Uncertainty in adaptation to climate change in forest management

Emina Krcmar[1], Shirley Mah[2], Gordon Nigh[2], Christine Fletcher[2] and G. Cornelis van Kooten[3]

Report from FFESC project 2009-010

[1]University of British Columbia, Vancouver, BC
[2]BC Ministry of Forests, Lands and Natural Resources Operations, Victoria, BC
[3]University of Victoria, Victoria, BC

Executive Summary

The purpose of this study is to develop a conceptual framework to support decision making in forest planning under uncertainty related to climate change. There are many possible climate change scenarios, but no single scenario can be recommended as the "best." This creates conditions of "deep" uncertainty for decision making. Among various concepts developed to address decision challenges under deep uncertainty, we employ one based on robustness as a criterion for evaluation. Rather than looking for optimal plans assuming that future conditions are known, the robust approach searches for "good-enough" plans under a range of unknown future conditions.

For the Quesnel study area, the overall objective of strategic forest planning is to provide a balance between several competeing interests under uncertainties related to climate change. To achieve this overall objective, we developed multi-criteria forest planning models that address both a timber supply goal and a diversity-related goal for tree species in the region.

The timber-supply goal was formulated as maximization of a period harvest while maintaining a stable harvest flow over time. The first step in formulation of the diversity-related goal is to define the landscape-level species composition targets. In the absence of an established methodology, we define the species targets in terms of the species projected frequency of occurrence under several climate change scenarios. The ecological goal is then formulated as minimization of an average deviation of the modeled species frequency of occurrence from the target species frequency of occurrence.

In this report we present, assess and compare the outcomes of forest planning models under two renewal options: (i) the "status quo" option that preserves pre-harvest species composition at the landscape-level, and (ii) another that promotes forest resilience by allowing changes to the species composition. The second renewal option is introduced in forest management planning as means for adapting to changing climate.

Assuming the status quo renewal option and solving the multi-criteria forest planning model for each of the individual climate scenarios produced a set of alternative forest management plans. Under the conditions assumed, no "robust" plan was identified. In other words, under the current renewal option, there are no forest plans that achieve both the timber supply and landscape-level species composition targets for all of the climate change scenarios considered. The examination of criteria values for the forest plans under the status quo renewal option provided insights into climate conditions to which forest plans were most vulnerable. This examination allows for reducing the initial set of climate scenarios. In the next stage, the multi-criteria forest planning model was solved for the individual climate scenarios from the reduced set under the assumption of an adaptation renewal option that promotes forest resilience by changing the landscape-level species composition. After analyzing criteria values for the forest plans generated under the adaptation renewal option and the reduced set of climate change scenarios, we identified two potential robust plans with criteria values good-enough for all climate scenarios from the reduced set. Selecting the forest management plan for implementation will depend on other factors that

are beyond the scope of this project. Stakeholders may request repeating the decision process with additional and/or different ecological, economic and social goals and criteria.

All results of the case study are valid only under the given assumptions and represent relative rather than absolute values. For example, if the assumptions about the reduced growth and yield changed or if the species targets varied, the criteria values for the forest plans generated would differ.

Forest management decisions under climate change should be made in accordance with thorough analyses of the criteria values across different climate change scenarios and associated plans. Note that this study addressed only the timber supply and landscape-level species composition criteria for evaluating the plan performance. The incorporation of other performance measures such as additional ecological, economic and social criteria may result in very different decisions.

A special interest for decisions makers and policy makers is that the proposed framework is:

- *Iterative* as forest plans are generated iteratively over time
- *Interactive* as stakeholders' input can be included into the model development and into the selection of robust forest plans
- *Balancing* since the framework includes multiple goals allowing for assessment of trade-offs among competing interests
- *Deals with uncertainty* by including a range of future climates into decision process
- Provides *robust forest plans* that are good-enough under the worst case climate scenarios

There is a clear need for further large-scale, longer-term studies of forest management under uncertainty related to climate change. This study also illustrates a need for educating the public and stakeholders about deep uncertainty and approaches to deal with it.

Acknowledgements

Funding for this project was provided by the Future Forest Ecosystem Scientific Council. Administrative support was provided by the Department of Forest Sciences, University of British Columbia in Vancouver. We thank Phil Winkle for providing a link to the Quesnel Timber Supply Mitigation Committee, Tongli Wang for generating climate variable/BEC zone projections for the project study area, Arnold Moy for GIS support and Linda Wong for computational help.

Contact

Emina Krcmar
University of British Columbia
Department of Forest Sciences
2424 Main Mall, Vancouver, BC V6T 1Z4
Tel: (604) 822-8949
Email: ekrcmar@mail.ubc.ca

Table of Contents

List of Tables

List of Figures

Appendix: List of Tables

Introduction

Managing forests under climate change is a difficult task largely because of the complexities and uncertainties involved. Uncertainty about climate change is compounded by the impacts that climate change has on forests and forest ecosystems, and on the forest sector and forest-based communities. Further, it raises questions whether current management objectives are appropriate to future changes.

The basic assumption of this study is that there is uncertainty in the timing, location and magnitude of future climate change, that impacts of climate change on biophysical forest components are uncertain, that little is known about socio-economic effects, and, finally, that stakeholders' attitudes towards and response to climate change are uncertain. Much has been written about uncertainty related to climate change (Toth 2000, Lemprière et al 2008, Metsaranta et al 2011), but uncertainties are rarely explicitly considered in real-life climate adaptation planning (Preston et al. 2011). There are many possible climate change scenarios, but no single scenario can be recommended as the "best," which is a source of great uncertainty. While some uncertainties related to climate change will decrease over time with better information available in the future, other uncertainties will remain and become even deeper, but decisions will nevertheless have to be made.

Most traditional decision support tools in forest management are based on the assumption that all parameters are known with certainty. This assumption implies that it is possible to generate and compare the outcomes for a range of feasible plans and then select one plan according to some evaluation criteria. The rare decision support tools that address uncertainty in forest planning and management assume that a probability distribution of uncertain parameters is provided and that a plan with the highest expected utility of the outcomes is selected.

In this study, we develop a conceptual framework for forest management decisions under climate change using the Quesnel forest district as a case study. For the initial analyses in the context of the Quesnel study area, a robust plan is defined as the one that keeps all criteria values within certain limits under projected scenarios of climate change.

Methodology

Multi-Criteria Decision Analysis

A forest manager searches for management plans that balance multiple goals. The success of a plan in accomplishing different goals is measured using social, economic and environmental indicators. Let a (performance) criterion of plan *x* be denoted by $g^k(x),\ k \in K$. The set X of feasible forest management plans is generated under constraints on land availability, harvest, regeneration, and silviculture activities, the initial and terminal inventories, and the non-negativity constraints. A planning problem can then be formulated as:

$$Max\{g^k(x),\ k \in K\} \text{ , subject to } x \in X \qquad \text{(MC)}$$

where *x* is a plan from a set *X*. The use of maximization does not reduce the application of the (MC) formulation as minimization is directly converted into maximization by

$$Min\, g(x) = Max[-g(x)] \text{ , subject to } x \in X$$

A methodological approach designed for developing and evaluating alternative plans while accounting for multiple, and often conflicting, goals is referred to as multi-criteria decision analysis (MCDA). More narrowly MCDA can be defined as a tool to help decision-makers identify plans that maximize their satisfaction across several criteria. One way to solve a MCDA problem is to construct an aggregate criterion to be optimized. A distance between the current criteria values and the target values can be used as the aggregate criterion (Belton and Stewart 2001).

In real life problems, multiple criteria are usually in conflict and there are no feasible plans that achieve simultaneously the highest values for all criteria. Nevertheless, an *ideal* point that consists of the best criteria values would be a natural planning target. For any criterion *k*, the upper bound $g_k^* \geq g_k(x),\ x \in X$ can be used as the best criterion value $g_k^*,\ k \in K$, while the lower bound $g_{k*} \leq g_k(x),\ x \in X$ is used as the worst criterion value $g_{k*},\ k \in K$. The best criteria values $g_k^*,\ k \in K$ are incorporated into an *ideal* vector g^* and the worst criteria values $g_{k*},\ k \in K$ into a *nadir* vector g_*. Both ideal and nadir points are used to construct the aggregate criterion in terms of the normalized distance from the desired reference point. Let $d_k(x) = \dfrac{g_k^* - g_k(x)}{g_k^* - g_{k*}},\ k \in K$ denote the distance of the current criterion value from its best value, normalized by the range of values $g_k^* - g_{k*}$. The plan *x** that minimizes the weighted sum of distances $d_k(x)$ is a solution to (MC). In other words, *x** is a solution to the program $\underset{x\in X}{Min}\, S(w,x) = \underset{x\in X}{Min} \sum_{k\in K} w_k d_k(x)$ where weights $w_k \in (0,1),\ k \in K; \sum_{k\in K} w_k = 1$ reflect the relative importance of the criteria.

Dealing with the climate change uncertainty

One of the assumptions of the (MC) model is that all parameters are known with certainty. When climate change is explicitly taken into account, the model can be reformulated as

$$Max\{g_c^k(x),\ k \in K\} \text{ , subject to } x \in X,\ c \in C \qquad \text{(MC\_C)}$$

Parameter *c* takes the values across the set of climate change scenarios *C*. All other parameters and variables are defined as for (MC). Although in theory the set of climate change scenarios *C* is infinite and the set of associated model parameters continuous, we assume that *c* takes discrete values from a finite set *C*.

The current climate projections are subject to large uncertainties (Refsgaard et al. 2012). Forest management decisions under climate change are especially hard to make because of uncertainties related to climate projections as well as uncertainties inherent to forest ecosystems. These decisions are also influenced by a range of stakeholders with different interests and different risk perceptions.

For many years, uncertainty has been recognized by UN Intergovernmental Panel on Climate Change (IPCC) as important (Moss and Schneider 2000; IPCC 2007). The complex nature of uncertainty in the climate-related decision-making is encapsulated by Schneider (2003):

> "… the climate change debate is characterized by deep uncertainty, which results from factors such as lack of information, disagreement about what is known or even knowable, linguistic imprecision, statistical variation, measurement error, approximation, subjective judgment, and disagreement about structural models, among others. … Moreover, climate change is not just a scientific topic but also a matter of public and political debate, and degrees of uncertainty may be played up or down (and further confused, whatever the case) by stakeholders in that debate."

In all management decisions the negative impacts of uncertainty can be reduced with the robust action plans that try to avoid disasters under the potentially worst case climate conditions (Dessai and Hulme 2007). The concept of robustness is closely related, but not restricted, to the notions of flexibility, stability and sensitivity (Roy 2010). In this report, we limit the complex notion of robustness to the concept of satisficing, a term used to describe a cross between satisfying and sufficing (Simon 1957). Rather than looking for optimal plans assuming that future conditions are known, a robust approach searches for satisficing or "good-enough" plans under a range of unknown future conditions. Robust decisions always reflect some degree of pessimism, resulting in reduced levels of the objective (Roy 2010; Groves and Lempert 2007). Robust decision making is not a specific technique but, rather, an iterative and interactive framework that helps identify and evaluate potential robust plans. The best plans relative to a certain measure of robustness are called robust plans (Roy 2010). Commonly used robustness measures are absolute robustness, absolute deviation and relative deviation (Roy 2010). Under the concept of absolute robustness, the robust plan in this report is defined as a plan that maximizes the criteria values for the worst scenario.

Frameworks for forest management planning under climate change

Under climate change, there is a need for major changes in the way forest renewal is conducted in British Columbia (Campbell et al 2009). Adaptation to climate change encompasses management activities that aim to reduce the potential negative impacts of climate change and to capture opportunities arising from the potential positive impacts of climate change. Strategic forest planning that considers multiple timber and non-timber values should also include adaptation to climate change.

Both the physical parameters of climate change and the response of forest ecosystems over the next several decades are highly uncertain. As a consequence, managers are faced with a situation in which there is no single optimal forest plan. They need a flexible framework for designing strategic forest plans that take climate change into consideration.

Strategic forest management plans could be designed following the established steps of adaptive management framework (Taylor et al. 1997).

Framework for (strategic) forest planning under climate change

Generate forest management plans for the current planning horizon

Step 1: Data collection

Step 2: Define goals, criteria, objectives and targets

Step 3: Generate forest management plans that balance multiple goals

Step 4: Select plan(s) that achieve "good-enough" outcomes for all climate conditions considered

Step 6: Implement the plan(s)

Step 7: Monitor

Step 8: Evaluate

Next planning horizon

Go to Step 1.

The plan needs to be evaluated on a short-term basis (i.e. 3-year or 5-year) using specific assessment criteria based on the initially formulated goals.

Further we provide details of Steps 1 to 4:

Step D1*i*: Biophysical, social and economic data; select climate change scenarios $C=\{c_i\}$, $i \in I$

Step D1*ii*: Select an adaptation option $a \in A$

Step D2*i*: Define criteria $G=\{g^k\}$, $k \in K$

Step D2*ii*: Set targets $Q=\{q^k\}$, $k \in K$

Step D2*iii*: Formulate the multiple-criteria model (MC_C)

Step D3*i*: Generate forest plans, $F_c=\{f_c\}$, $c \in C$ by solving (MC_C).

Step D3*ii*: Determine the criteria values $\{g^k(f_c)\}$ for each $g^k \in G$ and each $f_c \in F_c$.

Step D4*i*: Are there forest plans $f_c \in F_c^1 \subseteq F_c$ so that $g^k(f_c) \geq q^k$, for all $c \in C$?

Step D4*ii*: Yes. $F_c^1 \subseteq F_c$ is the set of robust forest plans for target Q. STOP.

Step D4*iii*: No. Are there forest plans $f_c \in F_c^2 \subseteq F_c$ and climate scenarios $c \in C_{op} \subseteq C$ so that $g^k(f_c) >> q^k$?

Step D4iv: Yes. $C_{op} \subseteq C$ is the set of climate scenarios that provide opportunities for plans $f_c \in F_c^2$.

Step D4*v*: No. Are there climate scenarios $c \in C_{vl} \subseteq C$ $c \in C$ so that $g^k(f_c) < q^k$ for all forest plans $f_c \in F_c$?

Step D4*vi*: Yes. $C_{vl} \subseteq C$ is the set of climate scenarios that plans $f_c \in F_c$ are vulnerable to. Set $C = C_{vl}$.

Step D4*vii*: Have all the adaptation scenarios been applied?

Step D4*viii*: Yes. No robust solution for the target set Q. GOTO Step *D4x*.

Step D4*ix*: No. New adaptation scenario *a*. GOTO Step *D2i*.

Step D4*x*: Can the targets be relaxed?

Step D4*xi*: Yes. Relax the targets, next Q. GOTO Step *D2ii*.

Step D4*xii*: No. GOTO Step D4*vii*.

The forgoing framework allows for gradual adaptation and learning about climate change and its impacts on forest ecosystems. Although the strategic forest plan, including adaptation to climate change, is developed for a long planning horizon, implementation addresses only parts of the landscape scheduled for harvesting and renewal in the first few years of the horizon. Implementation of the plan is to be monitored and evaluated after 5 years (or earlier). At this stage, the whole process is repeated using the newly acquired knowledge about climate change and the effects that arise when the plan has been implemented.

Forest planning under climate change in the Quesnel study area

The Quesnel Timber Supply Area (TSA), located in the central interior of British Columbia, covers approximately 2 million ha (Figure 1, BC MFR 2007a). The forest industry is the most important sector in the area, with two pulp mills, five large sawmills, a plywood plant, a medium-density fibreboard plant and several smaller, value-added manufacturing operations.

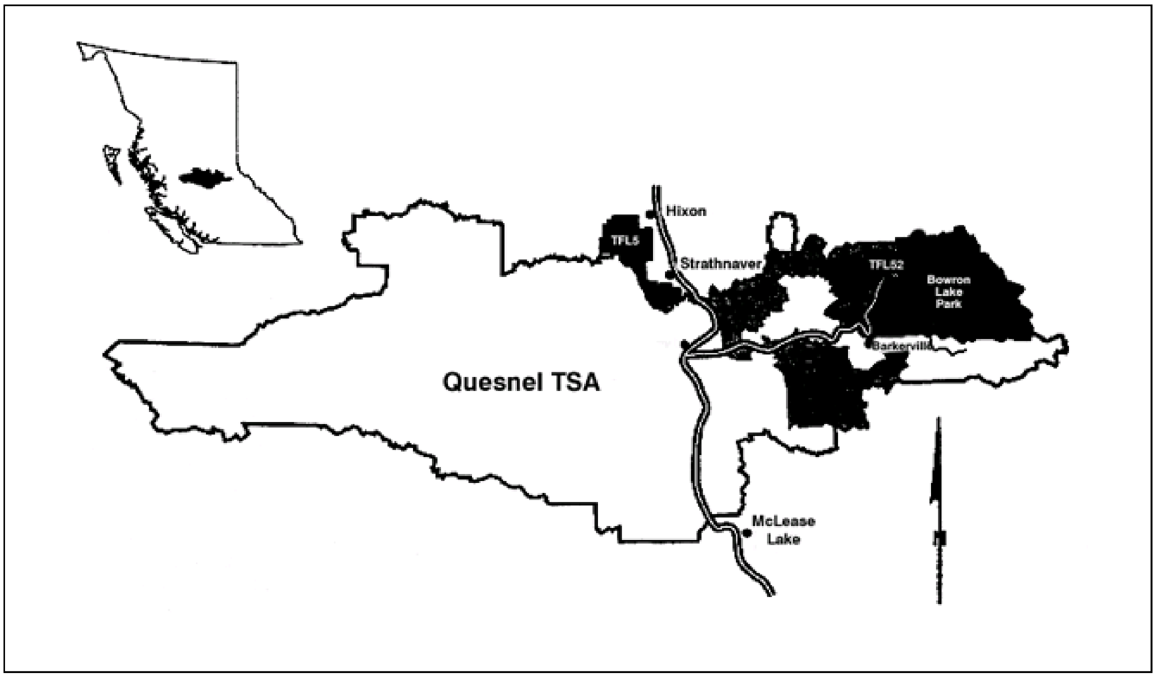

Figure 1. Map of the Quesnel TSA

The Quesnel community has recently experienced a boom in wood processing, mainly due to a large amount of mountain pine beetle infested wood that had to be processed. Forest planning over the long term needs to address timber supply concerns as well as those for the forest ecosystems and aim to reduce the potential negative impacts of climate change.

One way to reduce these impacts is by facilitating the shifting of species distributions and composition. Under climate change, species distribution and composition will change mainly by natural regeneration after harvesting and natural disturbances. To overcome the lower natural establishment rate of certain species, planting rules can be changed to allow for modifications of the existing species distribution and composition.

The success of forest management plans in accomplishing different goals can be measured using social, economic and ecological criteria. For the Quesnel study area, the overall objective of strategic forest planning is to provide a balance between several competeing interests under uncertainties related to climate change. The timber supply goal addresses the adequate supply of fiber for mills and satisfying contractual obligations with the Province and industry. The ecological goal addresses the landscape-level species composition (Mah et al 2012). The goals, criteria and objectives of strategic forest management planning under climate change for the Quesnel study are presented in Table 1.

Table 1. Goals, criteria and objectives of strategic forest managemnt planning under climate change for the Quesnel study

Goal	**Criterion**	**Objective**
Achieve high period harvest over time	(average) PrVol (m3)	Max PrVol
Maintain stable harvest flow	(average) FlowDev (m3)	Min FlowDev
Meet species occurrence frequency target	(average) SpFreq (%)	Max SpFreq

To formulate a strategic planning model, forest cover attributes (e.g., species, site index, age) are aggregated into strata $m \in M$. If some forest characteristics are to be emphasized in the model, M can be partitioned accordingly. Denote by M_s a set of management strata for selected species $s \in S$. Let p be a management treatment from the set of treatments P_{mt} appropriate to stratum m in period t, where $t \in T$ is a decadal period in a planning horizon. Management treatments include various combinations of harvest and reforestation activities. A decision variable $x = x_{mpt}$ represents the area of forestland in stratum m managed by treatment p in period t.

The timber-supply goal is accomplished through the even flow of harvest volume over time coupled with maximization of the period volume because this drives fiber supply as high as possible.

Let v_{cmpt} (m^3/ha) be the merchantable volume from a hectare of stratum m managed by treatment p in period t under assumed climate scenario c.

Denote by $Vol_{t,c}(x)$ the harvest volume (m^3) in period t and by $FlowD_c(x)$ the average deviation from the stable flow, both under assumed climate scenario c.

Period harvest:

$$Vol_{t,c}(x) = \sum_{m \in M} \sum_{p \in P_{mt}} v_{cmpt}\, x_{mpt}$$

Average harvest flow deviation:

$$FlowD_c(x) = \underset{t}{avg}\, | Vol_{t+1,c}(x) - Vol_{t,c}(x) |$$

The ecological goal addresses the landscape-level composition of certain species from set S. The related criterion is formulated as the average deviation of the modeled occurrence frequency $F_{tcs}(x)$ for plan x from the target occurrence frequency TF_{tcs} of species $s \in S$ in period t under climate scenario c. Both the modeled occurrence frequency and the target frequency of occurrence of species are expressed as portions (%) of the study area.

Average deviation from target frequency of occurence: $TreeD_c(x) = \underset{t,s}{avg} \mid F_{t\,c\,s}(x) - TF_{t\,c\,s} \mid$

When the target frequencyof occurence of species is fully achieved, $TreeD_c(x)$ is zero. In all other cases, $TreeD_c(x)$ reflects the average deviation from the target frequency. If the ecological goal is to achieve the target occurrence frequency, the criterion $TreeD_c(x)$ is to be minimized.

The multi-criteria model (MC_C) is formulated as

(FREQ) Min $TreeD_c(x)$

(VOL) Max $Vol_{t,c}(x)$

(EVEN) Min $FlowD_c(x)$

subject to $x \in X,\ c \in C.$

The set X consists of the technical constraints on land availability, harvest, renewal, and silviculture activities, the initial and terminal timber inventories, and the non-negativity constraints. Here c is a climate related parameter and C is a set of climate change scenarios.

Model implementation

Approximately 1 million hectares of the Quesnel TSA are classified as the timber harvesting land base (THLB). The THLB is divided into strata according to biogeoclimatic (BEC) zones, tree species, site index and age classes. The forest resources include five dominant species: interior Douglas-fir, spruce (except black spruce), lodgepole pine, some western cedar, and deciduous species (mainly aspen) growing on poor, medium and good productivity classes. Land base classification details are presented in Tables 2 and 3.

Table 2. Quesnel TSA land base classification

Land base classification	Area (ha)	Percentage of total land base area
Total land base area	2,077,267	100%
Non-contributing forest landbase	330,096	15.9%
Timber harvesting landbase (THLB)	992,372	47.8%

Table 3. Tree species across Quesnel THLB[a]

Species	THLB area (ha)	Percentage of THLB
Fir	49,469	4.98%
Spruce	139,821	14.09%
Pine	758,741	76.46%
Cedar	571	0.06%
Deciduous	43,769	4.41%
Total	992,372	100%

[a] Source: Cortex et al. (2006)

To reduce the potential negative impacts of climate change different forest renewal options may be applied to facilitate a shift of species distribution and a change of species composition. For the case study, two renewal options are analyzed. The status quo option A0 is the one currently employed for the Quesnel THLB, with regeneration of harvested stands that preserves pre-harvest species frequency of occurrence. Another renewal option addresses forest resilience to changing climate by promoting changes to the species composition (BC MoFR 2008).

For each of the renewal options, we designed models that determine the area and the period of application of harvest/regeneration treatments to meet the objectives over a 100-year planning horizon divided into decades.

Management assumptions used in developing models for the Quesnel TSA are based on two documents: a consulting report developed for the Quesnel TSA (Buell et al. 2006) and silviculture recommendations obtained from Phil Winkle (June, Sept 2010). The two silviculture treatments considered are natural regeneration and planting. The treatments differ in the landscape–level species composition under different renewal options (Table 4).

Table 4. Landscape-level renewal assumptions

		Renewal option	
Treatment	**Description**	**A0**	**A1**
Natural	all deciduous stands and poor coniferous stands after harvest/natural disturbance	pre-harvest species frequency of occurrence over the landscape is maintained	pre-harvest species frequency of occurrence over the landscape is maintained
Planting	all medium and good coniferous stands after harvest/natural disturbance	pre-harvest species frequency of occurrence over the landscape is maintained	pre-harvest frequency of occurrence of species may change to meet the target frequency of occurrence of species and timber supply goals

In addition to the renewal of fir and spruce stands by preserving the pre-harvest composition, we added the possibility to plant species that are adaptable to climate change.

Table 5. Stand- level renewal assumptions[a]

Species/Site	Regeneration delay (years)	Regeneration method
Fir (good, medium)	2	Plant
Spruce (good, medium)	2	Plant
Pine (good, medium)	2	Plant
Cedar (good, medium)	2	Plant
Fir, Spruce, Pine (poor)	2	Natural
Deciduous (all)	2	Natural

[a] Source: Buell et al (2006)

The climate change scenarios set *C* consists of the eleven scenarios presented in Table 6. The "no change" scenario is used to create reference levels for the outcomes, while the remaining ten scenarios are those recommended for application in BC (Spittlehouse and Murdock 2010). The 'no change' climate scenario is based on the assumption that the average climatic conditions observed for 1961-1990 will prevail in the future.

Table 6. Climate change scenarios

c	Model	Emissions	Run	Description
0				No change
1	CGCM3	A2	4	Warm and wet
2	HadCM3	B1	1	Cool and moist
3	HadGEM	A1B	1	Hot and dry
4	GFDLCM21	A2	1	
5	CSIROMK30	B1	1	
6	NCARCCSM30	A1B	5	
7	GISS-EH	A1B	3	
8	CGCM3	A2	5	
9	ECHAM5	B1	1	
10	MRICGCM232A	B1	5	

The projected BEC climate envelopes across Quesnel THLB for the climate change scenarios are presented in Table 7. All projections are made for the selected eleven climate change scenarios and three projection periods 2020, 2050 and 2080.

Table 7. Projected area (ha) of BEC zone climate envelopes across Quesnel THLB

c	Projection period	BG	BWBS	CWH	ESSF	ICH	IDF	IMA	MH	MS	PP	SBPS	SBS
0	*2020/50/80*	0	0	0	43574	13817	8830	0	0	174613	0	429247	322289
1	*2020*	0	0	1714	15204	140788	178978	0	0	18629	0	174026	463034
1	*2050*	52	0	4416	1195	150170	355466	0	0	14758	839	10632	454845
1	*2080*	0	0	4363	52	422504	521967	0	0	11132	0	0	32355
2	*2020*	0	0	0	10478	80721	25912	0	0	9271	157	363111	502721
2	*2050*	0	103	0	416	99334	20699	0	0	1874	52	115608	754286
2	*2080*	0	16817	0	104	65655	58900	0	0	934	262	23727	825972
3	*2020*	0	0	0	1714	65665	86963	0	0	470	943	236988	599628
3	*2050*	0	0	0	0	79735	775916	0	0	1198	102580	0	32942
3	*2080*	0	0	0	0	158584	560955	0	0	0	238598	0	34234
4	*2020*	0	0	0	12972	70579	106552	0	0	15273	2097	220370	564528
4	*2050*	0	0	0	3636	79838	238018	0	0	9010	17600	84802	559469
4	*2080*	0	0	0	0	106002	773112	0	0	23137	83475	0	6644
5	*2020*	0	0	0	31201	15733	16219	0	0	83274	0	505829	340113
5	*2050*	0	0	0	7990	57214	25743	0	0	2190	105	368566	530563
5	*2080*	0	0	0	10434	70456	93290	0	0	1406	52	306484	510248
6	*2020*	786	0	0	7321	65275	201922	0	0	417	52	214948	501649
6	*2050*	1257	0	51	208	95590	436058	0	0	0	4237	3436	451532
6	*2080*	52	0	0	0	98928	423028	0	0	0	7956	1668	460740
7	*2020*	840	0	0	22443	21378	94142	0	0	76210	0	363585	413776
7	*2050*	2310	0	0	9546	51469	240355	0	0	109661	1204	279815	298012
7	*2080*	210	516	0	936	68701	613969	0	0	120653	21716	44771	120900
8	*2020*	0	0	519	26962	93263	131689	104	0	16710	0	246275	476848
8	*2050*	0	0	4679	7786	363140	298048	0	52	4581	0	37637	276449
8	*2080*	0	0	4623	0	516071	408923	0	0	3646	53	0	59057
9	*2020*	52	0	0	25933	24772	32543	0	0	81108	0	441627	386337
9	*2050*	0	0	104	22607	123780	95957	208	0	12240	0	295926	441549
9	*2080*	0	0	104	22607	123780	95957	208	0	12240	0	295926	441549
10	*2020*	0	0	0	59069	19286	16890	0	0	61240	0	206184	629699
10	*2050*	0	0	0	19857	24967	19246	0	0	31299	0	364462	532540
10	*2080*	210	0	52	16244	104263	131911	0	0	1356	0	233974	504363

Figure 2 illustrates the current distribution of BEC zones across the Quesnel THLB; Figures 3, 4 and 5 illustrate projected distributions of BEC zone climate envelopes for the selected climate change scenarios and the respective projection periods 2020s, 2050s and 2080s. All projections presented in Table 7 and illustrated by Figures 3, 4 and 5 were generated by Climate BC/WNA (Wang 2011).

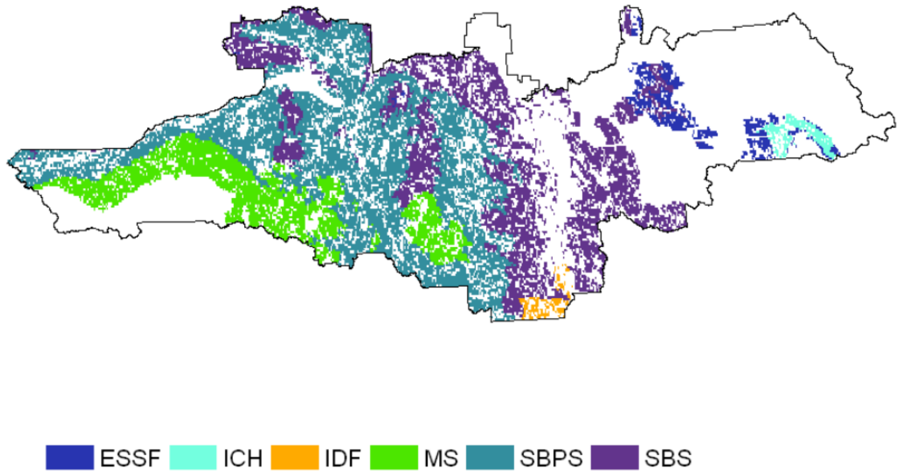

Figure 2. Current BEC zones across Quesnel THLB

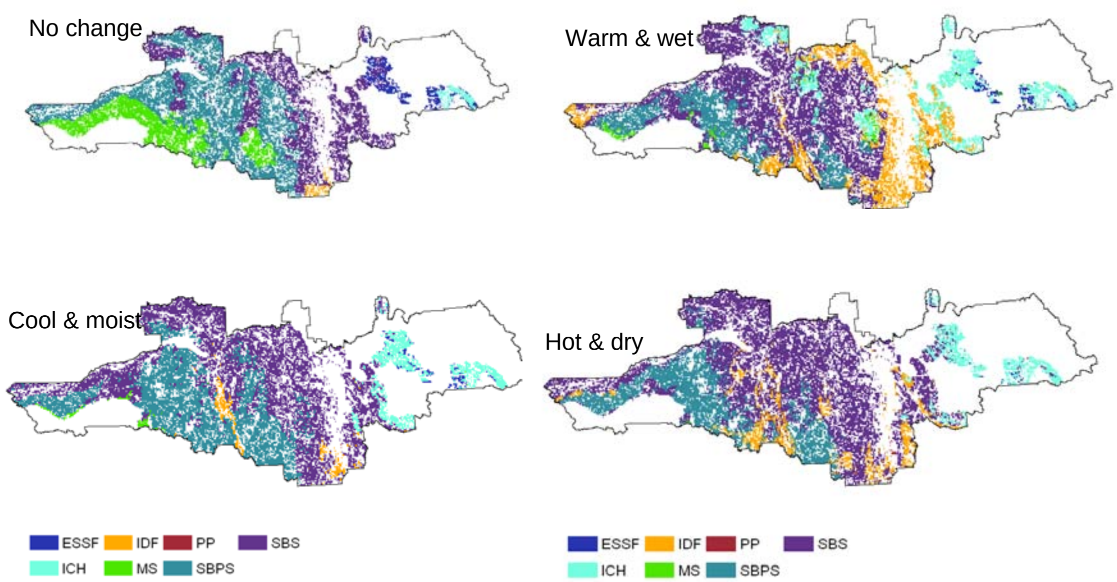

Figure 3. Projected climate envelopes for BEC zones across Quesnel THLB in 2020s for selected climate change scenarios

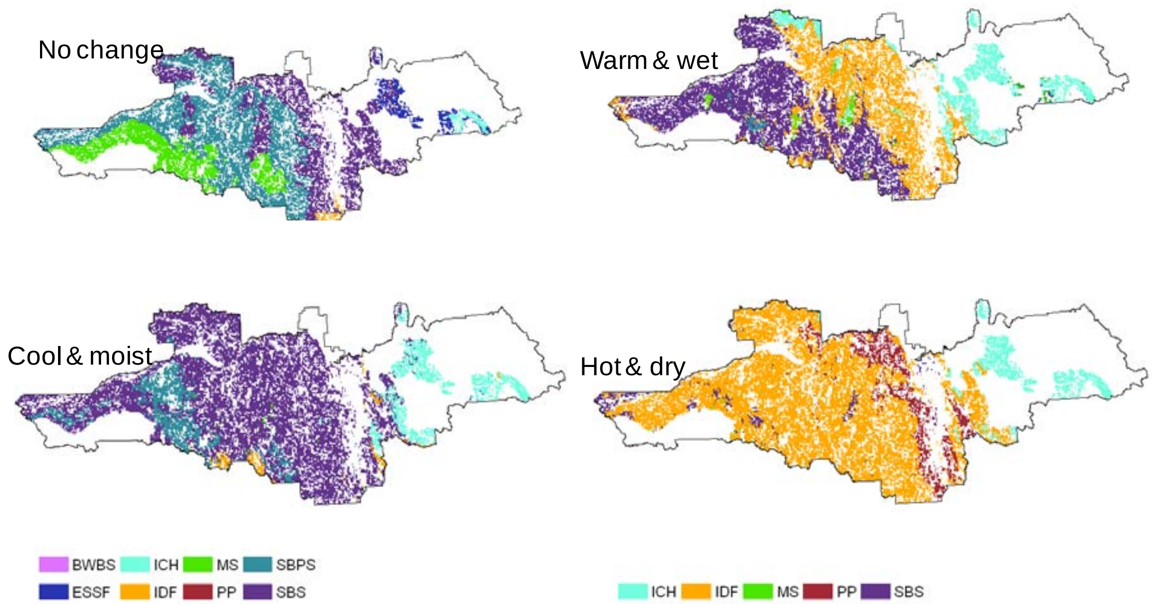

Figure 4. Projected climate envelopes for BEC zones across Quesnel THLB in 2050s for selected climate change scenarios

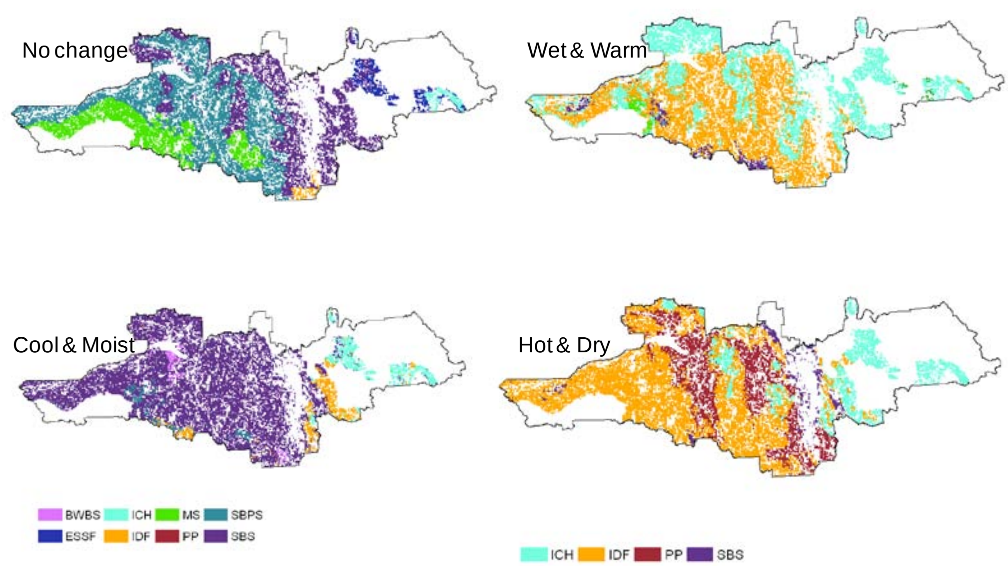

Figure 5. Projected climate envelopes for BEC zones across Quesnel THLB in 2080s for selected climate change scenarios

Species composition

The renewal option A1 can be considered adaptation of forest management to the changing climate. One of the first steps in integrating this adaptation option into a planning process is to define the landscape-level species composition targets (Mah et al 2012). In the absence of an established methodology, we define the targets in terms of the projected frequency of occurrence of tree species at the landscape-level under selected climate change scenarios. We projected the frequencies of occurrence of the three species (lodgepole pine, spruce and interior Douglas fir) in the Quesnel study area for the reference period 1961-1990, and the 2020s, 2050s and 2080s similar to Hamann and Wang (2006) and Wang et al. (2012). The occurrence frequency of major species in British Columbia has been estimated for each BEC zone (Hamann et al. 2005). By associating the occurrence frequency of the key species for the Quesnel study area with the projected climate envelopes for the eleven climate change scenarios (Table 6), we projected the future occurrence frequency of these species assuming no barriers to species migration (Table 8).

Table 8. Projected frequency of occurrence of three species in the Quesnel THLB

	Projection period	**Spruce**	**Pine**	**Fir**
C#0	2020/2050/2080	5.0%	44.7%	9.1%
C#1	*2020*	4.2%	27.2%	15.6%
	2050	3.0%	18.2%	23.4%
	2080	0.3%	10.6%	30.4%
C#2	*2020*	5.7%	38.1%	8.8%
	2050	5.6%	27.2%	8.9%
	2080	5.8%	23.2%	10.5%
C#3	*2020*	5.4%	32.3%	11.6%
	2050	0.2%	12.4%	44.4%
	2080	0.3%	10.2%	39.1%
C#4	*2020*	5.1%	7.1%	29.8%
	2050	4.2%	6.6%	20.3%
	2080	0.1%	4.3%	1.8%
C#5	*2020*	5.6%	7.8%	46.3%
	2050	5.9%	7.5%	38.4%
	2080	5.3%	6.9%	33.8%
C#6	*2020*	4.7%	6.2%	27.2%
	2050	2.9%	4.7%	11.8%
	2080	3.0%	4.9%	11.9%
C#7	*2020*	5.1%	7.4%	38.2%
	2050	3.8%	6.7%	31.0%
	2080	1.1%	4.6%	11.3%
C#8	*2020*	4.7%	6.7%	29.8%

	2050	2.1%	5.5%	11.4%
	2080	0.5%	4.5%	4.1%
C#9	*2020*	5.5%	7.8%	43.0%
	2050	4.8%	6.9%	32.2%
	2080	4.8%	6.9%	32.2%
C#10	*2020*	5.5%	7.8%	32.6%
	2050	5.9%	7.7%	39.3%
	2080	4.8%	6.7%	28.9%

Note that the projected occurrence frequencies of spruce, pine and fir under "no change" climate scenario (c=0) differ significantly from the current species frequency in the area (Table 3). The current occurrence frequency 76.5% of pine-leading stands is significantly higher than the projected occurrence frequency of pine in the study area. Note that the landscape composition dominated by older pine stands has been considered as one the causes of the recent MPB epidemic (Safranyik and Carroll 2006). Maintaining similar tree species composition in the future may cause further ecological, economic and social challenges in the area.

We set up the target occurrence frequency equal to the projected frequency of occurrence of tree species under specific climate scenario. As an example, the current, projected and target occurrence frequencies for three species under 'no change' (*c*=0) climate scenario are presented in Table 9.

Table 9. Current, projected and target occurrence frequency of the three species in Quesnel THLB

Species	**Spruce**	**Pine**	**Fir**
Current frequency of occurrence	5.0%	76.5%	14.09%
Projected occurrence frequency (under c=0)	5.0%	44.7%	9.10%
Target occurrence frequency (under c=0)	5.0%	44.7%	9.10%

Forest growth and yield

Growth and yield of the tree species suitable for the projected BEC zone climate envelopes was estimated using TIPSY v.4.1d (BC MFR 2007b). The recent results for lodgepole pine show a reduction in yield of approximately 10% on the sites maladapted to the projected climate (O'Neill and Nigh 2011). We decided to couple these results with some estimates of tree decay and mortality, insect infestation and wild fires due to potentially severe drought and other extreme events. To incorporate the negative impacts of climate change on tree species distributed outside the projected BEC zones, the stand yield estimates are reduced by 30%.

The management problem for Quesnel was formulated as a series of multi-criteria linear models (Krcmar et al. 2009; Krcmar and van Kooten 2008). The model was coded in GAMS (Brooke et al. 2004) and solved using the CPLEX solver on the GAMS platform.

Results

A MCDA model developed by Krcmar et al. (2005) was modified and adjusted to include impacts of climate change. For each of the two adaptation options, a series of linear models was developed and coded in GAMS. For each adaptation option, several forest management plans were generated assuming that future climate will follow patterns projected by different climate change scenarios. Several outcomes were calculated for each management plan to evaluate the timber supply and ecological impacts. Timber supply impacts were assessed by the period harvest volume and fluctuations of harvest volumes between periods. Ecological impacts were assessed in terms of the tree species occurrence frequency relative to the target tree species occurrence frequency.

Results under renewal option A0

Model (MC_C) designed for the Quesnel study area was solved for each scenario from set $C=\{c_i$, i=0,1,..,10} thereby producing eleven individual forest plans A0-F={$A0\text{-}plan_i$, i=0,1,..,10}. Assuming that different climates may occur in the future, average occurrence frequency of the key species relative to the target occurrence frequency, minimum period harvest volume and maximum flow deviation were determined for each individual plan.

Tables 10, 11 and 12 include the criteria values for the eleven forest plans and climate change scenarios from set *C* under renewal option A0. Construction of the tables is described in detail in the Appendix using A0-Plan0 and A0-Plan3 as examples.

We describe in detail the implementation of the framework for forest management planning under climate change to the Quesnel study area. Assume that decision-makers set up the desired values for the three criteria -- average occurrence frequency of species, minimum period harvest volume and maximum flow deviation between periods -- at 70%, 26 million m^3 and 1 million m^3.

For climate scenario c=3, the average occurrence frequency of species is below a desired value of 70%. This can be interpreted as the vulnerability of the *A0-F* plans in terms of the occurrence frequency of species for the climate scenarios from C_{vl}^1 ={ 3}. For climate scenarios from C_{vl}^2 ={1, 3, 4, 8}, minimum period harvest is below a desired value of 26 million m^3. On the other hand, maximum deviation between period harvests exceeds 1 million m^3 for climate scenarios from C_{vl}^3 ={1, 3, 4, 6, 8}. This means that the *A0-F* plans are vulnerable in terms of the harvest flow to climate scenarios from C_{vl}^3. The set of vulnerability of the *A0-F* plans with regard to all criteria is defined as the union of the individual vulnerability sets, $C_{vl} = \bigcup_k C_{vl}^k$ = {1, 3, 4, 6, 8}.

Upon the framework implementation, no robust forest plans are found among *A0-F* plans for all climate scenarios from *C*. However, the initial set *C* of eleven climate scenarios was reduced to a subset C_{vl} of five climate scenarios to which forest plans were particularly vulnerable across all criteria. None of the *A0-F* plans can be considered a robust plan for climate scenarios from both sets *C* and C_{vl} because the criteria values are far from the desired values especially under climate scenarios *c*=1 or *c*=3.

Table 10. Average occurrence frequency (%) of the key species for the plans *A0-F* and climate scenarios *C*

	A0-Plans											
c/Plan	0	1	2	3	4	5	6	7	8	9	10	Min
0	85.0	70.2	85.0	84.8	84.8	85.0	84.5	84.8	84.7	85.0	85.0	70.2
1	70.5	70.2	70.5	70.5	70.4	70.5	70.2	70.5	70.4	70.5	70.5	70.2
2	79.8	79.4	79.8	79.6	79.6	79.8	79.3	79.6	79.5	79.8	79.8	79.3
3	67.3	66.8	67.3	67.1	67.0	67.3	66.8	67.1	67.0	67.2	67.3	66.8
4	70.9	70.4	70.9	70.7	70.6	70.9	70.4	70.6	70.6	70.8	70.9	70.4
5	83.2	82.8	83.2	83.0	83.0	83.2	82.7	83.0	82.9	83.2	83.2	82.7
6	72.2	72.0	72.2	72.3	72.2	72.2	71.9	72.2	72.1	72.2	72.2	71.9
7	74.9	74.4	74.9	74.7	74.6	74.9	74.4	74.7	74.6	74.8	74.9	74.4
8	71.7	71.3	71.7	71.6	71.5	71.7	71.2	71.5	71.4	71.7	71.7	71.2
9	81.7	81.2	81.7	81.5	81.4	81.7	81.2	81.4	81.4	81.6	81.7	81.2
10	81.0	80.6	81.1	80.9	80.8	81.1	80.6	80.8	80.8	81.0	81.1	80.6

Table 11. Minimum period (million m3) for the plans *A0-F* and climate scenarios *C*

	A0-Plans											
c/Plan	0	1	2	3	4	5	6	7	8	9	10	Min
0	30.298	27.224	28.325	27.315	27.832	27.915	28.304	28.407	27.415	28.806	29.471	27.224
1	26.804	27.224	26.836	26.689	27.088	25.540	26.880	26.696	26.818	26.362	26.751	25.540
2	28.070	27.630	28.220	27.261	27.748	26.857	27.849	27.615	27.358	27.721	27.675	26.857
3	26.754	26.612	26.782	27.182	26.488	25.489	26.843	26.104	26.936	26.309	26.160	25.489
4	27.012	27.447	27.064	27.088	27.658	25.757	27.129	27.257	27.229	26.586	26.981	25.757
5	29.310	28.144	28.410	27.391	27.908	28.097	28.354	28.486	27.488	28.883	28.876	27.391
6	27.403	27.192	27.322	26.976	27.058	26.039	27.652	26.665	27.108	27.141	26.721	26.039
7	27.753	27.816	27.858	27.280	27.800	26.513	27.756	28.375	27.395	27.366	27.772	26.513
8	26.725	26.935	26.749	26.932	26.804	25.458	26.785	26.415	27.258	26.276	26.471	25.458
9	29.089	28.001	28.340	27.340	27.855	27.576	28.260	28.263	27.440	28.834	28.333	27.340
10	28.871	27.512	27.671	27.156	27.650	26.779	27.779	27.689	27.253	27.750	28.961	26.779

Table 12. Maximum deviation (million m3) between period harvests for the plans *A0-F* and climate scenarios *C*

	A0-Plans											
c/Plan	0	1	2	3	4	5	6	7	8	9	10	Max
0	0.000	0.342	0.436	0.755	0.609	0.325	0.763	0.480	0.670	0.224	0.163	0.763
1	1.156	0.000	0.309	0.265	0.128	0.603	0.174	0.371	0.178	0.453	0.443	1.156
2	0.736	0.318	0.000	0.383	0.288	0.383	0.249	0.297	0.286	0.182	0.325	0.736
3	1.258	0.243	0.353	0.000	0.252	0.664	0.303	0.486	0.133	0.475	0.584	1.258
4	1.044	0.105	0.302	0.263	0.000	0.520	0.218	0.283	0.217	0.443	0.352	1.044
5	0.340	0.518	0.291	0.643	0.504	0.000	0.539	0.387	0.555	0.118	0.186	0.643
6	1.024	0.153	0.241	0.176	0.190	0.514	0.000	0.432	0.149	0.386	0.496	1.024
7	0.730	0.300	0.231	0.498	0.293	0.348	0.358	0.000	0.429	0.333	0.205	0.730
8	1.155	0.141	0.262	0.126	0.175	0.651	0.156	0.410	0.000	0.424	0.517	1.155
9	0.391	0.460	0.205	0.521	0.421	0.104	0.464	0.382	0.448	0.000	0.257	0.521
10	0.614	0.481	0.395	0.599	0.431	0.370	0.506	0.400	0.504	0.437	0.000	0.614

The Quesnel forest planning problem is further analyzed for the reduced set C_{vl} while introducing a new renewal-adaptation option A1.

Results under adaptation option A1

To increase the period harvests, reduce fluctuations of harvest flow over time and meet the targets for species occurrence frequency, we generated a set *A1-F*={ A1-Plani, i=1,3,4,6,8} of forest plans under the renewal-adaptation option A1 assuming that climate may follow patterns projected by one of the scenarios from $C_1 = C_{vl}$ = {ci, i=1,3,4,6,8}. Tables 13, 14 and 15 include values of three criteria— average occurrence frequency of the key species, minimum period harvest volume and maximum harvest flow deviation—calculated for the five forest plans from *A1-F* and climate change scenarios from C_1. Construction of the tables is described in details in the Appendix using A1-Plan1 and A1-Plan6 as examples.

Table 13. Average occurrence frequency (%) of the key species for the plans *A1-F* and climate scenarios C_1

c	A1 Plan1	A1 Plan3	A1 Plan4	A1 Plan6	A1 Plan8
1	81%	83%	80%	83%	73%
3	78%	85%	77%	85%	69%
4	80%	85%	80%	85%	73%
6	83%	84%	82%	84%	75%
8	81%	82%	81%	81%	74%
min across *c*	78%	82%	77%	81%	69%
				max min=	82%

Table 14. Minimum period harvest (million m3) for the plans *A1-F* and climate scenarios C_1

c	A1-Plan1	A1-Plan3	A1-Plan4	A1-Plan6	A1-Plan8
1	29.989	31.048	32.241	27.306	24.728
3	29.334	31.653	31.589	27.257	24.845
4	29.911	31.412	32.939	27.545	25.100
6	29.851	31.358	32.258	28.105	24.996
8	29.649	30.916	31.974	27.214	25.136
min across *c*	29.334	30.916	31.589	27.214	24.728
				max min=	31.589

Table 15. Maximum deviation (million m3) between period harvests for the plans *A1-F* and climate scenarios C_1

c	A1-Plan1	A1-Plan3	A1-Plan4	A1-Plan6	A1-Plan8
1	0.000	0.279	0.171	0.280	0.128
3	0.303	0.000	0.403	0.506	0.149
4	0.304	0.387	0.000	0.505	0.286
6	0.241	0.336	0.202	0.000	0.174
8	0.156	0.202	0.290	0.237	0.000
max across *c*	0.304	0.387	0.403	0.506	0.286
				min max=	0.286

After examining the criteria values in Tables 13, 14 and 15, two plans are selected as the potential robust plans. The plans A1-Plan3 and A1-Plan4 both achieve superior values for the period harvest volumes and average frequency of occurrence of the key species compared to other plans from *A1-F*, but are somewhat inferior to other plans from *A1-F* in terms of the maximum harvest flow deviation (Figures 6 and 7). Both plans have the average frequency of occurrence of the key species relative to the target frequency over 77%, minimum period harvest volume above 30 million m^3 and maximum flow deviation between periods does not exceed 0.5 million m^3. Note that all three criteria values achieved for A1-Plan3 and A1-Plan4 are improved relative to the desired criteria values under the renewal option A0 (no adaptation).

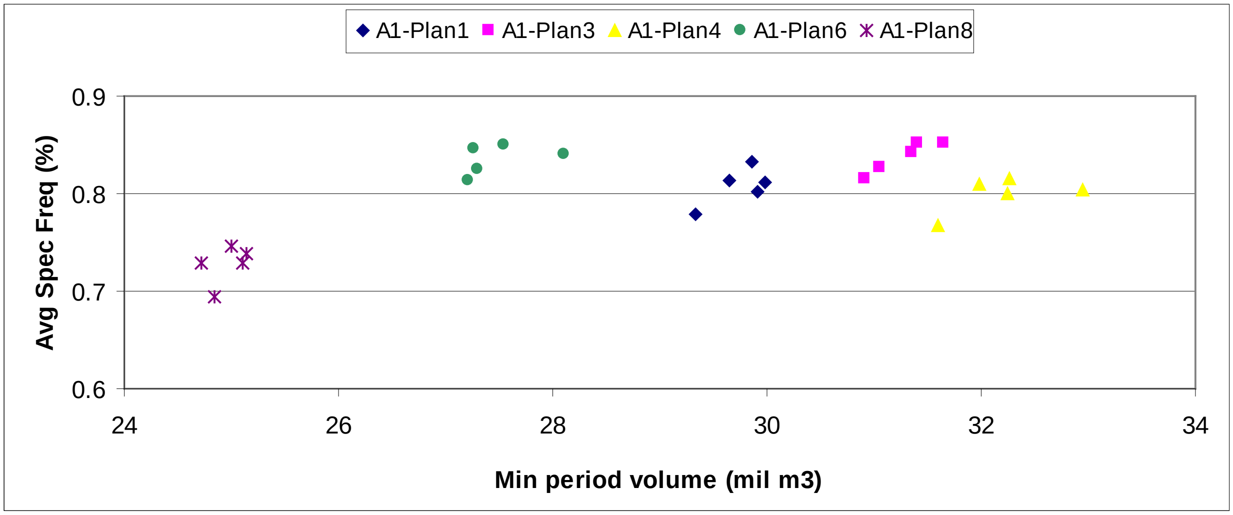

Figure 6. Minimum period harvest and average species occurrence frequency for the A1 plans

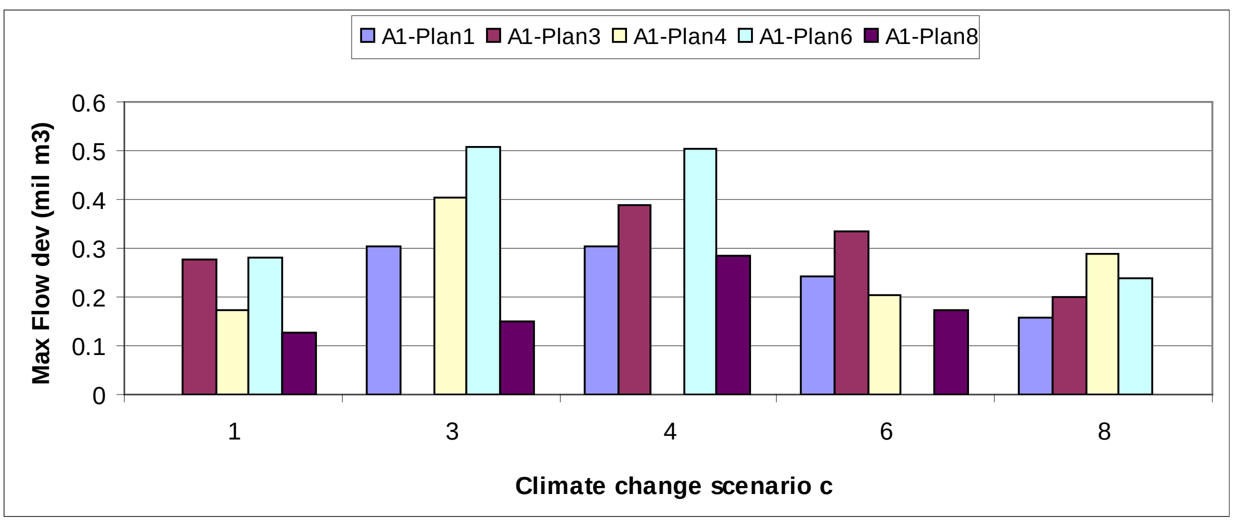

Figure 7. Maximum flow deviation for the A1 plans

The potential robust plans are also examined from the perspective of the projected occurrence of species over time (Tables 16 and 17). A1-Plan3 was generated as a solution of the (MC_C) program assuming that future climate will follow the climate pattern projected by the scenario c =3 (HadGEM-A1B). The plan involves intensive harvest of pine followed by reforestation using a combination of fir and pine. Fir planting dominates planting of pine over the whole horizon and this dominance is particularly significant in the first half of the horizon. In the first period, all harvested pine stands are reforested by fir. In period 2, harvested pine stands are reforested with fir and a small portion with pine. Starting in period 4, reforestation with pine increases and reaches approximately one third of the area of fir plantations. The original pine stands include fir and pine in the ratio of 5:2 by the end of the planning horizon (Table 16).

Table 16. Projected area (ha) by species in each period over the horizon for A1-Plan3

Species	Period								
	1	2	3	4	5	6	7	8	9
F[a]	49,469	49,469	49,469	49,469	49,469	49,469	49,469	49,469	49,469
S[b]	139,821	139,821	139,821	139,821	139,821	139,821	139,821	139,821	139,821
P[c]	758,741	610,383	524,097	316,360	222,171	187,876	163,379	92,508	10,441
C[d]	571	571	571	571	571	571	571	571	571
D[e]	43,769	43,769	43,769	43,769	43,769	43,769	43,769	43,769	43,769
FPL[f]		148,357	183,355	391,092	391,092	391,092	391,092	445,358	520,191
SPL[g]									7,234
PPL[h]			51,288	51,288	145,478	179,772	204,270	220,875	220,875

[a] fir; [b] spruce; [c] pine; [d] cedar; [e] deciduous; [f] original pine stands planted by fir;
[g] original pine stands planted by spruce; [h] original pine stands planted by pine

A1-Plan4 was determined as a solution of the (MC_C) program assuming that future climate will follow the climate pattern projected by the scenario $c = 4$ (GFDLCM21-A2). A1-Plan4 involves intensive harvest of pine followed by planting using a combination of fir, spruce and pine. In the first period, harvested pine stands are planted with approximately equal portions of fir and spruce. After the pine harvest in period 2 the stands are planted with approximately equal portions of pine, fir and spruce. In period 3, the area planted with fir and spruce almost doubles relative to the fir and spruce planting in the previous period. From period 4, the area replanted with pine increases steadily. By the end of planning horizon, the original pine stands are covered with approximately equal portions of pine, fir and spruce (Table 17).

Table 17. Projected area (ha) by species in each period over the horizon for A1-Plan4

Species	Period								
	1	2	3	4	5	6	7	8	9
F[a]	49,469	49,469	49,469	49,469	49,469	49,469	49,469	49,469	49,469
S[b]	139,821	139,821	139,821	139,821	139,821	139,821	139,821	139,821	139,821
P[c]	758,741	595,153	504,215	364,901	248,965	213,136	150,186	63,364	10,441
C[d]	571	571	571	571	571	571	571	571	571
D[e]	43,769	43,769	43,769	43,769	43,769	43,769	43,769	43,769	43,769
FPL[f]		74,964	74,964	137,159	137,159	137,159	181,745	181,745	233,419
SPL[g]		88,624	88,624	157,735	157,735	157,735	157,735	244,557	245,806
PPL[h]			90,938	98,946	214,882	250,711	269,074	269,074	269,074

[a] fir; [b] spruce; [c] pine; [d] cedar; [e] deciduous; [f] original pine stands planted by fir;
[g] original pine stands planted by spruce; [h] original pine stands planted by pine

The A1-Plan4 seems like a suitable one for implementation because of the fewer changes of the current renewal patterns compared to A1-Plan3. Selecting the forest management plan for implementation will depend on other factors that are beyond the scope of this project. Stakeholders may request repeating the decision process with additional and/or different ecological, economic and social goals and criteria.

Discussion and conclusions

We developed a framework for supporting forest management planning under climate change. The framework addresses uncertainty of the climate change projections and its impact on forest management decisions. Uncertainty related to climate projections affects a number of variables and parameters involved in forest planning. Our study explicitly addresses uncertainty regarding the species composition and forest productivity, both related to the climate projection uncertainty. Note that other uncertainties inherent to forest planning are beyond the scope of the study.

All results of the case study are valid only under the given assumptions and represent relative rather than absolute values. No potential positive impacts of future climate on forest productivity (Nigh et al. 2004) are taken into account. If these impacts were considered or if the assumptions about the reduced growth and yield changed, the projected criteria values would likely differ significantly.

Forest management decisions under climate change should be done in accordance with thorough analyses of the criteria values across different climate change scenarios and associated plans. Note that, in this study, we used only the timber supply and landscape-level species composition as the performance measures for the plan evaluation. The incorporation of other performance measures, such as additional ecological, economic and social criteria, may lead to different decisions.

A special interest for decisions makers and policy makers is that the proposed framework is:

- *Iterative* as forest plans are generated iteratively over time
- *Interactive* as stakeholders' input can be included into the model development and into the selection of robust forest plans
- *Balancing* since the framework includes multiple goals allowing for assessment of trade-offs among competing interests
- *Deals with uncertainty* by including a range of future climates into decision process
- Provides *robust forest plans* that are good-enough under the worst case climate scenarios

Literature

BC MFR (2008) Chief Forester's standards for seed use. BC Ministry of Forests and Range, Victoria, BC. Available at www.for.gov.bc.ca/code/cfstandards/CFstds20Nov2008.pdf

BC MFR (2007a) Quesnel Timber Supply Area—map. BC Ministry of Forests and Range, Victoria, BC. Available at www.for.gov.bc.ca/hts/tsa/tsa26/maps.htm

BC MFR (2007b) TIPSY. Available at www.for.gov.bc.ca/hre/gymodels/TIPSY/index.htm

Belton, V. and Stewart, T.J. (2001). *Multiple criteria decision analysis: An integrated approach*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Brooke, A., Kendrick, D., Meeraus, A. and Raman, R. (2004) *GAMS: A user's guide*. GAMS Development Corporation, Washington, DC.

Buell, M., Sutherland, G. and Williams, D. (2006) Quesnel TSA Silviculture Plan (Type 2) and Habitat Analysis (Type 3). Quesnel TSA Strategic Forest Analysis Steering Committee. Cortex Consultants, Victoria, BC.

Campbell, E.M., Saunders, S.C., Coates, K.D., Meidinger, D.V., MacKinnon, A.J., O'Neill, G.A., MacKillop, D.J. and DeLong, S.C. (2009) Ecological resilience and complexity: a theoretical framework for understanding and managing British Columbia's forest ecosystems in a changing climate. B.C. Min. For. Range, For. Sci. Prog., Victoria, B.C. Tech. Rep. Available at www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr055.htm

Cortex Consultants, Inc. and Mike Fenger and Associates (2006) Quesnel TSA Silviculture Strategy (Type 1). Available at http://www.for.gov.bc.ca/ftp/hfp/external/!publish/fft_standards_on_cms_web/Silviculture StrategyDocuments/Quesnel_TSA_26/QuesnelTSAType1Report.pdf

Dessai, S. and Hulme, M. (2007) Assessing the robustness of adaptation decisions to climate change uncertainties: A case study on water resources management in the East of England. *Global Environmental Change* 17: 59-72.

Groves, D. G. and Lempert, R.J. (2007) A new analytic method for finding policy-relevant scenarios. *Global Environmental Change* 17: 73–85.

Hamann, A., Smets, P., Yanchuk, A.D. and Aitken, S.N. (2005) An ecogeographic framework for in situ conservation of forest trees in British Columbia. *Canadian Journal of Forest Research* 35: 2553–2561.

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M.Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Krcmar, E., Bizikova, L. and Chan-McLeod, A. (2009) Framework to support impact analyses of renewal plans of forestlands affected by mountain pine beetle. Mountain Pine Beetle working paper 2009-22. Mountain Pine Beetle Program Project # 7.24. Natural Resources Canada. Canadian Forest Service. Pacific Forestry Centre, Victoria, BC.

Krcmar, E. and van Kooten, G. C. (2008) Economic development prospects of forest-dependent communities: analyzing trade-offs using a compromise-fuzzy programming framework. *American Journal of Agricultural Economics* 90(4): 1103 - 1117.

Krcmar, E., van Kooten, G. C. and Vertinsky, I. (2005) Managing forest and marginal agricultural land for multiple tradeoffs: compromising on economic, carbon and structural diversity objectives. *Ecological Modelling* 185 (2–4): 451-468.

Lemprière, T.C., Bernier, P.Y. , Carroll, A.L. , Flannigan, M.D., Gilsenan, R.P., McKenney, D.W., Hogg, E.H., Pedlar, J.H. and Blain, D. (2008) The importance of forest sector adaptation to climate change. Inf. Rep. NOR-X-416E. Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB.

Mah, S., Astridge, K., DeLong, C., Wickland, C., Todd, M., McAuley, L., LePage, P., Coates, D., Heemskerk, B., Banner, A. and Hall, E. (2012) A landscape-level species strategy for forest management in British Columbia: exploration of development and implementation issues. B.C., Victoria, B.C. Tech. Rep. 067. Available at www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr067.htm

Metsaranta, J.M., Dymond, C.C., Kurz, W.A. and Spittlehouse, D.L. (2011) Uncertainty of 21st century growing stocks and GHG balance of forests in British Columbia, Canada resulting from potential climate change impacts on ecosystem processes. *Forest Ecology and Management* 262: 827–837.

Moss, R.H. and Schneider, S.H. (2000): Uncertainties in the IPCC TAR: Recommendations to lead authors for more consistent assessment and reporting. In: Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC [eds. R. Pachauri, T. Taniguchi and K. Tanaka], World Meteorological Organization, Geneva, pp. 33-51.

Nigh, G.D., Ying, C.C. and Qian, H. (2004) Climate and productivity of major conifer species in the interior of British Columbia, Canada. *Forest Science* 50(5): 659-671.

O'Neill, G.A. and Nigh, G. (2011) Linking population genetics and tree height growth models to predict impacts of climate change on forest production. *Global Change Biology* 17: 3208 – 3217.

Preston, B.L., Westaway, R.M. and Yuen, E.J. (2011) Climate adaptation planning in practice: an evaluation of adaptation plans from three developed nations. *Mitigation and Adaptation Strategies for Global Change* 16 (4): 407-438.

Refsgaard, J. C., Arnbjerg-Nielsen, K., Drews, M., Halsnæs, K., Jeppesen, E., Madsen, H., Markandya, A., Olesen, J. E., Porter, J. R. and Christensen, J. H. (2012) The role of uncertainty in climate change adaptation strategies—A Danish water management example. *Mitigation and Adaptation Strategies for Global Change*, (in press)

Roy, B. (2010) Robustness in operational research and decision aiding: A multi-faceted issue. *European Journal of Operational Research* 200: 629–638.

Safranyik, L. and Carroll, A.L. (2006) The biology and epidemiology of the Mountain Pine Beetle in lodgepole pine forests. In*: The mountain pine beetle: a synthesis of biology, management, and impacts on lodgepole pine* [eds. L. Safranyik and B. Wilson], Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC, pp: 3-66.

Schneider, S.H. (2003) The Case for Climate Change Action. U.S. Senate Committee on Commerce, Science and Transportation. Hearing on "The Case for Climate Change Action". October 1, 2003. Available at: http://stephenschneider.stanford.edu/Publications/PDF_Papers/SHSCongress1.pdf

Simon, H. A. (1957) Models of Man: Social and Rational. Wiley, New York.

Spittlehouse, D. and Murdock, T. (2010) Choosing and applying climate change scenarios. Report from FFESC project 014 (25 June 2010).

Toth, F. (2000) Decision analysis frameworks. In R. K. Pachauri, T. Taniguchi, and K. Tanaka, editors. *Guidance papers on the cross cutting issues of the third assessment report of the IPCC.* IPCC, Geneva, pp. 53-68.

Taylor, B., Kremsater, L.L. and Ellis, R.M. (1997) Adaptive management of forests in British Columbia. B.C. Min. For., For. Pract. Br., Victoria, B.C.

Wang, T., Campbell, E.M., O'Neill, G.A., Aitken, S.N. (2012) Projecting future distributions of ecosystem climate niches: uncertainties and management applications. *Forest Ecology and Management* 279: 128-140.

Wang, T. (2011) Climate models for downscaling and translating climate change scenarios into ecological and forest scenarios for British Columbia and western North America Available at www.genetics.forestry.ubc.ca/cfcg/climate-models.html#1.ClimateBC/WNA

Appendix

Table A1. Biogeoclimatic zones in BC

Biogeoclimatic (BEC) Zones	BEC abbreviations
Alpine Tundra	AT
Spruce—Willow—Birch	SWB
Boreal White and Black Spruce	BW
Sub-Boreal Pine—Spruce	SBPS
Sub-Boreal Spruce	SBS
Mountain Hemlock	MH
Engelmann Spruce—Subalpine Fir	ESSF
Montane Spruce	MS
Bunchgrass	BG
Ponderosa Pine	PP
Interior Douglas-fir	IDF
Coastal Douglas-fir	CDF
Interior Cedar—Hemlock	ICH
Coastal Western Hemlock	CWH

Table A2. Average frequency of occurrence relative to the target frequency over the horizon for A0-Plan0 and A0-Plan3

	A0-Plan0				A0-Plan3			
c	Fir	Spruce	Pine	Avg Freq	Fir	Spruce	Pine	Avg Freq
0	96%	91%	68%	85%	95%	91%	68%	85%
1	82%	88%	41%	71%	82%	88%	41%	71%
2	95%	92%	52%	80%	95%	92%	52%	80%
3	73%	88%	41%	67%	73%	88%	41%	67%
4	79%	89%	45%	71%	78%	89%	45%	71%
5	95%	91%	63%	83%	94%	91%	63%	83%
6	82%	89%	45%	72%	82%	89%	45%	72%
7	82%	89%	54%	75%	81%	89%	54%	75%
8	85%	88%	42%	72%	85%	88%	42%	72%
9	94%	91%	60%	82%	93%	91%	60%	81%
10	94%	91%	58%	81%	94%	91%	58%	81%

Table A3. Period volume (million m3) over the horizon for A0-Plan0 and A0-Plan3

c/Period	1	2	3	4	5	6	7	8	9	10	min
	A0-Plan0										
0	30.298	30.298	30.298	30.298	30.298	30.298	30.298	30.298	30.298	30.298	30.298
1	28.478	29.949	28.415	27.566	27.435	28.768	26.859	26.914	28.996	26.804	26.804
2	29.615	30.206	29.591	28.460	28.398	29.180	28.070	28.140	29.633	28.129	28.070
3	29.009	30.103	28.963	27.025	26.818	28.667	26.852	26.897	29.071	26.754	26.754
4	28.907	30.069	28.858	28.121	28.020	29.076	27.144	27.173	29.198	27.012	27.012
5	30.499	30.386	30.504	29.677	29.656	29.939	29.310	29.338	30.020	29.326	29.310
6	28.781	30.070	28.725	27.545	27.403	28.807	27.591	27.642	29.406	27.559	27.403
7	29.761	30.246	29.740	29.254	29.192	29.768	27.856	27.878	29.441	27.753	27.753
8	28.936	30.059	28.887	27.275	27.143	28.515	26.752	26.816	28.928	26.725	26.725
9	30.177	30.319	30.171	29.136	29.089	29.618	29.150	29.180	29.931	29.165	29.089
10	29.056	30.068	29.014	29.763	29.745	29.990	28.871	28.908	29.851	28.886	28.871
	A0-Plan3										
0	28.213	27.315	28.400	30.473	30.653	30.264	29.189	29.202	29.693	31.037	27.315
1	26.759	27.044	26.689	27.734	27.799	27.696	27.092	27.068	27.216	27.237	26.689
2	27.662	27.261	27.751	28.636	28.762	28.545	27.813	27.740	28.310	28.641	27.261
3	27.182	27.182	27.182	27.182	27.182	27.182	27.182	27.182	27.182	27.182	27.182
4	27.101	27.150	27.088	28.291	28.384	28.222	27.414	27.439	27.342	27.468	27.088
5	28.380	27.391	28.588	29.853	30.016	29.688	28.600	28.580	29.072	29.963	27.391
6	27.015	27.144	26.976	27.711	27.768	27.678	27.597	27.570	27.820	28.041	26.976
7	27.794	27.280	27.896	29.424	29.550	29.282	27.812	27.835	27.870	28.274	27.280
8	27.125	27.136	27.117	27.443	27.507	27.415	26.975	26.932	27.172	27.148	26.932
9	28.121	27.340	28.285	29.310	29.449	29.175	28.484	28.462	28.947	29.791	27.340
10	27.205	27.156	27.222	29.939	30.104	29.768	28.323	28.296	28.763	29.484	27.156

Table A4. Maximum deviation between the period harvest volumes (million m3) over the horizon for A0-Plan0 and A0-Plan3

c	A0-Plan0	A0-Plan3
0	0.000	0.755
1	1.156	0.265
2	0.736	0.383
3	1.258	0.000
4	1.044	0.263
5	0.340	0.643
6	1.024	0.176
7	0.730	0.498
8	1.155	0.126
9	0.391	0.521
10	0.614	0.599

Table A5. Average frequency relative to the target frequency over the horizon for A1-Plan1 and A1-Plan6

	A1-Plan1				A1-Plan6			
c	**Fir**	**Spruce**	**Pine**	**Avg Freq**	**Fir**	**Spruce**	**Pine**	**Avg Freq**
1	96%	73%	74%	81%	82%	86%	79%	83%
3	87%	73%	73%	78%	90%	86%	78%	85%
4	89%	74%	77%	80%	86%	87%	82%	85%
6	98%	74%	77%	83%	82%	88%	82%	84%
8	97%	73%	74%	81%	79%	86%	79%	81%

Table A6. Period volume (million m3) over the horizon for A1-Plan1 and A1-Plan6

c/Period	1	2	3	4	5	6	7	8	9	10	min
	A1-Plan1										
1	27.799	27.839	27.807	28.088	28.136	28.076	27.306	27.853	28.322	27.773	27.306
3	28.341	28.185	28.333	27.929	27.509	27.955	27.257	28.246	29.000	27.954	27.257
4	28.238	28.122	28.232	28.183	28.735	28.279	27.545	28.637	29.369	28.157	27.545
6	28.105	28.105	28.105	28.105	28.105	28.105	28.105	28.105	28.105	28.105	28.105
8	30.493	30.438	30.420	29.805	29.757	29.673	29.926	29.815	29.649	29.858	29.649
	A1-Plan6										
1	27.799	27.839	27.807	28.088	28.136	28.076	27.306	27.853	28.322	27.773	27.306
3	28.341	28.185	28.333	27.929	27.509	27.955	27.257	28.246	29.000	27.954	27.257
4	28.238	28.122	28.232	28.183	28.735	28.279	27.545	28.637	29.369	28.157	27.545
6	28.105	28.105	28.105	28.105	28.105	28.105	28.105	28.105	28.105	28.105	28.105
8	28.267	28.165	28.260	27.966	27.838	27.887	27.214	27.562	27.939	27.636	27.214

Table A7. Maximum deviation between the period harvest volumes (million m3) over the horizon for A1-Plan1 and A1-Plan6

c	A1-Plan1	A1-Plan6
1	0.000	0.280
3	0.303	0.506
4	0.304	0.505
6	0.241	0.000
8	0.156	0.237