2008

FORREX SERIES 23

Impacts of Climate Change on British Columbia's Biodiversity

A Literature Review

FORREX
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Donald V. Gayton

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National Library of Canada Cataloguing in Publication Data

Gayton, Don, 1946-
Impacts of climate change on British Columbia's biodiversity [electronic resource] : a literature review / Donald V. Gayton.

(FORREX series, ISSN 1495-9658 ; 23)
Includes bibliographical references.
ISBN 978-1-894822-49-7

1. Biodiversity--Climatic factors--British Columbia. 2. Biotic communities-- British Columbia. 3. Ecosystem management--British Columbia. I. FORREX II. Title. III. Series: FORREX series (Online) ; 23

QH106.2.B7G392 2008 333.9509711 C2008-902171-1

For more information about Forrex visit: www.forrex.org

This report is published by:

Forrex
Suite 702, 235 1st Avenue
Kamloops, BC V2C 3J4

This publication is funded by the Province of British Columbia through the Forest Investment Account–Forest Science Program.

ABSTRACT

This literature review summarizes research on current and potential impacts of climate change on biodiversity in British Columbia. The review, which is preceded by a brief summary of observed and predicted climate changes, brings together the relevant information contained in those publications for the benefit of natural resource managers. Contemporary increases in atmospheric carbon dioxide concentration, average annual temperatures, and sea surface temperatures have been documented, and climatologists predict these increases will continue through this century. Research suggests that whole ecosystems and biogeoclimatic zones will not respond as a unit; rather, individual components of ecosystems will respond. Species will respond to these climate changes either by adapting in place, migrating, or going extinct. Examples of species responses have already been recorded in British Columbia. Finally, the review summarizes research on how to mitigate climate change impacts on biodiversity. Mitigation will require implementing conservation principles, reducing non-climate stressors, providing latitudinal and elevational migration corridors, and instituting long-term monitoring to define causality between climate change and biotic responses. Perhaps the most important single piece of advice to natural resource and biodiversity managers is to implement, to the extent possible, good conservation practices.

KEYWORDS: adaptation, biodiversity, British Columbia, climate change, ecosystems, species.

ACKNOWLEDGEMENTS

Thanks to Jenny Fraser and to anonymous reviewers who provided invaluable input to this review. Thanks also to Shelley Church for review co-ordination and to Sue Thorne and Julie Schooling for their editing and layout contributions.

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Citation—
Gayton. D. 2008. Impacts of climate change on British Columbia's Diversity: A literature review. FORREX Forest Research Extension Partnership, Kamloops, BC. FORREX Series 23. URL: ***http://www.forrex.org/publications/forrexseries/fs23.pdf***

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INTRODUCTION

Climate change is rapidly becoming a dominant issue for land and resource managers charged with maintaining British Columbia's biodiversity. Much of the early discussion around the impacts of climate change on biodiversity was either theoretical or global in scope and offered little in the way of practical information for managers. However, recent publications, both from BC and abroad, have focused on actual biodiversity impacts and adaptation measures. This review, which is preceded by a brief summary of observed and predicted climate changes, summarizes the relevant information contained in those publications for the benefit of natural resource managers. The review does not cover the mechanisms of climate change, greenhouse gas mitigation, or carbon sequestration. It should also be noted that the impact of climate change on biodiversity is now a vibrant research topic, with new and relevant publications appearing on a weekly basis.

CLIMATE CHANGE: THE NATURE OF THE RISK

The Intergovernmental Panel on Climate Change (IPCC) has concluded that the global atmosphere is warming, and that most of the warming observed over the last 50 years can be attributed to the burning of fossil fuels, land clearing, and other human activities that release greenhouse gases into the atmosphere. The IPCC states that the recent observed rate of warming—0.6°C increase in average annual temperature during the 20th century—was likely faster than at any other time in the past 1000 years (Houghton *et al.* 2001).

Climate models project that, irrespective of future anthropogenic emissions, excess greenhouse gases already in the atmosphere will continue to drive climate change and its impacts—including impacts on biodiversity—for centuries to come. The rate of atmospheric warming projected for the 21st century (1.4 to 5.8°C by 2100) is likely greater than experienced at any time during the past 10 000 years (Albritton *et al.* 2001) .

Climate change goes beyond temperature; it affects precipitation, evaporation, relative humidity, and wind patterns. Embedded within changes to climate normals are changes in the variability of climate, and the frequency of extreme weather events (Hulme 2005). Climate change affects abiotic components such as glaciers, rivers, lakes, and oceans, which in turn drives changes in the biota that are linked to them. Manifesting differently from one region to another, climate change varies even within British Columbia's borders. Indeed, substantial regional differences in BC have been noted in the past and are anticipated in the future (Walker and Pellatt 2001).

Although it is tempting to do so, it is not possible to ascribe specific weather events, for example, a record storm or a new daily temperature maximum, to climate change. Only through collecting and analyzing long-term weather records can researchers identify and describe climate trends. The climate picture is further complicated by periodic events such as El Niño, longer natural (non-anthropogenic) climate trends associated with solar activity, changes in the earth's orbit, and other similar factors.

OBSERVED CLIMATE CHANGE IN BRITISH COLUMBIA

Trend analysis suggests that British Columbia is already experiencing climate change (data are from BC Ministry of Water, Land and Air Protection 2002, except where noted):

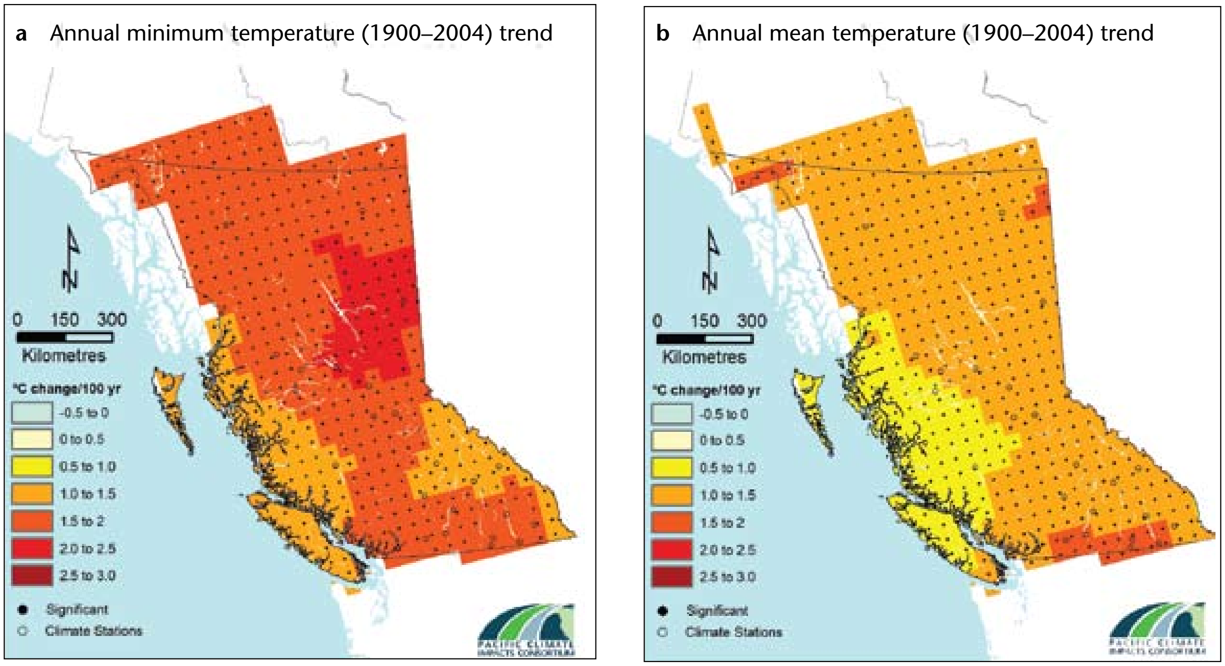

FIGURE 1. Annual minima (a) and mean (b) temperature trends have varied across the province, with winter minima changing more dramatically than annual means. Source: Modified from *Climate Overview 2007, Hydroclimatology and Future Climate Impacts in British Columbia* (Rodenhuis *et al.* 2007)

- From 1895 to 1995, average annual temperatures increased by 0.6°C in BC coastal regions (about equal to the global average); by 1.1°C in Central and Southern Interior regions (twice the global average); and by 1.7°C in northern BC (nearly three times the global average). Winter temperatures increased more than summer temperatures.
- Between 1950 and 2002, mean annual temperature increases ranged from 0.6°C on the coast to 2.5°C in the northeastern part of the province. Night-time minima increased more than daytime highs (Taylor 2005).
- Between 1941 and 2001, sea surface temperature (SST) along the BC coast increased by 0.9 to 1.8°C.
- Between 1888 and 1992, growing degree days (GDD)—a measure of the heat energy available for plant and insect growth—increased by 5 to 16 percent across the province.
- From 1929 to 1998, average annual precipitation increased in southern BC by 2 to 4 percent per decade.
- Frost-free season length, as measured at 13 representative weather stations throughout BC, increased by 21 days between 1950 and 2004 (Environment Canada 2007).
- Limited observational records suggest that, between 1935 and 2000, snow depth and snow water content decreased in some parts of BC. Between 1945 and 1993, lakes and rivers throughout BC increasingly became free of ice earlier in the spring. These provincial trends are consistent with global trends and are associated with changes in hydrology.
- Between 1895 and 1995, two large glaciers in southern BC retreated more than a kilometre each.
- The Fraser River now discharges more of its total annual flow earlier in the year (Morrison 2001). Similar patterns have been documented for other snowmelt-dominated systems in BC and the Pacific Northwest (Mote 2003).

- Climatic change between regions has varied substantially in the past several decades. In coastal regions, the wet season has become shorter and wetter while the dry season has become drier and longer. In the Southern Interior, hydrologic spring is now earlier and summer is extended, resulting in low fall flows. Throughout northern regions, streamflows have increased throughout the year (Whitfield 2001).

OBSERVED IMPACTS ON BIODIVERSITY IN BRITISH COLUMBIA

There is limited historical data available to confirm links between climate change during the past century and observed changes in biodiversity in BC, but a number of plausible connections have been documented.

Between 1888 and 1992, Growing Degree Days (GDD)—a measure of the heat energy available for plant and insect growth—increased by 5 to 16 percent across the province (BC Ministry of Water, Land and Air Protection 2002). Warmer winters and longer growing seasons, as well as fire suppression, are associated with the current mountain pine beetle (*Dendroctonus ponderosae*) epidemic in BC. Mountain pine beetle (MPB) over-winters as a larva, which is vulnerable to cold winter temperatures in its early stages, unlike late-stage larvae which can withstand temperatures close to –40°C. As climate change results in longer growing seasons and milder winters, more larvae reach the late larval stage before winter sets in, and, therefore, more survive to emerge the following year. An analysis of climate normals clearly shows an increase in the climatically suitable range of the MPB from the period 1921–1950 to the period 1971–2000. Over the past three decades, pine beetle populations have expanded into the new climatically suitable habitats (Carroll *et al.* 2003). An outbreak of needle blight in lodgepole pine can also be attributed to climate change (Woods *et al.* 2005).

Other examples of climate change impacting biodiversity have been documented. Bunnell and Squires (2005) found trends toward earlier arrivals, later departures, and northward range extensions in long-term (73 to 117 years) observations of eight selected bird species in BC, with some species transitioning from migrants to year-round residents during the period studied. Also, lower reproductive success in sockeye salmon has been linked to warm-water years and southern stocks in particular may be vulnerable to long-term warming (Macdonald and Grout 2001). In 2004, a hot, dry summer and low water levels resulted in Fraser River temperatures of 20 to 21°C, about four degrees warmer than normal. Such temperatures can be lethal to sockeye salmon, which prefer water temperatures of 15°C or cooler. Fewer than 10 000 of the expected 90 000 salmon in the early Stuart run on the Fraser River reached spawning grounds that year. The full biological and socio-economic costs of this event will be apparent in 2008, when the fish born in 2004 return to the river to reproduce (Wappel 2005).

Between 1941 and 2001, sea surface temperatures (SST) along the BC coast increased by 0.9 to 1.8°C (BC Ministry of Environment 2002). Sea surface warming has been associated with reduced marine productivity, and changes in the marine distribution and migration patterns of salmon (Beckmann *et al.* 1997). In an example of predator–prey decoupling, SST warming may be responsible for an observed decline in southern populations of Cassin's auklet. Marine copepods (small crustaceans) are a primary food source for auklet chicks, and in years of relatively cool SST, the timing of copepod emergence corresponds closely with that of chick hatching. In warmer years, copepods emerge, grow to adult size, and retreat to deeper water early in the season. Fledgling auklets are thus denied this food source, and their viability is reduced as a result (Bertram 2001).

PROJECTED FUTURE CLIMATE CHANGE IN BRITISH COLUMBIA

Climate change scenarios are developed using a set of global climate models and greenhouse gas emission scenarios, and are applied over large areas of the landscape. For these reasons, the scenarios represent a range of possible future climates rather than specific predictions.

The projected rate of global warming (increase in average annual temperature) for the 21st century is from 1.4 to 5.8°C and is much faster than the observed warming in the 20th century (Houghton 2001). The actual rate of warming is uncertain, since it will depend on how fast greenhouse gases continue to accumulate in the atmosphere and how the climate system responds. The best current information (BC Ministry of Water, Land and Air Protection 2002) suggests that British Columbia can expect the following:

- Average annual temperatures warming by 1 to 4°C by 2100
- Northern BC warming faster than other parts of the province, and the Interior warming faster than the coast
- Winter temperatures warming faster than summer temperatures
- Average annual precipitation increasing up to 20 percent by 2100
- Winter precipitation continuing to increase, and a greater proportion of winter precipitation falling as rain
- Declining snowpack in southern BC at low and mid elevations
- Earlier spring freshet, resulting in increased flood risk, greater water turbulence, and related scouring
- Declining summer streamflows on many snow-dominated river systems, resulting in warmer water temperatures and lower water quality
- Reduced summer soil moisture in some regions
- Substantial changes to hydrology, particularly to glacier-fed rivers.

The disappearance of the glaciers in the Columbia River Basin may cause the July through October flows of that river to drop by 20 to 90 percent (Brugman *et al.* 1997). Simulations of future Columbia River streamflow show increased winter flows, decreased summer flows, and summer drought-associated low flows occurring two to three times more often than presently (Hamlet 2003). Rising winter temperatures will also affect hydrology through the timing and duration of snowmelt. Spittlehouse *et al.* modelled winter snowpack in the south Okanagan and found that by the end of the century, snowmelt could start seven days earlier and end 11 days earlier than at present; in some years, snowmelt will be complete by the end of March (Spittlehouse *et al.* 2006).

Not all areas will experience significant climate change. BC has, and will have in the future, "climate refugia"—sites and regions where the degree of change is much less than surrounding areas.

ECOSYSTEM RESPONSES TO CLIMATE CHANGE

General Observations

Changes in climate and related systems will drive changes in ecosystem structure (e.g., predominant vegetation, age class distribution, and species composition), function (e.g., productivity, decomposition, nutrient cycling, and water flows), and distribution within and across landscapes. British Columbia's

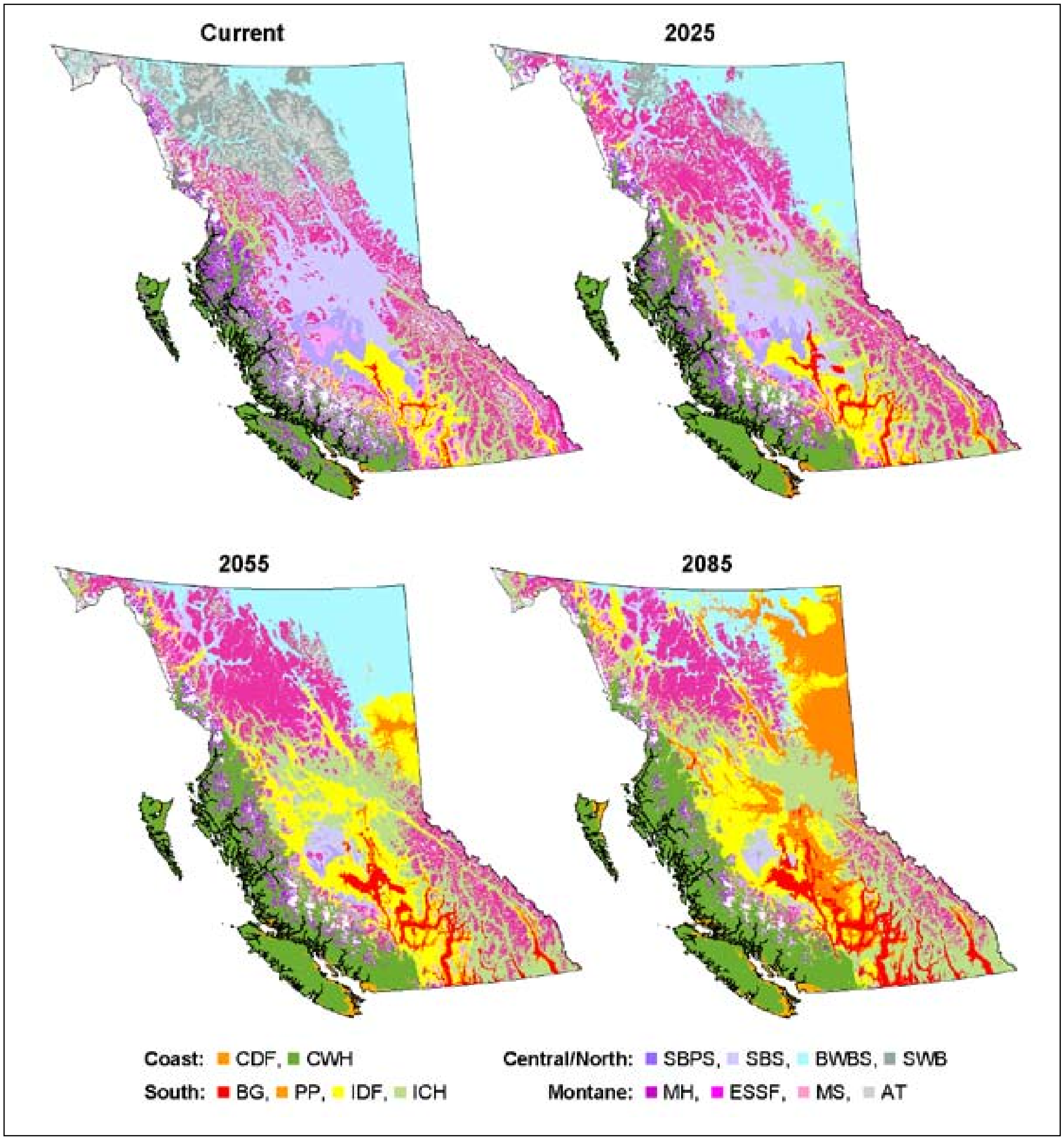

FIGURE 2. Effects of climate change on ecosystem and tree species distribution in British Columbia.
Source: Reproduced from Hamann and Wang (2006) with permission.

flora and fauna have altered substantially in response to previous epochal climate change (Hebda 1994, 1997, 1998) and will do so again. Changes in species composition will either be *in situ*, with subdominants replacing dominants, or *ex situ*, with species migrating from other regions, or some combination of both (Neilson *et al.* 2005).

Future climate is expected to roughly parallel the Xerothermic Interval of the Holocene (10 000–7000 years before present [BP]). Vegetation trends will also mirror that Interval, with increases in weedy, drought-tolerant, and alkali-tolerant species, and decreases in moisture-loving and acid-tolerant species (Hebda 1994). Dunlop and Howden (2001) conclude that, at the ecosystem level, the greatest impacts of climate change will result from increased dominance of species that are favoured by changed conditions. Generally, these are the low seral, weedy, and invasive non-native species (Malcolm *et al.* 2005). Low-elevation portions of southern British Columbia, including uplands, wetlands, coastal areas, and shallow waterbodies, currently host a wide variety of alien plant species and noxious weeds (Harding *et al.* 1994; BC Ministry of Agriculture, Food and Fisheries 2002; Gayton 2004), and new alien species continue to be introduced. Many of these species are aggressive and highly adaptable, and will invade ecosystems that are disrupted by climate change.

Hamann and Wang (2006) modelled the existing climate parameters of British Columbia's biogeoclimatic subzones against climate change predictions. They found dramatic increases in potential area for the Bunchgrass (BG) and Interior Cedar–Hemlock (ICH) subzones, and substantial losses in area for Alpine Tundra (AT) and Spruce–Willow–Birch (SWB) by 2025. Spittlehouse (2006) and Hebda (1997) predict a major northward expansion of the Interior Douglas-fir (IDF) subzone climatic envelope. Spittlehouse additionally predicts a loss of western redcedar from all sites where current growing conditions are marginal for the species. He also states, that, by the next century, many biogeoclimatic units will see a change in the climate envelope outside of the range in which they currently exist (Spittlehouse 2006). Krannitz and Kesting (1997) confirm the vulnerability of the Alpine Tundra, and Hebda (1997) identifies the Coastal Western Hemlock (CWH) subzone as being particularly vulnerable. Hebda further identifies the Bunchgrass, Ponderosa Pine, Interior Douglas-fir, and Interior Cedar–Hemlock biogeoclimatic zones as being particularly responsive to climate change, but cautions that "there are insufficient data on climatic characteristics of ecosystems, species and ecological processes to predict impacts in more than a general way" (Hebda 1997).

Prevailing patterns of biotic disturbances such as insect and disease outbreaks are expected to increase with climate warming (Harding and McCullum 1997). Already, an outbreak of Dothistroma needle blight on lodgepole pine in northwestern BC has been ascribed to increases in summer precipitation (Woods *et al.* 2005). Insects have a far greater capacity to adapt to change than other components of a forest ecosystem, and the number and variety of forest insect pests is bound to increase as the climate warms. This includes the mountain pine beetle, which is predicted to expand northward and eastward beyond its current range (Carroll *et al.* 2003). The number and range of infectious diseases affecting humans in North America is expected to increase with climate change (Commission on Geosciences, Environment and Resources 2001) and it is logical to assume that will also be the case with mammalian wildlife.

The patterns of abiotic disturbances will change as well. Hawkes (2005) predicts an increase in the length of British Columbia's fire season of 7 to 14 days by 2045. He also predicts an increase in area burned, and an increase in fire severity as a result of climate change. Benton (2003) predicts an increase in the length of the fire season in the Columbia Basin of between 38 and 52 days. The occurrence of spring meltwater surges, flooding, debris flows, and high intensity rainfall events are also projected to increase (Province of British Columbia 2004). Alterations in abiotic disturbance regimes will all have biotic consequences.

Ecosystem adjustments to climate change are most likely to be individualistic, taking place at the species, rather than the community or ecosystem level. In other words, existing ecosystems will experience the loss of some species, changes in the dominance of others, and the arrival of new species. New arrivals will interact with persisting species, plus exotic arrivals, to create new ecosystems (Lertzman 1988; Hebda 1994; Huntley 2005). Conversely, ecosystems will not migrate en masse into northward or upslope areas with newly suitable climate envelopes. Rather, only some species will migrate to the newly suitable area. Shifts in vegetation are not entirely due to climate; soil, groundwater levels, competition, compatible pollinators, natural disturbance rhythms, and other factors can also intervene (Iverson and

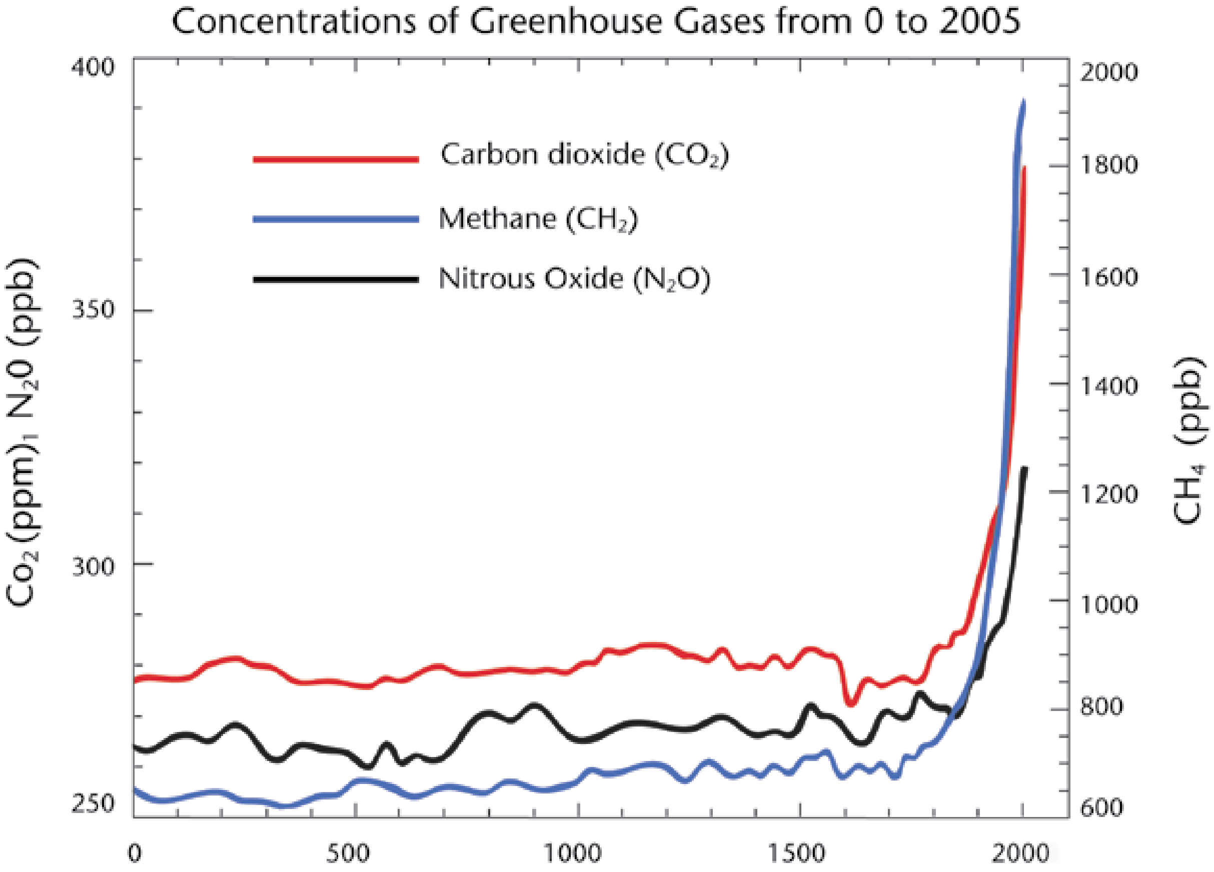

FIGURE 3. Atmospheric concentrations of important long-lived greenhouse gases over the last 2,000 years. This simple trend line lies at the root of climate change. Increases since about 1750 are attributed to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion air molecules, respectively, in an atmospheric sample. Source: *Intergovernmental Panel on Climate Change Group 1, Chapter 2, Final Figures*. FAQ 2.1., Figure 1 at ***http://www.ipcc.ch/graphics/graphics/ar4-wg1/ppt/figure02.ppt#282,26,FAQ***

Prasad 1998). The blending and reconstituting of ecosystems will pose difficult theoretical questions about what constitutes "natural" vegetation in a climate-changed world (Hannah *et al.* 2005).

Plants do respond to increased levels of carbon dioxide by exhibiting increased growth rates (Lloyd and Farquhar 1996). This has been proposed as a global buffering mechanism, wherein greater vegetative biomass is able to sequester more carbon dioxide from the atmosphere. However, several studies have suggested that plant-available nitrogen rapidly becomes the limiting factor in a carbon dioxide-enriched environment (Reich *et al.* 2006; Oren *et al.* 2001), effectively negating the buffering mechanism.

Ancillary to climate change are anthropogenic increases in ultraviolet radiation due to ozone layer depletion. Ultraviolet radiation has been shown to have negative impacts on vegetation (Caldwell *et al.* 2003) and amphibians (Blaustein 2003), many of which are endangered in BC.

Impact on Forested Ecosystems

The response of forests to climate change is of crucial importance to British Columbia. Species with long life cycles, such as trees, will experience a different climate in their reproductive phase than they did in their establishment phase. On the positive side, ecological communities dominated by long-lived species, such as forests, are seldom in equilibrium with the prevailing climate (Noss 2001), and this lag phase may allow the opportunity for passive and assisted adaptation.

There are a number of factors that may impede the establishment of trees in newly suitable climatic areas. The new sites may be too far from the species' previous range to allow for dispersal, and competing vegetation, unsuitable soil and/or hydrology, insect and disease outbreaks, and altered disturbance patterns may also impede the establishment of tree species in newly suitable areas (BC Ministry of Forests and Range 2006). As winters become milder, tree species that have chilling requirements to break dormancy (for either bud break or germination) may be harmed (Root and Hughes 2005). Trees not meeting their chilling requirements exhibit slower growth rates and are more subject to late spring frosts. For example, Douglas-fir (*Pseudotsuga menziesii*) has a chilling requirement of approximately 13 weeks with an average daily temperature below 5°C and, therefore, warmer winters may affect Douglas-fir viability and distribution, particularly along BC's southern coast, where winter temperatures are already close to the minimum chilling threshold (Lavender 1986).

Projected climate change impacts on forested ecosystems include: disturbances related to extreme weather events, simplification of ecosystems, migration of species, stand age reduction, and, extinctions or local extirpations (Dudley 1998). Other predicted impacts are an increase in invasive species establishment and dominance (Harding *et al.* 1994; Dukes and Mooney 1999) and the formation of new species assemblages. Climate change will undoubtedly produce local combinations of temperature, precipitation, seasonality, day length, and atmospheric conditions that do not currently exist anywhere on earth and for which there may be no analogous paleoclimatic conditions (Thomas 2005; Hannah *et al.* 2005). Even if future climates do have paleoclimatic analogues, there is no guarantee that existing ecosystems will persist. Natural succession will no longer reliably lead to the community composition it would have had in the absence of climate change (Lovejoy 2005). On the other hand, Hamann and Wang (2006) suggest that many of our broadleaved tree species will benefit from climate change. They also identify limber pine (*Pinus flexilis*) and western larch (*Larix lyallii*) as potentially losing significant habitat, but warn that their prediction for these two species is based on limited data.

BIODIVERSITY RESPONSES TO CLIMATE CHANGE

The common benchmark of biodiversity is the number of species found within a given area, but the reality is far more complex. Biodiversity also encompasses the genetic diversity within populations; the number of populations, subspecies, and geographic races; and the number of recognized communities or ecosystems. Biodiversity is also usefully defined as including biological processes (Hannah *et al.* 2005).

Climate change impacts living organisms, populations, and species by affecting reproduction, fecundity, establishment, and dispersal (Harding and McCullum 1997; Parson 2003); phenology and migration, growth rates, and mortality; length of growing or biologically active season; geographic distribution, population size, and response to disturbance. The IPCC has recognized that "climate is the major factor controlling the global patterns of vegetation structure, productivity and plant and animal species composition" and that changes in climate averages, climate variability, and climate extremes all affect biodiversity (Gitay *et al.* 2001). In fact, the research of Currie (2001) suggests that temperature and water availability account for more than 75% of the variability in plant species richness over broad spatial scales. Changes to climate will also alter interactions between species, including patterns of competition, symbiosis, mutualism, predation, and dominance.

The research suggests climate change will affect every aspect of biodiversity—from individual organisms through to populations, species, and ecosystems. Its impacts will be incremental to other drivers such as anthropogenic habitat degradation, habitat loss, pollution, and altered natural disturbance regimes. It is likely that negative synergy between climate change and these non-climate stressors will lead to dramatic and unpredictable species and ecosystem responses (Harding and McCullum 1997; Hannah *et al.* 2005).

In British Columbia's topographically heterogeneous environment, climate change effects will vary continuously with aspect and elevation. Alpine areas will be particularly affected due to their restricted geographical area and narrow elevational stratification of species and communities (Krannitz and Kesting 1997; Dunlop and Howden 2001). In BC, warmer summers could result in a dramatic upward shift in treeline, at the expense of alpine tundra communities (Krannitz and Kesting 1997). Alpine ecosystems, quite literally, will have no place to go. Large regions of low relief may also be heavily impacted, since a change in climate has the potential to make an extensive area inhospitable to elements of the existing biota, while simultaneously outpacing the in-migration rates of newly adapted native species.

Biota respond to climate normals as well as climate extremes. In fact, strong empirical evidence points to climate extremes such as cold periods, droughts, and severe storms as the primary determinants of species distribution, rather than climate averages (Parmesan 2005). Since one of the consequences of climate warming is more energy in the atmosphere, there is good reason to expect an increase in the frequency and/or severity of extreme weather events (Albritton *et al.* 2001), followed by changes in species distribution and diversity.

Species Responses to Climate Change

Simply stated, species can respond to altered climate in four different ways: they can adapt to the new conditions, evolve, migrate to areas of more suitable climate, or go extinct (Gitay *et al.* 2001).

Adaptation (here defined as the capacity of a genotype to express varying phenotypes depending on environmental conditions): Some species may alter their morphology, physiology, life history, phenology, diet, and/or behaviour, in response to climate change. The most successful species in a climate-altered future will likely be the broadly adapted types with wide ranges of habitat tolerance, high levels of genetic variation, high reproductive potential, rapid dispersal ability, and high phenotypic plasticity.

Evolution: Species may respond genetically through selection and develop characteristics more suited to changed conditions within a few generations (Rice and Emery 2003). For instance, one group of researchers was able to delay autumn migration in blackcap warblers by more than a week after only two generations of artificial selection (Pulido *et al.* 2001). Evolutionary responses will vary depending on a population's location within the species' geographical boundaries. At the northern edge of a species' range, the environment may become more like that experienced at the range's core, and selection, plus gene flow, should permit a relatively rapid evolutionary response (Thomas 2005). However, populations on the margin of a distribution range generally display less genetic variation than those at the core, so capacity for gene flow may be limited (Descimon 2001). The likelihood of "decoupling" co-dependent species (e.g., plants and pollinator insects) increases at the margins of a species' range. Populations at the warm southern margin of a species' range are more at risk of extinction than those at the northern limit (Descimon 2001). Non-native invader species are more likely to successfully respond to rapid environmental change than native species because of higher levels of genetic variation, higher reproductive and dispersal potential, higher phenotypic plasticity, and fewer natural enemies (Elton 1958; Brown and Sax 2005).

Migration: Some species disperse relatively rapidly and may be able to move to locations with newly favourable climates. Migration (rather than evolution) appears to have been the primary response of species to past climate change (Noss 2001). Malcolm *et al.* (2005) states that dispersal for many species depends on their ability to move through natural ecosystems that are connected and relatively undisturbed—a condition increasingly uncommon in BC. Even where migration corridors exist, the rate of warming expected during the 21st century will exceed the dispersal capacity of many species. For example, the climate conditions suitable for the boreal forest may be displaced northwards by 200 to 1200 kilometres by 2100 (Dokken *et al.* 2002), whereas in the past most plant species likely migrated at only 20 to 200 kilometres per century (Malcolm *et al.* 2002). There is evidence that changing patterns of species richness in the late Pleistocene and early Holocene epochs failed to keep pace with climate change (Currie 2001). More mobile species such as certain insects and birds will be able to migrate in synchrony with climate change (Parmesan 2005), whereas migration will be difficult for flightless invertebrates and small forest vertebrates (Noss 2001).

Extinction: In temperate regions, the biodiversity of terrestrial organisms tends to be higher in warmer areas and lower in cooler ones (Currie 2001), and increases in species richness could be a long-term outcome of climate change in BC. However, species extinctions are a predicted consequence of global warming (Schwartz *et al.* 2006). The period of rapid warming at the end of the last North American glaciation was accompanied by major range shifts in some taxa, and extinction in others (Pielou 1991). The degree of threat depends on the magnitude and the rate of climate change, the sensitivity of each species to climate change itself, plus the climate-related changes to its habitat. Some highly sensitive species and ecosystems will likely be affected by future warming of less than 1°C, while a warming of 1 to 2°C would result in more numerous and more serious impacts (Houghton *et al.* 2001). The threat to general biodiversity also increases with the rate of climate change. The geological record suggests that high species richness is related to stable conditions and that abrupt impoverishment of species has occurred during times of rapid change (Dokken *et al.* 2002). The rate of warming observed during the 20th century is likely faster than at any other time in the past 1000 years (Canadian Council of Ministers of the Environment 2003), and the rate of warming projected for the next century is likely to be faster than at any other time during the past 10 000 years. The IPCC has concluded that "while there is little evidence to suggest that climate change will slow species losses, there is evidence it may increase species losses." (Dokken *et al.* 2002).

Proving climate change causality in species or population extinctions is difficult, but several inferences have been made. One study showed that increasing precipitation variability caused the extinction of two California butterfly populations. The researchers could not prove if the variability increase was the result of anthropogenic activity, but the increase was consistent with those predicted by global climate models (McLaughlin *et al.* 2002).

It bears repeating that climate change-induced species losses will be incremental to—and possibly negatively synergistic with—those already occurring due to other anthropogenic impacts.

Species And Ecosystems at Risk

Species most vulnerable to extinction will be those with small populations, slow rates of dispersal, restrictive elevation, climate requirements, and/or those whose habitat is limited or occurs in patches. Migratory species face particular extinction risk, since they require multiple habitats in a particular seasonal order, thus increasing the probability of climate change-induced disruption of their habitat requirements. Also at risk are endemics, species with narrow elevational ranges, and species with limited dispersal ability or long reproductive cycles (Dunlop and Howden 2001; Hannah *et al.* 2005).

Ecosystems most vulnerable include those that are sensitive to climate, highly exposed to climate change, geographically restricted, or dominated by long-lived species. Alpine ecosystems, prairie wetlands, remnant native grasslands, and permafrost-based and ice-edge ecosystems are identified as being particularly at risk (Hebda 1994, 1997; Dokken *et al.* 2002).

A high percentage of British Columbia's endangered species are found in low-elevation grasslands, dry forest ecosystems, and the associated wetlands (Scudder, unpublished data). The potential ranges of these species are likely to expand northward and upward in the future. However actual range expansions may not occur if the root causes of their current endangerment are anthropogenic, and if these causes are likely to continue in the future. Invasive species are one of those root causes of native species endangerment; Voller and McNay (2007) surveyed the literature and documented 230 negative interactions between invasives and species at risk in BC.

In summary, climate change is likely to induce the following:

- Large-scale biome, ecosystem, and species shifts
- A breakdown and re-sorting of current plant communities and ecosystems
- A general expansion of species ranges northwards and upslope (note that for alpine and boreal species, this will mean range contractions)
- Loss of ecosystems, including some wetland and alpine areas
- Changes in habitat quality and availability
- Increases in growing degree days
- Changes in synchrony between species—for example, the timing of predator/prey or flower/ pollinator interaction
- Differential range shifting—for example, when a pollinator insect experiences a range expansion but its host plant does not

CLIMATE CHANGE ADAPTATION

Adaptation to climate change can be broken down into three categories: the adaptation of human communities (outside the scope of this paper), the autonomous adaptation of species and ecosystems, and assisted adaptation (the work we do to help species and ecosystems adapt). Assisted adaptation measures can be further broken down into reactive (initiated after climate change occurs) or anticipatory (initiated in advance of change) (Fraser 2003; BC Ministry of Forests and Range 2006). Biodiversity managers should attempt to provide opportunities for native species and ecosystems to respond to this climatic challenge to the limits of their natural capabilities, emphasizing anticipatory rather than reactive measures. The sheer magnitude of British Columbia's land mass means that any type of assisted adaptation can only be applied to selected key species and ecosystems (BC Ministry of Forests and Range 2006).

Perhaps the most important single piece of advice to natural resource and biodiversity managers is to implement, to the extent possible, good conservation practices (Gitay *et al.* 2001). In particular, the concept of ecological resilience (Hansen and Biringer 2003) has relevance for managing in a climate-altered future. In this context, ecological resilience is defined as the capacity of an ecosystem to absorb disturbance or stress and to recover to a similar stability domain (Hauessler *et al.* 2006). Central to the concept is managing, within the historic range of natural variability, for structure, function, and disturbance patterns. Ecosystems that are within their range of natural variability are assumed to be more resilient—better able to absorb external stresses (such as climate change)—and less likely to shift to an entirely different state.

WHERE DO WE DIRECT OUR MANAGEMENT EFFORTS?

Parks, protected areas, ecological reserves, and biodiversity corridors take on great significance in maintaining native biodiversity in a climate-altered future, so these areas should receive additional management attention (Hannah *et al.* 2005). Effective dispersal corridors should be established now, as species range adjustments to climate change are occurring already (Hebda 1999). A good network of protected areas that are free of other stresses provides one of nature's best opportunities to adapt to climate change (Welch 2005). However, many parks and protected areas were chosen on an ecosystem representation basis, and since these ecosystems are unlikely to remain stable in a climate-altered future (Lemieux *et al.* 2005), parks and protected areas should perhaps be re-assessed based on connectivity and migration corridors. Noss (2001) stresses maintaining habitat linkages parallel to climatic gradients, the provision of corridors plus "stepping-stone" habitats, and the provision of ecological reserves along elevational, as well as latitudinal, gradients.

Given the fragmented distribution of conservation lands, biodiversity management in "the matrix" (i.e., the areas in between conservation lands) becomes important. Unless there is some threshold level of conservation principles applied in the matrix, even the most conscientious management of parks and protected areas may not be sufficient to allow range change for many native species (Huntley 2005). This will be particularly true of north–south and upslope corridors, the most likely routes for range change in British Columbia.

Some authors have singled out "climate refugia" (areas historically or currently experiencing lesser degrees of climate change), and outliers (areas that contain populations that are separate from the main contiguous range of a species or ecological community) as deserving of enhanced biodiversity management, not only for their own intrinsic value, but also as effective source areas for native species out-migration (Hebda 1997; Hewitt 2005). Ecotones (e.g., transition areas between BEC subzones) are also important management areas, since the species inhabiting those zones are already adapted to frequent change (Lovejoy 2005).

Others have stressed the importance of identifying and managing low-lying zones of geographic overlap between glacial (cold epoch) and interglacial (warm epoch) species distributions, since these will be the zones of highest genetic diversity (Descimon 2001). In the BC context, these would likely be low-lying coastal areas, the major north–south river valleys (the Fraser, Okanagan, Columbia, and Kootenay valleys), mid-elevation mountainous areas where alpine communities mingle with montane communities, and the Central Interior, where boreal species distributions overlap with warm-adapted Great Basin flora and fauna. Species whose northern limits of distribution fall within BC will be of particular importance, since these would be the primary native recruits to fill the newly created niches resulting from altered climatic envelopes. Further research may identify specific geographical transition zones that contain northern range limits of multiple species, providing a rationale for enhanced management of these strategic areas.

WHAT SHOULD BE DONE?

In general, native species will colonize newly suitable climate habitats by migrating northward and/or upslope. The starting points of these "species relays" are the north–south river valleys and coastal areas, which are also subject to intense urban development, agricultural development, and habitat fragmentation, as well as alien species invasions. These and other starting points should be identified, and receive additional conservation and land use planning emphasis. Local and regional land use planners should make creating northward and upslope migration corridors a priority. Detailed topological, ecological, and land use analysis can identify best candidates for potential migration routes. Once identified, managers can use combinations of enhanced management, designation, and/or land purchase to make the corridors functional now and into the future.

Managers will also need to place much greater emphasis on long-term, repeat ecological monitoring of species and ecosystems to establish baselines and trends for such key parameters as climate tolerance, geographical distribution, rates of range change, migration ability, and reproductive success. Some of the monitoring should be of sufficient rigor to establish causality between climate change and changes to biodiversity (Noss 2001). Adaptive management of biodiversity with direct links to long-term monitoring data—a useful strategy under conventional circumstances—will become essential given the multiple uncertainties of climate change.

The logic behind using historical range of variability in climate change impact analysis is compelling (Noss 2001). Tree rings, fossils, pollen, and other paleoecological records can provide insights into the potential future impacts of climate change on biodiversity in British Columbia (Hebda 1998). They demonstrate that past ecosystems were both similar to, and different from, those present today. The early Holocene period (7000–10 000 BP) had temperatures similar to the more conservative predictions of future climate change but to find paleoclimatic analogues of the more drastic predictions, one has to go back millions of years. However, in both cases the pre-conditions (the climate preceding the climate in question) were dissimilar to those of today, so a precise paleoclimatic analogue for any climate change scenario does not exist (Hebda, 1998).

Reducing or eliminating non-climate-related stressors to biodiversity will be of prime importance. Markham (1996) states that "the potential impacts of climate change will be an academic question in relation to ecosystems we are unable to save from current and immediate threats." Given that there is a positive correlation between habitat loss and reductions in biodiversity (Brooks *et al.* 2002), maintaining existing habitat should be given additional priority, as should controlling the introduction and spread of non-native species (Taylor and Figgis 2007). Climate change will create new and open ecological niches; to prevent these niches from being filled by invasive alien species—until slower-moving native species are able to colonize—will require extraordinary levels of management, particularly in low-elevation, heavily disturbed areas. Hebda (1998) points out the possibility of lowland weeds such as knapweed (*Centaurea* spp.) and cheatgrass (*Bromus tectorum*) becoming able to invade disturbed mid-elevation sites as a result of climate change. Concerns about ecosystem and habitat fragmentation are a constant theme in biodiversity literature. One survey suggests that the relative impact of land use change on biodiversity will be greater than that of climate change in this century (Sala *et al.* 2000).

Forest seed planning zones and recommendations will need to be revised to reflect the new realities of altered climate (BC Ministry of Forests and Range 2006). Common gardens (the same sets of plant species or varieties planted in different geographic locations) and provenance trials have traditionally been an investigative tool of plant breeders, ecologists, and foresters. These techniques assume a much greater importance in an era of climate change. Existing common gardens and provenance trials in BC (those containing forest trees in particular) should be documented and monitored closely, and new ones should be established in strategic locations throughout the province. A priority should be testing species whose habitat is one or two subzones downslope or southward of the test location.

Although costly, some direct intervention may be required at the individual species level, through habitat restoration, establishing recovery programs, assisted migration, and *ex situ* conservation techniques such as captive breeding and nursery multiplication. Particular attention should be paid to forest tree species, which are of profound ecological and economic importance to BC.

Such a direct intervention has been proposed on Vancouver Island. There, declining fall flows on certain rivers are beginning to impact salmon spawning, and fisheries managers are looking into the possibilities of upstream dams to hold water back for fall release to ensure river depths are adequate for spawning (Globe and Mail 2007). Such actions are likely to have negative consequences for other organisms, but may be necessary to maintain a keystone species such as the salmon.

Ecosystem restoration in a time of accelerated climate change presents a conundrum. Classical ecosystem restoration uses historical ecosystems and species mixes as restoration templates, but these past ecosystems may no longer be achievable (or achievable only with heroic effort) in the climate-altered future (Harris *et al.* 2006). The reverse, a "clean slate" approach, where past ecosystem states—and the role of native species—are discounted, could also be risky, leading the broader public to discount the importance of ecological restoration (Eric Higgs, University of Victoria, pers. comm. March, 2008). Historical ecosystem information will actually become more important in our climate-altered future, as a knowledge of historical and paleological change will give us a better understanding of the range of ecosystems a particular site can support (Harris *et al.* 2006). Hebda (1998) suggests that the "new biodiversity" should develop, to the extent possible, from the historically inherent, pre-European biodiversity of the province's various regions.

Hobbs *et al.* (2007) suggests switching our emphasis from restoring particular ecosystem states to restoring ecosystem processes, and from restoring ecosystems to ecosystem services. Hebda (1999) supports the process orientation, and additionally suggests that restoration should focus on connecting natural habitats and populations on the landscape, and encouraging healthy populations of all indigenous species.

On the aquatic side, even slight increases in river and stream temperatures have been shown to cause growth retardation and increased disease in young salmon. Major increases will cause increased mortality. Therefore, managers should make every effort to keep spawning streams cool, including preserving and extending riparian buffers. Harvesting of wet woodland areas should be avoided to prevent the warming of overland seepage water (Quilty *et al.* 2004). Pink, chum, and sockeye salmon stocks from the Fraser River are expected to decline below the long-term mean due to higher water temperatures and lower summer and fall streamflows. This decline may be partially offset by increased salmon productivity in northern rivers (Beamish *et al.* 1997).

DEALING WITH UNCERTAINTY

In preparing for climate change, biodiversity managers face the same limitation that planners and other managers of human systems face—the uncertainty inherent in projections about the medium- to long-term future. Conservation planning can address this uncertainty to some extent by taking advantage of the following:

- Some aspects of climate change have greater certainty than others and managers can plan accordingly. For instance, predicting future sea-level rise and the subsequent inundation of coastal wetlands has a relatively high degree of certainty. Expected sea-level rise on BC's south coast will be in the range of 1–6 mm per year (Thomson and Crawford 1997). The Nature Conservancy is one organization that is developing and testing strategies to address projected sea-level rise along the coast of North Carolina. Strategies include establishing or restoring near-shore oyster beds or reefs, dunes, and native vegetation; establishing non-invasive, non-native vegetation; scarifying or removing small roads; and plugging ditches (Pearsall 2005). Other impacts where scenarios tend to show greater certainty include reductions in snowpack and associated changes in hydrology and ecology of snow-dominated river systems.
- Climate envelope models and studies of the distant past ("hindcasting," as per Hebda 1998) can help biodiversity managers project trends and identify potential climate refugia and locations

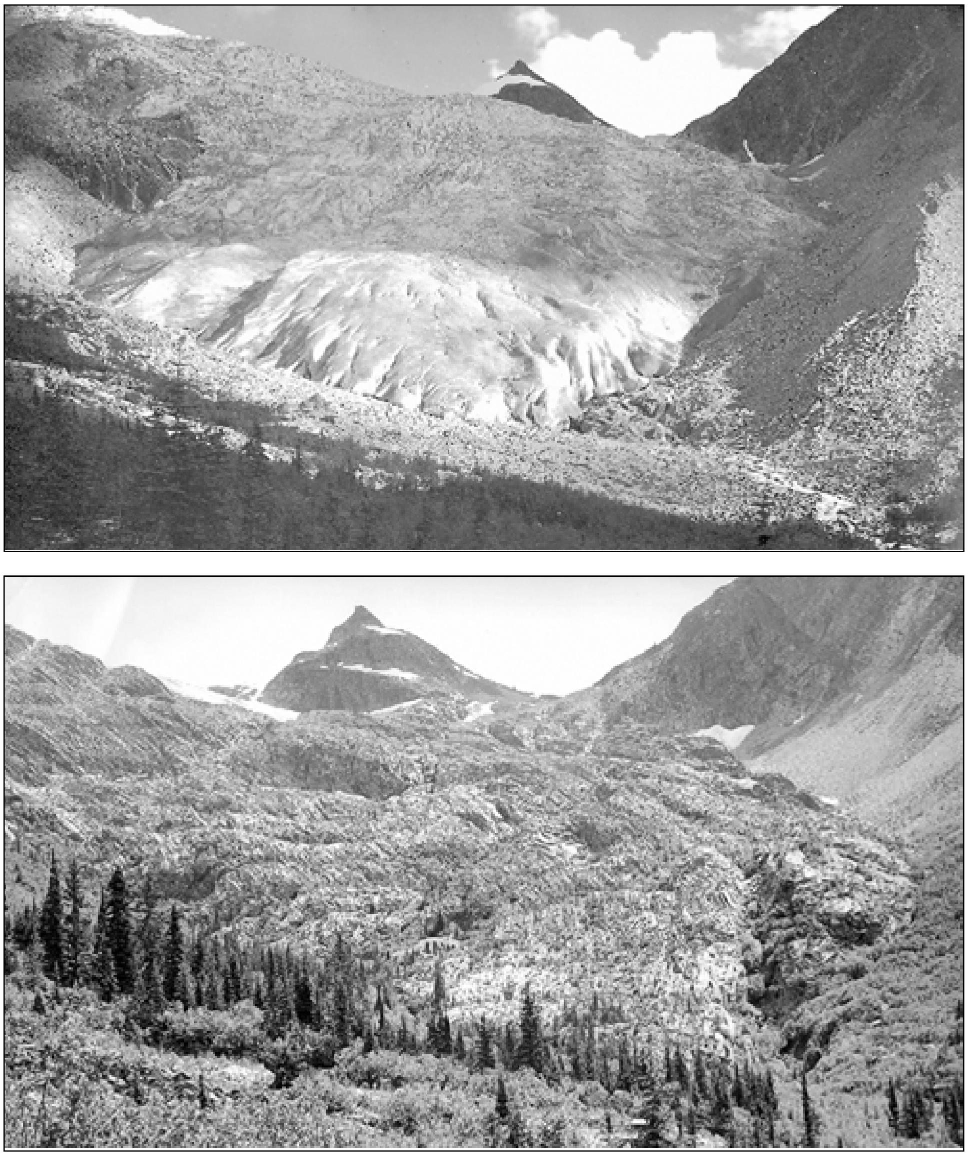

FIGURE 4. Repeat images of the Illecillewaet Glacier, the first (a) taken in 1902 and the second (b) taken in 2002, are evidence of a substantial warming of modern climate. Source: (a) Whyte Museum of the Canadian Rockies (Detail of EV653/NA-1069, Vaux family fonds) (b) Henry Vaux, Jr.

where the potential for disruption is high under various future climate scenarios. They can also identify ecosystems that are more likely to thrive, or not, under future climate conditions.

- Maintaining and restoring migration corridors, particularly those that allow migration upslope and polewards is another strategy. The Yellowstone to Yukon (Y2Y) initiative seeks to ensure that the wilderness, wildlife, native plants, and natural processes of the Rocky Mountains continue to function as an interconnected web of life. Y2Y has identified 17 critical cores and corridors that will not only facilitate survival of key wildlife species, but also facilitate northward migration (URL: ***http://www.y2y.net/overview/default.asp***).
- Conservation efforts directed toward buffering natural systems that are currently sensitive to year-to-year weather variations and extreme weather events (e.g., salmon spawning in years of high river temperatures) can also induce longer term resilience to climate change.

CONCLUSIONS AND RECOMMENDATIONS

Our natural resource management culture has traditionally responded to major abiotic disturbances via the short-term crisis intervention paradigm, as in the case of floods or forest fires. We have little management experience in preparing for the protracted, global-scale disturbance that climate change represents. We are charged with managing a provincial land base that contains tiny pockets of very high biodiversity, together with vast areas of relatively low biodiversity, making the allocation of scarce stewardship resources difficult. Meeting the challenge of climate change will demand the best of our abilities as resource managers, and the three-pronged strategy of climate change adaptation, carbon sequestration, and greenhouse gas emission reduction is the logical course to pursue. The difficult question facing all resource managers is: How drastic a change do we make—in implementation, planning, and policy—to address climate change? As a minimum, the following general approaches should be considered:

- Proactive and robust climate change adaptation strategies should become an integral part of all land use planning processes, both public and private. Spittlehouse and Stewart (2003) and the Future Forest Ecosystems document (BC Ministry of Forests and Range 2006a) present useful frameworks for forest management planning.
- The principles of good conservation practice should be observed and implemented.
- Non-climate stressors, such as over-harvesting of natural resources, habitat fragmentation, excessive roading and soil disturbance, alien species introductions, etc., should be controlled and minimized wherever possible.
- Long-term, repeat monitoring of selected ecosystems, species, and/or ecosystem processes should be put in place, and formal connections made between monitoring results and management. Some portion of the monitoring effort should be of sufficient rigor to determine causality between climate change and biodiversity impacts.
- Modelling of climate impacts on ecosystems and individual species of interest, such as the work by Hamann and Wang (2006), should be continued and expanded. Comparisons of recent (±30 years) climate data with biodiversity responses, as per Murdock *et al.* 2007, should be pursued. The modelling efforts should be linked to the monitoring work.
- Land management organizations, government ministries, and relevant professional societies should commit to assisting their employees and members to keep abreast of major developments in climate change and biodiversity conservation, through some combination of providing extension materials, email lists, study groups, conferences, and workshops.
- Measures should be undertaken to enhance communication between agencies managing conservation lands, to ensure co-ordination of effort in developing and maintaining multijurisdictional migration corridors.
- Land management organizations should "put their own house in order" by reducing greenhouse gas emissions wherever possible (see ***http://www.bcclimateexchange.ca/index.php***) and exploring opportunities for enhanced carbon sequestration.

The province of British Columbia has a highly complex physiography and ecology. It contains 35 mountain ranges, continuous variations of elevation and aspect, previously glaciated and unglaciated areas, 26 000 kilometres of coastline, numerous islands, rivers flowing to both the Arctic and Pacific oceans, and a diverse geology originating from several separate tectonic plates (Francis 2000). It contains extensive areas of relatively low biodiversity, together with small "hotspots" of impressively high biodiversity. Our province's biophysical complexity will certainly be an asset to species and ecosystems as they adjust to new climates, but that same complexity also makes planning for climate change extraordinarily difficult. To add to this difficulty, BC contains more federally listed species at risk than any other province in Canada.

Given this level of complexity, we must demand more of ourselves as British Columbians, and not be content with minimal responses to the challenge of climate change. Although we will undoubtedly incur some species and ecosystem losses, a proactive and comprehensive program of analysis, conservation, and mitigation measures will ensure the best possible future for our province's treasured biodiversity.

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