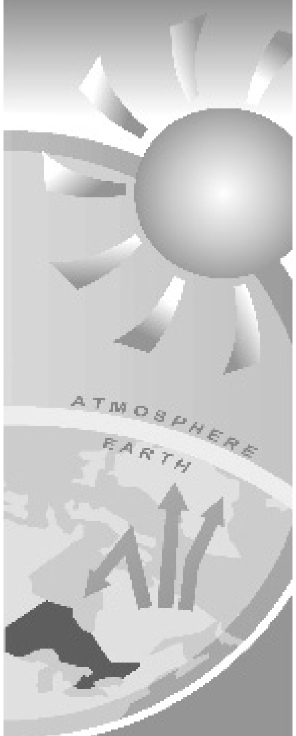
Ministry of Natural Resources

30

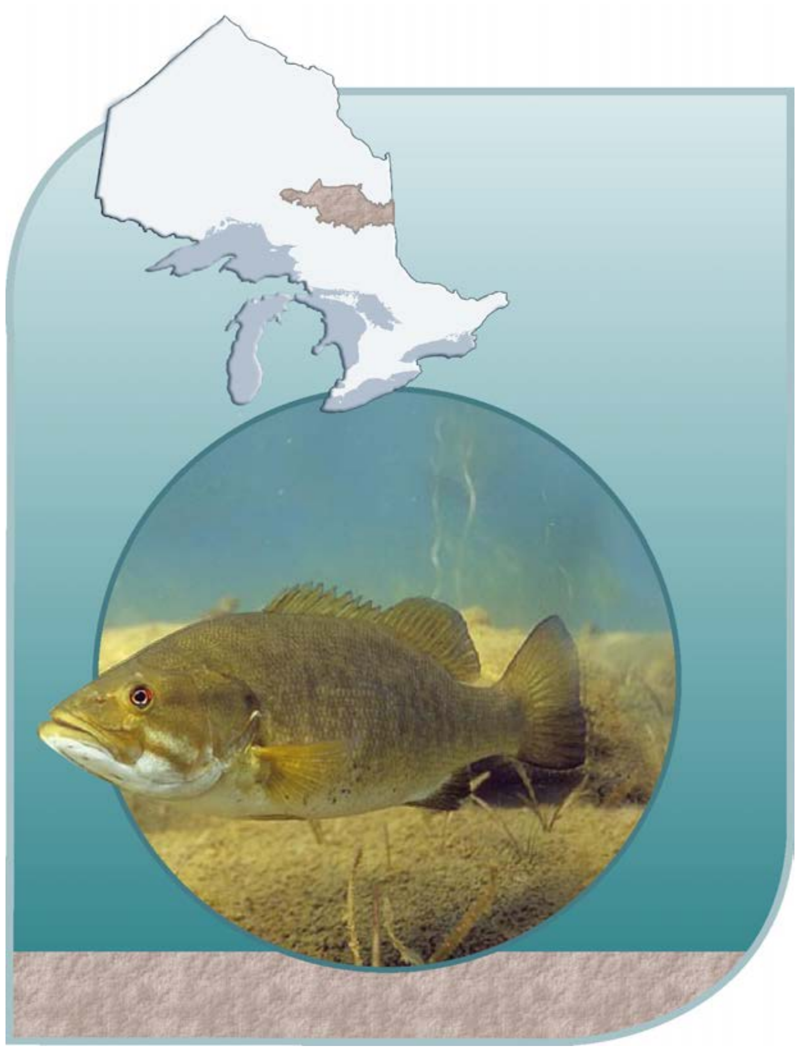
CLIMATE CHANGE RESEARCH REPORT

CCRR-30



Responding to Climate Change Through Partnership

Climate Change Vulnerability Assessment for Aquatic Ecosystems in the Clay Belt Ecodistrict (3E-1) of Northeastern Ontario



Ontario

Sustainability in a Changing Climate: An Overview of MNR's Climate Change Strategy (2011-2014)

Climate change will affect all MNR programs and the natural resources for which it has responsibility. This strategy confirms MNR's commitment to the Ontario government's climate change initiatives such as the Go Green Action Plan on Climate Change and outlines research and management program priorities for the 2011-2014 period.

Theme 1: Understand Climate Change

MNR will gather, manage, and share information and knowledge about how ecosystem composition, structure and function – and the people who live and work in them – will be affected by a changing climate. Strategies:

- Communicate internally and externally to build awareness of the known and potential impacts of climate change and mitigation and adaptation options available to Ontarians.
- Monitor and assess ecosystem and resource conditions to manage for climate change in collaboration with other agencies and organizations.
- Undertake and support research designed to improve understanding of climate change, including improved temperature and precipitation projections, ecosystem vulnerability assessments, and improved models of the carbon budget and ecosystem processes in the managed forest, the settled landscapes of southern Ontario, and the forests and wetlands of the Far North.
- Transfer science and understanding to decision-makers to enhance comprehensive planning and management in a rapidly changing climate.

Theme 2: Mitigate Climate Change

MNR will reduce greenhouse gas emissions in support of Ontario's greenhouse gas emission reduction goals. Strategies:

- Continue to reduce emissions from MNR operations though vehicle fleet renewal, converting to other high fuel efficiency/low-emissions equipment, demonstrating leadership in energy-efficient facility development, promoting green building materials and fostering a green organizational culture.
- Facilitate the development of renewable energy by collaborating with other Ministries to promote the value of Ontario's resources as potential green energy sources, making Crown land available for renewable energy development, and working with proponents to ensure that renewable energy developments are consistent with approval requirements and that other Ministry priorities are considered.
- Provide leadership and support to resource users and industries to reduce carbon emissions and increase carbon storage by undertaking afforestation, protecting natural heritage areas, exploring opportunities for forest carbon management to increase carbon uptake, and promoting the increased use of wood products over energy-intensive, non-renewable alternatives.
- Help resource users and partners participate in a carbon offset market, by working with our partners to ensure that a robust trading system is in place based on rules established in Ontario (and potentially in other jurisdictions), continuing to examine the mitigation potential of forest carbon management in Ontario, and participating in the development of protocols and policies for forest and land-based carbon offset credits.

Theme 3: Help Ontarians Adapt

MNR will provide advice and tools and techniques to help Ontarians adapt to climate change. Strategies include:

- Maintain and enhance emergency management capability to protect life and property during extreme events such as flooding, drought, blowdown and wildfire.
- Use scenarios and vulnerability analyses to develop and employ adaptive solutions to known and emerging issues.
- Encourage and support industries, resource users and communities to adapt, by helping to develop understanding and capabilities of partners to adapt their practices and resource use in a changing climate.
- Evaluate and adjust policies and legislation to respond to climate change challenges.

Climate Change Vulnerability Assessment for Aquatic Ecosystems in the Clay Belt Ecodistrict (3E-1) of Northeastern Ontario

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Summary

Changes in air temperatures, precipitation patterns, and extreme weather events associated with climate change have and will continue to influence aquatic ecosystems. Increased water temperatures, and changes in the timing of the spring freshet, the duration of ice cover, wetland composition, productivity of various species, as well as the establishment of invasive species have been documented in several systems. The wetland, stream, and lake ecosystems in the Clay Belt (Ecodistrict 3E-1) of northeastern Ontario are also being affected by climate change. The objectives of this study were to assess the vulnerability of several aquatic ecosystem indicators to inform the development of climate change adaptation options for those ecosystems in Ontario's Clay Belt. Using the Canadian Coupled Global Climate Model 3 (CGCM3) with two climate change scenarios (B1 and A2), we projected that, by 2071, 13% and 15% of the wetlands, respectively, within the northern portion of the ecodistrict may be vulnerable to drying and shrinkage from a combination of increased air temperatures and decreased precipitation. Within the same timeframe, increases in air temperatures may reduce the distribution of coldwater stream fish species within 13 (CGCM3-B1) and 61 (CGCM3-A2) of the 90 quaternary watersheds within the ecodistrict. As well, maximum surface water temperature of lakes may increase by 4 ºC and 100% of the lakes within the ecodistrict may have suitable thermal habitat for smallmouth bass (*Micropterus dolomieu*). Walleye (*Sander vitreus*) productivity (kg) may increase by as much as 10% in Clay Belt lakes. The results presented here do not include the potential effects of anthropogenic stressors such as groundwater withdrawals, stream regulation, or pollution that may exacerbate the changes in quality and quantity of aquatic habitats. Several recommendations are provided to improve the monitoring of aquatic ecosystems and allow for more effective adaptation to climate change.

Résumé

Évaluation de la vulnérabilité des écosystèmes aquatiques aux changements climatiques dans la ceinture d'argile (3E-1) du nord-est de l'Ontario

La variation des températures de l'air, la configuration des précipitations et les conditions météorologiques extrêmes associées aux changements climatiques ont influencé et continueront d'influencer les systèmes aquatiques. L'augmentation des températures de l'eau, les variations du moment des crues printanières, la durée de la couche de glace, la composition des zones humides, la productivité des différentes espèces et la venue des espèces envahissantes ont été documentées dans plusieurs systèmes. Les zones humides, les courants d'eau et les écosystèmes des lacs de la ceinture d'argile (écodistrict 3E-1) du nord-est de l'Ontario sont également touchés par les changements climatiques. La présente étude vise à évaluer les indicateurs de la vulnérabilité de plusieurs écosystèmes aquatiques pour augmenter les options d'adaptation aux changements climatiques pour les écosystèmes de la ceinture d'argile de l'Ontario. Au moyen du Modèle canadien du climat du globe 3 (MCCG3) et de deux scénarios de changements climatiques (B1 et A2), nous avons établi qu'en 2071, 13 % et 15 % des zones humides, respectivement, de la partie nord de l'écodistrict pourraient être vulnérables à la sécheresse et à la contraction résultant à la fois de l'augmentation des températures et de la diminution des précipitations. À la même période, l'augmentation des températures de l'air pourrait réduire la distribution des poissons qui vivent en eaux froides dans 13 (CGCM3-B1) et 61 (CGCM3-A2) des 90 bassins versants quaternaires de l'écodistrict. De plus, la température maximale de l'eau de surface pourrait augmenter de 5 ºC et la totalité des lacs de l'écodistrict pourrait avoir un habitat thermal convenant à l'achigan à petite bouche (*Micropterus dolomieu*). La productivité (kg) du doré jaune (*Sander vitreus*) (kg) pourrait augmenter de 10 % dans les lacs de la ceinture d'argile. Les résultats présentés ici ne tiennent pas compte des effets possibles des stresseurs anthropiques comme le retrait des eaux souterraines, la régulation des cours d'eau ou la pollution qui pourraient exacerber les changements de la qualité et de la quantité des habitats aquatiques. Plusieurs recommandations sont formulées sur l'amélioration de la surveillance des écosystèmes aquatiques dans le but d'améliorer l'adaptation aux changements climatiques,

Acknowledgements

This study was made possible through funding from the Ontario Ministry of Natural Resources (OMNR) and Ontario Ministry of the Environment (OMOE) Clay Belt Climate Change Adaptation Strategy. The authors thank Nigel Lester who provided the AHI database and the walleye productivity model, and Steve McGovern, Jeff Amos, and Len Hunt who provided advice and guidance; Paul Gray, Jenny Gleeson, and Rachelle Lalonde who coordinated the Clay Belt Climate Change Vulnerability Assessment; and Gilbert Racine (all with OMNR) who provided climate scenario data. We thank Dan McKenney and Kevin Lawrence (Natural Resources Canada) who provided data for the climate change maps. We also thank Paul Gray and Nicholas Jones for reviewing an earlier version of the manuscript, and Trudy Vaittinen for report production.

Foreword

This is one in a series of reports to help resource managers evaluate the vulnerability of natural assets to climate change. Given that vulnerability assessment techniques continue to evolve, it is important for resource managers to learn by doing and to pass on knowledge gained to support MNR and others engaged in adaptive management. Accordingly, the vulnerability assessment reports included in the Climate Change Research Report Series have been prepared using the best available information under the circumstances (e.g., time, financial support, and data availability). Collectively, these assessments can inform decisionmaking, enhance scientific understanding of how natural assets respond to climate change, and help resource management organizations establish research and monitoring needs and priorities.

Cameron Mack

Acting Director, Applied Research and Development Branch

Contents

Introduction

Climate change is significantly affecting aquatic ecosystems around the world. In wetlands, these effects are evident through the melting of permafrost peatlands (Parish et al. 2008). In the Great Lakes region, projected declines in water levels are expected to change the water budgets of wetlands and as a result the distribution and abundance of wetland vegetation, bird, and fish communities (Mortsch et al. 2006). In streams and rivers (hereafter all flowing waters are called streams), long-term increases in water temperatures and associated changes in stream biota have been already detected (e.g., Durance and Ormerod 2007). In Ontario, increases in stream temperatures may provide more suitable habitat for species that prefer warmer temperatures throughout the ice-free season but may limit the distribution of species that prefer cooler temperatures (Chu et al. 2008). Climate change may also alter the timing of the spring freshet, affect groundwater dynamics, and disrupt annual stream flow patterns (Mohseni et al. 2003).

Worldwide, surface temperatures of lakes have been trending upwards (Schneider and Hook 2010). Biological consequences of these changes are evident in fish community dynamics (e.g., Jeppesen 2010). In Ontario, higher air temperatures could lead to overall reductions in lake volume, warmer surface water temperatures, shallower thermoclines in stratified lakes (with reduced spring winds), longer ice-free periods and growing seasons, and greater risk of hypoxia (Dove et al. 2011). Human activities, such as non-native species introductions, river regulation, groundwater withdrawal, shoreline development, and point and non-point source pollution will further stress these ecosystems.

While agreement is widespread of the need to recognize and prepare for climate change, and to develop and integrate risk management strategies into current and new programs, climate-sensitive adaptive processes are only now being designed and tested. Steps in such an adaptive management process include assessing readiness and capacity to respond, conducting vulnerability analyses to identify and prioritize adaptation needs, and developing adaptation strategies and monitoring programs to measure adaptation success and determine whether vulnerabilities have been reduced or eliminated (Figure 1).

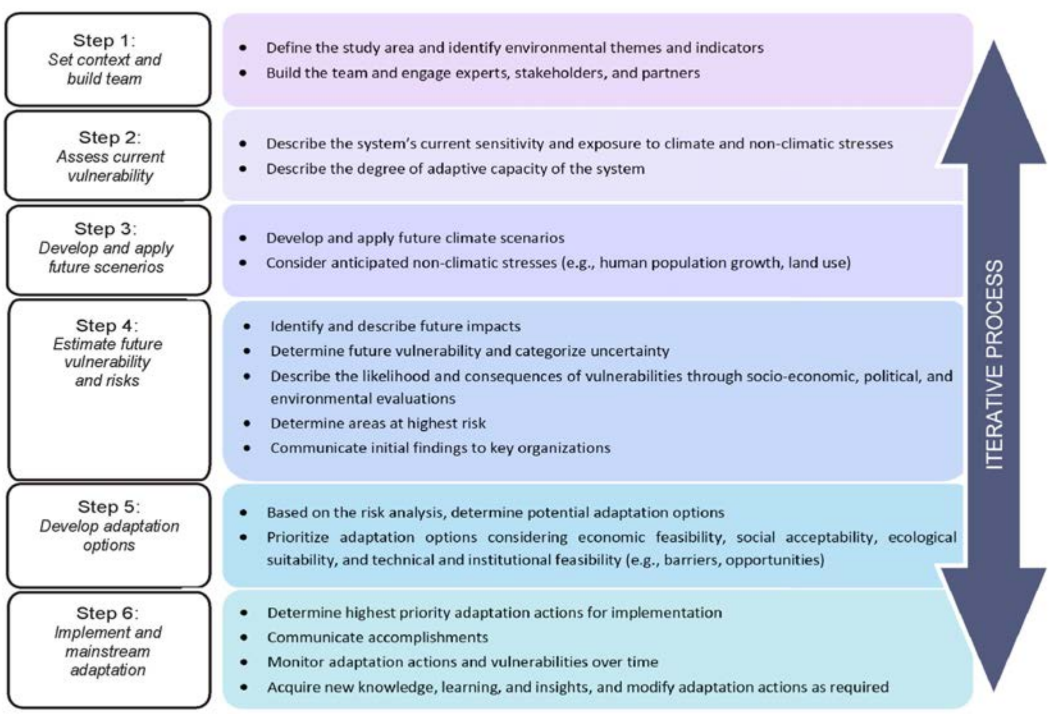

***Figure 1**. A conceptual framework that can be used by agencies to help determine organizational readiness to adapt to climate change, complete vulnerability analyses, and develop, implement, monitor, and adjust adaptation options as required (Source: Gleeson et al. 2011).*

As part of its response to Climate Ready: Ontario's Adaptation Strategy and Action Plan (OMOE 2011) and Sustainability in a Changing Climate Strategy (OMNR 2011), the Ontario Ministry of Natural Resources undertook a vulnerability assessment for the Clay Belt (Ecodistrict 3E-1) in northeastern Ontario (Lalonde et al. 2012). The Clay Belt covers approximately 41,287 km² (4.2% of Ontario's total area) and >15% of that area comprises aquatic ecosystems (Figure 2). Land cover in the ecodistrict is predominantly coniferous forest with 4,780 km² of wetlands and >1,600 km² of lakes and streams. Projections made using climate change models indicate that air temperatures will increase throughout the entire Clay Belt area, with regional differences in effects on precipitation patterns (McKenney et al. 2010). Based on the vulnerability and adaptation framework, the main objective of this study was to identify vulnerability indicators for wetland, stream, and lake ecosystems in the Clay Belt. These indicators represent measures that can be used to quantify the sensitivity of each system to climate change, develop adaptation options, and inform an adaptive strategic planning process.

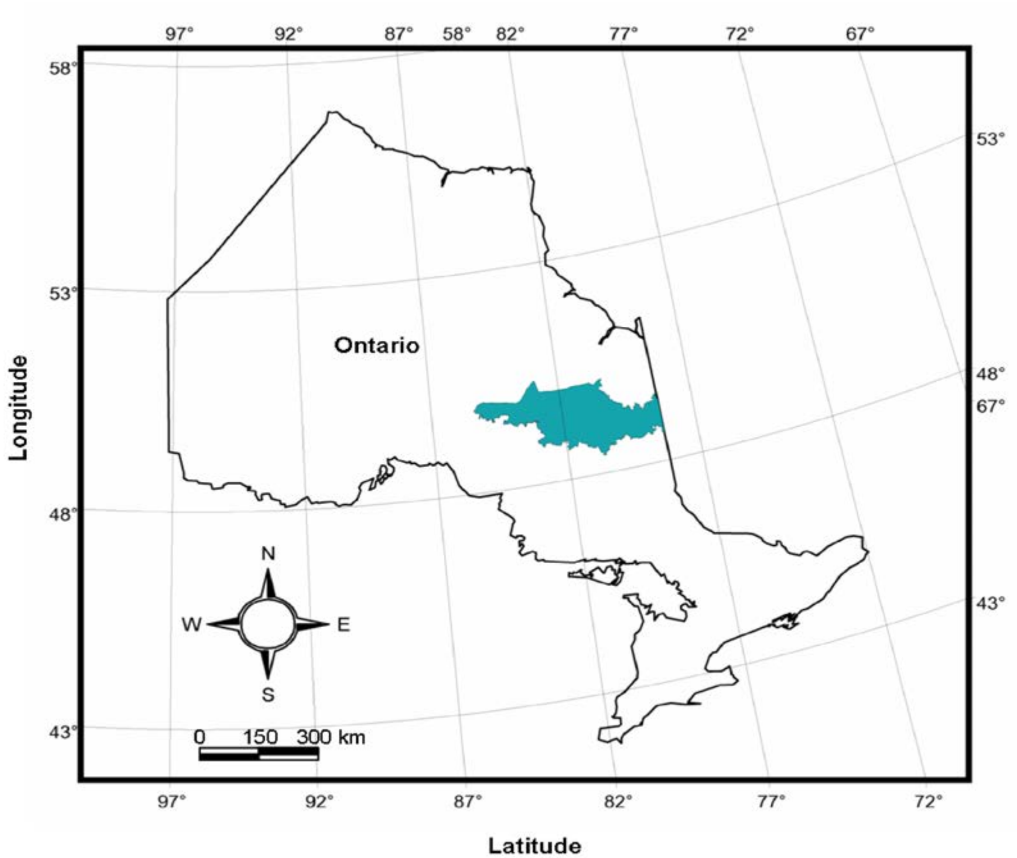

***Figure 2**. Location of the Clay Belt (Ecodistrict 3E-1) (shaded area) in northeastern Ontario.*

Methods

The potential effects of climate change on the wetland, stream, and lake ecosystems of the Clay Belt were represented using five indicators: wetland vulnerability, a coldwater stream fish index, maximum lake surface water temperature, smallmouth bass (*Micropterus dolomieu*) thermal habitat availability, and walleye (*Sander vitreus*) productivity. Existing empirical models were used to relate the ecosystem indicators to climate. Present climate conditions were estimated using 1971 to 2000 Canadian climate averages. The Canadian Coupled Global Climate Model 3 (CGCM3) was used to project future climate for the 2011-2040, 2041-2070, and 2071-2100 time periods for B1 and A2 emissions scenarios (IPCC 2007). The B1 scenario represents an environmentally focused future with lower emission levels than the A2 scenario in which high emission levels are driven by rapid economic development (IPCC 2007). Current and future climate conditions were provided by Natural Resources Canada and Ontario Ministry of Natural Resources' Northeast Region following the methodology outlined in McKenney et al. (2010).

Wetlands

The vulnerability of the wetlands in the Clay Belt to climate change was assessed using projected air temperature, precipitation, and groundwater discharge potential based on a 'base flow index' that relates groundwater to underlying surficial geology (Neff et al. 2005). These variables were selected because changes in any one will affect the water budget of wetlands. Vulnerability was defined as degraded quality or loss of wetland area due to drying that may result from increased evapotranspiration at warmer air temperatures, water loss associated with decreased precipitation, and/or groundwater inflow.

Land cover 2000 (OMNR 2000) was used to identify and map the wetlands within the Clay Belt in ArcGIS® 9.2 (Environmental Systems Research Institute Inc., Redlands, California, USA). The change in growing season (April to September) air temperatures and total precipitation from current conditions for the climate scenarios were spatially joined to the wetland polygons in ArcGIS. Area-weighted base flow index values were calculated for each of the wetland polygons, again using ArcGIS.

With climate change, growing season air temperatures throughout Ecodistrict 3E-1 may increase by 0.2 to 3.6 ºC (Table 1). By 2100, precipitation in some areas of the Clay Belt may decrease by 8% but in general it is expected to increase up to 34% (Table 1). Because it may be years before changes in groundwater quantity, recharge rates, and timing of discharge occur and even longer before they affect wetland systems (Chu et al. 2008), for these analyses groundwater discharge potential was held constant. Base flow index values ranged from 0 to 0.821 with values closer to one indicating more groundwater inflow (Table 1).

As a rule of thumb, a 10% increase in precipitation is needed to offset the increases in evapotranspiration associated with 1 ºC of warming (Trenberth 2011). This relationship was used to develop a vulnerability matrix for the wetlands based on the changes in temperature, precipitation patterns, and groundwater flow (Table 1). The underlying premise was that comparatively greater increases in air temperature, decreases in precipitation, and low groundwater inflow are associated with greater vulnerability to climate change.

Table 1. *Vulnerability matrices for wetlands in Ontario's Clay Belt as a result of base flow (groundwater discharge potential), and changes in growing season (April to September) air temperatures and total precipitation projected using the Canadian Coupled Global Climate Model 3 under the B1 and A2 scenarios for three future time periods.*

Scenario	Time period	Base flow index value[1]	Increase in air temperature (°C)	Change in precipitation (%)	Vulnerability
B1	2011-2040	0.00-0.28	0.00-0.64	-8.0 to 2.0	high
		0.28-0.82	0.64-1.26	3.0 to 14.0	mid
		0.00-0.28	0.64-1.26	-8.0 to 2.0	high
		0.28-0.82	0.00-0.64	3.0 to 14.0	low
		0.00-0.28	0.00-0.64	3.0 to 14.0	low
		0.28-0.82	0.64-1.26	-8.0 to 2.0	mid
		0.00-0.28	0.64-1.26	3.0 to 14.0	mid
		0.28-0.82	0.00-0.64	-8.0 to 2.0	mid
	2041-2070	0.00-0.28	0.55-1.23	-2.0 to 10	high
		0.28-0.82	1.24-1.85	11.0 to 23.0	mid
		0.00-0.28	1.24-1.85	-2.0 to 10	high
		0.28-0.82	0.55-1.23	11.0 to 23.0	low
		0.00-0.28	0.55-1.23	11.0 to 23.0	low
		0.28-0.82	1.24-1.85	-2.0 to 10	mid
		0.00-0.28	1.24-1.85	11.0 to 23.0	mid
		0.28-0.82	0.55-1.23	-2.0 to 10	mid
	2071-2100	0.00-0.28	0.84-1.45	1.0 to 12.0	high
		0.28-0.82	1.46-2.13	13.0 to 26.0	mid
		0.00-0.28	1.46-2.13	1.0 to 12.0	high
		0.28-0.82	0.84-1.45	13.0 to 26.0	low
		0.00-0.28	0.84-1.45	13.0 to 26.0	mid
		0.28-0.82	1.46-2.13	1.0 to 12.0	mid
		0.00-0.28	1.46-2.13	13.0 to 26.0	mid
		0.28-0.82	0.84-1.45	1.0 to 12.0	mid
A2	2011-2040	0.00-0.28	0.15-0.79	-1.0 to 11.0	mid
		0.28-0.82	0.80-1.45	12.0 to 25.0	low
		0.00-0.28	0.80-1.45	-1.0 to 11.0	high
		0.28-0.82	0.15-0.79	12.0 to 25.0	low
		0.00-0.28	0.15-0.79	12.0 to 25.0	low
		0.28-0.82	0.80-1.45	-1.0 to 11.0	mid
		0.00-0.28	0.80-1.45	12.0 to 25.0	mid
		0.28-0.82	0.15-0.79	-1.0 to 11.0	mid
	2041-2070	0.00-0.28	1.14-1.79	4.0 to 16.0	high
		0.28-0.82	1.80-2.40	17.0 to 29.0	low
		0.00-0.28	1.80-2.40	4.0 to 16.0	high
		0.28-0.82	1.14-1.79	17.0 to 29.0	low
		0.00-0.28	1.14-1.79	17.0 to 29.0	low
		0.28-0.82	1.80-2.40	4.0 to 16.0	mid
		0.00-0.28	1.80-2.40	17.0 to 29.0	mid
		0.28-0.82	1.14-1.79	4.0 to 16.0	mid
	2071-2100	0.00-0.28	2.31-3.00	9.0 to 20.0	high
		0.28-0.82	3.01-3.60	21.0 to 34.0	low
		0.00-0.28	3.01-3.60	9.0 to 20.0	high
		0.28-0.82	2.31-3.00	21.0 to 34.0	low
		0.00-0.28	2.31-3.00	21.0 to 34.0	low
		0.28-0.82	3.01-3.6	9.0 to 20.0	high
		0.00-0.28	3.01-3.6	21.0 to 34.0	high
		0.28-0.82	2.31-3.00	9.0 to 20.0	mid

[1]Values closer to 1.0 indicate higher groundwater flow.

Streams

An index developed by Chu et al. (2008; Table 2), which describes the likelihood that coldwater fish species (e.g., brook trout, *Salvelinus fontinalis,* and mottled sculpin, *Cottus bairdii*) may be retained in streams throughout quaternary watersheds in southern Ontario, was used as an indicator of the vulnerability of Clay Belt stream ecosystems to climate change. This index is based on maximum air temperature and groundwater discharge potential and indicates that watersheds with high groundwater discharge potential may provide thermal refugia for coldwater species during a period of rapid climatic change. Using ArcGIS and the climate scenario data, area-weighted base flow index and maximum air temperature values were calculated for each of the quaternary watersheds in the ecodistrict. These values were compared to the likelihood index to rank the watersheds by their potential (high, medium, and low) to retain coldwater fish species.

Table 2. *Likelihood that streams in Ontario's Clay Belt will retain coldwater fish species by 2055 based on maximum air temperature projections estimated using the Canadian Coupled Global Climate Model 3-A2 scenario and groundwater discharge potential (Source: Chu et al. 2008).*

Attribute	Likelihood of retaining coldwater fish species		
	Low	Medium	High
Maximum air temperature (°C)	>26.9	<26.9>26.07	<26.07
Base flow index value[1]	<0.36	0.36-0.54	>0.54

[1]Values closer to 1.0 indicate higher groundwater flow.

Lakes

Maximum surface water temperature, smallmouth bass thermal habitat, and walleye productivity were used to assess the potential effects of climate change on lake ecosystems. Smallmouth bass were selected as an indicator species because their northward expansion has been well documented in Ontario (Brown et al. 2009), and their colonization of new lakes can negatively affect resident fish communities (Sharma et al. 2007). Walleye were selected because they are one of the most important fishery resources in the Clay Belt and changes in their habitat and productivity may have significant socioeconomic consequences (Minns 2009).

A Canada-wide empirical model developed by Sharma et al. (2007) was used to project maximum surface water temperatures and thermal habitat for smallmouth bass from lake location (latitude and longitude) and mean July and mean annual air temperatures. Lakes greater than 0.1 km^2 (n = 1,313) (to avoid including ponds in the analyses) were selected from the Ontario Provincial Hydrometric Network (OMNR 2010) using ArcGIS. Mean July and mean annual air temperatures were calculated using ArcGIS for each of the lakes for present and future conditions. These values were used to project maximum surface water temperatures and thermal habitat for smallmouth bass in the lakes.

A provincial model developed by Lester et al. (2004) was used to estimate the changes in walleye productivity with climate change. This model can be used to estimate productivity based on the surface area, depth, water clarity, total dissolved solids, and growing degree days (above 5 ºC) of each lake. These data were compiled from MNR's Aquatic Habitat Inventory (AHI) and broad-scale monitoring databases for 158 lakes in the Clay Belt. Growing degree day estimates for each lake for the two climate scenarios were calculated using ArcGIS and used to forecast the changes in walleye productivity.

Results

Wetlands

Future vulnerability: Moderate because some wetlands in the central and southern regions may remain intact.

By 2071 under the CGCM3-B1 and -A2 model-scenarios, respectively, 13% and 15% of wetlands in Ontario's Clay Belt ecoregion may be highly vulnerable to drying under the projected increased air temperature, decreased precipitation, and altered groundwater conditions (Table 3; Figure 3). This effect is expected to be most evident in the northern portion of the ecoregion, which is projected to receive less precipitation relative to the southern portion of the Clay Belt (Figure 3).

Non-climate-related stressors such as peat extraction, agricultural activities, and urban development may also affect wetland conditions. Run-off from urban and agricultural lands may contain pollutants, nutrients, and sediments that can compromise water quality. In turn, this can negatively affect plant growth, community composition, and overall availability of wetland habitats (Mortsch et al. 2006).

The strengths of the analyses reported here are that:

- They incorporate the dominant physical variables (air temperature, precipitation, and groundwater inflows) that influence wetlands.
- They offer easily interpretable guides for setting priority areas for wetland conservation.
- They provide a framework for assessing how wetland changes may influence habitat availability and the distribution of wetland-dependent species.

Uncertainties that need to be addressed in future studies are:

- The pattern of drying in each wetland. In this study, each wetland was treated as a single unit and assigned a vulnerability ranking. However, entire wetlands may not be affected uniformly. For example, drying or shrinking may occur around the edges only, leaving the middle intact.
- The types of shifts in wetland plant diversity and composition that will affect wetland type (e.g., bog, fen, etc.) and other species diversity.

Table 3. *Total area (km^2) and percent (in parentheses) of wetlands in Ontario's Clay Belt expected to be vulnerable to air temperature and precipitation changes projected using the Canadian Coupled Global Climate Model 3 under the B1 and A2 scenarios for three future time periods.*

Vulnerability	CGCM3 B1			CGCM3 A2		
	2011-2040	2041-2070	2071-2100	2011-2040	2041-2070	2071-2100
High	841.7 (18%)	798.6 (17%)	624.5 (13%)	783.4 (16%)	690.2 (14%)	739.4 (15%)
Medium	2,990.3 (63%)	3,452.9 (72%)	3,705.6 (78%)	2,271.9 (48%)	3,524.5 (74%)	3,374.2 (71%)
Low	945.9 (20%)	529.5 (11%)	450.9 (9%)	1,725.7 (36%)	566.3 (12%)	667.4 (14%)

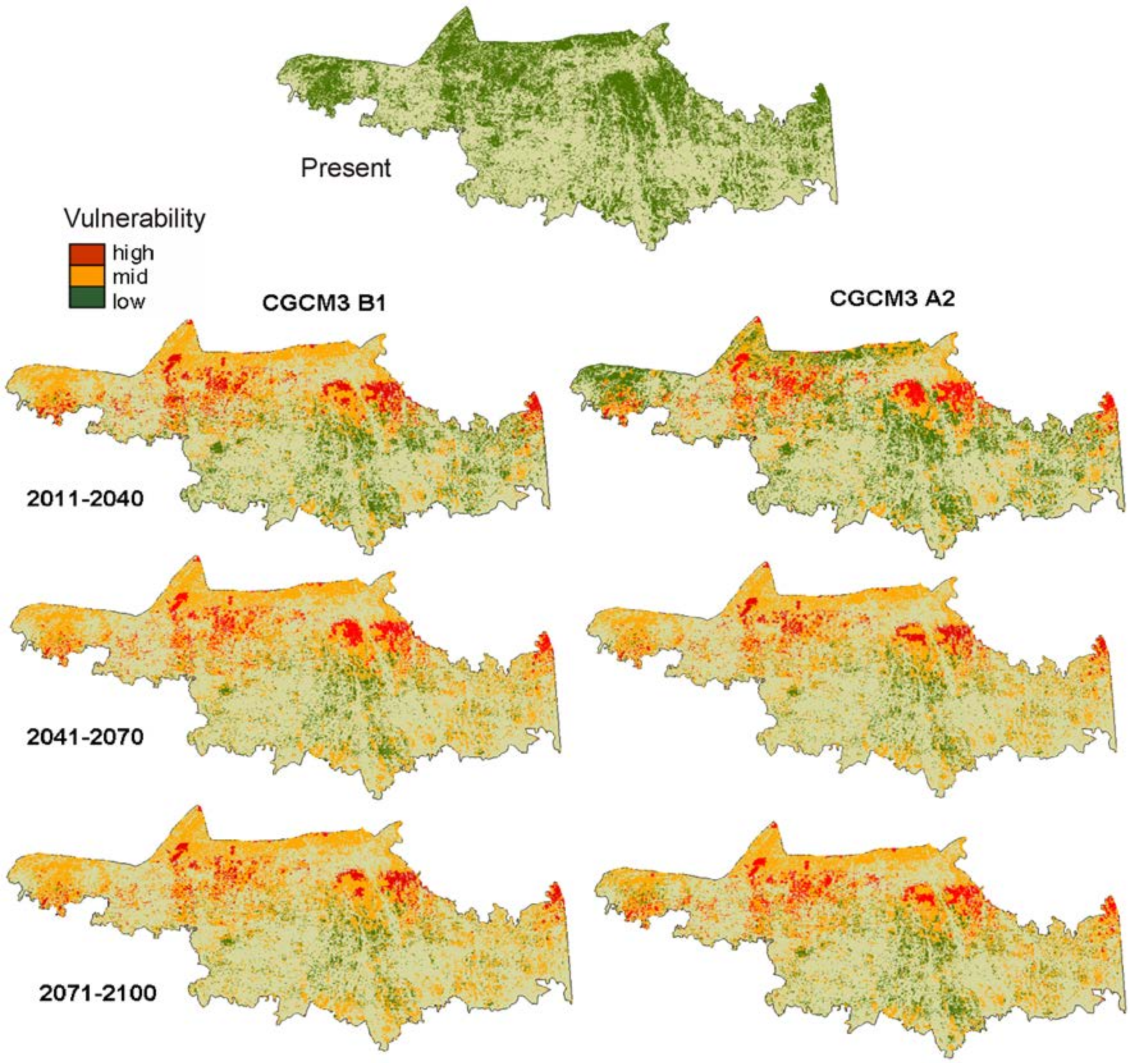

Figure 3. *Relative vulnerability of wetlands in Ontario's Clay Belt to groundwater inflows and changes in air temperature and precipitation associated with climate change projected using the Canadian Coupled Global Climate Model 3 under the B1 and A2 scenarios for the present and three future time periods.*

Streams

Future vulnerability: High because no quaternary watersheds have a high likelihood of retaining coldwater stream fish species under either climate scenario.

Of the 90 quaternary watersheds in the Clay Belt, 32 have not been sampled. Based on the fish species composition in the surrounding quaternary watersheds, it is likely that they also contain coldwater stream fishes. By 2071 under the CGCM3-B1 and -A2 model-scenarios, respectively, 13 (14%) and 61 (68%) of the 90 quaternary watersheds have a low likelihood of retaining coldwater fish species (Table 4; Figure 4). Watersheds with higher groundwater inflows and comparatively lower increases in air temperature have the highest potential for retaining coldwater species (Table 2).

Other climate variables and human activities will compound the potential changes in stream habitats. For example, changes in precipitation patterns, groundwater recharge rates, snow accumulation and melt patterns, stream regulation, riparian deforestation, and groundwater and surface water withdrawals could also disrupt fluvial and thermal regimes in the streams.

The strengths of the analyses are:

- They incorporate the dominant physical variables (air temperature and groundwater inflows) that influence the thermal regimes of streams.
- They offer easily interpretable guidance for prioritizing watersheds for conservation. Watersheds at risk in the short-term (i.e., those with a low likelihood to retain coldwater fish species) may be given high conservation priority. Alternatively, if climate change is assumed to be inevitable, watersheds that are likely to retain some coldwater species could be assigned high conservation priority because they will naturally offer more suitable habitat and thermal refugia for coldwater fishes in the future.

Uncertainties that should be addressed in future studies are:

- The distribution of coldwater fish species in streams. Coldwater species are not uniformly distributed within the watersheds, therefore adaptation strategies may need to differ among watersheds.
- Other factors such as stream regulation and surrounding land use need to be incorporated into the analyses because they also influence fish habitat and species distributions in streams.

Table 4. *Number of quaternary watersheds in Ontario's Clay Belt where coldwater stream fish species may occur given air temperature projections estimated using the Canadian Coupled Global Climate Model 3 under the B1 and A2 scenarios for three future time periods.*

Likelihood of retaining **coldwater fish species**	CGCM3 B1			CGCM3 A2		
	2011-2040	2041-2070	2071-2100	2011-2040	2041-2070	2071-2100
High	2	1	0	2	0	0
Medium	88	70	77	88	55	29
Low	0	19	13	0	35	61

Lakes

Future vulnerability: High because maximum surface water temperatures may rise making all Clay Belt lakes suitable for smallmouth bass under both climate scenarios.

By 2071 under the CGCM3-B1 and -A2 model-scenarios, respectively, the maximum surface water temperature of lakes may increase to 23.9 ºC and 25.4 ºC from the current 21.2 ºC (Figure 5). All 1,313 lakes in Ecodistrict 3E-1 may contain suitable smallmouth bass habitat by 2041, compared to the current 982 (Figure 6). For the same period and scenarios, total walleye biomass of the 158 lakes included in the analyses (Table 5; Figure 7) may increase by 9% and 10%, respectively (Table 6). Walleye productivity may increase in some lakes and decrease in others (Figure 8). However, productivity is projected to increase in larger lakes, which will result in an overall increase in total walleye biomass in the Clay Belt.

Non-climate-related stressors such as anthropogenic species introductions, including baitfish and vegetation, runoff from urban and agricultural lands in the form of point and non-point source pollution, and the natural ingress of species suited to the emerging climate conditions will all affect Clay Belt lake ecosystems. In addition, it is possible that demographic and social changes in the Clay Belt will affect the use of resources within these ecosystems.

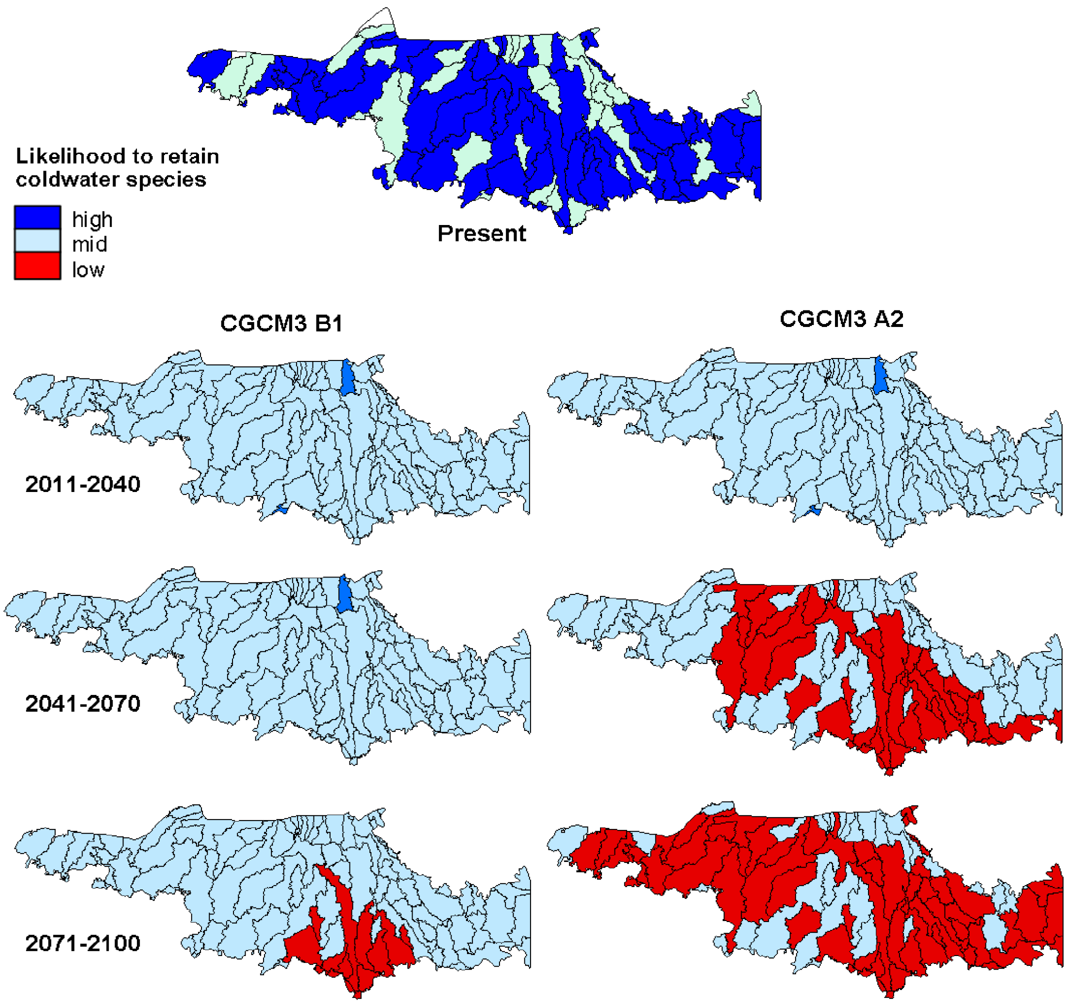

Figure 4. *Relative likelihood that streams within the quaternary watersheds of Ontario's Clay Belt will retain coldwater fish species under air temperature projections estimated using the Canadian Coupled Global Climate Model 3 under the B1 and A2 scenarios for three future time periods relative to present conditions.*

The strengths of the analyses reported here are:

- They apply established models for temperature, thermal habitat, and walleye productivity to estimate possible changes with climate.
- They use the best available data for lakes in the northeast Clay Belt.
- They offer easily interpretable guidance for prioritizing fisheries management.

Uncertainties that need to be addressed in future studies are:

- Other factors that influence the availability of suitable habitat for walleye and smallmouth bass (e.g., light or substrate).
- Changes in lower trophic-level dynamics, particularly potential changes in prey species for smallmouth bass and walleye.
- Vectors for the expansion of smallmouth bass into different water bodies (which were not considered here) need to be included.

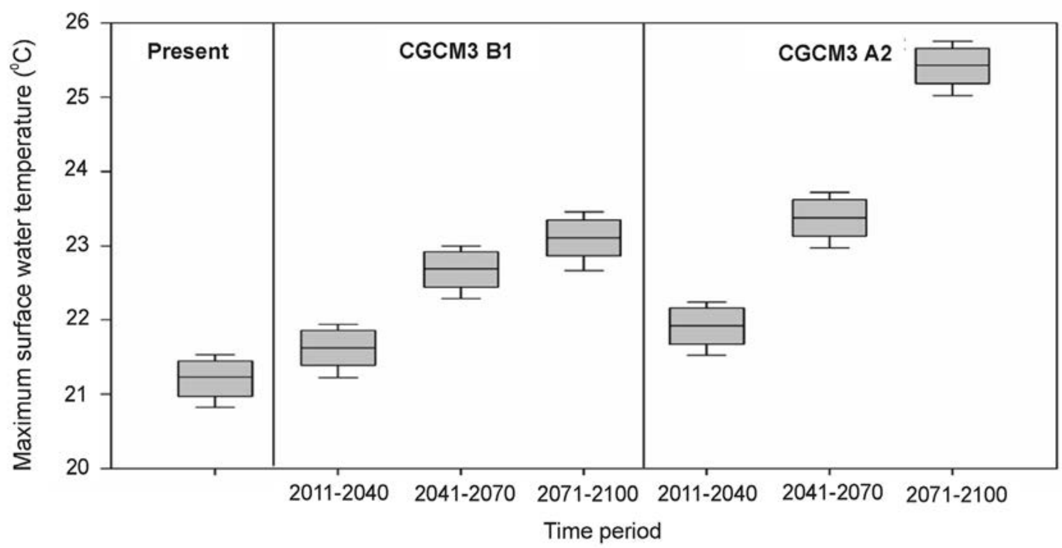

Figure 5*. Maximum surface water temperatures (ºC) of lakes in Ontario's Clay Belt now and for three future time periods based on air temperature projections estimated using the Canadian Coupled Global Climate Model 3 under the B1 and A2 scenarios.*

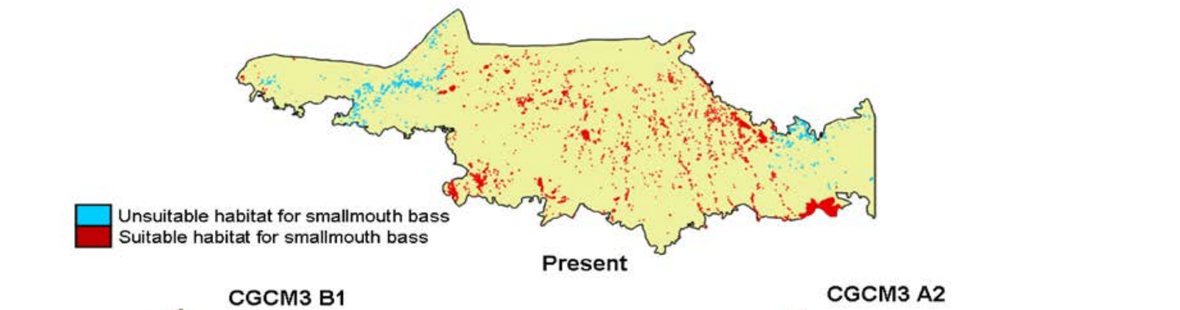

Figure 6. *Habitat suitability of lakes in Ontario's Clay Belt for smallmouth bass now and for three future time periods based on air temperature projections estimated using the Canadian Coupled Global Climate Model 3 under the B1 and A2 scenarios.*

Table 5. *Lake characteristics, thermal-optical habitat (km²), and walleye productivity (kg·ha⁻¹) of 158 lakes sampled in Ontario's Clay Belt.*

Attribute	Minimum	Mean	**Maximum**	Standard deviation
Lake area (km^2)	1.60	763.54	79,771.60	6,345.01
Maximum depth (m)	1.20	11.49	44.00	9.00
Mean depth (m)	0.50	3.29	11.10	2.20
Secchi depth (m)	0.23	2.04	8.20	1.14
Total dissolved solids ($mg·L^{-1}$)	21.75	80.77	220.66	39.79
Growing degree days (above 5 ºC)	1,073.00	1,156.08	1,214.00	39.50
Thermal-optical habitat (km^2)	0.07	35.38	2,183.80	178.58
Walleye productivity ($kg·ha^{-1}$)	0.40	8.47	16.63	3.41

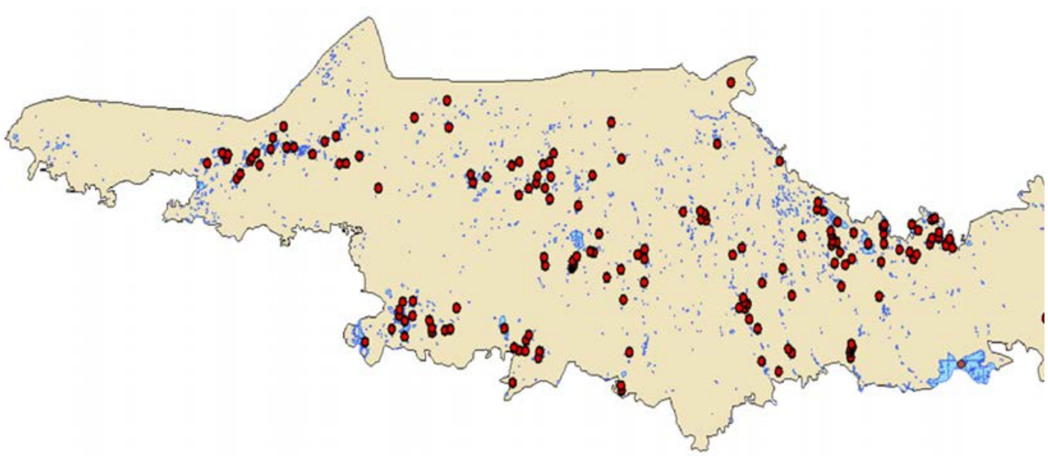

Figure 7. *Location of lakes (n = 158) in Ontario's Clay Belt used to examine the potential effects of changes in growing degree days (above 5 ºC) on walleye productivity.*

Table 6. *Total walleye biomass (kg) estimated for 158 lakes throughout Ontario's Clay Belt for the present and three future time periods based on air temperature projections estimated using the Canadian Coupled Global Climate Model 3 under the B1 and A2 scenarios.*

		CGCM3 B1			CGCM3 A2		
	Present	2011-2040	2041-2070	2071-2100	2011-2040	2041-2070	2071-2100
Total biomass (kg)	663,537	699,606	717,987	721,244	707,644	724,888	728,472

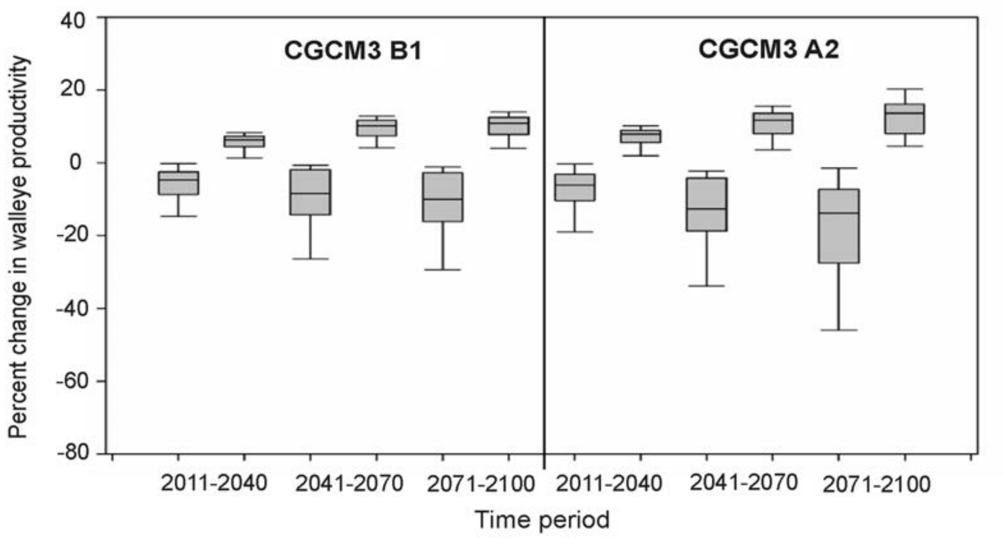

Figure 8. *Percent change in walleye productivity (grouped by decreases or increases) relative to present conditions in 158 lakes in Ontario's Clay Belt based on changes in growing degree days estimated using the Canadian Coupled Global Climate Model 3 under the B1 and A2 scenarios for three future time periods.*

Discussion

Our indicator results suggest that climate change has broad implications for the composition, structure, and function of aquatic ecosystems. For example, in the northern regions of the Clay Belt habitat for wetland-dependent species may be limited. This may change the distribution of plant and animal species presently inhabiting those wetlands. Other species may come to occupy those same areas or existing wetland species may adapt to the changing conditions (Mortsch et al. 2006).

Reductions in coldwater fish species distributions in some of the quaternary watersheds signify changes in the thermal regimes of the streams. This may affect the overall productivity, metabolic activity, growth rates, survival, timing of spawning events, and distribution of many stream organisms (Chu et al. 2010).

Warmer maximum surface water temperatures of lakes indicate changes in the thermal dynamics of these systems (e.g., shifted thermocline depths, longer periods of stratification, and increased duration of the ice-free season). This will affect the nutrient dynamics, dissolved oxygen concentrations, productivity, and availability of suitable habitat for warmwater species inhabiting the epilimnion, coolwater species in the metalimnion, and coldwater species in the hypolimnion (Dove et al. 2011).

Increases in the availability of suitable habitat for smallmouth bass throughout the Clay Belt represent the potential for smallmouth bass establishment if introduced to those systems. This may negatively affect fish communities already inhabiting those lakes, especially diverse cyprinid communities (MacRae and Jackson 2001). For example, Jackson and Mandrak (2002) estimated a loss of 25,000 populations of fathead minnows (*Pimephales promelas*), finescale dace (*Chrosomus neogaeus*), northern redbelly dace (*Chrosomus eos*), and pearl dace (*Semotilus margarita*) after the expansion of the smallmouth bass following climate warming in Ontario.

The changes in walleye productivity reflect changes in suitable walleye habitat in the lakes given different climate projections. Walleye are a coolwater species, preferring temperatures of 22 ºC. Therefore, in lakes where walleye productivity increases, warmer temperatures increase suitable habitat and productivity but in other lakes temperatures may become too warm; decreasing habitat and subsequently productivity. The changes in walleye productivity will affect the predator-prey dynamics of these systems, with declines and increases in walleye productivity leading to higher or lower recruitment in the prey populations, respectively. Changes in walleye productivity will also affect the socioeconomics of the recreational walleye fishery within the ecodistrict (see Hunt and Kolman 2012).

Recommendations

Wetlands

- Broad-scale data, not currently available for wetland types (e.g., bogs, fens, marshes etc.) throughout the Clay Belt, need to be collected to effectively determine the fate of wetlands as the climate changes.
- A network of monitoring stations needs to be established in Clay Belt wetlands to support the detection of changes in wetland extent and quality.
- Wetland species (e.g., waterfowl and amphibians) need to be monitored to determine the effect of changes in wetland extent on their distribution and populations.

Streams

- Currently, only two HYDAT (Water Survey of Canada) stations exist in Ecodistrict 3E-1. This network needs to be expanded to ensure that accurate baseline flows, and temperatures and water levels of streams are established and changes monitored.
- Thirty-two of the 90 quaternary watersheds in the Clay Belt have no readily available stream fish data. A water quality monitoring network that includes a fish and benthic invertebrate inventory should be established for streams.
- Data from hydropower environmental assessment reports could be compiled and used to help inform the development of a stream monitoring network throughout the Clay Belt.

Lakes

- Continued support of the broad-scale monitoring program is necessary to establish present conditions of lakes in the Clay Belt and monitor changes over time. Broad-scale sampling should be maintained and if possible expanded. Broad-scale sampling allows for the monitoring of water quality as well as zooplankton and fish populations.
- A better understanding of the natural and anthropogenic processes driving invasive fish species expansions would help inform the management and/or control of those species.

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