Bringing Adaptation to Ground in British Columbia

Discussion Paper

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Abstract

Natural resource practitioners are increasingly making decisions that consider future climates. This article examines the regional patterns of change in temperature and precipitation within British Columbia. Based on a review of the literature, regionally specific tables are provided with examples of conservation-oriented adaptation actions to help species and ecosystems adapt to future conditions.

KEYWORDS: adaptation; British Columbia; climate change; literature review; management actions

Introduction

The climate is changing and affecting the natural world (IPCC 2007, 2013; Spittlehouse 2008; Heller & Zavaleta 2009; Rodenhuis et al. 2009; Pojar 2010; Morgan & Daust 2013). The IPCC (2013) 5th Assessment Report affirms that "warming of the climate system is unequivocal" and that "global water cycle response" varies by region and season, although there is less certainty in the extent of precipitation changes. British Columbia is a topographically complex area of coastal islands, long shorelines, alpine areas, mountains, plateaus, and valleys. It contains five of the 15 terrestrial ecozones of Canada (Federal, Provincial and Territorial Governments of Canada 2010), more than any other province or territory in the country. This variability in topography, climate, and hydrology supports the highest diversity of ecosystems in Canada. In British Columbia, adaptation to climate change needs to consider regional variability, and specifically, the ecological and biological processes that will ultimately affect species and ecosystems.

The Future Forests Ecosystem Initiative (FFEI) (BCMFLNRO 2008–2011) was established to adapt British Columbia's forest and range management framework to climate change. The Future Forests Ecosystems Science Council (FFESC) (BCMFLNRO 2009–2012) was subsequently established as research support for the FFEI. The FFESC research program has produced a significant body of knowledge that has already informed policy adaptation and practice in the forestry sector (BCMFLNRO 2012). The recommendations have a strong focus on forest and range ecosystem management (Haeussler & Hamilton 2012a); the details of policy recommendations are provided in Haeussler & Hamilton (2012b) Appendix II of their report.

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This article presents conservation-oriented adaptation actions that, if implemented, could help address the extent and severity of climate change effects on all types of ecological systems and species in British Columbia. These actions are more effective when supported by enabling policy that recognizes the importance of adapting to climate change. For example, the British Columbia Ministry of Forests, Lands and Natural Resource Operations stocking standards have been adjusted in the wake of a policy review that acknowledged a different future. Anticipated climate changes are reviewed at provincial and regional scales. A synopsis of published and gray literature on climate change effects and adaptation actions is presented for natural resource practitioners in British Columbia.

Provincial-scale climate pattern and anticipated changes

Overview of anticipated climate changes

Changes in climate are typically presented as expected average changes (anomalies) in temperature and precipitation from some baseline time period as derived from global climate models (Werner 2011). The anticipated changes in British Columbia's temperature and precipitation until the 2050 time period vary by region (Table 1). Variability of change is greater seasonally than annually. The Okanagan and Columbia sub-regions have the greatest projected summer warming, and the Peace sub-region has the greatest projected winter warming. The South Coast and Okanagan sub-regions have the greatest projected reduction in summer precipitation. Anticipated annual precipitation increases are lowest for the Coast Region and are generally higher for the Northern and Southern Regions. Climate change projections for British Columbia are continually refined using newer information and tools. For the most current information and analysis tools for British Columbia, see the Pacific Climate Impacts Consortium regional analysis tools[1] and the Plan2Adapt tool (PCIC 2014).

Table 1: Regional 2050s (2041–2070) average temperature and precipitation climate change anomalies relative to 1961–1990 climate normal.[a] Regions are as defined in Figure 1; sub-regions are from Werner 2011. Negative temperature and precipitation anomalies are shown with a "-" sign.

Temperature anomaly (°C)						
Region	**Sub-region**	**Winter**	**Spring**	**Summer**	**Fall**	**Annual**
Coast	South Coast	2.0	2.0	2.5	2.1	2.2
	North Coast	2.2	2.0	2.1	2.0	2.1
Northern	Northwest	2.7	2.1	2.3	2.2	2.3
	Peace Basin	3.1	2.2	2.4	2.3	2.5
Southern	Okanagan	2.4	2.2	3.2	2.4	2.5
	Columbia	2.4	2.1	3.1	2.3	2.5
	Fraser	2.4	2.2	2.6	2.2	2.4
Precipitation anomaly (%)						
Region	**Sub-region**	**Winter**	**Spring**	**Summer**	**Fall**	**Annual**
Coast	South Coast	5	6	-14	8	4
	North Coast	9	8	-5	9	7
Northern	Northwest	15	12	8	13	12
	Peace Basin	19	17	4	17	12
Southern	Okanagan	7	9	-14	9	3
	Columbia	13	12	-9	12	8
	Fraser	11	11	-7	12	6

[a] These were calculated using 23 downscaled projections from eight Global Circulation Models run under the B1 (except for HADGEM1), A1B, and A2 scenarios (modified from Werner 2011).

Figure 1: Coast, Northern, and Southern Regions, as referenced in this article. Boundaries are based largely on ecoprovinces (Demarchi 1996).

Some fluctuations in regional climate are related to the El Niño/Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) phenomena. To the extent that ENSO and PDO are superimposed on climate change, they may vary in strength and relative effect, temporarily amplifying or cancelling underlying climate change signals, and thus affecting short-term climate variability. In the Pacific Northwest, warm phases of ENSO (El Niño) and PDO increase the likelihood of a warmer-than-average winter and spring and decrease the likelihood of a wetter-than-average winter. The opposite tendencies are true for cool phase ENSO (La Niña) and PDO; i.e., they increase the likelihood that winters will be cooler and wetter than average (Rodenhuis et al. 2009; Moore et al. 2010).

The stability of British Columbia's ecosystems is being affected by various climate-induced changes, which results in direct and indirect changes to environmental site features. Both direct and indirect effects on natural systems may trigger habitat changes, which may affect species survival and trigger species population explosions or collapses (Bentz et al. 2010; Woods 2011).

Changes in seasonal and daily temperatures can directly affect plant species growth and reproductive response when directly triggered by threshold temperatures. Earlier spring warming may alter phenological responses (Parmesan 2006; Running and Mills 2009); for example, some plants will initiate growth earlier, taking advantage of warmer temperatures, while others may respond to precipitation changes and not to temperature (Griesbauer & Green 2010). Vegetation productivity may increase as a result of an increase in the number of growing degree-days and overall length of frost-free periods (Spittlehouse 2008). These changes also affect the habitat and distribution of plant species (Parmesan 2006; Flower & Murdock 2009; I-Ching-Chen et al. 2011).

Warming temperatures and changing precipitation affect disturbance processes such as landslides, drought, and fire. These observed changes in natural disturbance patterns may be the most evident effects of climate change (Wiensczyk 2012). Increased frequency and magnitude of storm events and related disturbances such as flooding, windthrow, and landslides will occur (Spittlehouse & Stewart 2003; Guthrie 2009; Bentz, et al. 2010). Major disturbances and individual storm events may alter localized landscapes (Guthrie 2009). These in turn can influence the stability of ecosystems in both negative and positive ways (e.g., landslides may eliminate vegetation but increase the diversity of site conditions for future vegetation development [Geertsema & Pojar 2007]).

Changes in natural disturbance processes, site conditions, and behavioural and genetic responses of species, along with decoupling of species food webs represent only some of the indirect effects of climate change on ecosystems, species habitat, and populations (Dale et al. 2001; Walther et al. 2002). Interactions between these effects can create even more complexities. Increased evaporation from higher temperatures and reduced summer precipitation might result in more frequent and prolonged growing season soil moisture deficits and changes in nutrient cycling (Nadelhoffer et al. 1997). These direct moderating influences on soils will have multiple indirect effects on vegetation cover at localized sites. For example, the effect of greater growing degree-days on ecosystem productivity may be counteracted by the accompanying change in soil moisture and nutrient availability. Recovery after this type of shift may be compromised by the local seed bank's ability to provide germinants that will survive to reproductive maturity, and the ability of adjacent seed sources to disperse into disturbed areas. All of these factors may alter plant and animal species habitat over time. Vascular plants, lichens, mosses, fungi, and soil biota that have adapted to the relatively stable climate of the last 4000 years will likely be maladapted to the rapidly changing climate (Wang et al. 2008; Wilson & Hebda 2008; Aitken et al. 2009). Both physical changes on the landscape and changes in species response and habitat ranges will alter successional pathways and/or trigger the development of novel ecosystems (Hobbs et al. 2009; Anderegg et al. 2012). The time frame for this will depend on the rate of change in warming, precipitation, and disturbance factors (Chapin & Starfield 1997).

The potential role of provincial parks, protected areas, and conservation lands in climate change adaptation

The land managed by the British Columbia Ministry of Environment as parks and protected areas is a system of representative ecosystems of diverse patch size dispersed throughout the province. Parks and protected areas provide unique opportunities and challenges to climate change adaptation (Hannah 2008). As protected areas, they have fewer stressors and the potential for more resilience; however, anticipated ecological changes across the landscape will affect protected areas as part of the provincial land base. As the ranges of native species change on the landscape, the species found within the boundaries of any specific park will change, which will have consequences for ecosystems and their functions.

The synergistic effect of climate change and current and future non-climate stressors is recognized as a modern twist on the climate changes that have preceded this one (Kimmel 2009). Fragmentation is the top stressor, particularly in areas of the province that have small parks (Gaston et al. 2008). The larger protected area complexes in the network have fewer non-climate stressors, which adds to their ecological resiliency and capacity to conserve biodiversity. It will benefit the Province to manage these lands in close cooperation with other managers of Crown and private land to maintain options for movement and reorganization of ecosystems (McKinney et al. 2010; Pojar 2010).

Regional climate change-driven shifts in aquatic and terrestrial systems

The effects of climate change are not distributed evenly across British Columbia due to regional climatic and physiographic differences (Table 1) (Pike et al. 2010; Haughian et al. 2012). For the purposes of this discussion, the province has been divided into three regions (Figure 1), where boundaries largely follow ecoprovinces (Demarchi 1996). Further downscaling provides higher spatial resolution to accommodate localized conditions (Haughian et al. 2012; Meyn et al. 2013). The following regional summaries illustrate the potential effects of climate change on terrestrial and aquatic ecosystems and species in British Columbia.

Coast Region

The proximity of the Pacific Ocean and coastal mountain ranges moderate coastal temperatures and provide high precipitation on windward slopes of Haida Gwaii, Vancouver Island, and the mainland coast, resulting in the wettest climates in British Columbia (Meidinger & Pojar 1991). Winter precipitation falls primarily as rainfall on the leeward slopes and at lower elevations; snowfall increases at higher elevations, resulting in mixed rain and snow regimes. In the subalpine and alpine mountain regions, nival (snow dominated) regimes receive 50–80% of precipitation in the form of snow (Rodenhuis et al. 2009).

Anticipated climate change to 2050

The average annual warming by mid-century is projected to be just over 2°C, with the greatest increase in the South Coast sub-region during the summer (Table 1). More precipitation is predicted during the year, with a shift to more rain, less snow, and overall declining snow accumulation (Werner 2011). Summers are expected to be drier, particularly in the South Coast sub-region.

Hydrologic and geomorphologic effects

The Canadian Regional Climate Model projects a decline in snowpack by as much as 55%, with the greatest declines occurring in the coastal mountain ranges (Rodenhuis et al. 2009). Responses to these changes include a higher proportion of runoff occurring earlier in the fall and winter, and earlier depletion of the spring snowpack, which will cause reduced snowmelt streamflow augmentation in late spring and summer (Rodenhuis et al. 2009). These changes may increase the number and magnitude of rain-on-snow events, and in turn, increase flood events. The changes in runoff timing and magnitude could affect sediment supply and instream processes of scour and deposition that influence stream morphology and aquatic habitat suitability (Schnorbus et al. 2011).

Temperature-sensitive (cold water and cool water) aquatic species will be affected by increases in stream and lake temperatures (Parkinson et al. 2013, 2016). Cold water inputs that ameliorate summer stream temperatures are reduced by decreased snow accumulation and accelerated melt in late spring and summer. This affects species such as coastal cutthroat trout (Slaney & Roberts 2005), which can cause population stress and may favour invasive species that are adapted to altered flow regimes (Bunn & Arthington 2002).

The coast area is highly dissected by streams in headwaters with steep slopes. The distribution of natural landslides typically increases with increasing precipitation (Guthrie 2005; Guthrie & Brown 2008; Jakob & Lambert 2009; Guthrie et al. 2011) and clustering of storm cells embedded within larger weather systems (Guthrie & Evans 2004). Landslides that initiate in headwater streams and gullies that are connected to main stem river channels are a significant factor influencing stream channel stability and aquatic habitat on the coast (Jakob & Lambert 2009).

Natural disturbance regime effects

Old coastal forests of British Columbia regenerate primarily through the process of gap phase replacement, a result of the mortality of individual trees in small patch dynamics (Lertzman et al. 1996). Tree mortality is commonly due to the effect of pathogens and wind (Dorner & Wong 2003; Daniels & Gray 2006). As single tree mortality due to insects and fungal disease (Dorner & Wong 2003) increases in importance with climate change, larger scale outbreaks of insect and disease pests may result in conversion of the small patch gap phase forest dynamics to a disturbance regime of more frequent and larger patch- or stand-regenerating events.

Natural disturbances on the coast include stand-replacing events such as major blowdown events, avalanches, landslides, and debris flows (Swift & Ran 2012). Time intervals between major forest blowdown events due to hurricane force winds (Dorner & Wong 2003) and increased landslides due to increased precipitation may result in synergistic effects occurring between geo-physical events, storms, and insect and disease damage (Dorner & Wong 2003).

Large fires on the north coast of British Columbia are rare (Banner et al. 1993), and only the driest sites are likely to experience small fires. Fuel moisture is correlated with fire frequency (Meyn et al. 2013), and fire is most strongly influenced by summer fuel moisture (Dorner & Wong 2003). With warmer summers and decreasing summer precipitation, fire frequency will become a greater challenge to fire management on the coast overall (Balshi et al. 2009). For example, more frequent fires are expected on high-susceptibility sites of the southern mainland coast dry and submaritime climates (Brown & Hebda 1999), and in the drier Gulf Islands and lowlands of southeast Vancouver Island (Wilson & Hebda 2008). Regional analysis of climate change is likely necessary to more fully understand the extent of regionally variable projected responses of fire events and area burned (Haughian et al. 2012; Meyn et al. 2013).

Sea level rise

Rising sea levels are primarily a result of increases in the volume of sea water due to increased flow of freshwater from the melting of ice sheets, glaciers, and ice fields, and to the expanding volume of water as it warms (Thomson et al. 2008). The 5th IPCC report attributes as much as 75% of the rise in sea level to these two factors (IPCC 2013). Anticipated effects are more frequent flooding and an increase in saltwater contamination (Kareiva et al. 2008). For example, river floodplain reaches near sea level may experience higher and more frequent flooding as a result of higher tides and storm surges in estuaries (Peterson et al. 2008). Rising sea levels may also increase the risk of saltwater intrusion into coastal groundwater aquifers, with displacement of freshwater by denser salt water (Peterson et al. 2008). This may be further exacerbated by pumping demand (Allen & Suchy 2001) for agriculture and human consumption during the summer when temperatures are higher and aquifer pumping draws down seasonal aquifers.

Sea level rise and storm surge may also re-form British Columbia's coastal ecosystems. Coastal sand dune ecosystems are influenced by offshore currents and onshore winds, and future regional climatic conditions may result in either highly dynamic shifting dunes or long periods of stabilization which allow the establishment of forested ecosystems (Page et al. 2011). Erosion of beaches, mudflats, and bluffs contributes to the offshore materials of sub-tidal and intertidal sand bars, which in turn, result in landward deposition and accretion away from these original sources. Inland expansion or coastal squeeze and loss of these ecosystems will be influenced by physical landforms and anthropogenic-related development (Peterson et al. 2008). There may be gradual rebuilding of estuarine systems where there is no physical limitation to estuarine conditions developing inland (i.e., no barriers such as an immediate steep coastline, dykes, transportation infrastructure, or urban areas). Thus, there may be an initial loss due to erosional processes, followed by establishment of estuarine marshes upslope, resulting in at least short- to medium-term negative effects (Walker & Sydneysmith 2008).

Southern Region

The climatic and topographic influence of the mountains results in the diversity of ecosystems and wildlife species found in the southern interior of British Columbia (Meidinger & Pojar 1991). These same factors influence the hydrologic regime in the southern interior, where much of the annual precipitation falls as snow, which results in nival and glacial-dominated hydrologic regimes.

Anticipated climate change to 2050

Anticipated annual warming trends to mid-century are 2.4–2.5°C above the 1961–1990 climate normal, which is approximately the same as in the Northern Region (Table 1). However, more of the warming occurs in the winter, with a 2.4°C temperature anomaly. Other models project winter temperature increases by as much as 7°C (Spittlehouse 2008). Trends in precipitation indicate a decrease in summer and an increase in all other seasons by mid-century, with an average annual precipitation anomaly of 3–8% (Table 1). Other projections vary from -5 to +15% by the early part of the century (2020), and from 0 to 55% by the end of the century (Spittlehouse 2008). Given general warming trends, more winter precipitation events are expected to occur as rain rather than snow.

Hydrologic and geomorphologic effects

Increases in average annual temperature are expected to reduce winter snow accumulation at higher elevations and accelerate spring melt, which will alter the timing and volume of streamflows (i.e., peak flows and low flows in snowmelt-dominated stream systems) (Pike et al. 2008, 2010). The anticipated effects include an earlier start to spring freshet and a longer late summer and early autumn low flow period. Glacial melting (recession and downwasting) and reduced snowpack accumulation will also reduce groundwater volumes that contribute to late summer and early autumn streamflows (Pike et al. 2008, 2010). Climate-driven changes that affect low flow durations and volumes, combined with projected increased air temperatures, will result in increased summer stream and lake temperatures (Pike et al. 2008, 2010).

Increases in annual temperature are also expected to result in earlier melting of lake and river ice. In temperature-sensitive streams, reduced cold water contributions from glacial meltwater, and/or groundwater discharge may limit cold water inputs that moderate summer stream temperatures. Water quality in many streams may be affected if a changing climate results in increased sediment inputs from landslides, channel bank erosion, and chronic surface sediment sources (e.g., roads) that are connected to sensitive stream channel segments (Pike et al. 2010).

Natural disturbance regime effects

Increased summer air temperatures and reduced summer precipitation may increase drought, extend the wildfire season, and increase the susceptibility of existing forests to wildfire (Haughian et al. 2012). Meyn et al. (2013) showed that fire variability was more related to summer drought than to climate oscillations, but in southeastern British Columbia, both oscillations and drought had strong effects. Increased air temperatures and prevalence of drought conditions may reduce natural controls on insect populations and pathogens, thereby favouring conditions for insect and disease outbreaks. The anticipated result of these biophysical effects may include increased frequency, severity, and extent of natural disturbance events and agents—wildfire, insects, and pathogens—in existing forest ecosystems (Spittlehouse & Stewart 2003; Bentz et al. 2010).

Grassland ecosystems

Increased temperatures and summer drought may lead to a loss of native plant cover and surface organic material, which could increase the risk of soil erosion and potentially the risk of desertification of British Columbia's interior grasslands (Taylor 1996). These conditions may be aggravated by overgrazing (which contributes to soil disturbance following the loss of vegetation) (Sharma 1997), soil compaction (Krzic et al. 2014), and pugging (Forest Practices Board 2009).

Northern Region

The Northern Region is characterized by a wide range of geo-climatic conditions and biota, including dry plateaus, coastal and interior rainforests, northern boreal plains, regions of permafrost, and alpine and subalpine regions.

Anticipated climate change to 2050

Projections indicate that by mid-century there will be a 2.3–2.5°C increase in mean annual temperatures in the north compared to the 1961–1990 base period (Table 1). These increases will be greater in winter than in summer (3.1 versus 2.4°C). Some projections of temperature increases are as high as 4.5°C by the end of the century (Daust 2013). Werner (2011) projects increases in annual precipitation of 12%, with most of the change occurring in winter (15–19%). The combined effects of warming and increased precipitation are anticipated to shift the distribution and range extent of conifer species in mountainous regions and in the drier areas on the interior plateau (Wang 2010).

Hydrologic and geomorphologic effects

Watersheds in northern British Columbia are predominately influenced by snow pack and spring runoff (Pike et al. 2010). In spite of increased winter precipitation (historically snow), changes in temperature may increase the amount of winter rain, resulting in reduced duration and depth of snow cover (Pike et al. 2010; Daust 2013).

Unlike the southern part of the province, where increased streamflow from accelerated glacier melt has already occurred, the northwest glacial melt is currently associated with the phase of increased summer streamflows (Pike et al. 2010).

Warmer temperatures will result in longer ice-free periods for lakes and streams, and thawing of permafrost, which will lead to faster degradation of the organic matter in peat soils and the associated release of carbon dioxide (Pike et al. 2010). Melting of permafrost in mountainous regions reduces slope stability and increases landslides (Smith & Burgess 2004; Geertsema et al. 2006, 2007). Sturm et al. (2005) found that increased temperatures are leading to encroachment of shrubs into ground cover plant communities in Alaska. Similar situations are anticipated in permafrost areas of northern British Columbia.

The effects of hydrological changes on aquatic ecosystems include increased stream temperatures and a more dynamic water regime. Increased storm intensity leads to increased erosion (scour) and increased risk of landslides (Guthrie 2009). Lower summer flows and general warming of the landscape increases water temperatures overall. Some salmon populations and bull trout are particularly sensitive to increased water temperature (Brett 1952; Parkinson & Haas 1996; Parkinson et al. 2016). Fraser River salmon could be at significant risk before the end of the century as a result of increased stream temperatures (Morrison et al. 2002). Aquatic communities and spawning beds could be negatively affected by increases in inorganic sediments that are delivered to streams as a result of an increase in erosion and landslides and by changes in water chemistry and water quality due to temperature changes in streams and lakes (Pike et al. 2010).

Natural disturbance regime effects

Climate change is projected to increase fire frequency and the amount of area burned in the north (Flannigan et al. 2005). Predicted increases vary from 200 to 300% of the area currently burned in the Boreal Plains and Boreal Cordillera Ecozones to 50–100% in the Taiga Plains Ecozone, but predictions are less certain for the Boreal Plains (Flannigan et al. 2005; Haughian et al. 2012). Balshi et al. (2009) predicted that area burned will double in each decade to 2050, relative to the 1990s, and that while western British Columbia and Alaska had greater predictability of area burned, trends for mountainous areas were not very predictable. Meyn et al. (2013) analyzed 80 years of data and found that a decrease in area burned was more strongly dependent on increased summer precipitation than changes in summer temperature. The authors recommended that analysis of fire risk and area burned must be considered in areas such as northwestern British Columbia, where fire is more precipitation dependent.

Atmospheric convection processes are expected to increase as the climate warms, and will likely lead to an increase in the frequency and intensity of windstorms in northern British Columbia (Lambert and Fyfe 2006; Pojar 2010; Haughian et al. 2012). Forest health is also anticipated to be negatively affected by climate change and insect disturbances (Spittlehouse and Stewart 2003). Diseases such as Dothistroma needle blight have been shown to increase with wetter, warmer weather in northwest British Columbia (Woods 2011), and insect outbreaks such as the recent mountain pine beetle outbreak are linked to winter warming (Bentz et al. 2010; Woods 2011).

Inland rainforests may experience similar changes in disturbance processes as the coastal rainforest, with a shift from gap dynamics to more widespread insect and disease mortality (Stevenson 2011). Higher rates of individual tree mortality, increased area of standing and downed dead wood, and larger patch sizes of regenerating forest may result in a decreasing area of continuous old forest landscapes. This will have cascading effects for wildlife (Beever & Belant 2012) and nutrient cycling (Stevenson 2011). The wetter environment of the inland rainforest is less vulnerable to disturbance regime changes than the moist and drier subzones of the Interior Cedar Hemlock zone, where fire is a frequent stand initiating or maintaining disturbance (Stevenson 2011).

Grassland ecosystems

Northern, high-elevation grasslands have ecosystem drivers that are distinctly different from grasslands in southern British Columbia (MacKenzie 2012). Frequently, the lack of tree cover is associated with cold air ponding or cold air drainages (MacKenzie 2012), and the occurrence of grassland ecosystems is due to cold winters and summer frosts, instead of heat and summer drought conditions. Soils at these sites are too cold to support the growth of trees and too dry to support wetland development (MacKenzie & Moran 2004). The effects of warming temperatures and increased precipitation on these cold, dry soils may result in the development of novel ecosystems, either through the establishment of forest cover or wetland conditions.

Operational adaptation actions

The purpose of this paper is not to provide a complete guide to climate change adaptation actions, but rather to illustrate the context for action and the breadth of activities that could lead to more positive outcomes for the persistence of functional ecosystems in British Columbia. The following are some of these overarching actions or strategies:

- Increase the emphasis on ecological services (Glick et al. 2009).
- Maintain and/or restore connectivity across the landscape (Heller & Zavaleta 2009).
- Work with adjacent jurisdictions to coordinate objectives and anticipate the movement of species (Lemieux et al. 2008).
- Work across the land base to encourage ecological restoration and compatible land uses on adjacent properties (Lemieux et al. 2008).
- Alleviate existing pressures by improving land use planning and agricultural practices (Campbell 2008), and reduce existing stressors that are likely to interact synergistically with climate change by pollution or fragmentation.
- Restore habitats to increase heterogeneity and species richness (Glick et al. 2009).
- Incorporate redundancies into ecological system planning (Joyce et al. 2008; Lemieux et al. 2008).
- Provide a full spectrum of sensitive ecosystem and native biodiversity representation in protected areas (Noss 2001; Biringer 2003).
- Focus on key ecological process rather than on limited attributes (Campbell 2008; Lemieux et al. 2008; Wilson & Hebda 2008).

The tables of potential actions that follow (Tables 2–8) use an organizational framework developed by Millar and her colleagues from the U.S. Forest Service (Millar et al. 2007[2], 2008). They call their framework the 5Rs:

> Increase **Resistance:** "Maintain Status Quo or Desired State": Take action that protects/defends the highest priority ecological values from any impacts or alterations due to climate change.
>
> Manage for **Resilience:** "Health Care": Short-term actions address known change, and long-term plans address anticipated changes. The scale of action varies based on the current health of system or population.
>
> Enable **Response:** "Change Management": Implement strategies to proactively assist the response of vulnerable, high-value resources to anticipated climate change (e.g., increase the widths and extent of riparian buffers, adapt tree species stocking standards, include assisted migration of genetically/ecologically appropriate trees).
>
> **Realign:** "The Auto-Mechanic Approach": Use restoration, where it is consistent with current and future changes, on systems that are already outside their range of historic natural variability.
>
> Establish **Refugia:** "The Registered Retirement Savings Plan (RRSP) Approach": Protect sites where species persist during periods of changing regional climates (e.g., isolated areas of favourable microclimate).

Not all actions are neatly partitioned into this framework. For instance, actions to promote connectivity can be both resilience and response. Actions require the discretion of the natural resource practitioner to do further research to clarify and consider the context of each case.

Operational adaptation actions

The operational actions described in the following tables can be applied within and outside protected areas. Although the substantial protected areas system in British Columbia provides a critical buffer to some of the effects of climate change on species and ecosystems, it is important to note that protected areas alone will not be sufficient to conserve ecological and biological diversity (IUCN WCPA 2005), and that climate change affects the entire land base.

In the context of the climate-influenced changes described above, the following tables include a wide variety of ecological and biological sensitivities to climate change in British Columbia, and related adaptation actions as reported by specialists working in this field. The reported actions were gleaned from a number of published and unpublished works, including peer reviewed journals (e.g., Millar et al. 2007), government documents (e.g., U.S. EPA 2009), reports, (e.g., Utzig & Holt 2009; Morgan & Daust 2013), and presentations and facilitated workshops of the Future Forests Ecosystem Initiative (BCMFLNRO 2008–2011) and Future Forests Ecosystem Science Council (BCMFLNRO 2009–2012). A common theme throughout the literature is ecosystem management as the basis for action (Peterson et al. 2011).

The following tables list sensitivities to climate change and potential adaptation actions. Only the sensitivity component of vulnerability (Johnston & Williamson 2007) to climate change is included, and not the exposure or adaptive capacity factors. The sensitivities that are likely to result in negative consequences were selected. There is not a one-to-one relationship between the sensitivities and the actions, but rather a grouping of actions that relate to one or more sensitivities.

Table 2. Hydrologic and geomorphologic effects on species and ecosystems that are common to all regions

Sensitivities	Actions
Reductions in streamflows below minimum flow requirements to sustain aquatic life • Perennial streams becoming intermittent or ephemeral • Habitat isolation and fragmentation where low flows cannot facilitate aquatic organism movement • Summer low flows result in elevated stream temperatures. • Loss of summer streamflow in small coastal second-order streams will reduce habitat for coastal cutthroat and other temperature-sensitive trout and salmonid species.	**Resilience** • Replace perched culverts and failed culverts to restore fish passage (Mount et al. 2011). • Undertake a pilot recovery strategy of coastal cutthroat trout as an indicator species of other temperate-sensitive species (Slaney & Roberts 2005). **Realign and response** • Maintain sufficient water to manage summer low flows (Hauessler & Hamilton 2012b). • Increase riparian management standards (Haeussler & Hamilton 2012b). • Monitor fish-sensitive watersheds (Haeussler & Hamilton 2012b).
Increased water temperatures resulting in thermal effects on freshwater fish and other aquatic organisms • Reduced distribution of salmonids in temperature-sensitive systems • Salmonid populations may expand in warming headwater streams • Increased success of introduced invasive species (e.g., spiny rays) • Cold water guild species; e.g., bull trout; distribution is likely to contract	**Resistance** • Control the spread of invasive fish species (e.g., yellow perch, largemouth and smallmouth bass) where practical (Halfyard 2010). **Resilience** • Use existing legislation and guidance (e.g., Riparian Area Regulation) to promote the maintenance and restoration of riparian vegetation "cover" (Haeussler & Hamilton 2012b).

Table 2. (continued)

Sensitivities	Actions

	Realign
	• Designate temperature-sensitive (Haeussler & Hamilton 2012b; Reese-Hansen et al. 2012) or fisheries-sensitive stream status on provincial forest land and public tree farm licence land for critically sensitive streams where incremental riparian management objectives may be required to:
	  • maintain or increase the effectiveness of riparian thermal cover or to accelerate recovery,
	  • apply downstream "fish friendly" thermal regime targets, or
	  • identify and prioritize vulnerable streams for adaptive management (Tyedmers & Ward 2001).

Increased fine sediment effects on freshwater fish • More sediment supply from stream bank erosion, resulting in infilling of aquatic habitat and higher suspended sediment and turbidity that affects aquatic organisms such as fish and benthic invertebrates • Increased stress and disease in fish • Reduced reproductive success • Reduced hiding cover • Reduced forage for fish because of adverse effects on invertebrates	**Resistance** • Maintain natural slope hydrology and drainage on erosion- or landslide-prone terrain and avoid high-risk areas where possible (Chatwin et al. 1994). • Reduce at-source sediment supply that is attributable to land management practices, with an emphasis on reducing connectivity of sediment sources to streams, and promote rapid post-disturbance recovery (Chilibeck 1992). • Restore riparian vegetation. **Resilience** • Remove stressors (e.g., activities that are contributing to the loss of existing riparian vegetation along erodible alluvial channels). • Minimize footprint disturbance in sensitive riparian areas that are connected to streams (e.g., road crossings, riparian encroachment, or harvesting pattern) (BCMFLNRO et al. 2012; Haeussler & Hamilton 2012b). • Apply restoration techniques to promote recovery of chronic sediment source lost because of historical disturbance (Pike et al. 2010). • Retain vegetation cover in locations where it maintains slope stability in landslide-prone or highly erodible terrain (Haeussler & Hamilton 2012b). **Response** • Update road infrastructure (e.g., bridges, culverts) to climate-appropriate standards (Haeussler & Hamilton 2012b). • Increase reforestation of non-satisfactorily restocked areas to increase hydrologic recovery.

Table 2. (continued)

Sensitivities	Actions
	• Deactivate and restore roads to allow vegetation to re-establish and to restore natural drainage patterns (Haeussler & Hamilton 2012b). • Prohibit or limit infrastructure on current flooded areas, and improve road building (e.g., placement, culverts) (Palmer et al. 2008; U.S. EPA 2009). **Realign** • Design drainage infrastructure to accommodate more frequently occurring and higher amplitude high flood events (Haeussler & Hamilton 2012b; Palmer et al. 2008). • Adjust terrain stability ratings to accommodate increased landslide frequency due to effects of intense storm events (BCMFLNRO 2008–2011).

Loss of riparian ecosystems and habitat
• Increased erosion of stream banks and riparian areas from peak flow events
• Loss of instream, large, stable woody debris
• Increase in unstable instream debris and debris jams due to riparian blowdown, and bank erosion resulting in more stream channel instability
	Resistance
	• Restore lost riparian vegetation (Hauessler & Hamilton 2012b).
	• Maximize overstory retention within a 10-m buffer along riparian areas (Haeussler & Hamilton 2012b).
	• Following alteration, divert or redirect flows to natural watercourses to restore natural flow levels.
	• Restore flows or groundwater seepage where roads or other factors have disrupted flows (Crown Managers Partnership 2014).
	
	Resilience
	• Work with resource agencies, private landowners, and private industry to:
	  • avoid loss of riparian function along vulnerable stream reaches to safeguard resilience against peak flows and temperature increases (Crown Managers Partnership 2014)
	  • manage cattle and off-road vehicle access to avoid soil disruption and loss of vegetation (Crown Managers Partnership 2014)
	  • maintain hydro-riparian connectivity from hilltop to valley bottom (Haeussler & Hamilton 2012b)
	  • promote sensitive development approaches that avoid increasing the rates of terrain instability above the natural background potential for frequency and magnitude (Guthrie 2005)

Table 2. (continued)

Sensitivities	Actions
	Realign and response • Incorporate higher flood risk potential in floodplain zoning decisions (Palmer et al. 2008; B.C. Ministry of Environment 2011). • Install flow control measures to retain more spring runoff and manage release. • Manage hydrologic recovery through spatial distribution and rates of forest harvesting to reduce the potential for adverse increases in flood peaks (Palmer et al. 2008; Haeussler & Hamilton 2012b).
Wetland ecosystems and habitat • Localized or regional extended summer drought will lower summer water tables, resulting in shifts in wetland vegetation types, reduced surface wetted area, and temperature increases • Wetlands that are dependent on late spring snowmelt will be at risk, with earlier snowmelt runoff and less total runoff available for surface or groundwater inflow. • Non-native invasive plant species colonize, dominate, and infill wetlands.	**Resistance** • Consider diversion of groundwater to storage for later use (Palmer et al. 2008). **Resilience** • Restore lost or altered beaver habitat (Pollack et al. 2015). • Re-establish vegetation damaged by insects (e.g., mountain pine beetle) or disease on the perimeter of wetlands. **Response** • Recommend no net loss of wetlands (Environment Canada 1991) to address urban, agricultural, and industrial development effects on wetlands and associated hydrologic function. • Conduct monitoring and control (eradication) programs for invasive plants to maintain native vegetation (Peterson et al. 2008; Wilson & Hebda 2008).

Table 3. Hydrologic effects on grassland species and ecosystems (Southern Region).

Sensitivities	Actions
Grassland landscape • Desertification of already droughty areas • Loss of species habitat and reduced species population **Isolated wetlands** • Loss of ephemeral and summer wetland habitat due to increased evaporation • Drying of isolated marshes and alkaline ponds may be permanent (invasive species colonize and dominate sites).	**Resistance** • Manage resource use, recreation, and road access to resource extraction areas to reduce potential introductions of invasive species (Gayton 2014). • Develop early detection methods and rapid response controls for invasive species (Peterson et al. 2011). • Manage cattle grazing and off-road access in grasslands, and proactively manage the control of invasive species to maintain optimum native species cover (Gayton 2014), including non-vascular plants. • Undertake captive breeding programs to restore population viability of high-value at-risk species biodiversity (Garnett et al. 2013).

Table 3. (continued)

Sensitivities	Actions
	Resilience • For high-risk plant species, consider translocation to areas of potentially suitable habitat (Maslovat 2009). **Realign and response** • Amend the Range Practices Regulation and specify clear measurables related to soil disturbance on wet sites (Forest Practices Board 2002). • Apply a watershed planning approach to the maintenance of groundwater for wetlands and streams (Winkler et al. 2010).

Table 4. Hydrologic and geomorphologic effects on species and ecosystems (Northern Region)

Sensitivities	Actions
Wetlands: Bogs and fens • Increased decomposition of bog/fen organic soils • Groundwater input to bogs due to loss of permafrost (the barrier to groundwater inflow) • Species associated with wetlands will experience habitat disruption if the ecosystem shifts from one state to another **Permafrost** • Degradation of permafrost and increased risk of landslides in areas of thin and/or discontinuous permafrost	**Resilience** • Apply permafrost probability hazard ratings, including assessment of terrain stability and vulnerability of permafrost in the area (Stevens & Weston 2011). • Avoid harvesting bogs (Hauessler & Hamilton 2012b). **Response** • Create boreal refugia, particularly on low-nutrient sites (Haeussler & Hamilton 2012b).

Table 5. Natural disturbance regime effects on species and ecosystems that are common to all regions

Sensitivities	Actions
Reduced habitat for wildlife species that rely on mature forest cover • Stressed trees create more favourable conditions for insect and disease outbreaks • Increased crown fire incidence reduces forest cover in dry climates • Insect- and disease-induced shift from single tree and small patch forest gap formation to large patch disturbance (coast and inland rainforest) • Increased rate and larger areas of avalanching (Coast and North) • Loss of mature forest cover may reduce species abundance and alter distribution	**Resistance** • Implement wildfire management, including fire breaks of deciduous vegetation (Haeussler & Hamilton 2012b). • Implement insect control measures (pheromone baits, wire screens, spraying) where effective as per indications from local inventory (Haeussler & Hamilton 2012b). **Resilience** • Review existing management activities to ensure desired habitat diversity can be achieved (Haeussler & Hamilton 2012b).

Table 5. (Continued)

Sensitivities	Actions
• Reduced habitat connectivity or permeability • Increases in invasive species outcompeting natural vegetation **Reduced habitat for species that are dependent on post-disturbance habitats (e.g., woodpeckers)** • Post-disturbance or salvage logging removes critical post-disturbance structures (e.g., standing dead wood) • Natural post-disturbance vegetation recovery impeded by stand rehabilitation activities • Reduced future downed wood contribution due to chipping or pile and burning of non-merchantable timber	• Increase the forest reserve network in the managed forest matrix to offset losses of mature forest from natural disturbances in existing reserves (Haeussler & Hamilton 2012b). • Increase the retention of mature forest structure in harvested areas (Haeussler & Hamilton 2012b). • Accommodate alternative silviculture and harvesting methods (e.g., partial-cutting, variable retention) (Haeussler & Hamilton, 2012b). • Limit the amount or extent of salvage logging in forested ecosystems following severe natural disturbance to maintain critical habitat structures (Forest Practices Board 2009). • Identify mid-seral and immature forests to retain for longer periods (i.e., extended rotations or reserves) before harvest to recruit mature forest attributes (Haeussler & Hamilton 2012b). **Realign and response** • Adjust terrain stability ratings to accommodate increased landslide activity due to the effects of intense storm events (BCMFLNRO 2008–2011). • Avoid monoculture reforestation of species that may be at future risk of mortality from insect and disease outbreaks (BCMFLNRO 2008–2011). • Actively restore sites and manage for invasive species during and after all harvesting-related activities (e.g., roads and roadsides, log sorts) (Birdsall et al. 2012; Hauessler & Hamilton 2012b). • Conduct monitoring and control (eradication) programs for invasive plants to maintain native vegetation (Peterson et al. 2008; Wilson & Hebda 2008; Haeussler &Hamilton 2012b). • Increase the diversity of species in silviculture stocking standards and seed transfer at landscape and local scales (Spittlehouse & Stewart 2003; Mah et al. 2012). • Apply a "mixed-bag" approach to reforestation—facilitate tree species migration with a mixed planting of native coniferous and/or deciduous trees that are climatically and ecologically suited to a changing climate (BCMOFR 2009; Haeussler & Hamilton 2012b; Mah et al. 2012). • Develop tools to guide tree species selection that is suitable to a changing climate (BCMFLNRO 2014). • Develop pest-resistant genetic varieties (Ogden & Innes 2007).

Table 6. Natural disturbance regime effects on species and ecosystems (Northern Region)

Sensitivities	Actions
Effects on terrestrial forest ecosystems • Availability of local viable seed may be low (stressed trees or seed destroyed by severe fire), thereby reducing forest recovery • Loss of permafrost may disrupt seed beds and stability of growing sites	**Resilience** • Implement landscape-level planning for tree species targets and density (Mah et al. 2012). **Response** • Develop strategic planning around assisted migration of tree species (Ste-Marie 2014). • Apply tree species stocking standards tools that are specifically developed for conditions of northern regions (BCMFLNRO 2014).

Table 7. Organic processes and phenological changes on biological organisms.

Sensitivities	Actions
Phenological effects • Disruption of synchronicity of pollinators and plant phenology • Disruption of synchronicity of migrating species and phenology of food sources **Carbon balance shifts** • Loss of forest cover • Loss of forest soil carbon through increased rates of decomposition (e.g., northern permafrost thawing), avalanching, and erosional processes **Nutrient cycling** • Alteration of the rate of decay of standing and fallen woody debris • Soil temperature changes affect nutrient cycling organisms (decay and nitrogen cycle)	**Resistance:** • Conserve and manage for native pollinators to coincide with adjusted flowering timing (CAPA 1995; Drummond 2008; Hopwood 2008; Schweitzer et al. 2012). **Resilience** • Provide incentives for local beekeeping, and conduct research to enhance native species recovery in forestry (Schweitzer et al. 2012; Pronatura Veracruz 2014). • Restore and protect ecosystem integrity at high-value migrating stopover areas (Peterson et al. 2008). **Realign and response** • Establish representation targets for a mix of carbon sinks (old forest) and carbon scrubbing (young forest) (BCMFLNRO 2008–2011). • Sequester carbon through backlog planting and riparian underplanting (BCMFLNRO 2008–2011).

Table 8. Sea level rise (Coast Region)

Sensitivities	Actions
Estuarine ecosystems • Flooding of existing vegetation complexes • Increased organic input to flooded areas; more deposition of materials • Many small estuaries along the coast will likely be permanently inundated • Loss of estuarine habitat and ecosystems • Loss of shorebird tidal flat habitat, with possible partial recovery where tidal flats can expand inland	**Resistance** • Prioritize restoring estuarine and shoreline areas only where the physical site allows for inland development of estuarine systems (Peterson et al. 2008). **Resilience** • Remove barriers to diurnal flooding and freshwater streamflow (U.S. EPA 2009).

Table 8. (continued)

Sensitivities	Actions
	• Increase protected areas upstream to provide future estuarine habitat (U.S. EPA 2009). • Increase undeveloped or less developed areas around estuary (U.S. EPA 2009). • Improve marsh characteristics through restoration of native species and control of non-native invasive species (Peterson et al. 2008). **Response** • Restrict development that will act as a barrier to estuarine inland expansion (U.S. EPA 2009). • Limit upstream barriers and interventions to preserve downstream flow (e.g., dams or other hydro power enhancements affect freshwater streamflow to the estuarine area) (U.S. EPA 2009). • Remove hard shore protection and barriers to landward migration, and/or replace with soft protection through vegetation (U.S. EPA 2009). • Manage infrastructure development in and around estuaries, coastlines, and rivers to reduce the loss of future estuarine habitat (Peterson 2008). **Realign** • Create habitat for migrating and breeding shorebirds to offset the anticipated loss of habitat to sea level rise (U.S. EPA 2009). • Create artificial nesting sites of eelgrass mats that are constructed of dead eelgrass (Palestis 2009). • Plan for inland transition of existing infrastructure (U.S. EPA 2009). • Develop coastal flood hazard guidelines (B.C. Ministry of Environment 2011). • Develop estuarine management plans that account for sea level rise and increased storm surge, including measures that prevent the squeezing of estuarine ecosystems between the rising sea and the uplands (U.S. EPA 2009).
Coastal sand dune ecosystems • Erosion and altered accretion zones • Extreme erosion of marine sand bluffs • Loss of narrow coastal strip ecosystems • Loss of species habitat	**Realign and response** • Avoid hard seawalls that interrupt natural longshore recruitment of beach material (U.S. EPA 2009). • Build headland controls that will promote beach material recruitment in bays (U.S. EPA 2009). • Create development setbacks from erodible beach and bluff areas (U.S. EPA 2009). • Build storm berms that are backed by natural plantings to reduce the effects of storm surge (U.S. EPA 2009).

Summary

This article has presented a synopsis of the climate adaptation literature and published research for natural resource practitioners in British Columbia. The literature represents adaptation activities and options in the province and in other jurisdictions. When there are clear uncertainties about future conditions, a good strategy is to focus on "no-regrets" actions (Kittel et al. 2011). These actions enhance the adaptive capacity of species and ecosystems, no matter what the future brings. Natural resource management can no longer be limited to consideration of past conditions; considering the future is the current imperative for British Columbia's natural resource managers.

Notes

1. For continuously updated information, see Pacific Climate Impacts Consortium summaries for seven equivalent British Columbia sub-regions: http://www.pacificclimate.org/news-and-events/news/2013/regional-climate-summaries) (PCIC 2013).
2. Millar et al. (2007) present just four Rs for adaptation, and they include realignment as a subset of resilience. In Millar's 2010 presentation, "reduce" was removed and "refugia" was added.

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