Comparison of Regional Vulnerability Assessments

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Introduction to Vulnerability Assessment

Climate-change vulnerability assessments (Füssel and Klein 2006) provide a framework for characterising the potential implications of climate change to specific aspects of natural systems or human society. Ecosystem services lie at the juncture between natural systems and society, thus, understanding their vulnerability to climate change is of critical importance. Ecosystem services such as timber depend on the character and function of ecosystems (e.g., grassland ecosystems do not produce timber; Figure 1).Certain biophysical processes, including climate, act alone or in concert with particular management policies to have a disproportionally large influence on ecosystem character (e.g., species distributions) and function. Long-term changes in ecosystem character and function depend on an ecosystem's adaptive capacity—its ability to adjust in a way that retains historic function or to transform to a new functional state.

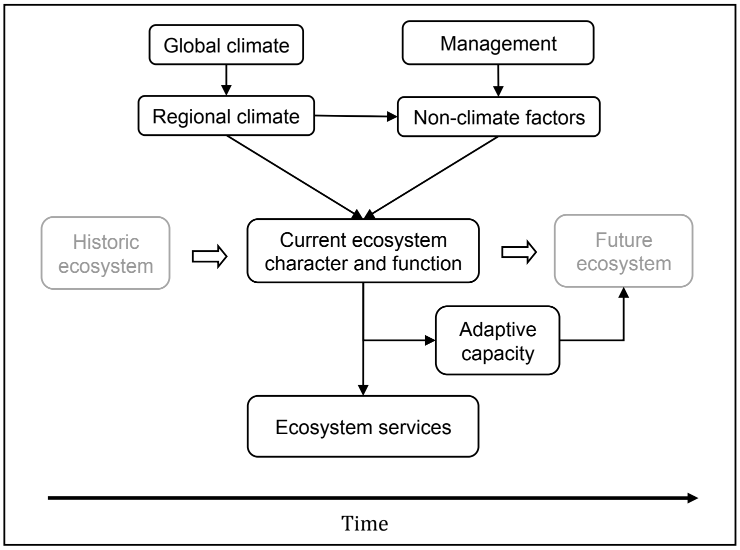

Figure 1. Conceptual diagram showing major factors and pathways influencing ecosystem services.

In the context of managed forests, climate change vulnerability assessments characterize **exposure** (projected regional climate change) and **sensitivity** (responsiveness of historic ecosystems to climate change) to determine potential **impacts** (e.g., level of change for a projected climate) to ecosystem character and function and to ecosystem services. Sensitivity is influenced by historic ecosystem character (e.g., species and seral stage diversity) and by **non-climate factors**, including ongoing forest management practices, that create cumulative impacts. Over the longer term, impacts depend on (1) **ecosystem adaptive capacity**: the inherent ability of species and ecosystems to adjust to the changing climate (e.g., breadth of environmental tolerance; ability to migrate or evolve); and (2) **management adaptive capacity**: the ability of managers to limit climate impacts through forest management practices and to support natural adaptation. **Vulnerability** captures the overall potential for long-term impacts to an ecosystem and related services, considering exposure, sensitivity and adaptive capacity. Vulnerability assessments identify **adaptation measures** (management actions) to reduce vulnerability. **In essence, vulnerability assessments are similar to impact assessments (e.g., CEA Practitioners' Guide 1999), except that they also explicitly consider the ability of ecosystems and management systems to adapt to the impact over time.**

The three regional vulnerability assessments—Nadina, Kamloops and West Kootenay—described below provide early examples of assessment approaches applied to forested regions of BC.

Introduction to Regional Case Studies

Three teams conducted climate-change vulnerability assessments (Füssel and Klein 2006) of forest management units in BC, with funding support from the Future Forest Ecosystems Science Council of BC (http://www.for.gov.bc.ca/hfp/future_forests/council/) and the Future Forest Strategy (http://www.for.gov.bc.ca/hcp/ffs/). Budgets ranged from about $100,000 to $200,000 per project (i.e., not including phase 2 of the Kamloops project). The studies shared the broad aim of identifying potential consequences of climate change ("vulnerabilities") and of describing management responses that reduce vulnerability ("adaptation") within each study region. All studies involved local forest managers, other stakeholders and topic experts in an effort to increase understanding of climate change and share expertise. The Kamloops study was conducted in two phases; information presented below comes primarily from the first phase (K1). Study details are available at project websites:

Nadina: http://bvcentre.ca/research/project/a_multi-scale_trans-disciplinary_vulnerability_assessment/
Kamloops (K1): http://www.for.gov.bc.ca/hcp/ffs/kamloopsFFS.htm; (K2): http://k2kamloopstsa.com
West Kootenay: http://www.kootenayresilience.org/index.html

Within each study the teams developed background information – creating initial hypotheses describing the rough magnitude of expected ecological change (e.g., about 2 to 4 x historic rate of fire; shift from forest to grassland) based largely on modeling and expert opinion. Vulnerability assessments – due to the complex nature of climate change itself coupled with a wide variety of potential ecological responses – require a multidisciplinary team with a diversity of expertise and good local knowledge. All project teams found that running workshops / forums was an effective, if time consuming, way to inform resource professionals (and others) about potential climate change and its potential effects. Workshops also provide a vehicle for effectively fostering two-way information exchange between participants and the project team – and as such are perhaps more likely to encourage creative solutions.

Study Areas

Each of the three study areas covers several million hectares and lies within mountainous areas in the interior of BC, in regions with active forestry sectors (Table 1; Figure 2). Current climate tends to be warm-dry, and continental in valleys and at lower elevations, and colder and wetter with some maritime influence at higher elevations (Hamann and Wang 2006), resulting in several BEC zones in each area (Figure 2). Kamloops has the highest diversity of zones, reflecting its diverse topography (see Ecoprovinces).

Table 1. Characteristics of case study areas.

Study Area Name:	Nadina	Kamloops	West Kootenay
Forest Management Unit	Morice and Lakes Timber Supply Areas (TSAs)	Kamloops TSA	Arrow and Kootenay Lake TSAs
Area	~3 M ha	~2.7 M ha	~2.6 M ha
Hydroclimatic region[A]	Fraser Plateau	Fraser Plateau	Columbia Basin
Ecoprovince[B]	Mainly Central Interior; Sub-boreal Interior, Coast and Mountains	Southern Interior, Southern Interior Mountains	Southern Interior Mountains
Dominant Climate[C]	Mainly warm-dry continental	Mostly very warm and very dry continental with some cool-wet maritime	Mixed cool-wet maritime (mountains) and warm-dry continental (valleys)
BEC Zones	SBS, ESSF, SBPS, CWH, BAFA	IDF, ICH, ESSF MS, SBS, PP, SBPS, BG, IMA	ESSF, ICH, IDF, IMA

[A] Rodenhuis et al. 2009.

[B] The British Columbia Ecoregion Classification: http://www.env.gov.bc.ca/ecology/ecoregions/index.html ; Agriculture and Agri-Food Canada: http://sis.agr.gc.ca/cansis/nsdb/ecostrat/intro.html.

[C] Ibid; Moore et al. 2010; Figure 1 of Hamann and Wang 2006.

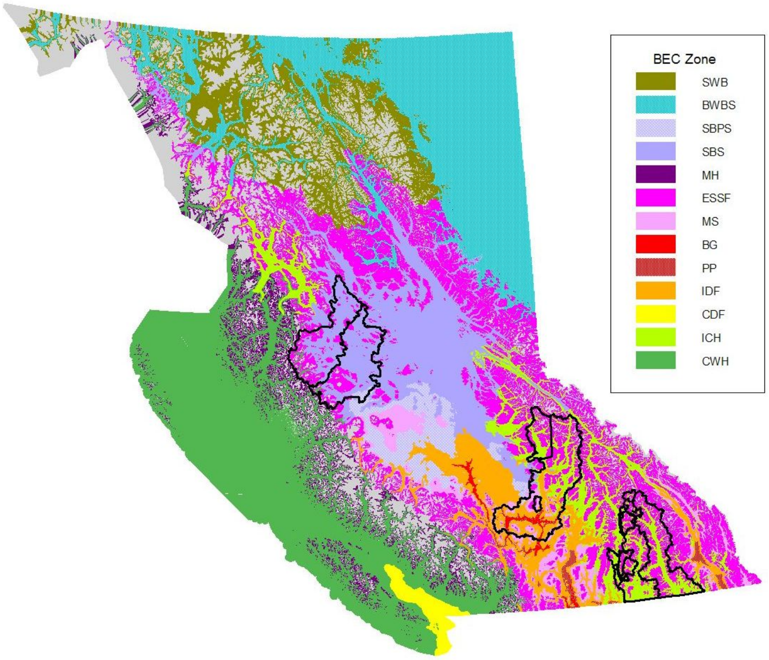

Figure 2. Location of study areas and BEC Zones found within each. From northwest to southeast, the study areas are Nadina, Kamloops and West Kootenay.

Case Study Methods

While details and specific foci varied, all three case studies followed a broadly similar approach to vulnerability assessment (Zielke and Bancroft 2009, Holt et al. 2012, Daust et al. 2011):

1. **Predict changes in climate** variables (e.g., temperature, precipitation) and in "climate envelopes" (i.e., climate associated with BEC subzones) for the study area (i.e., exposure), for different global climate scenarios (see climate scenarios below).

2. **Estimate possible changes in ecosystem character and function** ("ecological vulnerability")

    a. Divide the study area into subunits based on potential to respond similarly to climate change (i.e., similar exposure and/or sensitivity; e.g., specific subzones, variants, site series or physiographic units)

    b. Develop hypotheses and rationales (e.g., conceptual model or narrative) to support estimates of possible change, considering climate, disturbance, anthropogenic factors (e.g., fragmentation) and historic ecological character and function.

    c. Use expert workshops (with local ecologists, resource specialists, academics and practitioners), expert advice and literature as information sources.

3. **Estimate consequences to managed values** and to the effectiveness of forest management strategies (management vulnerability) resulting from changes to climate and ecosystems, based on literature, expert advice and workshops.

4. **Describe potential management responses** that reduce vulnerability (adaptation strategies), based on literature, expert advice and workshops.

5. **Identify likely management responses** (i.e., current "management adaptive capacity") by assessing the likelihood that managers will be willing and able to implement potential responses; record "barriers to adaptation."

6. **Rate the projected vulnerability** of managed forests (by ecosystem and/or managed value) in each subunit for different levels of adaptation:
    a. baseline vulnerability: potential impacts[1] without any management response (i.e., include inherent ecological adaptation);
    b. best case: potential impacts with full potential management response;
    c. likely case: potential impacts with likely management response (considering barriers).

7. **Recommend management, research, planning and policy actions** to address vulnerability and barriers to adaptation.

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[1] Impacts should consider both positive and negative changes.

The three case studies focused on different values for assessing vulnerability (Table 2). The West Kootenay study focused on ecosystems, while Kamloops and Nadina also focused on ecosystem services. West Kootenay identified a range of potential climate-induced biophysical changes relevant to forest ecosystem resilience (see box below). Kamloops organized biophysical changes by how they influenced the effectiveness of forest management policies (e.g., wildlife habitat areas, wildlife tree patches, reforestation practices) and managed values. The Nadina project focused on biophysical changes relevant to selected managed values. All studies considered historic and current management policies as part of the context for determining change.

Resilience theory aids in understanding the significance of projected ecological changes. Ecosystems affected by climate change may remain relatively similar to their current condition or may undergo a regime shift. The shift can be non-catastrophic, where the ecosystem recovers along a different successional pathway or can be catastrophic where the ecosystem remains in an early successional or stalled state and only recovers very slowly. In either case, a regime shift is likely to significantly alter the goods and services available from ecosystems.

Assessment units also varied by region. The West Kootenay project formally identified three subregions based on enduring topographical features (Table 2). The Nadina project informally identified regions and sites, based partly on topography. Kamloops created five subzone groups after considering variation in potential ecological impacts.

All studies projected climate envelope change and then used expert opinion to estimate ecological implications. The Nadina study developed "conceptual models" in expert workshops to guide assessment of ecological impacts. The Kamloops study developed "narratives"—stories describing plausible future conditions—in workshops (K1) and tested some estimates (K2) using mechanistic models of ecosystem function. The West Kootenay study used various workshops employing impact diagrams and surveys to estimate the implications of the projected climate envelope changes.

Where possible, the studies included rough estimates of the likely magnitude of change. West Kootenay rated the likelihood of a regime shift. All projects primarily conveyed uncertainty by including warnings in the text. No studies actually rated uncertainty. All studies provided some rationale for their estimates, allowing a subjective assessment of uncertainty.

Ecological change, and consequently change to ecosystem services, is difficult to estimate because of wide uncertainty about the extent of climate change and the response of a complex ecological system with many interacting components. Some aspects of change are relatively more certain than others. With climate change, warming is certain, but the exact rate of warming is difficult to predict; changes in precipitation are not certain in direction or magnitude; seasonal changes in both variables are uncertain. Increased disturbance related to climate is also fairly certain, although the importance of specific insect and disease agents is more uncertain. Where warmer, drier climates are projected, increased fire (subject to suppression efficacy) and drought are relatively certain. The timing of a regime shift is difficult to predict, but where trends in disturbance are clear and substantial, a shift is ultimately quite certain. The benefits of adaptation are similarly difficult to estimate.

Table 2. Differences among studies in focal values, assessment subunits and methods of estimating impacts.

	W. Kootenay	Kamloops	Nadina
Focal values (i.e., vulnerability of what)	1) Forest ecosystems	1) Forest ecosystems 2) Managed values and policies: – Timber – Biodiversity and wildlife habitat – Fish – Water – Valued plants – Urban interface – Visual quality	1) Trees and timber, 2) Biodiversity 3) Hydrology and aquatic ecosystems
Assessment subunits	"Regional landscapes" based on topography that determines climate exposure	"Subzone groups" based on variation in potential ecological impacts	Variable, based on impact: e.g., western mountains and eastern plateau
Methods for estimating impacts	Expert workshops, surveys, modeling and expert assessment of regime shift potential (resilience assessment)	Expert workshops, narratives and computer models	Expert workshops and conceptual models

All studies considered a similarly long list of factors in assessing vulnerability; they differed in the factors that they formally rated (Table 3). The West Kootenay study developed ratings of exposure, sensitivity and "effective adaptive capacity" (inherent ecological adaptive capacity and status-quo management) and combined them into an overall rating of baseline ecological vulnerability for each elevation band within each subregion. West Kootenay also characterised the significance of the projected changes by using the likelihood of a regime shift (substantial change to ecological character and function). The Kamloops and Nadina studies did not rate exposure, sensitivity nor ecosystem adaptive capacity separately, but rather rated impacts (level of sensitivity for a given level of exposure). Because they considered aspects of ecosystem adaptive capacity in their impact ratings, these ratings can be considered as roughly equivalent to baseline vulnerability. Kamloops rated baseline ecological and management vulnerability for each subzone group. It also rated best-case (optimistic management) and likely management vulnerability. The Nadina study applied the vulnerability concept to managed values rather than to subregions. It rated baseline and best-case vulnerability to each managed value from each biophysical change and then rated the overall impact to ecosystem services provided by each value.

Table 3. Factors either rated or considered in case studies.

Factors used in Vulnerability Assessment	W. Kootenay	Kamloops	Nadina
Exposure to climate change	Rated	Considered	Considered
Sensitivity to climate change	Rated	Considered	Considered
Non-climate factors	Rated	Considered	Considered
Potential Impact	Considered	Rated	Rated
Ecosystem adaptive capacity	Rated	Considered	Considered
Baseline vulnerability (considering ecosystem adaptive capacity)	Rated	Same as potential impact	Same as potential impact
Management adaptive capacity (potential management options and barriers to adaptation)	Considered	Considered	Considered
Best-case vulnerability (all potential management adaptation)	Considered	Rated	Rated
Likely vulnerability (given barriers to management adaptation)	Considered	Rated	Considered

Case Study Results and Discussion

Projected Climate Change

The vulnerability assessments used multiple climate projections to estimate future values of climate variables in their regions (Daust and Price 2011, Jones and Brown 2008, Utzig 2011). They each focused on two or three global climate projections, based on recommendations of climate scientists (Murdock and Spittlehouse 2011), to illustrate shifts in climate envelopes (Figure 3). Climate projections vary with model formulation and assumptions about greenhouse gas emissions. Over the past few years, without effective emission reductions, global emissions have been exceeding all of the modeled emission scenarios (Allison et al. 2009); however most of the variation in projected temperature and precipitation reflects differences in model formulation.

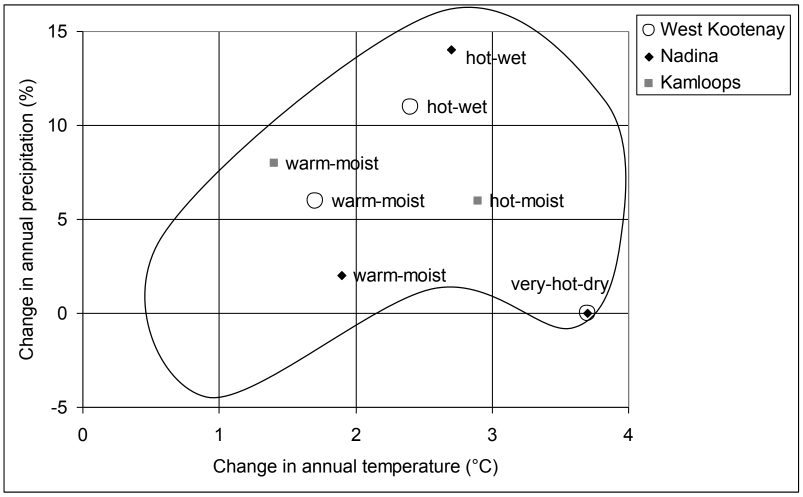


Figure 3. Change in annual temperature and precipitation in BC in 2050 (relative to 1960-1990 baseline) for climate projections used in case studies. Bounded area shows approximate range of climate model results for BC. Climate projections (listed in the box) identify model, emissions scenario and run. See Murdock and Spittlehouse (2011) for a description of projections.

Climate Projections*

West Kootenay
- CGCM3_A2_R1
- HadCM3_B1_R1
- HadGEM_A1B_R1

Nadina
- CGCM3_A2_R4
- HadCM3_A2_R1
- HadGEM_A1B_R1

Kamloops
- PCM1_B1_R2
- HadCM3_A1FI

*from most to least precip. within region

Regardless of the models and scenarios chosen, climate is projected to change substantially in the case study areas (Table 4 – 6). Temperature will rise. Annual precipitation will likely increase. Summer precipitation will likely decline in Kamloops and West Kootenay. Warmer temperatures will increase evaporative demand, even with increased precipitation, likely leading to drying in many ecosystems. More winter precipitation will fall as rain than snow. Limited information on extreme climatic events predicts an increase in the magnitude and intensity of extreme precipitation, drought and heat events globally (IPCC 2012).

Table 4. Historic median and weighted standard deviation of climate variables (for approximate location of Nadina from http://pacificclimate.org/tools-and-data/regional-analysis-tool); and projected median and range (90% of outcomes) of change from baseline (1960 to 1990) for circa 2055 (2040 to 2070) in the Bulkley-Nechako Regional District (which includes the Nadina) from multiple runs of different climate models and emissions scenarios ("ensemble" runs). Source: http://plan2adapt.ca

Climate Variable	Historic Median ± W. Std. Dev.	Median Projected Change	Range of Projected Change
Annual mean temp (°C)	1.8 ± 0.9	+1.8 °C	+1.3 °C to +2.7 °C
Summer mean temp (°C)	11.8 ± 1.1	+1.6 °C	+1.2 °C to +2.8 °C
Winter mean temp (°C)	-8.7 ± 0.7	+1.8 °C	+0.6 °C to +2.8 °C
Annual precipitation (mm/day)	1.7 ± 0.8	+9%	+2 to +16%
Summer precipitation (mm/day)	1.7 ± 0.3	+2%	-7 to +11%
Winter precipitation (mm/day)	2.0 ± 1.3	+11%	-2 to +21%
Winter snowfall (mm)	167 ± 108	+7%	-4 to + 16%
Spring snowfall (mm)	51 ± 46	-52%	-68 to -10%
Growing degree days > 5 °C (degree-days)	864 ± 161	+213 (deg x days)	+127 to +394
Frost free days	216 ± 12	+18 days	+11 to +29

Table 5. Historical and projected values of selected climate variables in the Kamloops TSA. Projections are for circa 2055. Data from Table 1 in Jones and Brown 2008.

Climate Variable	Historical (1961-1990)	Projected change for warm-moist	Projected change for hot-moist
Mean annual temperature	2.4 °C	1.1 °C	3.3 °C
Mean coldest month temperature	-8.9 °C	2.1 °C	2.0 °C
Mean warmest month temperature	13.4 °C	1.6 °C	5.6 °C
Frost-free period	68 days	28%	62%
Number of frost-free days	145 days	11%	31%
Mean annual precipitation	854 mm	4%	4%
Mean annual summer precipitation	343 mm	-1%	-9%
Precipitation as snow	396 mm	-1%	-12%

Table 6. Historical and projected values (ten projections) of selected climate variables in W. Kootenay. Projections are for circa 2055. Data from Utzig 2012.

Climate Variable	Historical (1961-1990)	Mean change	Range
Mean winter temperature	-7	+2 °C	+0.2 to +4.1 °C
Mean spring temperature	2	+2.5 °C	+0.9 to +4.2 °C
Mean summer temperature	13	+3.5 °C	+1.2 to +5.2 °C
Mean fall temperature	3	+2.5 °C	+0.5 to +3.9 °C
Mean winter precipitation (mm/day)	4.5	+8%	-11 to 25%
Mean spring precipitation (mm/day)	2.6	+11%	2 to 21%
Mean summer precipitation (mm/day)	2.6	-11%	-26 to +3%
Mean fall precipitation (mm/day)	3.1	+10%	-9 to +20%

Climate envelopes provide a good way for ecologists to envision change, helping them translate knowledge about important processes from one area to another. In each area, climate envelopes are projected to shift substantially before the end of this century; **most BEC subzone climate envelopes will cover little or none of their former range (Figure 4 and 5)**. In Nadina, Interior Douglas-fir climates may dominate the former Sub-Boreal Spruce zone in the hot-dry and hot-wet climate scenarios. In W. Kootenay, Ponderosa Pine, Grass-Steppe and Interior Cedar Hemlock (ICH) climates dominate the hot-dry climate scenario compared with the current preponderance of Engelmann Spruce Subalpine Fir and ICH.

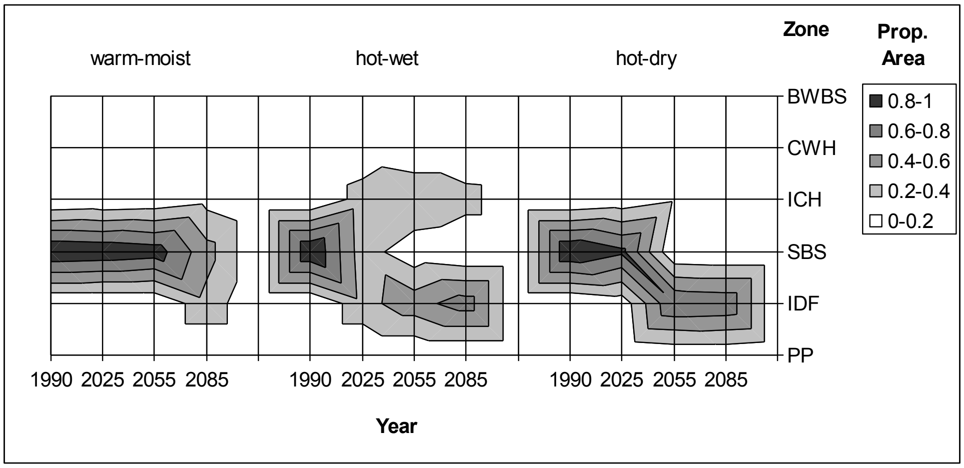
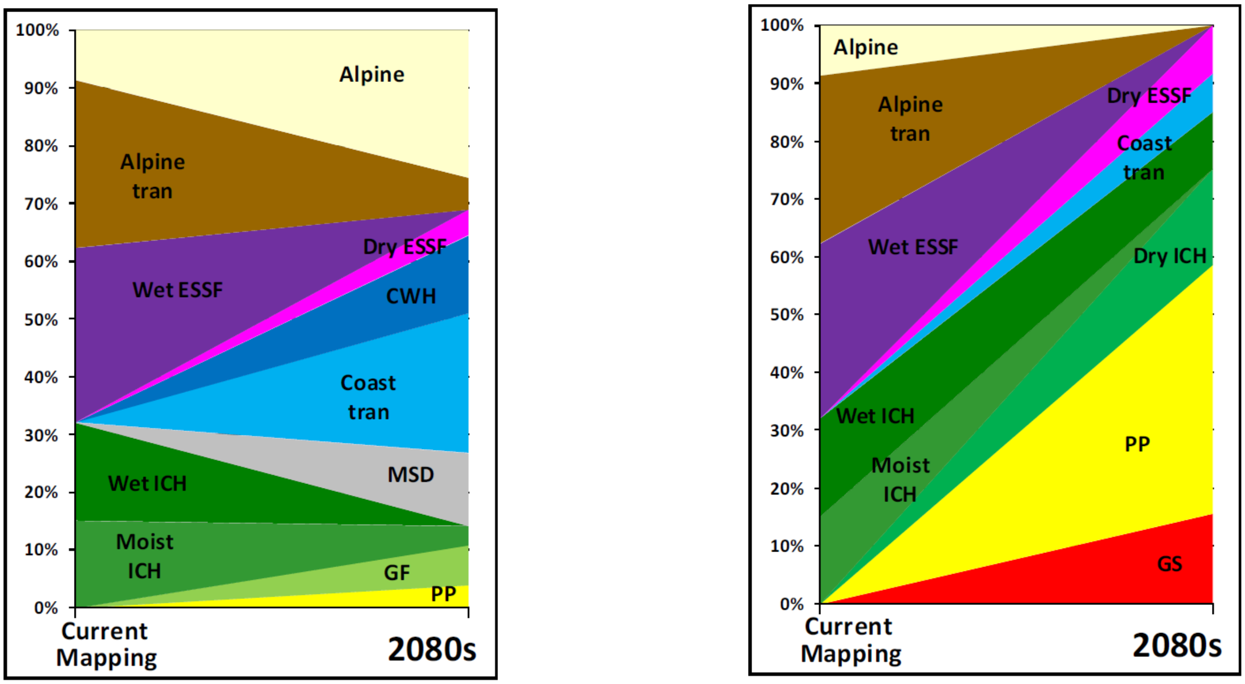


Figure 4. Proportion (shown by contour bands) of the 1990 Nadina SBS zone covered by different climate envelopes (BEC Zones) versus time for different climate projections.



a) b)

Figure 5. Projected change in climate envelopes in W. Kootenay for the a) hot-moist and b) very-hot-dry climate projections. In the first scenario climates shift to slightly drier conditions at lower elevations and more coastal conditions at upper elevations, with considerable alpine remaining. In the second scenario, climates become much drier at lower elevations and alpine conditions disappear. Under both scenarios, wet ESSF and moist ICH disappear.

Projected Impacts to Terrestrial Ecosystems

This section begins by examining changes in weather, site conditions and disturbance regimes that alter the character and function of ecosystems, and then examines impacts to tree species and ecosystems (i.e., mainly plant communities). Projected impacts are summarized mainly from Utzig and Holt 2012; Daust and Morgan 2011; Zielke and Bancroft 2009.

Weather, site conditions and disturbance

Climate change affects forest ecosystems in two important ways:

1. Altering temporal and spatial patterns of gap-creating and stand-replacing disturbance that affect seral stage and species distributions; and,
2. Altering weather patterns and site conditions that affect plant species survival and community composition: i.e., new climatic conditions (temperature, precipitation, seasonality, drought) exceed the range that species typically occupy or tolerate;

The same suite of disturbances affects all study areas, but the importance of each varies among regions (Table 7). In general, climate influences disturbance regimes by affecting insect and disease populations and the probability of hot weather and hence fire (and drought). Insects and disease are expected to be most important in Nadina forests. In W. Kootenay and Kamloops, fire coupled with drought could lead to regime shifts from forest to grassland or from gap-replacement forests to forests dominated by frequent stand-replacing fires.

Table 7. Approximate impact (nil, low, moderate, high) to forest ecosystems of climate-related biophysical changes, for subregions within each case study. Results will vary by climate scenario and time period (exposure).

	Disturbance			Weather and Site Conditions	
	Fire	Insects*	Disease*	Grassland Climate	Tree range reduction **
W. Kootenay North	↑↑↑	↑	↑	↑	↑
W. Kootenay Mid	↑↑	↑	↑	↑↑	↑
W. Kootenay South	↑	↑	↑	↑↑↑	↑
Kamloops dry and transitional (low elevation)	↑↑↑	↑↑↑	↑	↑↑	↑
Kamloops cold/wet & high elevation/plateau	↑	↑	↑	↑	↑
Nadina eastern plateau	↑	↑↑↑	↑↑	↑	↑
Nadina west mountains	-	↑↑	↑↑	-	↑

* in particular, these are highly uncertain.

**i.e., loss of climatic conditions historically associated with tree range, excluding shifts to grassland; expansion of tree species' ranges is not considered here.

Many insects are capable of causing tree mortality across large expanses of mature forest during outbreaks. Insects with potential to expand in mature West Kootenay forests in the short- to mid-term are spruce bark beetle, Douglas-fir beetle, western balsam bark beetle, and western hemlock looper (Table 8). Spruce, balsam and pine bark beetles all have potential to expand in the Nadina; a large mountain pine beetle outbreak has just killed a large proportion of the forest in the Nadina. Douglas-fir beetle may be an important mortality agent in Kamloops. Western false hemlock looper and spruce leader weevil, observed in rare instances in the West Kootenays, may expand to outbreak levels as annual temperatures warm and summer drought becomes more common.

Some pathogens may cause more damage as spring precipitation increases (Table 8). Dothistroma has potential to cause substantial mortality in the western mountains of the Nadina. In West Kootenay, species of concern include pine stem rusts, larch needle blight and cast, Swiss needle cast and Dothistroma. Armillaria root disease may expand in West Kootenay and substantially in Kamloops, causing mortality in trees experiencing greater stress caused by drought, insects and disease. Decline syndromes—poor growth and death caused by numerous interacting factors—may increase.

Table 8. Insect and disease agents considered to be potentially important in different case studies.

Insect or disease	West Kootenay	Kamloops	Nadina
Mountain pine beetle		X	X
Western pine beetle			
Spruce bark beetle	X		X
Western balsam bark beetle	X	X	X
Douglas-fir beetle	X	X	
Western hemlock looper	X		
Western false hemlock looper	X		
Douglas-fir tussock moth		X	

Insect or disease	West Kootenay	Kamloops	Nadina
Spruce budworm		X	
Spruce leader weevil	X		
Dothistroma needle blight	X		X
Pine stem rusts	X		
Larch needle blight and cast	X		
Swiss needle cast	X		
Armillaria	X	X	

The West Kootenay study estimated a minimum increase in area burned of 3 to 4 fold by 2050 across the study area. Nadina estimated that area burned could increase by up to two fold; fire is expected to increase in the eastern plateau and decrease or remain stable in the western mountains of Nadina. Kamloops projected an increased frequency of large fires across the TSA with particularly high hazard in low elevation valleys in the Dry IDF and ICH-IDF subzone groups where hot dry conditions combine with expected increases in tree mortality due to insects and disease.

Disturbances may interact, for example, beetle mortality may increase the risk of hot fires for a time. Disturbance may be worse in the short and mid-term (a transition period) as disturbance agents spread into high densities of susceptible hosts (e.g., mountain pine beetle outbreak) or, conversely, worse in the long-term as climate change becomes more pronounced. Extreme weather (e.g., heavy wet snow or ice) and animal damage can also cause considerable tree mortality but these disturbance agents were thought to be relatively less important in all studies.

In general, an increase in a disturbance agent coupled with susceptible forests brings the potential for substantial change, including regime shifts. Drought and fire are most influential where ecosystems are moving towards being dry, but currently still have expanses of dense forest and low fire disturbance rates (e.g. northern, currently wet forests in the West Kootenays; parts of the southern portion of the Kamloops TSA; dry sites in Nadina). Insects and disease are most influential in areas where cold (and/or dry spring conditions) has limited their population growth in the past (e.g., Nadina; ICH-IDF Transition subzone group in Kamloops).

Trees

Trees are both foundation species supporting biodiversity and an important source of wood fibre for local mills. Across a landscape, tree growing stock and seral stage distribution depend on the rate of tree growth within each stand and on the probability of trees and stands surviving to rotation age. Warmer growing seasons, coupled with increased CO_2, have the potential to increase tree growth, but potential benefits may not be realized due to increased climate-induced stress, increases in mortality and potential loss of productive forest area (e.g., Table 9).

Tree species vary in their ability to tolerate climate-driven environmental conditions. All studies noted that climatic conditions suitable for several tree species may decline substantially. In Kamloops, lodgepole pine, Douglas-fir and subalpine fir face high risk in dry subzones, transitional subzones and high elevation plateaus, respectively (Table 10). Site conditions suitable for western larch and western redcedar may decline substantially across the West Kootenays and at higher elevations, and spruce will likely become ecologically unsuitable. Trees in the Nadina seem fairly resilient: existing tree species face minor risk of widespread establishment failure due to abiotic conditions, however subalpine fir and some species of spruce may face some risk (Daust 2011, Nitschke 2010). Projected increases in drought and fire in W. Kootenay and Kamloops favour drought and fire-resistant species.

Climatic-induced impacts interact. Trees stressed by reduction in climatic suitability are more susceptible to insects and disease (which may be increased in vigour due to warming), tree mortality can increase fire hazard, and changes in temperature, coupled with increased disturbance can favour invasive species.

Table 9. Estimated climate-induced ecological impacts to trees in the Nadina Case Study. Magnitude of change rated as low, moderate or high (L,M,H), with intermediate categories.

Impact	Applicable subunit	Magnitude
Tree growth ↑	sites without moisture stress	M
	sites with moisture limitations	L
	overall	LM
Bark beetle mortality ↑	pine component	H
	spruce	MH
	balsam	MH
	overall	H
Diseases of young stands ↑	pine leading plantations in SBS mc2	MH
Fire mortality ↑	dry eastern plateau	H
	wet western mountains	L
Maladaptation due to climate-stress ↑	dry sites	H
	moist and wet sites	L
Forest-scale resilience ↓	may vary by BEC zone	M

Table 10. Overview of ecological impacts to subzone groups in the Kamloops TSA (based on Table 2.1 in Zielke and Bancroft 2009). The ranking is based on the degree of ecological alteration attributed to climate change.

Subzone group	BEC subzones	% of THLB	Ecological Impact	Rationale for ecological sensitivity (emphasizing the more extreme climate scenario)
Dry Subzones with lodgepole pine	MSxk, IDFdk, (SBPS)	28	HIGH	• Too hot and dry after 2050 for Pli. • Estimate 37% of THLB in young Pli that will not be ecologically suitable past 2050. • Increased fire risk.
Dry Subzones with Douglas-fir & Ponderosa Pine	IDFxh, PPxh	10	HIGH	• Continuing mortality in Fd will thin out and open up stands. • Increased grassland patches. • Increased fire risk.
Interior Cedar-Hemlock Transition to Dry Douglas-fir	ICHmw, ICHdw, IDFmw, (ICHmk)	26	MOD-HIGH	• Fd drops out of mixedwoods due to drought / Armillaria / D-fir beetle combo. • Lose considerable Cw, Sx, Ep past 2050 • Increased fire risk.

Subzone group	BEC subzones	% of THLB	Ecological Impact	Rationale for ecological sensitivity (emphasizing the more extreme climate scenario)
Dry- Moist Plateau / High Elevations	MSdm, SBSmm, ESSFdc, (ESSFxc)	15	MOD	• Increased growth in most species (except Bl) up to 2050. • Beyond 2050 – Bl drops out, Pli at high risk, Sx questionable on some sites lower down. May see a few large fires.
Cool/Cold & Wet	ESSFwc, ICHwk, (ICHvk)	21	LOW	• Increased mortality in old growth • Increased growth in young stands • Weevil increasing problem for young Sx.

Plant communities

Regional biodiversity will decline. Climate change will affect plant community structure, with consequences for ecosystem function and resilience; it will likely lead to extirpation of some species in each region. **Extirpation risk arises from loss of climatically-suitable site conditions and from loss of old seral habitat, due to climate-induced disturbance.** Increased climate variability may lead to periodic extreme conditions that exceed species tolerances, even though most years remain suitable. Drying, warming and increased disturbance promote invasive species. Invasive species will also affect biodiversity, but the timing and magnitude of impact are difficult to determine.

In each region, climate projections show loss of suitable climate for current ecosystems (e.g., Table 11). For example, in the Nadina, two of three climate projections show a complete loss of the SBSdk and SBSmc2 climate envelopes and all three show a complete loss of the ESSFmc. About 20 to 50% of plant species in the Nadina face extirpation risk (i.e., species found in the Nadina that are not associated with projected climate envelopes; Price and Daust 2012). Future ecosystem function will also likely be compromised because many species associated with future climate envelopes do not occur in the Nadina (about 10% to 60%) and may be unable to migrate (tree migration may not keep pace with climate change and habitat fragmentation hinders movement; Pearson 2006; McLachlan et al. 2005; Scott et al. 2009). Depauperate plant communities may impair ecosystem function and be less able to resist weedy invasive species.

Due to increased disturbance related to climate change, the area of old seral forest in the Nadina could decline to roughly 15% to 60% of historic natural abundance (Daust and Morgan 2011). Species strongly associated with old forest face an uncertain chance of extirpation, ranging from low (at 60% of natural old forest remaining) to high (at 15% of natural old forest remaining). Species strongly associated with old forest and a particular climate envelope face compounded risk.

Table 11. Estimated climate-induced biodiversity impacts in the Nadina Case Study. Magnitude of change rated as low, moderate or high (L,M,H), with intermediate categories.

	Ecological Impact	Location	Magnitude
Habitat/Site Conditions	Suitable microclimate and soil conditions ↓	bogs	H
		dry sites	MH
		mesic to moist sites	LM
		hydroriparian (varies by stream size, grade)	L to H
	Old forest ↓ and mixed-age forest ↑	SBS	H
		ESSF	MH
	Old forest connectivity ↓	hydroriparian	M
		upland	H
Species interactions	Risk to specialized species and communities ↑	Overall	MH
	Altered successional pathways (trees)	Overall	LM
	Invasive species (e.g., hawkweed) ↑	SBSdk	H
		SBSmc	MH
		ESSF and BAFA	M

The biggest impact to biodiversity and ecosystem function will come from regime shifts. Some ecosystems will change their character and function completely as they pass a potentially irreversible threshold. Important ecosystem shifts in the study regions include old forest to young forest (due to disturbance), and forest to weedy species, forest to grassland, alpine to forest, wetland to forest, and forest to different forest (including conifer to deciduous). Many ecosystems will shift character, providing different levels or types of services, but more importantly, **some ecosystems will likely become dysfunctional, trapped in a brushy, weedy phase that provides few desired services.**

In W. Kootenay, the low elevation assessment unit in the North Subregion, currently dominated by moist and wet ICH, is highlighted as one of the ecosystems most vulnerable to a catastrophic regime shift (Table 12). The mid-elevation portion of the Mid Subregion is also highlighted. These systems are predominantly gap-replacement (NDT1) forested ecosystems that are projected (by both bioclimate shifts and fire dynamics) to potentially become frequent fire dominated systems (NDT 3 / 4). There is the potential for catastrophic regime shift in these systems, where ecological recovery stalls in a weedy, brushy phase. The low elevation unit in the South Subregion is also projected to shift to a hotter, drier climate – and from forested to grassland, but the implications here may be of less consequence since ecosystems already contain species that would help them adapt to the new climate with less disruption. These ecosystems however are also prone to invasive species, which have the potential to change the future course of development after a regime shift.

The climate change predicted for West Kootenays is of sufficient magnitude that initial intuition about vulnerability may be incorrect. Drier, southern valley bottoms are not necessarily the most vulnerable – even though they are closer to a moisture threshold to lose forested ecosystems and are predicted to do so – but some northern areas and higher elevations may also experience extreme warming, and may be less able to adapt to the change. Because of a lack of adapted species in the immediate vicinity these areas are considered more vulnerable.

Note that the W. Kootenay analysis only comments on ecosystem vulnerability – clearly a shift from forest to grassland at low elevation in the south is significant from the perspective of many values, but the ecosystem itself is less vulnerable to moving into a catastrophic regime shift.

Table 12. Ecosystem vulnerability and probability of non-catastrophic and catastrophic regime shifts in W. Kootenay. Exposure is rated for each of three climate scenarios: warm-moist, hot-wet and very-hot-dry (see Figure 3). Vulnerability is a function of exposure, sensitivity and ecosystem adaptive capacity. Based on Utzig and Holt 2012.

Subregion	Exposure*	Sensitivity*	Eco. adaptive capacity*	Vulnerability*	Regime shift?**	Catastrophic regime shift?***
North < 1000m	H – M - H	M	**L**	**VH – H – VH**	Very likely	Likely
1000 - 1500m	M – H – VH	**VH**	M	M – M – **VH**	Likely to Very Likely	Likely
1500 - 2000m	VL – VL – VH	**VH**	M	L – L – **VH**	Unlikely	Likely
> 2000m	L – VL – M	M	L	L – VL – L	Unlikely	Very Unlikely
Mid < 1000m	M – L – M	L	L	M – M – M	Likely	Unlikely
1000 - 1500m	H – H – VH	M	H	**H – H – VH**	Likely to Very Likely	About as likely as not
1500 - 2000m	H – M – VH	**VH**	M	**H – H – VH**	Likely to Very Likely	Likely
> 2000m	L – L – M	M	L	L – VL – M	Unlikely	Very Unlikely
South < 1000m	M – L – M	VL	VL	L – L – M	Likely to Very Likely	Unlikely
1000 - 1500m	L – VL – H	VL	**VH**	VL – VL – **H**	About as likely as not	About as likely as not
1500 - 2000m	M – M – H	M to **H**	M	L – L – M	Unlikely	About as likely as not
> 2000m	L – L – M	L	L	VL – VL – L	Likely	Very Unlikely

*Rated in classes of very low (VL), low (L), moderate (M), high (H) and very high (VH); all classes have same breadth.

**Probability classes: Very likely (0.9 to 1); Likely (0.66 to 1); About as likely as not (0.33 to 0.66); Unlikely (0 to 0.33); based on IPCC 2012.

***The likelihood of a regime shift being catastrophic **if** it occurs.

Projected Impacts to Hydrology and aquatic ecosystems

Impacts to aquatic ecosystems arise from climate-induced changes to hydrological regimes, including changes in the amount and timing of peak flows and low flows, increased evaporation and increased frequency and magnitude of storm events. Vegetation cover will respond to the changing climate and disturbance regime, affecting interception of rain and snow, evapotranspiration and ultimately hydrology. Projected impacts identified in case studies (Daust and Morgan 2011, Zielke and Bancroft 2009) include increased water temperature, increased erosion, decreased flow (particularly in Kamloops) and increased risk of landslides (e.g., Table 13). In the cooler, mountainous regions of each study area, increased winter temperatures, increased precipitation and reduced snowfall in the spring (because more precipitation falls as rain) will likely shift the hydrological regime from snowmelt driven to hybrid rain/snow driven, leading to more frequent rain on snow events and smaller spring snowpacks.

Table 13. Estimated, climate-induced impacts to hydrology and aquatic ecosystems in the Nadina Case Study. Magnitude of impact rated as low, moderate or high (L,M,H), with intermediate categories.

Impact	Location	Magnitude
Summer water temp ↑	temperature sensitive watersheds (similar in other watersheds)	H
Spawning bed quality ↓	overall	H
Overland flow ↑	overall	L
Peak flow ↑	western mountains eastern plateau	MH LM
Flood risk ↑ (but uncertain)	overall	L
Landslides and surface erosion ↑	overall	LM

Projected Impacts to Ecosystem services

Timber supply will likely decline and become more variable over time (Table 14). Projections of lower timber supply have been made for BC and Canada (CNRTEE 2011). In the Nadina, the effects of climate change on timber supply are highly uncertain, reflecting the trade-off between 1) increased growth (10 to 25%) due to longer, warmer growing seasons with increased carbon dioxide concentrations; and 2) increased unsalvaged mortality (10 to 30%) due to increased natural disturbance from insects, disease, fire and drought (Table 4; Daust and Morgan 2011). Effects of tree mortality on timber supply depend greatly on amount salvaged, but post-disturbance harvesting is difficult to predict for two reasons. First, as disturbance increases, leading to a larger proportion of young forest over the landscape, disturbed stands are more likely to be young and unmerchantable. Second, the periodic nature of disturbance can overwhelm harvesting capacity and/or market demand. The Nadina study estimated cumulative impacts to timber supply in two ways: by extrapolating expert opinion directly and by using a simulation model that better captured the interactions among factors identified by experts. Both approaches considered increased growth, increased mortality from insects, disease, fire and drought and green-tree and post-disturbance harvesting.

In Kamloops, stand mortality is expected to increase as conditions become hotter and drier through the summer, especially beyond 2050 (Zielke and Bancroft 2009). Growing stock will decline, with substantial losses occurring in pulses of mortality that coincide with warmer, drier climatic cycles. The area available for timber harvesting may decrease. Some currently forested subzones may shift towards treed grasslands, particularly sites on south aspects or shallow soils. Warmer and drier summer conditions could spur expansion of recreational property into timber-harvesting land. The second phase of the Kamloops work used climate-sensitive models of tree regeneration, growth and disturbance. The models suggest that aggregate timber supply can be maintained for several decades, although the supply from certain ecological zones may decline. Timber supply is unlikely to be maintained in the longer term (i.e., 100 years of simulation).

In the W. Kootenay, although a direct analysis of timber supply was not undertaken, significant areas are projected to shift from forested to grassland, and fire frequency is expected to increase in all regions – with obvious – but as yet unquantified - implications for future timber supply (Utzig and Holt 2012).

Harvesting will become more costly, reflecting extra costs related to salvage, replanting failed plantations and stand tending to increase vigour.

Table 14. Estimated climate-induced changes in ecosystem services relevant to the forest industry, prior to adaptation in the Nadina Case Study. Based on Daust et al. 2011.

Ecosystem service change	Magnitude
Timber supply ↓	M-H
Percent salvage ↑	H
Plantation failures ↑	M
Road access per m^3 ↑	L
Shutdown periods ↑	L

Changes to hydrology and aquatic ecosystems can influence ecosystem services (Daust and Morgan 2011, Zielke and Bancroft 2009):

- **Increased stream temperature poses risk to salmonids**. Studies of the Fraser River system indicate that increased water temperatures could pose a significant risk to salmon before the end of this century (Morrison et al. 2002). Increased water temperatures in low elevation streams within warmer subzones in Kamloops could become lethal for salmonids.

- **Increased rates of erosion and landslides can add sediment to streams**, affecting water quality, aquatic communities and spawning beds. Increased peak flows and landslides also pose risk to infrastructure, and will increase forest harvesting costs.

- **Declining water flows in the southern half of Kamloops may disrupt fish habitat and affect domestic and agricultural water use**. Declines in water quality and quantity may lead to water restrictions and more expensive treatment.

The Kamloops project combined managed forest values to assess the overall impact of climate change (Table 15).

Reserves at all scales used for biodiversity conservation will be negatively affected by climate directly and by related changes in disturbance events (e.g., Table 16). Impacts to wildlife habitat reserves vary by species (Zielke and Bancroft 2009). Caribou face altered snowpack conditions, influencing foraging success and predation risk. Snowpacks could develop harder surfaces due to more frequent freeze-thaw cycles, facilitating predation. In winter, moose depend on valley-bottom riparian areas in a range of subzones. In drier subzones, riparian forage may decrease if wetland area decreases. Conversely, forest openings resulting from increased disturbance can increase forage. Increases in moose populations can increase predator population, with consequences for other ungulates.

Table 15. Overview of impacts to managed values in the Kamloops TSA by subzone group. High refers to high likelihood of substantial negative impact; moderate refers to high likelihood of limited negative impact; low refers to expected minimal impact. Based on Zielke and Bancroft 2009.

SUBZONE GROUP	% of THLB	Overall Impact	THLB area	Stand productivity	Growing stock	Biodiversity and habitat	Fish	Water	Valued plants	Urban Interface	Visual quality
Dry Subzones with Pli	28	MOD-HIGH	M-H	H	H	H	H	M-H	M-H	M-H	M
Dry with Fd & Py	10	HIGH	H	H	H	H	H	H	M-H	H	M-H
ICH-IDF Transition	26	MOD-HIGH	M-H	H	H	M-H	H	M-H	M	M-H	M-H
Plateau / High Elev	15	MOD	L	L	M	M-H	M-H	M	M	L-M	L-M
Cool/Cold & Wet	21	LOW-MOD	L	L	L	M?	L	M-H?	L	L	L

Table 16. Estimated climate-induced impacts to ecosystem services in the Nadina Study Area, prior to adaptation. Based on Daust et al. 2011.

Ecosystem Service Impact	**Magnitude**
Simplified communities ↑	MH
Extirpation ↑	H
Ecological function/ resilience ↓	M

Vulnerability

The overall vulnerability of the managed forest is a function of projected impacts and the projected adaptive capacity of ecosystems and forest management systems (see next sections). Vulnerability describes the net impact after adaptation. Baseline vulnerability accounts for ecological adaptation; best-case vulnerability accounts for all possible management adaptation; likely vulnerability accounts for likely management adaptation, when barriers to adaptation are considered.

Management actions can reduce impacts within limits. Kamloops and Nadina estimated the decrease in vulnerability due to all potential management actions (best-case vulnerability) (Daust and Morgan 2011, Zielke and Bancroft 2009). Applying all potential management actions can only reduce impacts partially and some impacts cannot be lessened (e.g., Table 17-19). Directly combating disturbance agents is likely a costly, losing battle given a fundamental shift in disturbance regimes within susceptible forests. Fire control will be necessary to protect important values, however.

Currently, we do not have the capacity to adapt to climate change. Kamloops rated likely vulnerability, considering management response (Table 19). When the current likelihood of implementing management actions is accounted for, management adaptive capacity has a minor influence on initial estimates of impact. All studies identified major barriers to adaptation that limit adaptive capacity.

Table 17. Reduction in forest-related impacts in the Nadina due to all potential management responses (adaptation). Based on Daust et al. 2011.

Ecological Change	Benefit of adaptation (baseline vulnerability to best-case vulnerability)
Tree growth ↑	LM → M
Bark beetle mortality ↑	H → LM over time*
Diseases of young stands ↑	MH → M
Fire mortality ↑	H → H**
Maladaptation due to climate-stress ↑	H → H
Forest-scale resilience ↓	M → M

*partly due to changes in forest age classes

**subject to assumptions about frequent ignitions in dry years overwhelming suppression effort

Table 18. Reduction in hydrological impacts in the Nadina due to all potential management responses (adaptation). Based on Daust et al. 2011.

Ecological Change	Benefit of adaptation (baseline vulnerability to best-case vulnerability)
Summer water temp ↑	H → H
Spawning bed quality ↓	H → MH
Overland flow ↑	L → L
Peak flow ↑	MH → M
Flood risk ↑ (but uncertain)	L → L
Landslides and surface erosion ↑	LM → L

Table 19. Estimates of baseline vulnerability (i.e., impacts without adaptation), best-case vulnerability (i.e., with all potential management responses) and likely vulnerability (i.e., with only likely management responses) for subzones in the Kamloops TSA, given the current adaptive capacity of the management system. Based on Table 6.1 in Zielke and Bancroft 2009.

Subzone Group	Baseline Vulnerability	Best-case Vulnerability	Likely Vulnerability	Area (%)
Dry with lodgepole pine	Mod to High	Low to Mod	Mod to High	28
Dry with Douglas-fir and ponderosa pine	High	Low to Mod	Mod to High	10
Transitional: cedar-hemlock to Douglas-fir	Mod to High	Low to Mod	Mod to High	26
Transitional: low elevation to plateau or high elevation	Moderate	Low	Moderate	15
Cool and wet	Low to Mod	Low	Low	21

Ecological Adaptive Capacity

Some ecosystems are more able to adapt to changing climatic conditions than others. High vulnerability occurs where ecosystems are not already partially adapted to projected disturbance regimes. For example, increased fire weather is less important in ecosystems where past fire disturbance has reduced fuel levels, or where fire-adapted tree species are present. Shifts from forest to native grassland cannot occur easily where there are no native grass seed sources, leading to an increased risk of invasive species. Recovery from large disturbances reflects ecosystem resilience, which depends in part on biodiversity. For example, increased fire frequency favours fire-adapted species and increased drought favours grasses, thus the proximity of these species determines long-term impacts.

The proximity of a system to some critical threshold today can affect its adaptive capacity – for example, dry ecosystems can have low adaptive capacity being close to the moisture threshold already. In the Nadina, within the SBS, dry sites are predicted to be least resilient: water deficits in the growing season are expected to increase in drier subzones and sites. In dry subzones in Kamloops, abundant lodgepole pine in developing young stands increases vulnerability. Climate will become less favourable for the pine stands over time. Beyond 2050, these stressed mid-aged lodgepole pine stands are projected to be highly susceptible to mortality due to a range of factors.

The regeneration stage is most exposed directly to weather and climatic factors and most susceptible to competition from species that could support a regime shift (e.g., forest to grassland or weeds). Disturbance has a large influence on the timing of regime shifts.

Management Adaptive Capacity

Adapting management practices to a changing climate has the potential to reduce the undesirable impacts of climate change. The first step in assessing adaptive capacity asks what potential management responses exist to reduce impacts of climate change so as to better achieve sustainable management goals. The second step asks how likely managers are to implement feasible changes and what "barriers to adaptation" prevent sensible management responses.

Although studies varied in focus and in the way in which they rated vulnerability, the resulting management recommendations were similar, likely because ecosystems face similar types of ecological changes (e.g., tree mortality for multiple reasons) and because the set of potential management actions is limited.

All studies identified similar barriers to adaptation that increase vulnerability, unless overcome. Currently management adaptive capacity is weak.

The next section of this report summarizes potential management responses to climate change. The following section discusses barriers to adaptation and recommends policy to remove barriers and support adaptation.

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