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An updated assessment of human activities, the environment, and freshwater fish biodiversity in Canada

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Abstract: Changes in resource development and expansions of urban centres suggest that the intensity and types of anthropogenic stressors affecting Canada's watersheds are changing. Chu et al. (2003) integrated indices of freshwater fish biodiversity, environmental conditions, and anthropogenic stress to identify priority watersheds for conservation and management. Here, we update those indices using recent climate and census data to assess changes through time. We also applied different conservation and management scenarios to evaluate the robustness of our prioritization approach. Between time periods, the environmental and stress indices expanded northward because of warmer temperatures at higher latitudes and more intense anthropogenic stress in the northern regions of the provinces. Conservation priorities increased in northern British Columbia, Alberta, and Ontario but decreased in southern British Columbia, Saskatchewan, and south-central Quebec. Under multiple scenarios, conservation priorities were consistently highest in British Columbia, the Maritimes, southern Ontario, and southern Quebec. Future research to refine this assessment should focus on developing a nationwide georeferenced assessment of freshwater fisheries stress, quantifying spatial changes in the stressors, and evaluating the sensitivity of each index to the weighting of the individual variables. This work highlights the necessity for conservation and management strategies in Canada to keep pace with changing patterns in climate and human activities.

Résumé : Les changements à l'exploitation des ressources et l'expansion des centres urbains devraient modifier l'intensité et les types de facteurs de stress d'origine humaine agissant sur les bassins versants canadiens. Chu et al. (2003) ont intégré des indices de biodiversité des poissons d'eau douce, de conditions ambiantes et de stress d'origine humaine afin de cerner les bassins versants prioritaires sur le plan de la conservation et de la gestion. Nous actualisons ces indices à la lumière de données climatiques et de recensement récentes afin d'évaluer les changements au fil du temps. Nous appliquons également différents scénarios de conservation et de gestion dans le but d'évaluer la robustesse de notre approche de priorisation. D'une période à l'autre, les indices de conditions ambiantes et de stress se sont propagés vers le nord en raison du réchauffement à hautes latitudes et de l'intensification des stress d'origine humaine dans les régions nordiques des provinces. Les priorités de conservation ont augmenté dans le nord de la Colombie-Britannique, en Alberta et en Ontario, mais diminué dans le sud de la Colombie-Britannique, en Saskatchewan et dans le centre-sud du Québec. Pour plusieurs scénarios, les priorités de conservation étaient uniformément les plus élevées en Colombie-Britannique, dans les Maritimes et dans le sud de l'Ontario et du Québec. La recherche future visant à raffiner cette évaluation devrait mettre l'accent sur l'établissement d'une évaluation pancanadienne géoréférencée des stress sur les ressources halieutiques d'eau douce, la quantification de l'évolution spatiale des facteurs de stress et l'évaluation de la sensibilité de chaque indice à la pondération des différentes variables. Ces travaux soulignent le fait que les stratégies de conservation et de gestion au Canada devront s'adapter aux motifs changeants du climat et de l'activité humaine. [Traduit par la Rédaction]

Introduction

Fish communities within freshwater ecosystems are shaped by continental-scale patterns, such as glaciation and recolonization, and local patterns, such as lake morphometry, water quality, and biotic interactions (Tonn 1990; Jackson et al. 2001). Human activities can negatively affect communities and alter the natural functioning of these ecosystems. The scale of these activities, stressors on the systems, and their impacts can be localized or pervasive (Fitzhugh and Richter 2004). Local and regional stressors can be direct, such as overexploitation, or cumulative, such as diffuse effects of habitat degradation associated with physical (e.g., barriers, shoreline hardening, and watershed deforestation) and chemical (e.g., nutrient transport disruption and point source contaminant loads) alterations throughout a watershed. Pervasive stressors, such as climate change and the introduction of invasive species, can have long-term and broad-scale consequences. Collectively, these multiple stressors affect the health and productivity of aquatic ecosystems and fisheries resources (Schindler 2001; Magurran 2009).

Maintaining and restoring the health of these ecosystems requires an understanding of the relative impacts of stressors and identification of reference points and targets that account for a stakeholder-negotiated level of allowable alteration or harm (Karr and Chu 1999). In some cases, the targets can be achieved through effective management action (e.g., prevention of the introduction of invasive species) or through mitigation and compensation (e.g.,

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habitat manipulations). Assessing the health of these ecosystems also requires quantification of the stressors themselves.

In 2003, Chu et al. (2003) developed conservation priority rankings for all of Canada's tertiary watersheds using indices of freshwater fish biodiversity, environmental conditions, and anthropogenic stressors. Tertiary watersheds, which are part of a national hierarchy of drainages across Canada, were used in the analysis because watershed assessments incorporate both the multiple scales and cumulative nature of stressors (Stroud 1992; Foran et al. 2000; Dubé et al. 2013). Watershed assessments also capture the connectivity among water bodies that may allow the impacts of stressors to spread downstream. Chu et al. (2003) summarized the biodiversity of both riverine and lake fish species for each watershed and found a "ring" of rare species around Canada and high species richness along the southern border. The environmental index was based on the 1961–1990 climate normals of growing degree-days above 5 °C, mean annual sunshine hours, mean annual vapour pressure, as well as the elevation range in the watersheds. This index decreased from south to north, a trend that was consistent with patterns in the diversity and structure of zooplankton communities in Canadian lakes (Pinel-Alloul et al. 2013) and aquatic productivity (Rigler 1977). Population census and business patterns data from 1996 were used to describe the anthropogenic stressors. The stress index had high values along the southern border of Canada and in central Alberta and British Columbia. All three indices were combined to show that watersheds in southern Ontario, southern Quebec, British Columbia, and the Maritimes had high conservation priority because they support diverse fish communities and productive environments and, at the same time, are at risk from anthropogenic stressors.

Since 1996, Canada's population has grown from approximately 28.8 to 35.1 million, with much of that growth occurring in metropolitan areas (Statistics Canada 2013). High-profile resource development of the Tar Sands in Alberta and potential development in the Ring of Fire (northern Ontario), as well as declines in timber harvest and the number of operational farms (Kelly et al. 2010; Canadian Council of Forest Ministers 2012; Statistics Canada 2012), have changed the stress landscape. At the same time, climate trends have shown regional changes in warming and precipitation (Qian et al. 2010). The objectives of this study were to examine the changes in the indices developed by Chu et al. (2003) using more recent environmental and stressor data and evaluate the robustness of the conservation prioritization algorithm (how the biodiversity, environmental, and stress indices are combined) under three different scenarios that reflected different conservation and management targets. These scenarios were (*i*) equal weighting to all three indices, (*ii*) prioritization of watersheds with species listed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), and (*iii*) prioritization of watersheds with high levels of anthropogenic stress.

Methods

Several datasets were needed to examine the patterns in freshwater fish biodiversity (BIO), environmental conditions (ENV), and anthropogenic stress (STR) in the tertiary watersheds across Canada. Tertiary watersheds are part of a standard four-level hierarchy representing, at the highest order, large-scale drainage patterns to the oceans, and at the lowest order, small-scale drainage to rivers (Water Survey of Canada 1977). In Canada, there are 953 tertiary watersheds that range in area from 131.4 to 135 652.4 km².

The same freshwater fish biodiversity data used in Chu et al. (2003) were used for this study (N.E. Mandrak, Great Lakes Laboratory for Fisheries and Aquatic Sciences, unpublished data). Although the distributions of some species have changed (Alofs et al. 2014), these changes have not been assessed for all freshwater fishes in Canada. Freshwater fish biodiversity was described in Chu et al. (2003) using a commonness (*I*), rareness (*Q*), and biodiversity (BIO) index developed by Minns (1987). The following equations describe the distribution of species among watersheds and the metrics we used to compare the fish communities among watersheds.

The first metric, q_j, defines the distributional attributes of each individual fish species across watersheds:

$$q_j = 1 - \sum_{i=1}^{n} S_{ij} / n \tag{1}$$

where q_j is species priority given their proportional occurrence, S_{ij} is presence (1) or absence (0) of species *j* in watershed *i*, and *n* is total number of watersheds. Well-distributed species have values close to 0 (low species priority), whereas rare species have values close to 1 (high species priority) (i.e., q_j is weighted towards rare species because their limited distributions may make them more susceptible to habitat alterations and (or) degradation associated with some human activities). They also may require higher conservation prioritization and management than common species (Minns 1987).

Metrics to define *I* and *Q* of the fish community in each watershed were then calculated as follows:

$$I = \sum_{j=1}^{m} S_{ij}q_j / \sum_{j=1}^{m} q_j \tag{2}$$

where *m* is the number of species and can be thought of as the relative diversity and commonness of the fish community in each watershed. It is calculated as the sum of the species priorities of all species present in the watershed of interest divided by the sum of the priorities for all species in all watersheds (229 species) (Minns 1987).

Q is calculated as follows:

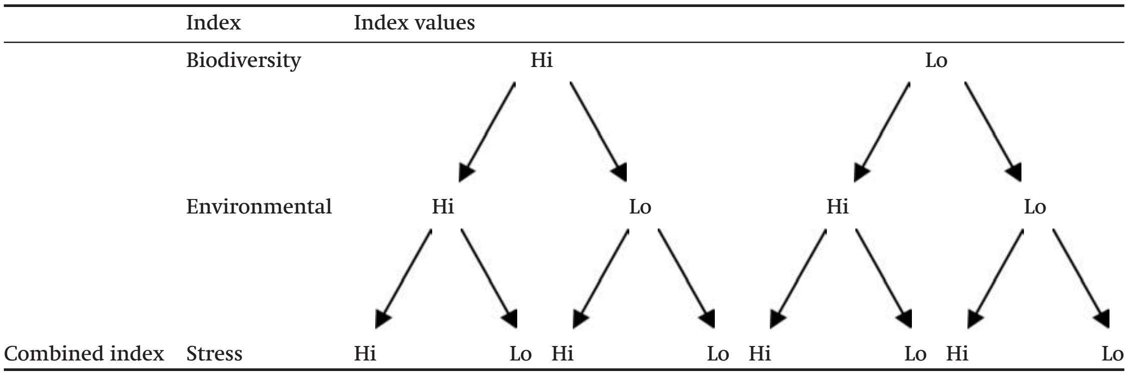
$$Q = \sum_{j=i}^{m} S_{ij}q_j / \sum_{j=1}^{m} S_{ij} \tag{3}$$

and can be thought of as the mean priority of the species present in the watershed of interest. It is calculated as the sum of the species priorities within a watershed divided by the number of species in that watershed.

Based on these indices, watersheds with comparatively high *I* will have communities with high species richness, whereas watersheds with high *Q* values will have communities composed of rare species. *I* and *Q* were combined into the biodiversity index (BIO) as $(I + Q)/2$ (Minns 1987). Therefore, communities with comparatively high BIO index values should have communities with many common and nationally rare species. Jenks natural breaks classification method (Jenks 1967), which determines classes by reducing the variance within classes and maximizing the variance among classes, was used to categorize the BIO index values.

To evaluate the behaviour of the three indices against known biodiversity values, the commonness, rareness, and biodiversity index values were plotted against the number of species assessed as Extinct, Endangered, Threatened, or Special Concern by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2014), and "species richness" is defined here as total number of species in each watershed minus the number of COSEWIC species. COSEWIC species richness provided proxy measurements of community rareness in each watershed, as many of these species are listed because they have limited ranges across Canada. We excluded taxa assessed by COSEWIC below the species level

Table 1. Classification of freshwater fish biodiversity, environmental conditions, and anthropogenic stressors in Canada's tertiary watersheds into an eight-level combined index.



Note: "Hi" and "Lo" are based on the 50th percentile of each index in Chu et al. 2003.

(e.g., large and small-bodied rainbow smelt (*Osmerus mordax*) occurring in Lake Utopia) (COSEWIC 2014). This produced a list of 49 COSEWIC species for our analyses. Species richness, as we have defined it, provided a proximate measure of the total number of common (non-COSEWIC) species in each watershed.

In Chu et al. (2003), a principal component analysis showed that much of the variation in environmental conditions was described by four variables: growing degree-days above 5 °C (GDD5); mean annual sunshine hours (SUNSHINE); mean annual vapour pressure (VAPOUR); and elevation range in the watershed (ELEVATION). The same variables were used in this study to develop an environmental index (ENV), except in this case, they were based on more recent climate norms (i.e., 1981–2010; Environment Canada 2013). Therefore, the environmental changes reported in this study are driven by changes in climatic variables: GDD5, SUNSHINE, and VAPOUR. Inverse distance weighting was used to interpolate among climate stations to generate continuous maps of GDD5, SUNSHINE, and VAPOUR. Zonal statistics were used to calculate the area-weighted values of each variable in each watershed. Elevation range values were the same as Chu et al. (2003). All spatial analyses were performed in ArcGIS 9.3 (Environmental Systems Research Institute Inc., Redlands, California, USA).

The STR index was developed using Census of the Population data from 2006 (Statistics Canada 2007) and Canadian Business Patterns from 2008 (Statistics Canada 2008). Data from the more recent 2011 population census were not used because of changes in the format and number of households polled (Coleman 2013). Canadian Business Patterns from 2011 were not readily available at the time of our study. The population census provided the dwelling densities in each watershed, whereas the business patterns data were used to calculate the densities of crop farms, forestry operations, petroleum manufacturers, waste and remediation facilities, and discharge sites (industrial chimneys and laundry facilities) in the watersheds (as in Chu et al. 2003). The population census and business pattern data are summarized by census subdivisions. The tertiary watershed boundaries were overlaid onto the census subdivisions and zonal statistics were used to estimate the area-weighted mean value for each variable in each watershed. These values were then divided by the total area of each watershed and multiplied by 1000 to standardize the densities to number·1000 km^{-2}. Road densities in each watershed were estimated from the National Road Network (Natural Resources Canada 2007). The total lengths of all roads in each watershed were calculated in ArcGIS 9.3, divided by the total area of each watershed, and multiplied by 1000 to standardize the densities to road length km·1000 km^{-2}. All variables were $\log_{10}(x + 1)$-transformed. The log-transformed values for each variable were divided by the maximum value of that variable in the Chu et al. (2003) dataset. These calculations ensured that the present values were comparable to Chu et al. (2003), in which the values for each variable were standardized to a maximum of one using the maximum value across all watersheds.

The standardized values for the four environmental variables were averaged to produce an ENV index value for each watershed. The STR index for each watershed was calculated as the mean of the standardized values for the seven stressor variables. Changes in the ENV (1961–1990 versus 1981–2010) and STR (1996 versus 2006/2008) indices for the two time periods were calculated as absolute differences and effect sizes (Cohen's *d*). The differences were mapped to determine if regional patterns of change could be identified. Jenks natural breaks classification method (Jenks 1967) was used to group the differences in the STR index (STR had a greater range of differences than the ENV index) for comparison and mapping purposes. These categories were applied to the ENV index to compare how the ENV and STR index maps differ between time periods. Differences in the underlying environmental or stressor variables were calculated for the 10 watersheds that showed the greatest and least change in the indices to provide a general understanding of how the underlying variable changes translated into changes in the indices.

The BIO, ENV, and STR indices were combined to produce an eight-category "combined index" (Table 1). To be comparable to the findings in Chu et al. (2003), the values for each index in each watershed were assigned a "Hi" or "Lo" designation based on the 50th percentiles of the BIO, ENV, and STR indices from Chu et al. (2003). The eight-category combined index represented all combinations of the Hi and Lo values for the BIO, ENV, and STR indices (e.g., Hi BIO – Lo ENV – Lo STR or Lo BIO – Hi ENV – Hi STR (Table 1). To compare the combined index between time periods, we counted the number of watersheds within each category and examined the spatial distributions of the eight categories.

Our approach for setting the conservation priorities diverged from Chu et al. (2003) to demonstrate how priority rankings of the watersheds may differ when management and (or) conservation objectives differ and to assess the robustness of our prioritization approach. Three scenarios were designed to address some of the existing management and conservation targets for Canadian watersheds: the management and conservation of COSEWIC species and freshwater biodiversity and prioritization of stressed watersheds for restoration and management (Fisheries and Oceans Canada 2009). As mentioned above, to compare the indices between the past and more recent time periods, the values for each index in each watershed were assigned a Hi or Lo designation based on the 50th percentiles of the BIO, ENV, and STR indices from Chu et al. (2003) for the 1961–1990 and 1996 time periods. Scenario A weighted the BIO, ENV, and STR indices equally, with Hi getting a score of +1 and Lo getting a score of –1. All nine unique combinations of the Hi and Lo values for each index produced a conservation priority scheme with four categories: Critical, High, Moderate, and Low (Table 2). Watersheds with comparatively

Table 2. Criteria for three conservation prioritization scenarios with different combinations of the "Hi" and "Lo" values (based on 50th percentile of the indices in Chu et al. 2003) of the biodiversity (BIO), environmental (ENV), and stress (STR) indices.

Index			Priority weighting scores				
BIO	ENV	STR	BIO	ENV	STR	Sum of priority scores	Conservation priority
Scenario A*							
Hi	Hi	Hi	1	1	1	3	Critical
Hi	Hi	Lo	1	1	–1	1	High
Hi	Lo	Hi	1	–1	1	1	High
Hi	Lo	Lo	1	–1	–1	–1	Moderate
Lo	Hi	Hi	–1	1	1	1	High
Lo	Hi	Lo	–1	1	–1	–1	Moderate
Lo	Lo	Hi	–1	–1	1	–1	Moderate
Lo	Lo	Lo	–1	–1	–1	–3	Low
Scenario B†							
Hi	Hi	Hi	1	1	1	3	Critical
Hi	Hi	Lo	1	1	–1	1	High
Hi	Lo	Hi	1	–1	1	1	High
Hi	Lo	Lo	1	–1	–1	–1	Moderate
Lo	Hi	Hi	–1	1	1	1	High
Lo	Hi	Lo	–1	1	–1	–1	Moderate
Lo	Lo	Hi	–1	–1	1	–1	Moderate
Lo	Lo	Lo	–1	–1	–1	–3	Low
Scenario C‡							
Hi	Hi	Hi	1	0	2	3	Critical
Hi	Hi	Lo	1	0	0	1	Moderate
Hi	Lo	Hi	1	0	2	3	Critical
Hi	Lo	Lo	1	0	0	1	Moderate
Lo	Hi	Hi	0	0	2	2	High
Lo	Hi	Lo	0	0	0	0	Low
Lo	Lo	Hi	0	0	2	2	High
Lo	Lo	Lo	0	0	0	0	Low

*Equal weight to BIO, ENV, and STR indices.

†Hi and Lo for biodiversity index based on presence (Hi) or absence (Lo) of COSEWIC listed species.

‡Stress index ranked highest followed by biodiversity with environmental index having no influence on the conservation priorities.

Hi BIO were given greater priority than watersheds with Lo BIO. Watersheds with Hi ENV generally were associated with warmer conditions (greater GDD5) than watersheds with Lo ENV. We assigned higher scores to Hi ENV watersheds than Lo ENV watersheds in Scenarios A and B because Canadian watersheds are in temperate and Arctic climates where coolwater and warmwater species distributions may be limited by the availability of suitable thermal habitat. Therefore, we assumed that Hi ENV watersheds have a greater likelihood of containing both coldwater (e.g., headwaters of streams, hypolimnion of lakes) and warmer water habitats (e.g., outlet reaches of streams and warmer epilimnetic waters than lakes in cooler (Lo ENV) environments) and therefore support more diverse fish communities. As shown in Chu et al. (2003), species richness generally increases with increases in growing degree-days. Hi STR watersheds were prioritized above Lo STR watersheds because anthropogenic changes impact aquatic habitats to varying degrees, and the cumulative effects of multiple stressors would have a greater impact on the environment and biota than comparatively fewer stressors. On one end of the spectrum, watersheds with Hi BIO – Hi ENV – Hi STR levels were given Critical conservation priority, and on the other, watersheds with Lo BIO – Lo ENV – Lo STR were given Low conservation priority (Table 2).

For Scenario B, the occurrence of COSEWIC species were used to generate the BIO index instead of *I* and *Q*. Watersheds with COSEWIC species in the fish community were given a score of +1, whereas watersheds without COSEWIC species were given a score of –1. The BIO, STR, and ENV indices were again given equal weight (Table 2).

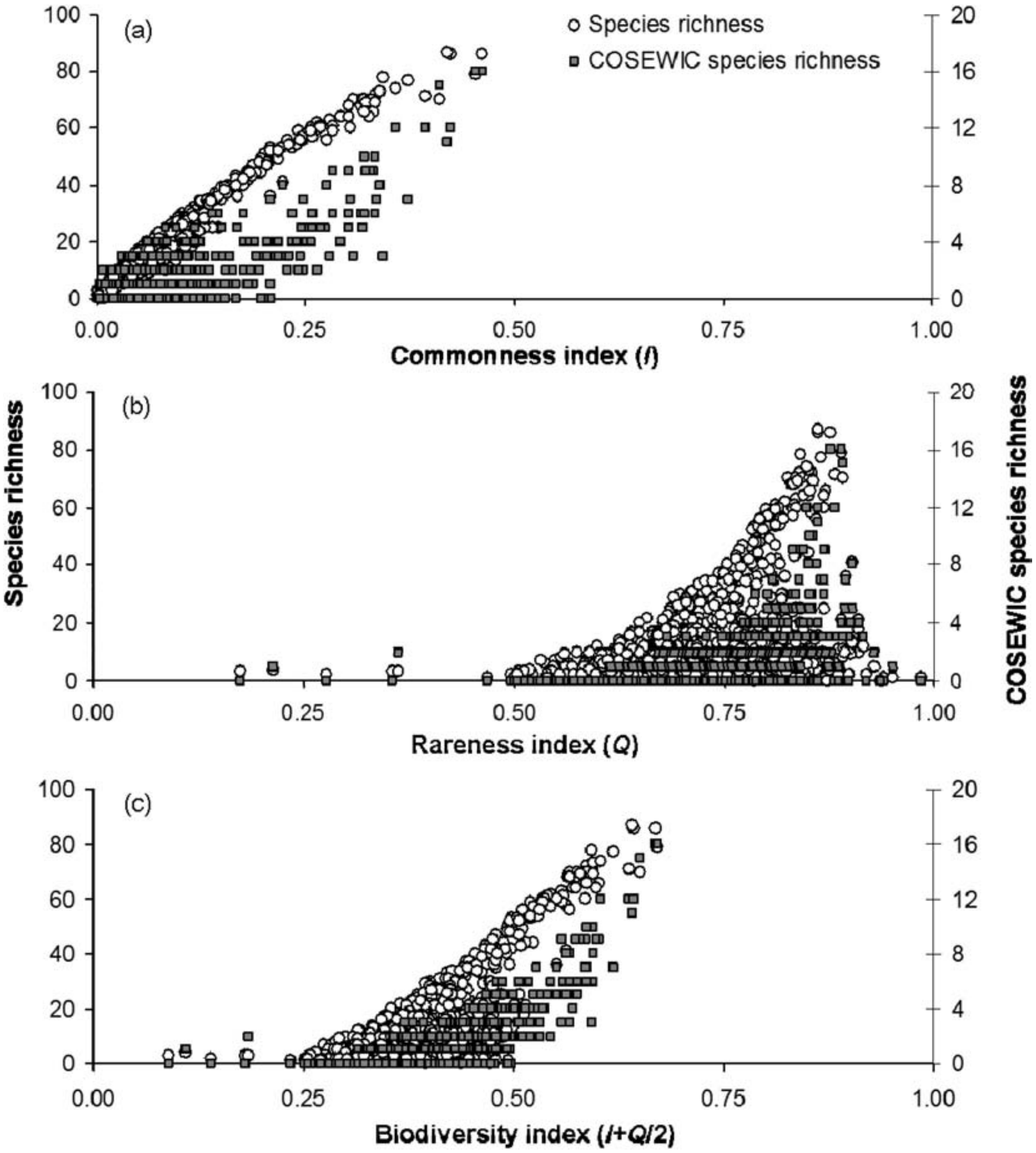
For Scenario C, conservation priorities were calculated by weighting the indices from highest to lowest: STR > BIO > ENV, with ENV having a neutral effect on priorities. This scenario assumed that watersheds with the greatest stress would require the greatest amount of conservation, restoration, and (or) management. This was also the only scenario to assign different weights to the BIO, ENV, and STR indices (Table 2).

These updated criteria for the conservation priorities under the three scenarios were applied to the BIO, ENV, and STR of the past and more recent index data so comparisons could be made between time periods. The sensitivity of the watersheds to the conservation priority criteria (relative weighting) and robustness of the nationwide pattern in conservation priorities were assessed by summarizing, for each watershed, any changes in priority. For example, a watershed that was categorized as Critical for the past (Chu et al. 2003) time period with Scenario A but High for the same or a different scenario in the more recent time period was flagged as "Critical–High". This allowed us to identify watersheds that have the same conservation priority regardless of time period or scenario. It also allowed us to identify watersheds sensitive to changes in the priority criteria and (or) the watersheds in which changes in their ENV or STR indices were enough to shift them from Hi to Lo or Lo to Hi (thus possibly changing their priority) between time periods.

Results

Plots of the *I*, *Q*, and BIO indices against species richness and number of COSEWIC species in each watershed indicated that the

Fig. 1. Committee on the Status of Endangered Wildlife in Canada (COSEWIC) species richness and species richness (total species richness – COSEWIC species richness) versus (*a*) commonness (*I*), (*b*) rareness (*Q*), (*c*) biodiversity index values for 953 tertiary watersheds in Canada.



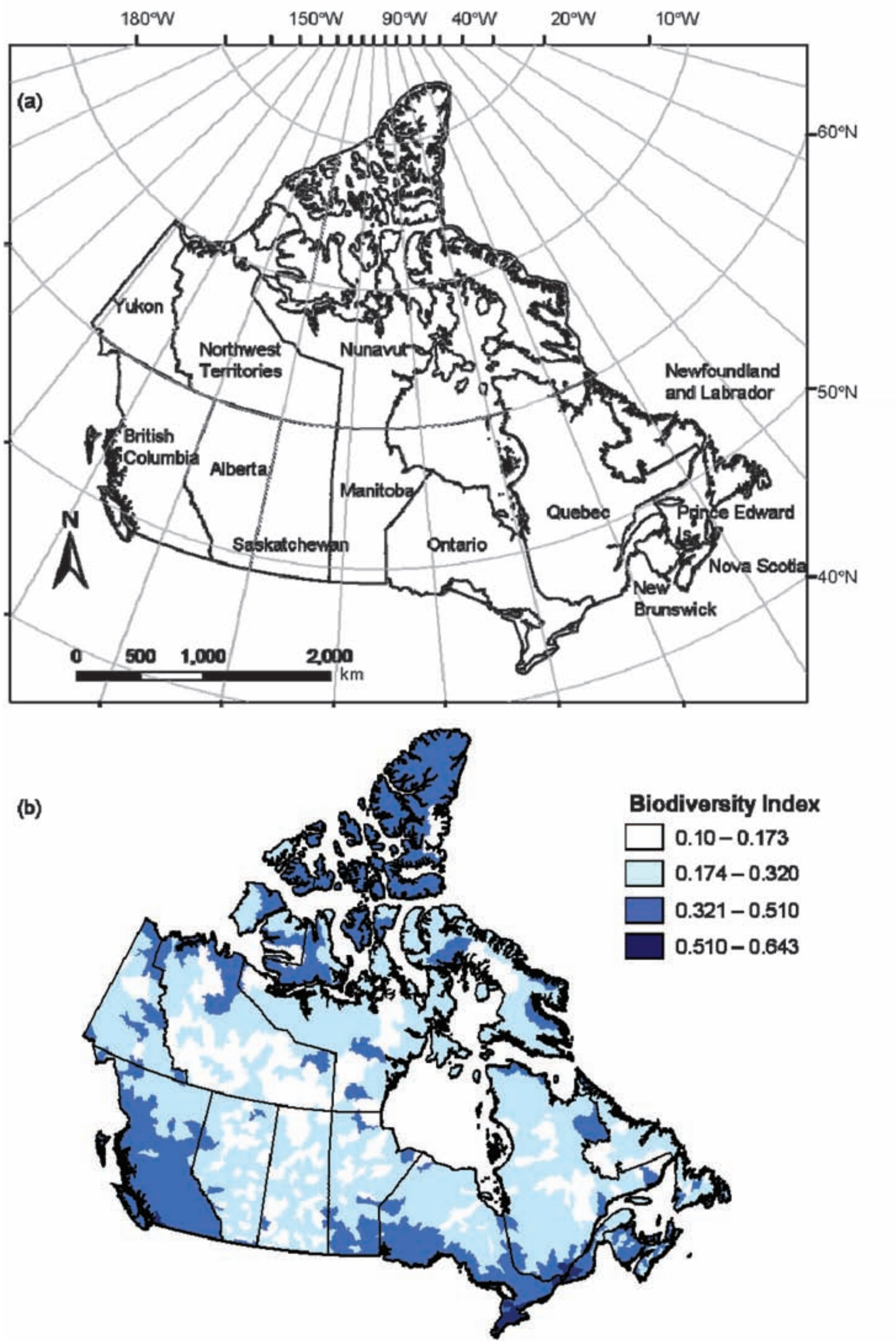
general relationship between rarity and commonness indices are as expected; watersheds with high *I* had high species richness, whereas watersheds with the highest *Q* had fish communities with ≤5 very rare species (Fig. 1). Watersheds with the highest BIO values had communities composed of many common and COSEWIC species, while watersheds with the lowest values had fish communities with few common or rare species (Fig. 1).

The fish biodiversity data were not updated for this current study. Therefore, the patterns of biodiversity remained the same as in Chu et al. 2003. Watersheds in southern Ontario, Quebec, and British Columbia had the highest BIO values (BIO > 0.50) and had fish communities composed of many common and rare species (Fig. 2). The most northern Arctic watersheds fell within the second highest biodiversity category because they had high *Q* values, indicating the sensitivity of the index to rare taxa even in depauperate communities. Watersheds with the lowest BIO values were generally centrally located in the Northwest Territories, Alberta, Saskatchewan, and southern Nunavut (Fig. 2*b*). These watersheds had few common or rare species.

Changes in the ENV index in the watersheds reflected changes in climatic conditions (growing degree-days above 5 °C, sunshine hours, and vapour pressure) between the 1961–1990 and 1981–2010 periods. Nationally, GDD5 increased by approximately 12%, but mean annual sunshine hours and mean vapour pressure decreased by less than 10% between periods (Table 3). The ENV index was highest in British Columbia, the Yukon, southern Ontario, southern Quebec, New Brunswick, and Nova Scotia (Table 4; Fig. 3). Between the two time periods, the ENV index increased in 670 watersheds, decreased in 245, and remained the same in 38 watersheds. Cohen's effect size between the two time periods was minimal (d = 0.11). The greatest increases were in Arctic watersheds and were due to increases in growing degree-days and sunshine hours (Table 5; Fig. 3). The ENV index decreased the most in Northwest Territories and southern Nunavut watersheds and was attributed to decreases in sunshine hours and vapour pressure (Table 5).

The STR index changed more than the ENV index (Figs. 3*e* and 3*f*). Nationally, the densities of crop farms, petroleum manufacturers,

Fig. 2. Canadian provinces (*a*) and biodiversity index values (*b*) for 953 tertiary watersheds throughout Canada. Watersheds with the greatest biodiversity values have fish communities composed of many common and rare species.



waste facilities, dwellings, and roads increased across the country, whereas forestry operations and discharge sites decreased between the two time periods (Table 3). Stress levels decreased in 478 watersheds, increased in 466 watersheds, and remained the same in nine watersheds. Cohen's effect size of the STR index values between the two time periods was $d = 0.04$. Regions with the highest STR index values were still in the Maritimes, southern Quebec, south-central Ontario, southern Manitoba, and much of Alberta and British Columbia (Table 4; Fig. 3). The regions with the highest increases in stress were Nova Scotia and watersheds in the northern regions of Ontario, Saskatchewan, Alberta, and British Columbia. The STR index decreased in south-central British Columbia and Quebec, New Brunswick, Newfoundland and Labrador, and southern Saskatchewan (Fig. 3). On average, the 10 watersheds with the greatest decreases in the STR index had decreases in crop, forestry, petroleum, waste facilities, and discharge sites (Table 5). Watersheds with the greatest increases had increases in all of the stress variables.

In British Columbia, increases in the STR index in the north and decreases in the south were related to corresponding changes in the number of crop farms and forestry operations. In Alberta, decreases in the STR index in some watersheds were associated with decreases in crop farms, forestry, and waste facilities, while

Table 3. Descriptive statistics of variables used to develop the environmental and anthropogenic stress indices for 953 tertiary watersheds across Canada.

		Past		Recent	
Index	Variable	Mean	SD	Mean	SD
Environmental	Elevation range (m)	699.18	428.56	699.18	428.56
	Growing degree-days (5 °C)	1129.57	475.69	1283.97	461.84
	Mean annual duration of bright sunshine hours (h)	1915.37	232.36	1904.76	221.92
	Mean annual vapour pressure (kPa)	0.68	0.13	0.65	0.15
Stress	Crop farms (number·1000 km^{-2})	2.85	9.64	3.80	9.70
	Forestry operations (number·1000 km^{-2})	2.36	6.42	1.91	5.33
	Petroleum manufacturers (number·1000 km^{-2})	0.18	3.01	0.33	5.18
	Waste management and remediation facilities (number·1000 km^{-2})	0.32	2.11	0.82	4.22
	No. of dwellings (number·1000 km^{-2})*	568.15	2084.30	658.96	2415.95
	No. of discharge sites (industrial chimneys and laundry facilities) (number·1000 km^{-2})	1.76	3.85	1.30	5.36
	Road density (km·1000 km^{-2})*	464.40	3777.76	751.30	5767.12

Note: Past environmental conditions were for 1961–1990 and 1996 for anthropogenic stress, and recent environmental conditions were for 1981–2010 for the environmental conditions and 2006/2008 for anthropogenic stress. SD is standard deviation.

*The values reported in Chu et al. (2003, their table 2) for these variables were the raw values, not the densities.

Table 4. Provincial summaries of mean ± standard deviation of biodiversity, environmental, and stress index values in tertiary watersheds across Canada.

			Environmental		Stress	
Province	No. of watersheds	Biodiversity	1961–1990	1981–2010	1996	2006/2008
British Columbia	111	0.49±0.05	0.89±0.02	0.89±0.14	0.22±0.02	0.19±0.11
Alberta	115	0.37±0.05	0.83±0.04	0.83±0.09	0.27±0.03	0.28±0.08
Saskatchewan	80	0.35±0.10	0.81±0.02	0.82±0.10	0.17±0.02	0.16±0.10
Manitoba	80	0.44±0.06	0.80±0.01	0.80±0.06	0.17±0.01	0.16±0.06
Ontario	131	0.57±0.04	0.86±0.03	0.85±0.08	0.28±0.02	0.26±0.07
Quebec	138	0.44±0.06	0.82±0.05	0.84±0.04	0.17±0.04	0.14±0.03
New Brunswick	28	0.45±0.03	0.86±0.00	0.87±0.05	0.24±0.01	0.27±0.12
Prince Edward Island	5	0.48±0.05	0.84±0.05	0.84±0.01	0.22±0.03	0.24±0.01
Nova Scotia	44	0.44±0.15	0.85±0.03	0.87±0.12	0.24±0.03	0.48±0.13
Newfoundland and Labrador	51	0.37±0.01	0.83±0.01	0.84±0.02	0.14±0.01	0.11±0.02
Northwest Territories	66	0.35±0.11	0.81±0.05	0.79±0.12	0.04±0.05	0.04±0.11
Nunavut	63	0.39±0.05	0.71±0.01	0.71±0.07	0.01±0.01	0.01±0.04
Yukon	40	0.40±0.04	0.86±0.03	0.89±0.04	0.06±0.02	0.10±0.03

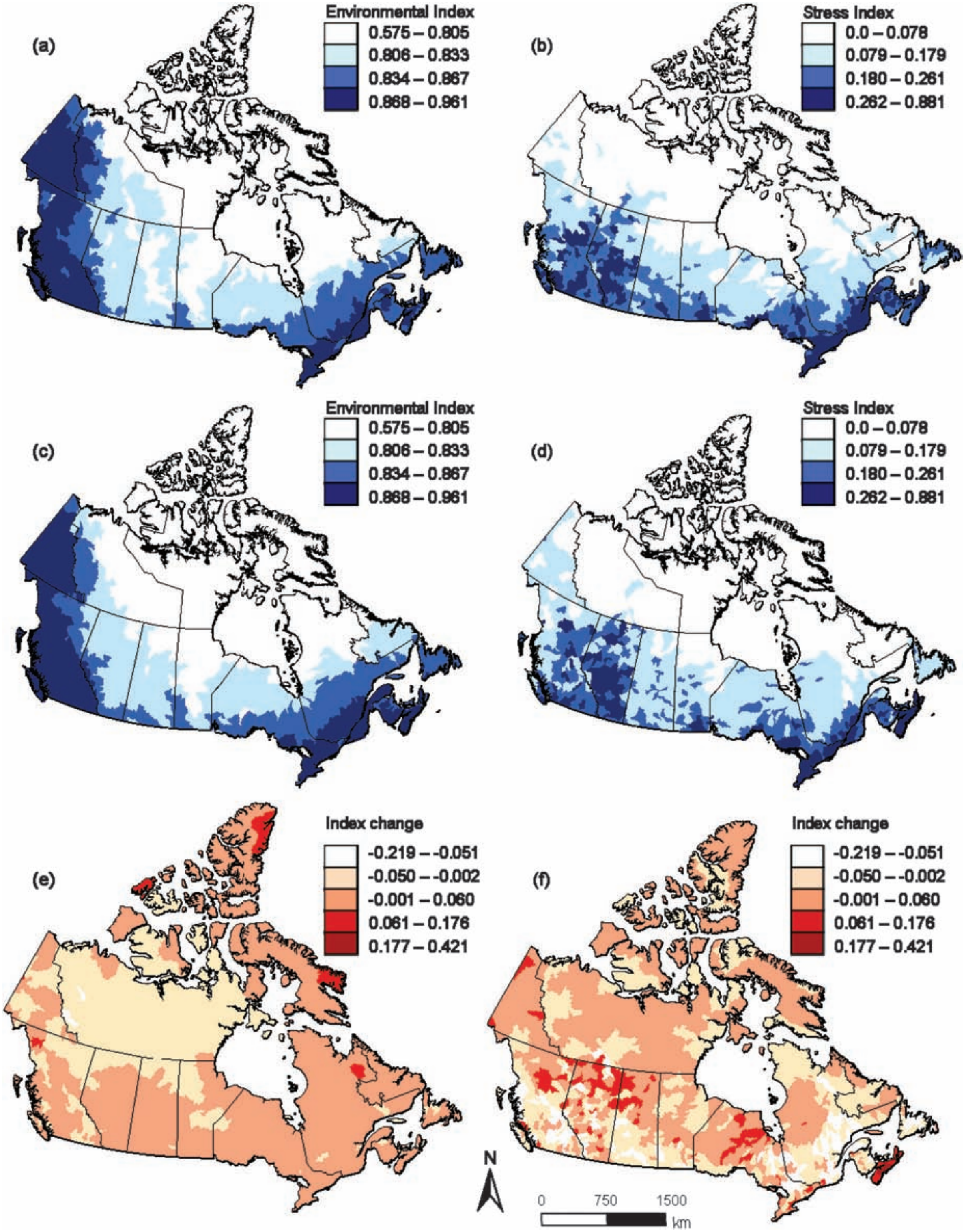
increases were associated with increases in all of the stressors. Saskatchewan's STR index increased in northern watersheds and decreased in southern watersheds. Increases were due to more crop farms, dwellings, and roads in the north and the decline in the number of crop farms in the south. Ontario followed the same pattern as Saskatchewan with increases in the north, but the increases were due to increases in all of the stressors. Decreases in the STR index in Quebec were associated with decreases in crop farms, forestry, and discharge sites. Declines in New Brunswick were also associated with decreased forestry activities, crop farms, and waste facilities. Nova Scotia was the only province in which stress increased in all of the watersheds and was attributable to increases in the road and dwelling densities (Fig. 3). The STR index decreased in Newfoundland and Labrador because of decreases in crop farms, forestry, and waste facilities, whereas increases in the Yukon were due to increases in the number of forestry operations and dwellings.

The overall pattern in the combined index changed little between time periods (Fig. 4). The most pronounced changes were found in northern Ontario and in southern watersheds in British Columbia, Alberta, and Saskatchewan. The number of watersheds within six of the categories of the combined index decreased between the two study periods (Table 6).

Conservation priority criteria were updated for this study. For Scenario A, in which the BIO, ENV, and STR were given equal weight, watersheds along the southern region of the country were given higher conservation priorities than northern watersheds (Figs. 5*a* and 5*d*). Watersheds with Critical priority were found throughout British Columbia, southern Ontario and Quebec, and the Maritimes. Watersheds with Low priority were found throughout northern regions of most provinces and much of the Northwest Territories and Nunavut. Between time periods, conservation priorities decreased in 119 watersheds, increased in 97 watersheds, and remained the same in 737 watersheds. Watersheds with increases in priority were found in northern British Columbia, throughout Alberta, southern Saskatchewan, northern Ontario, and central Quebec (Fig. 5*g*). Watersheds with decreased priority were predominantly in the Northwest Territories and southern British Columbia, Saskatchewan, and Quebec. The number of watersheds classified as Critical or Low priority decreased, and the number of watersheds categorized as High and Moderate increased (Table 7).

For Scenario B, in which the biodiversity index was replaced with the presence (Hi) or absence (Lo) of COSEWIC species, watersheds in south-central British Columbia, western Alberta, southern Ontario and Quebec, and the Maritimes were given Critical priority (Figs. 5*b* and 5*e*). Watersheds in Nunavut, much of the Northwest Territories, and the northern regions of Saskatchewan, Manitoba, Ontario, Quebec, and Labrador were categorized as Low priority. Between time periods, the conservation priority for 89 watersheds increased, while priorities decreased for 85 watersheds. The locations of the watersheds with increases or decreases in priority were similar to Scenario A (Figs. 5*g* and 5*h*). The number of watersheds classified as Critical, Moderate, and Low priority

Fig. 3. Tertiary watershed environmental index values for (*a*) 1961–1990, (*c*) 1981–2010, and (*e*) the difference (recent – past) between the two time periods and anthropogenic stress index values for (*b*) 1996, (*d*) 2006/2008, and (*f*) the difference (recent – past) between the two time periods.



watersheds decreased by 20, 3, and 12, respectively, while High priority watersheds increased by 35 (Table 7).

Scenario C weighted the stress index higher than the biodiversity and environmental indices. Critical and High priority watersheds were found throughout British Columbia and Alberta and southern regions of Saskatchewan, Manitoba, Ontario, Quebec, and the Maritimes (Fig. 5*c*). The overall pattern was similar between time periods. Conservation priorities increased in 39 watersheds throughout the north-central regions of British Columbia, Alberta, Saskatchewan, Manitoba, and Ontario and decreased in 84 watersheds throughout the southern regions of most of the provinces (Fig. 5*i*). The number of watersheds with Critical and

Table 5. Mean differences in environmental and stressor variables for watersheds that showed the greatest decrease (n = 10) or increase (n = 10) in the environmental (ENV) and stress (STR) index, that is, 20 watersheds for ENV and a different group of 20 watersheds for STR.

Variable	ENV decrease	ENV increase	STR decrease	STR increase
Growing degree-days (5 °C)	131.73	216.48		
Mean annual duration of bright sunshine hours (h)	–13.66	21.688		
Mean annual vapour pressure (kPa)	–0.25	–0.11		
Crop farms (number·1000 km^{-2})			–9.48	19.31
Forestry operations (number·1000 km^{-2})			–50.53	19.24
Petroleum manufacturers (number·1000 km^{-2})			–0.42	1.74
Waste management and remediation facilities (number·1000 km^{-2})			–1.08	30.12
No. of dwellings (number·1000 km^{-2})			2 557.69	12 841.38
No. of discharge sites (industrial chimneys and laundry facilities) (number·1000 km^{-2})			–2.70	1.46
Road density (km·1000 km^{-2})			862.86	1 727.28

High priority decreased by 37 and 6, respectively, while the number of watersheds with Moderate and Low priority increased by 37 and 6, respectively (Table 7).

The patterns in conservation priorities were similar for the three scenarios (Fig. 5). Priorities were highest in the south and decreased in the northern regions of Canada. Across all three scenarios, conservation priorities increased in northern British Columbia, Alberta, and Ontario, but decreased in southern British Columbia, Saskatchewan, and Quebec. The number of watersheds with Critical priority decreased in the more recent time period for all of the scenarios (Table 7). Scenario A, which used the BIO index, had approximately 50 more Critical watersheds than Scenario B, which ranked Hi or Lo biodiversity based on the occurrence of COSEWIC species (Table 7). Scenario C had more Critical watersheds than Scenarios A or B, but also had the greatest number of Low ranked watersheds. There was no consistent trend in the number of watersheds categorized as High, Moderate, or Low between time periods and scenarios (Table 7).

Sensitivity analysis of the prioritization approach indicated that 30% of the 953 tertiary watersheds in Canada were summarized as Critical (n = 143), High (n = 28), Moderate (n = 9), or Low (n = 107), regardless of time period or scenario (Fig. 6). These Critical watersheds were located in southern British Columbia, Ontario, Quebec, and the Maritimes, and many of the watersheds surrounding them (n = 130) were summarized as Critical–High. High–Moderate and High–Moderate–Low watersheds were mostly found in the central regions of the provinces and the western region of the Northwest Territories and Yukon and represented 24% (231 watersheds) of the 953 watersheds (Fig. 6). Watersheds (n = 205) throughout the central and northern regions of the country were classified as Moderate–Low. In general, conservation priorities for both time periods and the three scenarios were more robust in the south and north, with a mix of priorities reflecting changes in the ENV and STR indices and sensitivities to the priority criteria in the central regions of Canada (Fig. 6).

Discussion

Warming trends in climate, expansion of metropolitan centres, and changes in resource development have affected regional patterns of environmental conditions and anthropogenic stressors across Canada. Our study demonstrates how these changes can be quantified and classified into conservation priorities for Canadian watersheds that can be used to guide conservation and management.

The ENV and STR indices both increased northward between the two time periods. However, an effect size of d = 0.11 suggested that there was little change in the national mean ENV index between the two time periods. Spatially, the greatest increases were in six northern watersheds. This pattern was related to the increase in GDD5 and is consistent with climate trends, which show that northern latitudes of Canada are warming at faster rates than the rest of the country (Chylek et al. 2009). Declines in the ENV index (364 watersheds) were consistently associated with decreases in vapour pressure. This is consistent with New et al. (2000), who found similar decreasing vapour pressure trends throughout the Northwest Territories and Prairies between 1975 and 1995. Isaac and Van Wijngaarden (2012) found that summer and spring vapour pressure has been decreasing in the Northwest Territories, but the national pattern shows that vapour pressure has been increasing at different rates across the country from 1948 to 2010.

Effect size of the stress index was minimal (d = 0.04) between the two time periods, but there were spatial differences, which reflected a northern expansion of human activities. The most pronounced increases in stress were in the northern regions of British Columbia, Alberta, Saskatchewan, Ontario, and much of Nova Scotia. When ranked by mean stress, the provinces from lowest to highest are Nunavut, Prince Edward Island, Northwest Territories, Yukon, Saskatchewan, New Brunswick, Newfoundland and Labrador, British Columbia, Manitoba, Quebec, Alberta, Nova Scotia, and Ontario. The most stressed watersheds, defined as those with STR values greater than the 99th percentile, were found in Alberta, Ontario, and New Brunswick in 2003 and in Alberta, Ontario, and Nova Scotia in 2013. Dwelling density and road density increased consistently across the country. Watersheds with metropolitan areas saw increases in stress as the human population grew by 2.8 million between 1996 and 2006, with much of that growth in urban centres (Statistics Canada 2007). The density of roads increased as more roads were built, and in some areas, rural roads were also added to the National Road Network (Natural Resources Canada 2007).

It should be noted that our approach does not evaluate the conditions of the watersheds in the wake of decreases in stress. There could be persistent or delayed legacy impacts from activities like industrial logging that negatively affect ecosystems long after the activity has ended (Murphy and Koski 1989; Harding et al. 1998). Alternatively, watersheds could be responding positively to the decreases in stress. Future studies are needed to determine how quickly biodiversity may respond to decreases or increases in stress and to examine the ecological processes by which biodiversity, environment, and stress are linked.

Our indices provide guidelines for monitoring, research, and management. The STR index has been adopted in Ontario as one of the indicators for State of Biodiversity reporting as part of the *Ontario Biodiversity Strategy* (OBC 2011). One of the key components of this Strategy is the reduction in both direct and indirect pressures on Ontario's biodiversity. In this case, the STR index is being

Fig. 4. Eight-category combined index of freshwater fish biodiversity, environmental conditions, and anthropogenic stress indices for 953 tertiary watersheds in Canada for (*a*) past and (*b*) recent time periods. (See text for definitions of “Hi” and “Lo”.)

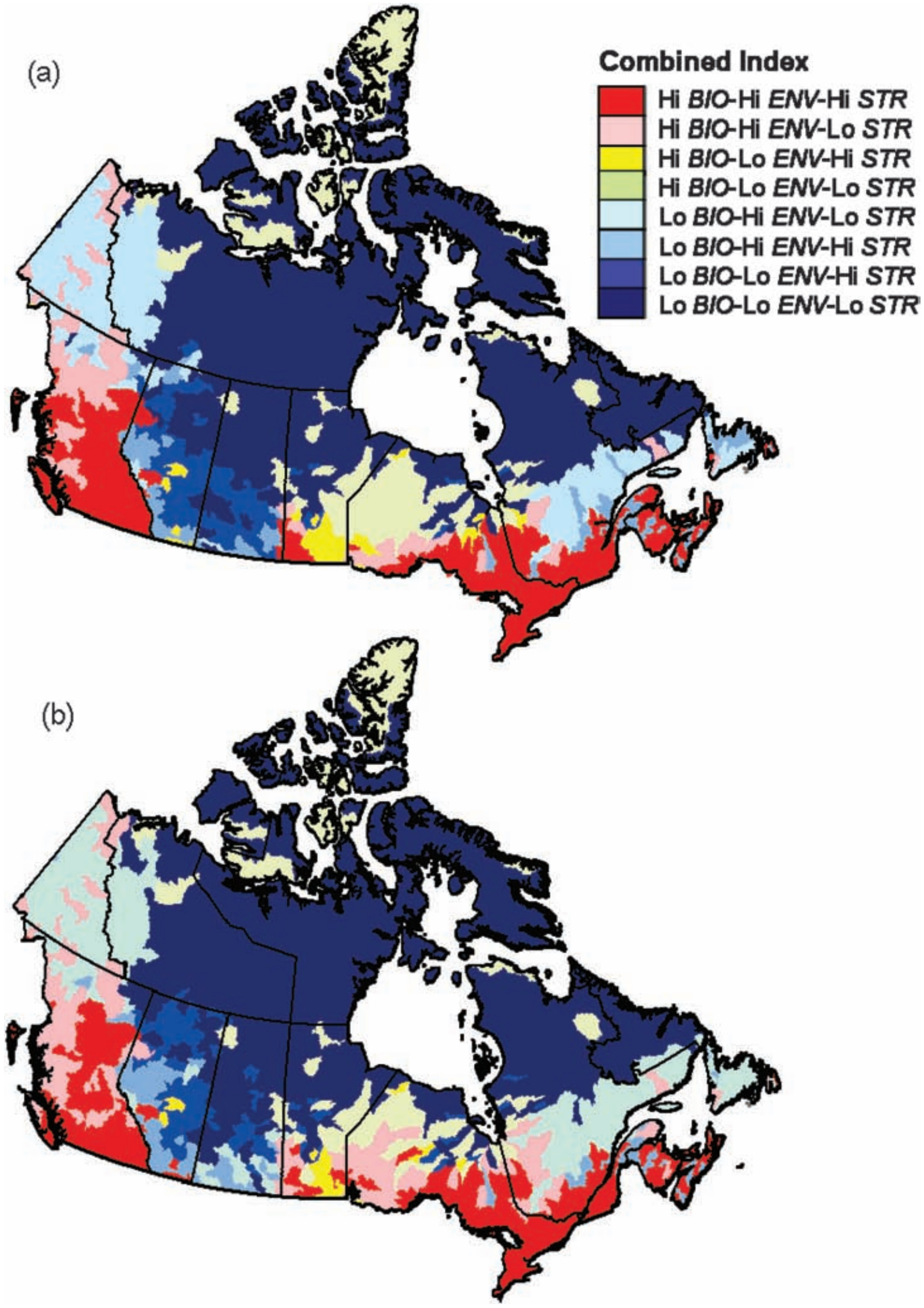
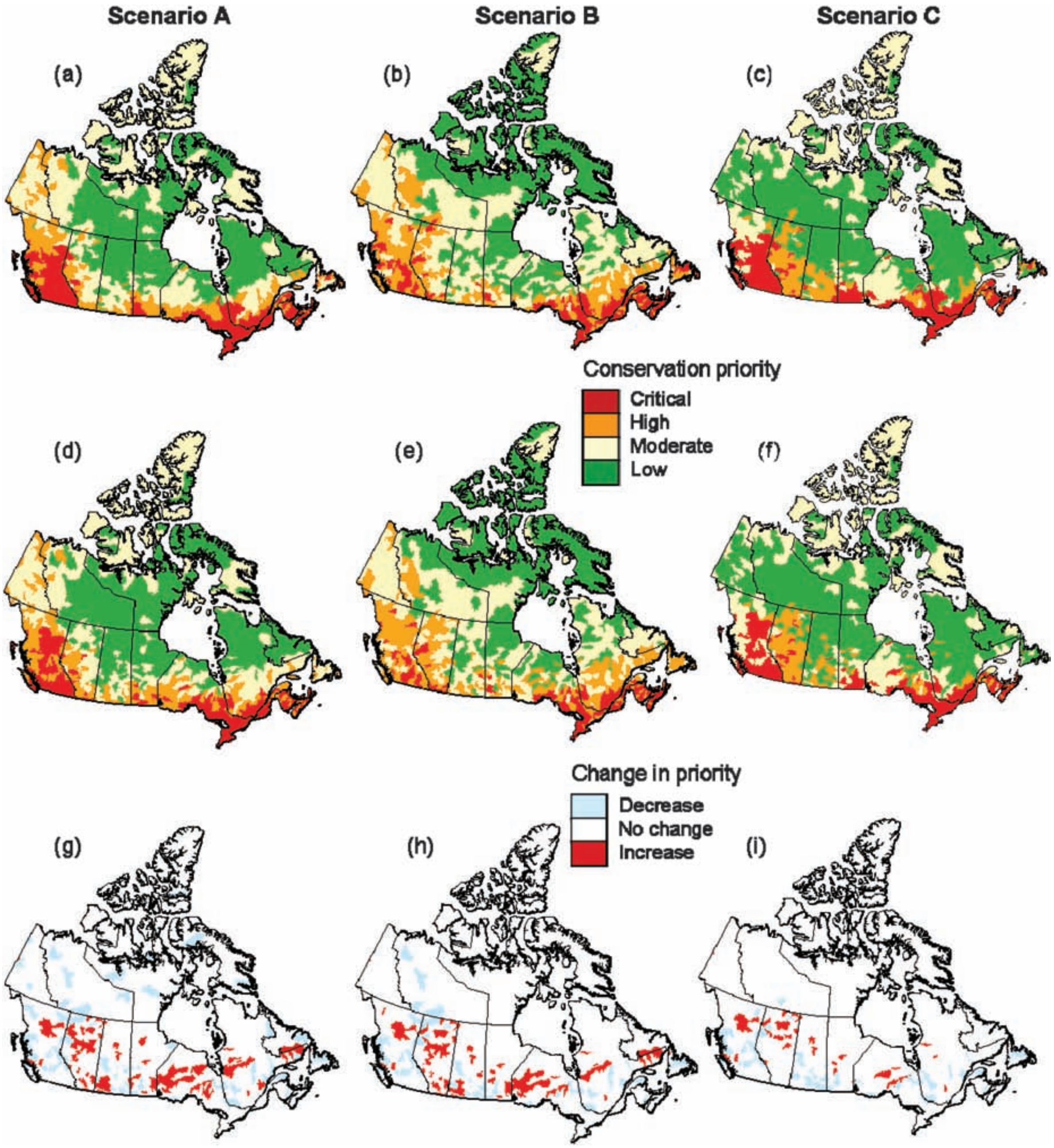


Table 6. Changes in the number of watersheds within each of the combined index categories based on indices of freshwater fish biodiversity (BIO), environmental conditions (ENV), and anthropogenic stress (STR).

Combined index	No. of watersheds based on 1961–1990 climate normals and 1996 human activity data	No. of watersheds based on 1981–2010 climate normals, and 2006/2008 human activity data
Hi BIO – Hi ENV – Hi STR	253	235
Hi BIO – Hi ENV – Lo STR	49	90
Hi BIO – Lo ENV – Hi STR	35	22
Hi BIO – Lo ENV – Lo STR	56	46
Lo BIO – Hi ENV – Lo STR	99	130
Lo BIO – Hi ENV – Hi STR	100	98
Lo BIO – Lo ENV – Hi STR	86	77
Lo BIO – Lo ENV – Lo STR	275	255

Note: “Hi” and “Lo” values are based on 50th percentile of the indices in Chu et al. 2003.

Fig. 5. Conservation priorities for 953 tertiary watersheds in Canada based on environmental conditions for 1961–1990 and 1996 levels of anthropogenic stress for (*a*) Scenario A, (*b*) Scenario B, and (*c*) Scenario C; environmental conditions for 1981–2010 and 2006/2008 levels of anthropogenic stress for (*d*) Scenario A, (*e*) Scenario B, and (*f*) Scenario C; and the differences between the two time periods (recent – past) under (*g*) Scenario A, (*h*) Scenario B, and (*i*) Scenario C. (See text for definitions of Scenarios A, B, and C.)



used to identify threats to aquatic ecosystems and the variability in those threats across the province.

In 2014, Lapointe et al. (2014) outlined 10 key management strategies for healthy, productive freshwater systems and sustainable fisheries. Listed among these is "identify and account for threats to ecosystem productivity". Our study can feed directly into this strategy, but a decision-support tool for management requires flexibility, as management objectives can vary. Our conservation priority criteria scenarios demonstrate how priorities may differ with different management objectives and (or) when the indices are weighted differently.

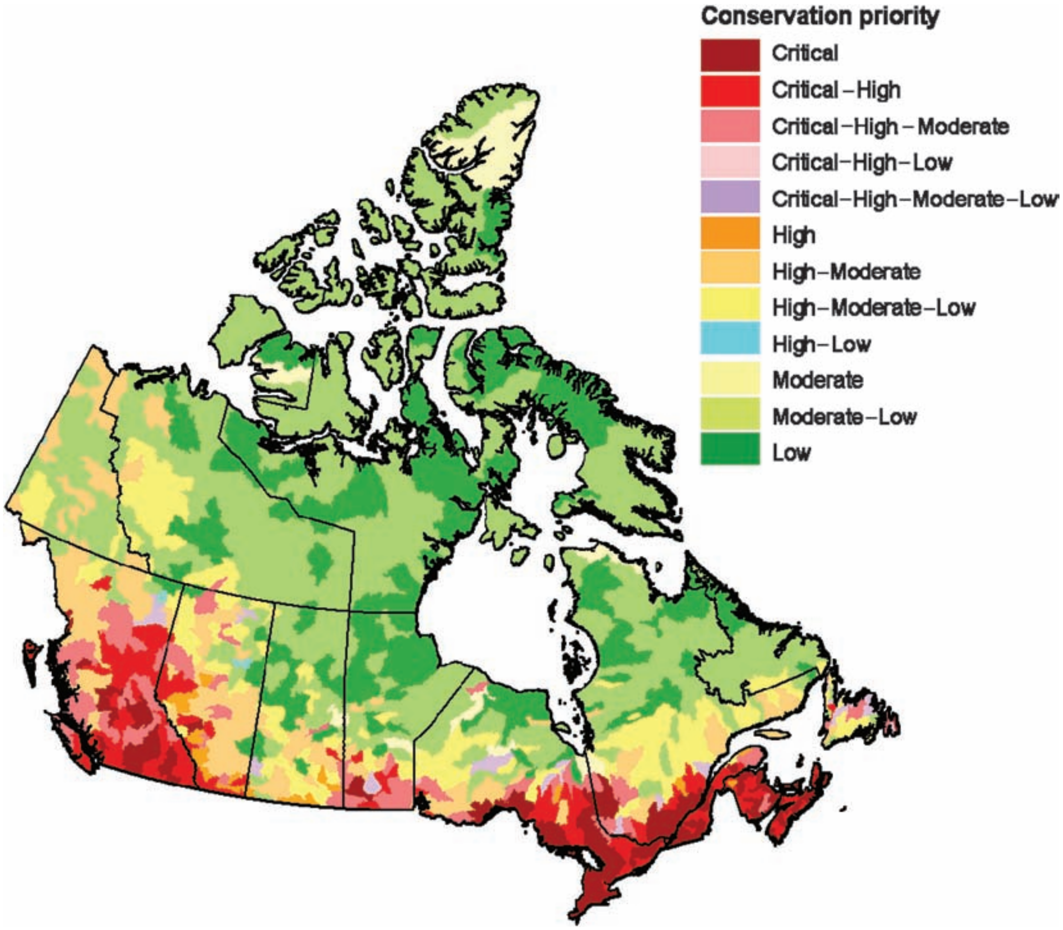
More watersheds were flagged as Critical when biodiversity was defined using the BIO index (Scenario A) instead of COSEWIC species occurrences (Scenario B). This is the result of the manner in which rareness (*Q*) is calculated in our study and in which the COSEWIC species are assessed. In our study, species are identified as rare based on the proportion of watersheds in which they occur, whereas species are assessed by COSEWIC primarily based on absolute spatial thresholds (e.g., area of occupancy thresholds of 5000 or 10 000 km^2; COSEWIC 2014), which are incredibly small areas relative to the total area of Canada. As a result, species with limited distributions in Canada, but exceeding 10 000 km^2, may not be assessed by COSEWIC as at risk. This suggests that some of the species flagged as rare in our study could be candidate species for future COSEWIC assessments. Our results also suggest that potential conservation and management actions based on the

Table 7. Conservation priorities for 953 tertiary watersheds in Canada based on indices developed for freshwater fish biodiversity, past environmental conditions for 1961–1990 and 1996 levels of anthropogenic stress, recent environmental conditions for 1981–2010, and 2006/2008 levels of anthropogenic stress.

	Scenario A		Scenario B		Scenario C	
Conservation priority	Past	Recent	Past	Recent	Past	Recent
Critical	265	244	213	193	307	270
High	196	210	259	294	169	163
Moderate	243	262	294	291	144	181
Low	249	237	187	175	333	339

Note: Criteria used to assign the conservation priorities were varied using three scenarios to assess the sensitivity and robustness of the conservation priorities to different conservation and management weightings. See text for descriptions of Scenarios A, B, and C.

Fig. 6. Sensitivity of 953 watersheds in Canada represented as a summary of the conservation priorities assigned to each watershed between the two time periods and among the three conservation priority scenarios.



presence of COSEWIC species alone could underestimate priorities for a number of watersheds and that our BIO index may be more sensitive and inclusive because it captures the biodiversity value of species that are not yet sufficiently rare to be listed by COSEWIC.

Declines in the number of Critical watersheds from the past to the more recent time period across all scenarios suggest that although stresses are expanding northward, there has been an overall decline in stress. These declines are attributable to decreases in one or more of the following stressors: number of crop farms, forestry operations, petroleum manufacturers, waste management facilities, and discharge sites. However, as discussed below, these trends need to be interpreted with caution because census data do not include changes in spatial extents or intensity of the stressors.

Similarities in the general pattern of the conservation priorities under the three different scenarios (i.e., increasing priority from south to north and 30% of the watersheds showing no change in priority) suggest that our prioritization approach is robust. The 143 Critical watersheds that were identified as Critical across all scenarios could form the basis for a nationwide watershed management plan.

Although we conducted a preliminary assessment of the sensitivity of our prioritization approach, subsequent research is needed to assess the sensitivity of the ENV and STR indices to (*i*) the variables used; (*ii*) spatial changes in the stressors; (*iii*) weighting of the environmental and stressor variables; and (*iv*) ecological processes linking variables to fish biodiversity and potential impacts of changes in the variables to aquatic habitats and fish communities.

A major shortcoming of this study is the lack of freshwater fishing stress data. A national assessment of freshwater exploitation is needed and can be accomplished in one of three ways. First, the census of business patterns currently combines commercial and recreational fishing effort of marine and freshwater stocks (Statistics Canada 2008). Future censuses could split these data into four categories that would allow researchers to summarize stress from inland effort: commercial freshwater; commercial marine; recreational freshwater; and recreational marine. Second, the national census could include a question(s) on fishing activities. This would provide geographic data of fishing effort across the country. Third, the nationwide recreational fishing survey conducted by Fisheries and Oceans Canada could be more geographically detailed. Currently, the surveys are summarized to the provincial or territorial level and do not account for varying levels of exploitation among watersheds, except in Ontario (Hogg et al. 2009; Fisheries and Oceans Canada 2012). Nationwide, georeferenced estimates of fishing effort and fisheries are particularly timely given recent changes to the *Fisheries Act*, whereby regulations now protect only the habitat associated with fisheries (Hutchings and Post 2013).

An updated national assessment of the distribution of species is also needed to account for increases in the knowledge of, and changes in, native species distributions and the spread of invasives. Alofs et al. (2014) found that the northern range boundaries of centrarchid species have shifted approximately 12.9–17.5 km·decade^{-1}, while the northern limits of baitfishes such as blacknose shiner (*Notropis heterolepis*), bluntnose minnow (*Pimephales notatus*), and golden shiner (*Notemigonus crysoleucas*) have moved southward, likely as a consequence of predation by recently introduced species.

The census data, and stress variables derived from them, are one representation of the change in human activities across the landscape and specifically measure the density of stressors. Additional data on the spatial changes in each variable would greatly improve our representation of stress. Given the general process of increasing corporate concentration in Canada (Brennan 2012), the spatial extents of some of the stressors (within the census subdivisions), such as forestry and petroleum manufacturing facilities, may diverge from the density estimates. To resolve this issue, future research could combine the census data with a time series of remotely sensed land cover. This approach would quantify any differences between the densities and spatial extents, as well as the spatial changes in the stressors themselves (Kerr and Cihlar 2003).

The environmental and stress indices were derived by giving each variable equal weight, which assumes that their potential impacts on watersheds and fish biodiversity are the same. Averaging the high and low values, which we delineated using the 50th percentile of the variables, is a simple approach to quantify and synthesize variation of the variables. It is an oversimplification of reality because stressors have different temporal and spatial footprints, which vary based on the magnitude and scale of the activity. Changes in the variables also may not lead to uniform changes in the indices, as each variable may have a different threshold at which habitat or biodiversity responses are induced. Future research should determine how the variables should be weighted to capture the influence of each stressor on freshwater fish biodiversity and habitats. This may be accomplished through a study or literature review of fish community response (e.g., species richness, indices of biotic integrity) along gradients of each environmental and stressor variable. The sensitivity of species richness to different levels of the variables could provide estimates for developing weighted indices and for identifying specific thresholds of impact. This blends into our fourth area of future research: identifying ecological processes linking the variables to aquatic habitats and fish communities that would include dynamic weightings representing positive and negative feedbacks among variables.

Explicit ecological linkages between the environmental and stressor data and fish biodiversity were not tested in our study, and as mentioned above, these should be explored in future research. However, using the same dataset as the 1961–1990 environmental data, Pinel-Alloul et al. (2013) found pelagic crustacean zooplankton community structure in Canadian lakes was related to mean daily global solar radiation, annual potential evaporation, effective growing degree-days above 5 °C, mean annual air temperature, and mean duration of bright sunshine hours. Solar radiation was the strongest individual predictor explaining 51% of the variation in community data. Local factors were poor predictors of community structure. These results were thought to support the “species richness–energy hypothesis”, whereby communities are shaped by energy availability in the environment. This supports our interpretation of the ENV index; higher ENV values likely support more biodiversity.

Our study represents a snapshot of simple relationships among freshwater fish biodiversity, environmental conditions, and anthropogenic stressors, yet we detected changes across the country in the last 10 years. To be effective, conservation and management of aquatic habitats and resources should aim to keep pace with changes in the types and concentration of human activities and environmental change across the landscape.

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