A Cumulative Effects Modelling Toolkit for the Skeena-Nass Watersheds area of Northwestern BC

March 28, 2022

VERSION 1.0

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0. Executive Summary

A *Cumulative Effects Assessment (CEA) Toolkit* was developed to support cumulative effects analysis at the landscape-scale in British Columbia (BC), Canada for assessing the impacts of development, natural disturbance and climate change on wildlife, salmon and hydrology. This toolkit was expanded and applied in the Skeena-Nass Watersheds area of northwestern BC (Skeena-Nass CEA Toolkit).

Landscapes are complex systems that consist of many elements and interactions, across multiple spatial and temporal scales, and with time lags. In addition to historic issues and values, newly emerging issues, such as climate change adaptation and carbon management, increase the complexity of managing landscapes. As a consequence, to effectively assess cumulative effects over broad areas requires a system perspective of the socio-ecological system of a study landscape.

Simply put, cumulative effects can be defined as the combined effects of past, present and foreseeable natural processes and human activities over time, on environmental and social values in a particular place. This implies a planning perspective rather than a project perspective. Key steps and challenges include

- Scale: selecting spatial grain and extent of study area, and time horizon for which to assess effects
- Scoping: identifying values deemed to be important in a landscape (i.e. the things about which society is concerned may undergo negative impacts)
- Efficiency: how to bound the assessment to make practical use of time and existing tools
- Specificity: how to address unique aspects of a study area (which may require development of new tools and methods)
- Uncertainty: how to address uncertainty in base information and key processes, as well as natural variability

In our “toolkit approach”, we decompose analysis of a landscape system into relatively independent parts or “components” (e.g. glacier dynamics, wildfire, coarse sediment loading, logging, pipeline layout, road networks, grizzly bear habitat). Where feedback between parts can be assumed negligible (e.g. we might assume that grizzly bears have no effect on wildfire, or that logging has insignificant effect on pipeline layout), separate analysis tools can be developed, in which the output of one component may be used as the input to another. In this way, a “network” of toolkit components can be constructed (i.e. a meta-model).

This document describes the cumulative effects toolkit adapted and extended the Skeena-Nass Watersheds area, and describes the general concepts of the toolkit and basic information on toolkit modules. More specifically, we describe the set of components (analysis tools and models) and how they were combined in the study landscape. The main body of the document focuses on general concepts, the study area, and how the toolkit can be efficiently adapted to other study areas. Appendices provide details of toolkit components (individual models or associated groups of models).

This toolkit approach to cumulative effects assessment supports a multi-faceted perspective on exploring landscape-scale risks and scenarios, and a structured flow of information among decision-makers, stakeholders, experts and analysts. Part of the design process for components added to the toolkit is to aim for generality and to facilitate transfer and adaptation to other study areas.

Note: The intent of this document is for discussion purposes only and in no way does it constitute formal commitment on the part of BC Government to implement the cumulative effects framework. Further, the document is not intended to reflect any endorsement by BC Government for any particular approach for assessing cumulative effects.

1. Introduction

One goal of cumulative effects assessment (CEA) is to gain insight into how multiple human activities and natural processes interact over broad areas and lead to changes in ecological and social values. Values are the things that people and governments care about and see as important for assuring the integrity and well-being of communities, economies, and ecological systems (Province of BC 2012). Landscapes are complex systems that consist of many elements and interactions, across multiple spatial and temporal scales, and with time lags. In addition to historic issues and values, newly emerging issues, such as climate change adaptation and carbon management, increase the complexity of managing landscapes. As a consequence, to effectively assess cumulative effects requires a systems perspective of the socio-ecological system of a study landscape (Duinker and Greig 2006, Noble 2010, Eng 2011, Morgan and Daust 2013). However, as complex systems, assessing landscapes in an integrated manner poses many planning and technical challenges.

To make CEA more manageable, we have been developing a "toolkit approach" in which a complex landscape system is decomposed into *components* that have relatively weak feedback. For example, wildlife habitat models in themselves can become quite complicated, and habitat depends on landscape conditions that change over time. If it is reasonable to assume that wildlife does not significantly modify their habitat at broad scales, then habitat assessments can be implemented as separate components from landscape dynamics. Components can be implemented as semi-independent models as part of a *toolkit* that can be connected by using the output of one component as input to another to support a complete CEA (e.g. glacier dynamics, wildfire, coarse sediment loading, logging, pipelines, road networks, grizzly bear habitat). In this way, a "network" of toolkit components can be constructed (i.e. a meta-model; Sturtevant et al. 2007).

This toolkit approach to cumulative effects assessment supports a multi-faceted perspective on exploring landscape-scale risks and scenarios, and a structured flow of information among decision-makers, stakeholders, experts and analysts. Part of the design process for components added to the toolkit is to aim for generality and to facilitate transfer and adaptation to other study areas. This approach builds upon, and extends, the approach to collaborative landscape analysis in Fall et al. (2001), and extends the toolkits developed for the Upper Nass/Iskut area of northwestern BC (Fall and Morgan 2013) and the Morice River area of northwestern BC (Fall and Morgan 2014).

The benefits of this toolkit approach include:

- Efficient use of decision maker time: Parsimonious results relevant to the needs of decision makers can be selected and applied.
- Efficient use of expert time: Experts can focus on their area of expertise without being overwhelmed by the entire system.
- Efficient use of analyst skills: Different analysts and modellers may use different platforms to implement components, provided there is a clear, documented standard for connecting components.
- Adaptability to other areas: Components can be flexibly selected, adapted and connected for use in a different study area. Any new components developed for a new study area become part of the toolkit, while this modularity avoids problems of a single, overly complex model evolving.

We applied this approach in the Skeena-Nass Watersheds area of northwestern BC. Landscape processes in this diverse area include wildfire, insect outbreaks, tree species succession, glacier dynamics, hydrological flow, and climate change. Human activities include mining, oil and gas pipeline development, logging, road development and hunting. Values include grizzly bears, moose, salmon, water quality and quantity, timber supply and mineral supply.

This document provides an overview of the cumulative effects toolkit we developed and applied in the Skeena-Nass Watersheds area, and describes the general concepts of the toolkit, basic information on toolkit modules, and how the toolkit could be adapted to other study areas. More specifically, we describe the set of components (analysis tools and models) and how they were combined in the study landscape. The main body of the document focuses on general concepts, the study area, and how the toolkit can be efficiently adapted to other areas. Appendices provide details of toolkit components (individual models or associated groups of models).

2. Study area and data inputs

The study area encompasses the Skeena and Nass River Watersheds in northwestern BC, and adjacent coast areas, as well as a portion of the upper Nechako River Watershed. This has a land area of about 12,461,000 hectares.

The study area includes the following management units:

- Bulkley TSA
- Cascadia TSA (portion)
- Fort St. James Forest District (portion in Skeena River Watershed)
- Kalum TSA
- Kispiox TSA
- Lakes TSA
- Morice TSA
- Nass TSA
- Former North Coast TSA (now part of the GBR North TSA)
- Pacific TSA (portion)
- Vanderhoof Forest District (portion in Skeena River, Francois Lake and upper Nechako River watersheds)
- TFL 1
- TFL 41
- TFL 25 (block 2)

Spatial data were provided by the BC government, which was converted to raster grids at a resolution of 1ha (100m x 100m). Some attributes were also stored at finer resolutions (e.g. elevation at 25m x 25m grid cells) and coarser resolution (e.g. climate data at 400m x 400m grid cells), as appropriate and with different resolutions nesting. Most of the analysis is done at a resolution of 1ha (100m x 100m grid cells), with a time horizon from several decades to several centuries.

Key attributes include a digital elevation model (particularly elevation, from which slope and aspect can be computed), land cover (non-forest, biogeoclimatic zone, glaciers), forest cover (species, stand age site index, etc.), mining attributes, habitat attributes for moose, grizzly and salmon, water quality/quantity variables, climate variables, and reporting attributes (e.g. watershed assessment unit). The specific requirements for each toolkit component are provided with the description of the component in the appendices.

Key natural processes in the study area include tree species succession, wildfire, Mountain Pine Beetle outbreaks, water balance, glacier mass balance, mass wasting, and climate change. Key human activities include oil and gas pipeline development, logging and road building. Key values of importance include resource capability, wildlife, water quality and quantity, and employment.

3. A cumulative effects assessment network

Cumulative effects assessment (CEA) can be viewed as a network of information flow among decision-makers, experts and analysts. The toolkit developed for the Skeena-Nass Watersheds study area can be described using as hierarchical network[1]. The highest level of the network (Figure 1) shows linkages among the key aspects of a CEA: (i) values and decisions, (ii) value indicators, (iii) scenarios, (iv) knowledge and expertise, and (v) toolkit and analysis. The contents of each of these high-level elements will change over time as a toolkit is adapted and evolved for a study area.

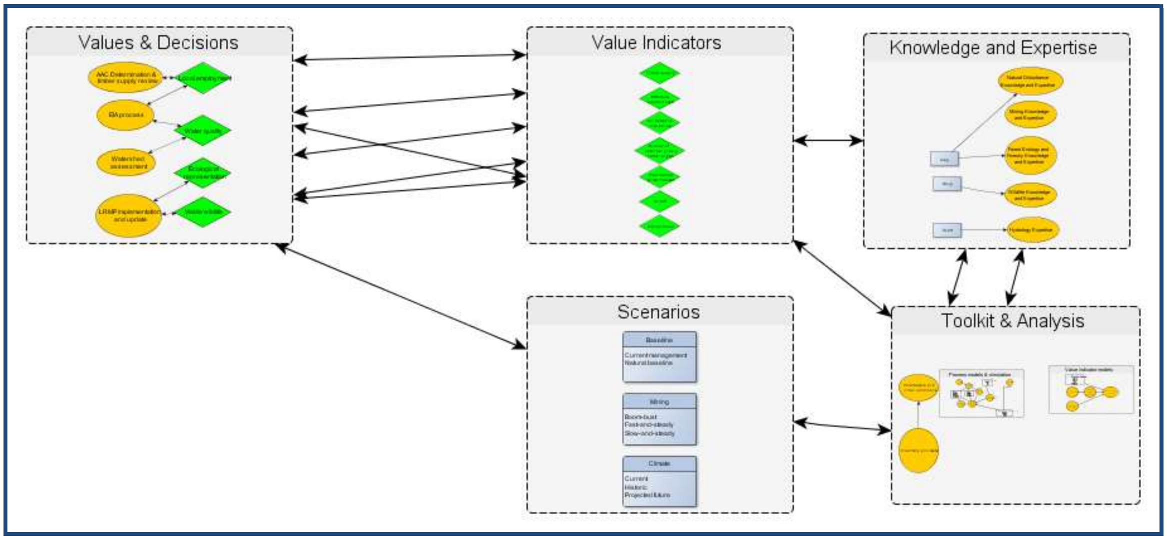

Figure 1. Highest level of CEA network

The focus of this document is the *toolkit and analysis* element. However, since a CEA is done to support natural resource *decisions*, key decision processes (e.g. allowable annual cut determination, environmental impact assessment, watershed assessment, land and resource management planning and updates) are guided by limits informed by socially important *values* for a landscape (e.g. viable wildlife populations, water quality, ecological representation, local employment, etc.). In natural resource management, societal values[2] are expressed as objectives for valued ecosystem services (e.g., maintain salmon spawning

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[1] This was done using the freely available graph drawing tool yEd (www.yWorks.com).

[2] *Societal values* are synonymous with *valued components* used in the federal CEA.

habitat). Values are often assessed using *value indicators* of ecosystem services, which link values to analysis results (Daust and Morgan 2013).

Indicators must be quantifiable metrics that can be measured empirically or assessed via modelling and analysis, and that can be interpreted in terms of risk to values.

Example *value indicators* include timber supply (which relate to employment and provincial revenue), effective clearcut area, water runoff, peak and low flows and expected coarse sediment load (which relate to water quality and quantity), area of old forest by site series (which relate to ecological representation and terrestrial biodiversity), number of potential grizzly natal ranges, and area of moose winter habitat (which relate to wildlife value)

The *scenarios* element refers to key assumptions of external drivers or inputs, which may include management alternatives (e.g. land use options, alternative pipeline configurations), baseline information (e.g. pre-management natural/historic situation), or to quantify uncertainty (e.g. historic, current and projected future climate conditions). Hence, scenarios may represent an over-arching analysis (e.g. to assess all indicators according to alternative land use plan scenarios) or more focused analysis (e.g. to perform a sensitivity analysis of water runoff to different historic and projected future climatic normals). For a CEA, one or more scenarios represent current management and related options or uncertainties.

Scenarios assessed using the Skeena-Nass CEA Toolkit are described in a companion document (Morgan and Fall 2022), as are assessments of selected value indicators (in particular related to grizzly bears, biodiversity and watersheds).

Process and value knowledge and expertise refers to the sources of knowledge to support and inform a CEA. This includes key knowledge bases (e.g. grizzly home range requirements) and experts who may (a) directly or indirectly assist analysts in implementing, refining and interpreting models and (b) assist decision-makers and stakeholders in designing ecosystem service indicators and interpreting analysis results in terms of significance to indicators and values (Fall et al. 2003, Daust and Morgan 2013).

The *toolkit and analysis* element (Figure 2) consists primarily of process models and ecosystem services indicator models. This element also includes base inventory information (e.g. forest cover, mineral potential, glacier cover, natural disturbance) and parameters, which together with relevant scenarios, are used to form the main model inputs for the initial/starting conditions.

The *process models and simulation* element (Figure 3) consists of models of key landscape processes and activities (human or natural) that interact to affect values directly or indirectly. In the study area, these include planning steps (defining timber harvesting land base, access and pipeline cost surfaces, road network layout, gas and bitumen pipeline placement, mineral ore mine placement), interacting dynamic landscape processes (including logging, road development, tree aging and succession, fire, Mountain Pine Beetle outbreaks), and hydrological processes (water balance, glacier mass balance, stream coupling to unstable terrain, coarse sediment hazard).

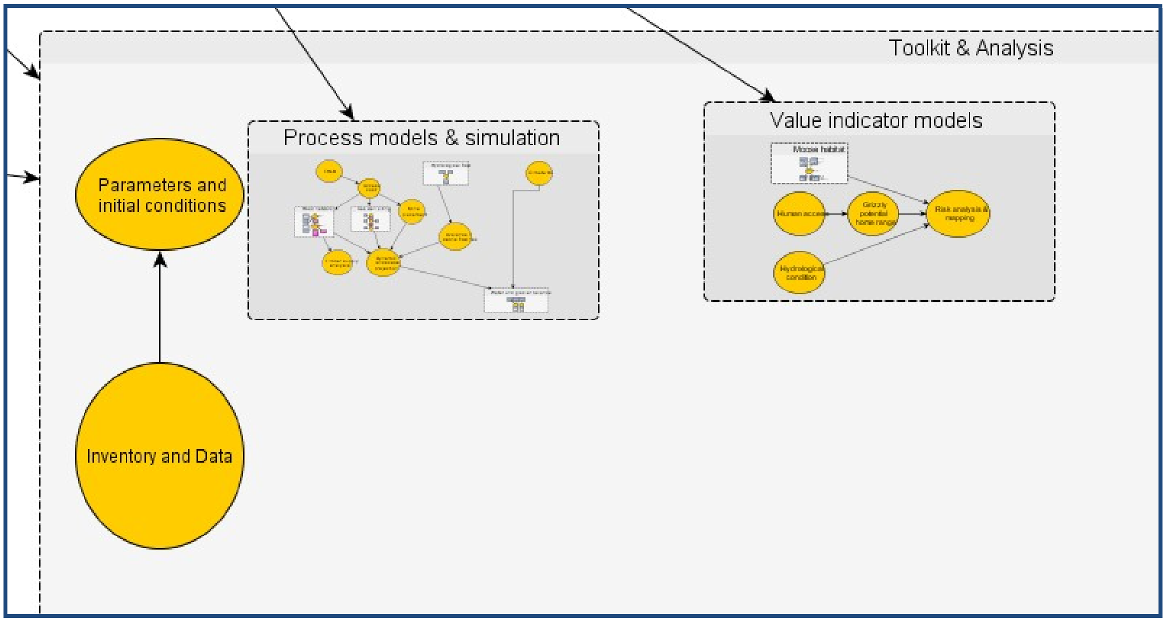

Figure 2. Toolkit and analysis element of the CEA network, with external links from value indicator, scenarios and knowledge and expertise elements.

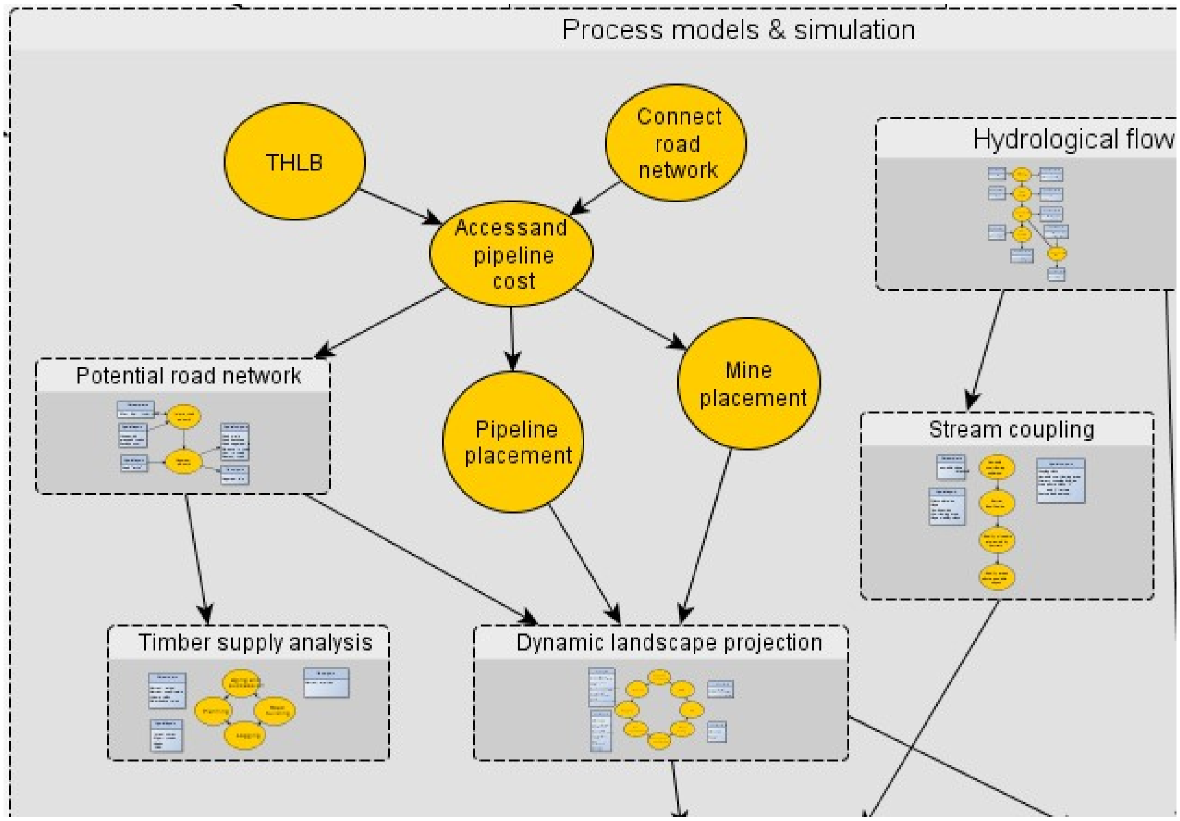

Figure 3. Process models element of the CEA network

The *value indicator models* element (Figure 4) focuses tools for interpreting landscape changes in terms of the key values, and includes models of moose winter habitat, grizzly secure areas, salmon spawning habitat, watershed and stream reach condition (such as peak and low flows, sedimentation), and risk analysis and mapping.

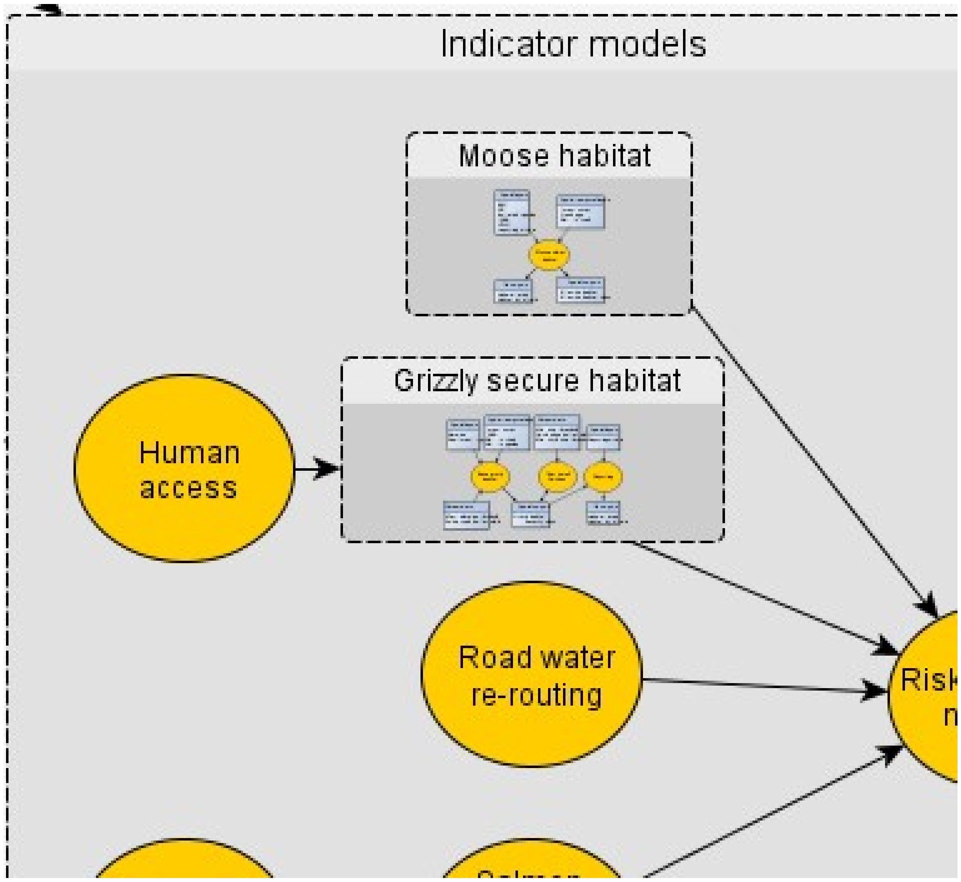

Figure 4.Value indicator models element of the CEA network

The specific details of each component in the toolkit network are described in the appendices. At a high level, however, the salient features of the toolkit include:

- Inter-operable components: output from one component may be used as input to other components in a seamless manner. Outputs are in standard, simple formats (GeoTiff raster grids and text tables).
- Decomposition into components: complex components are decomposed, where possible, into smaller simpler components.
- Hierarchical decomposition: More complex components can be divided into steps of sub-components to simplify implementation and application, but keeping the overall network structure clear.
- Decomposition into sub-processes: in cases where decomposition is not possible (e.g. where feedbacks are significant), a component can be divided into key interacting

elements that communicate via a dynamic shared state. For example, the dynamic landscape projection component consists of sub-models for tree species aging and succession, fire, logging, etc. Each sub-process interacts directly with the shared dynamic state, but only indirectly with other sub-processes.

- Hierarchically nested scenarios: Parameter setting for each component can be viewed as a scenario. For each scenario of a component, there can be many scenarios for components that depend upon its output. An overall scenario consists of parameter setting for all components. In many cases, parameter settings for selected components will be the same for all assessment scenarios. Appropriate naming of scenarios is important so that output folders can be created to support flow of information between components.

4. Applying the CEA toolkit in the Skeena-Nass Watersheds study area

First spatial and non-spatial data inputs were assembled. We started with the toolkit developed for the Morice River CEA (Fall and Morgan 2014). Each component was reviewed and adapted as needed, new components were designed and implemented, parameters were set, and the components were run. For components implemented in SELES (most components in the toolkit), one or more “scenario files” (SELES terminology for scripts to load inputs, set parameters, run the loaded model in SELES and save outputs) were set up. To help ensure that components are run in order (i.e. components that generate inputs are run before components that require those inputs), we define component “dependency levels”. Components that depend only on base data are defined as dependency level 0; the dependency level for other components is the maximum level for components upon which it depends plus 1. Scenarios are prefixed with the dependency level.

Application of the Skeena-Nass CEA toolkit, in particular description and results for selected scenarios, are described in an associated document (Morgan and Fall 2022).

4.1. Climate Refugia Assessment: Proof of Concept

The Skeena-Nass CEA Toolkit was expanded and applied for a climate refugia proof of concept to develop and explore new methods assess macro- and micro-refugia (Eng 2020, Fall 2020). Details of the additional Toolkit components are not included in this report.

4.2. Wetland Network Analysis

The Skeena-Nass CEA Toolkit was expanded to develop and explore new methods to asset wetland connectivity, in particular to identify a hierarchical, nested network of watersheds with their included wetland locations (Fall 2019). Details of the additional Toolkit components are not included in this report.

5. Adapting the CEA toolkit to other study areas

The toolkit approach facilitates adaptation to other study areas, and allows extension of model components of most relevance, as was done during adaptation from the Upper Nass/Iskut and Morice River study areas (Fall and Morgan 2013, 2014) to the Skeena-Nass study area. At a high level, the CEA network (Figure 1) can be revised to include or remove specific decisions, ecosystem services, indicators, sources of knowledge and expertise, and key scenarios. The CEA toolkit sub-network can be reviewed to first remove items not needed in the new study area, and then to add in any required new components.

For each existing component to be retained for the new study area, a review is required of the assumptions and inputs. There are three possible situations; 1) the component can be applied unchanged (e.g. for general components such as contributing area); 2) the component can be applied with changes only to parameters and other inputs (e.g. potential road network), or 3) the model itself may need to be modified (e.g. THLB if different aspects are included). While maximizing re-usable components improves efficiency, it is critical that assumptions be understood and reviewed. Experience has shown that adapting succession models between study areas is one of the most challenging elements, since succession is tied directly with local species and conditions, as well as locally available ecosystem knowledge. In the Morice River study area, the availability of a previously implemented succession model (from the LRMP analysis) facilitated adapting this component, while lack of such information for the much larger the Skeena-Nass study area limited our ability to model tree species succession in the latter.

For new components, the first step is to design high-level requirements and main inputs/outputs, as well as dependencies with other components (i.e. create a new node in the toolkit sub-network diagram). New components may need to be implemented from scratch or existing tools may be available to include or adapt to the toolkit. While building new tools for the toolkit may take significant time and human resources, a key advantage of the approach described here is that the toolkit can be expanded and generalized incrementally over time as CEA is applied in different landscapes.

5.1. Relation to the SELES Spatial Timber Supply Model

The SELES Spatial Timber Supply Model (STSM2020 and later versions; Fall 2021) is an adaptation of the CEA Toolkit described in this document, but with a focus on supporting timber supply analysis (such as required to inform the Chief Forester in making an Allowable Annual Cut determination as part of the Timber Supply Review process).

STSM2020 has been used, and is currently being used, in a number of forest management units across BC (including Haida Gwaii, Great Bear Rainforest, Mackenzie TSA, Nass TSA, Kispiox TSA, and Morice-Bulkley TSAs).

The structure of STSM2020 is the same as the Skeena-Nass CEA Toolkit, and can be used and expanded in the same manner as the Skeena-Nass CEA Toolkit. For example, model components have been integrated with the STSM2020 to link outputs from timber supply model projections and the Carbon Budget Model of the Canadian Forest Service (CBM-CFS3; Kurz et al. 2009) to support carbon projects in Haida Gwaii and the Great Bear Rainforest.

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Appendices

Each appendix describes one of more related model components. Basic components are described in full. More complex components are described briefly, with details in associated document files. At the start of each component description, we identify key dependencies (i.e. other components in the network that provide inputs directly to, or take outputs directly from, this component) and dependency level. Unless otherwise indicated, components were implemented using the SELES spatial modeling tool (Fall and Fall 2001).

Appendix 1. Timber harvesting land base

Directly depends on: base data only
Dependency level: 0

Directly used by: access cost, dynamic landscape projection

The timber harvesting land base (THLB) represents the best current estimate of forest that is economically viable and socially permitted for harvest. That is, the THLB represents the intersection of (a) forest with sufficient productivity, economic tree species, and economically and silviculturally viable access.; and (b) land not reserved from harvest for ecological or social reasons (e.g. protected areas or wildlife reserves).

Often the THLB is generated from base data using the assumptions in the most recent timber supply review (TSR) analysis, which define THLB based on a number of factors (e.g. exclusions due to low site index, riparian exclusions). While the economic exclusions are not regulated (e.g. harvest may, and often does, occur outside the THLB), the THLB forms a basis for assessing the potential timber supply on a landscape as well as the most likely areas in which harvesting will occur. One reason to build THLB "from scratch", rather than just using the THLB developed during the TSR analysis, is to allow flexibility to examine scenarios that use different definitions of THLB. As THLB is used by components other than just timber supply, it is one of the first toolkit components to be applied.

As in the Morice River CEA analysis, the base THLB for the Skeena-Nass was provided as part of the input data, using information from the most recent Timber Supply Review (TSR) analysis for each management unit. In addition, this component as used to:

(a) Create an expanded THLB for reduced-regulation scenarios by estimating THLB in areas removed for social or environmental values (e.g. protected areas); and
(b) Create a reduced THLB for increased-regulation scenarios by netting out areas with other social and environmental values (e.g. areas with riparian management).

Appendix 2. Hydrological flow: contributing area and soil moisture

A) Directly depends on: base data only
Dependency level: 0

Directly used by: stream coupling, water and glacier mass balance

Contributing area, defined here as the area (ha) that flows through each grid cell (i.e. size of the watershed area upslope from each cell), is a basic calculation used in the hydrological components. Cells with low values are shedding sites (e.g. ridges, local peaks), and cells with high values are accumulating areas in valley bottoms (e.g. rivers, lakes). The approach implemented here is based on Tarboton (1997).

This contributing area model component (Figure 5) requires only a grid of elevation. A first step creates a "pitless" elevation raster, where pits are defined as areas that do not have a downward or horizontal flow path to the edge of the study area. Pits may be caused by data errors or variance, resolution, or from gridding of flat areas such as lake basins. The second step is to compute contributing area and flow direction (aspect). Three versions were implemented: (i) the D8 algorithm, (ii), the D∞ algorithm as in SINMAP (Pack et al 1998) and (iii) a hybrid we developed called the D8∞ algorithm. See Tarboton (1997) for a description of D8 and D∞. In general, D8 transmits all flow from a cell to a single downhill neighbour, while D∞ diffuses flow to one or two downhill neighbours to follow aspect more accurately. The D8∞ algorithm transmits all flow from a cell to a single downhill neighbour, like D8, but also tracks and applies accumulated errors, like D∞.

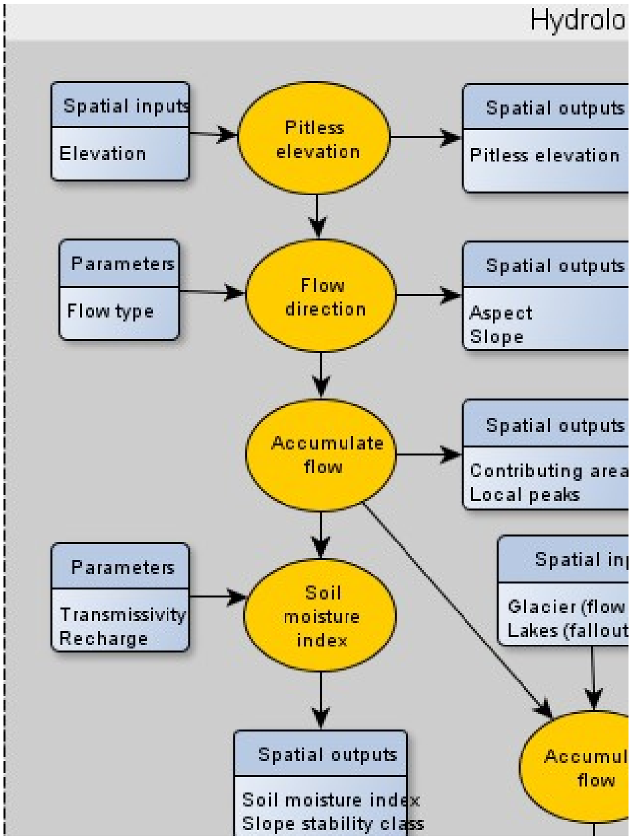

Figure 5 Hydrological flow (contributing area) component of CEA toolkit network.

For most applications, D∞ produces more accurate results (e.g. for soil moisture modelling), but D8 has the property that flow "*monotonically increases*" as it proceeds downslope from each cell to exactly one neighbour, the most downhill neighbour. That is, the flow within a cell is guaranteed to be larger than any uphill input cell. This does not hold for D∞, since flow at an input cell may be divided among two neighbours. This monotonicity property is useful for estimating stream size and traversing stream reaches.

However, a significant problem with D8 flow is grid biases (e.g. on a 20° slope, all flow is directly north, since 0° is closer to 20° than the northeast cell at 45°, which is a considerable error). The D∞ method was designed to address this error (Tarboton 1997), and instead of flowing to one neighbour, flow is apportioned between the two most downslope neighbours (e.g. in the above example, 5/9 of the flow would go north and 4/9 to the northeast cell). This reduces flow error caused by grid artefacts. However, it also loses a key benefit of D8 – that flow increases *monotonically* (i.e. the contributing area of a cell is always larger than that of any neighbour that flows into the cell).

We designed the D8∞ method to retain the benefits of both approaches. Like, D8, the D8∞ transmits flow from a cell to a single downhill neighbour. However, it tracks accumulated error as flow proceeds and uses this to offset flow direction downslope. Continuing with the above example, the first step of flow would transmit directly north with an error of 20°W. At the next step, the effective aspect would be 40°, which would lead to flow to the northwest cell (45°) and accumulated error would now be 5°E.

This model component is best applied at a relatively fine resolution. As such, we ran it at the 1 ha/cell scale (100m x 100m) as well as at the 0.0625 ha/cell scale (25m x 25m).

The contributing area model also allows use of a mask layer as input that specifies the area that "*contributes*" to the flow accumulation. The default is every cell in the landscape (to compute the general contributing area layer). Using a glacier mask, however, allows computing "*glacier contributing area*" – that is, the area (ha) of glaciers that flows through each grid cell (i.e. amount of upslope area that consists of glaciers). Glacier CA can be used to assess risk to changes in water flow (since glacier fed creeks have different timing of peak/low flows than rain-dominated creeks). Similarly, this component can be used to compute other attributes, such as length of pipeline upstream from each cell.

A second sub-component of the hydrological flow module is used to compute soil moisture index, based on Pack (1997). The "*relative soil wetness index*" (SW) is a function of "*specific catchment*" (Contributing area / cell width, with a value in m^2/m), slope, transmissivity, and recharge. Transmissivity is a parameter of soil depth and texture – it can be applied spatially, but often only a general parameter for an area can be estimated. Recharge is a parameter of precipitation, which can be applied spatially or as a single value. The default ratio of transmissivity to recharge (i.e. transmissivity / recharge) is 2000.

> *$SW = (recharge / transmissivity) * (specific\ catchment / SIN(\theta))$, where*
> *θ is slope in degrees and the result is bounded in the range from 0 to 1.*

Based on soil wetness, a slope "*safety factor*" (SF) is defined as:

> *$SF = \rho_s / \rho_w * (1 - TAN(\theta) / TAN(\varphi)) / SW$, where*
> *φ is the soil internal friction angle (default: $TAN(\varphi) = 1$)*
> *ρ_s / ρ_w is the ratio of the density of water (ρ_w) to soil wet bulk density (ρ_s), with a default of 2.*

The safety factor is then used to compute a "*stability index class*" (Pack 1997):

> *Unconditionally unstable*: $TAN(\theta) > TAN(\varphi)$
> Affected by wet conditions: $(1 - \rho_w / \rho_s) * TAN(\varphi) < TAN(\theta) \leq TAN(\varphi)$
>   *Generally unstable*, if $SF \leq 1$, otherwise *Generally stable*
> *Unconditionally stable*: $TAN(\theta) \leq (1 - \rho_w / \rho_s) * TAN(\varphi)$

A second "*stability class*", based on Utzig (2009) is also computed for use in the sediment hazard components as an estimate of potentially unstable terrain types where inventories are unavailable:

> *Stable*, if slope < 45% or SF > 4
> *Class IV*, if slope ≥ 100% or 1 < SF ≤ 4
> Class V, if SF ≤ 1

Soil wetness, safety factor, stability index class and stability class are output as grids.

Further details of this component can be found in an associated appendix addendum (Fall 2022).

Appendix 3. Access and pipeline cost

Directly depends on: timber harvesting land base and connected road network
Dependency level: 1

Directly used by: potential road network, pipeline placement, mine placement, dynamic landscape projection

Road access is required for many human activities in the study area, in particular for mining development and logging. As a preliminary step to model road access, an *access cost surface* was constructed. The access cost surface model from the Morice River CEA analysis was adapted as a CEA toolkit component. This cost surface has higher cost with increasing slope, higher cost across certain non-forest types, private land, archaeological sites, protected areas, and wildlife habitat. Different parameter settings can vary the weights applied to each factor as well as how factors are combined to create a cost value.

First, the following economic factor weights were summed, with a maximum value of 1:

(a) *Slope class*: < 5%: 0; 5-15%: 0.1; 15-25%: 0.2; 25-35%: 0.3; 35-45%: 0.4; > 45%: 1
(b) *Land cover*: glacier, river, gravel, clay, clearing and urban: 1; alpine: 0.2
(c) *Riparian*: by stream watershed size (contributing area): 1,000ha – 9,999 ha: 0.4; 10,000ha – 99,999 ha: 0.8; ≥ 100,000 ha: 1
(d) *Lacustrine*: lakes and wetlands: 1
(e) *Private land*: 1

Additionally, in areas with existing road/rail access, the economic cost value was overridden and assigned a value of 0.

Second, the following social values were summed, with a maximum value of 1:

(a) *Wildlife*: (caribou, grizzly bear, moose, mountain goat, northern goshawk): 1; based on ungulate winter range, habitat maps and wildlife management zones.
(b) *Land use*: provincial parks, ecological reserves, old-growth management areas. archaeological sites, and high biodiversity emphasis areas: 1.

Finally, the economic and social factor weights were averaged to obtain the final value for the cost surface for each cell in the study area (with a min. value of 1).

A related sub-model was used to generate a pipeline cost surface, based on slope and land cover, to explore the factors that best capture the location of proposed pipeline corridors.

Appendix 4. Slope to stream coupling

Directly depends on: contributing area, soil moisture (stability class)
Dependency level: 1

Directly used by: coarse sediment hazard

Slope to stream coupling refers to the potential of unstable terrain (class IV and V) to provide sediment inputs to streams and watercourses. This component essentially re-implements and refines the model described in Utzig (2009). Figure 6, duplicated from Utzig (2009) illustrates the conceptual basis for coupling model, which was designed to be applied at relatively fine resolution (25m cells in the Skeena-Nass study area).

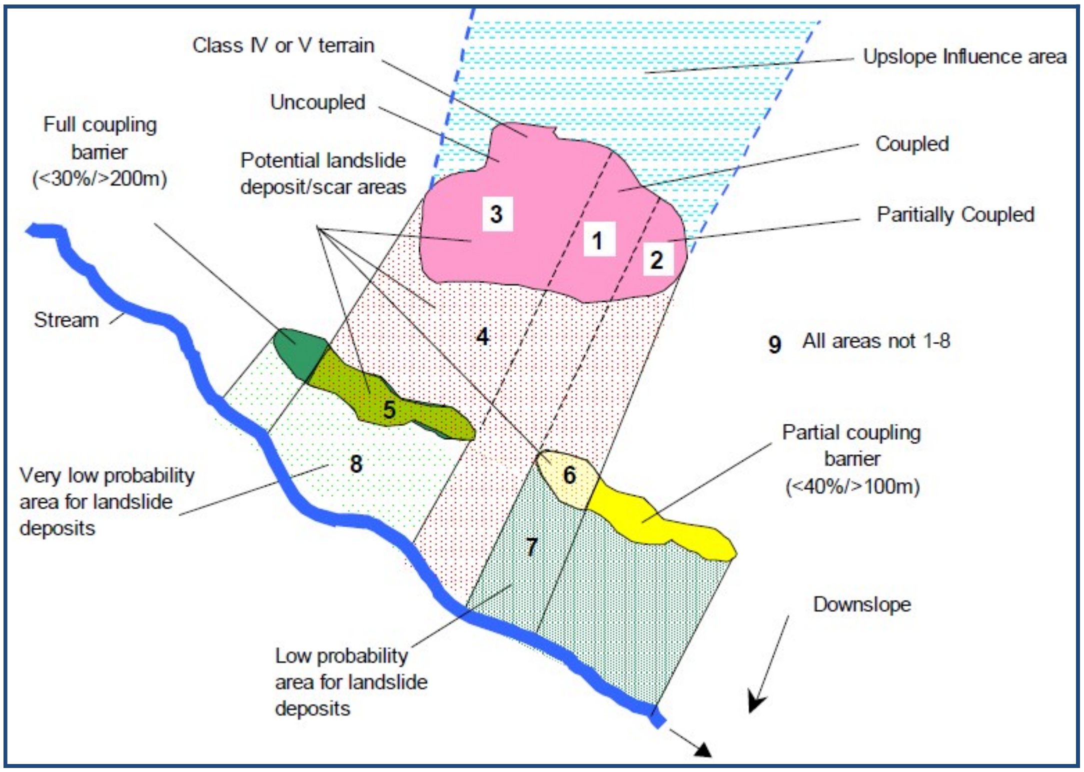

Figure 6. Conceptual diagram from Utzig (2009) of slope to stream coupling. Zones 1-3 represent unstable terrain with the potential for landslide initiation that may deposit sediment into streams. Zone 5 represents a major barrier to landslide deposits, and zone 6 represents a partial barrier. The area upslope from coupled unstable terrain represents a potential influence zone where drainage modification may increase likelihood of downslope landslide initiation.

The *slope to stream coupling* component of the toolkit (Figure 7) was implemented as a four-step process:

(1) The first step computes total and effective "*unstable contributing sediment*" based on pitless elevation, slope, aspect, streams and stability class (output from the soil moisture portion of the hydrological flow component). Total unstable contributing sediment is similar to contributing area, except it uses units of sediment load instead of area and accumulates only from areas downslope from class IV and V terrain. The parameter setting applied were as in Utzig (2009): class V terrain contributes an average of 1m depth each 1000 years (1,000 m^3/km^2/year); class IV contributes an average of 0.5m depth each 5000 years (100 m^3/km^2/year). For use, Utzig (2009) assumed 50% of the sediment load was coarse, and 50% was fine and organic. Effective unstable contributing slope, however, accounts for reductions in potential sediment load, and applied a 10% reduction overall, plus a reduction of 40% for each partial barrier and 90% for each total barrier.

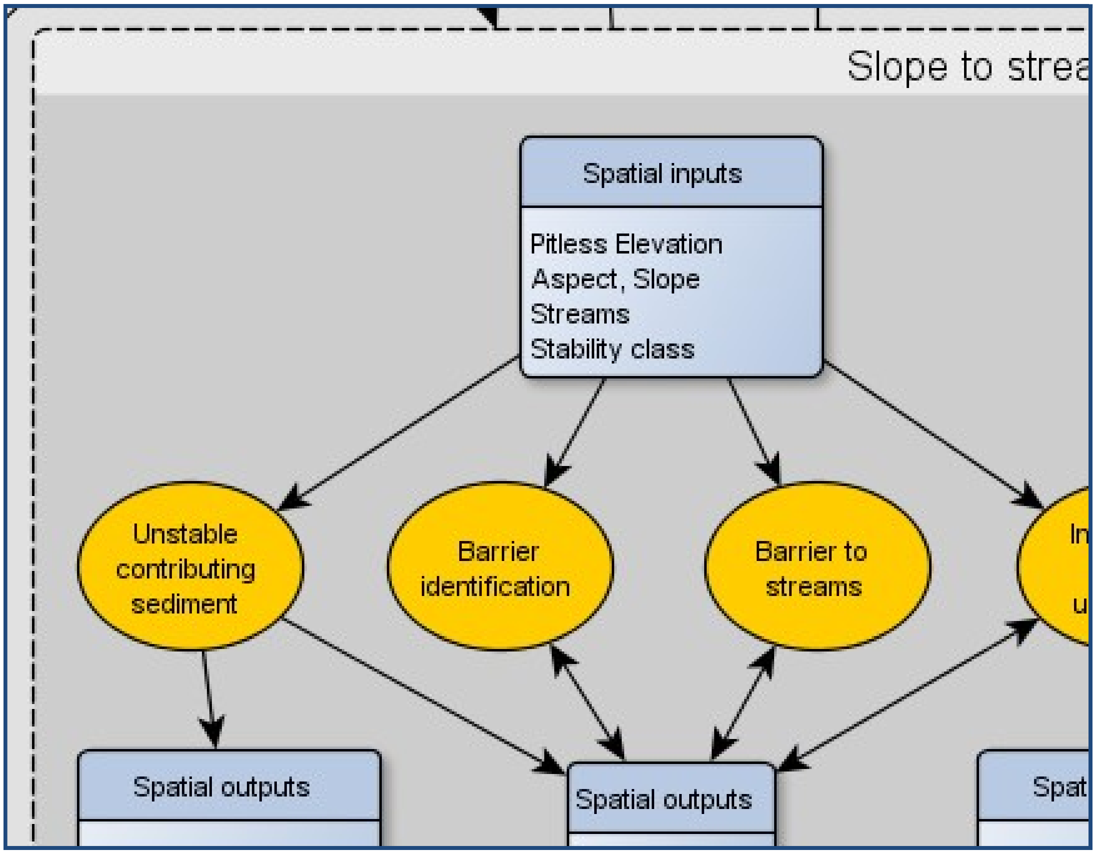

Figure 7 Slope to stream coupling component of CEA toolkit network.

For contributing flow, this component used the D8∞ algorithm to ensure that sediment flow was always to a single downhill neighbour (like D8), but has higher accuracy (like D∞). The D8∞ algorithm works best when modelling flow paths individually from source to receiving cells (in this case from class IV and V terrain to streams). See further details in the appendix on the hydrological flow component.

Flow of contributing sediment is applied for each class IV and V terrain cell separately, in order of decreasing elevation, with total and effective contributing sediment accumulated in each cell traversed. If a stream cell "*deposition point*" is reached, the coupling class at the source class IV or V terrain cell is recorded, depending on whether barriers were traversed along the flow path (*decoupled, partially coupled,* or *coupled*), as well as the stream coupling location. For efficiency, if flow reaches another class IV or V terrain cell, the current sediment load is recorded, and flow stops – the lower elevation unstable cell will take care of continuing the flow and the last step of the process (identifying upslope influence area) will take care of assigning coupling class. In addition, when barriers are identified, the upper perimeter is marked.

(2) The second step of the coupling component identifies partial and total barriers, based on pitless elevation, slope, aspect, steams, and the partially computed coupling class and barrier upper perimeters from step 1. Starting in the upper perimeter cells of barriers, flow proceeds downslope (using the D∞ method, so that barrier polygons are fully identified) until the barrier is exited. The coupling class layer is updated by classifying the total and partial barriers.

(3) The third step identifies areas below barriers and above receiving stream cells. Starting in barrier cells, flow proceeds downslope (using the D∞ method) until stream cells are reached. The coupling class layer is updated by classifying the areas below total and partial barriers.

(4) The last step identifies the upslope influence zone on class IV and V terrain. This sub-model starts in class IV and V terrain cells for which a coupling class has been defined – these are the lower "*cusp*" class IV and V terrain cells for which flow to the nearest stream does not traverse other class IV and V cells (although it may traverse barriers). These cells are processed in order of *increasing* elevation, and flow proceeds *upslope* (using the D∞ method) to ridge tops, identifying the upslope influence zone and assigning the unstable (indirect) coupling location. In addition, as flow traverses class IV and V cells that were not assigned a coupling class in step 1 (because they flowed into lower class IV and V cells), the coupling class and stream coupling location are assigned.

Appendix 5. Spatial graphs

Directly depends on: general utility; depends on use (e.g. access cost, ridge cost)
Dependency level: n/a

Directly used by: potential road network, gas well and pipeline placement, snow avalanche hazard, grizzly isolation

Spatial graphs are a mathematically formal method to construct and examine "*nodes*" (e.g. habitat, gas well sites, roads) that are connected by "*links*" to form a network across a study landscape (Fall et al. 2007). A number of tools have been built to extract a spatial graph given a grid that identifies patches and to analyse graphs in terms of connectivity. The two most common forms of graph relevant for the CEA toolkit are *minimum spanning trees* and *minimum planar graphs.* The minimum spanning tree joins all nodes with links of minimum total length (or cost) such that there is exactly one path (sequence of nodes and links) between each pair of nodes (i.e. no cycles). The minimum planar graph, which embeds the minimum spanning tree, includes all inter-node links of minimum length (or cost) such that no links cross. This creates a network, or mesh, which is essentially a triangulation of the nodes. If nodes are points, or single cells, and links are straight lines, the minimum planar graph is precisely the Delaunay Triangulation (Fall et al. 2007).

Spatial graph models are included in the toolkit as a general utility that can be used by different components. It is used in the Skeena-Nass CEA analysis for joining mountain peaks along ridges to identify ridge lines, and for assessing isolation of grizzly bear population units.

Appendix 6. Potential road network

Directly depends on: access cost
Dependency level: 2

Directly used by: dynamic landscape projection

Many human resource activities in the study area require road access, in particular mining development and logging. Different scenarios require different degrees and locations of roading. In order to provide more consistency, control and efficiency for the roading aspect of different scenarios, a component was designed to create potential future road segments *a priori* (Figure 8). During projection (simulation) of landscape dynamics for a given scenario, road segments will be enabled from this potential future road network as required, as well as potentially disabled after periods of disuse.

The potential road network component takes several grids as input:

(a) *Area to access*: identifies the area for which to construct road access. In general, this is the study area excluding areas that would never require access, such as protected areas, private land, lakes and archaeological sites.

(b) *Existing roads*: existing and mapped future roads.

(c) *Access cost*: a surface with relative costs for constructing a road (using output from the Access Cost module)

(d) *Water access*: identifies points on coastal areas (or lakeshores) with water access.

(e) *Road exits*: identifies locations of "*road exits*" from the study area – that is, the primary road cells at the perimeter of the study area from which traffic will enter and leave.

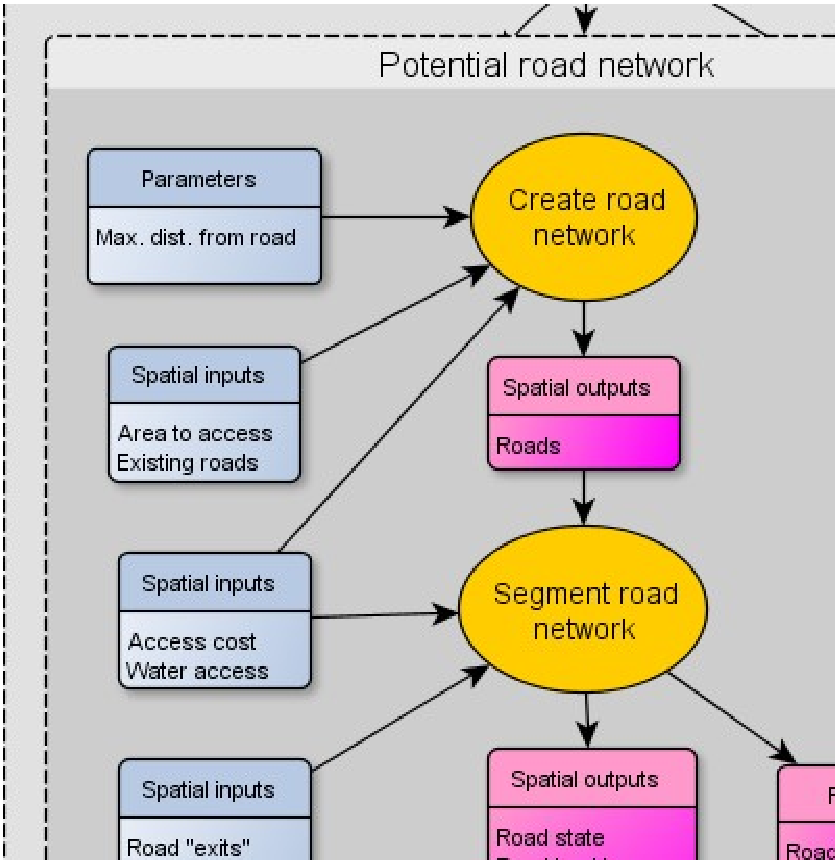

Figure 8 Pre-generation of potential future roads component of CEA toolkit network.

The component has one main parameter: *maximum distance from road* (the maximum distance any cell in the area to access should be from an existing or potential future road).

This module has two sub-models: one to create the road network and a second to divide the existing + potential future road network into segments. The primary outputs are grids of the constructed road network (e.g. as in Figure 9), grids of road attributes (existing/future state, minimal backbone, segment id, distance to nearest road, cost to nearest road and nearest road segment id) plus a tabular file of road segment information.

As a first step, a check is made to ensure that all existing road cells have a path to a road exit or water access point. Road segments with no connection to an exit are ignored.

The potential road network model then runs iteratively. Each step, the distance and cost to nearest road are first updated. Then a location needing access is stochastically selected, with higher probability with increasing distance from road. A new road segment is constructed by following the least-cost path to the nearest road cell, and the next iteration follows until all areas to access are within the maximum distance from a road.

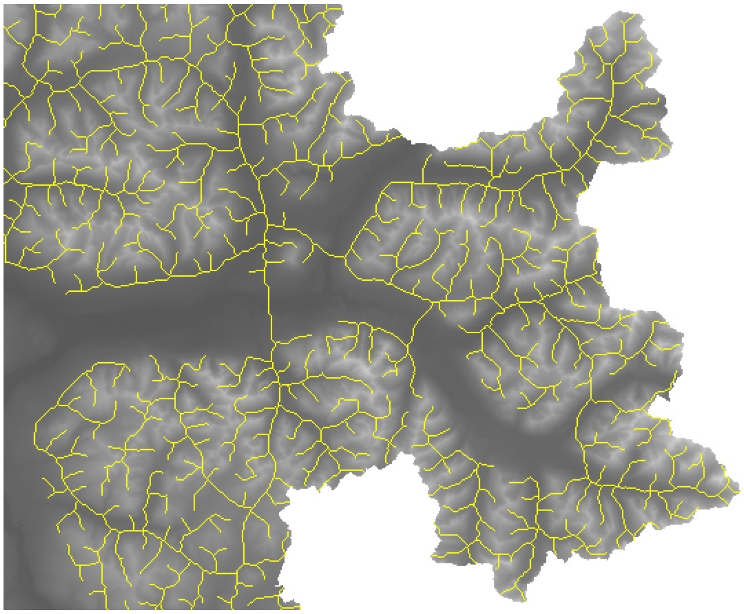

Figure 9 Example output: potential roadwork in Chukachida River tributary of the Stikine River, connected all cells, except those within protected areas, to within 1 km of a road segment. The Chukachida River valley bottom is a protected area, but one that allows road access across.

The second element is a sequence of sub-models to:

(a) Identify a "*road backbone*", which is a minimal set of road cells that don't disconnect roads. A backbone simplifies traversing road networks.

(b) Divide the road network into segments, where a segment is created whenever a road forks, or the end of a road branch is reached (or when a road crosses a layer of boundaries, such as management units).

(c) Construct surfaces for distance and cost to nearest road for existing and for existing + potential future roads, as well is identify nearest road segment id and location.

Appendix 7. Pipeline placement

Directly depends on: access cost
Dependency level: 2

Directly used by: dynamic landscape projection

At least 7 gas and bitumen pipelines have been proposed to cross the study area. the locations of which were provided in the input data. In the Skeena-Nass CEA analysis, this component was used to set up spatial data to enable inclusion of 1 or more pipelines in a given scenario.

The toolkit includes a more comprehensive component to lay out potential pipelines and a gas well network (see Fall and Morgan 2013), but this was not used in the Skeena-Nass study area. For example, if a pipeline location is only generally known (e.g. with a 2km wide potential corridor), this component can be used with a cost surface to identify a plausible pathway for an actual pipeline.

Appendix 8. Mine placement

Directly depends on: access cost
Dependency level: 2

Directly used by: dynamic landscape projection

There are 88 existing and proposed mines in the study area. The number of new mines to develop is a scenario parameter. Mine placement and lifespan were set up as a mine development schedule, where mine lifespan was based on averages for mines in BC.

Enabling a new mine simply involved ensuring road access and including mine related attributes in indicator output. Roads to mines would remain active as long as the mine remained active.

The toolkit includes a more comprehensive component to lay out potential mines (see Fall and Morgan 2013), but this was not used in the Skeena-Nass study area.

Appendix 9. Wind Farm placement

Directly depends on: access cost
Dependency level: 2

Directly used by: dynamic landscape projection

The number of new wind farms to develop is a scenario parameter. Wind farm placement and lifespan were set up as a wind farm development schedule. New wind farm locations were selected stochastically using a probability layer that was based on site suitability.

Enabling a new wind farm simply involved ensuring road access and including wind farm related attributes in indicator output. Roads to wind farms would remain active as long as the wind farm remained active, which was assumed to be in perpetuity.

Appendix 10. Potential transmission line network

Directly depends on: access cost, potential road network, mine placement, wind farm placement

Dependency level: 3

Directly used by: grizzly security areas, watershed indicators and stream reach indicators

Electric transmission lines are needed to transmit power from wind farm sites and to mine sites, in addition to the lines that connect communities and power sources.

This component starts with the existing transmission line network, and estimates additional line locations to connect proposed/modelled future mine and wind farm sites, in an analogous way to the road network components in a sequent of steps.

A 10.1. Future transmission lines

This is done the same way as for roads (and uses the same access cost surface), except:

- The area to access consists of potential mine sites and wind farm sites rather than THLB; and
- Transmission lines must reach these site (unlike future roads, in which THLB must be within a specified maximum distance to a road).

The output is a potential future transmission line network (that includes the current transmission lines)

A 10.2. Create transmission line segments

This is done the same way as for the potential roads network, except based on the current and potential future transmission line network

The outputs include transmission line "backbone, segment id, distance to transmission lines. See the Potential Road Network component for details.

A 10.3. Transmission line development

Transmission line development is driven by mine and wind farm development, and similarly creates a development schedule of transmission line segments.

Appendix 11. Dynamic landscape projection

Directly depends on: timber harvesting land base, access cost, potential road network, pipeline placement, mine placement, wind farm placement
Dependency level: 3

Directly used by: coarse sediment hazard, water and glacier mass balance, moose winter habitat, grizzly security areas, salmon spawning habitat, watershed indicators and stream reach indicators

The *landscape dynamics* component includes sub-models that capture interactions and feedbacks among dynamic landscape processes and spatial state (Figure 10). This component is perhaps the most complex in the toolkit. As many aspects as possible have been decomposed as separate “pre-processing components” (e.g. potential road network) that provide inputs to this model or “post-processing components” that utilize outputs (in particular, spatial time series outputs of attributes for forest cover, road state, natural disturbances and resource developments).

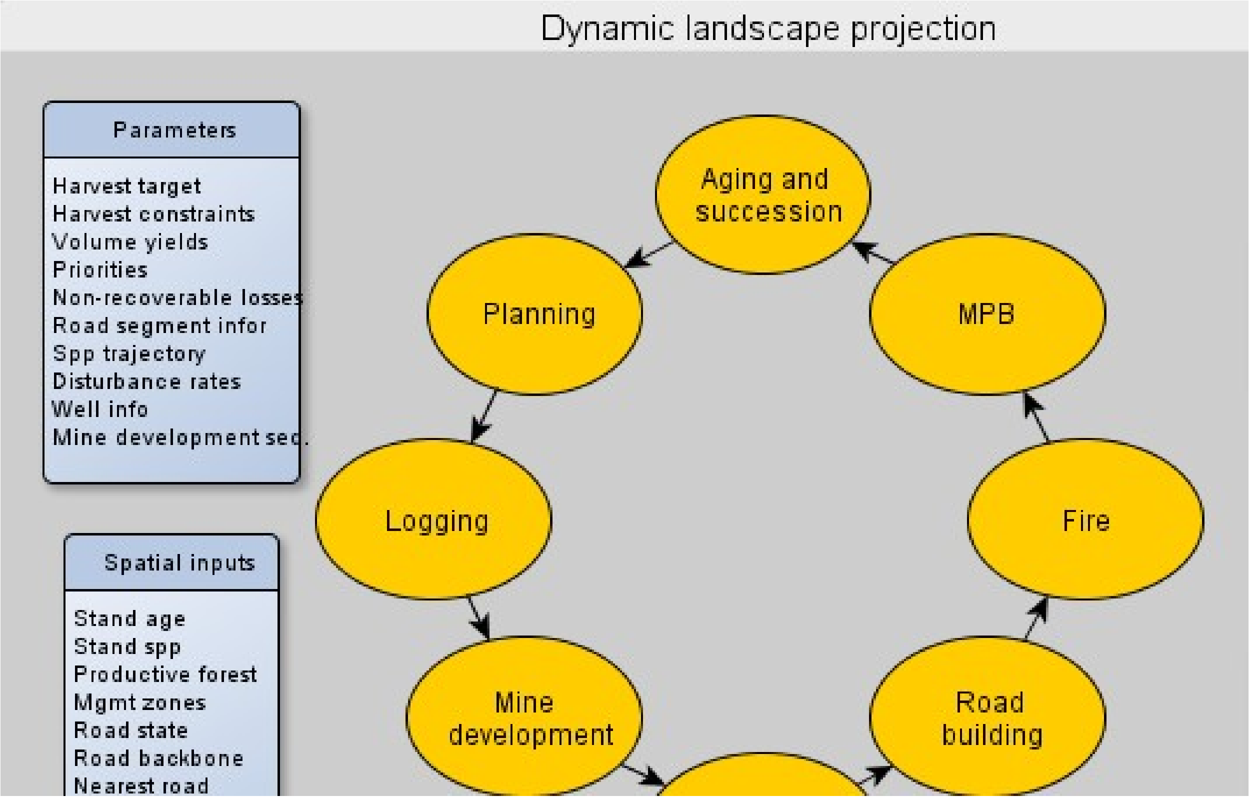

Figure 10 Dynamic landscape projection component of CEA toolkit network.

In addition to the sub-components shown in Figure 10, the Skeena-Nass CEA included sub-components for wind farm development and land-use change (human population change).

A 11.1. Tree aging and succession

In the Morice River CEA application, an expert-opinion based “successional pathway” model was implemented based on a workshop of forest ecology experts (Beukema and Pinkham 2001). However, no information was available over the Skeena-Nass study area to adequately model tree species changes due to succession. In the Skeena-Nass CEA, succession was limited to stand aging.

A 11.2. Wildfire

The wildfire sub-model is an annual empirical-based fire ignition and spread model parameterized using historical data (fire history database for BC) and expert opinion. This fire model was adapted from the Morice River CEA analysis. It was adapted more recently to apply climate change effects consistent with recent research on expected effects of climate change on forest landscapes in BC (Haughian et al, 2012).

The fire sub-model is designed to operate on a time step between 1 year and 10 years.

In general, annual *fire weather* cycles in the model between high fire years and low fire years. The frequency and duration of high fire years is estimated using historical fire data.

The number of fires each year is selected based on fire year type within each natural disturbance type (NDT, which is a function of BEC variant) x Ecoprovince (i.e. each NDT x Ecoprovince strata is modelled as a semi-independent instance of the fire model). We apply Ecoprovince as a stratum due to the broad scale of the study area in order to support climate change effects. Adding Ecoprovince as a stratum has no effect when climate change effects are not applied. The average rotation and mean size of individual fires are shown in **Error! Reference source not found.**. The target total area to burn within each NDT x Ecoprovince strata for the year is chosen from a negative exponential distribution using the rotation value and NDT x Ecoprovince strata size. Since fires may extinguish before reaching their target size (see below), fires are ignited as needed to reach the overall target area to burn (to satisfy the empirical return internal target).

Table 1 Mean number of fires per 100 km^2 by NDT and year type[3].

NDT / year type	**Low/normal fire year**		**High fire year**	
	Rotation (years)	**Mean fire size (ha)**	**Rotation (years)**	**Mean fire size (ha)**
1	2000	50	1000	50
2	530	563	174	796
3	210	1019	75	2020
4	181	309	66	563
5	1000	50	500	50

For each fire, the target size is selected from a negative exponential distribution with a mean of the expected fire size. Ignitions are chosen randomly from forested cells. Once ignited, fires spread in a randomized pattern to create moderately complex fire shapes with some unburned islands in a manner that mimics historic fire shapes. Spreading will stop when either the target fire size has been reached or because there are no eligible neighbours for spread.

Fire effects include resetting stand age and height, marking the forest cover type as burned, shifting standing merchantable THLB area to standing dead merchantable THLB area[4] and decrementing the target area to burn. Standing dead volume may be salvaged by the logging model (which may or may not be parameterized to prioritize salvage) over a period of 20 years post-fire.

A 11.2.1. Climate Change Effects on Wildfire

Climate change, when specified for a scenario, affects size and number of fires as well as spatial distribution using the same approach as in Morgan (2011) and consistent with Haughian (2012), and more conservative that the approach by Flannigan et al. (2005) for the boreal forest. According to Haughian (2012; Fig 1), the areas in the Skeena-Nass

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[3] Values need to be updated using historic fire data for the Skeena/Nass study area

[4] Note that timber volume is not modelled in in the very broad scale application in the Skeena/Nass CEA.

watersheds expected to shift to increased disturbance (e.g. from Sub-Boreal Spruce to Interior Douglas-Fir BEC zones) tend to be concentrated in the Central Interior Ecoprovince (e.g. much of Morice drainage), while areas expected to shift to decreased disturbance (e.g. from Sub-Boreal Spruce to Interior Cedar-Hemlock BEC zones) tend to be concentrated in the Sub Boreal Interior Ecoprovince.

The net effect of the projected changes on fire model behaviour is estimated as follows:

(a) Estimate spatial changes in disturbance: Future BEC projections for years 2020, 2050 and 2080 were obtained from ClimateWNA (Spittlehouse 2006). Some areas are projected to become wetter, and perhaps shift to the Interior Cedar-Hemlock BEC zone, while other areas are projected to shift to the Interior Douglas-fire BEC zone. In addition, general warming will tend to lengthen the fire season. The NDTs were not used directly to change the fire regime because this would not consider other geographic aspects that define the disturbance regime[5]. Instead, future BEC projections were used to identify the area by which the NDTs changed to a higher or lower disturbance level, and the local expected magnitude of that change.

(b) Use "disturbance change" grids to modify disturbance parameters: The grids of expected local changes were used to modify expected disturbance parameters within each NDT x Ecoprovince in proportion to average magnitude of change in that stratum. For example, if fire rotation in a given NDT x Ecoprovince combination increased by 40% in 25% of its area, remained unchanged in 75% of its area then the net change in fire rotation would be an increase of 10% (1.4 * 25% + 1.0 * 75% = 110%). Changes in disturbance rates are distributed equally between changes in expected fire size and number of fires (i.e. by scaling these two parameters by the square root of the net change).

(c) Model changes dynamically: During a simulation, the "disturbance change" grids are updated periodically (e.g. at years representing 2020, 2050 and 2080), and the fire parameters are recomputed as described above.

(d) Resulting fire statistics will be benchmarked against the net expected changes by Ecoprovince reported in Haughian (2012).

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[5] Based on advice from G. Utzig, pers. comm.

A 11.3. Mountain Pine Beetle

The Mountain Pine Beetle sub-model was adapted from another model built for Cranbrook in southeastern BC. This sub-model was designed to capture long-term dynamics of outbreaks, not the details of a single outbreak, and hence it has a structure similar to that of fire. The first modelled outbreak may start after year 20 (to account for recovery from the recent large-scale outbreak).

Outbreaks occur when the total area of susceptible pine (susceptibility rating at least 0.4) is higher than a parameter threshold (set at 100,000 ha). Susceptibility ratings are estimated using an adaptation of Shore and Safranyik (1992) that can be applied on broad scale spatial data (essentially using percentage of pine instead of percent of pine above a given diameter, and omitting stand density factor). Outbreak size is selected either as a mean derived empirically, or from a negative exponential distribution with the mean. Outbreaks can only start and spreading in stands with some pine.

Attack effects include resetting stand age and height, marking the forest cover type as disturbed by MPB, shifting standing live volume to standing dead volume and decrementing the target area to attack. Standing dead volume/area may be salvaged by the logging model (which may or may not be parameterized to prioritize salvage) over a period of 20 years post-MPB.

At present, the MPB model is not affected directly by climate change. Changes to fire, and possible changes to tree species via succession, would affect susceptibility ratings and hence indirectly affect outbreak dynamics. The susceptibility rating could also be adapted to use a climate factor that would be dynamically updated instead of the static location factor from Shore and Safranyik (1992).

A 11.4. Harvest projection and timber supply analysis

Harvest projection refers to spatial simulation of logging activities for a given “harvest target” (sequence of volumes or areas to harvest). Timber supply analysis refers to methods of identifying harvest targets that can be supported for a given scenario. In the context of the dynamic landscape projection component, harvest projection and timber supply analysis interact with stand aging and succession, and road access development, and can be applied with or without other dynamic processes. Harvest projection is used when projected forest attributes (e.g. stand age, growing stock) and roads are saved for a specific scenario for input to other components.

As described in Section 2, the Skeena-Nass study area include 14 management units (timber supply areas and tree farm licences). Each was modelled based on the most recent timber supply review (TSR) analysis or management plan, using the information specific to each management unit. Due to large spatial scale of the study area, modelling did not include volumes, and so full timber supply analysis could be done. However, the objectives and key assumptions from each management unit were included.

A 11.4.1. __Constraints__

Forest cover constraints are often specified in particular zones to either limit harvest rates or ensure a minimum level of retention of mature or old forest. In the Skeena-Nass study area, the same constraints as in the last TSR analysis or management plan were used, simplified to be based on age (since stand height information was not included for this large study area). The default (TSR scenario) forest cover constraints/objectives included:

- Visual quality: maximum level of the productive forest below 15 years: 0% (protection), 5% (retention), 10% (partial retention), 20% (modification) and 30% (maximum modification), by scenic zone.
- General integrated resource management: maximum level of 25% of the THLB below 10 years: by landscape unit.
- Caribou habitat:
    - Bulkley TSA: maximum level of 50% of the productive forest below 90 years by landscape unit.
    - Morice TSA: (a) Telkwa: maximum level of 25% of the THLB below 10 years, and a minimum level of 25% of the productive forest at least 90 years old, by landscape unit; (b) Medium: minimum level of 70% of the productive forest at least 80 years old, by landscape unit; (c) High: no harvest.
- Bulkley TSA ecosystem network (core 1 and 2): maximum level of 5% of the productive forest below 50 years, by landscape unit.
- Bulkley TSA corridors: minimum level of 70% of the productive forest above 80 years old, by landscape unit.
- Kispiox TSA SRMZ Zone 1: minimum level of 30% of the productive forest above 140 years old.
- Kalum TSA SRMZ Lakelse River zone: maximum level of 27% of the productive forest below 40 years.
- Kalum TSA SRMZ Kiteen Cedar Creek zone: no harvest.
- Morice TSA LRMP
    - Thautil-Gosnell HBEA: minimum level of 50% of the THLB above 100 years old.

  - Morice River Buffer 1 HBEA: minimum level of 50% of the forest above 100 years old.
  - Morice River Buffer 2 HBEA: minimum level of 70% of the forest above 100 years old.
  - Nanika River Buffer 2 HBEA: minimum level of 70% of the forest above 100 years old.
  - Grease Trail 400m Buffer: minimum level of 70% of the forest above 100 years old.
  - Le Tahl Giz / Old Fort Mountain HBEA: minimum level of 50% of the forest above 100 years old.
  - Lower Nadina River 5m Floodplain 500m buffer: minimum level of 50% of the forest above 100 years old.
  - Morice Mountain HBEA: minimum level of 70% of the forest above 100 years old.
  - Nadina – Owen HBEA: minimum level of 70% of the forest above 100 years old.
  - Upper Nadina River 5m Floodplain 500m buffer: minimum level of 50% of the forest above 100 years old.
- Landscape-level biodiversity: Former North Coast TSA:
  - Targets by BEC variant x site series groups based on land-use order that specify a minimum percent of forest above 250 years old.
- Landscape-level biodiversity: Morice TSA:
  - Targets by BEC variant group, separated by HBEA (high biodiversity emphasis area) or GMD (general management direction) based on LRMP that specify (a) a maximum percent of forest below 40 years, (b) a minimum percent of forest above 100 years old, and (c) a minimum percent of forest above old age (140 or 250 depending on BEC).
- Landscape–level biodiversity: other management units
  - Targets by BEC variant based on Biodiversity Guidebook that specify a minimum percent of forest older than 250 years depending on BEC variant and landscape unit biodiversity emphasis option (BEO), to be met by landscape unit.

Each simulation step, the areas affected by the constraints are updated, and areas not available for harvest due to constraints are identified. As logging proceeds, constraints are also updated, to account for constraint thresholds that are passed during that step.

A 11.4.2. *Merchantable volume*

The CEA toolkit is designed to support tracking of volume based on age and a table lookup (using analysis units). However, volume was not available over the entire Skeena-Nass study area.

In general, stands in the productive forest are assigned “timber analysis units” (or just analysis units) based on the TSR data package. Analysis units are usually a function of species, productivity (site index), management history (natural origin, older harvest without planning, recent harvest with planting) and other factors. Each analysis unit has a merchantable volume (m^3/ha) yield curve and minimum harvest age, provided as input from growth and yield models (often TASS or VDYP). Each simulation step, the volume for each cell is derived by looking up the volume based on analysis unit and age. The yield curves usually account for fine scale disturbance losses (e.g. root rot), but adjustment may be made to account for wildlife tree patches or other fine scale retention or reductions. Height is also assigned to each stand based on height curves, if available.

Planting is assumed to occur in all stands after harvest, which shift to managed analysis units. Following natural disturbance without salvage, stands shift to natural analysis units.

A 11.4.3. *Harvesting*

Each time step, cells eligible for harvest are selected based on the harvest preference specified (e.g. “relative oldest first”). Blocks are “grown” from initially selected cells (to meet target block size targets). New blocks are placed until the target harvest level (m^3/yr or ha/yr) for the period has been reached or until there are no more eligible stands for harvest. Partitions and priorities may be included to focus harvest (e.g. deciduous AAC partitions). A description of the logic is given below.

Limit harvesting disturbance to eligible land:

- the timber harvesting land base;
- eligible zones (age class structure allows harvesting; status updated with each disturbance);
- conventional operating areas within 2 km of an existing road or the ocean;
- helicopter operating areas within 5 km of a helicopter drop site, ocean or an existing road; and
- stands older than minimum harvest age.

Assign priority of new harvesting to each map cell based on

- stand age (relative to minimum harvest age or culmination age).
- Adjacency (lower probability for stands next to logged areas under 3m in height)
- Distance from road or helicopter access
- Select location of first grid cell to harvest based on eligibility and priority:

In harvested cells:

- if in the conventional operating area build a straight-line spur road from the cell to the nearest road network cell, and if inactive, activate road network cell (see section A 11.7). The first cell of a block is considered to be a landing, and at each 40ha size threshold, another landing is created (i.e. the model assumes approximately one landing per 40ha of forest harvested).
- mark cell as harvested and set stand age to zero;
- update tracking variables (e.g. annual area harvested and constraint areas for applicable zones); and
- reduce the area of THLB in the cell to account for new access roads, if first harvest in conventional operating area, and for within-block development.

Iteratively place new blocks in sequence until the harvest target is reach or until no there are no more eligible stands.

A 11.4.4. __Timber supply analysis__

Timber supply analysis aims to estimate sustainable harvest levels that can be supported on a given land base, generally subject to:

(a) Meeting existing land-use zoning and constraints

(b) Demonstrating long-term timber supply sustainability via a non-declining THLB growing stock.

(c) Any declines in timber supply must be controlled, not more than 10%/decade (or, in some cases, non-declining harvest levels).

Performing timber supply should be done to the standards of Forest Analysis and Inventory Branch (FAIB; Min. Forest, Lands and Natural Resources Operations). We have integrated the Spatial Timber Supply Model (STSM), developed in collaboration with FAIB and used to support a number of timber supply reviews and land use plans, into the "landscape dynamics and projection" component of the CEA toolkit. More details on the STSM and how it can be used for timber supply analysis can be found in Fall and Crockford (2006).

Timber supply analysis is needed to identify sustainable harvest levels for any unique scenario (set of assumptions or objectives), including land-use scenarios, assumptions regarding natural disturbance, interactions with other resource development activities, differences due to climate change, etc. Timber supply analysis is performed using the STSM using a semi-automated iterative sequence of steps for a given scenario.

To be clear, *timber supply analysis* refers to the goal of identifying the maximum sustainable harvest flow supported within a given scenario. The goal of maximization requires some consideration. One may aim to maximize long-term, short-term, time to maintain a current harvest level, etc. Also, given the uncertainty in the system, one must be careful that maximizing the modeled land-use scenario has a high chance of being feasible and sustainable in practice. This is one rationale for a simulation-based approach to timber supply analysis, with interaction and consideration by a human analyst.

To perform timber supply analysis, we need to state clear objectives and constraints for timber supply: Sustainable timber supply has two key aspects:

(i) Feasible harvest target: The annual harvest target must be achievable in all periods. If the target cannot be met in one or more periods over a long time horizon (e.g. 400 years), this indicates a harvest level that is too high according to forest cover and access constraints and other considerations.

(ii) Stable long-term growing stock: Stable growing stock over the long run is a key indicator of sustainable timber supply. If this is declining, harvests are higher than can be supported, while if it is increasing, there are some harvest opportunities. To assess this, we define "long-term" as 3-4 centuries. That is, between years 200-400 growing stock must be effectively non-declining. We allow a slight decline (e.g. 1% per century) to allow some flexibility.

The above give us a test to assess if a given harvest target is sustainable. From a given start point, if a harvest target is sustainable, we may look for further harvest opportunities by increasing harvest in one or more time periods. If not, we need to reduce the target in one or more periods. This provides a general approach to seek a maximum sustainable harvest target. However, there are many such targets, and the most desirable depends on other goals. Hence, we define some key constraints and objectives on the attributes of the maximum sustainable harvest target (based on guidelines from C. Fletcher, Forest Analysis and Inventory Branch):

(i) The harvest target must be maintained at or above the level of the maximum long-term harvest level (LTHL). This condition may not always be desirable, in particular for management units that have significant historic harvesting where a drop in some periods below the maximum LTHL may be necessary to achieve management objectives. In most units, however, this effectively captures the criteria that short- and medium-term management should not compromise future generations.

(ii) The maximum short-term harvest level, up to the current AAC, should be attempted and maintained as long as possible. This condition is designed to minimize short-term impacts, in particular if the current AAC must be reduced to meet objectives for a given land-use scenario. When assessing units that do not have an AAC (e.g. a portion of a TSA), selection of a starting target harvest is a subjective choice that should be made based on technical information (e.g. information on harvests from the overlapping TSAs/TFLs) and social choice.

(iii) The maximum decline between subsequent 10-year planning periods is 10% of the starting harvest level. This condition is designed to minimize the social and economic impacts of declining timber supply within any given decade.

These conditions can be used as guidance to find an appropriate maximum harvest flow for a given scenario. The general steps are:

(i) Determine the maximum even-flow harvest level: Using a binary search algorithm, iteratively assess different levels of constant volume harvest until the maximum level is found (Figure 11, step 1). This can be contrasted with the maximum theoretical long-range sustainable yield that can be calculated by summing up the cumulative mean annual increments for each cell according to its analysis unit). The maximum even-flow level will usually be less than the theoretical maximum long-term harvest level due to stand age structure, timing of harvest, forest cover constraints, etc.

(ii) Increase the short-term harvest level: Using another binary search algorithm, iteratively assess different levels of short-term increases (“shifts” of short-term) until the maximum level is found (Figure 11, step 2). For example, in a TSA, the current AAC may be attempted for 8 decades (before declining to the long-term level). If this is unsustainable, it may be reduced to 4 decades, otherwise it may be attempted for 12 decades. Careful design of the harvest pattern to shift is based on the results of the first step plus the guidelines described.

(iii) Refine the long-term harvest level: sometimes, increasing the short and mid-term harvest levels results in an increased capacity of the long-term harvest level (e.g. Figure 11, step 3). This may occur, for example, if the area harvested in the short-term is closer to the LRSY, and so the age-structure is transformed earlier to support a higher long-term level. The point at which harvest can increase requires examination of harvest indicators (e.g. after bottlenecks of harvest availability and after growing stock starts to increase significantly). In some cases, this may increase the entire long-term level, while in others it may result in a long-term level that is higher than the mid-term. It is important to note, however, that the lower mid-term level in this latter condition is not a consequence of higher harvest in the short-term, but is due to interactions between stand age structure and regeneration.

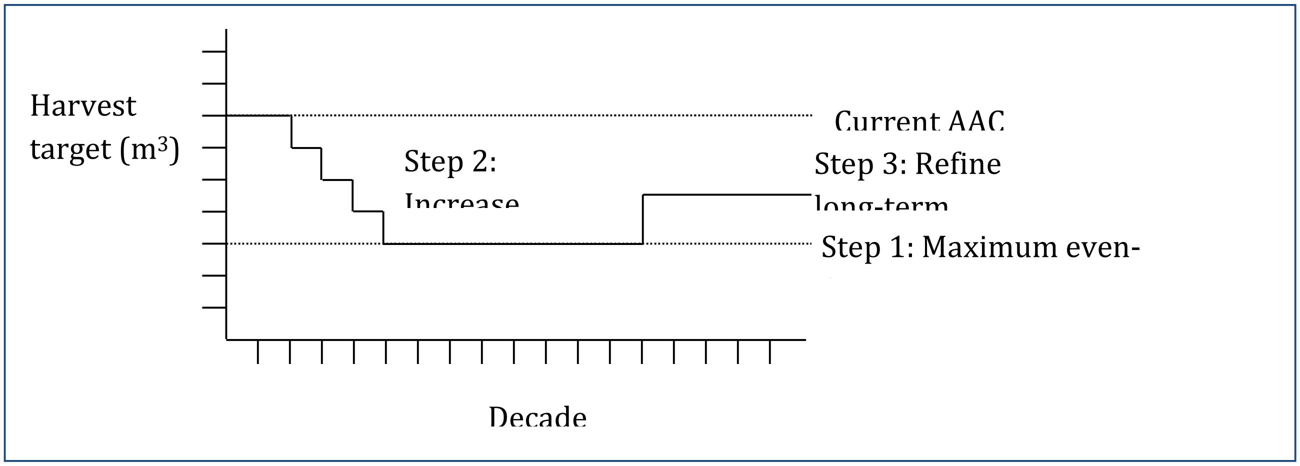

Figure 11. Illustration of the steps of assessing sustainable timber supply with STSM. Step 1 is to estimate the maximum even-flow harvest level (constant harvest level; lower dashed line). Step 2 is to increase the short-term level consistent with the even-flow level (steps from current AAC line down to level identified in step 1). In this example, the current AAC can be maintained for two decades before declining in 10% steps to the harvest level identified in step 1. Step 3 is to refine the long-term harvest level based on the results of the previous two steps. In this example, after 130 years, the long-term harvest level can increase by about 15%.

The approach outlined is most useful for situations where the initial harvest level is above the long-term level due to differences in volume between old-growth forests and second growth forests. This is a common situation in central and northern coastal B.C. Adaptations are straightforward for cases where the short-term is lower than the long-term level (e.g. in certain units on Haida Gwaii).

A 11.5. Gas well and pipeline development projection

Gas well and pipeline development sequencing is assumed to have negligible feedback from other resource activities and from natural disturbance. As such, most of the complexity of well development is captured in the gas well and pipeline placement module, to be run before dynamic landscape projection. More specifically, the last step of the gas well development model creates a projection (schedule) of selection, location, and drilling of exploration and production wells. During dynamic landscape project, the gas development sub-model simply lays out this *a priori* defined development of wells and pipelines. Since wells require road access, creating a new well leads to new road segments becoming enabled (which in turn may affect logging as well as value indicators).

In the Skeena-Nass analysis, only projected pipeline development was applied.

A 11.6. Mine development projection

As with gas development, mine development sequencing is assumed to have negligible feedback from other resource activities and from natural disturbance. Identification of mine locations is provided as an input (but the CEA also includes a mine placement module, to be run before dynamic landscape projection). During dynamic landscape project, the mining sub-model schedules the *a priori* defined development of mines. Since mines require road access, creating a new mine leads to new road segments becoming enabled (which in turn may affect logging as well as value indicators). Once a mine is placed, construction is assumed to commence. Additional parameters specify the duration of mine operations and the timing of phases (development, production, and reclamation).

A 11.7. Wind farm development projection

As with gas development, wind farm development sequencing is assumed to have negligible feedback from other resource activities and from natural disturbance. Identification of wind farm locations is provided as an input. Since wind farms require road access, creating a new wind farm leads to new road segments becoming enabled. Once placed, wind farms are assumed to be perpetual.

A 11.8. Road development projection

The dynamic landscape projection component includes spatial road access restrictions and incremental road development based on a road network developed in a preceding component. As resource developments proceed, required road segments are enabled (changed from potential future to existing). This aspect updates the road state information as well as distance/cost to nearest active road segment.

The different resource development sub-models connect cutblocks, gas well, mine sites, and wind farms to the nearest existing or potential future road location in the main road network. If the nearest road segment is a potential future road, the segment is then activated along with any "downstream" potential future roads to the nearest existing road. This method of modelling road development allows an approximation of the amount of road required to meet a harvest request in conjunction with well and mine development, allows access restrictions to influence harvesting while resource development reduces access constraints over time.

A 11.9. Land-use change (human population change)

The land-use change sub-model projects changes in land-use type, which was classified as one of: natural, rangeland, agricultural, urban or industrial.

The annual rate of change for each land type is an input parameter, and may represent growth (positive value) or contraction (negative value).

Each human land use type is restricted to change to other types as follows (i.e. as a Markov chain, when the change in natural type counter-balanced the changes for the human land-use types):

- Growth: change to a more intense human land-use from a less intense land use (e.g. Urban land-use may grow via change from Rangeland) or natural.
- Contraction: change to less intense human land-use or natural from a more intense human land-use (e.g. Rangeland may contract via change to Natural).

In addition to the individual cell-level probabilistic changes, this sub-model:

- Increases the likelihood of changing to a land-use if one or more neighbours had the same land-use ("contagion"), where contagion is higher for urban and industrial uses than for agriculture and rangeland.

- Makes change in patches by selecting a target size from a normal distribution based on observed contagion levels by type. Patch sizes are expanded using a stochastic probability to randomize resulting patch shapes.

These probability adjustments are done in a way to maintain the overall change parameter inputs.

If change is from natural to human land-use, then any forest is de-forested. Conversely, if change is to natural, then re-forestation is initiated with forest of age 0.

Appendix 12. Water flow balance and glacier mass balance

Directly depends on: hydrological flow (contributing area), climate WNA, dynamic landscape projection
Dependency level: 4

Directly used by: scenario risk analysis

The water flow balance and glacier mass balance component operates on a monthly timestep of interacting sub-models (Figure 12). The water balance sub-models (snow and ice melt and accumulation and groundwater flux) are based on Moore et al. (2012) and Stahl et al. (2008), in which monthly grids of temperature and precipitation from Climate WNA (Spittlehouse 2006) are used to capture build-up and melt of snow and ice, and soil water storage and release. The methods for setting up the Climate WNA grids is described in Fall (2014). The resulting outputs are spatial, and are also summarized by watershed to obtain monthly average flows for a given climate scenario.

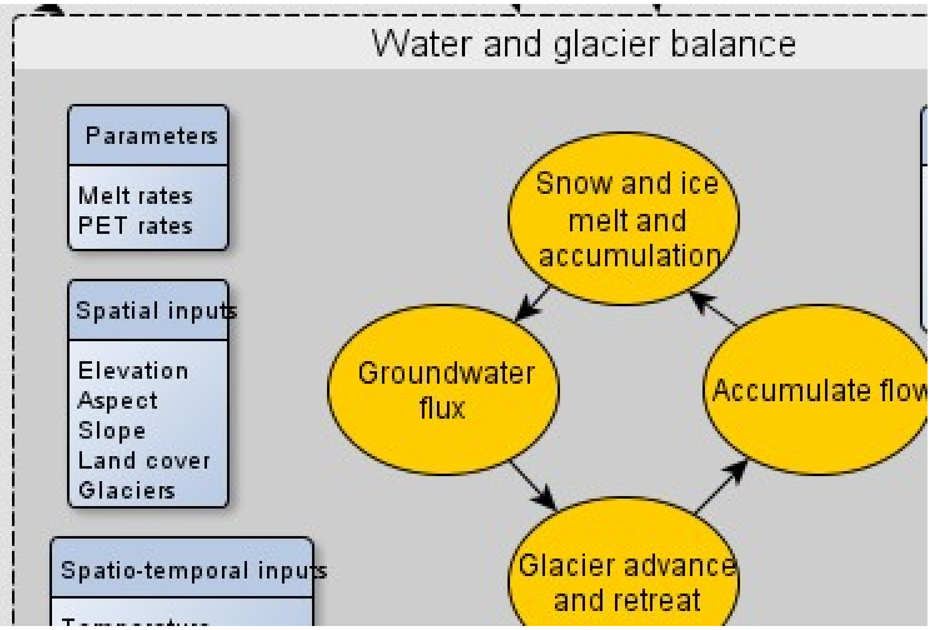

Figure 12 Water flow balance and glacier mass balance component of CEA toolkit network.

The glacier mass balance sub-model (glacier advance/retreat) is based primarily on Stahl et al. (2008). Water balance sub-models use temperature and precipitation grids to drive build-up and melt and accumulation of snow, and melt of exposed ice. Further, glaciers are modelled as units using a relation between mass of ice and areal extent. As a net glacier mass increases or decreases, area at the tongue grows or shrinks accordingly.

In addition, at the end of each year, the hydrological flow accumulation model is used to spread local runoff values downhill to obtain cumulative flow values for each cell of the landscape. This sub-model is only run on an annual step to reduce computational burden.

Details of this component are documented in an associated appendix addendum (Fall 2022).

Appendix 13. Snow avalanche hazard

Directly depends on: hydrological flow (contributing area), dynamic landscape projection, spatial graphs
Dependency level: 4

Directly used by: scenario risk analysis

The snow avalanche hazard component has a series of sub-model steps (Figure 13). This model is based on avalanche expertise in the Columbia Mountains (Revelstoke) of south-eastern BC. The sub-model steps build up information, primarily from a digital elevation model and forest cover, with which to compute position of slopes with respect to prevailing winds and topographic shape to identify areas most likely to experience avalanches. The resulting output is a spatial map of an avalanche risk index.

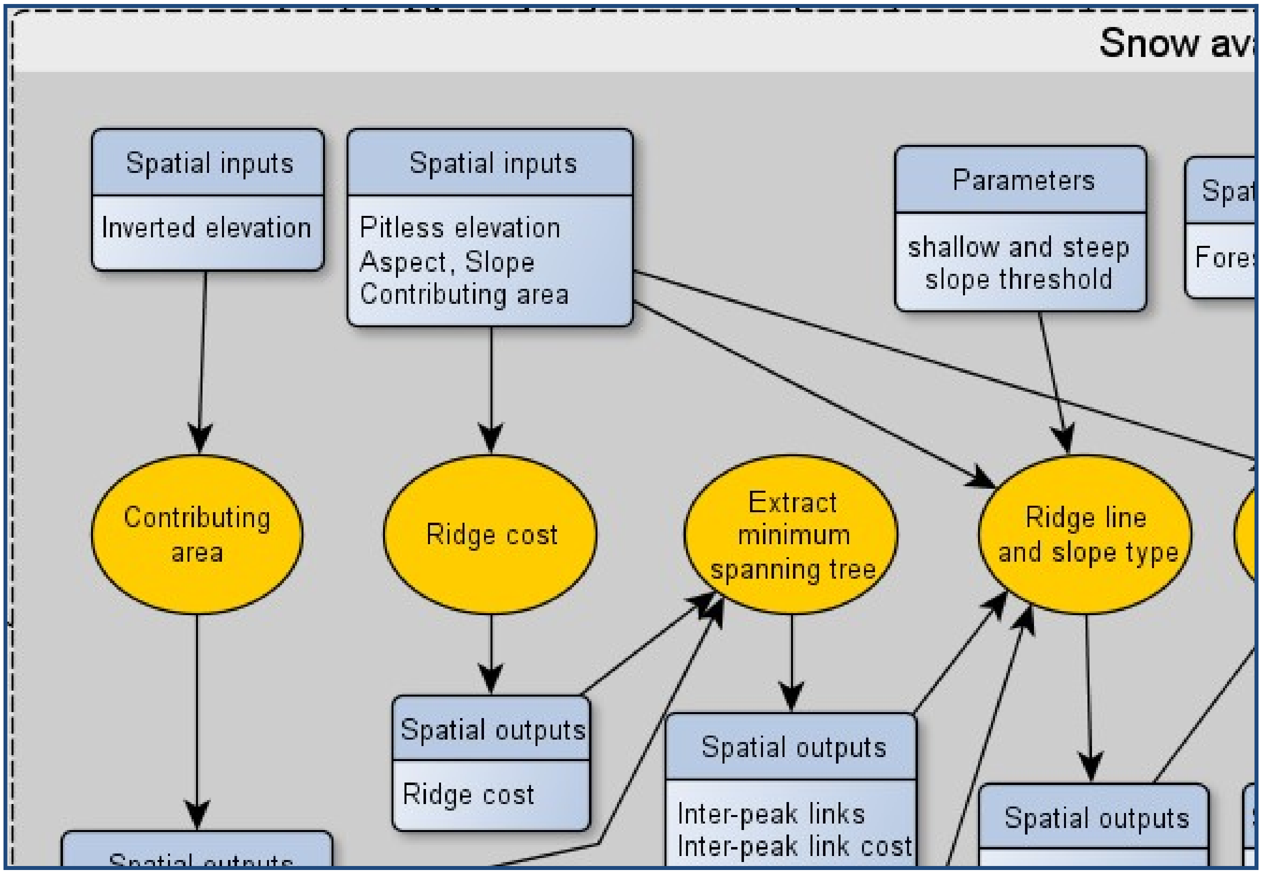

Figure 13 Snow avalanche hazard component of CEA toolkit network.

Avalanche risk/wind index model steps. It takes as primary input pitless elevation, aspect, slope and contributing area, as well as an “inverted elevation” layer in which elevation values were reversed (by applying the function *inverted elevation = max. elevation – elevation + 1).*

The first step is to run the contributing area hydrological flow model on the inverted elevation. This creates an inverted contributing area. Pits are not filled in the inverted elevation raster since these represent mountain peaks. The results are then used to identify local peaks (local maxima of elevation, which might be a mighty mountain top or a mole hill).

The second step defines a "ridge cost" layer (cost of "flowing off" a ridge line). Cost increases with slope (slope tends to be lower along a ridge than down off the ridge) and contributing area (contributing area increases down from a ridge, and tends to be low along a ridge, which is a shedding area). Cost is "infinite" for large contributing area (i.e. ridges do not go down and across deep valleys, but can go down a bit and across shallow passes).

The third step is to build a minimum spanning tree (MST) between peak cells using least-cost paths (based on the ridge cost layer), but not connecting across deep valleys (where cost is "infinite"). This defines clusters of peaks, connected along ridges ("inter-peak ridges"). Output is saved in MST tables and grids (inter-peak links and inter-peak link cost)

In the fourth step, the inter-peak MST and inverted contributing area are used to define "ridge line type": *inter-peak ridges* (inks in the MST with relatively low cost (no descending too much) and *ascending ridges* (areas with high inverted contributing area values that connect valley cells to peaks along ascending ridges). This step also defines “ridge slope type” (type slopes below ridges). "*Crests*" are defined as slope breaks from shallow or moderate slope to steep. "*Toes*" are defined as slope breaks from steep to shallow or moderate slope. This is done by starting at ridges and flowing downhill, and is the most challenging part of the process. The resulting values are:
1: *precipitous crest* (crest at a ridge or shallow at crest)
2: *rounded crest* (moderate slope at crest)
3: *steep slope below a precipitous crest*
4: *steep slope below a rounded crest*
5: *shallow slope at toe below a precipitous crest* (plus moderate slope below toe)
6: *shallow slope at toe below a rounded crest* (plus moderate slope below toe)

The fifth and last step is to compute a general avalanche risk index (currently called a *wind index*, and based on expert description of slope and wind characteristics with respect to snow avalanche risk). Wind index values is the highest value that meets one of the following conditions:

1. cell surrounded by cells with forest cover
2. cell either surrounded by open forest or it faces prevailing winds
3. cell on an open (non-forested) slope greater than a minimum slope parameter
4. starting zone on the lee side of a sharp ridge (ridge slope types *precipitous crest, steep below precipitous crest* or *toe below precipitous crest*)
5. starting zone on the lee side of a rounded ridge (ridge slope type *rounded crest*, *steep below rounded crest* or *toe below rounded crest*)

The snow avalanche risk index depends on forest cover, which can be input as a time series from a dynamic landscape projection. Further details can be found in an appendix addendum (Fall 2022).

This toolkit component was not used in any scenarios in the Skeena-Nass analysis.

Appendix 14. Coarse sediment hazard

Directly depends on: slope to stream coupling, dynamic landscape projection
Dependency level: 4

Directly used by: scenario risk analysis

The coarse sediment hazard value indicator component (Figure 14) uses the slope to stream coupling outputs combined with projections of roads and pipelines from the dynamic landscape projection component to assess sediment loading in streams, summed by assessment watershed. Sediment loading is reported both as the total expected loading (base natural loading, modified by roads and pipelines in class IV and V terrain and upslope influence areas) as well as changes over base natural loads.

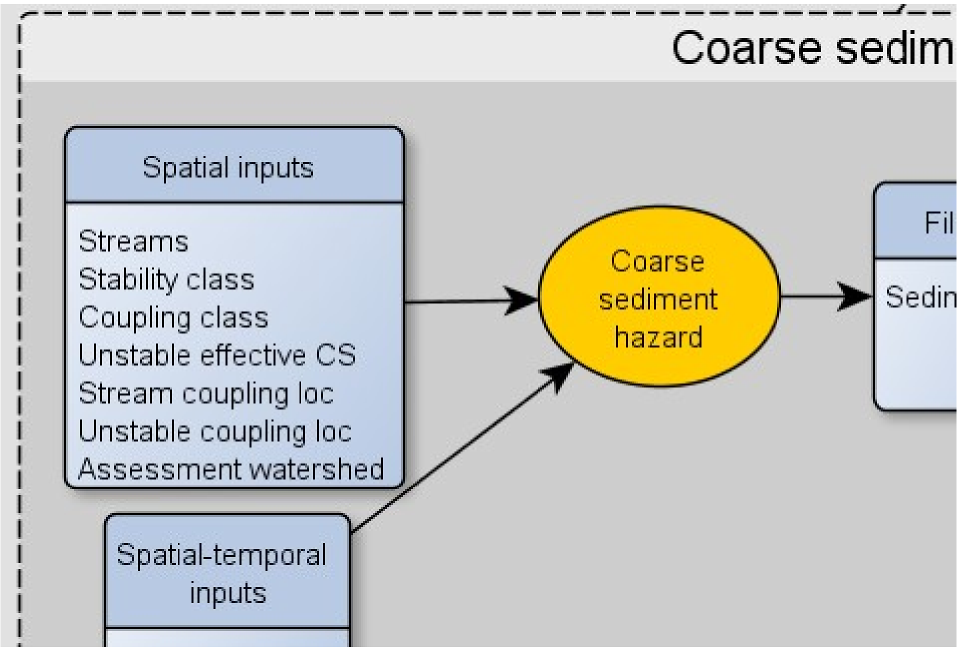

Figure 14 Coarse sediment hazard value indicator component of CEA toolkit network.

Appendix 15. Moose winter habitat

Directly depends on: dynamic landscape projection
Dependency level: 4

Directly used by: scenario risk analysis

The moose winter habitat indicator value indicator component (Figure 15) creates an estimate of foraging habitat, shelter habitat and net effective habitat suitability (complementary juxtaposition of foraging and shelter habitat).

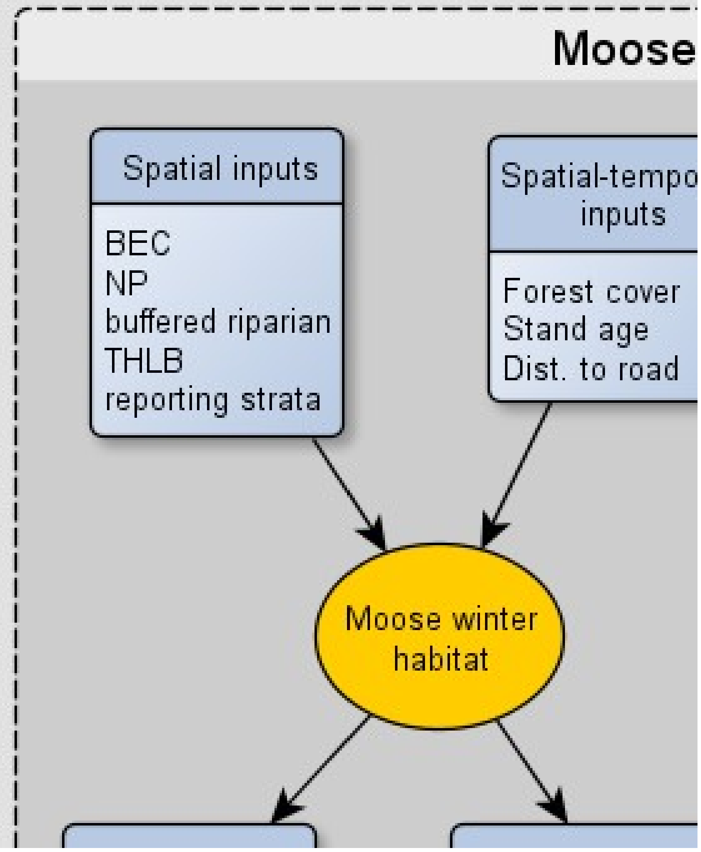

Figure 15 Moose winter habitat value indicator component of CEA toolkit network.

Inputs include spatial attributes for computing foraging and shelter habitat (forest cover (tree species), stand age, non-productive cover type, 100m riparian buffers). Outputs include grids of effective shelter habitat, effective foraging habitat and net effective habitat, as well as summary files of area of habitat (and habitat disturbed or not by roads – i.e. within a 1 km road buffer) within specified strata (assessment watershed, ungulate winter range unit, major watershed, ecosection, landscape unit, BEC).

Potential feeding habitat includes swamps, non-productive brush, other non-productive, areas in riparian buffers, deciduous stands, and stands between 10 and 30 years. In addition, potential feeding habitat must be within 100m of coniferous stands. Potential shelter habitat is defined as coniferous stands at least 60 years old. Effective habitat consists of potential feeding/shelter habitat within 100m of potential shelter/feeding habitat.

The model can be run on a single landscape state (e.g. current conditions) or on a time series of landscape changes, as output from the dynamic landscape projection component for a particular scenario.

This model component was not used in the Skeena-Nass CEA.

Appendix 16. Human access on landscape

Directly depends on: dynamic landscape projection
Dependency level: 4

Directly used by: grizzly bear secure habitat

The human access component estimates human pressure on the landscape in terms of relative access presence based on a model developed by C. Apps. Population centres within and external to the study area are the source of human presence. For each population centre (and for exit points on major highways to capture extrinsic populations), relative pressure is obtained via diffusion spread from the centre. Spread is based on rate of movement (average vehicle speed on roads and average walking speed once off road, modulated by slope and land cover). The value obtain is the travel time from the population centre (where longer times indicate lower likelihood of encountering a human). The relative human pressure index for a population centre is computed as the population size times “travel time decay rate per hour” to the power of travel time (in hours), where the travel time decay rate is a parameter less than or equal to 1 and represents the rate at which human presence declines with the time it takes to reach a place on the landscape. Unless we knew the number of outdoor trips per capita, the human access pressure is a relative index. The overall index is obtained by summing surfaces from each population centre. In general, the human access index is best computed over large areas.

This component was run over the entire province in order to capture the influence of every human population centre. The resulting human pressure grid was clipped to the Skeena-Nass study area.

Appendix 17. Grizzly bear secure habitat

Directly depends on: dynamic landscape projection, human access (to be added)
Dependency level: 5

Directly used by: scenario risk analysis

The grizzly bear secure habitat component (Figure 16) creates an estimate of areas of “secure natal habitat”; that is, habitat for female grizzly that have adequate size that is free from active roads (and human interactions). This component is based primarily on Gibeau et al. (2001). This component takes as input several spatial attributes and non-spatial parameters, and output a spatial layer of secure grizzly habitat and a summary file. We illustrate the steps of this model using an example sub-area from within the Morice River watershed.

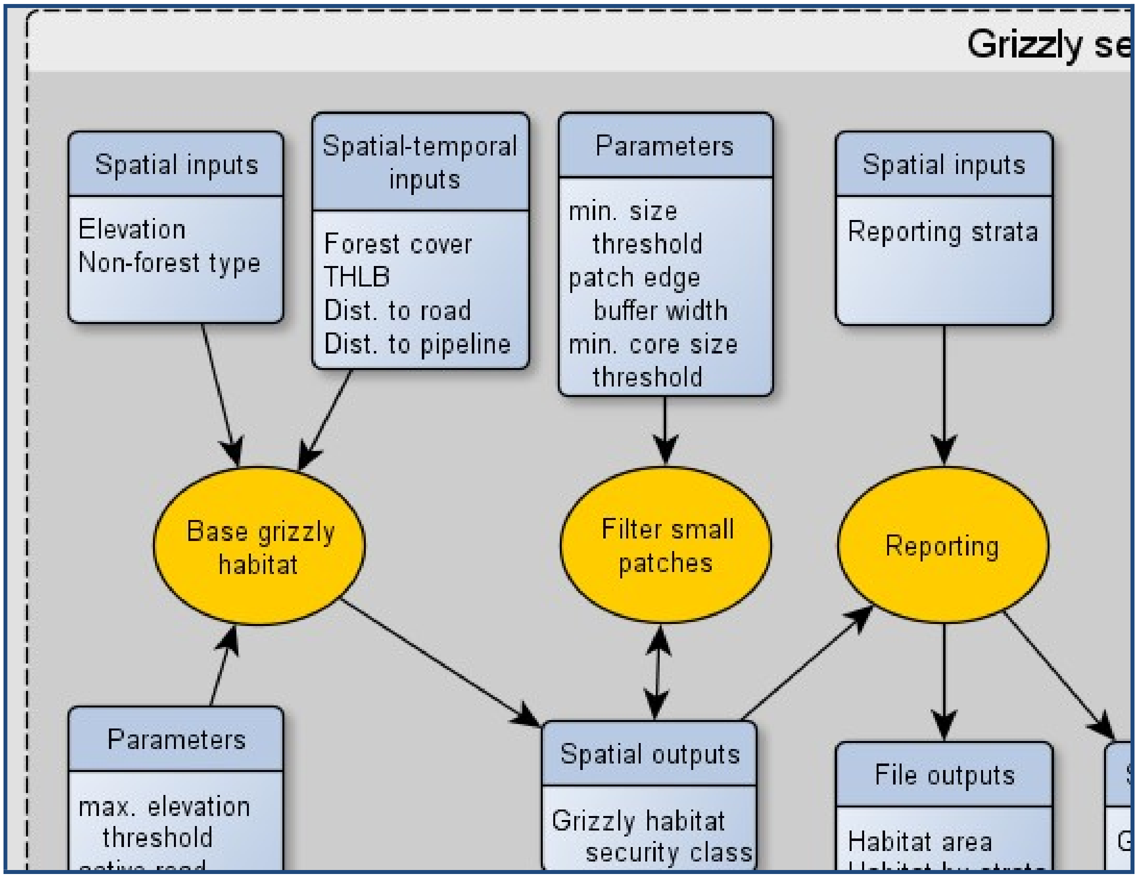

Figure 16 Grizzly bear secure habitat value indicator component of CEA toolkit network.

Inputs include spatial attributes for computing habitat (elevation, non-forest, forest cover, glaciers, land-use type, distance to roads, pipelines, mines, wind farms and transmission lines) plus parameters to specify maximum elevation, buffer widths on roads (human disturbance) and habitat patches (interior of secure areas), and minimum size of secure area and secure core area (Table 2). We adjusted the parameters used in Gibeau et al. (2001) to the study area to account for differences between the Rocky Mountain area in south-eastern BC where the parameters were developed and the study area. We slightly increased road buffer width so that circular moving windows based on this distance have an area of 1 km2. We also added two new parameters, based on discussions with T. Hamilton to account for edge effects on secure areas.

Table 2 Parameters applied for in the Skeena-Nass CEA contrasted with parameters used in Gibeau et al. (2001.

Parameter	**Gibeau et al. (2001; (south-eastern BC)**	**Skeena-Nass study area (north-western BC)**
Maximum elevation (m)	2,500	2,500
Active road definition	> 100 human visits/month	Permanent high-use roads and roads with at least 12,000 m^3/year log transport
Active road buffer width (m)	500	566
Minimum secure area (ha)	900	1,000
Secure area edge buffer width (m)	n/a	566
Minimum secure core area (ha)	n/a	n/a

A 17.1. Step 1: base suitable habitat

The first step defines areas as suitable or unsuitable for habitat, independent of human presence effects on security (Figure 17). In the Skeena-Nass study area, this uses a PEM-based habitat model, where classes 1 to 4 are considered as habitat, and classes 5 and 6 as non-habitat. Non-habitat also includes areas of ice, glaciers, lakes, rivers, urban and industrial.

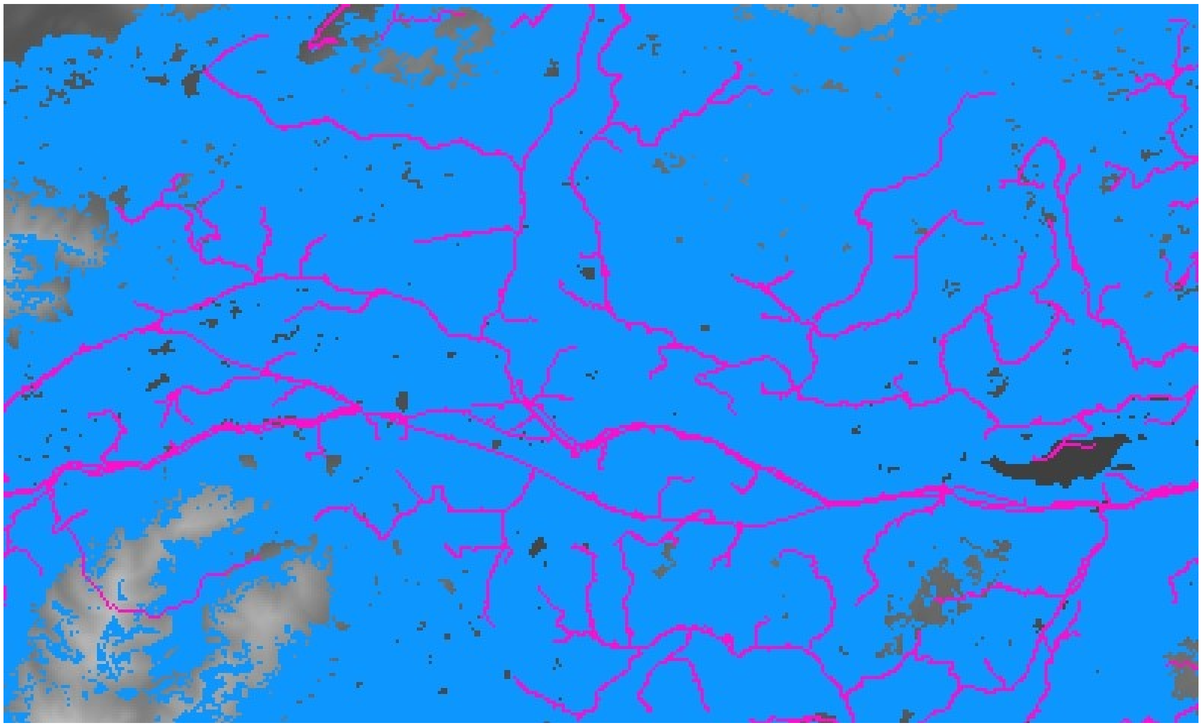

Figure 17. Example: initial grizzly bear habitat independent of human presence (blue) with high-use roads overlain (pink). Non-coloured areas represent non-habitat.

A 17.2. Step 2: primary human presence effects

Areas within 566m of high use roads, pipelines, mines, wind farms, transmissions lines, urban, industrial and agricultural areas are considered to be high human presence and identified as non-secure due to primary human presence (Figure 18).

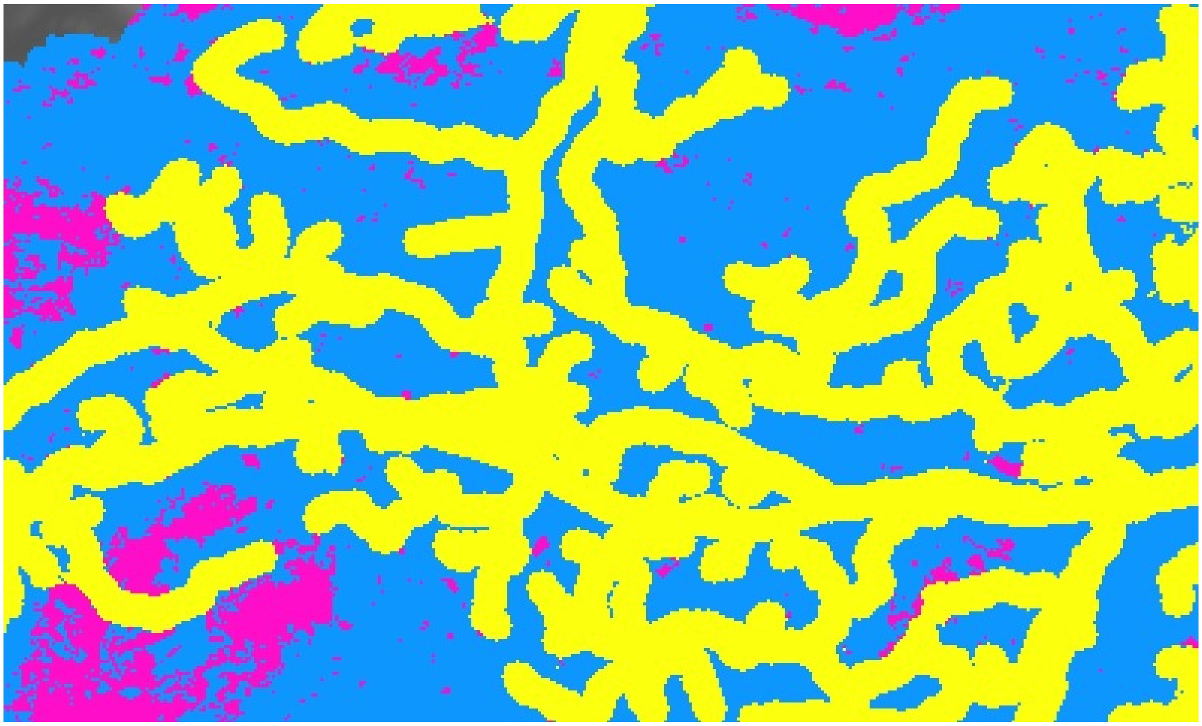

Figure 18. Example: Primary effects of high human presence on grizzly secure habitat. Primary non-secure areas due to high human presence (yellow), primary secure habitat (blue) and primary secure non-habitat (pink).

A 17.3. Step 3: secondary human presence effects: fully secure habitat

The areas that are do not have high human presence (primary secure areas) may still be considered non-secure due to shape. Narrow "bridges" and thin "peninsulas" have too much influence from areas of high human presence to be considered as secure.

To identify these "secondary human presence effects" areas of high human presence are buffered twice to re-classify some secure areas as non-secure or partially secure due to humans.

The first moving window over the landscape is used to calculate the percent of high human presence cells in a 1 km^2 buffer around each cell (radius 566 m). Any areas within 566m of high human presence are considered as non-secure. This identifies the "remoteness" of the 1 km^2 neighbourhood for each cell.

A second 1 km^2 moving window is used to count the number of fully secure cells within the 1 km^2 window surrounding each cell.

The secure cells from Step 1 are re-classified as follows (Figure 19):

- *Fully secure:* 100% of the cells in the surrounding 1 km^2 neighbourhood are at least 566m from high human presence. That is, *every cell within the 1 km^2 neighbourhood is at least 566m from high human presence* (i.e. such cells are at least 1,128m from high use roads, urban, etc.).
- *Partially secure:* some, but not all, of the cells in the surrounding 1 km^2 neighbourhood have high human presence within 566m. These cells are in habitat areas that are narrow and overly affected by nearby high human presence.
- *Non-secure*: all the cells in the surrounding 1 km^2 neighbourhood have high human presence within 566m.

Note that this step is applied to habitat and non-habitat (as non-habitat areas such as small wetlands should not reduce security).

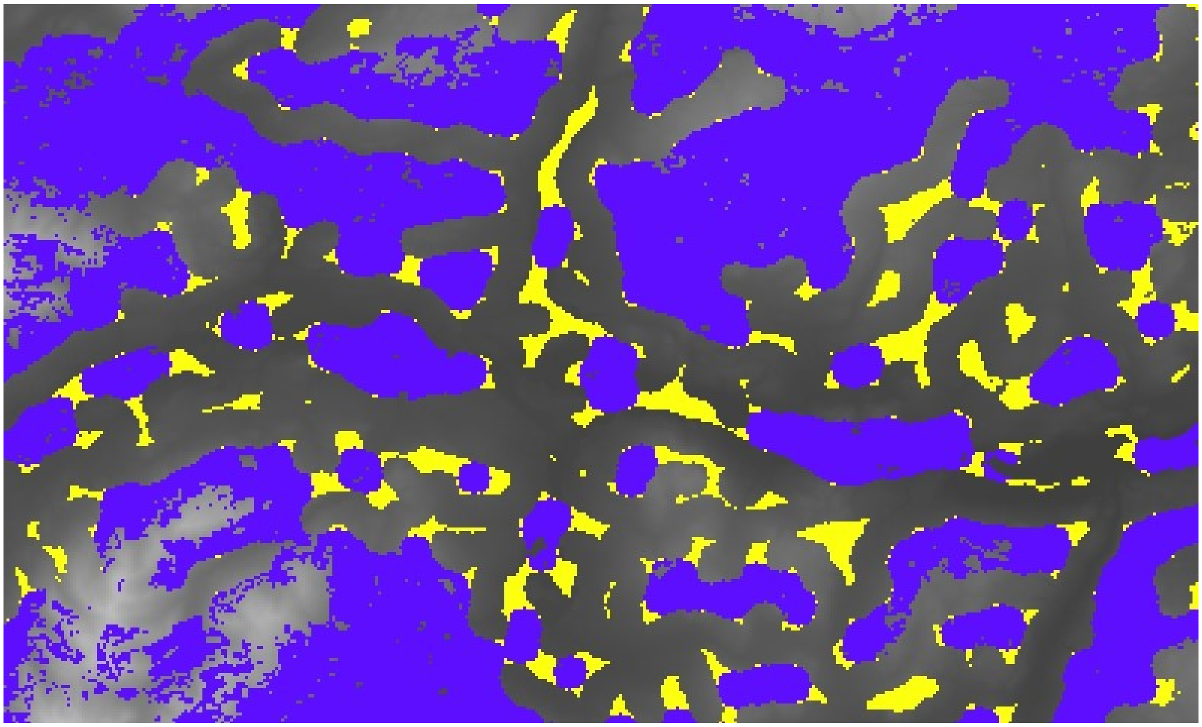

Figure 19. Example: Secondary effects of high human presence on grizzly secure habitat: Partially or fully secure habitat (blue) indicates habitat for which there is at least one fully secure neighbouring cell within a 1km^2 surrounding window. For habitat that is not fully or partially secure (yellow), no neighbours within 1km^2 surrounding window are fully secure (and hence these areas are narrow and overly affected by nearby high human presence).

A 17.4. Step 3 secure patch size

The remaining secure habitat forms patches. In the next step, the size and core area (area more than a threshold distance from a patch perimeter) are computed for each patch. If a patch size is below the minimum secure area threshold, all area within the patch is considered as non-secure due to not meeting minimum size (Figure 20). If the core area of a patch is below the minimum secure core area threshold, all area within the patch is considered as non-secure due to not meeting minimum core size (we did not apply a minimum core size in this example). Remaining patches are considered as secure areas.

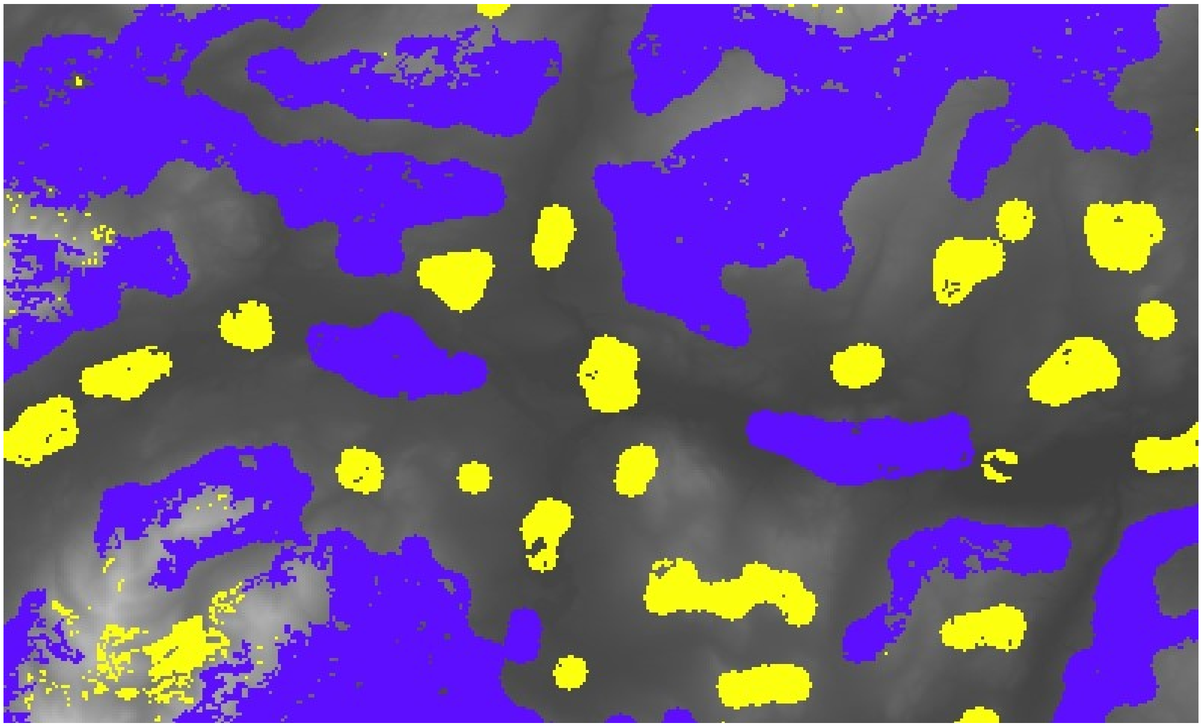

Figure 20. Example: effects of minimum secure area to filter out small habitat patches

A 17.5. Final outputs

Outputs include grids of habitat security class (Figure 21; unsuitable, non-secure due to human presence, non-secure due to size, non-secure due to core size, partially secure and fully secure), as well as summary files of area of habitat within specified strata (assessment watershed, landform, grizzly bear population unit, ecosection, landscape unit, BEC).

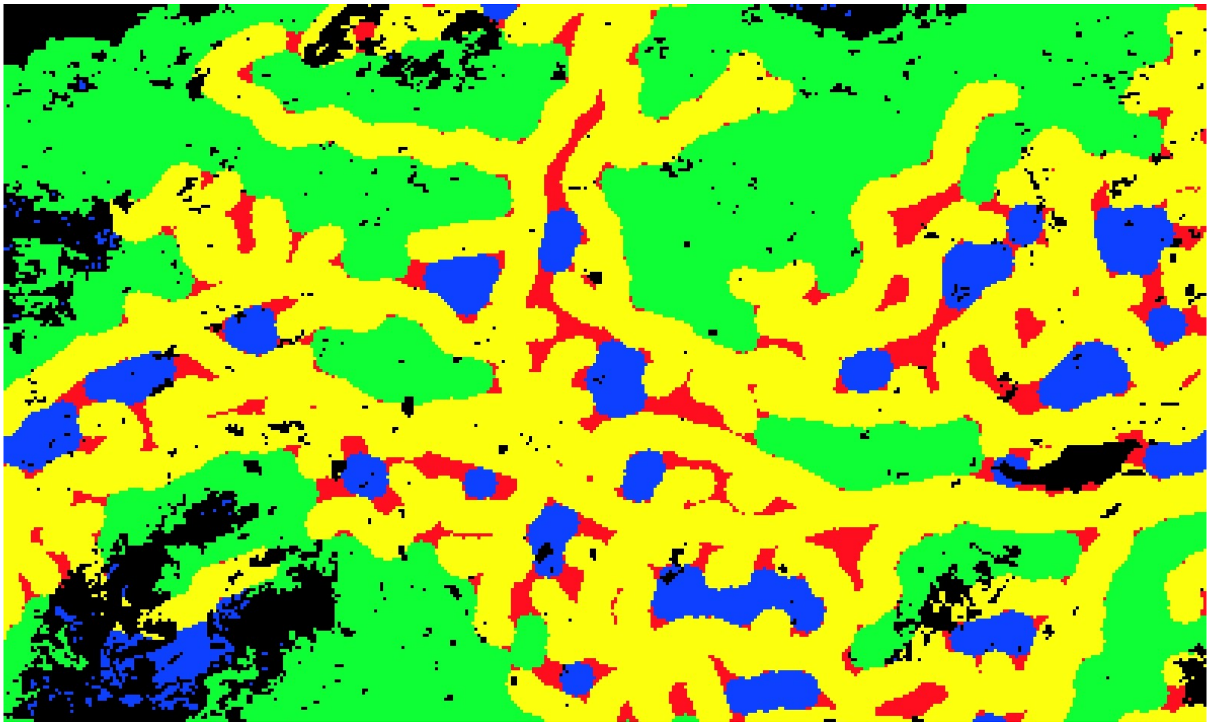

Figure 21. Example: final security class outputs (with some classes combined for clarity). Colours represent security class: secure habitat (full and partial; green); non-secure habitat due to primary human presence effects (yellow); non-secure habitat due to secondary human presence effects (red); non-secure habitat due to patch size (blue); and non-habitat (black).

Figure 22 shows the relation of the resulting secure grizzly habitat and human presence associated with high-use roads.

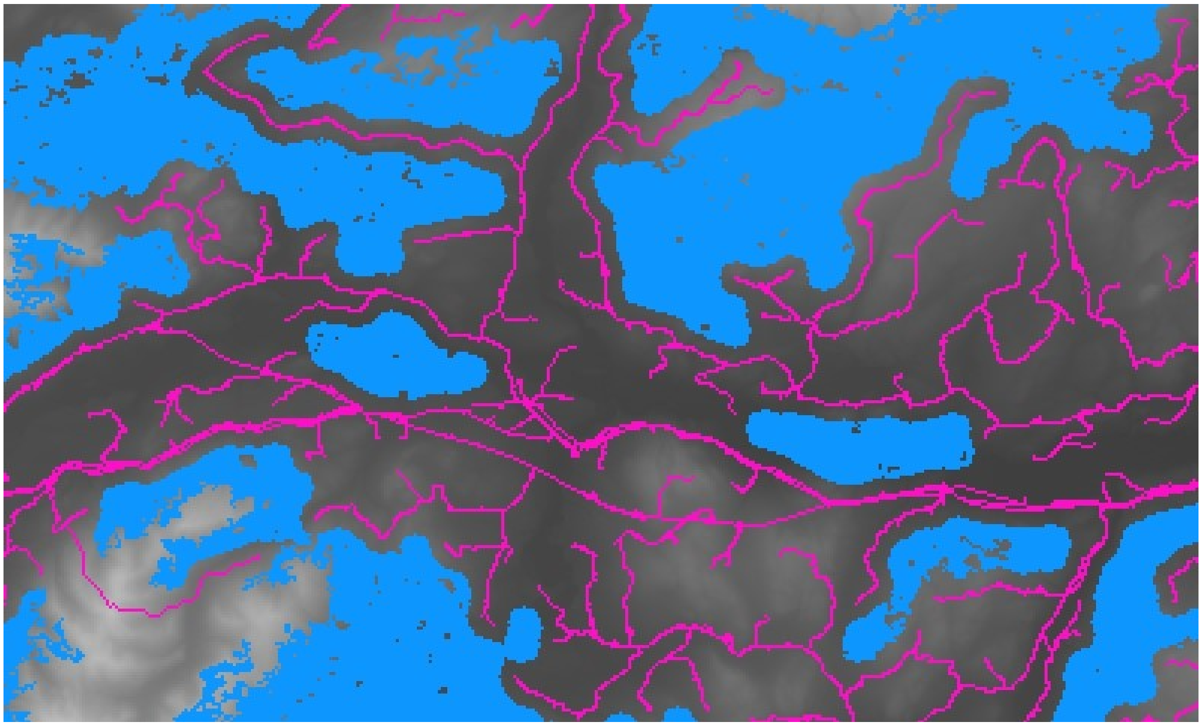

Figure 22. Example: final net secure habitat (blue) with high-use roads overlain (pink). Non-coloured areas represent non-habitat outside study area, or habitat considered as insecure due to primary road effects, secondary road effects or minimum patch size.

Appendix 18. Grizzly bear population isolation

Directly depends on: dynamic landscape projection, human access (to be added)
Dependency level: 5

Directly used by: scenario risk analysis

The grizzly bear population isolation component assesses the connectivity among the following grizzly bear population units (GBPUs) in the Skeena-Nass study area:

- Babine;
- Bulkley-Lakes;
- Cranberry;
- Francois;
- Khutzeymateen;
- North Coast;
- Stewart; and
- Upper Skeena-Nass.

This component uses spatial graphs to assess connectivity and isolation between GBPUs in the study area. See the Appendix on Spatial Graphs for some background and references. This component is applied in a sequence of steps, based on outputs from a specific dynamic scenario (e.g. SSP4).

A 18.1. Cost Surface

The first step creates a projection of grizzly movement cost surfaces based on roads, railways, transmission lines, mines, wind farms, pipelines, land-use type. Other that railways, these change over the time frame of the specific scenario.

Relative movement cost is defined as the cost (risk, effort, time) to move relative to the most ideal terrain (e.g. level intact forest), and is assigned as follows:

- 100 (highest relative cost): High use (high human presence) areas, including urban and industrial land-use, mines, wind farms, and high-use roads.
- 50: moderate use roads, railways, pipelines
- 25: transmission lines, low-use roads
- 10: water bodies, glaciers and snow, inactive roads (very low use)
- 1: otherwise

A 18.2. Spatial Graph Based on Uniform Points

The second step is to identify spatial graphs that can be used to assess the connectivity between GBPUs. Most connectivity analyses are based on connections between habitat habitats. In this component, the units are large GBPUs, which contain a mixture of habitat of varying security).

We define the "nodes" for this analysis using a uniform distribution of points, defined as the centroids of a lattice (or tessellation) of fixed size hexagons across the entire study area. Hexagon sizes applied were 1 km^2, 10km^2 and 100km^2).

This creates a uniform distribution of points across the landscape to use as graph nodes. Connections between nodes are between adjacent hexagons, the centres of which are either in the same GBPU (*internal links*) or different GBPUs (*external links*).

In addition, for the smaller scale (1 km^2 and 10km^2), a 10km wide buffer between GBPUs (i.e. 5km on either size of the GBPU boundary) was cleared of nodes to assess broader scale connections between GBPUs by forcing external links to cross longer distances. This was done in part because GBPUs are designed to enclose more intact areas (from a grizzly bear perspective), and their boundaries tend to be in areas with high human presence (e.g. large valleys with towns and highways).

To illustrate, Figure 23 shows a portion of the study areas near a GBPU boundary. A lattice of hexagons of size 10km2 were used to identify centroid points for nodes (boundaries shown in white). A buffer of width of 10km^2 is cleared of hexagon centroids between GPBUs. Links connect hexagon centroids (shown with coloured lines) by following least-cost paths based on the cost surface, which may cause deviations from straight lines, and distorts hexagon boundaries (which enclose areas closest to their centroid in least-cost space).

Internal links (within the same GBPU) are short and are used to assess movement within a GBPU at a relatively fine temporal scale (e.g. foraging) , while external links (between different GBPUs) are longer and are used to assess movement at a relatively longer temporal scale (e.g. dispersal).

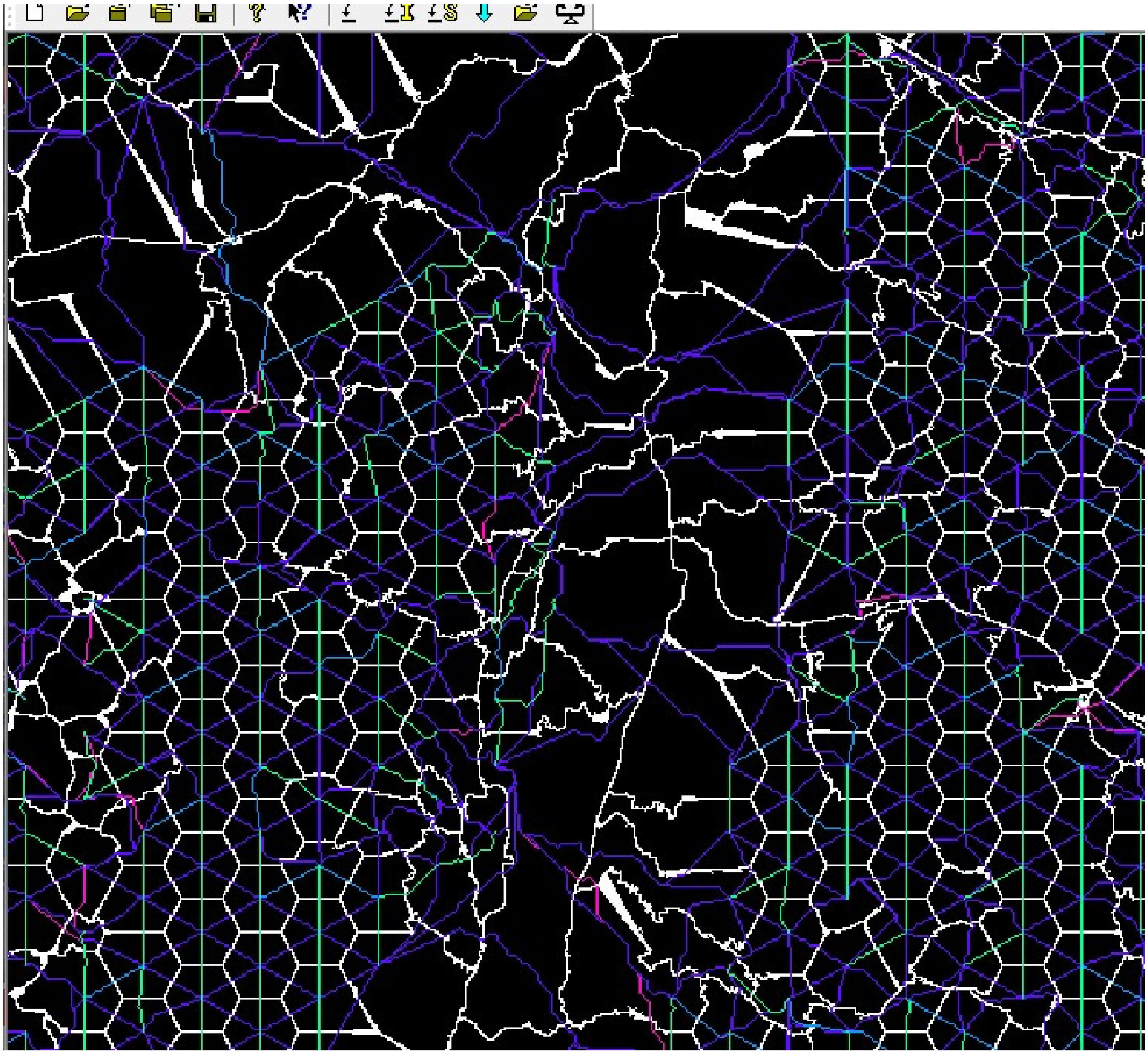

Figure 23. Example lattice of hexagons of size 10km2 (boundaries shown in white) near a GPBU boundary (hexagon centre points cleared over a distance of 10km^2), and links between hexagon centroids (shown with coloured lines). Links follow least-cost paths between nodes, so the cost surface may cause deviations from straight lines, which also distorts hexagon boundaries (which enclose areas closest to their centroid in least-cost space).

At each time step for a scenario, the projected cost surface is loaded, and the minimum planar graph is extracted for the hexagon centroid points. The result is saved in spatial and tabular files to represent the spatial graph (patch and link information, such as link length and cost).

A 18.3. Analysing and Reporting on Internal and External Graph Links

The third step iteratively loads the extracted spatial graphs to assess the internal and external connectivity of each GBPU.

Each link is assigned a "*connectivity class*" as follows:

- *link cost per metre = total link cost / total link length*
- *link connectivity rating = 1 / link cost per metre*
- *link connectivity class: classify the link connectivity rating into 5% classes up to 100% (i.e. 21 classes: 0, 0-0.05, … 0.95-1, >= 1)*
- *relative link connectivity class: same as link connectivity class, except the link cost is first divided by the "natural" link cost (i.e. the link cost in the absence of human impacts, accounting for natural cost factors such as water).*

The following information is summarized and output for each GBPU:

- Total area
- Number of nodes (hexagon centroids)
- Number of links (separately for internal and external)
- Mean link cost (total link cost/total link length; separately for internal and external)
- Total link connectivity rating (1/mean link cost; separately for internal and external)
- Link class frequency distribution: percent of links by link connectivity class (separately for internal and external)
    - In 25% link connectivity classes (1-4), where class 4 > 75%.
    - In 5% link connectivity classes (0-20) for external, where class 0 is 0% and class 20 is > 95%.
- Mean relative link cost ((total link cost minus natural link cost)/total link length; separately for internal and external)
- Total relative link connectivity rating (1/mean relative link cost; separately for internal and external)
- Relative link class frequency distribution: percent of links in each link connectivity class (separately for internal and external)
    - In 25% link connectivity classes (1-4), where class 4 > 75%.
    - In 5% link connectivity classes (0-20) for external, where class 0 is 0% and class 20 is > 95%.

When assessing external links, the total length and cost are divided by 2 to avoid bias (i.e. the length and cost is divided between the two GBPUs).

The resulting output can be analysed further to categorize the connectivity or isolation of each GBPU with other GBPU (external connectivity). In particular, the frequency distributions of link connectivity class (absolute and relative) provide overall information about the movement potential across GBPU boundaries. GBPUs that have a high percent of external links in poor connectivity classes and/or with a low percent in high connectivity classes indicate more isolated GBPUs. Using relative links is helpful for GBPUs that have relatively high natural barriers near their boundaries (e.g. glaciers, large lakes, fiords).

Appendix 19. Road water re-routing

Directly depends on: dynamic landscape projection, hydrological flow
Dependency level: 4

Directly used by: scenario risk analysis

Roads divert water flow into ditches parallel to the road and then through culverts and under bridges perpendicular to the road. Where ditches divert water flow, it reduces downstream soil moisture and runoff. These tend to be in relatively drier (low contributing area) portions of the landscape. Where diverted water passes under a road through a culvert or enters a larger watercourse, it increases flow.

The road water re-routing component estimates the degree to which a road network affects water flow. Specifically, it computes contributing area using the hydrological flow models, but on a modified flow direction (aspect) layer, in which flow direction is parallel to all roads (along the downslope direction), except where there is a mapped culvert, larger watercourse, or where there is no downslope direction parallel to the road (e.g. in topographic dips, in which water must flow under the road to follow gravity).

The resulting contributing area layer can then be compared with the base contributing area layer that ignores the effect of roads. Areas are classed in terms of the percent increase or decrease is contributing area due to the road network.

This component was not used in the Skeena-Nass CEA.

Appendix 20. Stream reach network

Directly depends on: watercourses, pitless elevation, contributing area
Dependency level: 1

Directly used by: salmon, watershed and stream reach indicators

Stream reaches are defined here as sections of watercourses that have a contributing area of at least 1000 ha (i.e. medium to large watercourses). This component creates a stream reach network by dividing such watercourses into segments between 2k and 10km in length. Segments are created when the maximum length is reached or when there is a substantial change in stream size (contributing area).

In the Morice River study area, a total of 36,794 stream segments were created in the network.

Appendix 21. Indicators: Salmon, stream reach, biodiversity, grizzly, and human density

Directly depend on: dynamic landscape projection, stream reach network, grizzly security class
Dependency level: 4 and 5

Directly used by: scenario risk analysis

These are a set of components of indicator models that produce outputs relevant to salmon, hydrological change, biodiversity, grizzly bears, and human density. These models all have a similar structure, and so are described together.

In general, these models summarize results from prior steps into a set of strata (e.g. ecosection, landscape unit, BEC variant, stream reach, assessment watershed, grizzly bear population unit). Result fields include attributes such as stand age class, grizzly security class, etc., which are output to an indicator text file.

Note: these indicator sub-models are subject to change as analysis needs adjust.

A 21.1. Salmon indicators

The salmon indicators are static and dynamic attributes that link salmon habitat with other static and dynamic attributes. The reporting strata include:

- Year: current or projected year
- Scenario: e.g. CurrCond, SSP1
- Assessment watershed
- Major watershed
- Trout Unit
- Ecosection
- Landscape unit
- BEC variant
- Management unit

Static reporting fields include (only for the current conditions scenario):

- Area (ha) in stratum
- Length (km) of stream

- Length of salmon habitat (km) for all species, and by individual species (Chinook, Chum, Coho, Pink even-year, Pink odd-year, Sockeye)
- Terrain Class IV and V partially and fully coupled to streams (ha)
- Topographic position index: sum of TPI for the 0m/500m scales (units TPI-ha)
- Slope-ha: sum of slope % over area (units: slope%-ha)
- Area of steep slopes (>= 8%) terrain (ha)

Dynamic reporting fields include:

- Land use type area (ha)
    - permanent natural land-use (e.g. lakes, glaciers, parks)
    - range land use (e.g. ranches, but not the large areas in the north)
    - agricultural and rural land use
    - natural land-use (e.g. working forest)
    - urban land use
    - industrial land use
- Length (km) of existing pipelines or assumed in model scenario
- Length (km) of all proposed pipelines
- Number of existing aggregate, coal and mineral mines
- Area (ha) of future mine sites (specified)
- Length (km) of highways, mainline roads, resource and restricted roads, urban roads, and skid trails
- Length (km) of open (active) mainline roads, resource and restricted roads, and skid trails
- Length of roads across class IV and V terrain, coupled to streams (km), by road type
- Length of open roads across class IV and V terrain, coupled to streams (km), by road type
- Roads within 100m of stream reach (km), by type
- Open roads within 100m of stream reach (km), by type
- Culverts (stream crossings) on stream reaches of order 1 and 2 (100-999 ha and 1,000-9,999 ha contributing area)
    - length of stream (km) with 0, 1, 2 or 3+ culverts downstream (to nearest larger order stream or water body)
- Equivalent clearcut area (ECA; ha)
- Equivalent clearcut riparian area (ECRA; ha):
    - area of initial productive forest that becomes deforested (roads, urban, agriculture)

  - area of high slope productive forest from natural origin disturbance (fire, MPB) by 10-year age class up to 100+ years old
  - area of low slope productive forest from natural origin disturbance (fire, MPB) by 10-year age class up to 100+ years old
  - area of high slope productive forest from human origin disturbance (logging) by 10-year age class up to 100+ years old
  - area of low slope productive forest from human origin disturbance (logging) by 10-year age class up to 100+ years old

A 21.2. Stream reach indicators

The dynamic stream reach indicators include attributes related each stream reach segment and its local catchment area. The reporting strata include:

- Year: current or projected year
- Scenario: e.g. CurrCond, SSP1
- Stream reach id (based on network of stream reaches)
- Assessment watershed
- Major watershed
- Ecosection
- Trout Unit
- BEC variant

Reporting fields include:

- Area of stream reach (ha; sum of cells in reach)
- Local catchment area of stream reach (reach plus upland that flows directly into reach)
- Stream reach order (1: 100-999ha, 2:1000-9999ha, 3:10000-99999ha, 4:100,000-999,999ha, 5:>=1,000,000 ha)
- Contributing THLB: area of all THLB uphill from reach.
- Local reach THLB: area of THLB associated directly upland from reach (i.e. in local catchment)
- Area of salmon habitat (ha) for all species, and by individual species (Chinook, Chum, Coho, Pink, Sockeye)
- Length (m) of road in stratum
- Length (m) or road within 100m of a reach

- Area of road across terrain Class IV and V fully and partially coupled with reach
- Number of active road crossings:
    - on stream reach
    - or below reach
    - on or above reach
- Area of pipeline within 1km of reach
- Area of logging within 10m of stream during prior 100 years
- Area of logging within 30m of stream during prior 100 years on slopes < 8%
- Area of logging within 30m of stream during prior 20 years on slopes >= 8%
- Area of logging on floodplains or within 30m of stream during prior 100 years

A 21.3. Biodiversity indicators

The dynamic biodiversity indicators include attributes for assessing biodiversity state and risk. The reporting strata include:

- Year: current or projected year
- Scenario: e.g. CurrCond, SSP1
- Assessment watershed
- Major watershed
- Ecosection
- BEC variant
- Site Index Class (0-4.9, 5-9.9, … 9: 45-49.9, 10:50+)

Reporting fields include:

- Area (ha) of forest in stratum
- Area of forest by distance from active roads (<= 100m, 100m to 500m, and > 500m)
- Area of old forest by distance from active roads, where "old age" as defined by the Biodiversity Guidebook and BEC variant (<= 100m, 100m to 500m, and > 500m)
- Area of "primary" forest by distance from active roads, where "primary" is defined as having no history of logging prior (<= 100m, 100m to 500m, and > 500m)
- Area by intactness index class, where intactness is as defined in the Climate Refugia proof of concept (Fall 2020) (>= 90, 50-90, < 50)
- Area of forest in estimated refugia class (defined here as age > 50% of the average for the NDT, after 250 years simulation of natural disturbance only with 100 replicates)

  - area of forest in estimated refugia class based on RCP2.6
  - area of forest in estimated refugia class based on RCP4.5
  - area logged in estimated refugia class based on RCP2.6
  - area logged in estimated refugia class based on RCP4.5
- Area of enduring features (ha; based on Eng 2020 and Fall 2020)
  - area of forest in estimated "climate buffering" enduring features
  - area of forest in estimated "disturbance avoidance" enduring features
  - area of forest in estimated "special habitat" enduring features
  - area logged in estimated "climate buffering" enduring features
  - area logged in estimated "disturbance avoidance" enduring features
  - area logged in estimated "special habitat" enduring features

A 21.4. Grizzly bear indicators

The dynamic human density indicators include attributes related to grizzly bear population units. The reporting strata include:

- Year: current or projected year
- Scenario: e.g. CurrCond, SSP1
- Trout Unit
- Landform
- Grizzly bear population unit
- Ecosection
- Landscape Unit
- BEC variant

Reporting fields include:

- Area (ha) in stratum
- Land use type area (ha)
  - permanent natural land-use (e.g. lakes, glaciers, parks)
  - range land use (e.g. ranches, but not the large areas in the north)
  - agricultural and rural land use
  - natural land-use (e.g. working forest)
  - urban land use
  - industrial land use
- Area of protected areas and conservancies (ha)

- Length (km) of existing pipelines or assumed in model scenario
- Length (km) of all proposed pipelines (does not include existing pipelines)
- Number of existing aggregate, coal and mineral mines
- Area (ha) of future mine sites (specified)
- Number of future wind farms (proposed and/or modelled)
- Length (km) of existing or projected transmission lines
- Length (km) of potential future transmission lines
- Area of productive forest
- Area of productive coniferous forest
- Area of productive coniferous mid-seral (40-80 or 40-120 depending on BEC)
- Length (km) of all active roads
- Length (km) of roads used in period. Open (in use) roads are roads with any use (e.g. permanent, or at least 1 ha logged in decade)
- Length (km) of maximum future roads (full build out; includes existing/active roads)
- Area by road density class (ha):
    - Class 1: 0 km/km2
    - Class 2: 0.1 to 0.3 km/km2
    - Class 3: 0.31 to 0.6 km/km2
    - Class 4: 0.61 to 0.75 km/km2
    - Class 5: above 0.75 km/km2
- Area by relative human pressure index class
    - Class 1: 0 < relative pressure <= 1,000 (remote)
    - Class 2: 1,000 < relative pressure <= 5,000 (low-moderate)
    - Class 3: 5,000 < relative pressure <= 10,000 (moderate-high)
    - Class 4: 10,000 < relative pressure <= 20,000 (high)
    - Class 5: relative pressure > 20,000 (very high)
- Area by security class area (ha) based on "active" roads (at least 1 ha logged during decade step)
    - area of habitat that has full security
    - area of habitat that has partial security
    - area of non-habitat that has security
    - area of habitat that is not secure (due to roads or patch size)
    - area of non-habitat that does not have security
- Area by Grizzly BEI class 1-8 (ha)

A 21.5. Human density indicators

The dynamic human density indicators include attributes related to land-use change and human population. The reporting strata include:

- Year: current or projected year
- Scenario: e.g. CurrCond, SSP1
- Landform (9 classes)
- Grizzly bear population unit
- Landscape Unit
- BEC variant

Reporting fields include:

- Area (ha) in stratum
- Land use type area (ha)
    - permanent natural land-use (e.g. lakes, glaciers, parks)
    - range land use (e.g. ranches, but not the large areas in the north)
    - agricultural and rural land use
    - natural land-use (e.g. working forest)
    - urban land use
    - industrial land use
- Number of humans (sum of human density over area)
- Area by relative human pressure index class
    - Class 1: 0 < relative pressure <= 1,000 (remote)
    - Class 2: 1,000 < relative pressure <= 5,000 (low-moderate)
    - Class 3: 5,000 < relative pressure <= 10,000 (moderate-high)
    - Class 4: 10,000 < relative pressure <= 20,000 (high)
    - Class 5: relative pressure > 20,000 (very high)
- Area by slope class (to approximate potentially-habitable vs. not-habitable)
    - Classes: <= 10%, 10%-25%, 25%-50%, 50%-100%, and > 100%