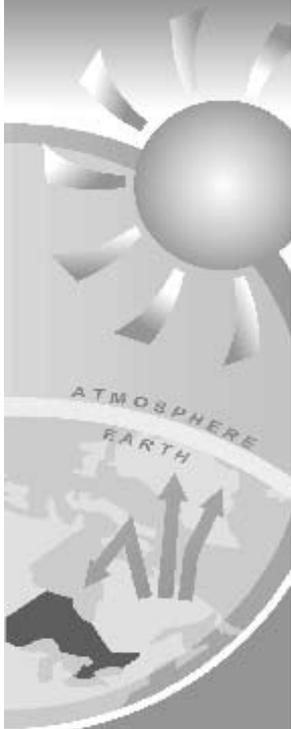


22

CLIMATE
CHANGE
RESEARCH
REPORT
CCRR-22



*Responding to
Climate Change
Through Partnership*

Wildlife Vulnerability to Climate Change: An Assessment For the Lake Simcoe Watershed



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 through 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.

Wildlife Vulnerability to Climate Change: An assessment For the Lake Simcoe Watershed

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Summary

We used wildlife indicators to assess the ecological conditions of the Lake Simcoe Watershed and to identify vulnerabilities to climate change within the watershed for the period 2010-2100. We measured avian guild richness, anuran calling and breeding phenology, mammal species richness, and landscape fragmentation. Overall, avian species richness has increased since 1985, particularly in the forest interior and cavity nesting guilds. This increase was heterogeneous across the landscape. Several subwatersheds, including Georgina Creeks, Hawkestone Creeks, Oro Creeks South, and Ramara Creeks, consistently contained the fewest species of each avian guild and thus may represent vulnerabilities in the watershed. However, during the next 90 years we expect overall avian species richness to increase in response to changes in summer and winter temperatures and precipitation. Anuran reproduction is also likely to be affected by climate change as reflected through changes in calling behaviour. We found that the calling date of amphibians in the Lake Simcoe region was linked to spring temperatures. Based on relationships identified between amphibian calling and average monthly spring temperature, we developed future calling scenarios using climate change models. These scenarios suggested that spring breeding amphibians may call 13 days earlier by 2100, consequently lengthening their breeding period. Mammal species richness across Canada is positively related to mean annual temperature. Thus, we expect that mammal species richness will increase by up to 20% by 2100. As an example, we modelled range expansion by the Virginia opossum (*Didelphis virginiana*) and demonstrated that within the next 30 years its range may fully encompass the Lake Simcoe Watershed. Finally, we determined that habitat fragmentation in the watershed is high compared to other measured watersheds in North America. Climate change in the Lake Simcoe Watershed will likely be characterized by shifts in animal distributions and changes in their reproductive timing. The fragmented nature of the watershed, however, may impede distribution shifts and thus hinder the ability of some species to respond to a changing climate. We conclude by providing recommendations to improve the resilience of wildlife populations in the Lake Simcoe Watershed to climate change.

Résumé

La vulnérabilité de la faune aux changements climatiques : évaluation du bassin hydrographique du lac Simcoe

Nous nous sommes servis d'indicateurs fauniques pour évaluer les conditions écologiques du bassin hydrographique du lac Simcoe et identifier les vulnérabilités aux changements climatiques pour la période 2010-2100. Nous avons mesuré la richesse des guildes aviaires, les appels des anoures et la phénologie reproductive, la richesse des espèces de mammifères et la fragmentation de l'habitat. De façon générale, la richesse des espèces aviaires a augmenté depuis 1985, surtout à l'intérieur des forêts et chez les guildes qui nichent dans les cavités. Cette augmentation est hétérogène dans le paysage tout entier. Plusieurs sous-bassins hydrographiques, dont ceux des ruisseaux Georgina, des ruisseaux Hawkestone, des ruisseaux Oro Sud et des ruisseaux Ramara contenaient de façon systématique le nombre le moins élevé de chaque guildes aviaires, ce qui pourrait représenter des vulnérabilités dans le bassin hydrographique. Cependant, au cours de 90 prochaines années, nous nous attendons à ce que la richesse des espèces aviaires augmente de façon générale en raison des changements des températures estivales et hivernales ainsi que sur le plan de la précipitation. La reproduction anoure est aussi susceptible de subir les conséquences des changements climatiques, ce qui se manifeste par la modification du comportement d'appel. Nous avons constaté que la date à laquelle commençait le comportement d'appel des amphibiens de la région du lac Simcoe était lié aux températures printanières. En nous fondant sur les rapports constatés entre l'appel des amphibiens et les températures printanières moyennes, nous avons élaboré des scénarios d'appel futurs en nous servant de modèles de changements climatiques. Ces scénarios laissent présager que les amphibiens qui se reproduisent au printemps pourraient commencer à appeler 13 jours plus tôt d'ici 2100, ce qui prolongerait leur période de reproduction. La richesse des espèces de mammifères partout au Canada est liée de façon positive aux températures moyennes annuelles. Nous prévoyons donc que la richesse des espèces de mammifères augmentera de jusqu'à 20 % d'ici 2100. À titre d'exemple, nous avons modelé une expansion de l'aire de répartition de l'opossum de Virginie (*Didelphis virginiana*) et avons démontré qu'au cours des 30 prochaines années, son aire de répartition pourrait englober le bassin hydrographique du lac Simcoe tout entier. Enfin, nous avons déterminé que la fragmentation de l'habitat dans le bassin hydrographique est élevée à comparer aux autres bassins hydrographiques mesurés en Amérique du Nord. Les changements climatiques dans le bassin hydrographique se traduiront probablement par des déplacements sur le plan de la distribution des animaux et des changements au niveau des périodes de reproduction. La nature fragmentée du bassin hydrographique, cependant, est susceptible d'entraver les déplacements sur le plan de la distribution et nuire à la capacité de certaines espèces de réagir à un climat en évolution. En conclusion, nous proposons des recommandations pour améliorer la résilience des populations fauniques du bassin hydrographique du lac Simcoe à l'égard des changements climatiques.

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We thank Bird Studies Canada for contributing Ontario Breeding Bird Atlas and Amphibian Marsh Monitoring data for the Lake Simcoe region. Thanks also to Jochen Jaeger who provided valuable comments and advice on fragmentation metrics as well as Doug Tozer and Debbie Badzinski for their input on anuran calling phenology. We acknowledge Kathleen Gould for her valuable contributions to climate envelope modelling and mapping. We also thank Paul Gray, Rob Rempel, and Lisa Buse for helpful comments on an earlier version of the manuscript and Trudy Vaitinen for formatting the report. This project was funded by the Climate Change Program, Ontario Ministry of Natural Resources.

Foreword

In a rapidly changing climate, decision-makers require a sense of the vulnerability of ecological and social systems to create goals and objectives for the future and propose actions to reduce or eliminate that vulnerability. In this context, vulnerability is the degree to which a system is susceptible to, or unable to cope with, the adverse effects of climatic change. In a world where climate change and other stressors are affecting natural and social systems, resource managers are working to integrate climate models (top-down projections of possible future climates) with vulnerability analyses (bottom-up assessments of how species and systems might be affected) to inform decision-making.

Climate models are projections rather than predictions: they require us to make assumptions based on best available information at the time. There is inherent uncertainty in these projections that derives from the degree of uncertainty in the assumptions. In addition, the response of Earth's climate to future greenhouse gas emissions is uncertain, and shifts in human behaviour in response to a changing climate and corresponding reductions to the rate and volume of greenhouse gas emissions are not fully known. Nevertheless, climate models provide a valuable tool to assess the vulnerability of ecosystems to a changing climate and assist resource managers in deciding on actions to improve ecosystem resilience and adaptation.

Vulnerability analysis uses a suite of ecological and social indicators to provide information about how a system is responding to change. Some indicators, such as an animal's thermoregulatory tolerance, are species specific while others, such as water temperature, provide information about the changing dynamics of entire systems. With this knowledge, management actions can be used to reduce or eliminate the vulnerability or support adaptation. Effective monitoring to measure change is also necessary, and raises the question: "Will existing monitoring inform effective decision-making in a rapidly changing climate?" Accordingly, existing monitoring programs should be re-examined to ensure they include the climate sensitive indicators measured at a frequency and/or scale that is relevant to expected changes in climate.

In the absence of complete information, vulnerability assessments are based on a variety of qualitative (e.g., expert opinion solicited during workshops) and quantitative (e.g., measures of species phenotypic and genetic plasticity) indices. These indicators can support practitioners' planning needs. As with any adaptive management process, ongoing assessment and modification are necessary as new information emerges.

Vulnerability assessment techniques continue to evolve and it is important for practitioners to learn by doing and to pass on knowledge gained. Accordingly, this and other vulnerability assessments have been prepared using the best available information under the circumstances (e.g., time, financial support, and data availability). We include these in our research report series to support MNR and others engaged in adaptive management. Collectively these assessments can inform decision-making, enhance scientific understanding of how natural assets respond to climate change, help practitioners design their own vulnerability assessments, and help resource management organizations establish research and monitoring needs and priorities.



Anne Neary
Director, Applied Research and Development Branch

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Introduction

Although agreement is widespread on 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. An adaptive management process includes steps to assess readiness and capacity to respond, to conduct vulnerability analyses to identify and prioritize adaptation needs, develop adaptation strategies, and to monitor adaptation success and determine if vulnerabilities have been reduced/eliminated (Figure 1). We were requested to complete a vulnerability assessment for the Lake Simcoe Watershed using selected wildlife indicators in support of the Lake Simcoe Climate Change Adaptation Strategy as called for in the Lake Simcoe Protection Plan (Government of Ontario 2009). This work supports the Expert Panel on Climate Change Adaptation (2009) recommendations and Ontario's Adaptation Strategy and Action Plan: 2011-2014 (Government of Ontario 2011).

In this report, we document the development and application of a vulnerability assessment that can be used with other tools and techniques to assess wildlife vulnerabilities to climate change and inform an adaptive strategic planning process. Vulnerability is the degree to which a system is susceptible to and unable to cope with adverse effects of environmental change, including climate variability and extremes (IPCC 2007). It follows that vulnerabilities in a system are those with poor ecological health or integrity that are incapable of maintaining natural processes under the influence of environmental change. Ecological integrity refers to the ability of an ecosystem to maintain a functional and adaptive community of organisms at a state comparable to historical conditions or to other similar ecosystems that have not been degraded by human activities (Carignan and Villard 2002, Stoddard et al. 2006).

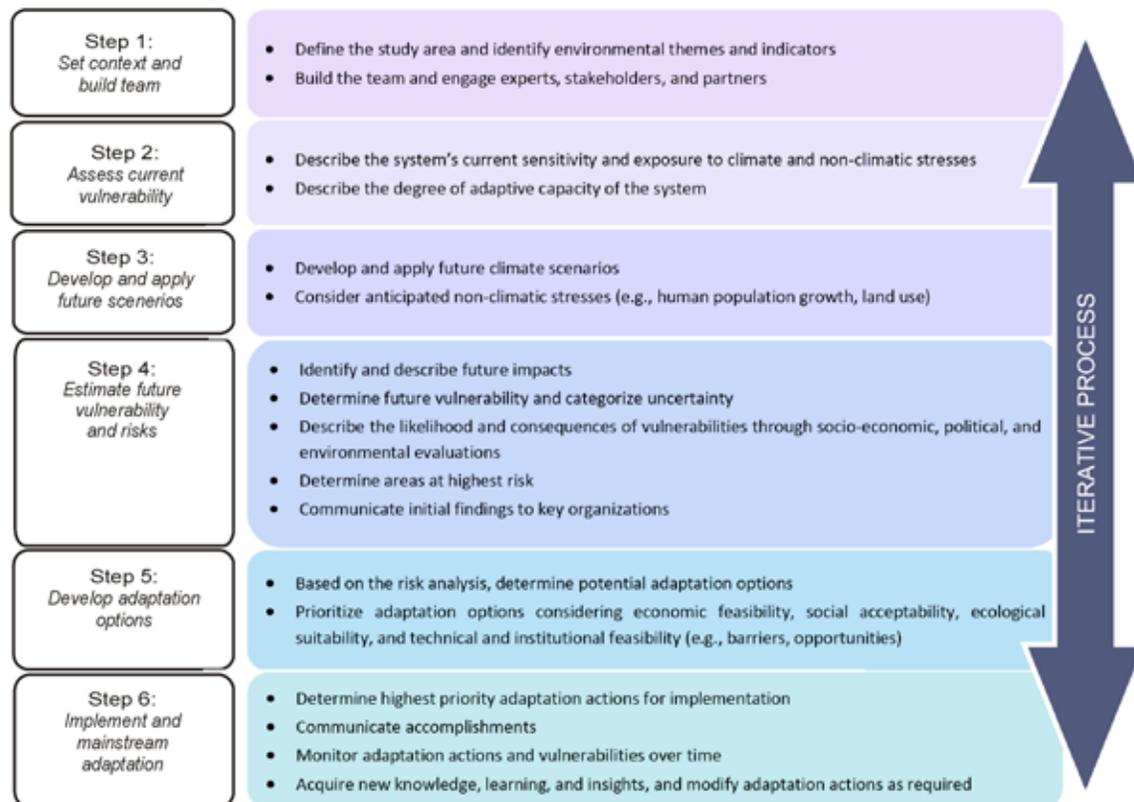


Figure 1. Steps in the vulnerability assessment to inform development of a climate change adaptation strategy for the Lake Simcoe Watershed (Source: Gleeson et al. 2011).

Given the practical difficulties in measuring ecological integrity of wildlife, we elected to measure present ecological conditions and use scenarios of future departures from these conditions to assess wildlife vulnerabilities. Thus, we identified indicators of wildlife richness and ecological processes in the Lake Simcoe Watershed (44°26'12"N, 79°20'21"W; Figure 2). We assessed how these measures would respond to climate change scenarios based on projections from the Canadian Global Climate Model (v. 2 and 3.1) under emissions scenario A2 (Canadian Climate Change Scenarios Network; <http://cccsn.ca>). We selected wildlife indicators that describe local biodiversity, community and range boundary dynamics, population size and landscape fragmentation, all of which are potentially susceptible to land use practices and climate change and/or interact with these stressors to affect wildlife populations. Understanding the potential for changes in these measures will reveal vulnerabilities in the Lake Simcoe Watershed. Thus, in this report we provide a vulnerability assessment for wildlife in the Lake Simcoe Watershed.



Figure 2. A map of the Lake Simcoe Watershed in Ontario (44°26'12"N, 79°20'21"W) showing subwatersheds. The blue polygon represents Lake Simcoe proper.

Methods

We selected four indices – avian guild richness, anuran calling and breeding phenology, mammal species richness, and landscape fragmentation – to describe the present ecological state of the Lake Simcoe Watershed and compared the resulting ecological patterns to temperature variables to identify relationships. Where relationships existed or where previous research indicated relationships, we predicted how these indices would change based on projected climate change scenarios.

Avian guild richness

We assumed that subwatersheds with low avian guild richness reflected poor ecological conditions (and therefore vulnerabilities) whereas subwatersheds with high avian guild richness reflected relatively better ecological conditions. We selected species from four functional guilds to assess the integrity of the Lake Simcoe ecosystem including: forest interior species, cavity nesting species, aerial foraging species, and wetland obligate species. Data were from Ontario Breeding Bird Atlas surveys conducted from 1981 to 1985 and 2001 to 2005 (Ontario Breeding Bird Atlas 2001). We examined changes in species occurrence between the two survey periods to explore patterns of and shifts in species composition.

Anuran calling and breeding phenology

Several common North American anuran species have begun calling earlier in the season, consistent with observed increases in spring temperatures over the past century (Gibbs and Breisch 2001). We explored temporal trends in spring temperatures and calling behaviour of seven common anuran species (Table 1) in the Lake Simcoe region between 1995 and 2008 (Bird Studies Canada's amphibian marsh monitoring program data; Marsh Monitoring Program 2009) in relation to current climate to understand the effects of changing climate on reproductive phenology. For these seven species, we estimated the peak calling periods per year based on the average day of the year when the most frogs were calling (i.e., highest calling code). Calling code is an index of the number and intensity of individual frogs per species heard calling during the marsh monitoring survey, and ranged from 0 to 3. Thus, we estimated peak calling date as the mean day of year weighted by the highest calling code. We completed multiple regressions for the three earliest calling species to assess the relative influence of survey methodology and spring temperatures on calling phenology and to identify relationships between peak calling date and average monthly spring temperature. For each parameter, importance weights (W_i) were estimated by applying Akaike's Information Criteria to the regression models. Importance weights quantify (on a relative basis) how well each parameter predicts peak calling date for the species. Based on these relationships, we projected future climate change effects on the breeding behaviour of spring breeding anuran populations in the region using the Canadian Global Climate Model 3.1 (CGCM3.1) under emissions scenario A2. For this indicator, we used this model rather than CGCM2 because it provided monthly maximum and minimum temperatures from which we could estimate the mean monthly temperatures necessary for developing future scenarios of anuran calling behaviour.

Mammal species richness

Species at their northern range boundary that are limited by climate may benefit from a changing climate and expand their ranges with increasing annual temperatures. When at the southern edge of their range, however, populations are more likely to contract due to pressure from southern counterparts (MacArthur 1972, Myers et al. 2009). Several species have already demonstrated significant northerly shifts in distribution in response to climate change (Brocke 1970, Bowman et al. 2005, Moritz et al. 2008, Myers et al. 2009).

Mean annual temperature is a strong predictor of regional mammal species richness in Canada (Kerr and Packer 1998). We assessed potential changes in mammal species richness in the Lake Simcoe Watershed to the year 2100 based on current temperature and future mean annual temperature using the CGCM2 with the A2 climate scenario. We forecasted mammal species richness based on the species – energy model developed by Kerr and Packer (1998):

$$\text{Mammal species richness} = 1.960 \times (\text{Mean annual temperature in } ^\circ\text{C}) + 38.1 + \epsilon,$$

where ϵ is the residual variance. Finally, as an example of changing mammal richness, we used climate envelope modelling to explore the range expansion of the Virginia opossum (*Didelphis virginiana*) in Ontario. The distribution of the Virginia opossum is restricted by winter temperatures and has undergone expansion with increasing winter temperatures (Kanda 2005).

Landscape fragmentation

Landscape fragmentation results in smaller and more isolated habitat patches and thus smaller and more isolated populations of wildlife that are under increased risk of localized extinction (Fahrig 2002). In fragmented landscapes, species are less able to shift their distributions to compensate for changes in habitat. Thus, a synergy exists between climate change and habitat fragmentation that may reduce biodiversity beyond what is projected by species - energy models (Varrin et al. 2007). We quantified fragmentation by aggregating land cover types into natural and anthropogenic cover types using the Southern Ontario Land Resource and Information System (Ontario Ministry of Natural Resources 2007) database. Based on these aggregated cover types, we identified highly fragmented subwatersheds and thus potential vulnerabilities for wildlife populations in the Lake Simcoe Watershed. We assumed that native species would be associated more with natural than anthropogenic cover types. We measured landscape fragmentation using *effective mesh size* (Jaeger 2000) to identify subwatersheds vulnerable to climate change. Effective mesh size is a metric of fragmentation that can be interpreted generally as the average size of habitat patches in the watershed (km²) or the probability that two random animals will occur in the same patch of habitat and therefore be connected (Table 1). We used effective mesh size to assess how the structural landscape could affect wildlife populations and thus identify which systems are likely to be more vulnerable to climate change.

Results

Avian guild richness

Overall, avian species richness in the Lake Simcoe region has increased since 1985 ($F_{1,57} = 6.97$, $p = 0.01$). More specifically, species richness of birds in forest interior ($F_{1,57} = 5.54$, $p < 0.0001$) and cavity nesting guilds ($F_{1,57} = 8.08$, $p = 0.006$) have significantly increased since 1985. Richness in wetland obligate and aerial foraging bird guilds, however, has not changed (all $F_{1,57} < 1.16$, $p > 0.2$). We detected no relationship between avian guild richness and our measures of fragmentation or the size of the watershed (km²; all $r < 0.19$, $n = 23$, $p > 0.35$).

The Georgina Creeks, Hawkestone Creeks, Oro Creeks South, and Ramara Creeks subwatersheds consistently had the lowest species richness in each of the four guilds (Table 1; Figure 3). Conversely, Innisfill Creeks, Upper Talbot River, and Hewitts Creeks had the highest species richness in each guild (Table 1). A paucity of species from representative guilds suggests a degradation of the characteristics of habitat required to support that guild in the system. For example, few interior forest bird species in the Georgina Creeks subwatershed suggests that forest cover in that system lacks suitable interior habitat necessary to sustain a relatively healthy assemblage of interior forest species. Systems with low guild species richness reflect poor ecological conditions for that particular guild and that the system may have reduced ability to cope with changing environmental conditions. Thus, areas with low guild richness may identify vulnerabilities in the watershed.

Several species that are at the northern extent of their geographic distributions are new arrivals or have expanded their range in the watershed since 1985. For example, hooded warblers (*Wilsonia citrina*; Melles et al. 2010), blue-winged warblers (*Vermivora cyanoptera*; Dabrowski et al. 2005), and Acadian flycatchers (*Empidonax vireescens*; Emlen et al. 1986), are newly occurring in the Lake Simcoe region and their range expansion is likely attributable to changing climatic conditions.

Table 1. Land cover characteristics and estimated richness of species in each guild group in subwatersheds constituting the Lake Simcoe Watershed. Richness estimates are based on area weighted averages in each subwatershed from Ontario Breeding Bird Atlas squares (10 km x 10 km; Ontario Breeding Bird Atlas 2001). Effective mesh size represents the average size of meshed habitat patches (km²) and the probability that two patches in the subwatershed will be connected.

Subwatershed	Richness				Subwatershed area (km ²)	Effective mesh size (km ²)	Effective mesh size (probability)
	Forest Interior	Aerial Forager	Cavity Nester	Wetland Obligates			
Pefferlaw Brook	48.3	22.0	29.2	12.1	446.2	67.92	0.15
Black River	67.4	31.1	42.3	22.7	375.4	75.76	0.20
West Holland	46.6	25.2	29.4	17.6	351.9	22.10	0.06
Beaver River	21.4	18.8	17.1	15.8	327.3	24.28	0.07
Upper Talbot River	62.6	43.2	39.8	29.6	294.0	71.99	0.24
East Holland	40.8	25.9	36.3	19.0	247.1	19.04	0.08
Ramara Creeks	22.3	14.8	14.5	11.0	137.2	14.12	0.10
Innisfil Creeks	56.6	31.6	42.9	34.5	107.2	8.88	0.08
Whites Creek	31.4	23.1	20.2	12.2	105.4	9.09	0.09
Oro Creeks North	37.9	16.9	21.0	12.7	75.3	10.94	0.15
Lower Talbot River	32.5	26.0	21.1	20.9	70.2	6.40	0.09
Maskinonge River	20.5	17.6	16.6	9.9	63.5	2.24	0.04
Lovers Creek	52.2	35.0	38.7	18.3	59.9	4.86	0.08
Oro Creeks South	22.6	14.0	19.7	4.3	57.4	8.82	0.15
Georgina Creeks	17.9	14.7	20.4	6.4	49.3	6.45	0.13
Hawkestone Creek	36.2	15.8	19.1	7.9	47.8	10.67	0.22
Barrie Creeks	51.9	33.9	43.8	23.9	37.5	0.75	0.02
Hewitts Creek	54.9	28.0	41.4	25.2	17.5	0.61	0.03

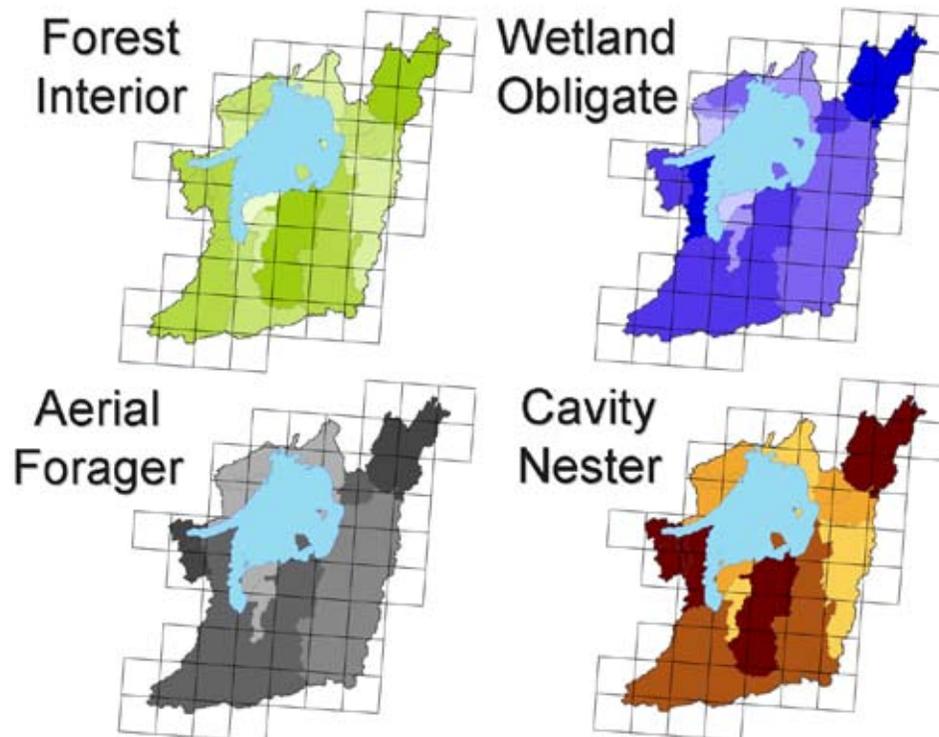


Figure 3. A map of species richness in four avian guild groups estimated in each Lake Simcoe subwatershed based on surveys conducted in Ontario Breeding Bird Atlas survey squares (shown in gray) from 2001 to 2005 (Ontario Breeding Bird Atlas 2001). Subwatershed richness estimates are area weighted averages from the atlas squares (Table 1), with darker colours indicating greater guild group species richness.

Anuran calling and breeding phenology

Between 1995 and 2008, mean monthly temperature strongly increased in April ($r = 0.667$, $n = 13$, $p = 0.013$), increased slightly in July ($r = 0.523$, $n = 14$, $p = 0.081$), but did not change in May or June (both $r < 0.01$, $n = 12$, $p > 0.05$). We found that the average first survey date per year was not related to average monthly spring temperature ($p > 0.08$) but did get earlier over time (1995-2008; $r = -0.547$, $n = 14$, $p = 0.43$).

Since 1995, spring breeding anurans have begun calling earlier in the year (Figure 4). Nearly all species demonstrated a negative trend in peak calling date between 1995 and 2008 (Table 2). To compare the breadth of responses across the anuran community, we rank transformed the slopes and intercepts of the regression relationships between peak calling date and year for each species. The ranked regression slopes (coefficients) were positively related to the ranked intercept ($r_s = -0.929$, $n = 7$, $p = 0.003$; Figure 5), suggesting that peak calling dates are advancing more rapidly for early breeding than for late breeding species.

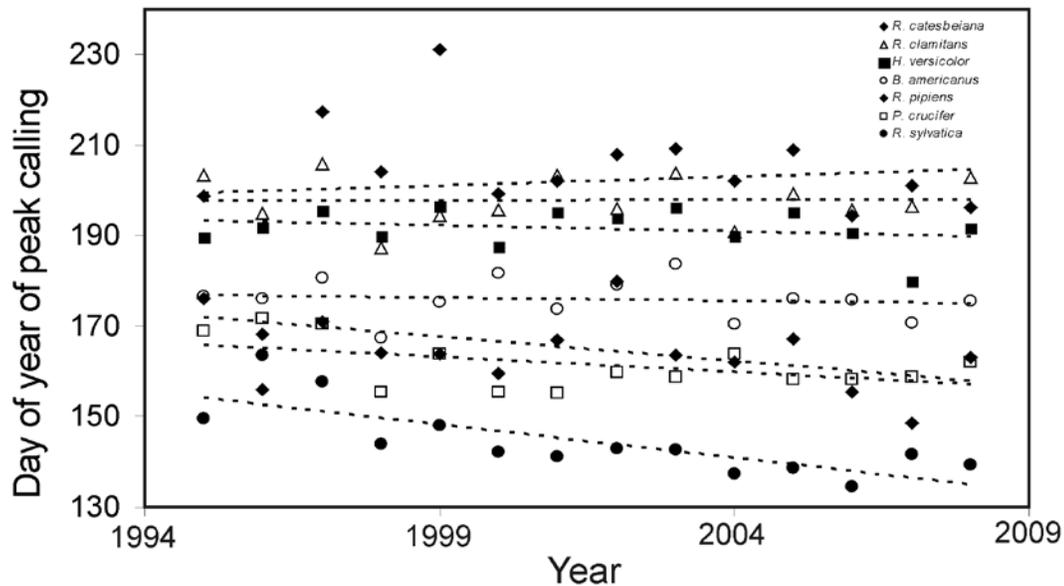


Figure 4. Trends in peak calling date for seven anurans detected at survey stations in the Lake Simcoe Watershed between 1995 and 2008. Peak calling date is the average day of year when the highest numbers of frogs per species were calling.

Table 2. Linear regression results of changes in peak calling dates of anurans in the Lake Simcoe Watershed between 1995 and 2008. The unit of intercept is peak calling date and is expressed as the day of the year. Negative coefficients indicate a phenological advance in calling dates (i.e., earlier in the season). SE represents standard error around the coefficient.

Species	Scientific name	Intercept ¹	Coefficient	SE	p-value
Wood frog	<i>Rana sylvatica</i>	153.724	-1.47	0.344	0.001
Northern leopard frog	<i>Rana pipiens</i>	172.18	-1.065	0.448	0.035
Spring peeper	<i>Pseudacris crucifer</i>	166.357	-0.669	0.332	0.067
Gray tree frog	<i>Hyla versicolor</i>	194.164	-0.26	0.297	0.398
American toad	<i>Bufo americanus</i>	176.326	-0.151	0.303	0.628
Green frog	<i>Rana clamitans</i>	198.042	0.005	0.374	0.99
Bull Frog	<i>Rana catesbeiana</i>	200.455	0.397	1.117	0.729

¹ The unit of the intercept is the day of year of peak calling.

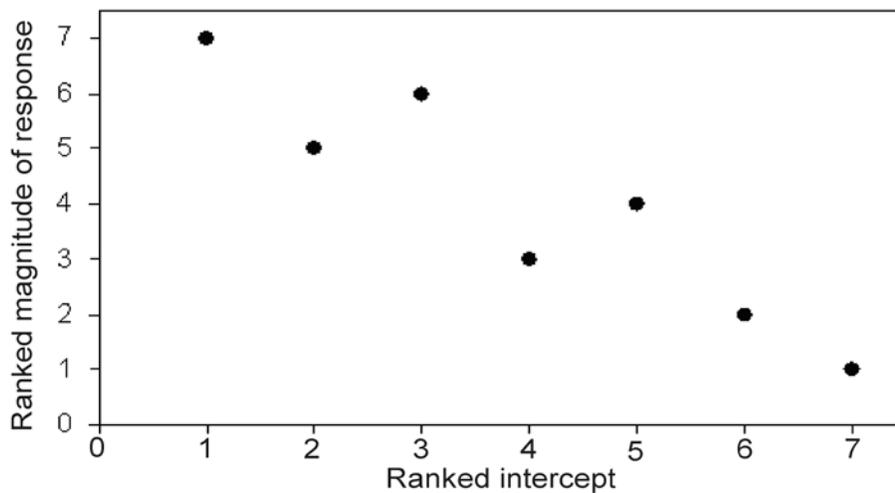


Figure 5. The relationship between the ranked intercept and the magnitude of response for the trends in peak calling dates of seven anuran species in the Lake Simcoe Watershed between 1995 and 2008 (ranked values derived from coefficients and intercepts in Table 1). Greater magnitude of response indicates that the species' peak calling date has changed relatively more during the monitoring period. Greater intercept values indicate species that call later in the season.

Exploratory analysis revealed that peak calling date for some species was negatively correlated with mean monthly temperature in April (spring peeper [*Pseudacris crucifer*]: $r = -0.839$, $n = 11$, $p = -0.001$; wood frog [*Rana sylvatica*]: $r = -0.796$, $n = 11$, $p = 0.003$), and May (American toad [*Bufo americanus*]: $r = -0.626$, $n = 12$, $p = 0.029$), indicating that peak calling date was linked to spring temperature. We conducted multiple regressions of peak calling date for wood frog, northern leopard frog (*Rana pipiens*), and spring peeper against spring temperature and average date of first survey visit each year to assess effects of temperature while considering potential influence of survey methodology. Model selection results indicated that the temperature parameter was the most important predictor of peak calling date for all three species; importance weights of temperature

Table 3. Multiple regression results of peak calling date for the Northern leopard frog, spring peeper, and wood frog. The estimate represents the regression coefficient describing the strength and direction of relationship with the independent variables, temperature or date of survey visit (visit). SE represents the standard error of the estimate and was used to identify the upper and lower 95% confidence intervals (CI).

Parameter	Estimate	SE	95% CI	
			Upper	Lower
Northern leopard frog				
Intercept	158.04	36.84	240.12	75.97
Temperature	-1.79	1.39	1.31	-4.89
Visit	0.50	0.36	1.30	-0.30
Spring peeper				
Intercept	179.06	6.72	194.05	164.08
Temperature	-3.23	0.71	-1.65	-4.82
Visit	0.01	0.22	0.50	-0.48
Wood frog				
Intercept	145.22	38.73	231.50	58.93
Temperature	-4.30	0.54	-3.11	-5.50
Visit	0.47	0.30	1.13	-0.19

for each species were 0.99 for wood frog and northern leopard frog and 1.00 for spring peeper. Survey visit was moderately important for northern leopard frog and wood frog ($Wi = 0.25$ and 0.31 , respectively) but not for spring peeper ($Wi = 0.09$). The added influence of survey visit on calling phenology of wood frogs and northern leopard frogs confounds a straight forward interpretation of temperature relationships for these species. However, the lack of the added effect of survey visit on calling phenology of spring peepers permits a simple interpretation of climate change impacts for this species.

The CGCM3.1-A2 climate scenario projected that by the year 2100 average spring (April) temperatures in the watershed will increase by 4°C . The earliest breeding species in our study were wood frog, spring peeper, and northern leopard frog, whose peak calling date got earlier over time and with increasing spring temperatures. When we applied the top ranking regression model for spring peepers to projected spring temperatures in 2100, results indicated that peak calling date may occur up to 13.1 days earlier. Wood frog calling behaviour, although complicated by the additive influences of the date of first survey visit and spring temperature, suggests that their calling date would advance even more so than that of spring peepers. The peak calling dates of late spring-breeding species, such as green frog and bullfrog, were not influenced by temperature ($p > 0.05$) and thus we predicted no direct shift in late-breeding anuran call dates in response to increasing temperatures. These scenarios highlight the potential for a 15% increase in the breadth (from 47 days to 54 days) of the breeding season (time between earliest and latest calling date) for the anuran community in the Lake Simcoe Watershed by 2100.

Mammal species richness

When combined with the climate model CGCM2-A2, species-energy relationships presented a scenario where mammal species richness would increase 20% by the year 2100 – a linear response to changes in mean annual temperature. The models suggest that current climate conditions support a community of approximately 51 species but this number may increase to 53 species for the 2011-2040 period, 57 species for 2041-2070, and 60 species for 2071-2100.

Cold winter temperatures limit the Virginia opossum's distribution by reducing overwinter survival (Kanda 2005, Tyndale-Biscoe and MacKenzie 1976, Wiseman and Hendrickson 1950). In southern Ontario, the -12°C January minimum temperature isotherm (averaged from 1970-1993) coincides with their northern range boundary (1970-1993; Dobbyn 1994). We used the -12°C minimum January isotherm from the CGCM2-A2 climate model to assess potential northern range boundaries of opossums in Ontario for the periods 2011-2040, 2041-2070, and 2071-2100. Results indicated that by 2011-2040 the range of opossums will fully encompass the Lake Simcoe Watershed (Figure 6). The distribution of other species, such as the common grey fox (*Urocyon cinereoargenteus*) and eastern fox squirrel (*Sciurus niger*) have also substantially expanded their distributions (Fritzell and Haroldson 1982 and De Vos 1964, respectively). The northern range boundary of these species currently reaches southern Ontario and is suspected to be limited by climate (Judge and Haviernick 2002, Moncrief et al. 2010) making them likely candidates for future range expansions into the watershed.

Landscape fragmentation

Based on our calculations of effective mesh size in subwatershed sheds, the mean probability across all subwatersheds that two random animals will occur in the same habitat patch is 0.11 (excluding islands). The Upper Talbot River, Hawkestone Creek, and Black River systems are the most well connected (Table 1; Figure 7). The most fragmented systems include Barrie Creeks, Hewitts Creek, Maskinonge River, West Holland, and Beaver River. The latter also represent the systems with the highest vulnerabilities since wildlife populations inhabiting them would be comparatively small and isolated (Table 1; Figure 7).

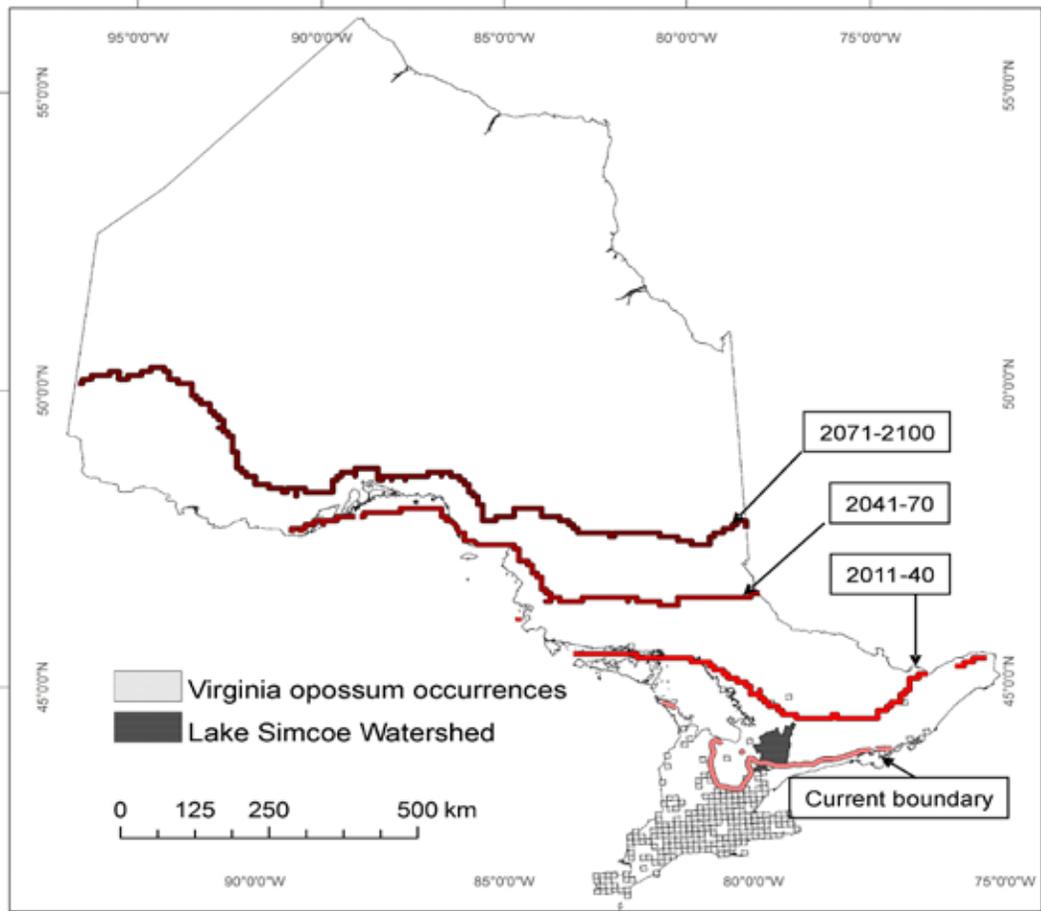


Figure 6. Projections of the northern range boundary of the Virginia opossum (*Didelphis virginiana*) in Ontario based on the -12°C mean minimum January isotherms for current and future climate scenarios produced using the CGCM2 climate model and A2 scenario. Virginia opossum occurrences are based on the 1970 to 1993 Ontario mammal atlas data (Dobbyn 1994).

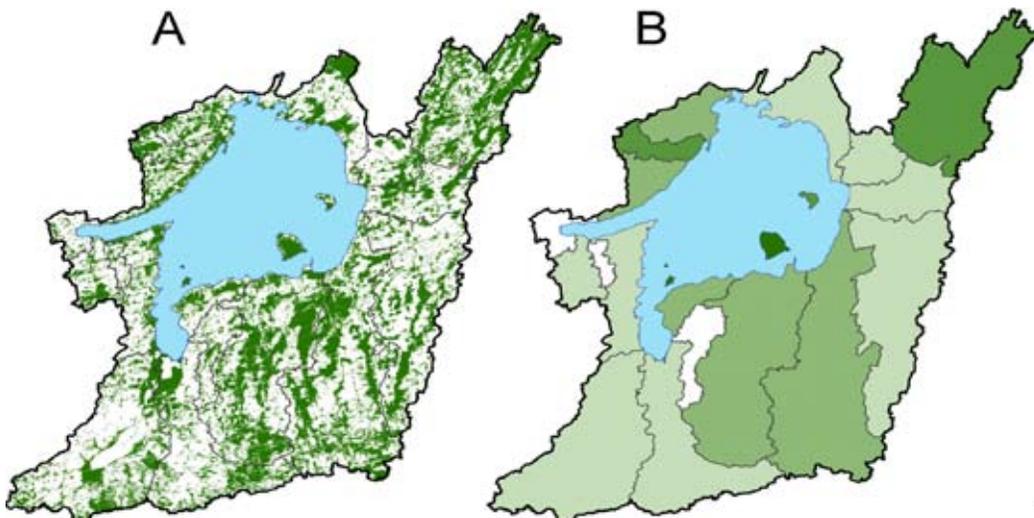


Figure 7. Maps of natural cover (A) and measures of landscape fragmentation (effective mesh size; B) for each Lake Simcoe subwatershed. In panel A, natural cover is indicated in green and unnatural cover is white. Effective mesh size represents the average size of natural cover fragments in each subwatershed. Lighter coloured polygons represent lower effective mesh size and therefore higher levels of fragmentation (B; see Table 1).

Discussion

We set out to identify wildlife vulnerabilities to climate change in the Lake Simcoe Watershed. We considered wildlife vulnerability as the inability of a species, community, or ecological process to persist through environmental change. A vulnerable system would be one experiencing reduced ecological health or integrity. However, the concept of ecological integrity is contentious due to the dynamic nature of ecosystems and the absence of static ecological reference points. Alternatively, we sought to describe current levels of biodiversity and ecological processes and then made predictions about how climate change might affect these conditions. Based on the CGCM climate models (v. 2 and 3.1) under the A2 emissions scenario, mean annual temperatures in the Lake Simcoe Watershed may rise by 4°C to 5°C by 2100. This temperature change would drastically affect the ecosystem and the associated wildlife populations. Three of the four wildlife indicators that we measured – avian guild richness, anuran breeding phenology, and mammal richness – were linked to climate. Rising temperatures in the Lake Simcoe Watershed are expected to increase bird (Currie 2001, Evans et al. 2005) and mammal (Kerr and Packer 1998) species richness and accelerate reproduction in spring-breeding anurans.

Increased richness of bird and mammal species may be characterized by a shift in composition as some species expand into and others recede out of the watershed (Myers et al. 2009). Since many of the species subject to these range shifts are commonly occurring and abundant, the effects of such a community shift on local systems may be substantial. The effects will also be complex as the changes are likely to affect all trophic levels (Both et al. 2009; Myers et al. 2009). Shifting ranges make local populations vulnerable to introduced pathogens, invasive species, or interspecific hybridization (Bowman et al. 2005, Brook et al. 2008, Garaway et al. 2010), and ultimately can cause rarity or extinction of northern species. Already, we are observing northerly range expansions of southern birds and mammals into the watershed in response to climate change (Bowman et al. 2005, Melles et al. 2010). These trends in bird and mammal richness point to two related processes leading to wildlife vulnerabilities in the Lake Simcoe Watershed: introduction of southern competitors and pathogens and increased extinction risk of northern, cold-adapted species (Table 4).

Early breeding amphibians have begun calling and thus breeding earlier in the year in response to a warming climate (Figure 5). Climate models project increased temperatures that are expected to cause spring-breeding anurans to breed earlier in the season. Although these projections do not consider other factors such as environmental pollutants, ultra-violet radiation, non-native invasive species, habitat destruction, and disease (Blaustein and Kiesecker 2002), temperature appears to be a major factor influencing anuran populations.

Table 4. Processes leading to wildlife vulnerabilities to climate change in the Lake Simcoe Watershed.

Process
Introduction of southern competitors and pathogens
Increased extinction risk of cold-adapted species
Increased interspecific hybridization
Selection for species able to rapidly move through fragmented landscapes
Selection for early breeding
Selection for high genetic variability for fitness related traits
Enhanced asynchrony in ecological systems

Continued monitoring of anurans is necessary to understand how populations respond to these multiple and possibly interacting factors. Trends in spring calling by amphibians point to two key processes leading to system vulnerabilities (Table 4). While early breeding anurans are expected to accelerate their breeding period, late breeding species are not. This demonstrates the asymmetric effects of rapid climate change on timing of breeding. Further, any change in breeding dates would have to be matched by a change in the availability of food sources, which demonstrates the potential for climate change to create asynchronies in ecological systems.

Landscape fragmentation will influence the ability of these organisms to continue shifting their distributions in response to a changing climate. We measured landscape fragmentation with effective mesh size and found that suitable habitat in the Lake Simcoe Watershed was more fragmented than that in other measured watersheds in North America (Girvetz et al. 2008). Fragmented landscapes are less permeable to animal dispersal and may introduce barriers to movement that result in lower levels of biodiversity compared to what is expected based on species - energy relationships (Varrin et al. 2007). Thus, habitat fragmentation may result in selection for species with good dispersal ability over those with poor dispersal ability (Table 4). To augment the resilience of all wildlife populations to the effects of fragmentation under projected climate change, land managers could increase landscape connectivity in the Lake Simcoe basin by promoting establishment of natural cover, beginning with the most highly fragmented subwatersheds (Table 1).

We applied observed biological relationships to future climate models and predicted the effects of climate change on each of the indicators. These predictions highlight potential symptomatic responses by wildlife to climate change and thus identify vulnerabilities in the watershed ecosystem. Nonetheless, these vulnerabilities should be interpreted with caution due to inherent uncertainty in both the climate change models and the biological relationships that we identified. Furthermore, the potentially confounding influences of other factors that may contribute to the observed patterns of the wildlife indicators should be considered. For example, we did not incorporate hydroperiod or habitat quality into our modelling of anuran calling behaviour and yet these factors may influence their reproductive behaviour (Brooks 2004). Here we have presented a starting point for further investigations. Future research is required to identify climate change-related links to biodiversity and ecosystem processes and also to uncover potential confounding and unaccounted factors that might influence the state of the wildlife indicators (Carignan and Villard 2002).

Recommendations

Address landscape connectivity: Although our models generally predict increases in species richness, the highly fragmented state of natural cover in the watershed may interfere with these population-level processes and thus threaten species persistence under current predictions of future climate change. Information gaps about functional connectivity in the watershed need to be filled. In particular, research is required to link structural landscape features with wildlife dispersal patterns to identify functionally connective habitats in the landscape. This research is a necessary prerequisite to making informed decisions about ecosystem restoration, land preservation, or management activities that will contribute to increased landscape connectivity. Priority might be given to the most highly fragmented subwatersheds. Moreover, initiatives to predict functionally connective habitats for representative species should be encouraged. Of course, any predictions of functional connectivity will need validation to demonstrate their effectiveness for wildlife populations.

Investigate relationships between flying insects, aerial foragers, and climate: We noticed that several subwatersheds sustain relatively few species of aerial foragers compared to elsewhere in the Lake Simcoe system. The guild of aerial foragers has undergone drastic population declines and range contractions throughout North America (Nebel et al. 2010). Declines in populations of flying insects are the suspected primary cause of declining aerial foraging bird populations. Several studies have demonstrated that insects are sensitive to changes in temperature (Bale et al. 2002, Reynolds et al. 2007, Richter et al. 2008). Fluctuations in insect abundance may significantly affect organisms that depend on them for food and the plants that depend on them

for pollination (Memmott et al. 2007). Therefore, we recommend research to identify relationships between the spatial and temporal trends in flying insect populations and the distribution and abundance of aerial foraging birds. This research could be framed in the context of climate change effects.

Examine link between climate and reproductive success of turtles: Reptiles may be particularly susceptible to the effects of climate change because temperature dictates the sex ratio of offspring in several species. Indeed, the development of painted turtle (*Chrysemys picta*) offspring respond to moderate fluctuations in July temperatures (less than 2°C) and an increase of 4°C would virtually halt development of male offspring (Janzen 1994). Thus, reptiles with temperature-dependent sex determination are ideal candidates as indicators of climate change. Despite their potential as useful wildlife indicators of climate change, there is an absence of empirical data describing reptile occurrence and reproduction in the watershed. We recommend an investigation of the occurrence, demography and abundance of reptiles and an exploration of the relationships between these parameters and climate conditions in the watershed. This research is necessary to make useful predictions about impacts of climate change on reptile populations.

Explore trends in wetland hydroperiod and anuran reproduction in relation to climate to substantiate predictions of climate change effects on anurans: Anuran populations are declining globally in response to a suite of factors including environmental change (Wake 1991). We recommend continued monitoring of trends in anuran calling in collaboration with Bird Studies Canada's Marsh Monitoring Program. Since calling behaviour is often used as a surrogate indicator of reproductive behaviour, establishing a stronger link between calling behaviour and reproduction in anurans is of value. These data could be used to validate the predictive models outlined above and to empirically assess the extent to which the anuran community in the watershed is responding to climate change. Climate change is also expected to change the hydroperiod (i.e., period of inundation) of ephemeral wetlands. Our understanding of climate change effects on anurans would be improved by considering the hydroperiod of key wetlands over time and how the availability of habitat may change for amphibians and other wetland obligates (Brooks 2004).

Complete high resolution sampling for mammals: No existing database sufficiently documents the presence or absence of all mammalian species that potentially occur in the Lake Simcoe Watershed. To test predictions of increasing species richness with climate change, more frequent and higher resolution sampling of mammalian species in the watershed is required. These data should be collected repeatedly over time (e.g., every 5 or 10 years) using similar techniques and cover the extent of the watershed to permit a comprehensive analysis of the effects of climate change and land use on the mammalian community.

Collect additional climate data: Some climatic factors that are not routinely considered in climate change scenarios, such as snow depth and annual duration of snow cover, are known to influence the distribution of wildlife in the landscape (Hansson 2002). These variables should be monitored for use in climate modelling.

Conclusions

We selected four wildlife indicators to assess the ecological condition of the Lake Simcoe Watershed and to identify potential vulnerabilities to climate change and land use practices. The four indicators: avian guild species richness, anuran calling and breeding phenology, mammal species richness, and landscape fragmentation were selected because they describe local biodiversity, community and range boundary dynamics, population size, and landscape fragmentation all of which are affected by or interact with climate to influence wildlife populations. With the exception of aerial foraging and wetland obligate birds, we found that overall avian richness has increased in the watershed. Based on species-energy models, mammal species richness is also projected to increase. This is a result of southern species expanding north relatively quickly as habitat conditions change and improve, while northern species recede northward due to detrimental biotic interactions with southern congeners. Reproduction in anurans is also expected to change as warmer temperatures encourage earlier reproduction in spring-breeding species. The shift in the timing of reproduction will likely affect interactions between species and lead to asynchronies in ecological systems. Finally, the Lake Simcoe Watershed is a relatively fragmented system. The small and isolated distribution of suitable habitat in the watershed is likely to impede dispersal and thus hamper the ability of species to shift their distributions in response to changing climates or biotic interactions. While conducting this research we identified several information gaps that should be addressed to improve our understanding of wildlife vulnerabilities to climate change. In particular, there is a paucity of knowledge about population trends and distribution of flying insects in the watershed and how these are related to aerial foraging birds and climate. The absence of information on reptile and mammal occurrence and distribution also hindered our ability to infer climate change effects on these taxa. We also noted an absence of important climate data that could be used to increase accuracy of models of climate change effects. As many of the wildlife responses to climate change are unavoidable, we conclude with recommendations about how to improve the resilience of wildlife populations in the watershed to climate change. Chief among these recommendations is the need increase functional connectivity throughout the watershed. A functionally connected landscape will benefit a suite of species with increased persistence during periods of significant environmental change.

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