

Freshwater conservation planning in the far north of Ontario, Canada: identifying priority watersheds for the conservation of fish biodiversity in an intact boreal landscape

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Abstract

Freshwater ecosystems show more biodiversity loss than terrestrial or marine systems. We present a systematic conservation planning analysis in the Arctic Ocean drainage basin in Ontario, Canada, to identify key watersheds for the conservation of 30 native freshwater fish, including four focal species: lake sturgeon, lake whitefish, brook trout, and walleye. We created species distribution models for 30 native fish species and accounted for anthropogenic impacts. We used the “prioritizr” package in R to select watersheds that maximize species targets, minimize impacts, and meet area-based targets based on the Convention on Biological Diversity commitment to protect 17% of terrestrial and freshwater areas by 2020 and the proposed target to protect 30% by 2030. We found that, on average, 17.4% and 29.8% of predicted species distributions were represented for each of the 30 species in the 17% and 30% area-based solutions, respectively. The outcomes were more efficient when we prioritized for individual species, particularly brook trout, where 24% and 36% of its predicted distribution was represented in the 17% and 30% solutions, respectively. Future conservation planning should consider climate change, culturally significant species and areas, and the importance of First Nations as guardians and stewards of the land in northern Ontario.

Key words: systematic conservation planning, conservation prioritization, species distribution modelling, freshwater biodiversity, freshwater connectivity, conservation targets

OPEN ACCESS

Citation: Southee FM, Edwards BA, Chetkiewicz C-LB, and O'Connor CM. 2021. Freshwater conservation planning in the far north of Ontario, Canada: identifying priority watersheds for the conservation of fish biodiversity in an intact boreal landscape. FACETS 6: 90–117. doi:[10.1139/facets-2020-0015](https://doi.org/10.1139/facets-2020-0015)

Handling Editor: Brett Favaro

Received: March 2, 2020

Accepted: September 11, 2020

Published: January 28, 2021

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Published by: Canadian Science Publishing

Introduction

We are in the midst of a global biodiversity crisis. A recent comprehensive report estimated that up to a million species face extinction, many within a few decades, unless there is drastic global action to conserve species and their habitats (Díaz et al. 2019). Increasing protected areas is one approach in conservation (Dudley and Stolton 2008). However, biodiversity loss continues (Butchart et al. 2010; Vörösmarty et al. 2010; Adams et al. 2015; Díaz et al. 2019) despite a global increase in land formally recognized as protected (sensu conservation targets) since 1933 when categories of protected areas were established and since 1994 when guidelines were adopted (Dudley 2008).

Attention to conserving biodiversity through area-based targets emerged in 1988, when 3%–4% of the planet's land area was formally protected under government- or state-recognized legislation. The Convention on Biological Diversity (CBD) signed in 1992 ([cbd.int/doc/c/efb0/1f84/a892b98d2982a829962b6371/wg2020-02-03-en.pdf](https://www.cbd.int/doc/c/efb0/1f84/a892b98d2982a829962b6371/wg2020-02-03-en.pdf)) recognized the importance of protected areas. In 2010, the CBD established the 20 Aichi Biodiversity Targets ([cbd.int/sp/targets/](https://www.cbd.int/sp/targets/)), including one (Aichi Target 11) to conserve at least 17% of terrestrial and freshwater areas and 10% of coastal and marine areas by 2020. In 2015, Canada released its national targets in response, in which Canada's Pathway to Target 1 (conservation2020canada.ca/home) commits Canada to meet the Aichi Target 11 goal (biodivcanada.chm-cbd.net/2020-biodiversity-goals-and-targets-canada). Ontario set an additional area-based target of 50% protection in the far north (Wilkinson and Schulz 2012) as part of a broader campaign to protect 50% of the Canadian boreal forest biome (e.g., the Canadian Boreal Conservation Framework). There have been calls to increase the targets following 2020, including calls for 30% by 2030 (Dinerstein et al. 2019) or 50% by 2030 (e.g., natureneedshalf.org/). In response, the Canadian government has stated that Canada will adopt an expanded area-based goal of protecting 25% of land and water by 2025, while working towards a target of 30% by 2030, and encouraging other countries to follow suit (pm.gc.ca/en/mandate-letters/2019/12/13/minister-environment-and-climate-change-mandate-letter). Although the specific targets vary and are changeable, the popularity and widespread adoption of area-based targets suggest that protected areas have an important role to play, and that targets must be based on social and ecological requirements for biodiversity.

There have been calls for decades to develop rigorous metrics to assess the management and effectiveness of protected areas to achieve conservation goals (Parrish et al. 2003; Watson et al. 2014; Adams et al. 2015; Di Minin and Toivonen 2015), with more recent research on outcomes-based metrics rather than area-based targets (Visconti et al. 2019; but see Woodley et al. 2019). Since 2004, protected area governance has included Indigenous Peoples and local communities, with an emphasis on the need for protected areas to benefit all people (Borrini-Feyerabend et al. 2013; Zurba et al. 2019). Despite these steps, protected area planning and designation is still driven by economics, and disproportionately designated in areas where land is inexpensive, rather than based on biodiversity, ecosystem services, or other social and cultural values (Venter et al. 2014, 2018).

Inland waters and freshwater ecosystems have the highest rates of biodiversity loss, and these losses have accelerated since the 1970s (Díaz et al. 2019). Consequently, freshwater species are among the most imperiled, with an 84% decline in global freshwater vertebrate populations since 1970 compared with a 40% decline for terrestrial vertebrates and a 35% decline for marine vertebrates (Díaz et al. 2019). Despite the urgent status of freshwater biodiversity, conservation planning to protect freshwater ecosystems lags behind both terrestrial and marine efforts. Freshwater ecosystems occupy less than 1% of the earth's surface, yet contain as much as 12% of all known species and a third of all vertebrate species (Juffe-Bignoli et al. 2016). Improvements in freshwater conservation can make a disproportionately large contribution in fighting the biodiversity crisis.

Conservation planning rarely includes explicit freshwater objectives or considers the unique characteristics of freshwater systems. For example, protected areas designed for terrestrial habitats or species may not adequately address the connectivity of freshwater systems, where impacts in headwaters can affect downstream habitats located hundreds of kilometres away and where changes to water flow, through damming or water extraction, can greatly alter the characteristics and habitats in freshwater networks (Nel et al. 2009; Linke et al. 2012; Juffe-Bignoli et al. 2016). Additionally, although terrestrial protected areas may provide some benefits to freshwater species (Abraham and Kelkar 2012; Hermoso et al. 2014; Britton et al. 2017; Chu et al. 2018), they are often inadequate for protecting freshwater biodiversity (Abell et al. 2011; Hermoso et al. 2014). Globally, freshwater

biodiversity benefits when the design and implementation of protected areas explicitly includes freshwater considerations (Juffe-Bignoli et al. 2016).

Systematic conservation planning uses spatial optimization to meet explicit targets while evaluating trade-offs between a set of decision variables (Margules and Pressey 2000; Wilson et al. 2009). This approach is widely accepted as an effective method to identify areas for biodiversity conservation; however, it has only recently been applied in the context of freshwater (Hermoso et al. 2016). In this study, we use conservation prioritization to evaluate scenarios that conserve freshwater fish species in the Arctic Ocean drainage basin in Ontario, Canada, while considering freshwater connectivity and avoiding areas with high human disturbance.

We focus on the Arctic Ocean drainage basin in Ontario for several reasons. This region is more water than land (Wells et al. 2010), underscoring the importance of freshwater values in conservation planning. Furthermore, the freshwater ecosystems in this region are large, mainly intact, contain some of the largest free-flowing rivers left in the world (Grill et al. 2019), and are the third-largest wetland (Abraham and Keddy 2005). Potential future development in the region includes all-weather roads, transmission corridors, mineral extraction, hydropower, and expanding forestry. Thus, this area offers an important and rare opportunity to consider proactive conservation planning before development, which is more cost-effective than retroactive action (Fuller et al. 2007).

We focus on freshwater fish biodiversity because fish are ecologically and socially important. Ecologically, there are at least 50 species of native freshwater fish in the Arctic drainage basin in Ontario, a limited number of invasive species and pathogens, and low human impacts compared with other subarctic regions of Canada (Browne 2007; Chu et al. 2014). Socially, freshwater fish are highly valued by First Nations and local communities. First Nations have long-standing relationships with freshwater fish, which are constitutionally protected and critical components of food security and food sovereignty (Noble et al. 2016) and important for livelihoods through recreational and commercial fisheries (Cooke and Murchie 2015).

Using conservation prioritization, we evaluate 12 scenarios to meet two area-based targets (17% and 30%) relevant to Canada's biodiversity commitments to protect 17% of terrestrial land and freshwater by 2020 and 30% by 2030. Our scenarios prioritize key areas for overall native fish biodiversity, and four focal fish species: lake sturgeon (*Acipenser fulvescens*), lake whitefish (*Coregonus clupeaformis*), brook trout (*Salvelinus fontinalis*), and walleye (*Sander vitreus*). Since there are existing provincial and federal protected areas in northern Ontario, we also explore the contribution of these existing protected areas to conserve freshwater fish biodiversity.

Focussing on the Arctic Ocean drainage basin in Ontario, we examine three questions:

1. What watersheds are selected to meet the 17% and 30% area-based targets while maximizing species distribution probabilities for 30 native fish species (i.e., native freshwater biodiversity), compared with four focal species individually (i.e., lake sturgeon, lake whitefish, brook trout, walleye)?
2. How well are the species distribution probabilities for the four focal species represented in the scenarios that prioritize species distribution probabilities for all 30 native fish species and vice versa?
3. How well does the existing protected areas network in northern Ontario contribute to the conservation of freshwater biodiversity?

Methods

Study area

The 714 730 km² Arctic Ocean drainage basin in northern Ontario, Canada, contains nine major river basins (Figs. 1a and 1b) and some of the largest naturally flowing rivers remaining in the world (Dynesius and Nilsson 1994). There are thousands of lakes, particularly in the Boreal Shield ecozone (Marshall and Jones 2011), and the largest wetland complex in North America is located in the Hudson Plains ecozone (Keddy et al. 2009), which is globally one of the most productive subarctic coastal wetland habitats (Far North Science Advisory Panel 2010; Abraham et al. 2011). In contrast to the Boreal Shield, there are few large, deep lakes in the Hudson Plains (Fig. 1b).

These freshwater ecosystems support at least 50 species of freshwater fish, making it the largest area of high fish biodiversity with low human impacts in Canada (Marshall and Jones 2011; Browne 2007). Walleye and northern pike (*Esox lucius*) are the most common top predators in the lakes and rivers flowing through the Boreal Shield ecozone; deeper lakes have lake whitefish, lake trout (*Salvelinus namaycush*), and cisco (*Coregonus artedii*). In the Hudson Plains ecozone, brook trout are often the top predator and some of the major rivers support lake sturgeon populations.

Here, we concentrate on 30 native freshwater fish species, as a measure of overall freshwater biodiversity, and four focal species: lake sturgeon, lake whitefish, brook trout, and walleye. The four species were selected because they are ecologically and socially important in the region. Ecologically, these four species are representative of the major fish community guilds (Browne 2007) and important “freshwaterscape species” identified previously through a site-based approach integrating knowledge of the characteristics, data gaps, and vulnerabilities of each species (McDermid et al. 2015). Socially, there are important recreational fisheries for walleye and brook trout in the road-accessible regions of northern Ontario and fly-in fisheries in the remote northern parts of Ontario (i.e., in the far north). Additionally, lake sturgeon is designated a species-at-risk at the provincial, federal, and international level (Haxton and Cano 2016) and is a culturally important species for First Nations and local communities.

The study area has two different management regimes: the Area of Undertaking, defined by commercial forestry, and the far north, which includes some of the most intact remaining boreal forest in the world (Brandt et al. 2013) (Fig. 1a). The far north has few all-season roads and a small industrial footprint, with a limited number of dams and mines, and mainly remote First Nations communities. However, there are ongoing economic interests in the far north, where the Ontario government and some First Nations are contemplating development projects, such as all-season road, mineral extraction (particularly in the so-called “Ring of Fire”, Hjartarson et al. 2014), hydropower facilities (Hatch Ltd. 2013), transmission lines (OMOE 2017), and expanding commercial forestry (OMOI and OMNDMF 2011; OMNR 2012). This, combined with proposed changes to the management of the far north by the Ontario government (OMNRF 2019a), means there is uncertainty about the conservation and protection of freshwater systems in the study area.

Watershed planning units and connectivity

The hydrological gradient in the study area flows in a northeast direction, from the Area of Undertaking into the far north of Ontario (Figs. 1a and b). Since the upstream effects of any development can be direct and cumulative on downstream watersheds (Pringle 2001, 2003; Freeman et al. 2007), we included the entire Arctic Ocean drainage basin in our conservation prioritization analysis (Fig. 1a) and developed a freshwater connectivity parameter.

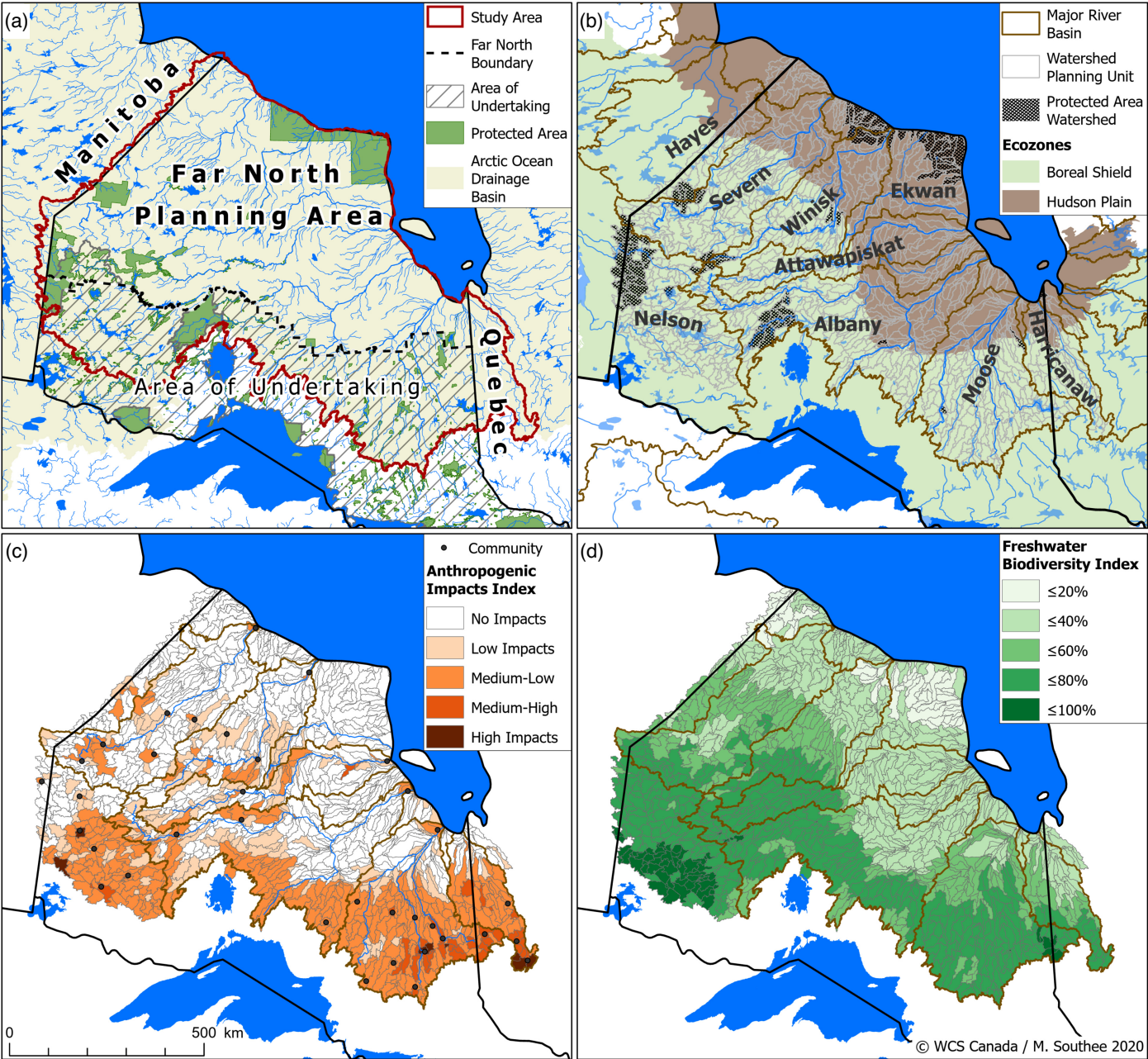


Fig. 1. (a) General location of study area; (b) major river basins, derived watershed planning units, and protected area watersheds with greater than 50% of their area covered by an existing protected area; (c) watershed planning units showing the anthropogenic impacts index derived from the first component of a PCA analysis of human disturbances; and (d) watershed planning units showing the freshwater biodiversity index which highlights areas of high and low freshwater biodiversity for all 30 native freshwater species.

First, we generated watershed planning units from six 30-m hydrology-enforced enhanced flow direction grids available from the Ontario Ministry of Natural Resources and Forestry (OMNRF) Ontario Integrated Hydrological Datasets. We used a threshold of 300 km² to create a drainage network based on the modelled overland flow accumulation resulting in 1417 stream segments and

corresponding watersheds ([Fig. 1b](#)) with an average area of 504 km² ([Maidmant 2002](#)). We completed the processing using the ArcHydro 10.5.0.13 toolset (Esri Water Resources Team) in ArcGIS 10.5 (Esri, Redlands, CA, USA).

Second, we calculated the connectivity between connected watersheds based on the methodology in [Hermoso et al. \(2012\)](#). The exterior boundary, or boundary length modifier (which is the connectivity parameter used for terrestrial or marine conservation planning), is not an appropriate measure of freshwater connectivity because fish can only move upstream and downstream between planning units ([Hermoso et al. 2011](#); [Linke et al. 2012](#)). Instead we measured the river length from each watershed outlet to the furthest downstream outlet (i.e., major river outlet into Hudson Bay), and calculated the distance between each pair of connected watersheds in each river basin.

Third, we used the inverse linear distance between watersheds as the connectivity parameter in the conservation prioritization analysis to penalize the selection of watersheds when adjacent upstream or downstream watersheds are not also selected ([Hermoso et al. 2012](#)). The inverse linear distance means there is a lower penalty applied to watersheds that are further away from each other, and a higher penalty is applied for adjacent watersheds when determining which watersheds should be selected to achieve the conservation target ([Hermoso et al. 2012](#)). A connectivity strength modifier of 2 was applied to the connectivity parameter to scale the range of values to the cost parameter (i.e., anthropogenic impacts index, as described below).

Assessing native freshwater fish biodiversity

Fish are the most commonly sampled freshwater biota in Ontario ([Marshall and Jones 2011](#)), but scientific surveys are limited within the study area, particularly in the far north. We developed species distribution models (SDMs) based on publicly available species occurrence, climate, and biophysical data sets. In the conservation prioritization analysis, the outputs from the SDMs were used as species representation targets.

We compiled species occurrence records from the Royal Ontario Museum (ROM) dated from 1920 to 2014 ([Mandrak and Crossman 1992](#)) and from three OMNRF databases dated from 1958–1995 and 2007–2012 ([Dodge et al. 1985](#); [Land Information Ontario 2009](#); [Sandstrom et al. 2010](#)). We selected the 30 most-common, native freshwater fish species that had sufficient occurrence records to make modelling feasible ([Table S1](#)).

We used eight climate and biophysical variables as predictor variables based on their ability to distinguish between biologically distinct fish responses and geographically distinct areas at different scales ([Tables 1](#) and [S2](#)). The climate variables were derived from the AdaptWest 1961–1990 climate normal ([AdaptWest Project 2015](#)) to align with the time frame in which the majority of fish occurrence

Table 1. Climate and biophysical variables used in species distribution models.

Climate Variables	Biophysical Variables
<ul style="list-style-type: none">• Mean annual solar radiation• Mean temperature of the warmest month• Summer precipitation (June to August)• Winter precipitation (December to February)	<ul style="list-style-type: none">• Elevation (30 m Ontario Ministry of Natural Resources and Forestry Ontario Integrated Hydrological Datasets digital elevation model)• Soil order• Landforms (categorized slope and topographic position index)• Land facets (with nonadjusted elevation and a modified heat load index)

records were collected, and the biophysical variables were derived from the Land Facets Data for North America (Michalak et al. 2018). Variable choice was informed by selecting candidate variables that are ecologically meaningful for freshwater fish, describe unique aspects of habitat suitability, and avoid collinearity (Braunisch et al. 2013; Leroy et al. 2016; Supplementary Material 1).

We used maximum entropy distribution modelling (Maxent; Phillips et al. 2006, 2017) to fit SDMs because it is specifically designed for use with presence-only occurrence records (Elith et al. 2011; Phillips and Elith 2013). We used Maxent v3.3.3 in R and followed the best practices outlined by Smith (2020). For all models, we used linear and quadratic features and selected the regularization parameter (*beta*) using Akaike's Information Criterion based on the methods described in Warren and Seifert (2011). Otherwise, we used the default settings.

Maxent generates species distribution probabilities, with values that range from 0 (lowest probability) to 1 (highest probability) across geographic space (Elith et al. 2006). Since our species distribution models generated probabilities at a 30-m grid resolution, which is smaller than the size of the watershed planning units, we attributed the mean species distribution probability for each species to each watershed planning unit (Fig. 2). These mean species distribution probabilities were used as the species representation targets in the conservation planning analysis. We also created a "freshwater biodiversity index" based on the overall mean species distribution probability for all 30 species in each watershed to highlight areas of high and low freshwater species distributions (Fig. 1d). This index was used for visualization only, and it was not used as a parameter in the subsequent analysis.

Anthropogenic impacts index

For the cost parameter in our conservation prioritization analysis, we created an anthropogenic impacts index based on 11 spatial data sets of human disturbances known to affect freshwater fish (Table 2). The anthropogenic impacts index was developed using a principal component analysis (PCA), which is a widely adopted method for distilling multifaceted information into a minimal set of uncorrelated input variables for use in subsequent analyses (Jolliffe and Cadima 2016).

Because of the limited human disturbance across much of the study area, there were many zero values in our initial data set (41% of the planning units). To reduce the impact of zero-inflation and improve the linearity of associations between variables, we used a $\log(x+1)$ transformation to standardize input variables before running the correlation based PCA (Quinn and Keough 2003). We used the "vegan" package (Oksanen et al. 2019), "permute" package (Simpson 2019), and "princomp" function in R to develop the PCA.

The first principal component from the PCA was assigned to each watershed and used as the "costs" in the conservation prioritizations (i.e., the prioritization analysis minimized the selection of watersheds with existing anthropogenic impacts) (Fig. 1c). The first axis captured 28.8% of the variation among watershed planning units, and a broken stick analysis determined it was the only meaningful component (Jackson 1993). This principal component was positively loaded with all 11 input variables (Table 2).

Existing protected areas

There are 169 existing provincial and federal protected areas covering 75 741 km² (10.6% of the study area), summarized in the Conservation Areas Reporting and Tracking System (CARTS) (CCEA 2017) (Fig. 1a). In Ontario, these include conservation reserves, migratory bird sanctuaries, national parks and wildlife areas, provincial parks, dedicated protected areas in the far north, valued ecosystem and natural habitats, and wilderness areas. We identified protected area watersheds where greater

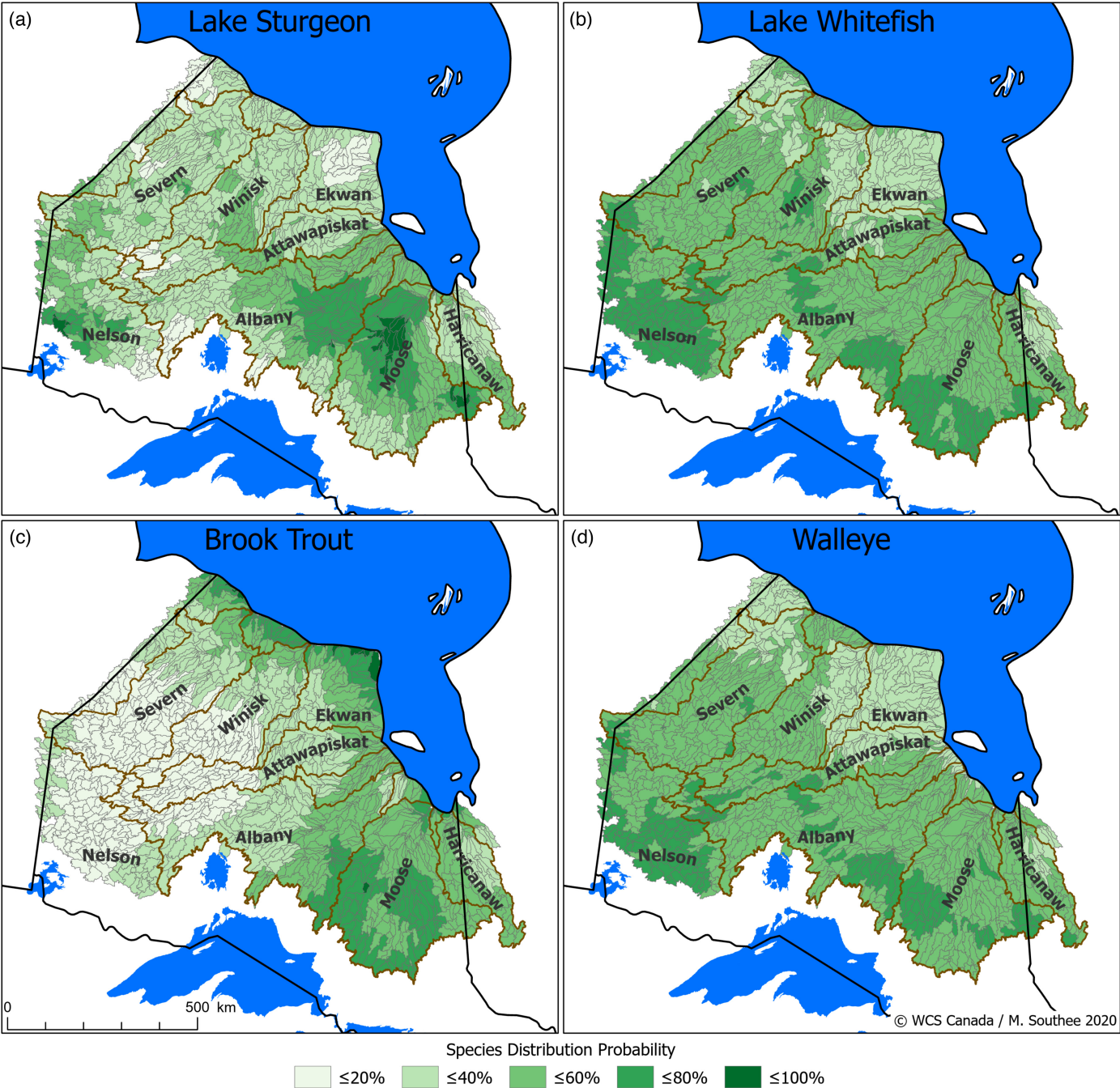


Fig. 2. Watershed planning units showing the mean species distribution probabilities for the four focal species: (a) lake sturgeon, (b) lake whitefish, (c) brook trout, and (d) walleye.

than 50% of the watershed overlapped with an existing protected area (Fig. 1b). One-hundred and twenty watershed planning units met this threshold, covering 57 353 km² (8% of the study area) and representing 26 protected areas (Table S3).

Table 2. Variables used in principal components analysis to develop the anthropogenic impacts index.

Input variable	Data set source
Number of producing mines ^a	GSC 2017, OGS 2017
Producing mines density ^a	GSC 2017, OGS 2017
Abandoned mines density ^a	GSC 2017, Ontario MNDM 2017a
Active aggregate sites density ^a	Québec MRNF 2016, Ontario MNRF 2017a
Inactive aggregate sites density ^b	Québec MRNF 2016, Ontario MNRF 2017b
Settlement density, including First Nation communities, towns, and cities ^c	Natural Resources Canada 2017
Population density ^a	Statistics Canada 2016, CIRNAC 2017
Percent of planning unit covered by anthropogenic land uses (including forestry, roads, mines, transmission lines, and other industrial activities) ^a	Global Forest Watch Canada 2014
Percent of planning unit covered by mining claims ^a	Québec MRNF 2016, Ontario MNDM 2017b
Number of dams ^c	Wildlife Conservation Society Canada, unpublished data
Dam density ^c	Wildlife Conservation Society Canada, unpublished data

^aIndicates variables with the most influence in the first component of the principal components analysis (loadings between 0.32 and 0.38).

^bIndicates variables with moderate influence (loading = 0.26).

^cIndicates less influential variables (loadings between 0.10 and 0.16).

Conservation prioritization scenarios

Systematic conservation planning aims to maximize the representation of conservation targets, in our case species distribution probabilities, while minimizing constraints to achieve spatially optimized conservation outcomes (Margules and Pressey 2000). We used the “prioritizr” package v4.0.4 (Hanson et al. 2019) in R with the Gurobi solver (Gurobi Optimization, LLC) to solve a “minimum set problem” based on a range of species representation targets (i.e., species distribution probabilities), while minimizing the values of the two other parameters (i.e., freshwater connectivity and anthropogenic impacts, as described above). Prioritizr uses integer linear programming to solve for a true optimal solution, making it computationally more efficient than other popular packages such as Marxan, which uses simulated annealing to solve for a near-optimal solution (Beyer et al. 2016).

We examined six different scenarios to meet the 17% and 30% area-based targets, for a total of 12 conservation prioritization analyses (Table 3). We ran two biodiversity scenarios: (i) with no additional constraints (unseeded) and (ii) with the existing protected area watersheds “locked in” to the solution (seeded). The biodiversity scenarios maximized species representation targets for all 30 species simultaneously. We also ran unseeded scenarios for each of the four focal species: lake sturgeon, lake whitefish, brook trout, and walleye (Table 3).

In all scenarios, we first solved the minimum set problem for a range of species representation targets, from 10% to 90%, using an interval step of 10%. We used these results to determine the interval that straddled the 17% and 30% area-based conservation targets; and reran each scenario using a smaller interval step of 1% to find the optimal solution to meet each area-based target.

Table 3. List of the 12 conservation prioritization scenarios. The unseeded scenarios had no constraints, and the seeded scenarios had the existing protected area watersheds locked in to the solutions.

Scenario	Conservation target	
	17% area-based target	30% area-based target
Biodiversity		
30 species	Unseeded	Unseeded
30 species	Seeded	Seeded
Focal species scenario		
Lake Sturgeon	Unseeded	Unseeded
Lake Whitefish	Unseeded	Unseeded
Brook Trout	Unseeded	Unseeded
Walleye	Unseeded	Unseeded

Results

We separate the results into three main findings based on our research questions. First, we identify the key areas for conservation of biodiversity and focal species; second, we discuss the performance of our models to maximize freshwater species representation targets under different scenarios; and third, we look at the conservation value of including the existing protected areas in the analysis.

Key areas for freshwater fish biodiversity conservation

In general, headwater planning units, coastal planning units, tributaries to large rivers, and watersheds with no upstream human disturbance were the most important areas in our solutions. Forty-seven watersheds were consistently selected in the solutions at the 17% area-based target, covering 3.7% of the study area; likewise, there were 190 watersheds consistently selected in the solutions at the 30% area-based target, covering 13.9% of the study area (Figs. 3a and 3b).

Importantly, the Kapiskau River watershed (located between the Attawapiskat and Albany River basins) and the southern tributaries to the lower Albany River were selected in all solutions. Furthermore, the biodiversity solutions consistently selected tributaries to the Severn River, sections of the Nelson River basin along the Ontario–Manitoba border, and watersheds at the headwater intersection of the Nelson, Severn, Winisk, and Albany River basin (Figs. 3c and 3d).

In the focal species solutions, there was a higher selection of watersheds in the Ekwon River basin, with these watersheds selected at the 17% area-based target for brook trout and at the 30% area-based target for lake sturgeon, lake whitefish, and walleye (Fig. 4). Watersheds in the Ekwon basin were not selected as extensively in the unseeded biodiversity solutions; however, they were selected in the seeded biodiversity solutions when they were “locked in” because of the inclusion of Polar Bear Provincial Park (Figs. 3c and 3d).

Freshwater species representation in different scenarios

Each biodiversity solution included a measure of the species representation for each the four focal species, and some species performed better or worse when evaluated independently. When lake sturgeon and brook trout were independently prioritized, they had higher species distribution probabilities represented relative to the biodiversity solutions (Table 4). Brook trout, a coldwater specialist, had the highest species distribution probability represented at the 17% and 30% area-based targets,

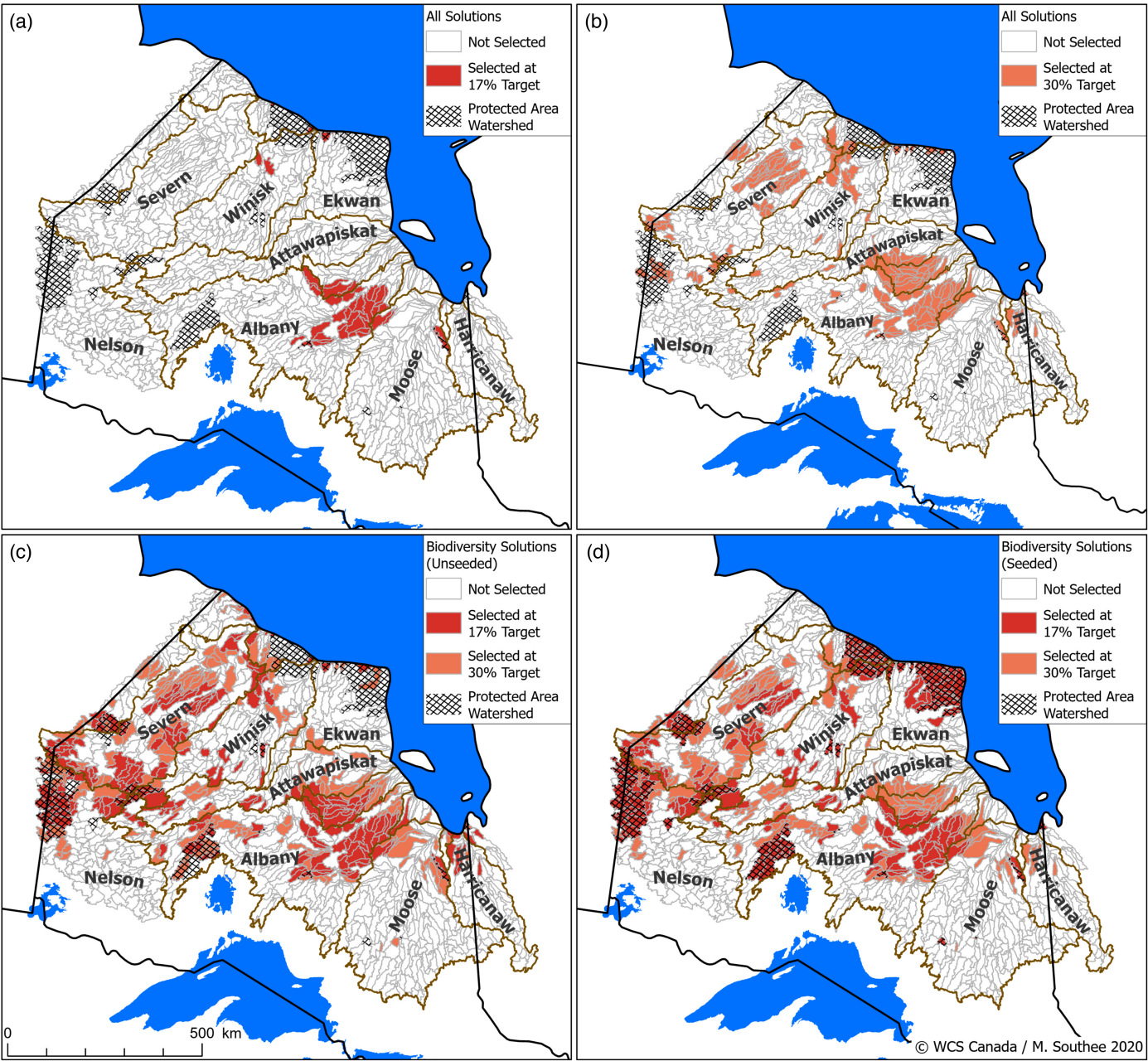


Fig. 3. Prioritizr optimization solutions showing the watersheds selected in all solutions (a) at the 17% area-based target and (b) at the 30% area-based target. Prioritizr optimization solutions showing the watersheds selected at the 17% and 30% area-based targets for the biodiversity solutions (c) with no constraints (i.e., unseeded) and (d) with the existing protected area watersheds locked in to the solution (i.e., seeded).

with 24% and 36% of its predicted distribution represented in the brook trout solutions, respectively (Table 4). It also showed the most divergent results from the other focal species, with a greater proportion of coastal watersheds along Hudson Bay selected at the 17% area-based target in

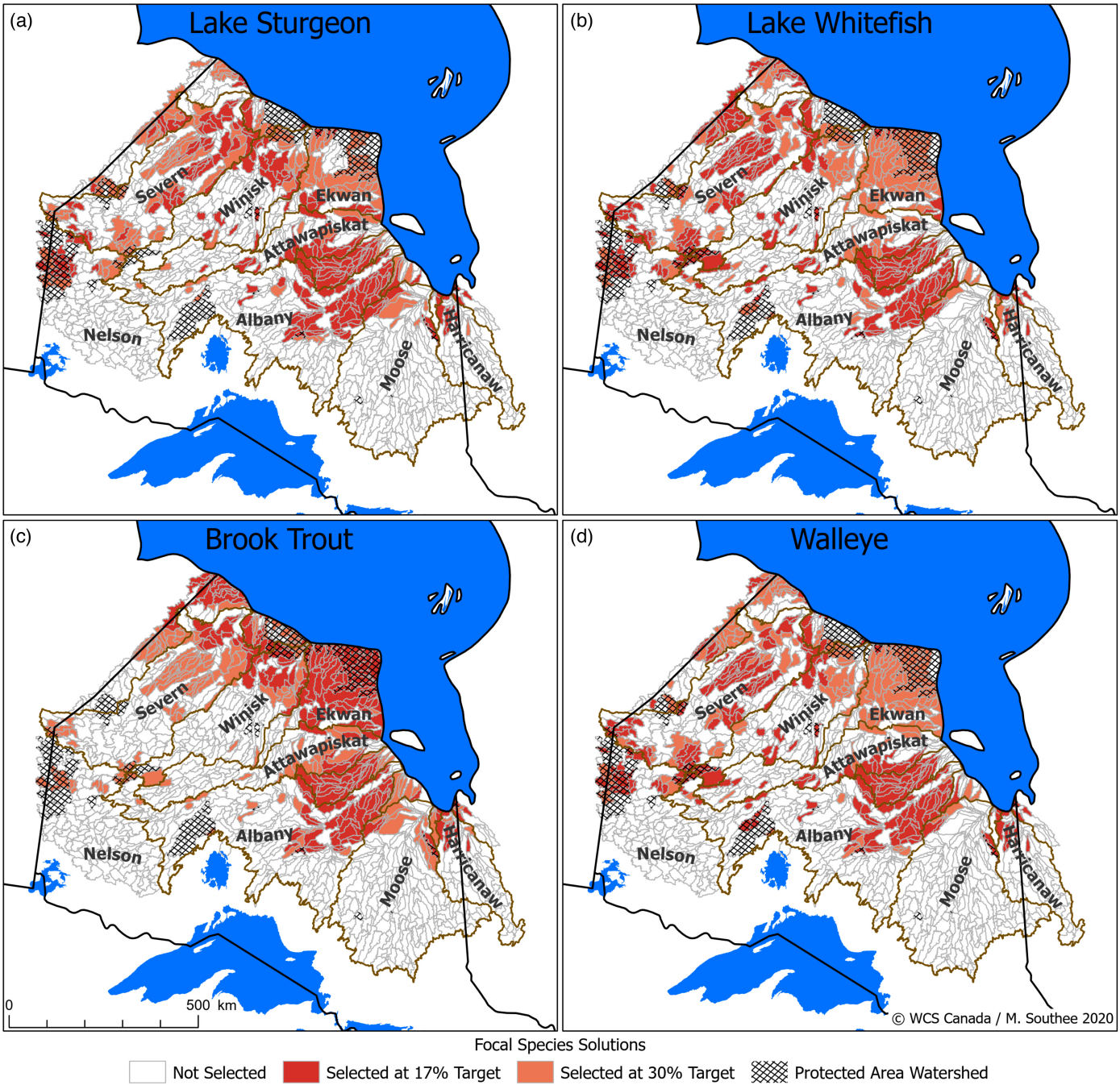


Fig. 4. Prioritizr optimization solutions showing the watersheds selected at the 17% and 30% area-based targets for each of the four focal species: (a) lake sturgeon, (b) lake whitefish, (c) brook trout, and (d) walleye.

comparison with other species. Lake whitefish and walleye (habitat generalists) had the lowest species distribution probabilities represented in the individual species solutions, with probability values that were equal to, or lower than, the values represented in the biodiversity solutions (Table 4).

Table 4. Amount of the species distribution probabilities represented in each scenario at the 17% and 30% area-based targets.

Species	17% area-based target			30% area-based target		
	Biodiversity scenario		Focal species scenario	Biodiversity scenario		Focal species scenario
	Unseeded (%)	Seeded (%)	Unseeded (%)	Unseeded (%)	Seeded (%)	Unseeded (%)
30 species (mean)	17.4	16.8	N/A	29.8	29.3	N/A
Lake Sturgeon	17.4	16.0	19.0	29.9	28.9	28.0
Lake Whitefish	17.6	17.0	17.0	30.3	29.5	26.0
Brook Trout	16.0	17.0	24.0	27.0	27.0	36.0
Walleye	17.9	17.2	17.0	30.6	29.9	27.0

Note: The mean value of the species distribution probability of all 30 species is reported for the biodiversity scenarios, and the individual values for the four focal species are reported in all scenarios. The unseeded scenarios had no constraints, and the seeded scenarios had the existing protected area watersheds locked in to the solutions. N/A, not applicable.

At both target levels, there was a higher mean species distribution probability represented for all 30 species in the unseeded biodiversity solutions compared with the seeded biodiversity solutions (17.4% vs. 16.8% at the 17% target; 29.8% vs. 29.3% at the 30% target) (Table 4). This relationship holds for lake sturgeon, lake whitefish, and walleye when looking at their individual species distribution probabilities represented in the biodiversity solutions (Table 4). However, brook trout showed the opposite trend where it had a higher species distribution probability represented in the seeded biodiversity solution (17.0%) relative to the unseeded solution (16.0%) at the 17% area-based target and no difference at the 30% area-based target (Table 4).

Conservation value of existing protected areas for freshwater fish biodiversity

A larger percentage of the existing protected area watersheds were selected in the unseeded biodiversity solution compared to the focal species solutions, with 38.3% and 58.6% of the protected area watersheds selected in the biodiversity solution at the 17% and 30% area-based targets, respectively (Fig. 3c). The smallest percentage of existing protected area watersheds were selected in the lake sturgeon solutions at both target levels, with only 14.3% and 47.0% selected in the solutions at the 17% and 30% area-based targets, respectively (Fig. 4c). At the 17% area-based target, the percent of existing protected area watersheds selected in the other three focal species solutions were 23.4% for lake whitefish, 24.6% for walleye, and 31.6% for brook trout. At the 30% area-based target, these values increased to 49.3% for brook trout, and 55.4% for lake whitefish and walleye (Figs. 4a, 4b, and 4d). Brook trout had the smallest increase (17.6%), while lake sturgeon had the largest increase (32.7%) in the percent of protected area watersheds selected at the two area-based targets.

A subset of the 49 watersheds overlapping Polar Bear Provincial Park in the Ekwan River, Winisk River, and Hudson Bay Coast basins was selected in all unseeded solutions, with the percentage of selected area ranging from 4.2% (for walleye) to 92.4% (for brook trout). The brook trout solutions had the largest selection of this protected area at both target levels, with 74.0% and 92.4% of the watersheds in Polar Bear Provincial Park selected at the 17% and 30% area-based targets, respectively (Fig. 4c). At the 30% area-based target, the selection of watersheds in Polar Bear Provincial Park was 20% lower in the unseeded biodiversity solution than in the focal species solutions.

Wabakimi Provincial Park (Albany River basin) was important in the unseeded biodiversity solutions, with 80.3% of the watersheds in Wabakimi Provincial Park selected at the 30% area-based target ([Fig. 3c](#)); however, it was less important for the four focal species. Specifically, there were no watersheds selected in Wabakimi for the brook trout and lake sturgeon solutions at the 17% area-based target, and only 4.0% and 4.9% of the watersheds in Wabakimi were selected for the brook trout and lake sturgeon solutions at the 30% area-based target ([Fig. 4](#)).

The Jog Lake Conservation Reserve (Albany River basin) and the North of the North French River Conservation Reserve (Moose River basin) were selected in all solutions at both area-based targets. Additionally, the Hannah Bay Migratory Bird Sanctuary, located on the Hudson Bay coast along the Ontario–Québec border, was selected in all solutions, except in the unseeded biodiversity solution at the 17% area-based target.

Other existing protected areas with moderate to high selection in all solutions, except brook trout, at the 30% area-based target included the protected areas along the Manitoba–Ontario border: Asatiwisi Aki Traditional Use Planning Area, Atikaki Provincial Park, Little Grand Rapids Dedicated Protected Area, Weeskayjahk Ohtahzhoganeeng Protected Area, and Woodland Caribou Provincial Park. Combined, these protected areas are part of the Pimachiowin Aki UNESCO World Heritage site which extends over the Poplar, Berens, Pigeon, and Bloodvein rivers and is the first “mixed” World Heritage site in Canada ([UNESCO 2018](#)).

The majority of the watersheds in the Cat Lake – Slate Falls Dedicated Protected Area were selected in most solutions, but were not selected at the 17% area-based target for lake sturgeon. This area is important for freshwater conservation because it spans the intersection of the headwaters for the Severn, Winisk, Albany, and Nelson River basins. Of note, the watershed planning units in and around this area were selected in the unseeded freshwater fish biodiversity solutions to meet both area-based targets, indicating that they are of high conservation value even without being explicitly locked into the solution.

Discussion

Performance of conservation prioritization scenarios based on area-based targets

We found that the conservation prioritizations performed reasonably well in representing the predicted species distributions for all 30 species, and for key focal species when meeting the existing and aspirational federal area-based targets of 17% and 30% ([Table 4](#)). However, the conservation prioritizations were most effective in the individual brook trout solutions. Brook trout are considered an indicator of high-quality, least-disturbed fish habitat and require specialized habitats including clear, cool, well-oxygenated streams and lakes and groundwater upwellings for spawning ([Haxton et al. 2020](#)). Relative to other species in our study area, these habitats may correspond to areas with lower human disturbance (e.g., Ekwan River basin).

Overall, the southern headwaters in our study area have both higher levels of human disturbance ([Fig. 1c](#)), and higher freshwater fish biodiversity ([Fig. 1d](#)). Although a few specialist species occur along the coast of Hudson Bay (e.g., sea-run brook trout; [Fig. 2c](#)), for the most part, higher species distribution probabilities for the 30 native freshwater fish species occur more often in the southern, lake-dominated landscape of the Boreal Shield relative to the northern, wetland-dominated landscape of the Hudson Plains ([Fig. 1d](#)). This pattern at the regional scale reflects a broader global pattern where ecosystems supporting higher levels of biodiversity are also subject to higher human demand ([Weinzettel et al. 2018](#)). Despite the high species richness in the southern headwaters, watersheds in

this region were only selected in the biodiversity solutions. We speculate that the lack of selection of the southern headwaters in the focal species solutions is due to the higher anthropogenic impacts in these watershed planning units, which outweighs the individual species representations, but there may be other factors that we have not considered or were not captured in our analysis.

The watersheds consistently selected in our analyses represent areas of relatively low human disturbance with few upstream impacts, moderate to high species distributions, or both. The results of the study support the use of a systematic conservation planning approach to identify watersheds where the costs associated with human disturbances are lower and freshwater fish biodiversity is maximized (Kukkala and Moilanen 2013).

Effectiveness of freshwater fish biodiversity solutions for the protection of focal species and vice versa

We found that there was overlap between the watershed planning units selected for freshwater fish biodiversity and for the focal species. However, there were some exceptions, particularly for brook trout. Brook trout is the most specialized focal species we examined, as indicated by their unique distribution patterns (Fig. 2). This result reinforces the need for unique habitat protections for specialists, since they are less likely to be adequately protected under approaches that optimize solutions for multiple species. Further, we note that while all our focal species have large ranges within our study area, area-based targets may not be meaningful for range-restricted focal species, and they may require different considerations.

Conversely, freshwater fish biodiversity protections may be more useful for generalist species. Our results suggest that by attempting to meet the needs of a diverse community of fishes, there is a risk of limiting the selection of specialized areas for a given focal species. This is a commonly observed trade-off in conservation planning, particularly when specialist species are also spatially rare or found in very low abundance (Hamaide et al. 2006). It is possible that optimizing for different elements of biodiversity, such as functional phylogenetics, could improve the achieved representation of niche space for different life history groups or species guilds (Strecker et al. 2011), and this should be a topic of further research.

While conservation strategies that maximize biodiversity outcomes are a pressing and prevalent objective for protected area planning, freshwater fish conservationists will continue to face the challenges of having to include approaches that also protect rare, endemic, and endangered species (Hamaide et al. 2006; Sowa et al. 2007). There is also a long history of focal species planning in commercial and recreational fisheries management, including government regulatory systems focussed on species at risk (Fisheries Act 1985; SARA 2002). Conservation planning has also focussed on “umbrella species” under the premise that because of their ecological requirements, their protection will have meaningful benefits for other fishes and communities (McDermid et al. 2015). Assessment of this assumption has been equivocal (Simberloff 1998; Roberge and Angelstam 2004).

However, area-based targets for biodiversity, in combination with special consideration for rare, endemic, and endangered species, have the potential to provide an effective approach. Lake sturgeon is a cultural keystone species and a species at risk, and key habitat for this species must be considered in any watershed or regional conservation planning process. Our solutions indicate that there was intermediate congruence between the lake sturgeon solutions and the biodiversity solutions as compared to the other focal species. The largest gaps in the lake sturgeon solutions (i.e., from the perspective of using lake sturgeon as an “umbrella” to conserve overall freshwater fish biodiversity) were in the Ekwon River basin, upper Albany River basin, and northwest portion of the Nelson River basin. Our results provide some support for including existing protected areas, in combination with

targeting new protections around priority areas for lake sturgeon, to build an effective regional conservation plan for both this threatened species and overall fish biodiversity.

Effectiveness of existing protected areas to support freshwater fish biodiversity

The existing protected areas in the study area were designated through a variety of land use planning processes based primarily on ecological, geological, and other cultural heritage features (OMNRF 2019b). More recently, community-based land use planning with some First Nations in the far north have prioritized freshwater fishes, their habitat, and freshwater connectivity (e.g., in Dedicated Protected Areas). The results from our conservation prioritization approach can provide support to future planning processes and offer opportunities to consider other areas to conserve freshwater fish biodiversity when evaluating new protection designations or development projects.

When examining all 30 species, “locking in” the existing protected area watersheds produced similar results at the 17% and 30% area-based targets relative to allowing the analysis to optimally select from any watershed in the study area. However, the representation of species distribution probabilities for lake sturgeon, lake whitefish and walleye were higher when the conservation prioritization was not constrained, suggesting that there are additional watersheds not captured in the existing protected areas network where the conservation outcomes for these focal species could be increased.

Large portions of Wabakimi Provincial Park were selected in the freshwater biodiversity solutions (Figs. 3c and 3d), but not in the focal species solutions (Fig. 4). Wabakimi is in the southern headwaters, where there is a higher overall mean freshwater fish distribution (Fig. 1d) and higher anthropogenic impacts outside the protected area (Figs. 1b and 1c). This result demonstrates that in areas with more human disturbance, protected areas can be critical for preserving the remaining areas with lower human disturbance that support freshwater fish biodiversity (Fischer and Lindenmayer 2007).

Conversely, in the more intact northern parts of our study area, protected areas are not necessarily more intact than the rest of the landscape in which they are embedded (e.g., the matrix). In the absence of human disturbance and competing demands for land and water use, there remains an important opportunity to proactively prioritize areas for protection based on both high freshwater fish biodiversity, as well as focal species of ecological and social value.

Interestingly, the coastal rivers in the Ekwan River basin, which make up a large part of the eastern side of Polar Bear Provincial Park near Cape Henrietta Maria, were not heavily selected in the biodiversity solutions, but were extensively selected in the brook trout solutions at the 17% area-based target and in the lake sturgeon, lake whitefish, and walleye solutions at the 30% area-based target. Although this area does not have high biodiversity overall, it is intact and has important habitat for sea-run brook trout and moderate habitat for our other focal species (Far North Science Advisory Panel 2010). Thus, while the Ekwan River basin is not the highest priority for overall freshwater fish biodiversity, it is a key area for socially and ecologically important freshwater fish species and a potential climate refugia as southern waters begin to warm (Chetkiewicz et al. 2017).

Limitations

This study shows that protected area planning in an intact landscape with area-based targets has promise for identifying areas for further consideration in protecting freshwater fish biodiversity and key freshwater fish species. However, there are limitations to our approach.

First, species occurrence information in this landscape was limited, requiring that conservation planning be based on predicted species distribution probabilities for the freshwater fish species. Knowledge scarcity across remote northern regions in Canada has been previously identified as a threat to effective freshwater conservation now and in the future (Chu et al. 2003; Alofs et al. 2014; McDermid et al. 2015; Edwards et al. 2016). Our species distribution models, based on biased and infrequently sampled occurrence records, may not have captured aspects of fish life history or temporally discrete habitat needs that are important for actual on-the-ground protection. The prioritization assessments could also have missed key habitats at finer spatial scales, which could have significant consequences for representativeness and effectiveness in the solutions. For example, lake sturgeon, which is a migratory species, needs big intact rivers and access to a variety of micro-habitats at different times and frequencies (Lacho 2013).

Second, we examined only a small part of overall biodiversity by focussing on freshwater fish. From an ecosystem function perspective, conservation action should ideally maximize multi-faceted diversity (including genetic diversity, trophic diversity, etc.), both within and across clades of taxa (Strecker et al. 2011). Further, consideration of freshwater conservation should not stop at the biodiversity within water itself. Land–water linkages are an important determinant of freshwater ecosystem integrity and productivity (Tanentzap et al. 2014), and protected areas achieve the best results for overall biodiversity when both freshwater and terrestrial priorities are simultaneously considered (Amis et al. 2009).

Third, watershed planning units were only considered as part of the existing protected areas network when >50% of their area overlapped with a designated protected area, but there are a number of “waterway class” provincial parks in the study area where only the mainstem river and a small buffer is protected (Fig. 1a). These protected areas, ostensibly designed for freshwater activities, were not picked up or considered as “protected” in this analysis, because only a small proportion of the watershed planning unit is protected relative to the entire watershed. In this freshwater-dominated region, with extensive hydrological connectivity, it is not sufficient to protect only the large, open waterbodies or mainstem rivers. Impacts to smaller tributaries, wetlands, and groundwater, as well as terrestrial environments, accumulate and concentrate in downstream lakes and rivers. As such, planning for freshwater conservation and protection is only effective when accomplished at the watershed scale (Pringle 2001; Linke et al. 2011).

Fourth, the assessment of protected areas was limited to publicly available and state-recognized protected areas. Areas protected by First Nations in their homelands are not publicly available as spatial boundaries, yet a number of First Nations in the study area have declared Indigenous Protected and Conserved Areas (IPCAs) within their traditional homelands (e.g., Zurba et al. 2019). For example, Kitchenuhmaykoosib Inninuwug (KI) First Nation is establishing an Indigenous Protected Area in the Fawn River Watershed (KI Homeland) that also supports the KI Water Declaration to protect a 13 025 km² area of boreal lakes, rivers, forest, and wetlands, including 661 km² Kitchenuhmaykoosib Aaki (Big Trout Lake), from any uses that harm their relationships with the land and water. Similarly, Moose Cree First Nation declared that the *Kah-pana-yow Sipi* or *Meh-ko-pwa-meh-štik Sipi* (the North French River) watershed within their traditional homeland is protected from development. IPCAs are lands and waters where Indigenous communities have the primary role in protecting and conserving ecosystems through Indigenous laws, governance, and knowledge systems and they are increasingly recognized by the federal government and some provincial and territorial governments as an important pathway for meeting area-based targets and commitments to protection (e.g., ICE 2018). However, these declarations are not recognized by Ontario or Canada and are therefore not included within the CARTS database. In addition, many of the protected areas identified within CARTS were created without consultation and consent of First

Nations, especially those established before 1982, and remain areas of contention in terms of conservation planning (ICE 2018). Consequently, our assessment of “protected areas” remains biased at this stage. Further, it remains unclear how dedicated protected areas identified by some communities in the far north of Ontario will be recognized and implemented moving forward as the provincial government reviews the *Far North Act, 2010* (OMNRF 2019a).

Recommendations for implementation and further research

Regardless of how comprehensively biodiversity is considered, conservation planning must also consider cultural significance and the importance of Indigenous and local community stewardship. Planning for freshwater conservation is better positioned to succeed if it considers both the needs of biodiversity and the benefits of biodiversity to humans (*sensu* freshwater ecosystem services; Hermoso et al. 2016). In northern Ontario, this includes recognition and support for IPCAs and co-management of the land and water with First Nations communities. Protected area planning and management in northern Ontario must include First Nations communities who maintain relationships to the land and water, have inherent Treaty and Aboriginal rights, and through their stewardship will deliver positive conservation outcomes for provisioning and other ecosystem services that extend beyond Ontario to Canada and the world (Bennett et al. 2018, Far North Science Advisory Panel 2010). There are a growing number of examples where co-governance systems for freshwater and marine protected areas are generating positive social and ecological outcomes (Gelcich et al. 2018; Plotkin 2018). Area-based freshwater conservation approaches may be a useful tool in planning by including social, cultural, and governance factors.

With area-based conservation planning, it is important to set specific and achievable targets for protection. We considered 17% and 30% of the Arctic Ocean drainage basin in Ontario based on existing and aspirational Canadian targets (CBD 2010; Dinerstein et al. 2019). In reality, protection tends to be disproportionately high in remote areas (Pimm et al. 2018), so for Canada to achieve their targets, they will likely rely on remote northern areas like those examined in this analysis, compared with more developed southern areas where competing demands are already high. The approach developed in this paper will allow for the expansion of area-based targets according to Canada’s and Ontario’s commitments and an opportunity to support First Nations rights and responsibilities across their homelands.

Climate change has the potential to be a dominant factor in driving the conservation outcomes of freshwater systems and their biota (Keller 2007; Schindler and Lee 2010), and it is predicted to significantly alter the diversity and distributions of freshwater fish, particularly in northern regions (Chu et al. 2005; Edwards et al. 2016). Accordingly, conservation planning needs to consider climate change trajectories and their implications for protected area effectiveness and longevity (Felton et al. 2009; Pettorelli 2012). While we did not examine future climate predictions and their impacts on freshwater biodiversity, this research can form the basis upon which to develop approaches to integrate the projected shifts in species distributions over time to produce adaptive freshwater conservation plans (Garcia-Moreno et al. 2014) that consider the protection of key watersheds for the maintenance of habitat and connectivity long-term.

As systematic conservation planning continues to advance and form the basis for providing biodiversity protection, evaluation of implementation success and effectiveness will be critical. There is a lack of published information on the success of systematic conservation plans (McIntosh et al. 2018), including those with freshwater conservation goals (Adams et al. 2015; Hermoso et al. 2016). In the few instances where protected area performance has been assessed for freshwater biota, evidence of positive results has been inconsistent (Adams et al. 2015). A carefully designed monitoring and assessment scheme must be implemented for protected areas established for freshwater biodiversity, so that

effectiveness can be evaluated and adaptive management can be employed where necessary. This must entail metrics measured over the long-term that can discern between design and management shortcomings (Hermoso et al. 2016) and appropriately account for natural ranges of variability, baseline shifts, and time lags (Adams et al. 2015). In northern Ontario, the development of community-based monitoring and Guardians programs also offers important opportunities to address First Nations governance in the research, monitoring, and conservation of freshwater fish.

In summary, systematic conservation planning for freshwater fish shows promise in an intact region of northern Ontario. Spatially optimized solutions to meet freshwater biodiversity and focal species representation targets can support efforts to deliver on area-based conservation targets, while also supporting Indigenous-led conservation and protection efforts and community-based approaches. But like with so many things, implementation will be key. There are many challenges to effective conservation outcomes for freshwater biota in the Arctic Ocean drainage basin, from competing land-use demands to mounting climate change vulnerabilities. However, with systematic conservation planning tools at the core, this largely intact and lived-in landscape presents a unique opportunity for implementation of proactive protection for freshwater ecosystems and services.

Acknowledgements

We wish to thank Drs. Virgilio Hermoso and Stephanie Januchowski-Hartley for teaching us the fundamentals of systematic conservation planning for freshwater ecosystems and for their original 2015 report that ultimately led to this paper. We thank Adam Smith for his helpful workshop on the use of Maxent at the North American Congress for Conservation Biology in 2016. We further thank Matt Strimas-Mackey for early advice on the implementation of prioritizr and Gurobi as our optimization solver. This work was funded by the generosity and ongoing support of the W. Garfield Weston Foundation.

Author contributions

FMS, BAE, and CMO conceived and designed the study. FMS, BAE, and CMO performed the experiments/collected the data. FMS, BAE, and CMO analyzed and interpreted the data. FMS, BAE, C-LBC, and CMO drafted or revised the manuscript.

Competing interests

The authors have declared that no competing interests exist.

Data availability statement

All relevant data are within the paper and in the Supplementary Material.

Supplementary material

The following Supplementary Material is available with the article through the journal website at doi:[10.1139/facets-2020-0015](https://doi.org/10.1139/facets-2020-0015).

Supplementary Material 1

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