Climate change,
natural disturbance
and timber supply analysis
Expanding the timber supply analysis toolkit

Methods and application in Morice TSA

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Table of Contents

0. Executive Summary 4
1. Introduction 5
  1.1. Climate change effects and timber supply analysis 5
    1.1.1. Direct methods to address climate change impacts on timber supply 6
    1.1.2. Indirect methods to address climate change impacts on timber supply 7
    1.1.3. Tools for timber supply modelling 8
2. Methods: General 9
  2.1. Study area, scale and data inputs 9
  2.2. Benchmarking to TSR base case analysis 10
3. Methods: climate change effects and changes in natural disturbance 10
  3.1. Climate effects on timber supply 10
    3.1.1. Stand growth rates 10
    3.1.2. Stand regeneration 10
    3.1.3. Stand-scale natural disturbance 11
    3.1.4. Landscape scale natural disturbance 11
  3.2. Potential operational responses to climate effects on timber supply 11
  3.3. Tools for climate change effects in timber supply analysis 12
    3.3.1. Dynamic operational adjustment factors (Dynamic OAFs) 12
    3.3.2. Natural analysis units and emergent NRLs 13
  3.4. Climate change effects: experimental design 14
  3.5. Reporting timber supply risk: risk “tranches” 16

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4. Results: General 17
    - 4.1. Base case benchmarking 17
5. Results and Discussion: climate change effects 18
    - 5.1. Dynamic OAF and emergent NRL experiments 18
    - 5.2. Timber supply risk assessment: risk “tranches” 23
        - 5.2.1. Base risk classes 23
        - 5.2.2. Climate change risk classes 24
6. Conclusions 25
    - 6.1. Climate change effects 25
7. Literature Cited 27

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0. Executive Summary

This report documents a research project to develop and test new methods to incorporate climate change factors into timber supply analysis and the timber supply review process. Methods were tested using the Morice TSA as a case study. Two main questions or perspectives were taken:

(i) How might climate change influence forest dynamics and in turn, timber supply? These influences can be addressed in part by designing practical methods to include climate change factors in forest estate modelling.

(ii) What risks does determining an allowable annual cut (AAC) at a particular level pose to future timber supply in a forest subject to climate change? There is substantial uncertainty and complexity regarding potential climate change impacts on forests. We define "timber supply uncertainty" as the general likelihood of achieving a given level of timber supply. Uncertainty increases with time, and is also influenced by the specifics of a study area.

To address these questions, we

(i) Designed practical methods to include climate change factors in forest estate modelling, in particular stand- and landscape-scale changes in natural disturbance, extreme weather events (such as increased drought), and changing forest conditions (e.g. increased regeneration failure). Two methods in particular were implemented: (a) the capability to model dynamic changes in stand-level disturbance (*dynamic operational adjustment factors*) and (b) the capability to model dynamic changes in landscape-level disturbance by different natural disturbance agents (*natural analysis units / emergent non-recovered losses).* These two tools provide a parsimonious approach to including some climate change effects in forest estate models.

(ii) Designed methods to produce timber supply uncertainty outputs from a forest estate model, in particular specifying climate-associated risks to different components of timber supply (e.g. existing mature stands, future regenerated stands), and reporting of risk categories in timber production and growing stock.

We tested prototype versions of the methods developed using parameters developed for Morice Timber Supply Area. For each new method, we performed an experiment and compared results against a spatial benchmark of the 2013/14 timber supply review analysis base case. These experimental scenarios demonstrate the feasibility of the methods designed, and illustrate the types of outcomes and information such methods can produce.

In summary, the new timber supply methods provide some initial steps towards including climate change effects in timber supply analysis. The methods were designed to be general to increase potential that they could be adapted to other timber supply modeling tools and approaches.

1. Introduction

Timber supply analysts face increasingly complex issues arising from increasing societal demand for knowledge of the complex dynamics and management of forested landscapes. For example, to understand and address the consequences of changing environmental conditions and natural disturbance regimes, legal recognition of Indigenous peoples rights and title, and a changing regulatory and policy environment. To address some of these issues as part of timber supply analysis, analysts need an expanded toolkit of methods that can be applied in forest estate modelling. This report documents methods developed, implemented and tested to address how climate change, in particular changes in natural disturbance, can be incorporated into timber supply analysis.

We explored these methods by using the Cumulative Effects Toolkit[1] developed to support cumulative effects analysis at the landscape-scale in British Columbia (BC), Canada, and adapted for assessing the impacts of development, natural disturbance and climate change on wildlife, salmon and hydrology in the Morice timber supply area of northwestern BC. The new methods were implemented in the landscape dynamics (forest estate model) component of this cumulative effects analysis (CEA) toolkit.

One benefit of using the Morice CEA toolkit is that other values can be assessed in a streamlined manner (e.g. the effects of watershed access constraints can be linked with a moose habitat model, and then with a risk assessment framework, to explore in more detail the potential effects on moose habitat of different watershed access policies).

To help interpret results, we start with a benchmark of the 2014 Morice timber supply review (TSR) analysis for the base case scenario (current management)[2]. This step is important because the TSR analysis used a different tool (Woodstock), which differs from the CEA timber supply tool in two key respects: (a) Woodstock is a linear optimization tool vs. a simulation tool and (b) Woodstock is non-spatial.

1.1. Climate change effects and timber supply analysis

Climate change has the potential to affect many elements of forest ecosystems, across all spatial scales (Kirilenko and Sedjo 2007). Without attempting an exhaustive list, these include changes to regeneration (e.g. due to more or less precipitation), changes to tree growth rates (e.g. caused by a change in drought frequency, increases in C02 concentration), changes to fine-scale tree mortality (e.g. change in winter temperatures influencing spread of root rot) and changes to broad-scale tree mortality (e.g. changes to fire regime, changes to survival of bark beetles, changes to extreme weather events). Effects of climate

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[1] Fall and Morgan 2014

[2] BC Ministry of Forests, Lands and Natural Resources Operations 2014.

change are expected to increase over time, but with uncertainty regarding the magnitude (and sometimes direction) of potential changes. Timber supply analysis to support the AAC determination process inherently explores long-term (e.g. 100 year) effects of changes in the composition of the timber inventory. In particular, short-term sustainable harvest levels depend on the mid- and long-term capacity of a landscape to supply timber. Hence, the potential effects of climate change on timber supply have direct bearing on AAC determinations. However, the exact nature of the interaction between AAC determination (short term harvest levels) and climate change effects on forest ecosystems is not obvious.

While a number of factors may be important in a given landscape, the main issues for the AAC determination process are (a) does a given level of short-term harvest pose a risk to future timber supply and other forest values; and (b) does risk of future climate change impacts increase the uncertainty that a given level of short-term harvest cannot be achieved.

In general, the second question is simpler: short of a broad-scale catastrophe, future effects of climate changes do not seem so likely to cause a short-term (10 year) disruption in timber supply. Even the recent outbreak and spread of Mountain Pine Beetle did not disrupt short term timber supply (to the contrary, salvage efforts led to increases). Such disruptions are quite likely to impact mid-term timber supply (as anticipated in some MPB-impacted areas), but this type of impact relates to the first question.

We suggest that the first question regarding the risk of an AAC determination on future harvest levels and forest values is the most pertinent when considering climate change. Part of the reason is related to uncertainty: we have relatively high certainty about the state of the forest today, and decreasing certainty the further we project into the future. However, over a long-time frame, relatively rare events become more likely (i.e. the odds increase), and with climate change, events that are currently relatively rare may become more common.

1.1.1. Direct methods to address climate change impacts on timber supply

While climate change effects on long-term timber supply will be variable and complex, the main issue is the risk that short-term harvest level may interact with climate change to negatively impact future timber supply and future forest values. The obvious approach to address this is to identify factors important to timber supply that will be affected by climate change in the study area (e.g. change in fire regime and drought frequency), and then to implement suitable disturbance process models to include these effects in a forest estate model. This approach effectively asks the question:

How might climate change affect forest dynamics and impact timber supply, in particular short-term timber supply?

The challenge with this approach is that it could increase the "analytical burden" of TSR significantly. The analyst would first need to determine the expected changes in climate for the study area (e.g.

precipitation, temperature, extreme weather, etc.), possibly under more than one climate scenario. Then the analyst would have to determine which of the factors affecting forests would be significant in the study area (affecting growth rates, stand-level mortality, and landscape level mortality, plus changes in variability), and how to integrate these factors into the timber supply model. Due to the number of factors involved and to the uncertainty (and variability), this approach could require a lot of sensitivity analysis scenarios.

Hence to incorporate climate change factors ***directly*** into timber supply analysis requires a *parsimonious* set of methods that balance the desire for forest estate modelling that more completely reflects impacts associated with climate change, with the need to keep analysis tractable within the context of the TSR process.

1.1.2. Indirect methods to address climate change impacts on timber supply

There is an alternative to directly modelling climate change factors in a forest estate model. As the Chief Forester is in part concerned with the risks posed by an AAC determination (over 5-10 years) on future timber supply and forest values (e.g. if a given AAC increases the risk of shortfalls or exacerbates a future bottleneck), the above question could be inverted to:

How might an AAC determination affect future timber supply subject to impacts from climate change?

In other words, how does timber harvest during an AAC determination period interact with uncertainty associated with potential effects of climate change on timber supply?

That is, while the importance of how climate change may affect timber supply (short to long term) is clear, from an AAC determination perspective, it may be more pertinent and practical to consider the narrower issue of effect of an AAC determination on mid to long term timber supply in the context of climate change. In a sense, this is consistent with the timber supply review process, in which timber supply analysis aims to help the Chief Forester understand whether a particular harvest level over the effective term of an AAC is consistent with objectives for controlled, and ideally gradual, transitions to fairly stable mid and long term timber supply.

This perspective helps to narrow the challenge of how to incorporate the complexity and variety of climate change effects into a timber supply analysis. The objective is no longer to incorporate every climate-change factor that may have a significant impact on timber supply over the duration of an analysis (centuries), but rather to focus on (a) the degree to which short-term harvest levels interact with longer-term levels and (b) those climate-change factors identified as influencing this interaction in the particular study area. That is, attention needs to focus only on factors that may affect the level of risk to future timber supply associated with a particular AAC level.

For example, suppose climate change knowledge for a study area indicates that trees may grow 5% slower in 100 years due to decreased summer water availability. While this effect may have important implications for future timber supply, it may not interact with short-term timber supply over the next 10 years. However, if tree growth is expected to slow by 5% within 20 years, it may imply that harvest over the next 10 years needs to be reduced to avoid future shortfalls.

Put another way, instead of considering first the importance of every climate change factor that influences timber supply (which would be a daunting task), it might be more feasible to consider the dependence of short-term harvest levels on the structure of the current and future forest. Hence to incorporate climate change factors ***indirectly*** into timber supply analysis requires methods to stratify timber supply outputs (harvest flows) from lower to higher levels (or “tranches” using a term from investment risk) of risk or uncertainty.

Instead of starting with climate change and potential effects on a forest, this approach focuses on the dependence between short-term harvest levels and uncertainties in the future forest condition. The general idea is to identify the proportion of the short-term harvest level that depends on future forest timber supply and growing stock with different levels of uncertainty (under specific assumptions, such as harvest order preference and future regeneration). For example, the uncertainty associated with stand regeneration in 50 years may be higher than uncertainty associated with volumes in existing mature stands in 20 years. Different levels and compositions of short-term timber supply may rely more or less on existing mature stands, and may influence the rate of the shift from existing mature stands to future managed stands.

This approach can be used to cast timber supply in terms of upper and lower envelopes of possibility or likelihood. In the short-term, these envelopes are narrow, but widen over time due to uncertainty and variability in factors that influence forest stand structure. The lower envelope could be considered as a ***robust*** or ***resilient*** timber supply, while the upper envelop could be considered as a ***potential*** timber supply. This information may also help identify the kinds of effects (and hence the climate change factors) that are important for timber supply and an AAC determination.

1.1.3. Tools for timber supply modelling

To address these questions, we developed and tested novel methods to improve how some anticipated effects of climate change can be incorporated into timber supply analysis. A number of studies have identified a range of potential impacts (affecting establishment, growth, and stand- and landscape-scale disturbance). While such effects can and have been integrated with simulations of harvest (e.g. in cumulative effects analysis), our goal was to seek a balance between *comprehensiveness* (i.e. ability to include multiple interacting factors) and *parsimony* (i.e. limiting level of detail to avoid proposing overly complex timber supply methods). We developed two new tools to include some climate change effects in timber supply models that are incremental to existing methods:

(a) Dynamic "operational adjustment factors" (OAFs). We propose that allowing OAFs specified at the timber supply area scale (not the stand model scale) to change dynamically over time can capture a number of climate change effects on stand growth rates (e.g. from changes in $C0_2$ concentration, drought) and fine-scale mortality (e.g. root rot conditions).

(b) Natural analysis units and emergent "non-recovered losses" (NRLs). NRLs usually specify a volume (or area) of timber that is considered non-recoverable due to natural disturbance. However, NRLs are typically applied by adding to the harvest target. This means that only available, mature stands are disturbed, and that stands are disturbed in the same "order" as the "harvest preference order". Each natural disturbance agent affects stands using its own criteria, which differ from those employed by people during timber harvests (e.g. they do not respect late seral targets), and from each other. We propose that in addition to timber analysis units (*timber AUs*) (which group stands with similar management and silvicultural characteristics), that we define "natural AUs" based on similar net natural disturbance regime (i.e. the combination of disturbance agents that affect stands). The set of relevant disturbance agents can then be identified for each natural AU, and the characteristics of each disturbance agent can be specified using simple descriptors such as rotation, preference and patch size distribution. Specifying landscape-scale disturbance in this way would cause NRLs to be *emergent* (i.e. an output) from timber supply analysis, which is a prerequisite to exploring the potential effects of climate change on timber supply in terms of changes to natural disturbance regimes.

To demonstrate feasibility of these methods, we performed an experiment in the Morice TSA to explore dynamic OAFs and natural analysis units, and compared results against a previous spatial benchmark of the 2013/14 timber supply review analysis base case, and with stratified timber supply "risk classes" outputs.

2. Methods: General

2.1. Study area, scale and data inputs

The study area encompasses the entire Morice timber supply area (TSA) in northwestern BC, which also coincides with the Morice Land and Resource Management Plan (LRMP) area. This is an area of about 1,501,000 hectares. Spatial data, provided by the BC government, was converted to raster grids at a resolution of 1ha (100m x 100m). Key attributes include a digital elevation model, land cover (non-forest, biogeoclimatic zone, glaciers), forest cover (species, stand age site index, etc.), habitat attributes for moose, grizzly, marten and salmon, and reporting attributes (e.g. watershed assessment unit)[3].

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[3] See Fall and Morgan 2014 for the specific requirements of the landscape dynamics toolkit component.

As in the TSR analysis, we used a time step of 5 years. We assessed timber supply over a 400 year horizon to ensure long-term stability of growing stock and feasibility of harvest over several rotations.

2.2. Benchmarking to TSR base case analysis

Using the spatial and non-spatial information applied in the TSR analysis, we independently developed harvest flows using the TSR base case management regime. Differences in outcome can be expected due to the different tools in use. The TSR analysis used a non-spatial optimization tool, Woodstock, to derive harvest flow. To be comparable, we benchmarked the base case using non-spatial parameters.

Once the base case was benchmarked, a more fully spatial base case scenario was applied (to include the effects of block size and road network access on harvest distribution patterns, but otherwise identical to the non-spatial benchmark). This is important to identify the effect on timber supply of shifting from a non-spatial to a spatial methodology. All experiment scenarios were done spatially.

3. Methods: climate change effects and changes in natural disturbance

3.1. Climate effects on timber supply

Regionalized climate models, such as ClimateWNA, can provide information on potential changes in climate trends (e.g. monthly temperature and precipitation). Climate and forest research is needed to interpret indirect effects, including changes to extreme weather events (wind storms, droughts, etc), as well as effects on landscape and stand scale process including the following:

3.1.1. Stand growth rates

- Increased CO_2 may lead to increased growth rates if this is a limiting factor.
- Changes in soil moisture may increase or decrease growth rates. Increases or decreases in precipitation during the growing season could lead to positive or negative effects related to increased or decreased drought stress. Increases or decreases in snow cover could change the availability of water during melt, affecting tree growth.

3.1.2. Stand regeneration

- Decreased precipitation: may lead to regeneration (or planting) failures, or a change in dominant species. In extreme cases, the biome may shift to a grassland ecosystem (e.g. a Ponderosa Pine BEC variant may shift to a Bunchgrass BEC variant), in which case there may be failures of tree regeneration.

3.1.3. Stand-scale natural disturbance

- Warmer winter temperatures may change fine-scale mortality from root rot and other fungi.
- Fine scale changes in conditions may change the level of natural "gaps" in stands (e.g. increased precipitation could increase fine-scale soil saturation, and areas without tree cover).

3.1.4. Landscape scale natural disturbance

- Fire: direct changes in fire season temperature and precipitation may change both the duration of the fire season and the intensity (and hence potentially size) of individual fires. Fire regimes may be indirectly affected by changes to stand-level disturbance (affecting fuel loads), growth rates (affecting canopy structure), etc.
- Insects: warmer winters could increase over-winter survival of bark beetles. Changes in summer weather could affect insect flight and dispersal. Changes to hosts (age, species, or health) could affect outbreak dynamics.
- Wind: changes to windstorms could change windthrow disturbances, in particular in exposed sites.

3.2. Potential operational responses to climate effects on timber supply

At a fundamental level, climate change means increased uncertainty in forest management.

Operational responses to changes in disturbance include changes to salvage priorities. Salvage opportunity will depend in part on the nature of stands affected by disturbance (e.g. whether stands are merchantable), access and the nature of the decay process. To include climate factors directly in timber supply requires an understanding of salvage dynamics and preferences. Furthermore, applying more spatially explicit forest estate modelling (e.g. capture road access constraints) may be important.

Other operational responses may include increased suppression efforts (i.e. effort to reduce effects of climate change factors), and focused harvest of susceptible stands (i.e. pre-empting disturbance, which may be feasible if susceptible stands can be identified). As with salvage, understanding these potential responses is important to adequately capture the interactions of climate change effects and management in timber supply analysis.

3.3. Tools for climate change effects in timber supply analysis

3.3.1. Dynamic operational adjustment factors (Dynamic OAFs)

OAFs have been used in both stand-scale modelling (to generate yield tables) and landscape-scape timber supply modelling (to modify yield tables, and often referred to as simply "volume adjustments"). I am only referring here to the latter.

A *dynamic OAF* is an OAF that can change value over time. Instead of a single value for each analysis unit, OAFs would be defined as a schedule (e.g. a table with a column for each AU and a row for each decade).

OAF1 is defined here as the "proportion of, or change to, normal growth from the volume tables" and OAF2 as the "proportion of, or change to, normal stand survival at age 100" (i.e. OAF2 effectively defines the slope of the linear survival). For example, an OAF1 of 90% means that 90% of the volume from the yield table counts as merchantable volume. Survival starts at 100% by definition, and the OAF2 value defines the proportion surviving at year 100. Note that these definitions are defined as the reverse of common definitions (e.g. a 90% OAF1 here corresponds to a more common definition of 10%). However, for OAF1, it is sometimes more convenient to discuss “loss of growth” rather than “reduction in proportion of normal growth” (i.e. and OAF1 of 75% may be described as a 25% loss of growth).

In growth & yield models, OAF1 is often used to capture stand gaps, endemic pests, etc. and OAF2 is often used to capture decay, waste and breakage.

OAF1 has been used in timber supply for modifying growth rate (e.g. to include genetic gains), for capturing volume left on site (e.g. for riparian reserves) and for volume cut and removed from the site but not contributing to AAC (e.g. monumental cedar). To be used for climate change, we need to separate the growth rate effects from other effects.

To support changes over time, OAF1 must be applied only to the volume increment (not the entire volume). For example suppose (a) a stand is age 0 at the start; (b) the volume table for the stand is 100 m^3 at age 50 and 120 m^3 at age 60; and (c) that OAF1 is 100% from years 0 to 50, and then changes to 75% at year 60. The net merchantable volume at year 50 is 100 m^3. At year 60, the incremental volume is 15 m^3 (i.e. 20 m^3 at 75% OAF1), leaving a net of 115 m^3. We wouldn't want to apply that 75% OAF1 to the entire gross volume of 120 m^3, which would result in a decrease in volume from 100m^3 at year 50 to 80 m^3 at year 60. This is not an issue for static OAFs, but must be done for dynamic OAFs.

Dynamic OAFs can address changes to "normal" stand growing conditions over time, which cannot be captured easily in growth curves (short of having a growth curve for each AU and for each stand initiating year). "Normal" stand growing conditions are the conditions applied when generating the yield tables (which reflect historical climate conditions).

Dynamic OAFs may be used to assess for some elements relevant to climate change:

(i) effect of increased CO_2 on growth rates (e.g. increasing OAF1 over time to capture gradual increase of CO_2)

(ii) drought (e.g. decreasing OAF2 over time to capture increases in tree-scale mortality from drought and/or decreasing OAF1 over time to capture decreases in growth rate)

(iii) changes to root rot or other fungi

(iv) regeneration problems due to changing site conditions

3.3.2. Natural analysis units and emergent NRLs

Non-recoverable losses (NRLs) are used to capture losses in the THLB due to natural disturbance. One problem with NRLs is that they are effectively "added" to the harvest target, which means that stand selection is the same as harvest selection (e.g. oldest first, although conceivably a priority or partition could be created for each disturbance agent). NRLs have been specified with dynamic changes over time.

A "*Natural analysis unit*" is defined here as stands that share similar natural disturbance regimes (analogous to how timber AUs share similar growing and silvicultural regimes). Timber AUs are often defined based on species, site index, management history (natural, existing managed, future managed), and other attributes (e.g. thinning). Natural AUs can be defined by natural disturbance type (NDT), species (e.g. pine for MPB disturbance, spruce for spruce bark beetle), exposure class (for wind throw), etc.

Unlike timber AUs that subject a stand to a single timber regime, a natural AU may subject a stand to multiple disturbance agents. For example, a natural AU defined as "NDT3-Pl-exposure class 2" could be used to subject stands to stand-replacing fire, MPB and wind throw.

To do this, each natural AU would index a table that defines the applicable stand-replacing natural disturbance agents. Another table would then define the characteristics of each natural disturbance agent, including:

(i) Rotation (e.g. 200 year), which may change over time

(ii) Coefficient of variation (e.g. 0% for static/constant, or 20% for +-20% of the expected mean per time step)

(iii) Proportion of immediate loss (e.g. 0% for insects, 20% for fire)

(iv) Age preference (e.g. analogous to harvest order: random, oldest first, logistic) + 1 preference parameter

(v) Patch size distribution type (e.g. uniform, negative exponential, normal) + 2 distribution parameters

To link natural disturbance effects with timber supply also requires the potential recovery of timber from disturbed stands: *salvage*. Upon disturbance, stand age is reset (and timber AU reset to a natural-origin stand). Standing live volume is moved to *recoverable dead volume*. The harvesting order may put a preference on salvage (based on min. harvest volume). If a stand is salvaged, volume is recovered and the AU is set to planted/managed. Over time, recoverable dead volume would decrease.

In a sense, this design creates a set of "natural disturbance priorities" that each apply a target (based on rotation, not an NRL target) to stands susceptible to that disturbance agent. Volume may be recovered by salvage or not. Volume not recovered in the THLB would be recorded as NRL (i.e. NRL would be emergent, which is important to be able to capture climate change effects).

Natural AUs and emergent NRLs may be used for:

(i) wind throw from increased storms (e.g. wind disturbance agent with decreasing rotation that affects stands with high exposure)

(ii) change to fire regime (e.g. changes to each NDT)

(iii) changes to bark beetle outbreaks

3.4. Climate change effects: experimental design

We designed an experiment to illustrate these method. The reference scenario is the implementation of the TSR base case that has spatial blocks and roading. We designed a set of experiments to vary combinations of:

1. Dynamic OAF1s:
    - No change (i.e. static 100% for all AUs to reflect “normal growth” as in the TSR)
    - Linear increase in growth impact up to 25% by year 100 across all AUs (i.e. OAF1 starts at 100%, declines linearly to 75% at year 100 and remains at 75% thereafter)
    - Linear increase in growth impact up to 50% by year 100

2. Natural AUs and emergent NRLs: disturbance rotation
    - No change (simplified here as a 200 year rotation in NDT 3 and a 500 year rotation in other NDTs 1, 2 and 5.)

- Linear increase to 50% in landscape-scale stand-replacing wildfire over 100 years (and remaining at that level thereafter)

3. Natural AUs and emergent NRLs: temporal stochasticity
    - Constant (same area disturbed each period)
    - 50% coefficient of variation (i.e. selected area disturbed per period from a normal distribution with a standard deviation equal to 50% of mean)

4. Natural AUs and emergent NRLs: disturbance preference order
    - Oldest-first: disturb stands in the a decreasing order of age
    - Random: select stands randomly for disturbance regardless of age

We assessed 18 scenarios, which were named by concatenating the dynamic OAF1 growth decrease (0, 25% or 50%), fire rotation increase (0 or 50%), fire stochasticity (0 or 50%) and fire preference (OF for oldest-first and Rand for random). For example, 25_50_50_OF means a dynamic linear increase in growth loss of 25% over 100 years, 50% linear increase of fire (shortening of rotation) over 100 years, 50% coefficient of variation in fires per period and fire applied using an oldest-first preference. The parameter settings for all experiment scenarios are shown in Table 1. Note that this experiment was designed to illustrate application of these tools, not as an attempt to forecast anything for Morice TSA. Also note that scenario 0_0_0_OF was designed to be broadly comparable to the TSR base case, except that NRLs are emergent and natural disturbance does not follow forest cover constraints.

Table 1. Parameter settings for dynamic OAF and natural AU experiment scenarios

Scenario name	Parameter setting at 100 years (assuming linear changes from present)			
	Dynamic OAF1	Fire rotation	Fire stochasticity	Fire preference
25_inputNRLs	25% impact	n/a (input NRLs)	n/a	n/a
50_inputNRLs	50% impact	n/a (input NRLs)	n/a	n/a
0_0_0_OF	No change	No change	Constant	Oldest first
0_0_0_Rand	No change	No change	Constant	Random
0_0_50_OF	No change	No change	50% CV	Oldest first
0_0_50_Rand	No change	No change	50% CV	Random
0_50_0_OF	No change	50% increase	Constant	Oldest first
0_50_0_Rand	No change	50% increase	Constant	Random
0_50_50_OF	No change	50% increase	50% CV	Oldest first
0_50_50_Rand	No change	50% increase	50% CV	Random
25_0_0_OF	25% impact	No change	Constant	Oldest first

25_0_0_Rand	25% impact	No change	Constant	Random
25_0_50_OF	25% impact	No change	50% CV	Oldest first
25_0_50_Rand	25% impact	No change	50% CV	Random
25_50_0_OF	25% impact	50% increase	Constant	Oldest first
25_50_0_Rand	25% impact	50% increase	Constant	Random
25_50_50_OF	25% impact	50% increase	50% CV	Oldest first
25_50_50_Rand	25% impact	50% increase	50% CV	Random

3.5. Reporting timber supply risk: risk “tranches”

Given uncertainties due to limited knowledge and data about how the forest system may change under climate change, including uncertainty about the degree of specific climate change factors, the actual risks to timber supply, in particular the AAC determination, may not be evident using standard timber supply outputs. A typical deterministic timber supply assessment, using the tools designed for including climate change effects or other methods, will indicate in a broad manner whether short term timber supply is likely to be impacted.

What typical timber supply outputs will not show is the degree of uncertainty associated with timber supply over time. For example, short or mid-term timber supply may not differ very much between scenarios that include or exclude climate change effects. However, the *likelihood* of achieving that timber supply may differ. To fully explore such a likelihood would require integrating timber supply assessment with natural disturbance models, and running multi-replicate simulations to explore the frequency with which near-term and future climate-related events impact the short term harvest (and, conversely, the degree to which short-term harvest interacting with such events may impact mid and long-term timber supply).

An alternative to yet more complex modelling is to consider timber supply through a lens of risk assessment. We developed methods to provide some basic information on climate-related risks to timber supply. First, let us define *climate-related timber supply risk* as risk that a short-term harvest level (i.e. AAC determination) will have unforeseen negative impacts on mid and long term timber supply. To simplify interpretation, suppose we divided timber supply into 2 or more risk classes, or *tranches*, ranging from lower risk to higher risk. The term “tranche” (literally “slice” in French) comes from investment, where a tranche is a portion of an investment that has a particular risk and reward. We used this term for classifying timber supply because the volume contribution to timber supply may be divided into two or more tranches (i.e. the risk tranches are not a categorization of stands but of harvest volume). Volume from a given stand may have different levels of uncertainty regarding availability to support timber supply (e.g. differences between current standing volume and projected increments).

Due to uncertainty about the future in general, and especially in the context of climate change, the proportion of timber supply in the high risk tranche will tend to increase over time, while the low risk tranche will tend to decrease.

Timber supply can be partitioned into risk tranches in several ways. First, tranches must be defined in a way that is additive. This ensures that higher risk tranches represent timber supply that is incremental or additional to lower risk tranches.

The timber supply volume for each risk tranche can be identified using step-wise timber supply experiments. This is similar to sensitivity analysis, in that timber supply is assessed for each tranche (as a scenario) incrementally. The key difference is that higher risk tranches must be incremental to lower risk tranches, and hence the set of experiments must be designed so that timber supply can be decomposed by risk class.

In the Morice TSA case study, for illustration we assessed two different sets of risk tranches:

(a) Base risk classes:
  - Tranche 1: existing mature volume only with no growth increment (but regenerated on natural yield curves).
  - Tranche 2: additionally includes volume growth increments on existing mature stands.
  - Tranche 3: additionally includes existing immature stands (but all still regenerating on natural yield curves).
  - Tranche 4: additionally includes regeneration on managed yield curves (i.e. to assess differences between unmanaged and managed yields)

(b) Climate change risk classes:
  - Tranche 1: timber supply subject to impacts on stand growth (linear up to 25% at and after 100 year) and landscape-scale natural disturbance (linear up to 50% increase at and after 100 years), with disturbance in random stand order (i.e. timber supply resilient to climate change impacts)
  - Tranche 2: additionally includes supply with no stand-scale effects of climate change
  - Tranche 3: additionally includes supply with no increase in landscape-scale disturbance.
  - Tranche 4: additionally includes supply from applying an oldest-first rather than random order for natural disturbance (i.e. timber supply that assumes no climate change impacts)

4. Results: General

4.1. Base case benchmarking

Figure 1 shows the harvest flows from the TSR base case compared with the non-spatial benchmark of the base case scenario. Also included is the spatial benchmark of the base case scenario. All harvest flows support the short term (1st five year) harvest level. The non-spatial benchmark has a similar mid-term harvest level as in the TSR analysis, but steps up to the long-term level 20 years later (after 80 years vs. 60 years). This is likely due to differences in scheduling of early harvest and harvest preference rules between the different tools used.

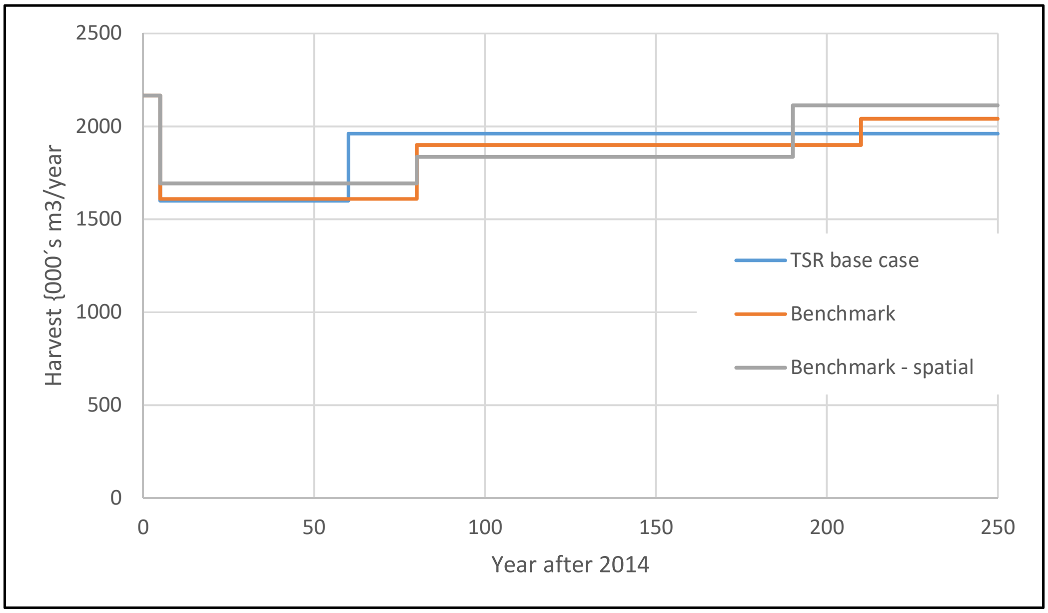

Figure 1. Benchmark of non-spatial TSR base case scenario (Benchmark) compared with the TSR analysis results (TSR base case). Also included is the harvest flow from a more spatial implementation of the base case (Benchmark – spatial), which is used as the baseline for all subsequent scenarios.

5. Results and Discussion: climate change effects

5.1. Dynamic OAF and emergent NRL experiments

Harvest flow results for the experimental scenarios are shown in the following figures.

Dynamically increasing stand-scale growth losses (OAF1) linearly up to 25% and 50% at year 100 (and remaining at those levels thereafter) results in an expected reduction of long-term timber supply by approximately 25% and 50% respectively (Figure 2). Effects on short and mid-term timber supply accrue over the first 4 decades.

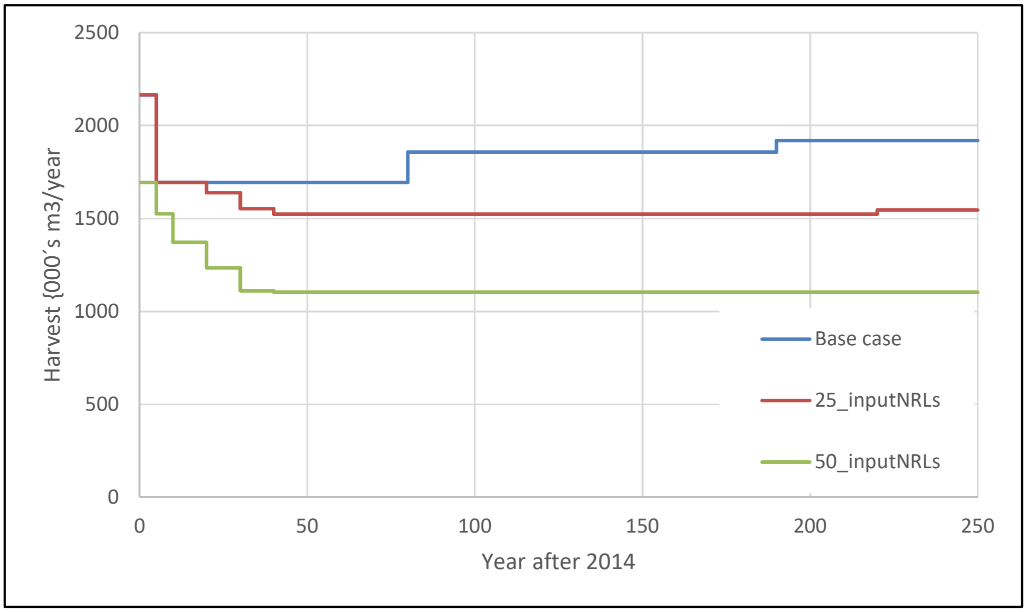

Figure 2. Harvest flows of comparing TSR base case with scenarios that decrease OAF1 dynamically over 100 years by 25% and 50%.

Comparing the base case scenario with scenarios that model emergent NRLs, but not climate change, illustrates some effects of explicitly modelling landscape-scale natural disturbance (Figure 3). To explain these differences, first we need to look at the key effects of natural AUs and natural disturbance in the most comparable emergent NRL scenario: 0_0_0_OF. The natural disturbance level in this scenario was about 4,100 ha / year, of which on average about 2,500 ha / year was in the THLB. The average volume disturbed was about 244,000 m^3/year in the THLB. In the TSR base case, the input NRLs were 60,686 m^3/year (and modelled as an addition to the harvest target), while scenario 0_0_0_OF resulted in an average emergent NRL of 114,600 m^3/year (69,800 m^3/year from with an average salvage of about 129,000 m^3/year (9.6% of the harvest target). Mean disturbance age was 174 years compared with just over 100 for logging (over the 400 year time horizon), while mean volume per hectare in the THLB was 96 m^3 compared with 248 m^3 for logging.

All emergent NRL scenarios result in but higher long-term impacts. This is expected given some key effects of modelling natural disturbance explicitly instead of as input NRLs:

(a) The area disturbed remains more or less constant over time, whereas applying NRLs as input, the area disturbed changes as volume per hectare harvested changes. In the TSR base case, the area disturbed by NRLs effectively decreased from an average of about 270 ha / year in the 1st century to an average of about 170 ha / year in the 4th century.

(b) Salvage effectively shifts the harvest order from that preferred for silviculture (e.g. stand age relative to age at culmination of mean annual increment) to that preferred by natural disturbance agents (in this case, oldest first or random).

(c) Stands are disturbed irrespective of forest cover constraints or road access. In this model set up, we did not allow disturbed sites to contribute to old-forest constraints.

(d) Natural disturbance affected non-contributing forest, and hence impacted forest cover constraints.

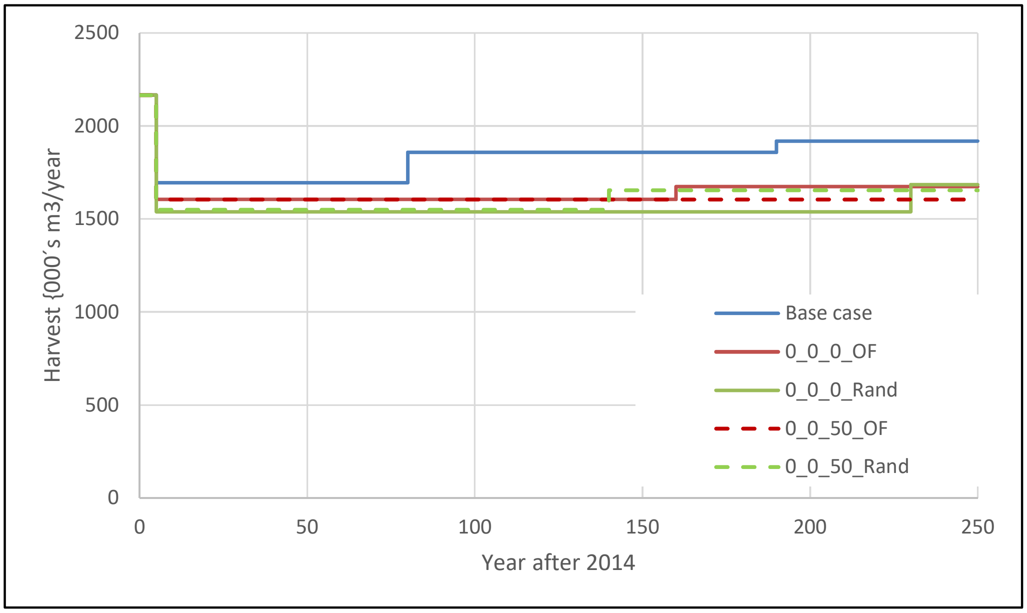

Figure 3. Harvest flows comparing the TSR base case (which applied NRLs as an input) with scenarios with "emergent NRLs" (but no climate change). Emergent NRL scenarios vary the natural disturbance order (oldest-first or random) and temporal variation (no variation and 50% coefficient of variation).

In Morice TSA, the net effect of these factors is to limit the ability of long-term timber supply to increase and to have a modest impact on mid-term timber supply (Figure 3). The effect of applying a random disturbance order instead of an oldest-first order is a modest downward pressure on timber supply. This is due to (a) impacting stands below merchantable age, which precludes salvage; and (b) increasing the level of disturbance in the THLB (since random order affects all stands with equal likelihood, but an oldest-first order is more likely to affect the non-contributing landbase). The effect of applying 50% temporal stochastic variation is modest - while the timing of increased or decreased disturbance may cause higher or lower impacts on ability to salvage, effects average out over long time horizons. Note that this experiment did not, however, place a limit on the level of potential salvage (and this may be limited for economic reasons not included here), which would lead to more timber supply impacts after large disturbance events.

Using the scenario with no climate change and random disturbance order (0_0_0_Rand) as a base for comparison, we can examine the effect of introducing a 50% increase in natural disturbance over 100 years, and remaining at that elevated level for the remainder of the time horizon (Figure 4). In general, the effect was to reduce timber supply across the entire time horizon. Long-term timber supply is affected directly by the increased disturbance, while near-term timber supply is constrained indirectly by the goal of maintaining level growing stock in the long-term (and hence effectively adjusting to accommodate future increases in disturbance). Overall, however, the impact is relatively modest for a significant increase in disturbance.

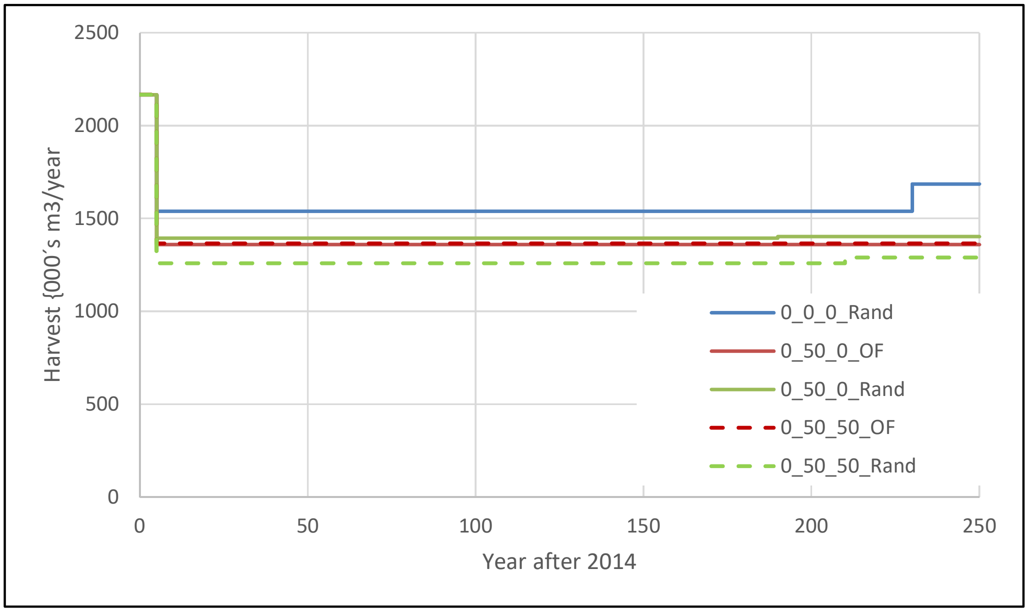

Figure 4. Harvest flows comparing no climate change (0_0_0_Rand – meaning no dynamic change to OAF1, no dynamic change to natural disturbance, no temporal variance and random disturbance order) with scenarios that apply 50% increase in natural disturbance levels by year 100. The climate change scenarios vary the natural disturbance order (oldest-first or random) and temporal variation (no variation and 50% coefficient of variation).

Applying dynamic OAF1s (25% decreased growth over 100 years and remaining at that impact thereafter) with emergent NRLs (Figure 5) combined the trends of both the dynamic OAFs (Figure 2) and emergent NRLs (Figure 3). The impact of dynamic OAFs is an approximate 25% impact in timber supply over the effect of the emergent NRLs. Both limit long-term timber supply, which in turn constrains near-term supply.

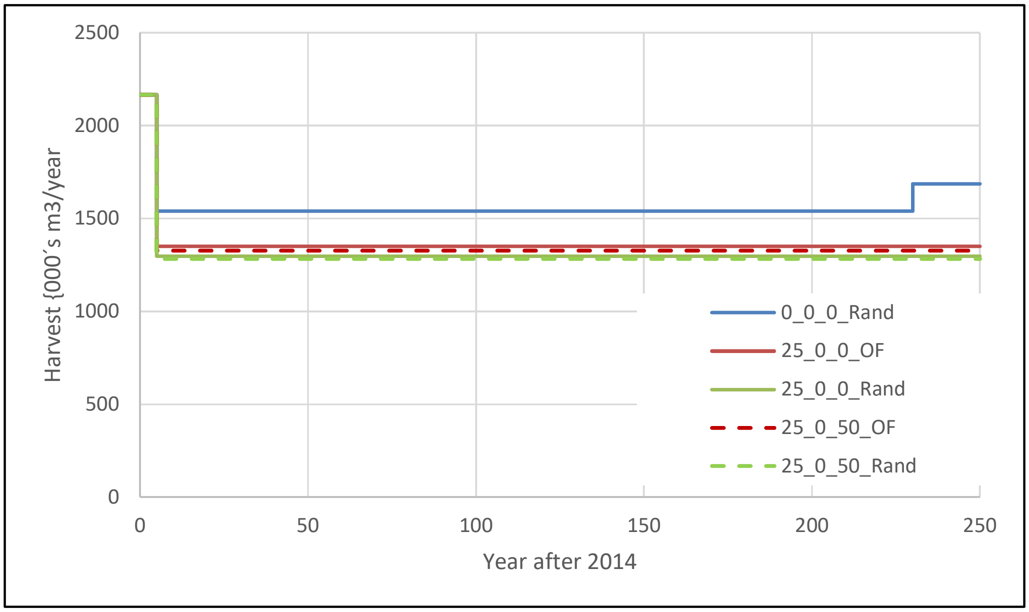

Figure 5. Harvest flows comparing no climate change (0_0_0_Rand – meaning no dynamic change to OAF1, no dynamic change to natural disturbance, no temporal variance and random disturbance order) with scenarios that apply 25% decrease in OAF1 over 100 years, but no change in natural disturbance levels. The climate change scenarios vary the natural disturbance order (oldest-first or random) and temporal variation (no variation and 50% coefficient of variation).

Combining climate change effects to both stand-level growth (dynamic OAF1 decreased by 25% over 100 years) and landscape scale natural disturbance (50% increase in natural disturbance over 100 years) results in additive effects (Figure 6). This is because changes to growth and the level of natural disturbance do not directly affect one another. The net effect on timber supply combined downward pressure from (a) explicit modelling of natural disturbance, which reduces long-term timber supply; (b) increases in future natural disturbance, which reduce long-term and, indirectly, near-term timber supply; and (c) decreases in future growth, which reduces long-term and, indirectly, near-term timber supply.

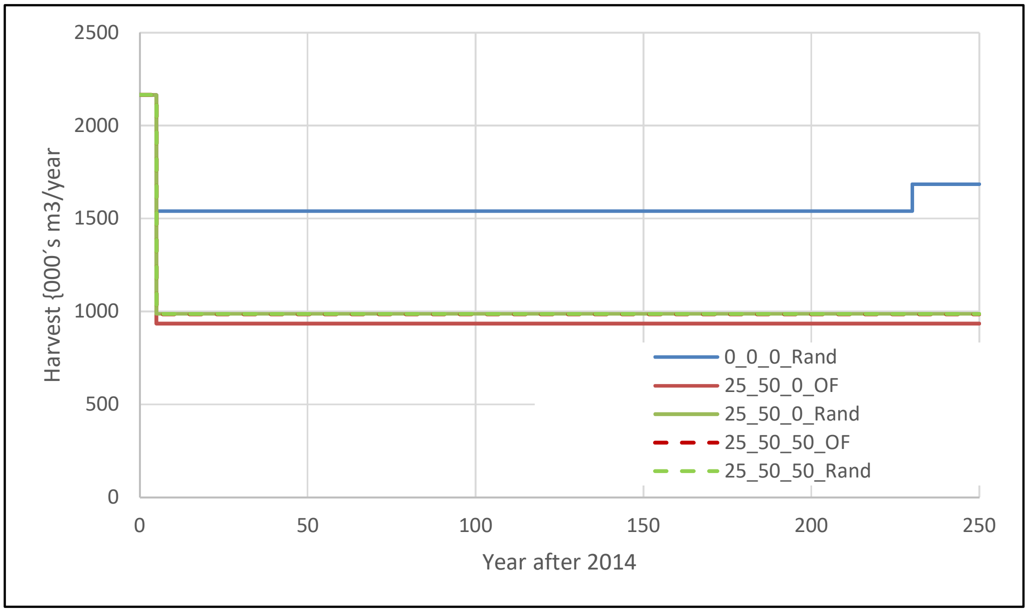

Figure 6. Harvest flows comparing no climate change (0_0_0_Rand – meaning no dynamic change to OAF1, no dynamic change to natural disturbance, no temporal variance and random disturbance order) with scenarios that apply 25% decrease in OAF1 over 100 years, and a 50% increase in natural disturbance levels by year 100. The climate change scenarios vary the natural disturbance order (oldest-first or random) and temporal variation (no variation and 50% coefficient of variation).

5.2. Timber supply risk assessment: risk “tranches”

5.2.1. Base risk classes

The results from applying the “base” risk classes indicates that over the mid to long term, a fairly high proportion (nearly 40%) of timber supply depends on the difference between managed and natural stand yields (Tranche 4 in Figure 7). Nearly 25% depends on existing managed stands (Tranche 3). Only a few percent depends on growth increment to existing natural stands, while over 1/3 depends on existing natural stands (regenerating minimally on natural yield curves; Tranche 1). Short-term timber supply depends heavily on existing natural stands, and to a lesser degree on existing managed stands, until after 10 years.

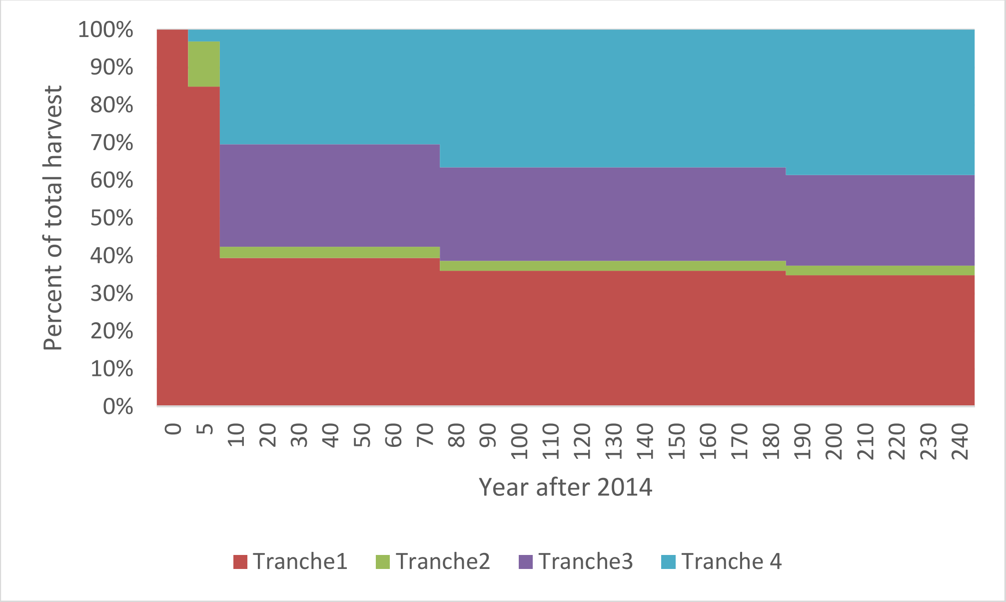

Figure 7. Harvest tranches for the base set of risk classes. Tranche 1 is existing merchantable volume plus future "unmanaged" volume (i.e. stands are regenerated on natural yield curves). Tranche 2 also includes volume increments on existing mature stands. Tranche 3 additionally includes existing immature stands (but all still regenerating on natural yield curves). Tranche 4 includes regeneration on managed yield curves.

5.2.2. Climate change risk classes

The results from the climate change risk classes indicate that about 60% of the timber supply over the mid to long-term appears to be resilient to fairly high levels of climate change impacts on both stand growth and natural disturbance (Figure 8; Tranche 1). About ¼ of supply after 10 years depends on stand growth remaining robust (Tranche 2). Between 13 and 18% depends on natural disturbance levels not increasing (Tranches 3 and 4).

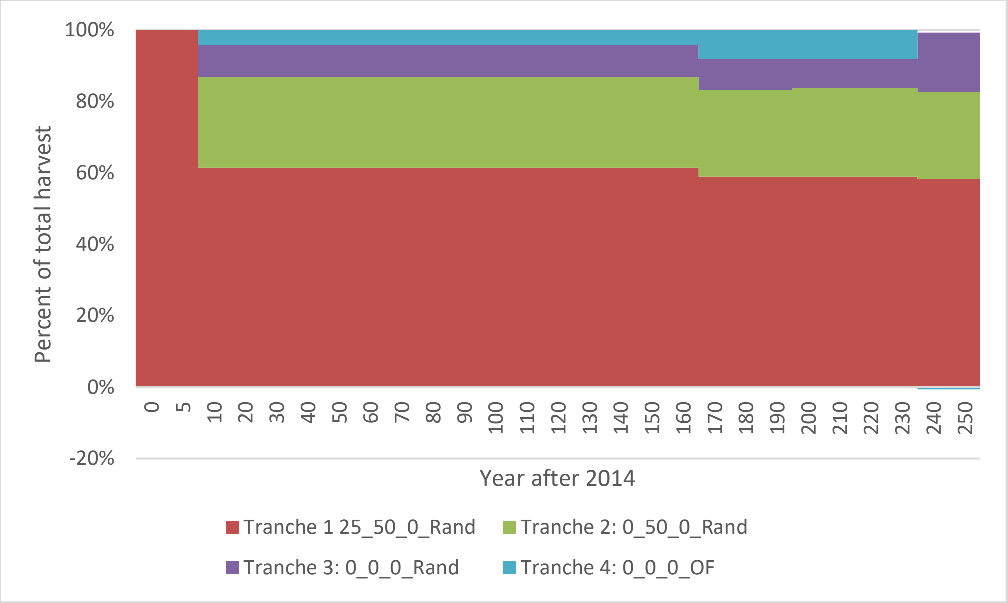

Figure 8. Harvest tranches for the base set of risk classes. Tranche 1 is supply even under climate change impact on stand growth (linear up to 25% at and after 100 year) and landscape-scale natural disturbance (linear up to 50% increase at and after 100 years), with disturbance in random stand order. Tranche 2 also includes supply with no stand-scale effects of climate change. Tranche 3 additionally includes supply with no increase in landscape-scale disturbance. Tranche 4 includes supply from applying an oldest-first rather than random order for natural disturbance.

6. Conclusions

The experiments applied demonstrate the feasibility of applying the new methods, as defined, in timber supply analysis.

6.1. Climate change effects

Changes in climate have the potential to lead to dramatic changes in forest landscapes, and consequent impacts on timber supply. However, as climate trends change incrementally over time, the effects on timber supply tend to be most evident in the long-term, moderate in the mid-term and low in the short-term. However, risks to future timber supply result from the interaction of forest stand structure, harvesting and disturbance. Hence, to account for climate change effects during a timber supply review requires consideration of the risks posed by an AAC determination in the context of changing climate conditions.

To fully examine the dynamic interaction of stand and landscape scale processes that may be affected by climate change in a forest estate model poses technical challenges and has the potential for “analytical burden” on timber supply analysis. Parsimonious methods are needed (a) to include the more important aspects of climate change effects into timber supply modelling; and (b) to assess risk of timber supply to future uncertainties.

To address this need, we developed two relatively simple tools for representing some climate change effects in timber supply models:

(a) *Dynamic OAFs*: allowing operational impact factors (OAFs), which represent the proportion of normal stand growth (OAF1) and stand-scale survival (OAF2) to change over time. Dynamic OAFs can be used to represent a range of stand-scale effects from climate change (e.g. drought, changes in $C0_2$ concentration, changes in fine-scale disturbance, etc.).

(b) *Emergent NRLs*: *natural analysis units* can be defined to group stands that share the same overall natural disturbance regime. Each natural analysis unit can be associated with a set of natural disturbance agents (e.g. wildfire in NDT 3, spruce bark beetles, wind throw in high exposure classes, etc.). In turn, the behaviour of each disturbance agent can be specified according to rotation, disturbance preference order, patch size, etc. Further, disturbance rotation may change over time. Combined with salvage and simplified decay of merchantability of disturbed (i.e. "standing dead") volume, this provides a relatively simple approach to model non-recovered losses as emergent from the interaction between forest stand structure, harvest, disturbance and climate change effects. These "*emergent NRLs*" contrast with input NRLs typically applied in timber supply modelling.

(c) Timber supply *risk tranches*: Components of a timber supply landscape system can be defined according to expected levels of risk under changing climate, and uncertainty in general. These components may be defined as elements of the state of the forest (e.g. existing mature volume, future managed yields) and/or elements of forest processes (e.g. potential increases in landscape scale disturbance or decreases in stand growth due to climate change). By defining a set of risk classes, or *tranches*, in which higher risk categories embed lower risk categories, the resulting nested timber supply assessments can be expressed in terms of the contributing of each risk class to timber supply. This provides a tool to help interpret the degree of risk associated with timber supply, and in particular how risk changes over time.

We demonstrated applicability of these methods using a case study in Morice TSA.

Below are some general lessons learned about incorporating climate change effects on forests into timber supply analysis:

- To capture incremental climate change effects on stand growth and yield requires an approach to modify yields dynamically, as it is less practical to produce yield tables for all possible combinations of expected climate change effects and time of stand initiation (i.e. post-disturbance yields depend on stand age)

- To capture climate change effects on landscape-scale natural disturbance implies that NRLs must be emergent
- To capture emergent NRLs, salvage must be modelled explicitly
- To model salvage implies that merchantability be defined using minimum harvest volume per hectare (and not just minimum harvest age)

Despite being primarily for illustrative purposes, the Morice TSA case study provided some insights into the interaction of timber supply and climate change effects:

- The harvest level achievable in the first decade is quite resilient to climate change effects (which will increase gradually) and hence a level close to the existing AAC does not appear at present to pose risks to future timber supply with respect to climate change. In large part, this is due to the salvage operations to recover timber from MPB-affected stands.
- After the first decade, maintaining the base case short-term harvest level could pose some risks to future timber supply, depending on how climate change effects develop in the study area.
- Climate change effects on landscape-scale disturbance and stand growth potentially have significant effects on timber supply in the long-term and, indirectly, in the near term, due to an objective to maintain fairly consistent timber supply through the mid-term.

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