Methods to collect Ontario fishes at risk: An inventory of past research

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Methods to collect Ontario fishes at risk: An inventory of past research

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Abstract

Developing detection protocols and population monitoring programs are ubiquitous priority recovery actions for Ontario fishes at risk. The objective of our study was to describe past fishes at risk sampling efforts to inform future updates to guidance on recommended sampling gear. We inventoried 162 research articles, technical reports, and graduate student thesis chapters (published by 2022) to extract sampling information for Ontario species. Sampling information was reported for 30 Ontario fishes at risk, with 32 gear types used across studies. The most studied species were eastern sand darter, grass pickerel, lake sturgeon, pugnose shiner, redside dace, and spotted gar. The most frequently used gear were seine, electrofisher, gill net, and trawl. Non-invasive detection methods included environmental DNA (eDNA), sidescan sonar, snorkelling, underwater camera, and visual surveys. Although sampling occurred across Ontario, most studies were in southwestern Ontario or eastern Lake Ontario/Upper St. Lawrence River regions and targeted stream and river habitats. Our results can be used to identify the species, habitat, and gear combinations with sufficient field sampling use and gear evaluation to inform the design of detection and population monitoring protocols, as well as those warranting future directed research. Although multiple methods are used to collect Ontario fishes at risk, sampling-related research has largely been single-method focused. Research is needed to test whether gear combinations improve species detection and fish biodiversity monitoring.

Résumé

Méthodes de collecte de poissons d’espèces en péril en Ontario : Un inventaire des recherches antérieures

Le développement de protocoles de détection et de programmes de suivi des populations constitue une priorité essentielle dans les mesures de rétablissement des poissons d’espèces en péril en Ontario. L’objectif de notre étude était de recenser les efforts passés de prélèvement des poissons d’espèces en péril afin d’éclairer les futures mises à jour des recommandations concernant les équipements de prélèvement. Nous avons procédé à l’inventaire de 162 articles de recherche, rapports techniques et chapitres de thèses d’étudiants diplômés (publiés jusqu’en 2022) pour extraire des informations sur les méthodes de prélèvement utilisées pour les espèces en Ontario. Les données sur les prélèvements ont été collectées pour 30 espèces de poissons menacées, en utilisant 32 types d’équipements différents à travers les diverses études. Les espèces les plus étudiées étaient le dard de sable, le brochet vermiculé, l’esturgeon jaune, le méné camus, le méné long et le lépisosté tacheté. Les équipements les plus fréquemment employés étaient la seine, l’électropêcheur, le filet maillant et le chalut. Parmi les méthodes non invasives, on trouve l’ADN environnemental (ADNe), le sonar à balayage latéral, le snorkeling, la caméra sous-marine et les relevés visuels. Bien que les prélèvements aient eu lieu dans toute la province, la majorité des études se sont concentrées sur le sud-ouest de l’Ontario ou les régions du lac Ontario et du fleuve Saint-Laurent oriental, en ciblant principalement les habitats de ruisseaux et de rivières. Les résultats de notre étude permettent de distinguer les

combinaisons d’espèces, d’habitats et d’équipements ayant fait l’objet d’un nombre suffisant de prélèvements sur le terrain et d’évaluations d’équipements, afin d’orienter la création de protocoles de détection et de suivi des populations, ainsi que les prochaines recherches spécialisées. Bien que plusieurs méthodes soient employées pour collecter les poissons d’espèces en péril en Ontario, les recherches sur les méthodes de prélèvement se sont principalement concentrées sur l’utilisation d’une seule méthode à la fois. Il est nécessaire de mener d’autres études afin de vérifier si l’utilisation combinée d’équipements permet d’améliorer la détection des espèces et le suivi de la biodiversité piscicole.

Acknowledgements

Thank you to Tim Haxton, Nick Jones, Steve Leney, and Sarah Parna for their helpful reviews of a previous version of this report.

Contents

Introduction

Watersheds in the Great Lakes-St. Lawrence basin support the highest richness of freshwater fishes in Canada (Mandrak and Crossman 1992, Chu et al. 2015). However, aquatic taxa in this region are threatened by several anthropogenic stressors, including agricultural and urban land cover changes, pollution, dams, fragmentation, climate change, and invasive species (Dextrase and Mandrak 2006, Chu et al. 2015). Due to high native species richness and abundant anthropogenic stressors, the region is considered an aquatic conservation hotspot (Staton and Mandrak 2006), with more than 25 species of freshwater fishes listed on the provincial Species at Risk in Ontario (SARO) list and Schedule 1 of the federal Species at Risk Act (SARA). Inventory and monitoring efforts are critical aspects of species conservation. Assessing the distribution and abundance of fishes at risk (and the host fishes of imperilled freshwater mussels) through time are priority actions in federal and provincial recovery planning processes (Drake et al. 2021). Additionally, long-term monitoring is a priority action towards biodiversity conservation in Ontario (OBC 2023).

Data collected through species inventory, research, and monitoring activities can be used to assess population status and trends, delineate areas of protected habitat, and evaluate threats and the effectiveness of recovery actions (Cudmore et al. 2006). Scientific guidance has been provided for detecting and monitoring fishes at risk in Ontario (Portt et al. 2008; Wilson and Dextrase 2008; Mandrak and Bouvier 2014; Lamothe et al. 2023a,b), focusing on appropriate sampling gear, site boundary definitions, sampling intensity, number of sites to sample, how often and when sampling should occur (i.e., timing window to avoid spawning period), and fish handling procedures. Portt et al. (2008) developed general protocols and methods for species detection to help determine if proposed projects may affect fishes at risk and, therefore, require review under SARA. Guidance was largely developed from expert opinion and past studies undertaken in the Laurentian Great Lakes basin to inform general fish community surveys. Dextrase et al. (2014) later estimated species-specific detection probabilities and the number of required repeat surveys to complement earlier guidance on sampling effort to detect Ontario fishes at risk. To support agricultural drain classification, Mandrak and Bouvier (2014) developed sampling design recommendations to improve the detection of sensitive fish species and SARA-listed fishes.

The development and implementation of species detection and population monitoring protocols are ubiquitous priorities identified in recovery strategies for Ontario fishes at risk, though progress towards this priority has been slow. The lack of long-term monitoring data for most freshwater fishes is a substantial challenge when assessing conservation status and the success of recovery actions (Lamothe et al. 2023b). New or revised future guidance in sampling protocols require an understanding of what gears are most likely employed to collect fishes at risk, the habitats in which these gears are deployed, and the objectives of sampling efforts. Systematic and narrative literature reviews have recently been used to guide new aquatic species at risk research by (i) measuring scientific progress in support of freshwater fish and mussel at risk recovery and prioritizing those topics where progress has lagged (Drake et al.

2021) and (ii) developing recommendations for future experimental approaches to move reintroduction efforts forward for imperiled fishes (Lamothe et al. 2019). To support the design of future rivers and streams monitoring in Ontario, which is expected to include a biodiversity component, Millar et al. (2023) reviewed scientific studies published from 2005 to 2022 to document gear used to sample riverine fish communities.

Our goal was to compile studies that could inform future guidance on sampling methods to detect and monitor fishes at risk, with special consideration of species-specific sampling guidance presented in Portt et al. (2008). In this study, we compiled primary and grey literature detailing sampling efforts for Ontario fishes published by 2022. To inform future guidance for gear selection, we considered: (i) what are the temporal and spatial patterns in sampling activities? (ii) how often are different sampling gears used? (iii) what species and habitats have been targeted? (iv) what were the primary sampling objectives? and (v) what sampling designs were commonly used?

Methods

Workflow

Our approach for conducting the review (workflow) is presented in Figure 1; technical terms are defined in a glossary (Appendix 1) and studies included in the review are listed in Appendix 2.

First, we compiled a list of species based on the SARO list and Schedule 1 of SARA, i.e., species assessed as endangered, threatened, and special concern. Additionally, we identified factors influencing the interpretation of sampling gear use, e.g., study objective, sampling design, habitat type, author impressions of gear utility. To describe gear usage for the collection of Ontario fish SAR, we searched the scientific literature published from 2002 to 2022 (20 years) using Google Scholar, ResearchGate, and Fisheries and Oceans Canada publication series using each species name with the keywords: *sampling, sampling methods, Ontario, Great Lakes,* and *fish species at risk*. Relevant references consisted of papers published in peer-reviewed scientific journals, graduate student thesis chapters, and grey literature (e.g., unpublished data, agency reports, workshop proceedings). The initial study list also included literature previously identified by study authors but within same timeframe. Our review did not include provincial or federal species at risk sampling permit data; therefore, unpublished activities undertaken by environmental consultants, conservation authorities, or NGOs as part of environmental impact assessments, municipal planning, or stewardship activities are not represented.

Four hundred and one studies were identified before screening. We excluded studies from the review if: (i) sampling methods were not sufficiently described, (ii) sampling effort was already reported in another study (to avoid duplication), (iii) sampling occurred in the United States, or (iv) sampling only targeted not-at-risk species. After screening, we retained 162 studies with information related to the sampling of 30 Ontario fishes at risk. We reviewed each study to collect information about study objectives and design, study location and sampling years, sampling gear or detection method, target species, and habitats. Extracted information from each study was compiled into a spreadsheet.

Data visualization

To visualize results we used:

- ***Stacked bar plots*** to depict the percentage of studies associated with gear deployment, gear type, and the eight most common gears across studies. Study percentages were visualized by source data, habitat type, site selection type, and study design. A temporal stacked bar chart was used to visualize effort across years based on the eight most common gears across studies plus environmental DNA.
- ***Word clouds*** to identify commonly used gears and frequently studied species, as well as species most often targeted by different gear.
- ***Alluvial plots*** to identify patterns across multiple categorical variables (habitat, gear, study design, and site selection approaches).
- ***Non-metric multidimensional scaling (NMDS)*** to identify patterns in gear types and species, focusing on differences among habitat types (riverine, lacustrine, and wetland). Multivariate solutions were based on the Canberra metric, which ranges between 0 and 1 and is used for comparing ranked lists (Faith et al. 1987). The number of axes (K) was chosen based on observed stress value criteria (stress <0.2) and a permutation approach. NMDS analysis was performed on the study count data, where K was set to 2, with a resulting stress estimate of 0.084. Specifically, the study count data was permuted 999 times (within species) and NMDS analysis was run on the permuted data for K=2.

We assessed the association between number of species and corresponding number of studies undertaken during each study year using the Pearson correlation coefficient.

R packages. All analyses were conducted using R version 4.1.2 (R Development Core Team 2021). R script and data associated with this research has been made publicly available on GitHub (R analysis – https:// github.com/elisemillar/SARGearReview). Plots were visualized using the packages ‘ggplot2’ (Wickham 2016), ‘ggalluvial’ (Brunson and Read 2023), and ‘ggworldcloud’ (Le Pennec and Slowikowski 2023).

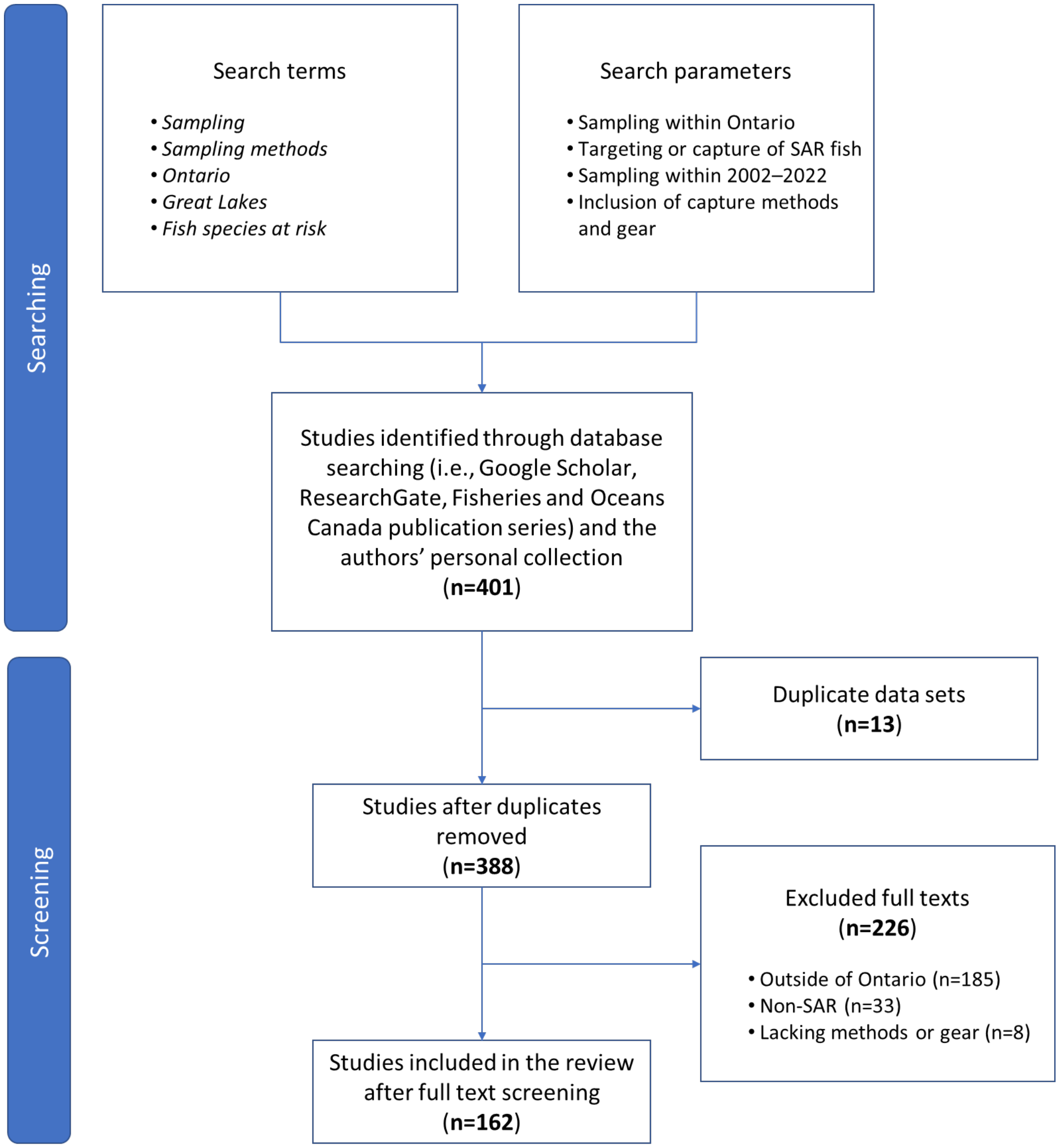


Figure 1. Outline of the sampling Ontario fish species at risk literature review project workflow. Numeric values (n) indicate the number of studies included in each step.

Results

Overview of studies

One hundred and sixty-two studies were included in our inventory: 82 scientific journal articles, 59 government technical reports, 10 graduate student thesis chapters, and 11 other report types. The mean number of studies initiated each year was 9.1 (standard deviation=4.5; range: 1–16). The number of studies varied over the review period (Figure 2). Years with many studies (i.e., >10) were 2002, 2005, 2007, 2010, and 2018. Overall, more studies were associated with the first decade of the review (n=110; 2002–2011) than the second (n=81; 2012–2021).

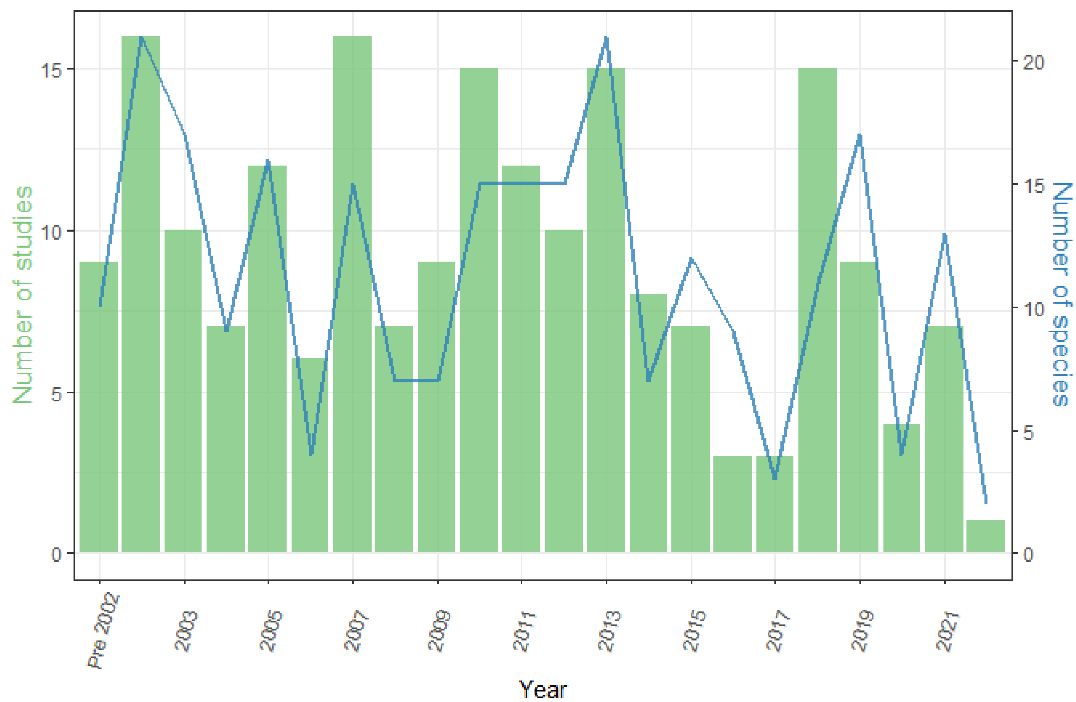


Figure 2. Annual variation in number of studies (bars) and targeted fish species at risk (line) per year over the research inventory timeframe.

Most (73.5%) studies were classified as research, while 14.8% were species inventories and 5.0% were population monitoring (Figure 3). The intent to collect or detect fish species at risk was classified as targeted for 65.2%, part of fish assemblage sampling for 22.7%, and incidental capture for 8.8% of studies evaluated. Overall, site selection for sampling was largely informed by historical fish SAR collection records or the researcher's knowledge of the species or study area. Studies solely classified as inventories (i.e., without additional objectives) only applied these strategies. Across all objectives, <20% of studies used a probability-based site selection approach (e.g., random sampling). Stratified random sampling was the most common site selection approach identified for population monitoring and research studies.

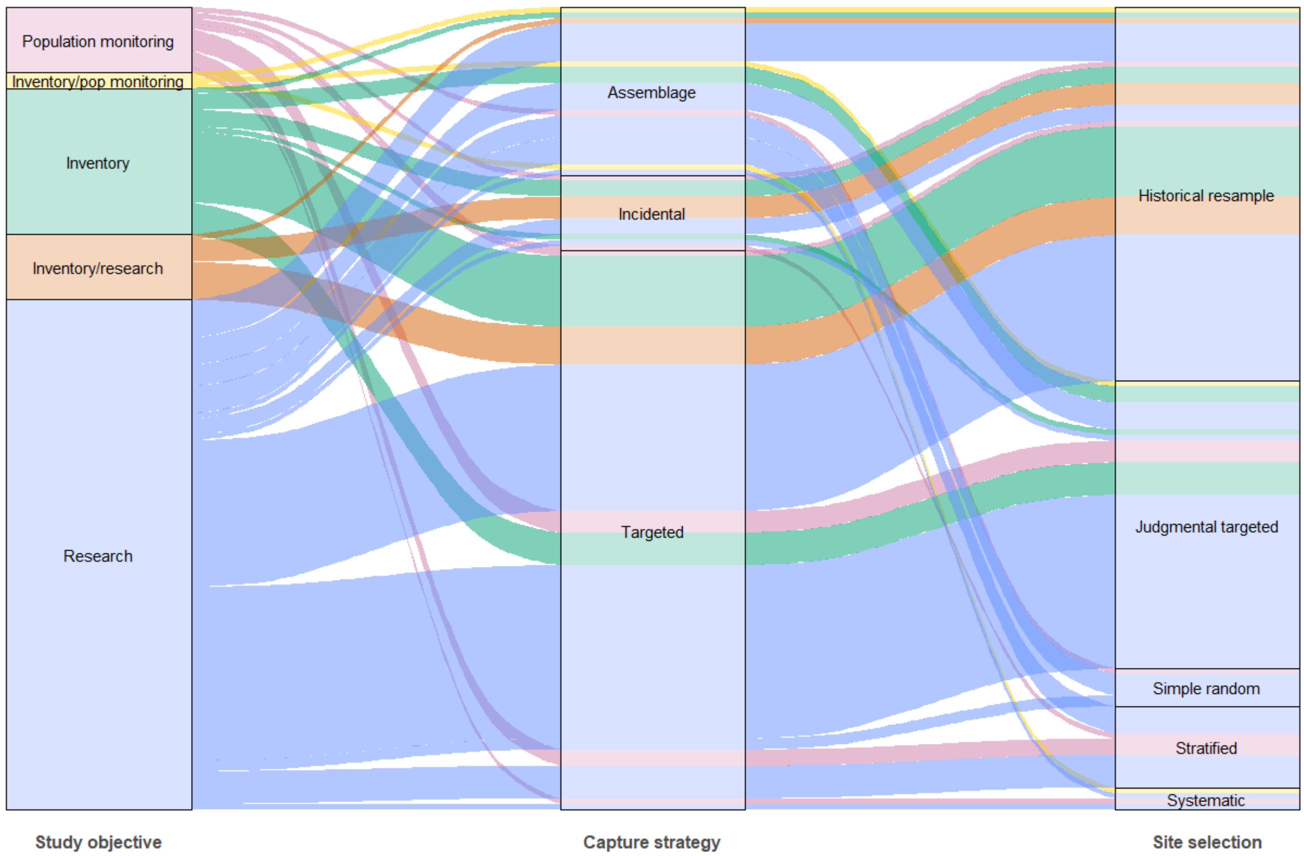


Figure 3. Alluvial plot displaying the frequencies of relationships among study objectives, capture strategy, and site selection methods employed in the studies included in this review of species at risk sampling methods. The vertical width of the coloured lines is proportional to the flow quantity (i.e., study counts).

Sampling was done in 84 tertiary Ontario watersheds, with 90.5% of sampling efforts in the Great Lakes-St. Lawrence primary watershed, 7.6% in the Nelson River primary watershed, and 1.9% in the southwestern Hudson Bay primary watershed (Figure 4). The mean number of studies across watersheds was 4.4 (standard deviation=4.2; range: 1–20). Most studies were done in the southwestern Ontario and eastern Lake Ontario/Upper St. Lawrence River regions. Southern Ontario watersheds with the highest number of studies included Grand River, Sydenham River, Thames River, and Trent River. Many studies were also in Lake Erie and Lake Ontario (including beaches and coastal wetlands). In Northern Ontario, the highest number of studies were in the Rainy River watershed. Fishes at risk sampling was more often reported in riverine habitats (n=114 studies) than lakes (n=40) or wetlands (n=24).

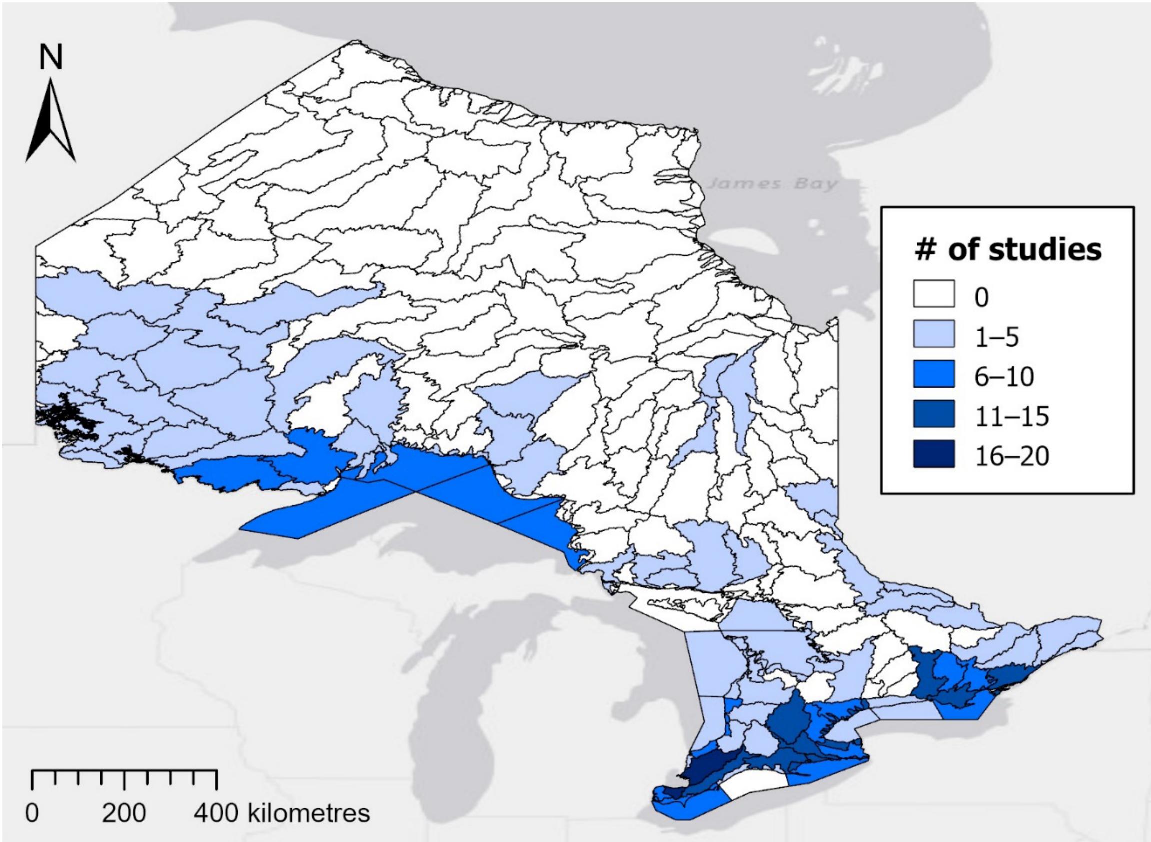


Figure 4. Spatial pattern of number of fish species at risk studies across 202 tertiary Ontario watersheds.

Study species

Past sampling information was identified for 30 Ontario fishes at risk. Thirty-seven per cent of studies provided information about sampling multiple species. The mean number of species (per year) was 11.4 (standard deviation=5.7; range: 2–21) (Figure 2). Species number was positively correlated to the corresponding number of studies undertaken that year (Pearson r=0.8, p<0.001). The most studied (10–16% of studies) species were eastern sand darter, grass pickerel, lake sturgeon, pugnose shiner, redside dace, and spotted gar (Figure 5A). Rarely studied (<2% of studies) species were cutlip minnow, gravel chub, northern brook lamprey, river darter, silver chub, silver lamprey, and shortnose cisco. Associated with different habitat types, the following species groups were evident from the NMDS bi-plot (Figure 6A): (i) lacustrine – deepwater ciscoes, pygmy whitefish, and silver chub; (ii) riverine – black redhorse, lake sturgeon, northern madtom, redside dace, river redhorse, and silver shiner; and (iii) wetland – grass pickerel, lake chubsucker, and warmouth. For some species, location relative to habitat convex polygons was intermediate; reflective of species distributions in multiple habitats (e.g., pugnose shiner in riverine and wetland habitats).

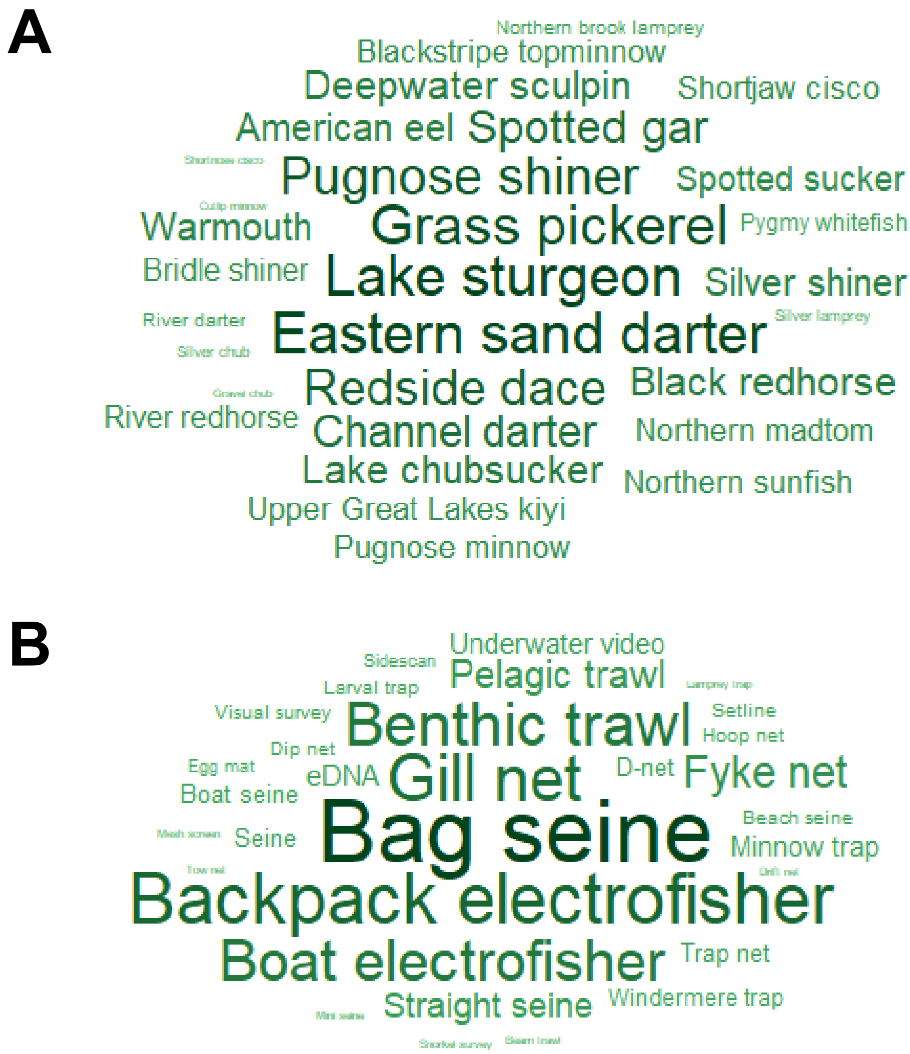


Figure 5. Word clouds depicting the most common species (A) and gear types (B) across the studies included in this review of Ontario fishes at risk sampling methods. The trend from few to many studies is displayed by increasingly larger and darker text.

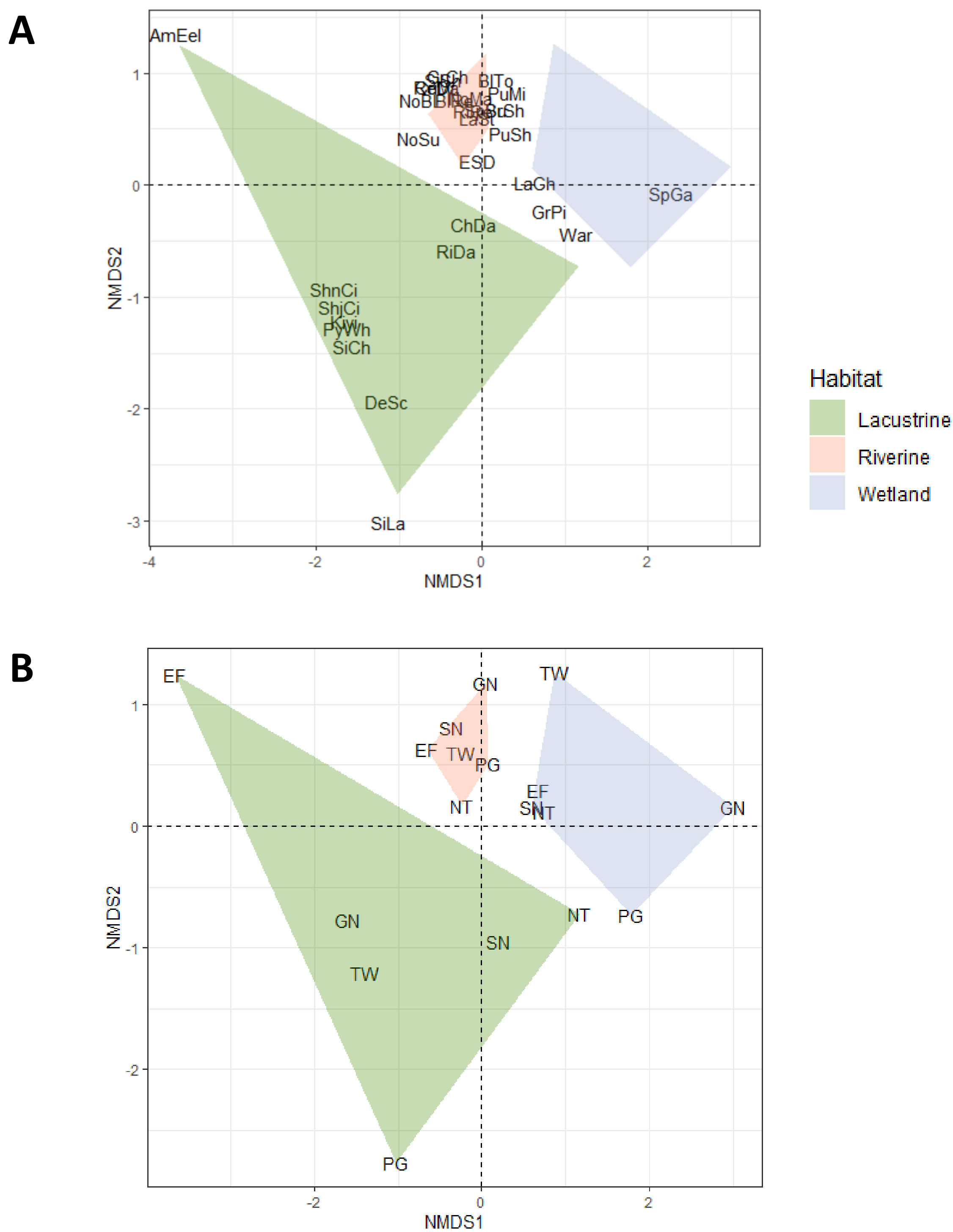


Figure 6. Non-metric multidimensional scaling (NMDS) bi-plots of study counts for species at risk fishes (A) and gear types (B) in review of Ontario fishes at risk sampling methods. Polygons represent convex hull of site scores for lacustrine (green), riverine (orange), and wetland (blue) habitats. Species abbreviations are provided in Appendix 3.

Gear use

Thirty-two sampling gears or methods (e.g., eDNA, underwater video) were used to collect, observe, or detect Ontario fishes at risk. The list included traditional active and passive fish sampling gear, as well as emerging or novel sampling/detection methods. The most used gears were bag seine, backpack electrofisher, gill net, benthic trawl, and boat electrofisher (Figure 5B). Methods that did not require handling (i.e., non-invasive) of fishes at risk included eDNA, sidescan sonar, snorkelling, underwater camera, and visual surveys. Forty-one per cent of studies indicated use of multiple gears or detection methods. Examples of gear combinations include: (i) bag seine and backpack electrofisher to sample wadeable riverine habitats, (ii) boat electrofisher and fyke nets to sample coastal wetlands, and (iii) benthic and pelagic trawls to sample non-wadeable riverine habitats. Over the years inventoried, the most consistently used gear for fish SAR collection were the backpack electrofisher, bag seine, and benthic trawl (Figure 7). Gill nets were consistently used before 2014 and eDNA-based detection of fish SAR started in 2012.

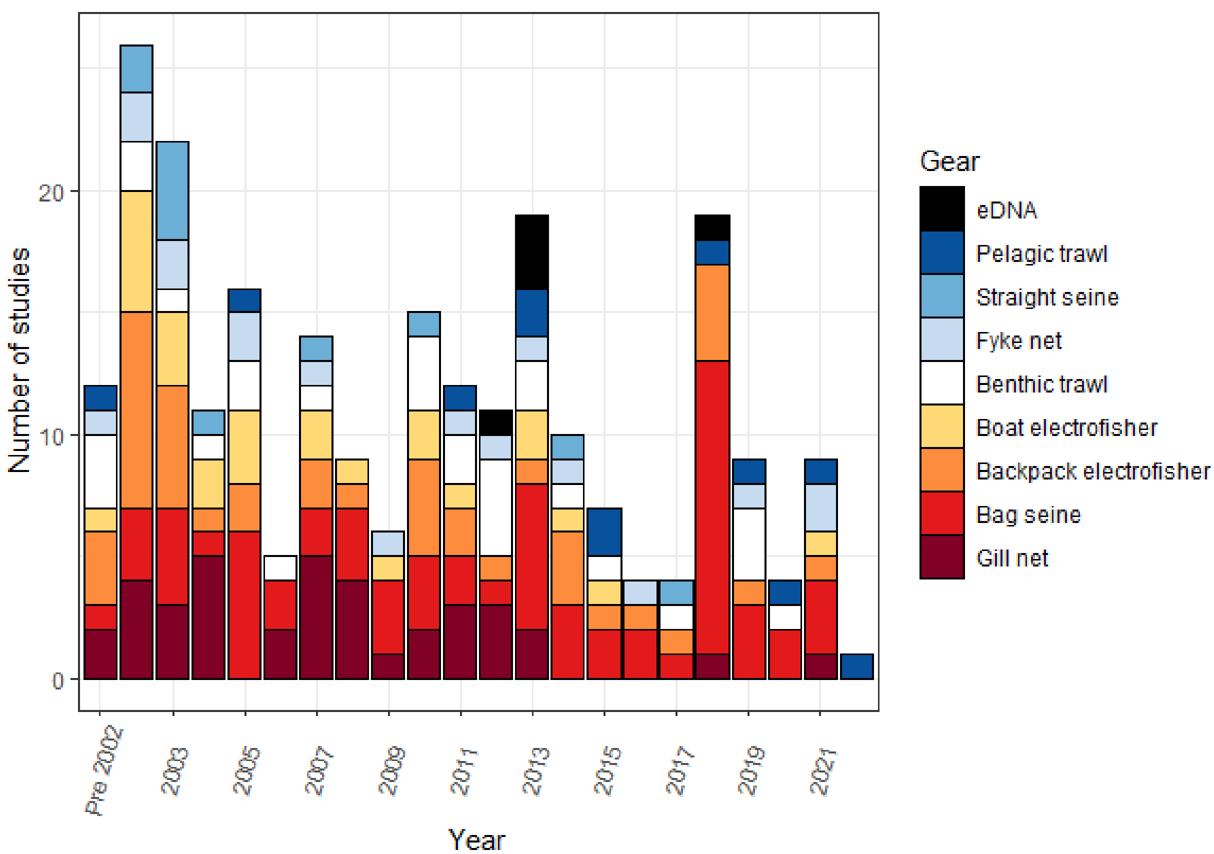


Figure 7. Number of studies per gear type stacked by year across the review timeframe (pre-2002 to 2022) of Ontario fishes at risk sampling methods. Displayed are the eight most common gear types plus eDNA.

Patterns in gear selection differed among wetland, lacustrine, and riverine sampling, likely reflecting requirements for different gears in relation to water depth, velocity, and aquatic vegetation (figures 6 and 8 – NMDS and habitat alluvial plot). In wetland habitats, fishes at risk were most commonly collected with a seine or net traps (e.g., fyke and hoop nets) (Figure 8). Gill nets and trawls were the primary gears used in all lake (lacustrine) habitats, with the seine frequently used in shallower lake habitats. The collection of fishes at risk from wadeable (<1.5 m water depth) stream and river habitats was most often done with a seine or backpack electrofishing unit. In deeper habitats (>1.5 m depth), boat electrofisher, gill net, and trawl were the primary sampling gear. An updated list of gears recommended by Portt et al. (2008) to collect SAR fishes from different habitats is provided in Table 1. For each species, the proportion of studies undertaken in each habitat type and the most often used gear are provided.

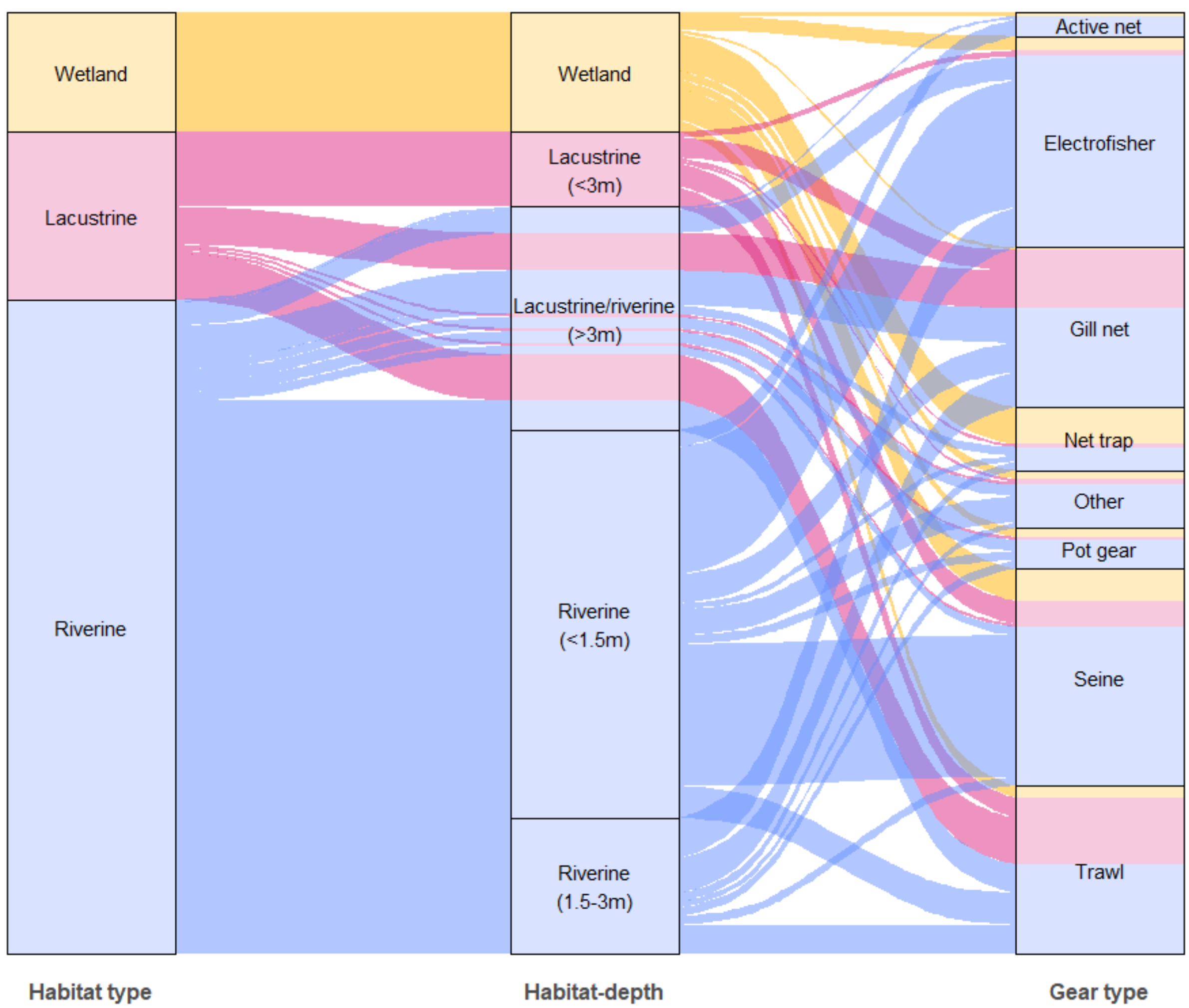


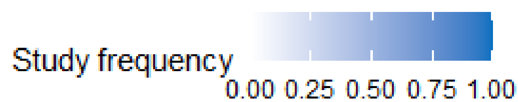
Figure 8. Alluvial plot displaying the relationships among habitat type, depth, and gear type employed by studies in our review of Ontario fishes at risk sampling methods. The vertical width of the coloured lines is proportional to the flow quantity (i.e., study counts).

Table 1. Variation in sampling gear usage to capture fish species at risk among different habitats. Habitats and gear types in each cell are based on Table 1 in Portt et al. (2008). For each species, the proportions of studies associated with each habitat were calculated using counts of gear used from 2008 to 2022 (darker=higher proportion; see colour legend at bottom). Dominant gear types are in bold font. Habitat types were stratified by water depth (m). EF=electrofisher; NA=not applicable.

Scientific name	Common name	Lacustrine (<3 m)	Lacustrine/ riverine (>3 m)	Riverine (<1.5 m)	Riverine (1.5–3 m)	Wetland
Acipenser fulvescens	Lake sturgeon	gill net, trawl	**gill net**, trawl	gill net	gill net	NA
Ammocrypta pellucida	Eastern sand darter	**seine**, trawl, net traps	trawl	**seine**, trawl, portable EF, boat EF	trawl	**seine**, net traps
Anguilla rostrata	American eel	boat EF	boat EF, trawl	boat EF, portable EF	boat EF	NA
Clinostomus elongatus	Redside dace	NA	NA	**seine**, portable EF	NA	NA
Coregonus kiyi kiyi	Upper Great Lakes kiyi	trawl	**trawl**, gill net	NA	NA	NA
Coregonus reighardi	Shortnose cisco	NA	gill net	NA	NA	NA
Coregonus zenithicus	Shortjaw cisco	trawl, gill net	**trawl**, gill net	NA	NA	NA
Erimyzon sucetta	Lake chubsucker	net traps	NA	**seine**, **trawl**, boat EF, portable EF	trawl	**seine**, net traps
Esox americanus vermiculatus	Grass pickerel	**seine**, net traps	boat EF	**seine**, trawl, portable EF, boat EF	**trawl**, boat EF	**seine**, net traps

Scientific name	Common name	Lacustrine (<3 m)	Lacustrine/ riverine (>3 m)	Riverine (<1.5 m)	Riverine (1.5–3 m)	Wetland
Exoglossum maxillingua	Cutlip minnow	NA	NA	portable EF, seine	NA	NA
Fundulus notatus	Blackstripe topminnow	NA	NA	**seine**, **trawl**, portable EF	trawl	seine, net traps, trawl
Ichthyomyzon fossor	Northern brook lamprey	NA	NA	portable EF	NA	NA
Lepisosteus oculatus	Spotted gar	net traps	NA	NA	NA	**net traps**, seine, trawl, gill net, boat EF
Lepomis gulosus	Warmouth	seine, net traps	NA	NA	NA	**net traps**, seine
Lepomis peltastes	Northern sunfish	gill net	gill net, trawl	**portable EF**, **seine**, trawl	trawl	NA
Minytrema melanops	Spotted sucker	NA	trawl	**trawl**, seine	trawl	seine, net traps
Moxostoma carinatum	River redhorse	NA	NA	boat EF	boat EF	boat EF
Moxostoma duquesnei	Black redhorse	NA	NA	seine	NA	NA
Myoxocephalus thompsonii	Deepwater sculpin	**trawl**, seine, gill net	**trawl**, seine, gill net	NA	NA	NA
Notropis anogenus	Pugnose shiner	NA	trawl	**trawl**, seine, boat EF, portable EF	trawl	seine, trawl, net traps
Notropis bifrenatus	Bridle shiner	gill net	gill net	boat EF	boat EF	**seine**, **trawl**, boat EF

Scientific name	Common name	Lacustrine (<3 m)	Lacustrine/ riverine (>3 m)	Riverine (<1.5 m)	Riverine (1.5–3 m)	Wetland
Notropis photogenis	Silver shiner	NA	boat EF	seine	NA	NA
Noturus stigmosus	Northern madtom	NA	trawl	trawl	trawl	NA
Opsopoeodus emiliae	Pugnose minnow	NA	NA	**trawl**, seine	trawl	seine, trawl, net traps
Percina copelandi	Channel darter	seine	trawl	**portable EF**, seine	trawl	NA
Percina shumardi	River darter	**trawl**, seine	**trawl**, boat EF	**trawl**, seine	**trawl**, boat EF	NA
Prosopium coulterii	Pygmy whitefish	gill net	**trawl**, gill net	NA	NA	NA



Word clouds provide visual representations of the relative frequencies that different species were targeted for collection using four commonly used gear (figures 9 and 10). The most common (top 4) species identified in studies using each gear were: (i) electrofishing – American eel, black redhorse, channel darter, and redside dace; (ii) trawl – deepwater sculpin, eastern sand darter, northern madtom, and pugnose shiner; (iii) seine – eastern sand darter, grass pickerel, pugnose shiner, and redside dace; and (iv) net trap – grass pickerel, northern madtom, pugnose shiner, and spotted gar.

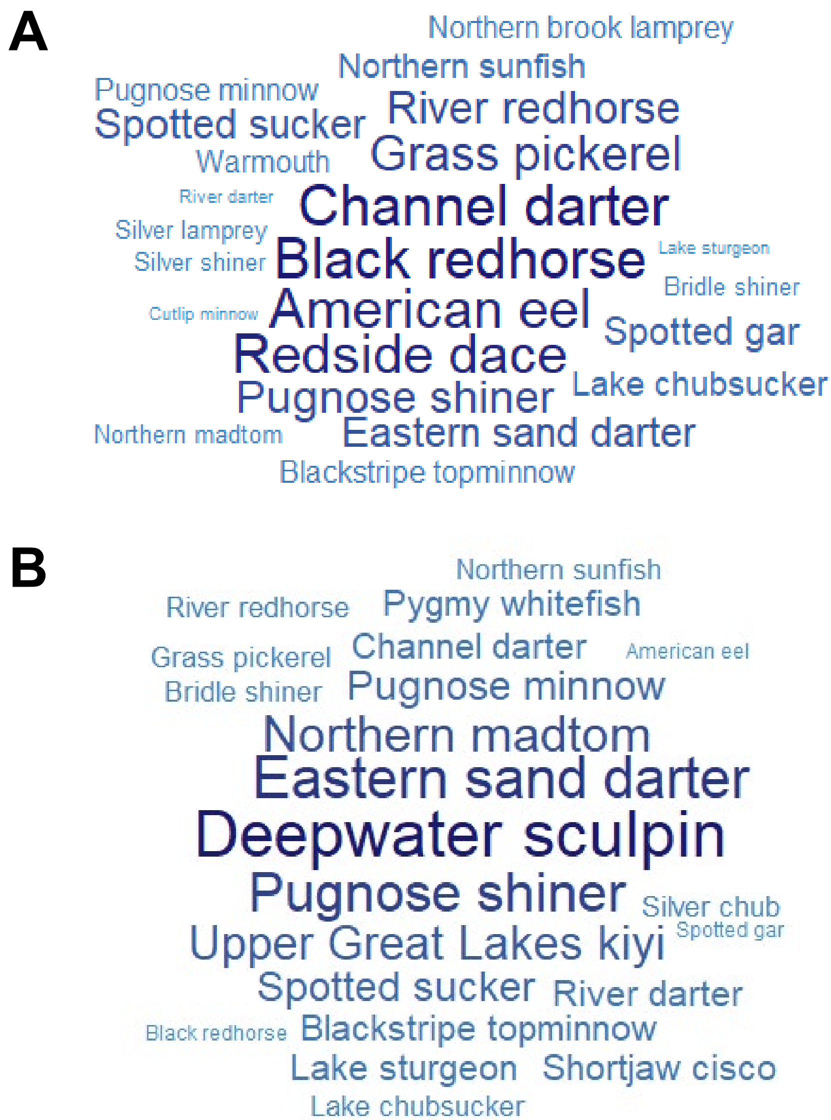


Figure 9. Word clouds depicting the most common species associated with electrofishing (A) and trawling (B) across the studies included in this review of Ontario fish species at risk sampling methods. The trend from few to many studies is displayed by increasingly larger and darker text.

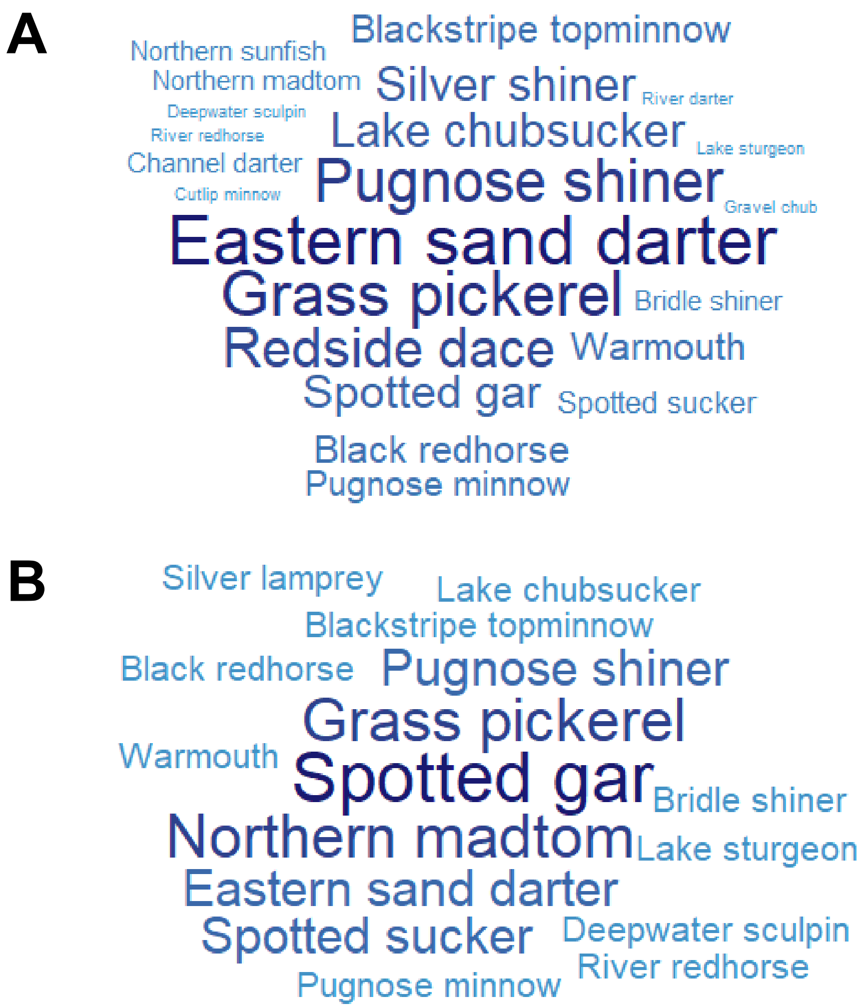


Figure 10. Word clouds depicting the most common species associated with seining (A) and net-trap (B) across the studies included in this review of Ontario fish species at risk sampling methods. The trend from few to many studies is displayed by increasingly larger and darker text.

Implications/next steps

Through our inventory of past studies, we identified five sampling gears commonly deployed to collect Ontario fishes at risk, and new non-capture methods for species detection (e.g., eDNA). Commonly reported gears are consistent with recommended standard gear types for sampling North American freshwater fishes (see Table 1.1 in Bonar et al. 2009). Sampling efforts were not comparable across regions of the province, among habitat types, or among species. Most studies were done in southern Ontario, with sampling most frequent in rivers and streams. Eastern sand darter, grass pickerel, lake sturgeon, pugnose shiner, redside dace, and spotted gar were the most often studied species. Our results can be used to identify the species, habitat, and gear combinations that reflect sufficient field sampling experience and gear evaluation to inform the design of detection and population monitoring protocols (see Lamothe et al. 2023a,b), as well as those requiring directed research in the future. Interest in the development of a province-wide integrated monitoring framework for rivers (Chu et al. 2022) may support or complement the identification of suitable species, habitat, and gear combinations, especially when objectives include monitoring fish biodiversity. For example, Millar et al. (2023) reviewed scientific literature (from 2005 to 2022) related to river and stream monitoring of fishes and updated a previous evaluation of sampling methods relative to habitat conditions and study objectives.

An iterative *learn-by-doing* approach can be used to refine fishes at risk sampling guidance. Pilot field studies can also be used to assess the effectiveness of gear to collect fishes at risk, or test which gear(s) maximize likelihood of detection. Our inventory identified examples of pilot studies for sampling American eel, blackstripe topminnow, eastern sand darter, redside dace, spotted gar, and spotted sucker, and for sampling methods such as backpack electrofisher, bag and beach seines, eDNA, and underwater video camera. Despite the reported use of multiple gears to study Ontario fishes at risk, research on the effectiveness of sampling gear has largely been single method focused with little effort to test whether gear combinations improve species at risk detection. If objectives of fishes at risk monitoring programs are multi-species focused, multiple sampling methods may address species- (and life stage-) specific differences in catchability and detection (Reid et al. 2009, Reid and Haxton 2017) and differences in gear suitability across habitat conditions (Casselman et al. 1990, Bonar et al. 2009). The value of multiple gear combinations to improve species detection and characterize species richness has been demonstrated for streams in the northeastern United States (Smith et al. 2013) and non-wadeable rivers in Iowa and Missouri (Neebling and Quist 2011, Dunn and Paukert 2020). Research is needed to identify combinations of sampling gear (and non-capture methods such as eDNA and underwater cameras) that optimize the inventory, research, and monitoring of at-risk fishes in Ontario.

Previous empirical and modelling studies have identified that substantial sampling effort may be needed to detect imperilled freshwater fishes in Ontario and to characterize distribution changes over time (Reid and Dextrase 2017, Reid and Haxton 2017, Lamothe et al. 2023a). The best option for limiting field sampling costs while ensuring reliable study results is to select gear (or gear combinations) and sampling strategies that maximize detection probability for rare species during each survey (Lamothe et al. 2023b). Improvements to species detection can also be made by increasing sampling intensity (e.g., more time spent electrofishing at a river site; Reid and Haxton 2017), using repeat-sample designs (e.g., >1 seine haul at a wetland site; Samarasin et al. 2017), or by surveying habitats when local abundance of target species is expected to be highest (e.g., night seining of Lake Erie beaches; Reid and Mandrak 2009). Although not appropriate for some research and monitoring applications, targeted sampling of specific habitat units (e.g., pools) or sites identified using local knowledge or biologist expertise can improve species detection or the efficiency of efforts to collect biological samples (e.g., DNA swabs for genetic research). It was beyond the scope of our study to investigate why most Ontario fishes at risk studies did not widely apply probabilistic (e.g., random) sampling site selection approaches, though we suspect issues such as limited resources, planning logistics, and limited species knowledge influenced study design decisions during the early part of our study timeframe.

Expert opinion could be solicited from research staff active in field data collection over the past 20 years to rank the effectiveness of different gear to collect target species and to identify habitats conditions that constrain deployment and effectiveness to detect species (e.g., Dextrase et al. 2014, Jones and Kim 2021). Information obtained through our inventory can be used to inform a future expert opinion survey or workshop to update fishes at risk detection guidance provided in Table 1 of Portt et al. (2008). The clear articulation of objectives and indicators is an essential design step for effective monitoring. To monitor population status, the effectiveness of recovery actions, and progress towards meeting recovery goals for species at risk, recovery planning documents for Ontario aquatic species at risk often describe monitoring indicators such as distribution, abundance, demographic characteristics, habitat extent and quality, and threats. The same group of fishes at risk sampling experts could also be surveyed to assess whether various monitoring indicators (e.g., abundance) are considered feasible, based on recommended sampling gear, expected field logistics, and program costs.

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Appendix 1. Glossary of technical terms

Boat electrofisher: an electrofishing unit mounted on a boat, powered by outboard motor or oars (Portt et al. 2008).

Boat Seine: a seine net fished from a boat (Portt et al. 2008).

Environmental DNA (eDNA): a non-invasive method of detecting fish species via the collection of tissue cells containing deoxyribonucleic acid (DNA) from an environmental sample, such as water.

Fish species at risk: species of fish in Ontario assessed as special concern, threatened, endangered, extirpated, or extinct according to COSEWIC and COSSARO.

Fyke net: a modified hoop net with one or two wings or a leader of webbing attached to the mouth to guide fish into the enclosure (Nielson and Johnson 1983). Classified as a net-trap by Portt et al. 2008.

Gill net: a passive capture device in which fishes are captured by becoming wedged or tangled in vertical walls of netting set out in a straight line (Nielson and Johnson 1983, Bonar et al. 2009).

Handheld net: includes all nets used to actively capture fish or benthic invertebrates, often during sampling by electrofishing or kick and sweep (e.g., dip nets and D-style nets).

Hoop net: a cylindrical or conical net distended by a series of hoops or frames, covered by web netting (Nielson and Johnson 1983). Classified as a net-trap by Portt et al. 2008.

Minnow trap: a small passive capture device with a conical mouth at each end to guide fish into the trap but not out of it. Classified as a type of pot gear in this study.

Portable electrofisher: includes all shallow water electrofishing methods such as backpack electrofishers, barge electrofishers, and shore units (Portt et al. 2008).

Seine: a net constructed of mesh panels attached to two handheld poles and hung from a float line with a weighted leadline attached to its lower edge. Typically fished via wading through water (Nielson and Johnson 1983) but see Boat Seine.

Setline: a method of fish capture by suspending a line across a section of water with shorter hooked and baited lines attached.

Side-scan sonar: a sonar system used to detect and image objects, including fishes, in the water column.

Site selection

Ad-hoc: sampling occurring for a specific purpose, usually as a one-off event.

Judgmental/targeted: non-random sampling in which samples are chosen based on the researcher's knowledge and judgment or to target a specific species or habitat.

Simple random: a subset of individuals (a sample) chosen from a larger set (a population), where each individual has an equal chance of being chosen and individuals are chosen randomly and completely by chance (Bonar et al. 2009).

Systematic: sampling that involves selection of a random starting point and sampling at specified intervals thereafter (Bonar et al. 2009).

Historical resample: the resampling of a population following a historical sampling event.

Stratified random: process of dividing a population into segments (strata) and sampling each stratum independently. If elements in each stratum are similar (homogenous), accuracy in parameter estimates may be higher (Bonar et al. 2009).

Study design

Before-After Control-Impact (BACI): used to examine the effects of human activities or natural changes by conducting data collection before and after the change.

Mark-recapture: used to estimate population size by capturing, marking, and releasing a small number of individuals back into the population. The number of marked individuals in the recaptured sample is counted.

Opportunistic: when sampling decisions are made during the process of collecting data. As knowledge of the setting is gained, sampling decisions can be made to take advantage of events as they unfold.

Spatial replication: spatial replicates are defined as surveyed points or transects that are nested in what is considered a site, such as a grid cell.

Temporal replication: temporal replicates are defined as surveyed points occurring in the same spatial location at different points in time.

Depletion/removal: a method to estimate fish abundance where fish are removed from a closed population or an enclosed area during multiple sampling events and the rate of reduction of catch over time is used to estimate the number of fish in the original population (Bonar et al. 2009).

Trap net: a large passive capture device that contains either rectangular frames that stabilize the net or floats and stakes that hold the net open (similar to fyke nets and hoop nets). The netting is arranged that so that fish can readily find their way into the trap but not out of it. Lead nets are usually present (Bonar et al. 2009). Classified as a net-trap by Portt et al. 2008.

Trawl: a bag-shaped net that is towed behind a boat along the top (i.e., surface trawl), through the middle (i.e., pelagic trawl), or at the bottom (i.e., benthic trawl) of the water column to catch fish by straining them through the water (Nielson and Johnson 1983).

Visual survey: fish surveys consisting of visual inspection (i.e., via shoreline, boat, snorkelling) or photography (i.e., photo, video) above or under the water surface.

Appendix 2. Studies included in review of fishes at risk sampling methods

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Appendix 3. Species abbreviations

Species	Acronym
American eel	AmEel
Black redhorse	BlRe
Blackstripe topminnow	BlTo
Bridle shiner	BrSh
Channel darter	ChDa
Cutlip minnow	CuMi
Deepwater sculpin	DeSc
Eastern sand darter	ESD
Grass pickerel	GrPi
Gravel chub	GrCh
Upper Great Lakes kiyi	Kiyi
Lake chubsucker	LaCh
Lake sturgeon	LaSt
Northern brook lamprey	NoBL
Northern madtom	NoMa
Northern sunfish	NoSu
Pugnose minnow	PuMi
Pugnose shiner	PuSh
Pygmy whitefish	PyWh
Redside dace	ReDa
River darter	RiDa
River redhorse	RiRe
Shortjaw cisco	ShjCi
Shortnose cisco	ShnCi
Silver chub	SiCh
Silver lamprey	SiLa
Silver shiner	SiSh
Spotted gar	SpGa
Spotted sucker	SpSu
Warmouth	War

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