Modeling Mosquito Dynamics and West Nile Virus Risk in Canada: A Systematic Mapping Review of Approaches and Research Gaps

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Abstract

Mosquito population dynamics are strongly shaped by environmental conditions and are central to mosquito-borne disease risk. In Canada, West Nile virus (WNV) remains the dominant mosquito-borne viral disease of public health concern, while climate change may alter mosquito distributions, seasonal activity, and the risk of WNV and other emerging mosquito-borne diseases. This systematic mapping review synthesizes Canadian studies on mosquito population dynamics, vector distribution, surveillance, WNV risk, and emerging mosquito-borne disease risk, with attention to modeling approaches, environmental drivers, biological-process representation, data sources, model support, and geographic coverage. A total of 50 studies met the eligibility criteria. Statistical and data-driven models formed the largest modeling category, while mechanistic mosquito population models provided the clearest representation of life-history processes. Temperature was the most consistently represented environmental driver, whereas precipitation was commonly included but represented in varying ways. Model support and transparency varied, with calibration reported more often than independent validation, uncertainty analysis, sensitivity analysis, out-of-sample prediction, or code and data availability. Studies were concentrated in Ontario and national-scale analyses; Atlantic and northern Canada were represented by a small number of empirical or surveillance studies but lacked eligible quantitative modeling studies. The main gap is the lack of integrated models linking climate-sensitive mosquito population dynamics, surveillance data, and WNV transmission. Future work should prioritize integrated, climate-informed frameworks to support mosquito and WNV risk assessment in Canada.

Keywords: mosquito population dynamics; West Nile virus; Canada; systematic mapping review; vector-borne disease modeling; climate change; surveillance data

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1 Introduction

Mosquito-borne diseases (MBDs) remain an important public health concern globally, with transmission dynamics strongly influenced by environmental conditions, vector ecology, host availability, and human exposure (Ng et al., 2019, Ludwig et al., 2023, Wang et al., 2011). In Canada, West Nile virus (WNV) is the most established mosquito-borne viral disease of public health concern, with transmission maintained through interactions among mosquito vectors, avian hosts, environmental variability, and human exposure risk (Zheng et al., 2014, Mallya et al., 2018, Baril et al., 2023, Ludwig et al., 2023). Although reported disease incidence varies across regions and years, climate change may alter mosquito population dynamics, extend seasonal activity, and increase vector suitability in areas that have historically experienced lower risk (Ng et al., 2019, Ludwig et al., 2019, Ogden et al., 2022, Khan et al., 2020). Understanding the ecological and climatic drivers of mosquito abundance, vector distribution, and WNV risk is therefore important for surveillance, risk assessment, vector control, and public health preparedness.

Mosquito population dynamics are highly sensitive to environmental conditions, particularly temperature and precipitation. Temperature influences key biological processes such as development, survival, reproduction, biting activity, and seasonal population growth (Yu et al., 2018, Frantz et al., 2024, Shutt et al., 2022, Abdelrazec and Gumel, 2017, Baafi and Hurford, 2025). Precipitation affects the availability, persistence, and quality of aquatic larval habitats, although its effects may vary depending on rainfall timing, habitat type, land cover, and local hydrological conditions (Wang et al., 2011, Ripoche et al., 2019, Baril et al., 2023, Gizaw et al., 2025). In temperate regions, seasonal processes such as diapause and overwintering are also important because they influence winter survival, spring emergence, and the timing of annual population resurgence (Yu et al., 2018, Frantz et al., 2024, Ludwig et al., 2023). These interacting drivers generate seasonal and interannual variability in mosquito abundance and disease risk, creating challenges for prediction and model development.

A range of modeling approaches has been used to study mosquito dynamics and MBD risk in Canada. Statistical and data-driven models have been widely applied to quantify associations between mosquito abundance, vector infection, human disease risk, and environmental variables, often using surveillance and weather data (Wang et al., 2011, Chen et al., 2013, Ripoche et al., 2019, Mallya et al., 2018, Ludwig et al., 2023, Baril et al., 2023, Gizaw et al., 2025). Species distribution, ecological niche, and machine-learning models have been used to characterize mosquito occurrence, habitat suitability, vector distribution, and potential range expansion under current or future climate conditions (Hongoh et al., 2012, Moua et al., 2021, Gorris et al., 2021, Talbot et al., 2023, Khan et al., 2020, Nair et al., 2025). Mechanistic approaches provide complementary insights by representing biological or transmission processes more explicitly. Mechanistic mosquito population models describe processes such as development, survival, reproduction, stage structure, environmental forcing, and diapause (Yu et al., 2018, Frantz et al., 2024, Shutt et al., 2022, Mancuso et al., 2023, Abdelrazec and Gumel, 2017), while mechanistic transmission models represent host–vector infection dynamics, spatial transmission risk, and climate-sensitive WNV propagation (Cissé et al., 2024, Cisse et al., 2025, Bouden et al., 2008).

Despite these advances, existing approaches often emphasize different components of the mosquito–environment–disease system. Statistical models are useful for empirical prediction and risk assessment, but they generally do not represent mosquito life-cycle processes explicitly (Wang et al., 2011, Ripoche et al., 2019, Mallya et al., 2018, Ludwig et al., 2023,

Gizaw et al., 2025). Species distribution and ecological niche models provide spatially explicit estimates of suitability or distribution, but often do not capture seasonal abundance dynamics, immature-stage processes, or host–vector transmission mechanisms (Moua et al., 2021, Gorris et al., 2021, Talbot et al., 2023, Khan et al., 2020, Nair et al., 2025). Mechanistic population models provide stronger biological interpretation, but may be limited by parameter uncertainty, simplified rainfall or habitat processes, or limited field data for calibration and validation (Yu et al., 2018, Frantz et al., 2024, Shutt et al., 2022, Abdelrazec and Gumel, 2017). Transmission models represent disease dynamics, spatial transmission risk, or climate-sensitive WNV propagation, but mosquito abundance is often simplified or treated separately from detailed population processes (Cissé et al., 2024, Cisse et al., 2025, Bouden et al., 2008). As a result, environmental drivers, mosquito population dynamics, data availability, and disease transmission are often studied in separate modeling frameworks.

Data availability also shapes model development. Canadian mosquito and arbovirus surveillance programs collect information on mosquito abundance, vector infection, and human cases, but the spatial coverage, temporal duration, and accessibility of these datasets vary across regions (Public Health Agency of Canada, 2024, Public Health Ontario, 2024). Regions with more visible surveillance records, public health reporting, and accessible environmental data have supported a larger number of modeling studies, particularly Ontario and national-scale analyses, whereas Atlantic and northern Canada were represented only by a small number of empirical or surveillance studies and had no eligible quantitative modeling studies. These data differences can influence not only where models are developed, but also which modeling approaches are feasible, how models are calibrated, and whether independent validation can be performed.

Although this review considered studies relevant to MBD risk in Canada, the disease-transmission modeling literature identified through the search was dominated by WNV. Therefore, the synthesis emphasizes mosquito population dynamics, mosquito surveillance, vector distribution, and WNV risk. Studies of invasive or emerging mosquito vectors, including *Aedes aegypti*, *Ae. albopictus*, *Ae. japonicus*, and other mosquito taxa, were also included when they provided Canadian data, Canadian geographic coverage, or Canada-specific projections relevant to future MBD risk. Empirical and surveillance studies addressing other mosquito-borne viruses, including Jamestown Canyon virus and snowshoe hare virus, were retained when they contributed to understanding mosquito surveillance, vector distribution, or MBD risk in Canada (Ng et al., 2019, Khan et al., 2020, Lowe et al., 2021, Chaulk et al., 2016, Hollett et al., 2025, Villeneuve et al., 2025).

Specifically, the review was guided by the following questions: What modeling approaches have been used to study mosquito dynamics, vector distribution, surveillance, and WNV risk in Canada? Which environmental drivers and biological processes are represented across these studies? What data sources, validation practices, uncertainty analyses, and transparency indicators support the quantitative modeling studies? What methodological, environmental, data-related, and geographic gaps limit the development of integrated mosquito and WNV modeling frameworks in Canada?

In this review, we provide a systematic mapping review of Canadian studies on mosquito population dynamics, vector distribution, surveillance, and WNV risk, while retaining broader MBD risk studies when they contribute to understanding Canadian mosquito surveillance, vector distribution, or emerging-risk contexts. We synthesize the literature with respect to study classification, environmental driver representation, biological process representation, data–model alignment, model support and transparency, and geographic coverage. By identi-

fying recurring methodological, environmental, data-related, and geographic gaps, this review provides a foundation for the development of more integrated, climate-informed mosquito and WNV modeling frameworks for Canada.

2 Methods

This study was conducted as a systematic mapping review of mosquito population dynamics, vector distribution, and West Nile virus (WNV) risk in Canada. The review followed a structured search, screening, classification, and synthesis procedure informed by relevant elements of PRISMA reporting guidance and scoping review methodology (Page et al., 2021, Tricco et al., 2018). The objective was not to conduct a meta-analysis or formal risk-of-bias assessment, but rather to map the existing literature with respect to modeling approaches, environmental driver representation, biological processes, data sources, geographic coverage, and research gaps. No formal review protocol was registered before conducting the study. However, the review followed a predefined search, screening, eligibility, classification, and extraction framework developed for the purpose of this systematic mapping review. The review process included senior-author review of included studies, full-text exclusions, and study classification decisions. A completed PRISMA-ScR checklist is provided in Supplementary Table S5.

To facilitate a structured synthesis, studies were classified according to study type, modeling approach, environmental driver representation, data sources, and geographic coverage. Particular attention was given to how different studies incorporated mosquito life-history processes, climate and weather variables, habitat and landscape characteristics, surveillance data, and disease transmission dynamics. This classification framework enabled the identification of common methodological patterns, data–model relationships, geographic patterns and gaps, and key limitations in the current literature. The methodological procedures used for literature identification, screening, classification, and synthesis are described in the following subsections.

2.1 Literature Search Strategy

A structured literature search was conducted to identify studies examining mosquito population dynamics, mosquito abundance, vector distribution, West Nile virus (WNV) risk, MBD risk, and related modeling or surveillance approaches in Canada. Searches were conducted in Web of Science, Scopus, and Google Scholar. The search strategy combined terms related to mosquitoes, WNV and MBD risk, modeling and surveillance approaches, environmental drivers, and the Canadian geographic context. Search terms included combinations of mosquito-related keywords (e.g., *mosquito*, *Culex*, *Aedes*), disease-related keywords (e.g., *West Nile virus*, *mosquito-borne disease*, *vector-borne disease*), modeling and risk-related terms (e.g., *model*, *forecast*, *risk*, *abundance*, *species distribution*, *habitat suitability*), environmental terms where applicable (e.g., *temperature*, *precipitation*, *climate*, *weather*, *seasonality*, *climate change*), and the geographic term *Canada*. Because the review was centered on mosquito population dynamics, vector distribution, surveillance, and WNV risk in Canada, the search strategy prioritized mosquito-, WNV-, vector-, modeling-, surveillance-, and climate-related terms. Studies addressing other mosquito-borne pathogens or disease risks, including Jamestown Canyon virus, snowshoe hare virus, California serogroup viruses,

eastern equine encephalitis virus, dengue, Zika, or malaria, were retained when they were identified through the search or supplementary checking and met the Canadian-context eligibility criteria.

Searches were conducted on April 24, 2026. No restriction was placed on publication year, but only studies published in English were considered. The exact search strings used for Web of Science and Scopus, together with the Google Scholar search phrases, are provided in Supplementary Table S2. Because Google Scholar does not provide the same level of reproducibility as bibliographic databases, Google Scholar searches were conducted using predefined search phrases, with results sorted by relevance. For each Google Scholar search phrase, the first 100 records were screened for apparent relevance. Potentially relevant records from the Google Scholar searches were then combined into a Google Scholar pool, and duplicates within this pool were removed. This resulted in 76 unique Google Scholar records being retained for combination with the Web of Science and Scopus records. The pooled reference set therefore included 198 candidate records before cross-source duplicate removal. The search date, search phrase, sorting method, number of records screened, and number retained are reported in Supplementary Table S2.

Backward and forward citation tracking of key included articles and relevant review papers was used to identify additional potentially eligible studies. Before finalizing the synthesis, a brief supplementary check of recent Google Scholar results and citation lists from key included studies was conducted. Six additional eligible studies were identified during this final checking process and were added to the synthesis because they met the inclusion criteria and addressed mosquito surveillance, vector distribution, WNV risk, or MBD risk in Canada.

2.2 Study Selection Process

The study selection process followed a structured screening procedure consistent with PRISMA-style reporting principles. Searches in Web of Science and Scopus identified 122 records. Google Scholar searches were screened by relevance, and after removal of duplicates within the Google Scholar pool, 76 unique potentially relevant records were retained. These records were combined with the Web of Science and Scopus records, resulting in 198 candidate records entering cross-source duplicate removal. After duplicate removal, 102 records remained.

An initial screening excluded 16 records that were not related to mosquitoes or were clearly outside the review scope, leaving 86 records for title and abstract review. Following title and abstract screening, 23 records were excluded because they fell outside the scope of the review or were not published in English. This resulted in 63 full-text articles being assessed for eligibility. During final supplementary checking and citation review before manuscript finalization, six additional eligible studies were identified and assessed at full text, resulting in 69 full-text articles assessed for eligibility.

Full-text screening was conducted using the predefined inclusion and exclusion criteria, with particular attention to whether each study had a direct Canadian component. Nineteen full-text articles were excluded because they were not relevant to the Canadian context, did not contain an eligible modeling, quantitative, empirical, surveillance, or review component, did not sufficiently address the objectives of this review, or represented broader methodological studies without a direct Canadian application. A total of 50 studies satisfied the eligibility criteria and were included in the final synthesis. Broader methodological or international modeling studies were used where appropriate to support background interpretation but were not included in the Canadian evidence map unless they contained Canadian

data, Canadian geographic coverage, Canada-specific projections, or explicit Canadian public health relevance. A summary of the study selection process is presented in Figure 1.

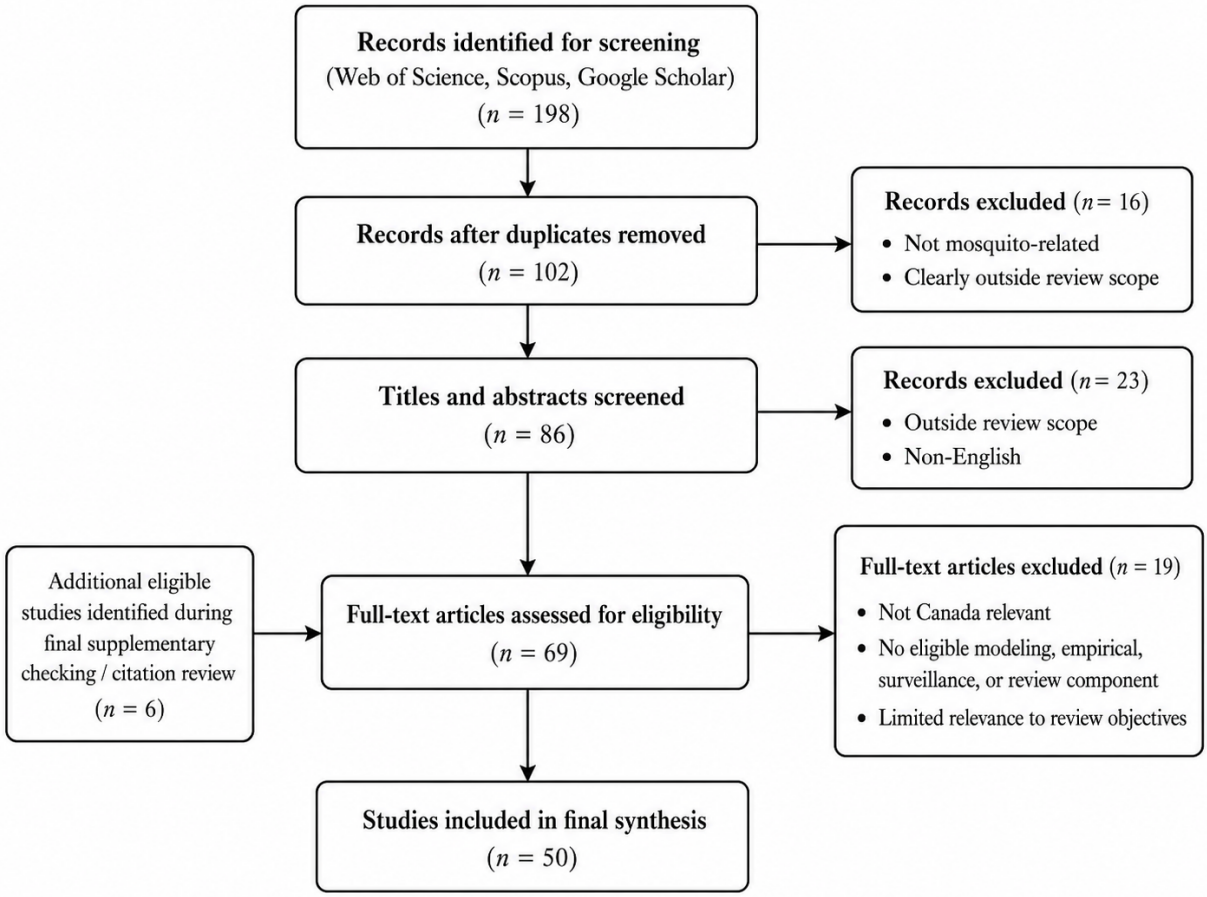

Figure 1: Study selection process for the systematic mapping review.

2.3 Eligibility Criteria

Studies were included if they met the following criteria:

- Investigated mosquito population dynamics, mosquito abundance, mosquito occurrence, mosquito ecology, West Nile virus (WNV) risk, or MBD transmission risk in Canada;
- Had a direct Canadian component, defined as the use of Canadian mosquito, environmental, epidemiological, surveillance, geographic, policy, or public health data, or an explicit focus on MBD risk within Canada;
- Focused on national, provincial, territorial, or regional contexts within Canada;
- Employed empirical, surveillance-based, statistical, spatial, species distribution, mechanistic, transmission, machine-learning, conceptual, or review-based approaches relevant to mosquito dynamics or MBD risk;

- Considered environmental, climatic, ecological, seasonal, surveillance, or public health drivers where applicable to the study objective;
- Were published in English.

Studies were excluded if they:

- Did not focus on mosquito population dynamics, mosquito ecology, mosquito occurrence, WNV risk, or MBD transmission risk in Canada;
- Were conducted exclusively outside Canada and did not include a direct Canadian data, geographic, policy, surveillance, or disease-risk component;
- Were broad methodological, experimental, or global modeling studies without an explicit Canadian application or interpretation;
- Focused solely on laboratory experiments without ecological, environmental, public health, surveillance, or modeling relevance to Canada;
- Did not provide quantitative, empirical, surveillance-based, modeling, conceptual, or review-based insights relevant to mosquito dynamics or MBD risk;
- Were not available in English.

2.4 Study Classification and Data Extraction

Data were extracted from each included study using a structured extraction framework. Extracted information included citation details, publication year, study type, geographic region, mosquito species, pathogen or disease focus, model class, model category, environmental drivers, data sources, calibration and validation information, key findings, reported limitations, and relevance to mosquito dynamics or MBD risk in Canada. The complete extraction table for all included studies is provided in Supplementary Table S1. All included studies and full-text exclusions were reviewed with the senior author, and uncertainties in study eligibility or classification were resolved through discussion.

Studies were classified according to their dominant study design and analytical approach. The classification categories were: empirical or surveillance studies, review or conceptual studies, statistical or data-driven models, species distribution, ecological niche, or machine-learning models, mechanistic transmission models, and mechanistic mosquito population models. Review and conceptual studies were retained to map interpretive, policy-oriented, and synthesis-based Canadian literature relevant to mosquito and MBD risk, but they were not treated as independent primary evidence for quantitative modeling findings. Studies were assigned to a single category to avoid double-counting in the synthesis. When a study contained elements of more than one approach, classification was based on the approach most central to the study objectives, analysis, and main findings.

Additional study characteristics, including vector species, pathogen focus, environmental drivers, data sources, calibration, validation, and climate projection assumptions, were extracted to support the comparative synthesis across categories. This approach allowed the review to summarize the structure of the literature while also comparing how studies represented environmental drivers, biological processes, data sources, and model-support indicators. Broader methodological or non-Canadian studies were used, where appropriate, to

support background context and interpretation, but were not included in the final synthesis unless they satisfied the Canadian-context eligibility criterion.

Title and abstract screening, full-text screening, data extraction, and initial study classification were conducted by the first author using the predefined inclusion and exclusion criteria and structured extraction framework. The extraction framework and classification outputs were reviewed during manuscript development with the senior author, who provided feedback on the organization of the synthesis, study categorization, and consistency between the extraction table, figures, and narrative interpretation. Uncertain classification decisions were revisited against the full texts, the predefined eligibility criteria, and the dominant study objective, analytical approach, and main findings of each article. Screening and extraction were not conducted as fully independent duplicate processes; however, structured eligibility criteria, a predefined extraction framework, consistency checks, and senior-author review were used to support transparency and consistency.

2.5 Model Support and Transparency Indicators

For studies that included a quantitative modeling component, additional information was extracted to describe model support and reporting transparency. Review, conceptual, empirical, and surveillance studies were excluded from this assessment because the indicators were designed for quantitative modeling studies. The model-support and transparency indicators included whether model calibration or fitting was performed, whether independent validation was conducted, whether uncertainty analysis and sensitivity analysis were included, whether code or data availability was stated, whether biological mechanisms were explicitly represented, whether out-of-sample prediction was tested, and whether climate projection assumptions were reported where applicable. Spatial scale and temporal resolution were also extracted as descriptive reporting fields and retained in Supplementary Table S1, but were not treated as model-support indicators. Each indicator was coded as *Yes*, *Partial*, *No*, or *Not applicable*. The *Not applicable* category was used for indicators that were not relevant to a given study design, such as climate projection assumptions for studies that did not include future climate or scenario projections. These indicators were used as descriptive measures of model support and reporting completeness, rather than as a formal risk-of-bias assessment or quality-ranking system.

Coding decisions followed predefined operational criteria. A study was coded as *Yes* when the indicator was clearly reported and directly implemented, *No* when it was absent or not described, *Partial* when the study included limited or indirect evidence of the indicator, and *Not applicable* when the indicator did not apply to the study design. For example, independent validation was coded as *Partial* when evaluation used temporally separated or internally withheld data but not a fully independent dataset. Uncertainty analysis was coded as *Partial* when confidence intervals, credible intervals, prediction intervals, uncertainty ranges, or scenario comparisons were reported without a fuller uncertainty propagation framework. Code or data availability was coded as *Partial* when input data sources were public or described but analysis code, processed datasets, or reproducible workflows were not fully available.

The definitions and coding criteria used for each model support and transparency indicator are provided in Supplementary Table S3. Study-level coding for the quantitative modeling studies is provided in Supplementary Table S1 to support reproducibility of the model-support summaries.

2.6 Synthesis Framework

A structured synthesis approach was used to compare studies and identify common patterns, strengths, limitations, and knowledge gaps across the literature. Given the diversity of study objectives, modeling frameworks, outcome measures, and data sources, a quantitative meta-analysis was not appropriate. Instead, studies were synthesized using qualitative assessment and descriptive quantitative summaries.

The synthesis was organized around six complementary dimensions:

- **Study and model classification:** comparison of the main classification categories, including empirical or surveillance studies, review or conceptual studies, statistical or data-driven models, species distribution, ecological niche, or machine-learning models, mechanistic transmission models, and mechanistic mosquito population models;
- **Environmental driver representation:** evaluation of how studies incorporated temperature, precipitation, seasonality, land cover, vegetation, and other ecological or environmental drivers;
- **Data–model relationships:** assessment of the types of data used to support different study and modeling approaches, including surveillance, climate, epidemiological, laboratory, and environmental datasets;
- **Data-source breadth:** evaluation of the extent to which studies incorporated multiple types of data sources, while recognizing that this measure captures the breadth of data types rather than data quality, sample size, spatial resolution, temporal coverage, or suitability for calibration and validation;
- **Model support and transparency:** descriptive assessment of calibration, validation, uncertainty and sensitivity analysis, code or data availability, biological mechanism representation, out-of-sample prediction, and climate projection assumptions among quantitative modeling studies;
- **Geographic coverage:** examination of the regional distribution of studies across Canada and its relationship with surveillance infrastructure, data availability, and modeling activity.

Collectively, these analyses were used to identify methodological trends, environmental driver integration patterns, data limitations, geographic gaps, and opportunities for more integrated mosquito and WNV risk modeling in Canada. Studies were counted once within the classification framework, whereas additional study characteristics such as vector species, pathogen focus, environmental drivers, data sources, and model-support indicators were summarized descriptively through the extraction framework and narrative synthesis.

3 Results

3.1 Study Characteristics and Scope

A total of 50 studies met the eligibility criteria and were included in the final synthesis. The included studies addressed mosquito dynamics, vector distribution, surveillance, and MBD

risk in Canada. The literature was dominated by studies related to West Nile virus (WNV), with most WNV-focused studies examining *Culex* mosquitoes, particularly species or species complexes associated with WNV transmission, including *Culex pipiens*, *Cx. restuans*, and *Cx. tarsalis*.

A smaller subset of studies focused on invasive or emerging mosquito vectors, particularly *Aedes aegypti*, *Ae. albopictus*, *Ae. japonicus*, and other mosquito species relevant to Canadian vector surveillance. Several empirical or surveillance studies also addressed other mosquito-borne viruses, including Jamestown Canyon virus and snowshoe hare virus, when these studies contributed to understanding mosquito surveillance, vector distribution, or MBD risk in Canada. Thus, although the review considered MBD risk broadly, the disease-transmission modeling component of the Canadian literature was primarily WNV-focused, while non-WNV studies contributed mainly to the literature on mosquito surveillance, vector distribution, emerging vector suitability, and mosquito-borne virus detection.

Study outcomes varied across the literature and included mosquito abundance, mosquito occurrence, habitat suitability, vector infection, human disease risk, climate suitability, projected range expansion, mosquito-borne virus detection, and transmission dynamics.

3.2 Classification of Study Approaches

The 50 included studies were classified according to their dominant study design or modeling approach (Figure 2). The final synthesis included 9 empirical or surveillance studies, 3 conceptual or review studies, and 38 studies with a quantitative modeling component.

Among the 38 modeling studies, statistical or data-driven models were the most common category ($n = 22$). Species distribution, ecological niche, or machine-learning models accounted for 7 studies. Mechanistic mosquito population models accounted for 6 studies, while mechanistic transmission models accounted for 3 studies.

Statistical and data-driven studies generally analyzed mosquito abundance, vector infection, human disease occurrence, or environmental risk using surveillance, epidemiological, spatial, or environmental datasets. Species distribution, ecological niche, and machine-learning studies focused mainly on mosquito occurrence, habitat suitability, geographic distribution, or projected range expansion. Mechanistic transmission models represented host–vector infection processes, while mechanistic mosquito population models represented biological processes related to mosquito abundance, including development, mortality, stage structure, seasonality, and environmental forcing.

3.3 Synthesis of Study Approaches

Across study categories, the reviewed literature differed not only in modeling approach, but also in the part of the mosquito–environment–disease system being represented. Empirical and surveillance studies primarily described observed mosquito occurrence, species composition, vector activity, or mosquito-borne virus detection. Statistical, spatial, and SDM/ENM/ML models were most often used for prediction, mapping, and risk assessment, while mechanistic models represented either mosquito population processes or WNV transmission dynamics. This section summarizes the major analytical roles and limitations of each study category; study-level details are provided in Supplementary Table S1.

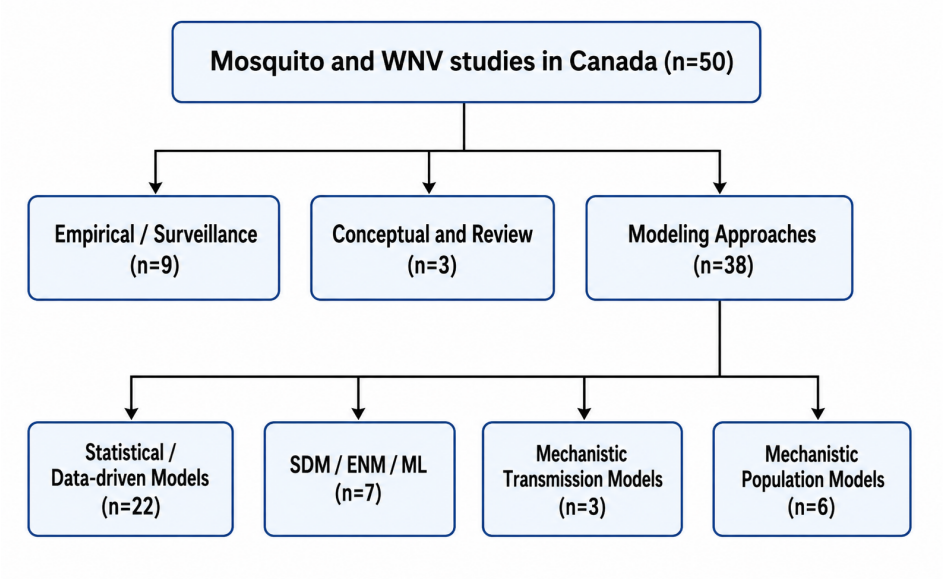

Figure 2: Classification of included studies on mosquito dynamics, vector distribution, and West Nile virus risk in Canada based on the final synthesis set ($n = 50$). Each study was assigned to a single category according to its dominant study design or modeling approach.

3.3.1 Surveillance and Empirical Studies

Empirical or surveillance studies accounted for 9 of the 50 included studies (18.0%) (Shahhosseini et al., 2020, Lowe et al., 2021, Pan et al., 2025, Shahhosseini et al., 2021, Roth et al., 2010, Stephen et al., 2006, Chaulk et al., 2016, Hollett et al., 2025, Villeneuve et al., 2025). These studies relied on field-based mosquito monitoring, trapping, species identification, molecular identification, citizen-science sampling, vector infection testing, and ecological or surveillance data to describe mosquito species composition, seasonal abundance patterns, host-feeding patterns, occurrence, vector distribution, and mosquito-borne virus detection in Canada.

The studies documented variation in mosquito communities across study locations and seasons. Reported outcomes included mosquito species presence, relative abundance, seasonal activity, detection of invasive or emerging vector species, WNV activity, potential WNV vector distributions, and detection of other mosquito-borne viruses such as Jamestown Canyon virus and snowshoe hare virus. These studies provided observational evidence on mosquito ecology, vector occurrence, and MBD risk, but generally did not include predictive or mechanistic modeling frameworks.

3.3.2 Conceptual and Review-Based Studies

Conceptual and review-based studies accounted for 3 of the 50 included studies (6.0%) (Zheng et al., 2014, Ng et al., 2019, Ludwig and Lapen, 2025). These studies synthesized existing knowledge on mosquito ecology, WNV risk, surveillance practices, environmental drivers, climate change, and MBD risk in Canada.

The reviewed studies discussed temperature, precipitation, seasonality, land use, surveillance capacity, and climate change in relation to mosquito abundance, vector distribution, transmission risk, and potential future shifts in MBD patterns. These studies did not con-

tribute quantitative model outputs to the synthesis, but provided background context on MBD risk, environmental determinants, and public health relevance in Canada.

3.3.3 Statistical and Data-Driven Models

Statistical and data-driven approaches represented the largest modeling category, accounting for 22 of the 50 included studies (44.0%) and 22 of the 38 quantitative modeling studies (57.9%) (Gizaw et al., 2025, Giordano et al., 2017, Albrecht and Kaufeld, 2023, Chen et al., 2013, Tam and Tsuji, 2016, Mallya et al., 2018, Ludwig et al., 2023, Baril et al., 2023, Ripoche et al., 2019, Wang et al., 2011, Temple et al., 2022, Rakotoarinia et al., 2022, Giordano et al., 2018, Yoo, 2014, Lysyk, 2010, Yoo, 2013, Gao et al., 2017, Rocheleau et al., 2017, Chen et al., 2014, Jackson et al., 2013, Wang et al., 2014, Ducrocq et al., 2022). These studies used regression-based, Bayesian, spatiotemporal, clustering, occupancy, and forecasting approaches to analyze mosquito abundance, vector infection, human disease occurrence, and environmental risk.

Temperature and precipitation were the most frequently incorporated environmental variables, often represented using lagged weather terms. Several studies also included land use, vegetation, demographic, socioeconomic, or spatial variables. Reported outcomes included mosquito abundance, WNV infection rates, vector presence, human disease risk, spatial clustering, and short-term forecasts of mosquito or infection activity.

Most statistical and data-driven studies represented mosquito or disease outcomes as functions of environmental, spatial, epidemiological, or surveillance-derived predictors. Explicit mosquito life-cycle processes, including development, mortality, reproduction, density dependence, overwintering, and diapause, were generally not represented within the model structure.

3.3.4 Species Distribution, Ecological Niche, and Machine-Learning Models

Species distribution, ecological niche, and machine-learning models accounted for 7 of the 50 included studies (14.0%) and 7 of the 38 quantitative modeling studies (18.4%) (Hongoh et al., 2012, Moua et al., 2021, Gorris et al., 2021, Talbot et al., 2023, 2024, Khan et al., 2020, Nair et al., 2025). These studies used occurrence records, surveillance data, environmental predictors, climate variables, land-cover data, or machine-learning methods to characterize mosquito distribution, habitat suitability, geographic risk, and potential range expansion.

The main outcomes were maps or estimates of mosquito occurrence, ecological suitability, vector distribution, WNV-related spatial risk, and projected suitability under current or future environmental conditions. These models represented mosquito occurrence or suitability as a function of environmental and spatial predictors. Seasonal population dynamics, immature-stage processes, and mosquito life-history mechanisms were generally not explicitly represented.

3.3.5 Mechanistic Transmission Models

Mechanistic transmission models accounted for 3 of the 50 included studies (6.0%) and 3 of the 38 quantitative modeling studies (7.9%) (Cisse et al., 2025, Cissé et al., 2024, Bouden et al., 2008). These studies represented WNV transmission processes involving mosquito vectors and vertebrate hosts, with a focus on host–vector infection dynamics, spatial heterogeneity, and transmission risk.

These studies used spatially explicit mechanistic frameworks, including host–vector transmission and geosimulation approaches, to examine WNV transmission under heterogeneous ecological, landscape, or climatic conditions. The modeled outcomes included transmission dynamics, infection spread, and amplification patterns across host and vector populations. Mosquito populations were represented in relation to the transmission process, while detailed mosquito life-cycle processes such as immature-stage development, density dependence, and diapause were not the main focus of these models.

3.3.6 Mechanistic Population Models

Mechanistic mosquito population models accounted for 6 of the 50 included studies (12.0%) and 6 of the 38 quantitative modeling studies (15.8%) (Yu et al., 2018, Frantz et al., 2024, Shutt et al., 2022, Mancuso et al., 2023, Tachiiri et al., 2006, Abdelrazec and Gumel, 2017). These studies used process-based or dynamical modeling approaches to represent mosquito abundance, population dynamics, or vector-related risk processes.

The reviewed mechanistic population models varied in structure and biological detail. Some studies represented temperature-dependent mosquito abundance or seasonal population dynamics (Yu et al., 2018), while others used age- or stage-structured formulations to describe mosquito development and population change (Frantz et al., 2024, Shutt et al., 2022, Abdelrazec and Gumel, 2017). A subset incorporated multiple environmental drivers, including temperature, rainfall, or water-related habitat processes (Shutt et al., 2022, Abdelrazec and Gumel, 2017). Other studies linked mosquito population dynamics or vector processes with spatial risk assessment or data-fusion approaches (Tachiiri et al., 2006, Mancuso et al., 2023).

Across this category, modeled outcomes included mosquito abundance, seasonal dynamics, population trajectories, and vector-related risk. The level of biological detail differed across studies, ranging from temperature-driven abundance models to structured population frameworks incorporating life-stage progression or environmental forcing.

The reviewed modeling approaches differed in their objectives, data sources, environmental drivers, biological structure, and modeled outcomes. Table 1 provides a comparative summary of the major modeling frameworks identified in this review.

3.4 Representation of Environmental Drivers and Biological Processes

The included studies varied in how environmental drivers and biological processes were represented across study categories. Table 2 summarizes the representation of key system components, including temperature, precipitation, seasonality, life-cycle processes, diapause, transmission, stochasticity, and spatial structure. Figure 3 shows the combinations of climate drivers incorporated across study categories.

Temperature was represented across all study categories, either alone or in combination with precipitation and seasonal variables. In statistical and data-driven studies, temperature was commonly included as an explanatory or predictive variable, often alongside lagged precipitation or seasonal terms (Wang et al., 2011, Chen et al., 2013, Ripoche et al., 2019, Baril et al., 2023, Gizaw et al., 2025). Species distribution, ecological niche, and machine-learning studies incorporated temperature mainly as part of environmental suitability, climate suitability, or distributional predictor sets (Hongoh et al., 2012, Moua et al., 2021, Gorris et al.,

Table 1: Summary of modeling approaches identified among quantitative modeling studies included in the review ($n = 38$). The table summarizes the main model classes, representative approaches, outcomes, environmental or data inputs, and commonly represented model components.

Model class	**Representative approaches**	**Main outcomes**	**Environmental or data inputs**	**Model representation**	**Less explicit components**
Statistical and data-driven models ($n = 22$)	GLM, GLMM, negative binomial regression, Bayesian models, occupancy models, clustering, spatiotemporal models, forecasting models	Mosquito abundance; vector presence; WNV infection rates; human disease risk; spatial clustering; short-term forecasts	Temperature; precipitation; lagged weather variables; land use; vegetation; demographic, socioeconomic, surveillance, and epidemiological data	Mosquito or disease outcomes represented as functions of environmental, spatial, epidemiological, or surveillance-derived predictors	Mosquito life-cycle processes, density dependence, immature-stage dynamics, overwintering, and diapause generally not represented explicitly
Species distribution, ecological niche, and machine-learning models ($n = 7$)	Species distribution models, ecological niche models, habitat suitability models, machine-learning classifiers, climate suitability models	Mosquito occurrence; habitat suitability; geographic distribution; vector suitability; projected range expansion	Occurrence records; surveillance data; climate variables; land cover; environmental suitability predictors	Mosquito occurrence or suitability represented as a function of environmental and spatial predictors	Seasonal abundance dynamics, population processes, immature stages, and transmission dynamics generally not represented explicitly
Mechanistic transmission models ($n = 3$)	Compartmental host–vector models; multi-agent geosimulation; spatially explicit host–vector transmission models; cellular automata frameworks	WNV transmission dynamics; infection spread; amplification patterns; spatial transmission risk; intervention or larvicide scenarios	Host and vector information; landscape or ecological heterogeneity; spatial structure; climate scenarios; surveillance and literature-derived parameters	Transmission represented through interactions among mosquito vectors, vertebrate hosts, and spatial, ecological, or climatic conditions	Detailed mosquito life-cycle processes, immature-stage dynamics, density dependence, and diapause not the main focus
Mechanistic mosquito population models ($n = 6$)	Temperature-driven abundance models; stage-structured models; age-structured models; process-based population models; data-fusion frameworks	Mosquito abundance; seasonal dynamics; population trajectories; life-stage progression; vector-related risk	Temperature; rainfall or water-related variables; habitat availability; photoperiod or seasonal forcing in some models; surveillance or biological data	Mosquito population change represented through biological processes such as development, survival, reproduction, stage structure, or environmental forcing	Spatial structure, stochasticity, validation, and multi-driver environmental forcing not consistently represented across studies

2021, Khan et al., 2020, Talbot et al., 2023, Nair et al., 2025). Mechanistic transmission and mechanistic population models represented temperature in relation to transmission processes, mosquito abundance, development, survival, or population dynamics (Yu et al., 2018, Frantz et al., 2024, Shutt et al., 2022, Abdelrazec and Gumel, 2017, Cissé et al., 2024, Cisse et al., 2025, Bouden et al., 2008).

Precipitation was also included in several study categories, although its form of representation varied. In statistical and data-driven models, precipitation was generally included as a weather or lagged environmental predictor. In species distribution, ecological niche, and machine-learning models, precipitation was included as part of environmental or climatic suitability predictors. In mechanistic mosquito population models, rainfall, precipitation, or water-related variables were represented across this category, although their form varied across studies and was often incorporated through habitat availability, carrying capacity, or related population processes (Shutt et al., 2022, Abdelrazec and Gumel, 2017). In mechanistic transmission modeling, climatic conditions were also incorporated in the geosimulation framework used to examine WNV propagation and intervention scenarios (Bouden et al., 2008). As shown in Figure 3, precipitation appeared in combination with temperature, either with or without seasonal processes.

Seasonal processes were represented through seasonal terms, lagged weather variables, climate suitability measures, photoperiod, diapause, or explicit seasonal forcing. Statistical and data-driven studies commonly incorporated seasonality through temporal predictors or lagged weather terms. Mechanistic mosquito population models included seasonal processes through temperature-dependent development, stage or age structure, seasonal forcing, or diapause-related processes in selected studies (Yu et al., 2018, Frantz et al., 2024, Shutt et al., 2022). Mechanistic transmission studies represented seasonal, spatial, or climatic variation in relation to WNV transmission dynamics (Cissé et al., 2024, Cisse et al., 2025, Bouden et al., 2008).

Representation of mosquito biological processes differed across model classes. Mechanistic mosquito population models provided the most explicit representation of mosquito population processes, including development, survival, reproduction, age or stage structure, environmental forcing, or population trajectories (Yu et al., 2018, Frantz et al., 2024, Shutt et al., 2022, Mancuso et al., 2023, Abdelrazec and Gumel, 2017). Statistical, species distribution, ecological niche, machine-learning, and transmission models more commonly represented mosquito-related outcomes as abundance, occurrence, suitability, infection risk, or transmission-related quantities rather than as explicit mosquito life-cycle processes.

Spatial structure was represented in empirical or surveillance studies, statistical and data-driven models, species distribution or ecological niche models, machine-learning models, and spatial transmission models. Explicit stochastic representations were less common across the modeling literature and were identified only in a limited subset of process-based or data-fusion approaches.

Table 2: Representation of key environmental drivers and biological processes across study categories identified in the review. Symbols indicate the extent of representation: ✓ = explicit representation; P = partial or indirect representation; L = limited or inconsistent representation across studies; × = not represented. For empirical/surveillance and conceptual/review studies, symbols refer to whether the component was assessed or discussed rather than formally modeled.

Study category	**Temp**	**Precip**	**Seasonal**	**Life-cycle**	**Diapause**	**Transmission**	**Stoch.**	**Spatial**
Empirical/Surveillance	✓	P	✓	×	×	P[d]	×	✓
Conceptual/Review	✓	✓	✓	P	P	P	×	P
Statistical/Data-driven	✓	✓[a]	✓	×	×	P[b]	×	✓
SDM/ENM/ML	✓	✓	P	×	×	×	×	✓
Mechanistic Transmission	✓	✓	✓	×	×	✓	×	✓
Mechanistic Population	✓	✓[c]	✓	✓	P	×	L	L

[a] Precipitation was commonly included as an empirical or lagged environmental predictor.
[b] Represents statistical prediction of vector infection or human disease risk rather than explicit host–vector transmission dynamics.
[c] Rainfall, precipitation, or water-related variables were represented across mechanistic population models, although their form varied across studies and was often incorporated through habitat availability, carrying capacity, or related population processes.
[d] Represents observational evidence of WNV activity, vector infection, mosquito-borne virus detection, or disease-risk relevance rather than explicit host–vector transmission modeling.

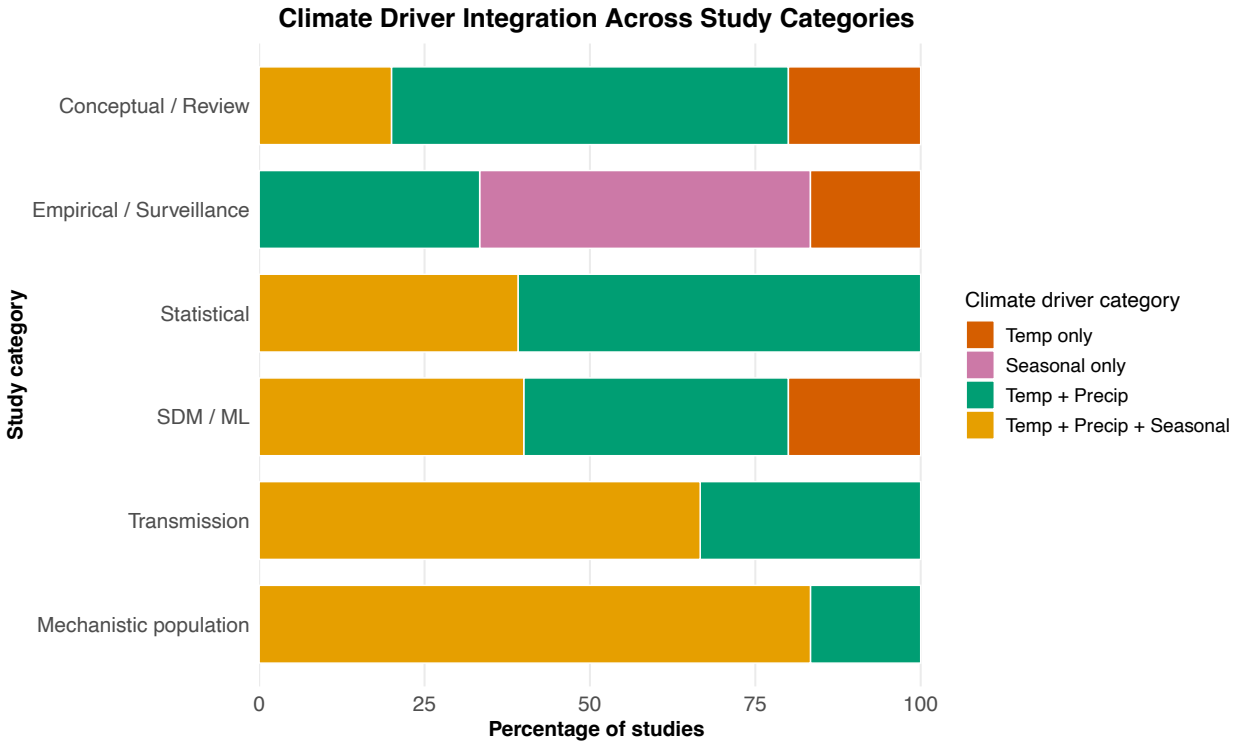

Figure 3: Integration of climate drivers across study categories. Bars represent the percentage of studies within each category that incorporated different combinations of environmental drivers, including temperature, precipitation, and seasonal processes such as photoperiod, diapause, or seasonal forcing. The categories shown are temperature only, seasonal only, temperature with precipitation, and temperature with precipitation and seasonal processes.

3.5 Data–Model Alignment

The reviewed studies showed distinct patterns in the types of data used across study categories. Figure 4 summarizes the percentage of studies within each category that used different data types, while Table 3 provides a comparative overview of common data sources, applications, and data-use patterns.

Climate data were used across all study categories and were the most consistently represented data type. Trap-count data and validation data were also frequently used, particularly in statistical/data-driven models, mechanistic transmission models, and mechanistic mosquito population models. Statistical/data-driven studies commonly combined trap counts, climate variables, land-cover or GIS data, epidemiological records, validation data, and vector infection data to analyze mosquito abundance, vector infection, human disease risk, spatial clustering, or short-term forecasts (Wang et al., 2011, Chen et al., 2013, Ripoche et al., 2019, Temple et al., 2022, Ducrocq et al., 2022).

Species distribution, ecological niche, and machine-learning studies relied mainly on climate data, occurrence or presence records, land-cover or GIS layers, trap counts, and validation data. These data were used to estimate mosquito occurrence, habitat suitability, ecological niches, vector distribution, and projected range expansion (Hongoh et al., 2012, Moua et al., 2021, Gorris et al., 2021, Talbot et al., 2023, Khan et al., 2020, Nair et al., 2025).

Mechanistic transmission models used climate data, epidemiological information, literature-derived parameters, trap counts, validation data, and vector infection data to represent WNV transmission dynamics and spatial transmission risk (Cissé et al., 2024, Cisse et al., 2025). Mechanistic mosquito population models used climate data, trap counts, validation data, laboratory trait data, literature-derived parameters, and, in some cases, land-cover or GIS data to represent mosquito abundance, seasonal dynamics, population trajectories, and life-stage progression (Yu et al., 2018, Frantz et al., 2024, Shutt et al., 2022, Mancuso et al., 2023, Abdelrazec and Gumel, 2017).

Non-modeling studies used climate data, surveillance records, trap counts, literature sources, and vector occurrence or species detection records. These studies contributed descriptive or review-based information on mosquito ecology, vector occurrence, surveillance patterns, WNV risk, and climate-related disease concerns (Shahhosseini et al., 2020, Lowe et al., 2021, Pan et al., 2025, Zheng et al., 2014, Ng et al., 2019, Ludwig and Lapen, 2025).

Overall, the heatmap shows that climate data were common across categories, while other data types were more concentrated in specific study groups. Laboratory trait data were most evident in mechanistic mosquito population models, vector infection data were most evident in statistical and transmission models, and occurrence or presence data were most evident in species distribution, ecological niche, and machine-learning models.

Table 3: Data–model alignment across reviewed study categories. The table summarizes the main data sources, common applications, and data-use patterns identified across non-modeling studies and quantitative modeling approaches.

Study category	**Common data sources**	**Main applications**	**Data-use pattern**	**Data coverage notes**
Non-modeling studies ($n = 12$)	Climate data; trap counts; surveillance records; literature sources; vector occurrence or species detection records; molecular identification or virus detection data in some studies	Description or synthesis of mosquito ecology, vector occurrence, surveillance patterns, WNV risk, mosquito-borne virus detection, and climate-related disease concerns	Primarily descriptive or review-based use of surveillance, ecological, climatic, molecular, and public health information	Data sources varied, with review studies relying mainly on published literature and empirical studies using field collections, trap data, molecular identification, or virus screening.
Statistical/data-driven models ($n = 22$)	Climate data; trap counts; validation data; land cover or GIS data; epidemiological cases; vector infection data in some studies	Analysis of mosquito abundance, vector presence, WNV infection rates, human disease risk, spatial clustering, and short-term prediction	Surveillance and environmental data were commonly linked through regression, Bayesian, spatiotemporal, clustering, occupancy, or forecasting models	Data use was concentrated on adult mosquito surveillance, climate variables, and observed disease or infection records; immature-stage and trait data were rarely used
SDM/ENM/ML models ($n = 7$)	Climate data; occurrence or presence records; land cover or GIS layers; trap counts; validation data	Mapping mosquito occurrence, habitat suitability, ecological niches, vector distribution, and projected range expansion	Occurrence, environmental, and spatial data were used to estimate suitability or distribution patterns across geographic areas	Models relied mainly on presence or occurrence records and environmental predictors; abundance, life-stage, and transmission data were generally not included
Mechanistic transmission models ($n = 3$)	Climate data; epidemiological data; literature parameters; trap counts; validation data; vector infection data	Representation of WNV transmission dynamics, infection spread, amplification patterns, and spatial transmission risk	Host–vector transmission processes were represented using ecological, epidemiological, spatial, and literature-derived information	Transmission-related data were used more directly than life-history data; detailed mosquito population data were not the main data source
Mechanistic mosquito population models ($n = 6$)	Climate data; trap counts; validation data; laboratory trait data; literature parameters; land cover or GIS data in some studies	Representation of mosquito abundance, seasonal dynamics, population trajectories, life-stage progression, and vector-related risk	Biological and environmental information was used to represent development, survival, reproduction, stage or age structure, and environmental forcing	Models often used literature or laboratory-derived parameters together with climate or surveillance data; field data for immature stages and local life-history processes were limited

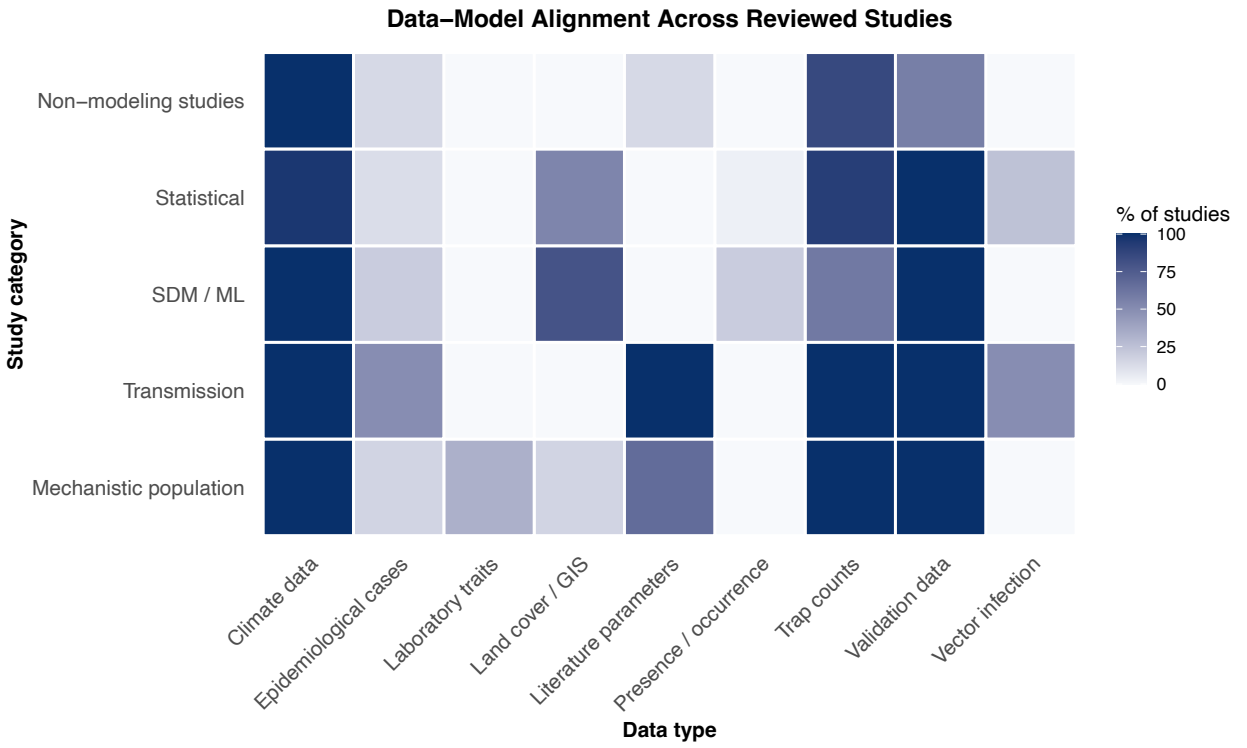

Figure 4: Data–model alignment across reviewed study categories. Cell shading indicates the percentage of studies within each category that incorporated a given data type, with darker shading representing greater use. The figure summarizes variation in data-source use across non-modeling studies and quantitative modeling approaches.

3.6 Data-Source Breadth Across Study Categories

Data-source breadth varied across study categories (Figure 5). The mean number of data types was lowest among conceptual/review studies, followed by empirical/surveillance studies, which generally relied on literature synthesis, surveillance records, occurrence information, climate data, or trap-count data. Quantitative modeling studies generally incorporated a broader range of data inputs.

Among the modeling categories, mechanistic transmission models had the highest mean number of data types, followed by mechanistic mosquito population models. Statistical/data-driven models and SDM/ENM/ML models showed similar average data-source breadth, reflecting the use of climate data, trap counts or occurrence records, spatial predictors, validation data, and, in some cases, epidemiological or vector infection data.

The variability in data-source breadth also differed across categories. Conceptual/review, statistical/data-driven, SDM/ENM/ML, transmission, and mechanistic population categories showed variation in the number of data types incorporated across studies, while empirical/surveillance studies showed less variation in this metric. The data-source breadth score summarizes the number of distinct data types used in each study and does not evaluate data quality, sample size, spatial resolution, temporal coverage, or suitability for model calibration and validation.

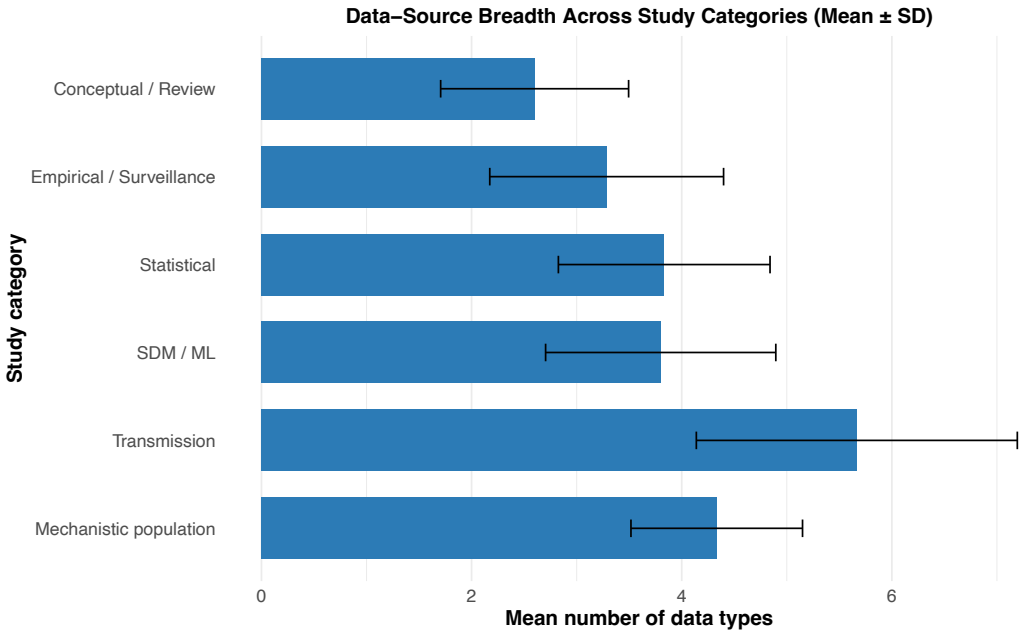

Figure 5: Data-source breadth across study categories identified in the review. Data-source breadth is defined as the number of distinct data types incorporated within a study, including climate data, mosquito trap counts, epidemiological case data, land-cover or GIS information, laboratory-derived trait data, literature-derived parameters, vector infection data, and validation datasets. Bars represent the mean number of data types used within each study category, and error bars indicate one standard deviation. The score measures breadth of data inputs only and does not assess data quality, sample size, spatial resolution, temporal coverage, representativeness, or suitability for model calibration and validation.

3.7 Model Support and Transparency

Model support and transparency indicators were assessed for the 38 studies that included a quantitative modeling component. These indicators summarized reporting of calibration, validation, uncertainty analysis, sensitivity analysis, code or data availability, biological mechanism representation, and out-of-sample prediction. Climate projection assumptions were extracted where applicable. Spatial scale and temporal resolution were also extracted and retained in Supplementary Table S1, but were not included in Figure 6 or Table 4 because they were treated as descriptive reporting fields rather than model-support indicators.

Calibration was the most frequently reported indicator. Thirty-one of the 38 modeling studies reported calibration or model fitting using observed data, three provided partial calibration, and four did not report calibration. Independent validation was reported in 18 studies, partially reported in five studies, and not reported in 15 studies. Out-of-sample prediction showed a similar distribution, with 18 studies reporting predictive testing using independent or withheld data, one study providing partial evidence of predictive assessment, and 19 studies not reporting out-of-sample testing (Figure 6).

Uncertainty and sensitivity analyses were reported less consistently. Nine studies included clear uncertainty analysis, 23 provided partial uncertainty information, and six did not report uncertainty analysis. Sensitivity analysis was reported in eight studies, partially addressed in 15 studies, and absent in 15 studies. Code or data availability was clearly reported in six studies, partially reported in 19 studies, and not reported in 13 studies.

Model support and transparency indicators also varied by model class (Table 4). Calibration was coded as *Yes* for 19 of 22 statistical/data-driven models, 7 of 7 SDM/ENM/ML models, 3 of 3 mechanistic transmission models, and 2 of 6 mechanistic population models. Independent validation and out-of-sample prediction were most frequently coded as *Yes* among statistical/data-driven and SDM/ENM/ML models. Biological mechanisms were coded as *Yes* for all three mechanistic transmission models and five of six mechanistic population models, but were not coded as *Yes* for statistical/data-driven or SDM/ENM/ML models. Climate projection assumptions were applicable only to studies with future climate or scenario projections and were assessed separately in the supplementary extraction table.

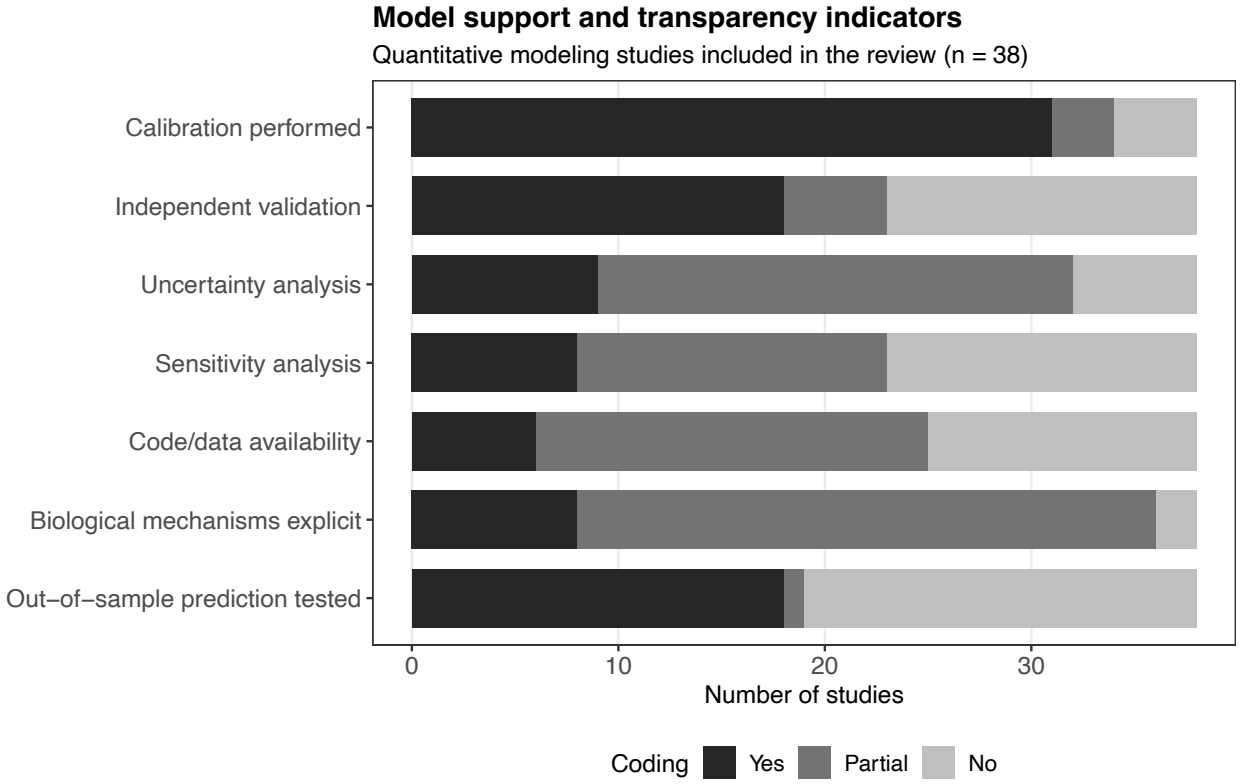

Figure 6: Distribution of model support and transparency indicators among quantitative modeling studies included in the review ($n = 38$). Bars show the number of studies coded as *Yes*, *Partial*, or *No* for each indicator. Climate projection assumptions are not shown because this indicator was applicable only to studies that included future climate or scenario projections.

Table 4: Model support and transparency indicators by model class among quantitative modeling studies included in the review ($n = 38$). Cell values indicate studies coded as *Yes* over the total number of studies in each model class.

Indicator	**Statistical** ($n = 22$)	**SDM/ENM/ML** ($n = 7$)	**Transmission** ($n = 3$)	**Population** ($n = 6$)
Calibration	19/22	7/7	3/3	2/6
Independent validation	11/22	6/7	0/3	1/6
Uncertainty analysis	5/22	3/7	1/3	0/6
Sensitivity analysis	2/22	2/7	1/3	3/6
Code/data available	3/22	3/7	0/3	0/6
Biological mechanisms	0/22	0/7	3/3	5/6
Out-of-sample prediction	11/22	6/7	0/3	1/6

Note: Statistical = statistical/data-driven models; SDM/ENM/ML = species distribution, ecological niche, or machine-learning models; Transmission = mechanistic transmission models; Population = mechanistic mosquito population models. Only indicators coded as *Yes* are shown. Partial support is described in the text and retained in the supplementary extraction table. Climate projection assumptions are omitted because they applied only to studies with future climate or scenario projections. Operational definitions for *Yes*, *Partial*, *No*, and *Not applicable* coding are provided in Supplementary Table S3, and study-level coding is provided in Supplementary Table S1.

3.8 Geographic Coverage

The geographic distribution of included studies was uneven across Canada (Figure 7). Ontario accounted for the largest number of studies ($n = 21$), followed by national-scale studies ($n = 12$). Studies from Ontario included statistical, spatial, mechanistic population, surveillance, and WNV risk analyses (Talbot et al., 2024, Mallya et al., 2018, Gao et al., 2017, Yu et al., 2018, Wang et al., 2011), while national-scale studies included climate suitability, vector distribution, and review-based analyses (Khan et al., 2020, Ng et al., 2019, Gorris et al., 2021, Nair et al., 2025).

Fewer studies were identified for Quebec ($n = 6$), the Prairie provinces ($n = 4$), British Columbia ($n = 4$), Atlantic Canada ($n = 2$), and northern Canada ($n = 1$). Quebec studies included mosquito surveillance, abundance mapping, short-term forecasting, and mechanistic WNV geosimulation studies (Ludwig et al., 2023, Shahhosseini et al., 2020, Ripoche et al., 2019, Bouden et al., 2008). Prairie studies included weather-driven mosquito abundance and WNV-related analyses (Baril et al., 2023, Chen et al., 2013, 2014). British Columbia studies included WNV range expansion, potential WNV vector distribution, spatial risk assessment, and mosquito habitat-related modeling (Roth et al., 2010, Stephen et al., 2006, Tachiiri et al., 2006, Jackson et al., 2013). Atlantic Canada and northern Canada were represented by a small number of empirical or surveillance studies (Chaulk et al., 2016, Hollett et al., 2025, Villeneuve et al., 2025).

Overall, the literature remained concentrated in Ontario and national-scale analyses. The inclusion of Atlantic and northern surveillance studies indicates that these regions are not entirely absent from the Canadian mosquito and MBD literature. However, eligible quantitative modeling studies for Atlantic Canada and northern Canada were not identified in the final synthesis.

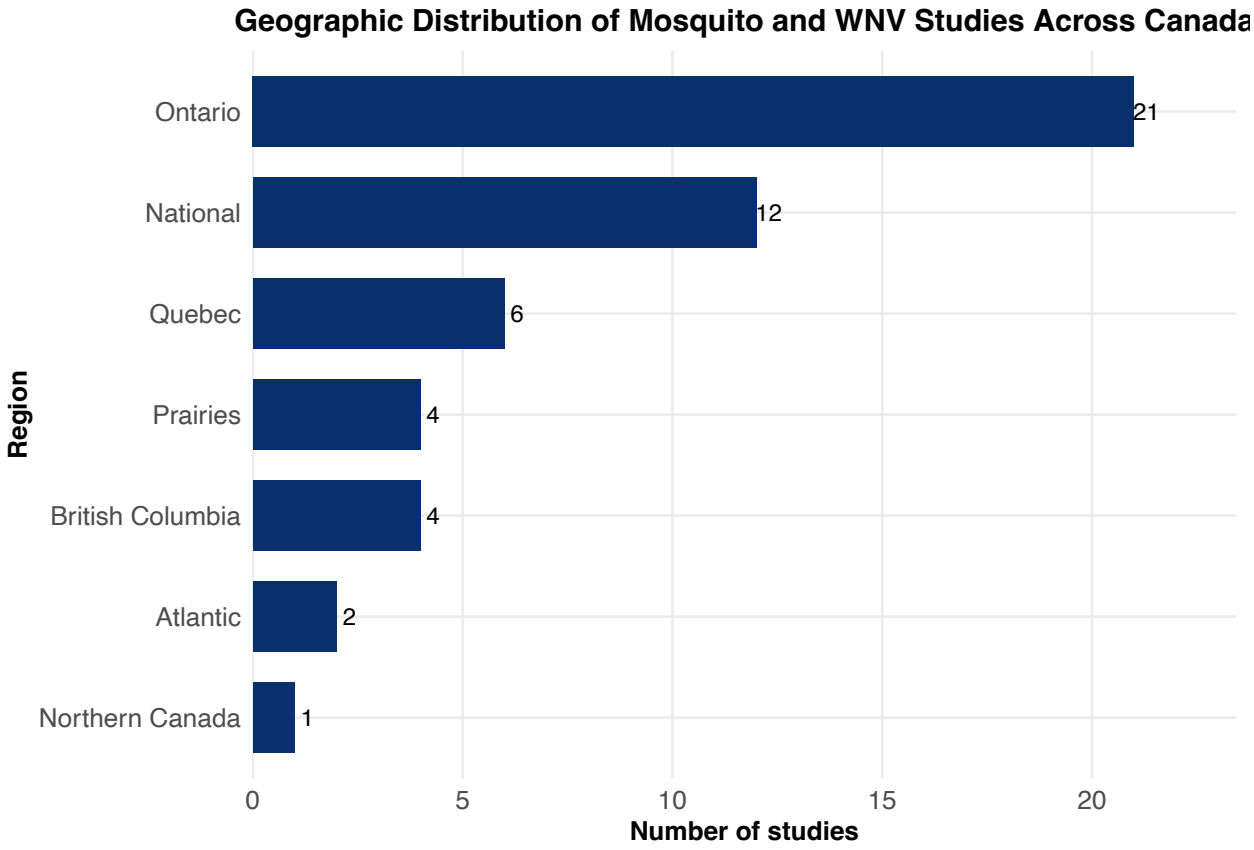

Figure 7: Geographic distribution of mosquito and West Nile virus studies across Canada. Bars indicate the number of included studies assigned to each region or to the national-scale category. Atlantic Canada and northern Canada were represented by a small number of empirical or surveillance studies, but no eligible quantitative modeling studies were identified for these regions.

3.9 Key Patterns and Consistent Findings

Several recurring patterns were observed across the reviewed literature. Temperature was the most frequently represented environmental driver and appeared across statistical/data-driven, SDM/ENM/ML, mechanistic transmission, mechanistic population, empirical/surveillance, and conceptual/review studies. It was used as a predictor of mosquito abundance, occurrence, suitability, infection risk, or population dynamics, depending on the study approach (Wang et al., 2011, Chen et al., 2013, Yu et al., 2018, Shutt et al., 2022, Frantz et al., 2024, Abdelrazec and Gumel, 2017, Bouden et al., 2008).

Precipitation was also commonly represented, most often in combination with temperature. Statistical and data-driven studies typically included precipitation as a weather or lagged environmental predictor, while mechanistic population models represented rainfall, precipitation, or water-related variables through habitat availability, carrying capacity, or related population processes (Ripoche et al., 2019, Baril et al., 2023, Gizaw et al., 2025, Shutt et al., 2022, Abdelrazec and Gumel, 2017). Mechanistic transmission modeling also incorporated climatic conditions in relation to WNV propagation and intervention scenarios (Bouden et al., 2008).

Species-specific responses were reported across several study types. WNV-focused studies primarily involved *Culex* species or species complexes, while studies of emerging vector suitability and broader mosquito surveillance included *Aedes* species and other mosquito taxa relevant to Canadian vector monitoring. Reported outcomes included species occurrence, abundance, habitat suitability, vector distribution, vector infection, mosquito-borne virus detection, and projected range expansion (Baril et al., 2023, Gorris et al., 2021, Talbot et al., 2023, Khan et al., 2020, Nair et al., 2025, Roth et al., 2010, Stephen et al., 2006, Chaulk et al., 2016, Hollett et al., 2025, Villeneuve et al., 2025).

Seasonality was represented through lagged weather variables, temporal predictors, seasonal forcing, photoperiod, diapause-related processes, or climate suitability measures. Statistical models commonly incorporated seasonal or lagged effects, while mechanistic population and transmission models represented seasonal variation through climate-dependent processes or seasonal transmission dynamics (Wang et al., 2011, Ripoche et al., 2019, Yu et al., 2018, Frantz et al., 2024, Cissé et al., 2024, Cisse et al., 2025, Bouden et al., 2008).

Across the results, the most consistent patterns were the frequent use of temperature, the common pairing of temperature with precipitation, the species-specific nature of mosquito outcomes, and the repeated representation of seasonal variation across study approaches.

4 Discussion

Canada needs integrated, climate-informed, and surveillance-calibrated mosquito and WNV models that connect stage-structured mosquito population dynamics with rainfall–habitat processes, diapause and overwintering, stochastic environmental variability, vector infection, host exposure, and transmission risk. This review situates that need within the existing Canadian literature by identifying where current empirical, statistical, spatial, mechanistic, and surveillance-based approaches are strongest, where they remain fragmented, and which components should be integrated in future mosquito, WNV, and emerging MBD risk models.

4.1 Overview of Main Findings

This systematic mapping review shows that mosquito and West Nile virus (WNV) research in Canada has developed through a diverse but fragmented set of empirical, statistical, spatial, mechanistic, and review-based approaches. The reviewed literature was dominated by WNV-focused studies, with most quantitative modeling work centered on *Culex* mosquitoes and their relationships with environmental conditions, vector infection, or human disease risk. The review also identified a small number of empirical or surveillance studies addressing broader mosquito-borne virus detection and vector surveillance, particularly in Atlantic and northern Canada. Among the 50 included studies, statistical/data-driven models formed the largest modeling category, followed by species distribution, ecological niche, or machine-learning models, mechanistic mosquito population models, and mechanistic transmission models.

The synthesis identified several cross-cutting patterns. Temperature was the most consistently represented environmental driver, while precipitation was also commonly included, although its form of representation varied across study categories. Seasonal processes were represented in different ways, including lagged predictors, seasonal forcing, photoperiod, diapause, and climate suitability measures. The review also showed that data use, model support, and reporting transparency varied across modeling approaches. Calibration was frequently reported, but independent validation, sensitivity analysis, uncertainty analysis, out-of-sample testing, and code or data availability were less consistently documented.

Taken together, these findings suggest that empirical prediction and spatial risk mapping are more developed in the Canadian literature than integrated process-based frameworks that jointly represent mosquito ecology, environmental variability, surveillance data, and transmission risk.

4.2 Empirical Prediction and Integrated Process-Based Risk Modeling

The Canadian mosquito and WNV modeling literature is methodologically diverse, but empirical prediction and spatial risk mapping are more developed than integrated process-based risk modeling. Statistical and data-driven models have supported analyses of mosquito abundance, vector infection, human disease occurrence, seasonal trends, spatial clustering, and short-term prediction, particularly where mosquito surveillance, weather, and disease data are available (Wang et al., 2011, Ripoche et al., 2019, Ludwig et al., 2023, Gizaw et al., 2025). Species distribution, ecological niche, and machine-learning models have further contributed spatially explicit insight into mosquito occurrence, habitat suitability, vector distribution, and potential range expansion under current or future climate conditions (Hongoh et al., 2012, Moua et al., 2021, Gorris et al., 2021, Khan et al., 2020, Talbot et al., 2023, Nair et al., 2025).

However, these empirical and spatial approaches generally do not represent the full biological pathway linking climate forcing, immature-stage dynamics, adult abundance, vector infection, and human or animal risk. Mechanistic population and transmission models contribute important biological and transmission detail, but these components are usually developed separately. Mechanistic mosquito population models represent mosquito abundance, development, survival, reproduction, stage structure, or environmental forcing, whereas mechanistic transmission models represent host–vector infection dynamics, spatial transmission risk, or

climate-sensitive WNV propagation (Yu et al., 2018, Frantz et al., 2024, Shutt et al., 2022, Abdelrazec and Gumel, 2017, Cissé et al., 2024, Cisse et al., 2025, Bouden et al., 2008).

As a result, the existing literature contains useful tools for empirical prediction, distribution mapping, mosquito population modeling, and WNV transmission analysis, but few frameworks integrate these components within a unified mosquito population and WNV risk modeling structure. This gap is important because surveillance-based prediction can identify where and when risk may occur, while integrated process-based models are needed to explain how environmental drivers, mosquito life-history processes, vector infection, and transmission risk interact under changing climatic conditions.

4.3 Temperature Representation and Precipitation–Habitat Mechanisms

The strong emphasis on temperature across the reviewed literature is consistent with its central role in mosquito development, survival, reproduction, seasonal activity, and pathogen transmission. Temperature was represented across statistical, spatial, mechanistic population, and transmission modeling approaches, either as an empirical predictor or as a driver of biological or transmission-related processes (Yu et al., 2018, Frantz et al., 2024, Shutt et al., 2022, Abdelrazec and Gumel, 2017, Bouden et al., 2008). This consistency provides a strong foundation for climate-informed modeling, but it also highlights the relative underdevelopment of other mechanisms that mediate mosquito responses to climate, especially rainfall-driven habitat dynamics.

Precipitation was also common, but its representation was less consistent. In statistical models, precipitation was often included as a weather or lagged environmental predictor, while in SDM/ENM/ML studies it was generally treated as part of environmental or climatic suitability. In mechanistic mosquito population models, rainfall, precipitation, or water-related variables were represented across this category, although their form varied across studies and was often incorporated through habitat availability, carrying capacity, or related population processes (Ripoche et al., 2019, Baril et al., 2023, Shutt et al., 2022, Abdelrazec and Gumel, 2017). This suggests that precipitation is recognized as relevant, but its mechanistic connection to larval habitat formation, habitat persistence, water availability, and density dependence remains less developed than temperature-dependent processes.

Biological process representation also varied across model classes. Mechanistic mosquito population models provided the clearest representation of life-history processes, while statistical and SDM/ENM/ML models generally represented mosquito outcomes as abundance, occurrence, suitability, infection risk, or spatial risk. Processes that are especially important in temperate regions, including diapause, overwintering, and spring re-emergence, appeared in only a limited subset of studies (Yu et al., 2018, Frantz et al., 2024, Shutt et al., 2022). This matters because temperate mosquito populations are shaped not only by summer weather conditions, but also by seasonal transitions, overwintering survival, and the timing of population reactivation.

Stochastic environmental variability was another limited component of the reviewed literature. Many models used observed weather data or deterministic climate forcing, while relatively few explicitly represented stochastic variability in rainfall, temperature, demographic processes, or parameter uncertainty. This is relevant for mosquito systems because interannual variation, extreme rainfall, drought, and temperature anomalies can affect mosquito

abundance and disease risk in ways that may not be captured by average seasonal patterns alone.

4.4 Data Availability, Model Choice, and Model Evaluation

The synthesis showed that data availability is closely linked to the types of models developed. Statistical and data-driven studies were strongly connected to mosquito surveillance, trap-count, climate, epidemiological, and validation datasets. SDM/ENM/ML studies relied mainly on occurrence records, environmental layers, climate predictors, land-cover data, and validation data. Mechanistic transmission models used host–vector, epidemiological, climatic, spatial, and literature-derived information to represent WNV transmission dynamics and spatial transmission risk (Cissé et al., 2024, Cisse et al., 2025, Bouden et al., 2008). Mechanistic population models used climate data, laboratory-derived traits, literature parameters, and, in some cases, trap counts or validation datasets (Yu et al., 2018, Frantz et al., 2024, Shutt et al., 2022, Mancuso et al., 2023). Empirical and surveillance studies contributed field collections, trap data, species identification, molecular identification, and virus screening data. These differences indicate that model choice is shaped not only by research objectives, but also by the availability, accessibility, and structure of supporting data.

The data-source breadth analysis adds an additional perspective on this pattern. Mechanistic transmission and mechanistic population models incorporated a relatively broad range of data types on average, but this breadth does not necessarily indicate stronger empirical support. A model may draw on several types of data, including literature parameters, climate records, and contextual datasets, while still having limited local calibration or independent validation. Conversely, a statistical model using fewer data types may be strongly supported if it is fitted and evaluated using long-term, spatially resolved surveillance data. Data-source breadth should therefore be interpreted as a descriptive measure of data diversity rather than as a measure of data quality or evidential strength.

The model support and transparency assessment also distinguished between model fitting and model evaluation. Calibration or model fitting was commonly reported, but independent validation, out-of-sample prediction, sensitivity analysis, uncertainty analysis, and code or data availability were less consistently documented. This distinction is important because a model can reproduce observed patterns without necessarily demonstrating predictive reliability under new conditions or in new locations. Statistical and SDM/ENM/ML studies were more often linked to validation or out-of-sample assessment, whereas mechanistic models more often represented biological mechanisms but were less consistently supported by independent validation or reproducible code and data.

Future modeling work in Canada would benefit from stronger integration between biological structure and empirical evaluation. Mechanistic models would be strengthened by clearer calibration, independent validation, uncertainty analysis, and transparent reporting of code, data, and assumptions. Statistical and spatial models would benefit from stronger incorporation of biological interpretation where appropriate. More generally, distinguishing between data used for calibration, validation, prediction, and contextual interpretation would improve the clarity and comparability of future studies.

Data-integration platforms, including the Canadian Mosquito and MBD Data Portal (CMDP), may help address some of these challenges by improving access to linked environmental, surveillance, geographic, climate-projection, and MBD datasets (Laboratory of Mathematical Parallel Systems (LAMPS), 2025). Platforms of this kind can support more

reproducible and integrated modeling by making relevant data sources easier to locate, compare, and combine.

4.5 Geographic Modeling Capacity and Surveillance Coverage

The geographic distribution of studies was uneven across Canada, with most studies focused on Ontario or national-scale analyses. Fewer studies were identified for Quebec, the Prairie provinces, British Columbia, Atlantic Canada, and northern Canada. The inclusion of Atlantic and northern surveillance studies indicates that these regions are not entirely absent from the Canadian mosquito and MBD literature. However, eligible quantitative modeling studies for Atlantic Canada and northern Canada were not identified in the final synthesis. This pattern indicates that current modeling evidence is shaped largely by regions with more visible surveillance records, public health reporting, or prior research activity.

Uneven geographic coverage is closely related to surveillance availability. Regions with sustained mosquito trapping, vector infection testing, climate data, and public health reporting provide stronger foundations for statistical analysis, spatial modeling, calibration, and validation. In contrast, regions with limited surveillance infrastructure or less accessible data are less likely to be represented in the modeling literature. This relationship between surveillance coverage and model development is especially important in Canada, where mosquito ecology and climate conditions vary substantially across provinces, territories, and ecological zones.

The limited modeling representation of Atlantic and northern Canada is notable in the context of changing climate conditions. Several studies have examined potential changes in mosquito distribution, vector suitability, or range expansion under future climate scenarios (Hongoh et al., 2012, Gorris et al., 2021, Khan et al., 2020, Nair et al., 2025). Recent surveillance studies from Newfoundland and Labrador and northern Canada also show that these regions are relevant to mosquito and mosquito-borne virus surveillance (Chaulk et al., 2016, Hollett et al., 2025, Villeneuve et al., 2025). However, regions that may experience changing mosquito habitat suitability or seasonal conditions are not equally represented in the existing Canadian modeling literature. Expanded surveillance and regionally targeted modeling would improve understanding of mosquito dynamics across a broader range of Canadian environments.

4.6 Toward Integrated Modeling Frameworks

A central implication of this review is that future mosquito and WNV modeling in Canada should move beyond separate, non-integrated modeling approaches toward frameworks that connect surveillance-based prediction, spatial suitability, mechanistic mosquito population dynamics, and host–vector transmission processes.

Integrated frameworks could combine stage-structured mosquito population dynamics with temperature, precipitation, seasonal forcing, diapause, stochastic weather variability, and surveillance-based calibration. These models could also be linked to WNV transmission processes by connecting dynamic mosquito abundance, vector infection, host exposure, environmental drivers, and surveillance data. The conceptual framework in Figure 8 illustrates one possible direction for connecting environmental forcing, mosquito population processes, surveillance data, and disease transmission within a unified modeling structure.

Improved representation of precipitation is a particularly important direction for future mechanistic modeling. Rather than treating precipitation only as an empirical predictor or a simple modifier of carrying capacity, future models could represent rainfall, evaporation, habitat persistence, and larval habitat availability more dynamically. Similarly, diapause and overwintering modules would be useful for modeling temperate mosquito populations, especially where seasonal population persistence and spring emergence influence annual abundance patterns.

The gaps identified in this review can be translated into concrete modeling priorities. Table 5 summarizes recurring limitations in the Canadian literature and corresponding directions for future mosquito and WNV modeling. These directions include improved rainfall–habitat modules, diapause and overwintering processes, coupled mosquito population and WNV transmission models, stochastic environmental forcing, and broader regional calibration across Canada.

4.7 Limitations of the Review

Several limitations should be considered when interpreting the findings of this review. First, the review focused on studies with a direct Canadian component. This focus allowed the synthesis to characterize mosquito, WNV, and MBD research within the Canadian context, but it excluded international studies that may contain modeling approaches or methodological developments relevant to future Canadian applications.

Second, classification of studies into distinct categories required judgment, especially for studies that included elements of more than one approach. To avoid double-counting, each study was assigned to a single category based on its dominant study design or analytical approach. As a result, studies with multiple methodological components may be represented by only one classification label. Screening, extraction, and initial classification were conducted primarily by one reviewer, although the extraction framework, classification outputs, figures, and narrative synthesis were reviewed with the senior author for consistency during manuscript development.

Third, some categories contained relatively few studies, particularly mechanistic transmission models and mechanistic mosquito population models. Findings for these categories should therefore be interpreted as a description of the currently identified Canadian literature rather than as a definitive characterization of all possible modeling approaches.

Fourth, the model support and transparency indicators were descriptive rather than formal quality or risk-of-bias measures. They summarized whether studies reported calibration, validation, uncertainty analysis, sensitivity analysis, code or data availability, biological mechanism representation, out-of-sample prediction, and climate projection assumptions. They did not assess the technical adequacy of each model, the quality of the underlying data, or the correctness of the modeling assumptions.

Finally, the review focused primarily on peer-reviewed studies that met the inclusion criteria. Although six additional eligible studies were identified during final supplementary checking and citation review before manuscript finalization, relevant government reports, surveillance summaries, technical documents, data portals, or other gray literature may not have been fully captured. Despite these limitations, the review provides a structured synthesis of Canadian mosquito, WNV, and MBD studies and identifies recurring methodological, environmental, data-related, and geographic gaps relevant to future model development.

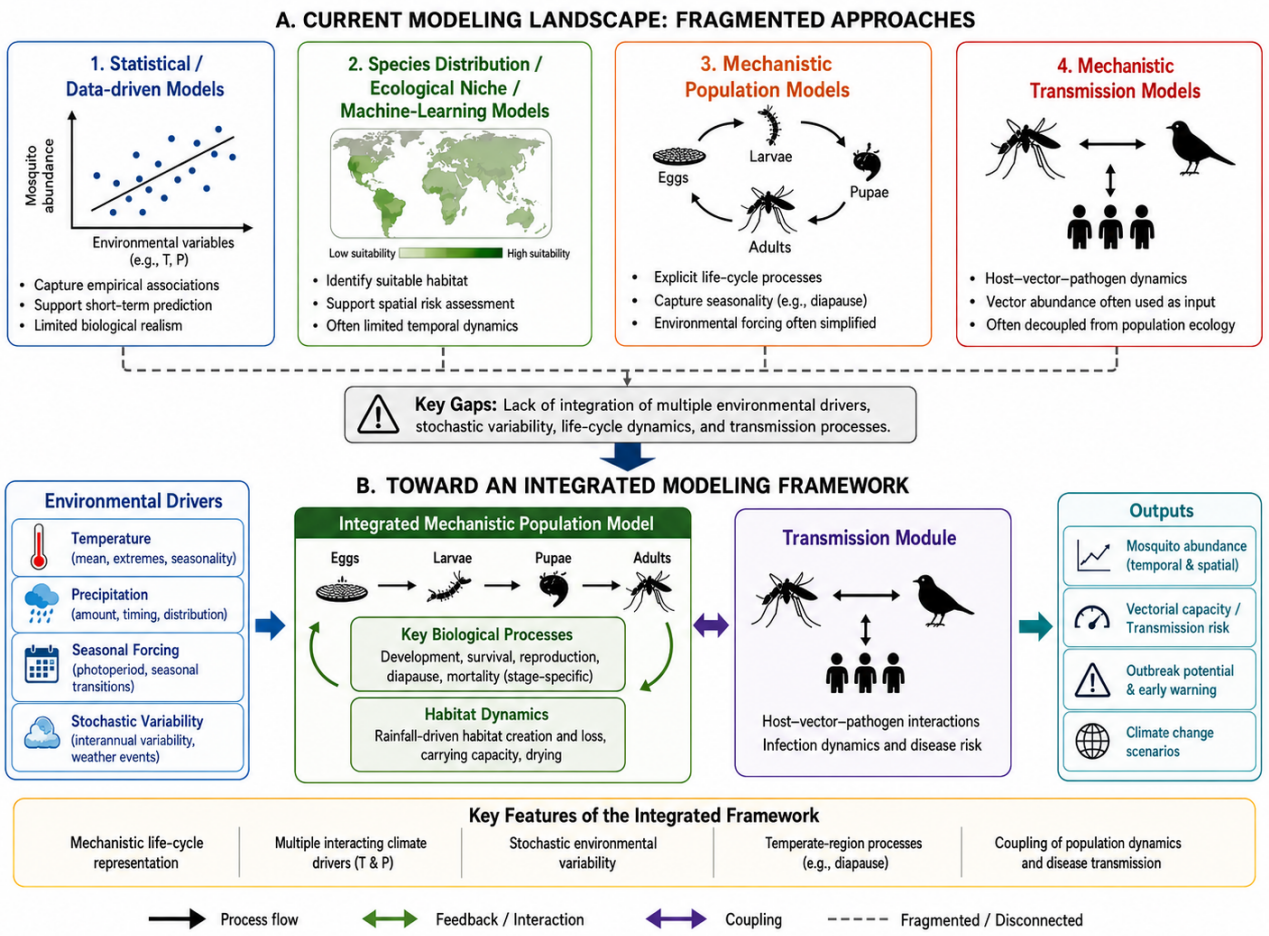

Figure 8: Conceptual illustration of the current fragmented modeling landscape and a proposed integrated framework for mosquito population dynamics and West Nile virus risk. The fragmented landscape summarizes the main quantitative modeling categories identified in the review: statistical/data-driven models, species distribution/ecological niche/machine-learning models, mechanistic mosquito population models, and mechanistic transmission models. Existing approaches capture different components of the mosquito–environment–disease system in isolation, whereas the integrated framework combines mechanistic population dynamics, environmental drivers, stochastic variability, seasonal processes such as diapause, surveillance data, and transmission dynamics.

5 Conclusion

This systematic mapping review synthesizes Canadian studies on mosquito population dynamics, vector distribution, West Nile virus (WNV) risk, and broader MBD risk, with attention to modeling approaches, environmental drivers, biological processes, data sources, model support, and geographic coverage. The reviewed literature included empirical and surveillance studies, conceptual and review-based studies, statistical and data-driven models, species distribution, ecological niche, and machine-learning models, mechanistic transmission models, and mechanistic mosquito population models. Together, these studies show a diverse but fragmented modeling landscape.

Several consistent patterns emerged across the synthesis. Temperature was the most widely represented environmental driver and appeared across all study categories, while precipitation was also commonly included, although its form of representation varied across study categories. Biological process representation varied across modeling approaches, with mechanistic mosquito population models providing the clearest representation of life-history processes, while statistical and spatial models more commonly focused on abundance, occurrence, suitability, infection risk, or short-term prediction. Seasonal processes, including lagged weather effects, seasonal forcing, photoperiod, and diapause, were represented unevenly across the literature.

The review also identified important data-related and geographic gaps. Model development was strongly shaped by data availability, with statistical approaches closely linked to surveillance and environmental datasets, while mechanistic models more often relied on literature-derived parameters, laboratory traits, and climate forcing. Model support and transparency also varied: calibration was commonly reported, but independent validation, uncertainty and sensitivity analysis, out-of-sample prediction, and code or data availability were less consistently documented. Geographically, studies were concentrated mainly in Ontario and national-scale analyses. Atlantic and northern Canada were represented by a small number of empirical or surveillance studies, but no eligible quantitative modeling studies were identified for these regions.

Overall, the findings indicate a need for more integrated mosquito and WNV modeling frameworks in Canada. Future models would benefit from combining mechanistic mosquito population dynamics, multiple environmental drivers, seasonal processes such as diapause, stochastic environmental variability, surveillance-based calibration and validation, and transmission dynamics within unified frameworks. Strengthening these connections would improve biological interpretation, predictive reliability, reproducibility, and public health relevance. As climate change continues to alter mosquito distributions, seasonal activity, and disease risk, integrated and well-supported modeling approaches will become increasingly important for surveillance, preparedness, and vector-borne disease management across Canada.

Table 5: Key gaps identified in the review and corresponding directions for future mosquito and West Nile virus modeling in Canada. The table links recurring limitations in the Canadian literature to proposed modeling responses and data needs.

Gap identified in the review	**Evidence from the synthesis**	**Proposed modeling response**	**Data needed**
Precipitation is often treated empirically	Rainfall is commonly included as a predictor in statistical models, while mechanistic models represent precipitation in varying levels of detail	Dynamic larval habitat or water-balance module linking rainfall, evaporation, habitat persistence, and immature-stage dynamics	Rainfall; evaporation; land cover; hydrological conditions; larval habitat data; mosquito trap counts
Diapause and overwintering are underrepresented	Diapause and overwintering processes are included in relatively few mechanistic mosquito population models	Temperate mosquito phenology module incorporating photoperiod, temperature-dependent diapause induction, overwintering survival, and spring emergence	Temperature; photoperiod; overwintering survival; seasonal emergence data; mosquito surveillance time series
Transmission and mosquito ecology are often decoupled	Transmission models often represent vector abundance separately from detailed mosquito population processes	Coupled mosquito population and WNV transmission model linking vector abundance, infection dynamics, host exposure, and seasonal mosquito ecology	Mosquito abundance; vector infection rates; bird host data; human or animal case data; environmental covariates
Stochasticity is rarely represented explicitly	Most models use deterministic or observed environmental inputs, with limited representation of weather variability, demographic variability, or parameter uncertainty	Stochastic weather-driven population or transmission model incorporating environmental variability, uncertainty, and ensemble scenario analysis	Weather ensembles; long-term climate records; surveillance time series; parameter uncertainty estimates
Geographic coverage is uneven across Canada	Ontario and national-scale studies dominate; Atlantic and northern Canada have limited surveillance representation and no eligible quantitative modeling studies	Regional or hierarchical models with region-specific calibration and shared information across Canada	Regional surveillance data; climate data; environmental layers; mosquito occurrence records; vector infection or virus detection data; public health data

Data Availability

The data extracted and synthesized in this review are provided in the supplementary materials. Supplementary Table S1 contains the study extraction table. Supplementary Table S2 provides the database search strings and Google Scholar search phrases. Supplementary Table S3 provides the definitions and coding criteria for the model support and transparency indicators. Supplementary Table S4 provides the search-source accounting and screening flow, including Google Scholar screening, within-source deduplication, pooled record counts, and cross-source duplicate removal. Supplementary Table S5 provides the completed PRISMA-ScR checklist. No new primary empirical data were collected or generated for this study.

Competing Interests

The authors declare that they have no competing interests.

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Author Contributions

J.B. conceptualized and led the review, including development of the review framework, literature search, study screening and classification, data extraction and analysis, figure and table preparation, interpretation of findings, and manuscript drafting. H.Z. provided senior supervision, funding support, guidance on the review scope, methodological framing, and synthesis structure, input on the interpretation of findings, and critical revision of the manuscript. Both authors reviewed and approved the final manuscript.

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Ethics Statement

This study is a review of previously published literature and did not involve the collection of new data from human participants, animals, or biological samples. Therefore, ethics approval was not required.

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Supplementary Materials for: *Modeling Mosquito Dynamics and West Nile Virus Risk in Canada: A Systematic Mapping Review of Approaches and Research Gaps*

Joseph Baafi and Huaiping Zhu

Supplementary Table S1

The complete study extraction database is provided as a separate spreadsheet file titled `Supplementary_Table_S1_extraction.xlsx`.

Supplementary Table S2

Table S2: Search strategy used to identify studies on mosquito population dynamics, vector distribution, surveillance, West Nile virus risk, and emerging mosquito-borne disease risk in Canada.

Database/source	**Search string or search phrase**	**Search date or timing**	**Screening details**
Web of Science	TS=((mosquito* OR Culex OR Aedes) AND Canada AND (model* OR forecast* OR risk OR abundance OR "population dynamics" OR "species distribution" OR "habitat suitability") AND (temperature OR precipitation OR climate OR weather OR seasonality OR "climate change" OR "West Nile virus" OR "mosquito-borne disease" OR "vector-borne disease"))	April 24, 2026	No restriction was placed on publication year. Only English-language studies were considered. Records from Web of Science and Scopus contributed to the 122 records identified from bibliographic database searches.
Scopus	TITLE-ABS-KEY((mosquito* OR Culex OR Aedes) AND Canada AND (model* OR forecast* OR risk OR abundance OR "population dynamics" OR "species distribution" OR "habitat suitability") AND (temperature OR precipitation OR climate OR weather OR seasonality OR "climate change" OR "West Nile virus" OR "mosquito-borne disease" OR "vector-borne disease"))	April 24, 2026	No restriction was placed on publication year. Only English-language studies were considered. Records from Web of Science and Scopus contributed to the 122 records identified from bibliographic database searches.
Google Scholar search 1	"mosquito population dynamics" Canada model	April 24, 2026	Results were sorted by relevance, and the first 100 records were screened.
Google Scholar search 2	"West Nile virus" Canada model forecast risk abundance	April 24, 2026	Results were sorted by relevance, and the first 100 records were screened.
Google Scholar search 3	Culex Canada temperature precipitation climate weather	April 24, 2026	Results were sorted by relevance, and the first 100 records were screened.
Google Scholar search 4	Aedes Canada "species distribution" "habitat suitability" MaxEnt "climate change"	April 24, 2026	Results were sorted by relevance, and the first 100 records were screened.
Citation tracking and supplementary checking	Backward and forward citation tracking of key included articles and relevant review papers, together with a final supplementary check of recent Google Scholar results and citation lists from key included studies.	During screening, synthesis, and final supplementary checking	Citation tracking and supplementary checking were used as additional checks for potentially relevant studies before manuscript finalization. Eligible records identified through this process are reflected in the additional-study box in the PRISMA-style flow diagram.

Supplementary Table S3

Table S3: Operational coding criteria for model support and transparency indicators used in the review. Indicators were applied only to studies with a quantitative modeling component. Codes were used as descriptive measures of reporting and model support, rather than as formal quality scores or risk-of-bias assessments.

Indicator	Yes criterion	Partial criterion	No criterion	Not applicable criterion
Calibration or model fitting	Model was fitted, calibrated, or parameterized using observed data.	Model used some empirical data or parameter adjustment, but calibration was limited, indirect, or not fully described.	No calibration or fitting to observed data was reported.	Not applicable only if the study did not include a quantitative model.
Independent validation	Model performance was evaluated using an independent dataset or clearly separate validation data.	Evaluation used internally withheld, temporally separated, cross-validation, or partially independent data.	No validation or independent model evaluation was reported.	Not applicable only if validation was not relevant to the study design.
Uncertainty analysis	Uncertainty was explicitly quantified using confidence intervals, credible intervals, prediction intervals, uncertainty propagation, ensemble outputs, or comparable methods.	Some uncertainty information was reported, such as uncertainty ranges, scenario comparisons, or limited confidence intervals, but without a fuller uncertainty framework.	No uncertainty analysis was reported.	Not applicable only if uncertainty assessment was not relevant to the study design.
Sensitivity analysis	The study systematically assessed how model outputs changed in response to parameter, input, or assumption changes.	The study included limited sensitivity checks, scenario comparisons, or informal assessment of selected assumptions.	No sensitivity analysis was reported.	Not applicable only if sensitivity analysis was not relevant to the study design.
Code or data availability	Analysis code, model code, or study data were clearly made available or linked.	Input data sources were public or described, but code, processed data, or full reproducible workflows were not completely available.	No code or data availability statement was provided.	Not applicable only if the study design did not involve reusable data or code.

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Indicator	Yes criterion	Partial criterion	No criterion	Not applicable criterion
Explicit biological mechanisms	The model explicitly represented biological or transmission mechanisms such as mosquito development, survival, reproduction, stage structure, diapause, host–vector transmission, or infection dynamics.	The model included indirect biological interpretation or proxy variables, but mechanisms were not explicitly modeled.	No biological or transmission mechanisms were explicitly represented.	Not applicable only if biological mechanism representation was outside the study scope.
Out-of-sample prediction	The study tested prediction using independent, future, external, or withheld data not used for model fitting.	The study included limited predictive assessment, such as internal validation, cross-validation, or temporally separated testing.	No out-of-sample prediction or predictive evaluation was reported.	Not applicable only if prediction was not part of the study objective.
Climate projection assumptions	Future climate or scenario assumptions were clearly described, including climate scenario, projection period, model source, or warming scenario.	Climate or future scenario assumptions were mentioned but incompletely described.	Climate projection assumptions were absent despite the study including future climate or scenario projections.	The study did not include future climate or scenario projections.

Supplementary Table S4

Table S4: Search-source accounting and screening flow for the systematic mapping review. Google Scholar results were screened by relevance, duplicates were first removed within the Google Scholar pool, and the resulting unique records were then combined with Web of Science and Scopus records for cross-source duplicate removal.

Source or stage	**Records screened or retrieved**	**Records retained or assessed at stage**	**Records advanced or outcome**	**Notes**
Web of Science and Scopus	122 records retrieved	122	Included in pooled duplicate removal	Records identified through structured database searches
Google Scholar searches	First 100 records screened per search phrase	76 unique records	Included in pooled duplicate removal	Potentially relevant Google Scholar records were first pooled and deduplicated within the Google Scholar set before being combined with database records
Pooled records from Web of Science, Scopus, and Google Scholar	198 candidate records	198	102 records after duplicate removal	Cross-source duplicate removal removed 96 duplicate records
Initial screening	102 records screened	86	86 records advanced to title and abstract screening	Sixteen records were excluded because they were not mosquito-related or were clearly outside the review scope
Title and abstract screening	86 records screened	63	63 full-text articles from the initial search advanced to full-text assessment	Twenty-three records were excluded because they were outside the review scope or not published in English
Full-text assessment from initial search	63 full-text articles assessed	63 full-text articles	63 full-text articles assessed for eligibility	Full-text articles were assessed using the predefined inclusion and exclusion criteria
Final supplementary checking and citation review	6 additional eligible studies identified	6 studies	6 additional studies advanced to full-text assessment	Additional eligible studies were identified before manuscript finalization and assessed at full text
Total full-text assessment	69 full-text articles assessed	50 included	50 studies included in final synthesis	Nineteen full-text articles were excluded; 50 studies were included in the final synthesis

Supplementary Table S5

The PRISMA-ScR checklist was completed to support transparent reporting of the review design, search strategy, study selection, data extraction, synthesis, limitations, and funding. Checklist items were summarized from the PRISMA Extension for Scoping Reviews reporting guidance (Tricco et al., 2018).

Table S5: Completed PRISMA-ScR checklist for the systematic mapping review.

Section	Item	Checklist item	Reported in manuscript	How the item was addressed
Title	1	Identify the report as a scoping or mapping review.	Title page	The title identifies the article as a systematic mapping review of mosquito dynamics and West Nile virus (WNV) risk in Canada.
Abstract	2	Provide a summary of the background, objectives, eligibility criteria, evidence sources, extraction approach, results, and conclusions.	Abstract	The abstract summarizes the review background, scope, number of included studies, major modeling categories, environmental drivers, model-support findings, geographic gaps, and implications for integrated mosquito and WNV modeling. The abstract is presented in paragraph form, consistent with the manuscript style, rather than as a structured abstract.
Introduction: Rationale	3	Describe the rationale for the review in relation to existing evidence and knowledge gaps.	Introduction	The Introduction describes the importance of mosquito population dynamics and WNV risk in Canada, the role of climate and environmental drivers, the diversity of modeling approaches, and the need to synthesize gaps across mosquito dynamics, surveillance, vector distribution, and WNV risk.
Introduction: Objectives	4	State the review objectives or questions.	Introduction	The Introduction states the review objective and guiding questions. It also states the main synthesis dimensions, including study classification, environmental drivers, biological processes, data–model alignment, model support and transparency, and geographic coverage.
Methods: Protocol and registration	5	Indicate whether a review protocol exists and whether it was registered or made available.	Methods	The Methods state that no formal review protocol was registered before conducting the study. The manuscript also states that the review followed a predefined search, screening, eligibility, classification, and extraction framework.

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Section	Item	Checklist item	Reported in manuscript	How the item was addressed
Methods: Eligibility criteria	6	Specify inclusion and exclusion criteria for selecting sources of evidence.	Methods, Section 2.3	The eligibility criteria specify inclusion and exclusion conditions related to Canadian relevance, mosquito dynamics, mosquito ecology, WNV risk, mosquito-borne disease risk, study type, data type, geographic focus, environmental or public-health relevance, and English-language publication.
Methods: Information sources	7	Describe the information sources used to identify evidence.	Methods, Section 2.1; Supplementary Table S2	The review searched Web of Science, Scopus, and Google Scholar. Backward and forward citation tracking of key included articles and relevant review papers was also used to identify additional potentially eligible studies.
Methods: Search	8	Present the search strategy in sufficient detail to support reproducibility.	Methods, Section 2.1; Supplementary Table S2	The Methods describe the search date, databases, Google Scholar screening approach, search-term domains, and duplicate-removal procedure. Supplementary Table S2 provides the database search strings and Google Scholar search phrases.
Methods: Selection of sources of evidence	9	Describe the process for screening and selecting sources of evidence.	Methods, Sections 2.2 and 2.4; Figure 1; Supplementary Table S4	The manuscript describes identification, duplicate removal, initial screening, title and abstract screening, full-text assessment, supplementary checking, exclusions, and final inclusion. Figure 1 summarizes the selection process, and Supplementary Table S4 provides search-source accounting and screening flow.
Methods: Data charting process	10	Describe the process used to extract, chart, or record information from included studies.	Methods, Section 2.4	The manuscript states that data were extracted using a structured extraction framework. It also describes senior-author review of the extraction framework, classification outputs, figures, and narrative synthesis during manuscript development.
Methods: Data items	11	List and define the main variables, concepts, or information extracted from each source of evidence.	Methods, Sections 2.4 and 2.5; Supplementary Tables S1 and S3	Extracted information included citation details, publication year, study type, geographic region, mosquito species, pathogen or disease focus, model class, model category, environmental drivers, data sources, calibration and validation information, key findings, reported limitations, and relevance to mosquito dynamics or mosquito-borne disease risk in Canada. Model-support and transparency indicators were also defined and coded.
Methods: Critical appraisal of individual sources of evidence	12	Optional item: describe any formal critical appraisal or quality assessment of included sources, if conducted.	Methods, Section 2.5	Not conducted. A formal risk-of-bias or quality appraisal was not performed because the objective was to map the literature rather than rank study quality. Instead, model-support and transparency indicators were coded descriptively for quantitative modeling studies.

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Section	Item	Checklist item	Reported in manuscript	How the item was addressed
Methods: Synthesis of results	13	Describe the methods used to summarize and synthesize the extracted evidence.	Methods, Section 2.6	The manuscript describes a structured synthesis framework based on study and model classification, environmental driver representation, data–model relationships, data-source breadth, model support and transparency, and geographic coverage. A meta-analysis was not conducted because of heterogeneity in objectives, model types, outcomes, and data sources.
Results: Selection of sources of evidence	14	Report the number of sources screened, assessed for eligibility, excluded, and included.	Results/Methods, Section 2.2; Figure 1; Supplementary Table S4	The manuscript reports 198 candidate records before cross-source duplicate removal, 102 records after duplicate removal, 69 full-text articles assessed, 19 full-text exclusions, and 50 studies included in the final synthesis. Figure 1 summarizes the study selection process.
Results: Characteristics of sources of evidence	15	Present characteristics of the included studies.	Results, Sections 3.1 and 3.2; Figure 2; Supplementary Table S1	The manuscript summarizes the final set of 50 included studies by study scope, pathogen or disease focus, mosquito species or species groups, study outcomes, and dominant study or modeling approach. Supplementary Table S1 provides study-level extraction details.
Results: Critical appraisal within sources of evidence	16	Optional item: present results of critical appraisal, if conducted.	Methods, Section 2.5; Results, Section 3.7; Supplementary Tables S1 and S3	Not conducted as a formal critical appraisal. The manuscript instead reports descriptive model-support and transparency indicators for the 38 quantitative modeling studies, including calibration, validation, uncertainty analysis, sensitivity analysis, code or data availability, biological mechanism representation, and out-of-sample prediction.
Results: Results of individual sources of evidence	17	Present relevant information charted from individual included studies.	Supplementary Table S1; Results, Sections 3.1–3.9	Study-level information is provided in Supplementary Table S1. The Results synthesize individual study information across study categories, environmental drivers, biological processes, data sources, model-support indicators, and geographic coverage.
Results: Synthesis of results	18	Summarize and synthesize findings across included sources.	Results, Sections 3.3–3.9; Tables 1–4; Figures 3–7	The Results synthesize evidence across empirical/surveillance studies, review/conceptual studies, statistical/data-driven models, SDM/ENM/ML models, mechanistic transmission models, and mechanistic mosquito population models. The synthesis also summarizes environmental driver representation, data–model alignment, data-source breadth, model support and transparency, geographic coverage, and key patterns.

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Section	Item	Checklist item	Reported in manuscript	How the item was addressed
Discussion: Summary of evidence	19	Summarize the main findings and link them to the review objectives and questions.	Discussion, Sections 4.1–4.6	The Discussion summarizes the major findings, including the dominance of WNV-focused and *Culex*-related studies, the prominence of statistical/data-driven approaches, the central role of temperature, variable precipitation representation, uneven model support and transparency, geographic gaps, and the need for integrated mosquito and WNV modeling frameworks.
Discussion: Limitations	20	Discuss limitations of the review process.	Discussion, Section 4.7	The manuscript discusses limitations related to the Canadian-context focus, study classification decisions, screening and extraction being led by the first author with senior-author review, small numbers in some model categories, descriptive model-support indicators rather than formal risk-of-bias or quality appraisal measures, and possible omission of relevant gray literature, surveillance summaries, technical documents, or data portals.
Discussion: Conclusions	21	Provide conclusions and implications for future research, policy, or practice.	Conclusion; Discussion, Section 4.6	The conclusion emphasizes the need for integrated mosquito and WNV modeling frameworks that combine mechanistic mosquito population dynamics, multiple environmental drivers, seasonal processes, stochastic variability, surveillance-based calibration and validation, and transmission dynamics.
Funding	22	Describe sources of funding and the role of funders.	Funding section	The Funding section reports support from the Natural Sciences and Engineering Research Council of Canada (NSERC). No separate funder role is reported beyond financial support.

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