounding cropland, distance to cropland edges, and intensification, directly impacts bird abundance and vital rates such as survival and fecundity in the Canadian Prairies Ecozone. Observational studies incorporating modeling show that agricultural intensification and proximity to croplands generally affect wetland bird abundance, survival, and productivity (e.g., Devries and Armstrong, 2011; Podruzny et al., 2002; Sliwinski and Koper, 2012; Weegman et al., 2024). Research on the effects of agriculture on plants is more limited, but within this literature, the impact of agricultural presence on plant abundance is the most tested relationship with the highest rate of significant effects (e.g., Roy et al., 2019). Consequently, monitoring designs in agricultural landscapes may benefit from prioritizing bird and plant abundance, as well as bird vital rates, to assess biodiversity.

Our literature review indicates that wetland research in the region predominantly traces the Driver-Pressure-State (DPS) pathway from agricultural land use to wetland ecosystem alteration through water contamination, a stressor with well-documented effects on wetland water chemistry, which then affects various wetland biotic metrics, highlighting the high frequency of significant impacts from agriculture across several taxa. Our results showed a high frequency of significant microbial responses, such as nutrient cycling, to agricultural herbicides and shifts in wetland water parameters like sulfate. For example, experimental trials demonstrated that altered primary productivity is caused by changes in concentrations of major ions such as sulfate, and by herbicide mixture concentrations equal to or greater than the Canadian Water Quality Guidelines for the Protection of Aquatic Life (Sura et al., 2012). Taxa like amphibians are included in fewer studies, but the available results indicate a high number of significant responses to changing water quality. For instance, altered amphibian growth and immunity are driven by high total dissolved solids at levels near water quality guidelines for sulfate toxicity and by pesticide presence at concentrations below lethal thresholds (Ruso et al., 2021). Thus, our data suggest that total dissolved solids, agricultural nutrients, and herbicides are potential indicators of water quality effects, while microbial nutrient cycling may reflect water quality-dependent biodiversity health.

Although direct tests of water contamination on birds are rare, available research identifies existing risks, including migratory bird survival from toxic algal blooms caused by agriculture-driven phosphorus enrichment (e.g., Murphy et al., 2000). Furthermore, contaminated wetland water is expected to have cascading food-web effects on ducks, as elevated total nutrients and turbidity have an impact on their aquatic invertebrate prey (e.g., Kirk et al., 2024), reinforcing the need to monitor agricultural nutrients. Finally, while our results indicate a low frequency of significant plant responses, some studies show an increased abundance of exotic and annual plants at the expense of native perennials. Because these shifts are associated with elevated nitrogen and phosphorus levels associated with surrounding agriculture (Roy et al., 2019), plant dominance could also be monitored in agriculturally impacted wetlands.

A literature gap persists regarding the frequency of statistical tests examining the effects of agriculture on wetland substrate physico-chemical conditions. However, among the limited data available, 90% of tests show significant plant responses to substrate changes caused by events like erosion, as illustrated by studies showing agricultural erosion has historically filled regional wetlands with sediment (Koroluk and de Boer, 2007) and continues to do so (Zarrinabadi et al., 2023, 2025). Although our review identified few studies focused on soil chemistry, testing wetland soil for agricultural contaminants may offer monitoring potential given the high prevalence of marshes and semi-permanent to ephemeral open water wetlands in the region that cannot be captured by water quality sampling. Carbon sink capacity was another understudied category in our literature review. This suggests a need for future studies that quantify how agricultural pressures, along with other drivers, influence carbon storage and the capacity of Canadian Prairies Ecozone wetlands to contribute to climate change mitigation.

Agricultural pressures such as water flow alterations also remain understudied in these regions, likely due to the total wetland loss that often follows ditching. Despite this limited research, available studies included in our literature review report that wetland draining affects surface water runoff, downstream flows, and water storage (Haque et al., 2018; Whitfield et al., 2024), altering the capacity of wetlands to mitigate flood and drought risk. Moreover, these physical modifications have the potential to heavily impact wetland-dependent biota, as our results show that bird abundance and *behavior* have a high frequency of significant responses to hydrological changes (94%; e.g., Daniel and Rooney, 2022; Weegman et al., 2024). Relevant studies in our literature review provide methodologies that monitoring programs can use to track such effects. For example, broad-scale changes in wetland extent, permanence class, and agricultural infilling might be tracked by coupling long-term aerial surveys with remote sensing and machine learning classification models (e.g., Bartzen et al., 2010; Paterson et al., 2023). Notably, we highlight the need for wetland extent tracking given the limited number of studies we identified on this topic. Moreover, wetland area is a key indicator used in international and national biodiversity monitoring programs (Ramsar Convention on Wetlands, 2025; Convention on Biological Diversity, 2025), and robust baselines are needed to assess changes over time, particularly in light of ongoing challenges in accounting for historical wetland losses and maintaining consistent national assessments across time (e.g., Environment and Climate Change Canada, 2025). At the local scale, the impacts of ditching and cropping on wetland function could be assessed using continuous, high-frequency hydrometric monitoring to capture altered surface and subsurface water flows (e.g., Haque et al., 2022), alongside isotopic soil tracers to quantify sediment and nutrient infilling (e.g., Zarrinabadi et al., 2025).

We found that the ecological effects of urban development to wetlands in the Canadian Prairies Ecozone are far less understood than those of agriculture due to a lower volume of published research. This research gap is particularly concerning given the rapid urbanization of areas such as Alberta's Grassland and Parkland Natural Regions (Downing and Pettapiece, 2006). Within this region, the majority of population growth is concentrated within the Calgary-Edmonton Corridor, where the human population share rose from 56% in 1981 to 68% by 2021 (McQuillan and Laszlo, 2022). Urban land use can affect water quality disproportionately to its spatial extent, as even small urban footprints in southern Alberta catchments are associated with elevated ions, nutrients, and metals (Orwin et al., 2022). Available research further indicates that urbanization affects wetlands differently than agriculture by replacing natural wetlands with artificial stormwater facilities (Rooney et al., 2015) and exposing downstream wetlands to municipal wastewater effluent (Quinlan et al., 2002). Moreover, there is evidence that urban wetlands have lower ecological value than agricultural wetlands because engineered urban wetland stormwater systems remove groundwater connectivity, degrading hydrological function and driving adverse biological consequences such as the replacement of native species with invasive weeds (Rooney et al., 2015). Notably, we found that the pressure of invasive species represents another critical research gap across both urban and rural systems, which is concerning because wetlands are highly vulnerable to biological invasions (Zedler and Kercher, 2004) that act as a major threat to wetland biodiversity alongside habitat loss (Lázaro-Lobo and Ervin, 2021). Despite the disproportionate degradation associated with urban development, the lack of literature on primary urban drivers and compounding factors such as biological invasions limits our ability to recommend monitoring indicators. Because management and policy approaches, such as the Alberta Wetland Policy, often center on maintaining social and ecological wetland values (Government of Alberta, 2013), we highlight a need for targeted urban research to develop indicators for wetland monitoring, such as the Aquatic Condition Index developed for Calgary, Alberta, which combines expert assisted statistical learning with GIS based indicators to assess urban wetland condition (Erratt et al., 2024).

The Alberta Wetland Policy integrates voluntary stewardship programs and landowner partnerships to advance wetland conservation and restoration, aiming to sustain provincial biodiversity and other wetland values in areas with severe historical losses, while acknowledging expected time lags and the potential for long-term failure of wetland restoration projects (Government of Alberta, 2013). Our literature review results may reflect some of the challenges associated with these initiatives, as approximately 65% of tested wetland bird responses showed no statistically significant reaction to conservation interventions, such as rotational grazing in wetland areas and surrounding upland habitats (e.g., Koper and Schmiegelow, 2006, 2007). The difficulty in demonstrating

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consistent, measurable benefits from these interventions reinforces the directive that avoiding impacts and conserving existing wetlands must remain the highest management priority (Maron et al., 2024).

8.2 Contrasting wetland DPS frameworks in prairies and boreal regions

In our Canadian Prairies Ecozone systematic review, we found several drivers, pressures, and frequently impacted wetland states similar to those reported in the Canadian Boreal Oil Sands review by Ficken et al. (2022). Natural drivers, specifically climate and landscape factors, account for a large proportion of the literature in both regions and demonstrate consistent empirical effects on wetlands across both regions. For example, our results on the Canadian Prairies Ecozone confirm that landscape factors consistently produce statistically significant downstream impacts on wetland hydrology. Factors such as topographic position, catchment area, and storage capacity all significantly affect wetland water levels and, consequently, wetland permanence (Daniel et al., 2022; Gala et al., 2011; Haque, 2018; Shaw et al., 2012). Concurrently, short term weather and broader climate patterns, the most frequently evaluated individual driver in our dataset, have separate but also frequent effects across abiotic and biotic states of wetlands. Evidence from multiple studies indicates that historic long-term climatic shifts (Heck and Mermut, 1992; Klassen, 1994), recent observations (e.g., Atashi et al., 2023; Larson, 1995), and future projections (e.g., Withey and van Kooten, 2013, 2014) regarding temperature and precipitation consistently cause significant fluctuations in wetland extent across the region. Climatic drivers also directly influence the populations (e.g., Anderson, 1978 for plants; Beauchamp et al., 1996 for ducks) and community dynamics (e.g., Card and Quideau, 2010 for microorganisms; Daniel and Rooney, 2024 for invertebrates) of all biotic taxa documented in the literature. Across the boreal region previously studied and the Canadian Prairies Ecozone, these spatial and climatic forces converge with anthropogenic drivers, concurrently altering all wetland abiotic factors, and having both direct and indirect influence over biotic states.

In terms of anthropogenic pressures, both the Ficken et al. (2022) and our review identify water contamination as a primary wetland pressure and highlight water chemistry and plants as potential indicators. However, the anthropogenic drivers of contamination and cascading biotic effects differ entirely between the two regions. In the Canadian Prairies Ecozone, agriculture is the most well-studied driver of wetland ecosystem change and produces the highest proportion of statistically significant impacts, with concerns including agrochemical accumulation and exposure (e.g., Cavallaro et al., 2019 on effects to aquatic insect communities; Degenhardt, 2010 on herbicide accumulation in sediments; Forsyth et al., 1994 on waterbird eggshell alterations correlated with DDT); and excess nutrients (Cavallaro, 2019 on aquatic insect communities; McDougal et al., 1997 on nutrient-driven wetland regime shift experimentation; Hassanzadeh et al., 2019 on nutrient loading modeling). Nutrient loading is linked to agriculture-driven erosion, as displaced sediments due to pressures such as drainage and tillage mobilize nutrients to wetlands (Badiou et al., 2018; Cade-Menun et al., 2013; Zarrinabadi et al., 2025; Whitfield et al., 2024). Conversely, boreal literature focuses predominantly on oil sands production, tailings, and wetland reclamation. Both regions share knowledge gaps regarding wetland pressures, particularly concerning water flow alterations, but the Canadian Prairies Ecozone also faces unique understudied pressures, such as grazing, which were not recorded in the boreal literature.

Within the Canadian Prairies Ecozone, the frequency of recorded relationships in our review generally reflects the natural distribution of prairie marshes and shallow open water. However, this coverage overlooks known fens in regions such as the Alberta Parkland (Downing and Pettapiece, 2006) and swamps across the ecozone (DeLancey et al., 2022; Montgomery et al., 2021). This lack of research on ecosystems explicitly covered by wetland policies in the region (e.g., Government of Alberta, 2013) may result from a true absence of research or potential misclassification, perhaps arising from differing provincial classification standards or the inherent difficulty of identifying some wetland classes, such as swamps (Mirmazloumi et al., 2021). This pattern contrasts with boreal research, which disproportionately focuses on artificial and reclaimed wetlands.

Regarding indicator selection for monitoring programs, both syntheses highlight surface water chemistry as a primary abiotic state and organism abundance as a biotic state that frequently yields significant responses. Although plants are a common potential indicator for both regions, the ecosystems diverge on other biological metrics. We established birds as the most heavily researched and highly responsive candidate indicator taxon in the Canadian Prairies Ecozone, while the boreal review found insufficient empirical support for birds and proposed invertebrates instead.

8.3 Comparing research effort with regional economic drivers and taxon-specific funding

Potential biases exist in research effort, particularly regarding how well studies align with the prevalent economic activities in each region and how funding targets specific taxa. Our results may have broad spatial relevance because most compiled studies used multi-site designs, included regional-scale evaluations, or covered broad areas of the Canadian Prairies Ecozone. These characteristics provide a good indication that the results are regionally applicable, although research effort may still not consistently reflect measured human footprints across the ecozone. An exploratory comparison of the drivers and pressures studied in the literature against the empirical human footprint surrounding wetlands in the Grassland and Parkland regions of Alberta (Alberta Biodiversity Monitoring Institute, ABMI, 2021) highlights regions with accurate and poor alignments (Appendix 4, exploratory analysis). The Grassland is mainly defined by a warm, dry prairie region of native grasslands and cultivated croplands, whereas the Parkland is distinguished by a transitional mosaic of native grasslands, aspen and willow shrublands, agricultural lands, and urban areas (Downing and Pettapiece, 2006). While research in the Grassland region generally aligns with the prevailing anthropogenic footprint, the Parkland

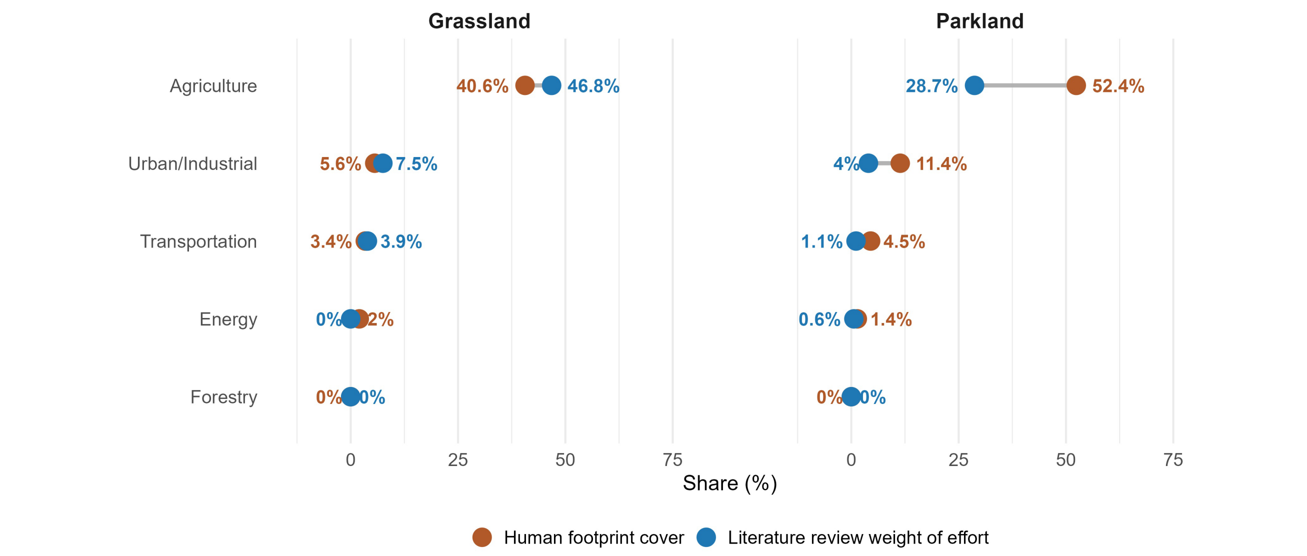

FIGURE 9
Gap between literature weight of effort and landscape footprint around wetlands in the Grassland and Parkland regions of Alberta (Alberta Biodiversity Monitoring Institute, 2021; Appendix 5). Data represent unscaled raw percentages. Total percentages of literature review research effort include other drivers not plotted (e.g., weather and climate). Total percentages of human footprint represent the total footprint across the studied landscape, including pristine areas. Literature review data points include n=585 relationships between a wetland stressor and a wetland response variable in the Grassland and Parkland Natural Regions of Alberta.

region remains understudied across all drivers (Figure 9), failing to capture the recent scale of documented agricultural, urban, industrial, and transportation drivers and pressures. Consequently, we recommend that future studies and monitoring programs compare research effort synthesized in literature reviews, such as this one, against known human footprint proportions associated with wetland stressors in regions sharing ecological and economic characteristics. This approach identifies locations where proposed indicators reliably reflect more closely the reality of wetlands surrounded by economic activities, while highlighting areas where significant mismatches indicate a need for further research to refine those indicators.

Beyond spatial discrepancies, taxonomic representation in the literature also seems to be biased by targeted funding sources. The high volume of bird research in the Canadian Prairies Ecozone yielded a consistently high frequency of significant responses, supporting their use as candidate indicators, but it also points to a systemic bias toward projects supported by specific environmental organizations, with Ducks Unlimited Canada accounting for over 70% and Delta Waterfowl supporting over 15% of the subset funded by conservation organizations (Appendix 5, exploratory analysis). Consequently, the scarcity of literature on other organisms may reflect restricted funding distribution rather than a lack of ecological importance.

8.4 Methodological limitations

Our findings are subject to methodological constraints regarding data extraction, as well as limitations inherent to literature reviews. First, we restricted our focus to primary relationships and main effects, excluding interaction effects and *post-hoc* analyses due to time and scope constraints and to avoid duplicating extracted variables, which may have potentially omitted important conclusions from the literature. Moreover, the applicability of our findings is temporally constrained because nearly half of the current literature is more than 16 years old, published before 2010, and the brief duration of most studies limits long-term extrapolations under a rapidly changing climate.

Our large language model-assisted approach generally proved useful for bulk repetitive tasks of abstract screening, metadata collection, and data extraction. Consistent with previous research evaluating large language models for these tasks (Gougherty and Clipp, 2024; Krishna Moorthy et al., 2025), we achieved high accuracy when extracting simple or categorical data, including geographic locations, taxonomic classifications, study designs, and temporal durations. During abstract screening, the approach performed well at retaining relevant literature, though it demonstrated moderate precision by including non-target papers. Conversely, our attempt at bulk data extraction failed completely because restricted context windows, a limitation common to most enterprise-grade models, caused the system to omit variables. This aligns with literature stating that performance remains limited by input volumes and requested response lengths (Dorm et al., 2026; Gartlehner et al., 2025; Krishna Moorthy et al., 2025; Stewart-Evans et al., 2025). Consequently, our paper-by-paper AI-assisted data extraction proved more effective; while time-consuming, extracting variables manually from nearly 400 papers would have required significantly more time without a large language model-assisted approach.

Classification of ecological variables using this AI-assisted approach proved more challenging, reinforcing that human domain experts must validate results, particularly when extracting non-categorical information such as statistical outcomes, in agreement with previous studies (Bayani et al., 2025; Gartlehner et al., 2025; Gougherty and Clipp, 2024; Konet et al., 2024; Krishna Moorthy et al., 2025; Serdiukov et al., 2026). In general, the automated approach misclassified proxies and required manual correction because it favored literal meanings over functional ecological applications. For example, it categorized stable water isotopes, nitrogen and sulfur isotopes, and radioisotopes as wetland water chemistry states, failing to recognize them as specialized proxies for hydrological mass balances, trophic relations, or historical soil erosion. Despite these challenges, our experience demonstrates that this technology holds potential to expedite evidence synthesis, especially as it continues to evolve to meet the demands of the rapid increase in environmental science publication effort.

9 Conclusion

Our review suggests that wetland monitoring programs in the Canadian Prairies Ecozone may consider bird and plant abundance as candidate biotic indicators in agricultural landscapes, alongside surface water chemistry and hydrological change, supported by a frequently documented pathway linking agricultural contaminants to water quality, and subsequent biotic impacts. This guidance is strongest for agricultural wetlands, but it also reflects an uneven research effort. Birds and agricultural pressures receive disproportionate attention compared to other taxa and urban wetlands. We also showed that the underrepresentation of certain taxa, including amphibians, plants, invertebrates, and fish, likely stems from historical research and funding biases rather than a lack of biological importance. Research priorities align with conservation investments, which have historically targeted waterfowl in the American and Canadian Prairie Pothole Region to support recreational hunting activities (Doherty et al., 2015; Loesch et al., 2012). While consistent funding has successfully improved waterfowl populations (Sainsbury et al., 2025), our results indicate that this historical focus leaves the broader range of wetland taxa and ecosystem services understudied. Furthermore, research coverage may fail to match the proportional distribution of wetland pressures (e.g., the Parkland region of Alberta lacks research on agriculture, urban, transportation, and energy drivers) or the natural distribution of wetland classes (e.g., the undersampling of swamps). Directing research toward other taxa and abiotic factors potentially affected by agriculture, as well as rapidly urbanizing regions, would address current evidence gaps and support the development of indicators responsive to specific economic activities. Moreover, focusing on locations where we mapped heavy human footprint data across the research area, mapping these layers to identify blind spots where highly pressured or degraded wetlands lack study. By addressing knowledge gaps and linking what is measured to where pressures are strongest, monitoring programs can better target relevant indicators, reduce research bias, and support wetland management and conservation decisions that protect wetland biodiversity, migratory birds, human values and wetland ecosystem services. Finally, the interactive dashboard provided serves as a visual user interface that makes a high volume of scientific findings accessible to policymakers and society, contributing to the democratization of knowledge via DPSIR approaches (Carnohan et al., 2023).

A long-term monitoring program that tracks wetland conditions across gradients of key human drivers and pressures is necessary to understand current conditions and inform management outcomes. Our synthesis highlights a high frequency of significant responses among abiotic factors, including water quality, hydrology, and soil physicochemical conditions, to multiple human pressures in the region, which may provide early signals of degrading wetland condition. Concurrently, bioindicators remain valuable for assessing stressor impacts on biota. Although avian metrics have high rates of significance to regional stressors, their migratory nature complicates sampling. Plants represent feasible alternative indicators, as they also show high frequency of responsiveness to stressors in the prairies. Moreover, plants are proven prairie wetland indicators in the US because they provide critical habitat, reflect soil and water conditions, and respond predictably to anthropogenic impacts (Tangen et al., 2022). Regarding wetland area metrics, most research focuses on how climate affects wetland extent, leaving a gap in studies examining the impacts of human development stressors. Tracking wetland extent over time within areas of key drivers and stressors will further inform management decisions. This effort could rely on remote sensing coupled with field observations to gather large-scale data for evaluating, reporting, and managing wetlands across the region. Moving forward, literature reviews may examine site-scale impacts, localized regions, and individual pressures. There is also a need to assess broad-scale changes to wetland extent and condition caused by key human pressures and cumulative effects. Thus, future studies may investigate how wetland loss or degradation affects downstream water bodies, particularly the resulting loss of critical ecosystem services such as flood and drought mitigation for humans and wildlife.

Author contributions

DA-P: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Visualization, Validation, Writing – original draft, Writing – review & editing. RR: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. DC: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MT-R: Conceptualization, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. NT: Conceptualization, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. VS: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declared that generative AI was used in the creation of this manuscript. As part of the methods (literature review data screening, data extraction, and data classification), prompts, technologies, and methods used are all described in the body of the paper.

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Supplementary material

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