Applying Climate Refugia in Conservation Planning and Assessment in BC:

Proof of Concept in the Skeena and Nass Water Basins

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Contents

Acknowledgments and Caveats

This proof of concept represents an initial application of climate refugia concepts as indicators in BC, and builds on the review and proposal of an associated document by M. Eng. Any errors or mis-interpretations rest entirely with me.

I would particularly like to thank Marvin Eng for providing a good place to start, and Don Morgan for ongoing collaboration in this line of work, especially in the Skeena-Nass. I am also thankful AdaptWest and its associates for providing very useful summarizes of the concepts and data for North America.

Summary and Conclusions

The review by Eng (2020) provided some guidance and recommendations on how to initiate the process of using climate refugia concepts in conservation assessment and planning in BC, and suggested focusing on three main types of spatial indicators to characterize sites:

1. Degree of ‘***intactness’***: the inverse of the intensity of the human footprint.
2. Density of ‘***enduring features***’: potential climatic micro-refugia and/or for abiotic diversity.
3. Probability of being an *in situ* regional climate ‘***macro-refugia’***.

Methods were developed and implemented using SELES (Spatially Explicit Landscape Event Simulator) and applied in the Skeena-Nass area to demonstrate a proof of these concepts. Application of these methods in a decision process will require review and revision of data (e.g. updated climate and local data) and parameters (e.g. climate analogs), and exploring uncertainties.

Degree of ‘intactness’

Intactness is inversely related to the ‘human footprint’. This method quantifies the location and magnitude of human footprint factors, ranging from little impact (e.g. remote wilderness) to very high impacts (e.g. urban centres and industrial sites). Intactness decreases with increasing human footprint.

Density of ‘enduring features’

Enduring features are spatially identifiable elements that may provide: (a) micro-climates where adverse changes in the regional climate may be ameliorated (e.g. cold air ponding); (b) unique/rare sites that provide specialized habitat (e.g. cliffs); and (c) areas relatively sheltered from natural disturbance (e.g. wetlands). Density of enduring features helps to identify areas with relatively high concentrations of such features.

Probability of Being a Regional Climate Macro-refugia

Regional climate macro-refugia are defined as areas where the future regional climate is ‘similar enough’ to the current climate to enable the persistence of the elements of biodiversity. Eng (2020) recommended focusing on the identification of *in situ* refugia, and in particular, places where the current climate defining a Biogeoclimatic subzone (or subzone grouping) will overlap with ‘analogous’ future climate for that subzone or grouping – herein called ‘stable analogs’. I also explored two other methods of identifying *ex situ* refugia described in the literature[1] to guide the development of an approach that deals with situations where *in situ* refugia, proposed by Eng (2020) may be overly limiting, because the individual areas are too small to be functional. I propose a combination of two, newly developed, methods of identifying areas around ‘stable analogs’ that may be of value in conservation planning and assessment: “*Analog Refugia Class*” (refugia potential for each climate analog) and “*Analog Climate Condition*” (classification of analogs based on area in refugia classes).

Conservation Class

Intactness, Density of Enduring Features and Macro-refugia (a combination of Analog Refugia Class and Analog Climate Condition) were combine into a single conservation class based on Eng (2020).

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[1] See Appendix A: ‘Climate Velocity’ (rate of spatial change of climate analogs) and ‘Shrinking Analogs’ (identifying potential refugia areas based on analog neighbourhoods).

1.0 Document Purpose and Introduction

The purpose of this document is to provide a proof of concept of climate refugia concepts, in particular those identified by Eng (2020), by way of an application in the Skeena-Nass water basins in northwestern BC. The review by Eng (2020) will be considered a companion document, and duplication of definitions and background will be minimized.

The review by Eng (2020) suggested focusing on three main types of spatial indicators to characterize sites. I developed and implemented spatial metrics for each, as well as a combined metric:

1. Degree of '***intactness'***: the inverse of the intensity of the human footprint, which was quantified based on the location and magnitude of different human footprint factors, ranging from little impact (e.g. remote wilderness) to very high impacts (e.g. urban centres and industrial sites). Intactness decreases with human footprint.

2. Density of '***enduring features***': potential of an area for climatic micro-refugia and/or for abiotic diversity were categorized by mechanism:

    - Micro-climates where adverse changes in the regional climate may be ameliorated (e.g. cold air ponding).
    - Specialized habitats (e.g. cliffs) are areas of unique/rare habitat niches.
    - Disturbance avoidance area (e.g. wetlands) are areas more sheltered from natural disturbance than the surrounding landscape.

    Density of enduring features was estimated by computing the average concentration of enduring features (weighted by value) within a defined distance of each location (1 km was used here).

3. Probability of being a regional climate '***macro-refugia'***: areas that may enable persistence of elements of biodiversity under climate change. This was based on areas with similar climates in the present and future, defined as "*climate analogs"*. I used groupings of Biogeoclimatic subzones for climate analogs, and developed three related methods:
    - "*Stable Analogs*": identification of areas where current and projected climate analogs overlap (i.e. *in situ* refugia, on which Eng (2020) recommended focusing).
    - "*Analog Refugia Class*": classification of all areas with a given analog (Biogeoclimatic BGC subzone group) in the present and/or future based on spatial distance to stable analogs and non-stable analogs to estimate relative potential as refugia. The highest potential are stable analog area and areas near stable analogs, and the lowest are areas with projected dramatic change (e.g. current BGC subzone groups expected to disappear in the future).
    - "*Analog Climatic Condition*": classification of the overall climate condition of an analog (BGC subzone group) based on the proportional area in each refugia class (by ecosection). Condition decreases as the area of stable or near stable refugia classes decreases).

In addition, two other existing methods were explored and documented in Appendix A:

- "*Climate Velocity*": The rate of spatial change of climate analogs.
- "*Shrinking Analogs*": identifying potential refugia areas based on analog neighbourhoods.

4. ***'Conservation class'*** combines Intactness, Density of Enduring Features and Macro-refugia (Analog Refugia Class and Analog Climate Condition) into a single integrated layer based on Eng (2020).

The focus of this report is on the technical development and application of methods, and presentation of exploratory results in the Skeena-Nass area. The methods provide a 'coarse filter' approach to biodiversity conservation (Ministry of Forests and Ministry of Environment 1995). Methods were implemented using SELES (Spatially Explicit Landscape Event Simulator; Fall and Fall 2001). The results presented should be interpreted as demonstrating the type of information that different indicators may produce, and are not meant as specific guidance in the Skeena-Nass study area.

The next steps proposed by Eng (2020) include further development and application of these methods in a pilot project that would involve more extensive collaboration to develop inputs and parameters (see Appendix B), a focus on a specific decision process, and a wider exploration of uncertainty, in particular, examining the 'model-agreement' or 'consensus-strength' map showing the degree of consensus among RCP x GCM scenarios (Wang et al. 2012).

In-depth consideration of the notions surrounding climate refugia will help facilitate a broader discussion about developing an approach to assessing and managing biodiversity conservation that considers the dynamic nature of the landscape.

2.0 Skeena-Nass Study Area

The Skeena-Nass study area includes the Skeena and Nass water basins, plus associated coastal watersheds and islands, and comprises about 12,460,000 ha of the southern portion of the Skeena Region of the BC Ministry of Environment (Figure 1). This area was chosen due to availability of data, its diverse landscape, and prior cumulative effects assessment (CEA) modelling work in this area. The models were implemented as additional components of the Skeena-Nass modelling toolkit.

This study area was assessed using 1-ha grid resolution (rasters).

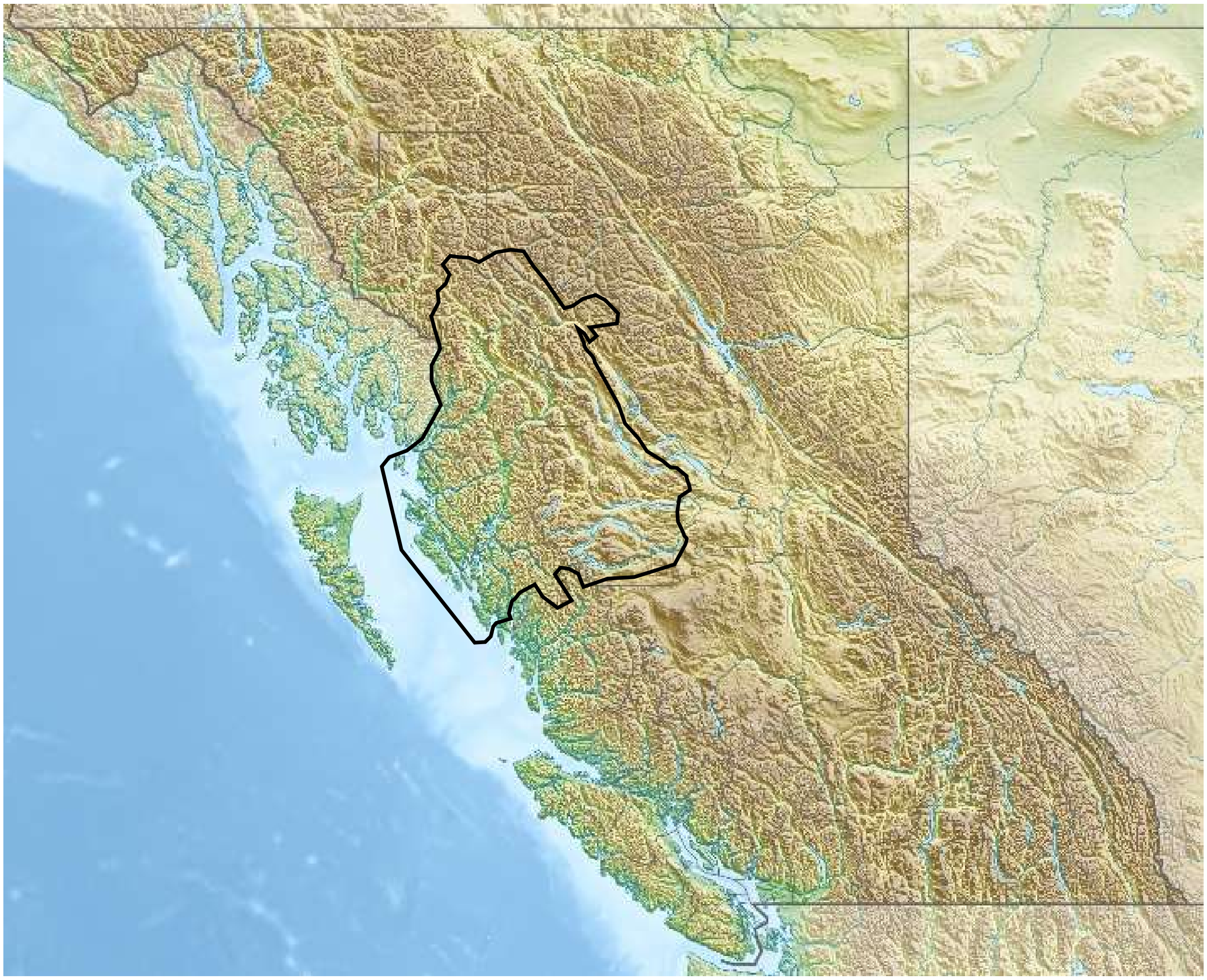


Figure 1. Location of the Skeena-Nass study area (outlined in black). Image credit: Carport / CC BY-SA (https://creativecommons.org/licenses/by-sa/3.0).

3.0 Degree of Intactness

3.1 Method

Eng (2020) provided a list of attributes that contribute to the human footprint, most of which were available in the study area. Each attribute requires an 'intensity score' (magnitude of impact), which needs to be developed with collaboration by experts. Linear features (roads, transmission lines, railways, pipelines) were buffered by 1 km with decreasing intensity as defined below. As recommended by Eng (2020), in this proof of concept, impact intensity scores were kept simple:

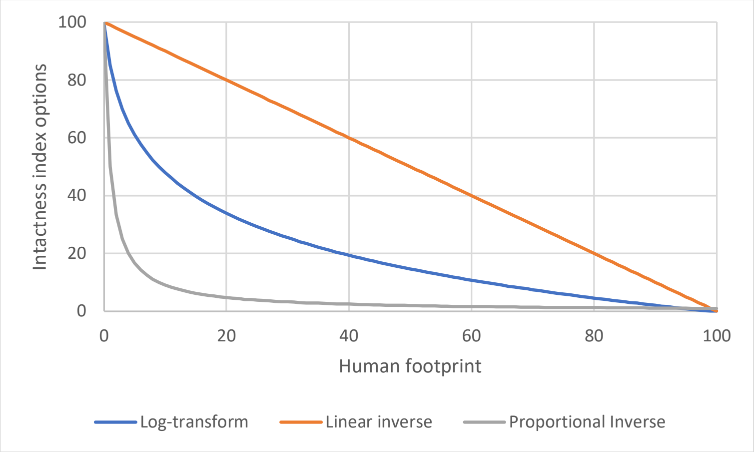
- Land use
  - Urban and Industrial: 100%
  - Agriculture: 50%
  - Range: 10%
- Mines and wind farms: 100%
- Logged areas
  - $\leq$ 20 years: 100%
  - 20-50 years: 50%
  - \> 50 years: 10%
- Transmission lines: 50% decreasing linearly to 0% at 1 km distance
- Railways: 100% decreasing linearly to 0% at 1 km distance
- Pipelines: 50% decreasing linearly to 0% at 1 km distance
- Roads: 100% decreasing linearly to 0% at 1 km distance (this can be refined based on level of use, road type, etc.)

Human footprint is computed as the maximum footprint at any 1-ha cell.

Intactness is a log-transform of human footprint: -100 * LOG_{100}(HumanFootprint+0.01)

Using a log transform emphasizes areas with lower footprint. Base 100 is used to scale from 0% (where human footprint is 100%) to 100% (where human footprint is 0%), as shown in the Figure 2. The '+0.01' factor ensures a footprint of 0% has full intactness, since LOG(0) is undefined. Other options include a linear inverse (i.e. 100% - HumanFootprint) or a proportional inverse (e.g. 100%/(HumanFootprint+1)), but the former seems to over-emphasize areas with relatively high human impacts (> 50%), while the latter under-emphasizes areas with moderate human impact.

Figure 2. Options to scale human footprint to intactness. The proof of concept applied the log-transform method.



3. 2 Results

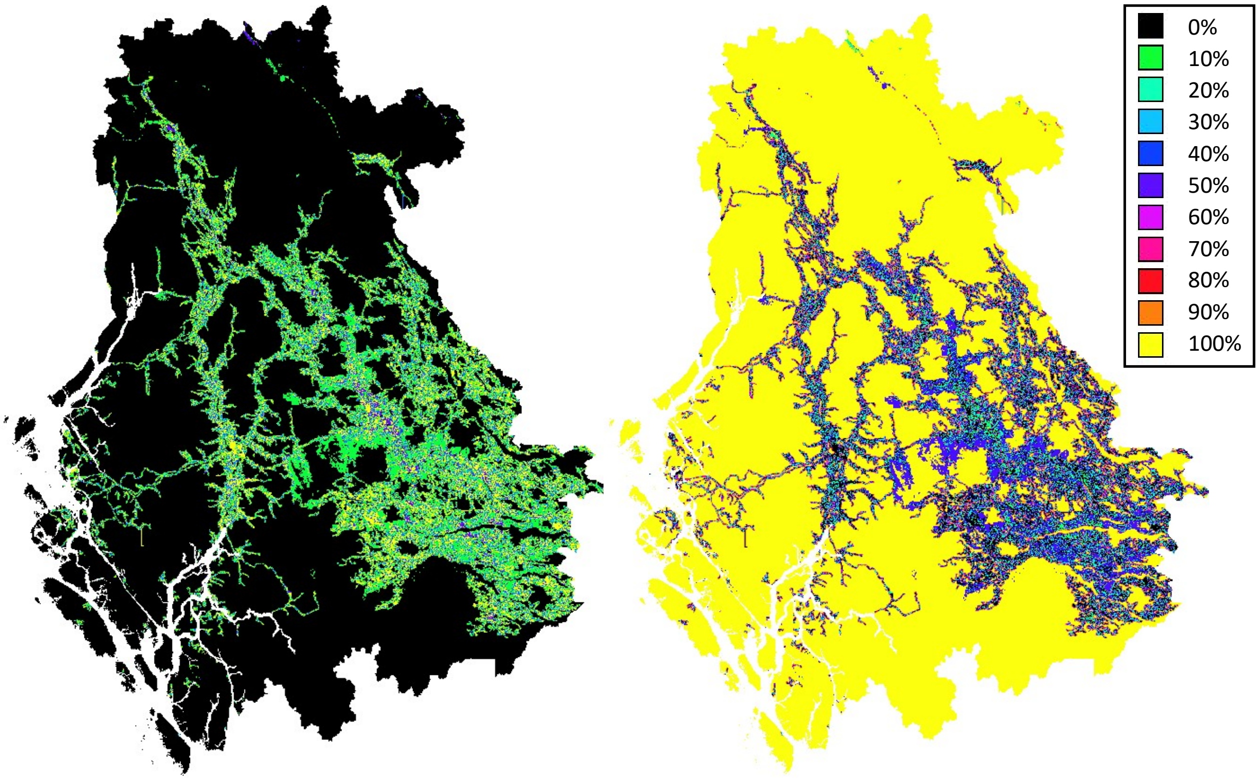


Figure 3. Human footprint index (left) and Intactness index (right). Values range from 0% to 100%.

3.3 Potential uses for Conservation Planning and Assessment

Ecosystems in areas with high intactness are more likely to persist, or be restored, under climate change than areas with low intactness. In areas of climate macro-refugia, these may help identify areas *resistant* to climate change (Eng, 2020).

3. 4 Future improvements

Developing rigorous ‘intensity scores’ that are broadly applicable across BC would help to ensure consistent use of this method. Further exploring and refining how human footprint is rescaled to intactness should be done in collaboration with experts.

4.0 Density of Enduring Features

“Enduring features” are defined by Eng (2020) as areas with a high likelihood of being micro-refugia, areas that contribute to abiotic diversity, and/or small natural features with ecological value disproportionate to their size.

4.1 Method

Eng (2020) provided an initial more-or-less complete list of enduring features relevant to BC, and a subset that occur in the Skeena Nass study area and are relatively easy to map. Table 1 lists these and identifies whether or not they were applied in the Skeena Nass proof-of-concept analysis.

Table 1. Enduring features recommended by Eng (2020) for Skeena-Nass proof-of-concept.

Feature	Mechanism category	Used in Skeena-Nass proof-of-concept?
Rocky outcrops	Specialized Habitat	no (lack of data)
Cliffs	Specialized Habitat	yes (slope $\geq$ 100%)
Waterfalls	Specialized Habitat	no (lack of data)
River bars	Specialized Habitat	no (lack of data)
Relative soil moisture	Specialized Habitat	no (lack of knowledge and data)
Riparian zones	Specialized Habitat	yes (100m buffers on freshwater)
Springs and headwaters streams	Climatic buffering	yes (headwater streams based on contributing area)
Beaver-modified landscapes	Climatic buffering	no (lack of data)
Temperature Inversions and Cold air pools	Climatic buffering	no (lack of data)
Complex terrain	Climatic buffering	no (recommendation from M. Eng)
Glaciers	Climatic buffering	yes
Heat Load Index	Climatic buffering	yes (function of aspect, slope and latitude)
Talus slopes	Climatic buffering	no (lack of data)
Wetlands Spring-fed	Climatic buffering	no (lack of data)
Glacier-fed streams	Climatic buffering	yes (proportion of contributing area coming from glaciers $\geq$ 5%)
Steep canyons (ravines)	Climatic buffering	yes (landform model)
Shorelines of Large Deep Lakes	Climatic buffering	yes (100m buffers)
Toe Slopes	Disturbance avoidance	yes (slope position model)
Islands	Disturbance avoidance	no (lack of data)
Shorelines minor	Disturbance avoidance	yes (100m buffers)
Wetland complexes	Disturbance avoidance	yes

Some of these features are available in base inventory, while others are derived from models, including

- Heat Load Index: implemented based on McCune and Dylan (2002)

- Glacier-fed streams: based on ratio of contributing area from glaciers to total contributing area
- Steep canyons: based on landform derived using a topographic position index model (Weiss 2001)
- Toe slopes (based on a slope position model)

Eng (2020) left two issues to address:

(a) Specifying initial 'values' for each feature, based on characteristics and expected persistence.

In the proof-concept, values for all enduring features were set to 100%, except that minor shorelines were set to 50 (to distinguish from shorelines of large lakes). The value for a cell was computed as the maximum value of any enduring feature.

(b) Developing a method of calculating a 'density' of enduring features, weighted by their value.

Density was computed using a circular moving window with radius of 1 km. For each cell, density is the sum of all enduring feature values in the window divided by the size of the window.

4. 2 Results

The following figures show the density of enduring features for each mechanism category and for all categories combined.

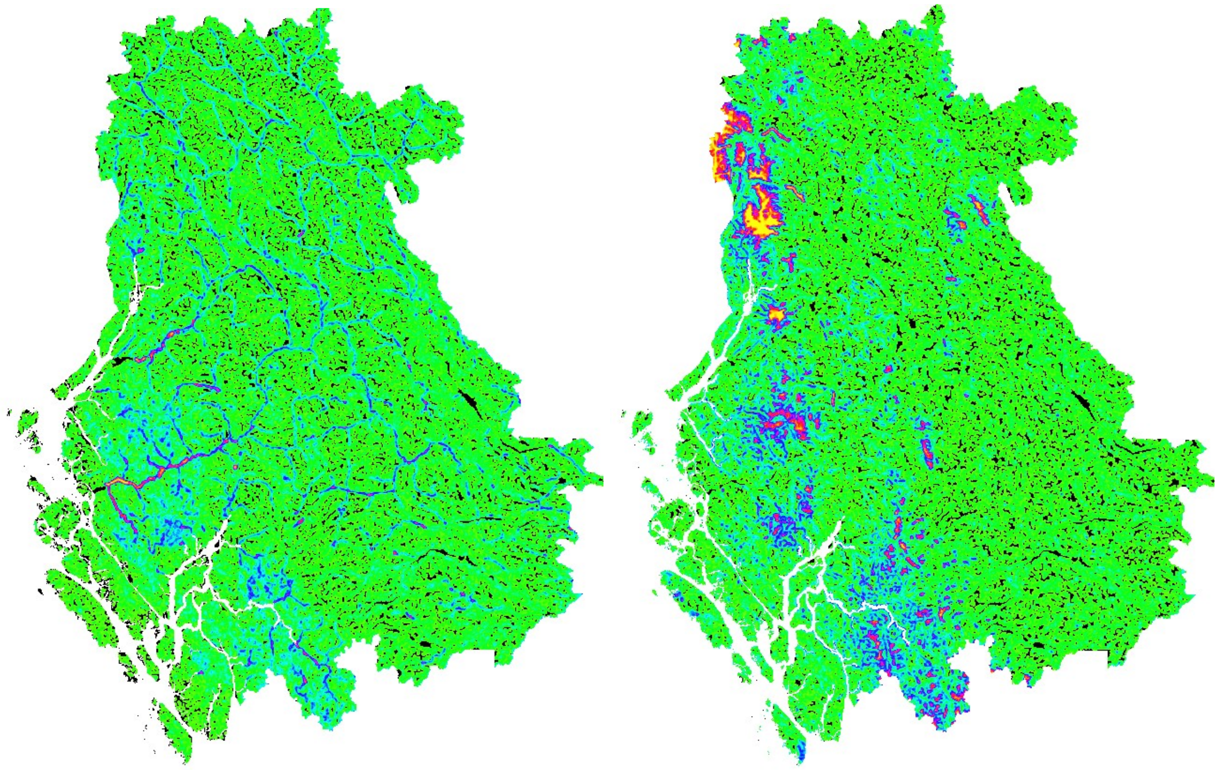


Figure 4. Left: Density of Specialized Habitat Features using a 1 km radius moving window. Right: Density of Climate Buffering Features using a 1 km radius moving window.

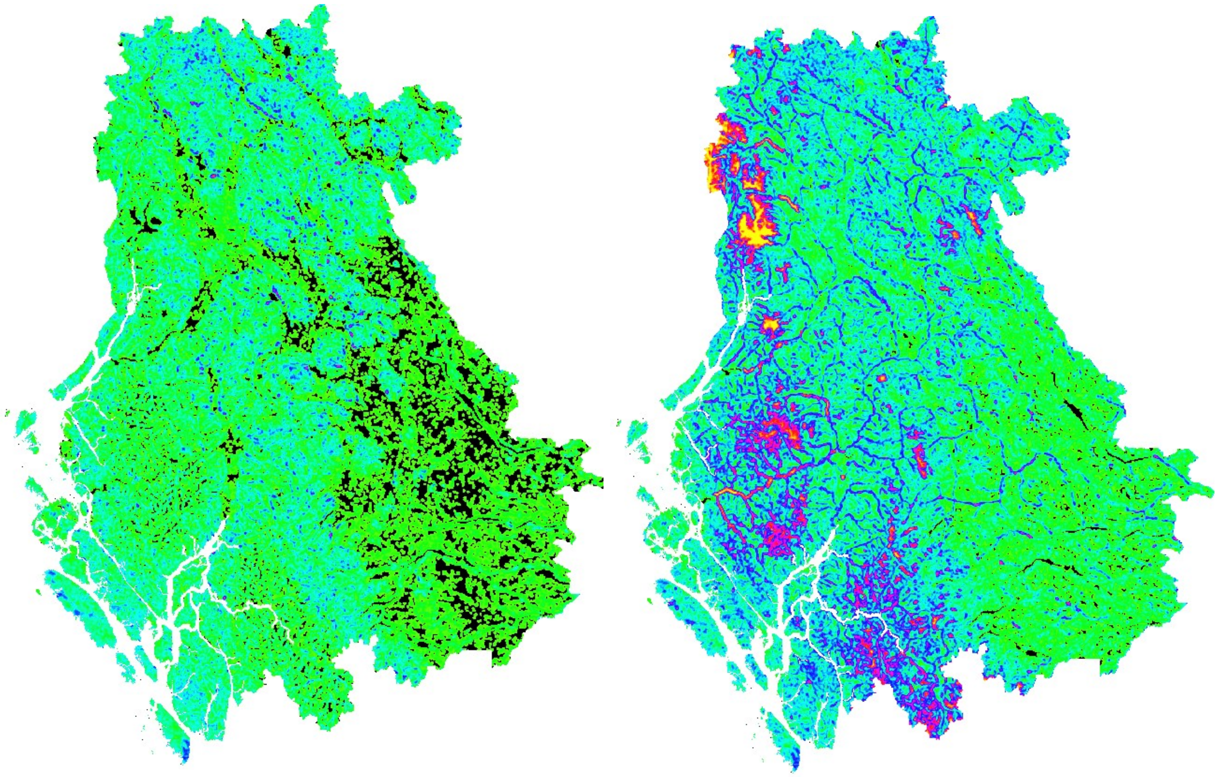


Figure 5. Left: Density of Disturbance Avoidance Features using a 1 km radius moving window. Right: Density of combined Enduring Features using a 1 km radius moving window.

4.3 Potential uses for Conservation Planning and Assessment

Areas with relatively high concentrations of enduring features can be prioritized for conservation, whether or not they occur in climate macro-refugia (Eng, 2020).

4. 4 Future improvements

Standardized sets of enduring features could be developed for BC, with information on source inventories and modelling methods to derive base features.

Value ratings for individual feature types should be developed in collaboration with experts for a particular decision process.

Assessment of other moving window radii could be explored.

5.0 Probability of Being a Macro-refugia

5.1 Climate analogs: Biogeoclimatic subzone groups

Wang et al. (2012) used statistical methods (Random Forests) to delineate the current climate envelope for each Biogeoclimatic Variant in BC. They then used 20 climate heating scenarios (RCP x GCM) to provide a projection of where those Variant level envelopes might occur in 2050 and 2080. Eng (2020) recommended using grouping of those Variants into Biogeoclimatic (BGC) subzones, and further, into BGC subzone groupings with similar 'on the ground' attributes. The 22 BGC subzone groupings that occur in the study area (Table 2, Figure 6) defined the *climate analogs* used to identify macro-refugia.

Table 2. BGC subzone groupings.

	BGC subzone group	BGC subzones included in group
1	BWBS-Dry	BWBSdk, BWBSdk1, BWBSdk2, BWBSmk, BWBSmw, BWBSmw1, BWBSmw2, BWBSun
2	BWBS-Wet	BWBSvk, BWBSwk1, BWBSwk2, BWBSwk3
3	Coast-Moist	CDFmm, CWHdm, CWHds1, CWHds2, CWHmm1, CWHmm2, CWHms1, CWHms2, CWHxm1, CWHxm2
4	Coast-Wet	CWHun, CWHvh1, CWHvh2, CWHvh3, CWHvm, CWHvm1, CWHvm2, CWHvm3, CWHwh1, CWHwh2, CWHwm, CWHws1, CWHws2
5	ESSF-Dry	ESSFdc2, ESSFdc3, ESSFdcw, ESSFdk1, ESSFdk2, ESSFdkw, ESSFdm, ESSFdmw, ESSFdv1, ESSFdv2, ESSFdvw, ESSFdku, ESSFxc1, ESSFxc2, ESSFxc3, ESSFxcw, ESSFxv1, ESSFxv2, ESSFxvw
6	ESSF-Moist	ESSFdc1, ESSFmc, ESSFmh, ESSFmk, ESSFmm1, ESSFmm2, ESSFmm3, ESSFmmw, ESSFmv1, ESSFmv2, ESSFmv3, ESSFmv4, ESSFmw, ESSFmw1, ESSFmw2, ESSFmww, ESSFun, ESSFwh2, ESSFwh3, ESSFwm, ESSFwm1, ESSFwm3, ESSFwm4, ESSFwmw
7	ESSF-Wet	ESSFvc, ESSFvcw, ESSFwc1, ESSFwc2, ESSFwc3, ESSFwc4, ESSFwc5, ESSFwc6, ESSFwcw, ESSFwh1, ESSFwk1, ESSFwk2, ESSFwm2, ESSFwv
8	High Elevation	BAFAun, BAFAunp, CMAun, CMAunp, CMAwh, ESSFdcp, ESSFdkp, ESSFdmp, ESSFdvp, ESSFmcp, ESSFmkp, ESSFmmp, ESSFmvp, ESSFmwp, ESSFunp, ESSFvcp, ESSFwcp, ESSFwmp, ESSFwvp, ESSFxcp, ESSFxvp, IMAun, IMAunp, MHmmp, MHunp, MHwhp
9	ICH-Dry	ICHdk, ICHdm, ICHdw1, ICHdw2, ICHdw3, ICHdw4, ICHmk1, ICHmk2, ICHmk4, ICHmk5
10	ICH-Moist	ICHmc1, ICHmc1a, ICHmc2, ICHmk3, ICHmm, ICHmw1, ICHmw2, ICHmw3, ICHmw4, ICHmw5
11	ICH-Wet	ICHvc, ICHvk1, ICHvk2, ICHwc, ICHwk1, ICHwk2, ICHwk3, ICHwk4
12	IDF/ICH	ICHxw, ICHxwa, IDFmw1, IDFmw2, IDFww, IDFww1
13	IDF-Dry	IDFdc, IDFdk1, IDFdk2, IDFdk3, IDFdk4, IDFdk5, IDFdm1, IDFdm2, IDFdw, IDFxh4, IDFun
14	IDF-Vdry	IDFxc, IDFxh1, IDFxh2, IDFxk, IDFxm, IDFxw
15	MH	MHmm1, MHmm2, MHun, MHwh, MHwh1, MHwh2
16	MS-Dry	MSdk1, MSdk2, MSxk1, MSxk2, MSxk3, MSxv
17	MS-Moist	MSdc1, MSdc2, MSdc3, MSdk, MSdm1, MSdm2, MSdm3, MSdv, MSdw, MSmw1, MSmw2, MSun
18	Open Forest / Grassland	BGxh1, BGxh2, BGxh3, BGxw1, BGxw2, IDFxx2, PPdh2, PPxh1, PPxh2, PPxh3
19	SBS-Dry / SBPS	SBPSdc, SBPSmc, SBPSmk, SBPSxc, SBSdh1, SBSdh2, SBSdk, SBSdw1, SBSdw2, SBSdw3
20	SBS-Moist	SBSmc1, SBSmc2, SBSmc3, SBSmh, SBSmk1, SBSmk2, SBSmm, SBSmw, SBSun
21	SBS-Wet	SBSvk, SBSwk1, SBSwk2, SBSwk3, SBSwk3a
22	SWB	SWBmk, SWBmks, SWBun, SWBuns, SWBvk, SWBvks, SWBdk

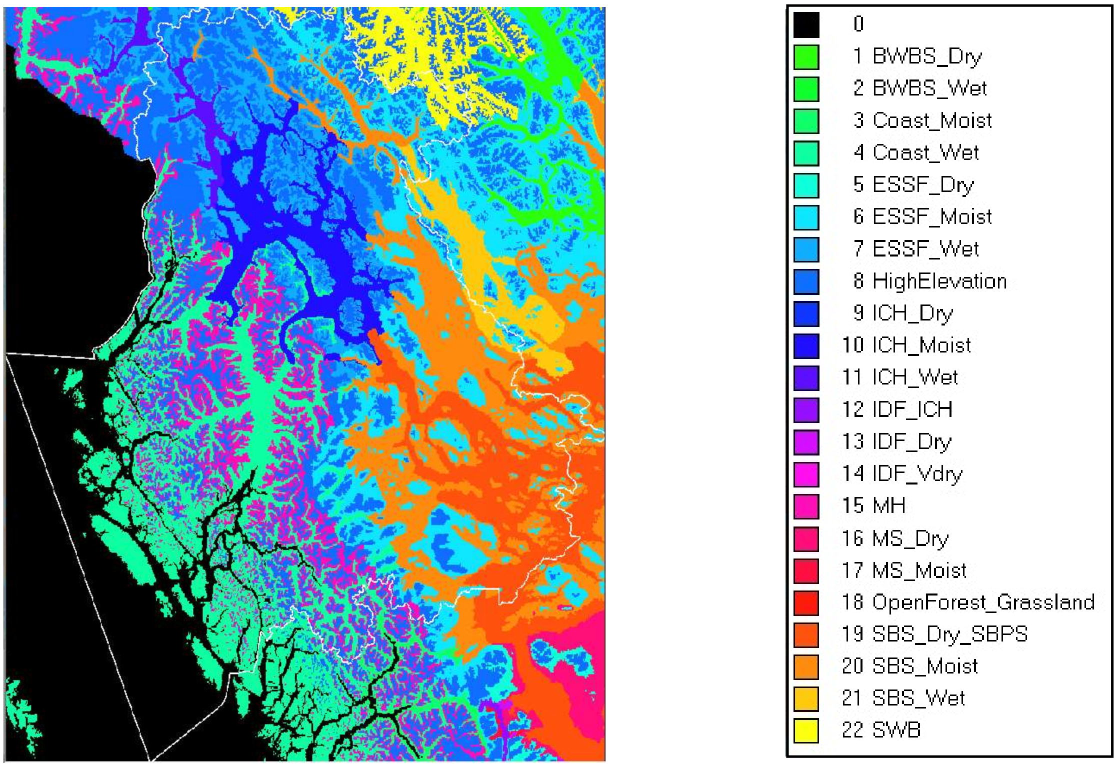


Figure 6. BGC subzone groupings used for climate analogs in proof-of-concept analysis.

5.2 Areas with Stable Climate Analogs

Eng (2020) proposed use of areas with unchanged Biogeoclimatic (BGC) subzone group climate analogs in the future. All analyses done for the proof-of-concept were done for 2050 and 2080.

5.2.1 Method

BGC projections provided by Wang et al. (2012) were reclassed into the BGC subzone groupings:

- The current BGC subzone grouping layer was intersected with future projected layers. Values were only retained in the result that were the same in both layers; other cells were set to 0.

The reverse of this shows areas with unstable analogs – retaining only the values in the current BGC subzone layer that are different from the projected future value.

5.2.2 Results

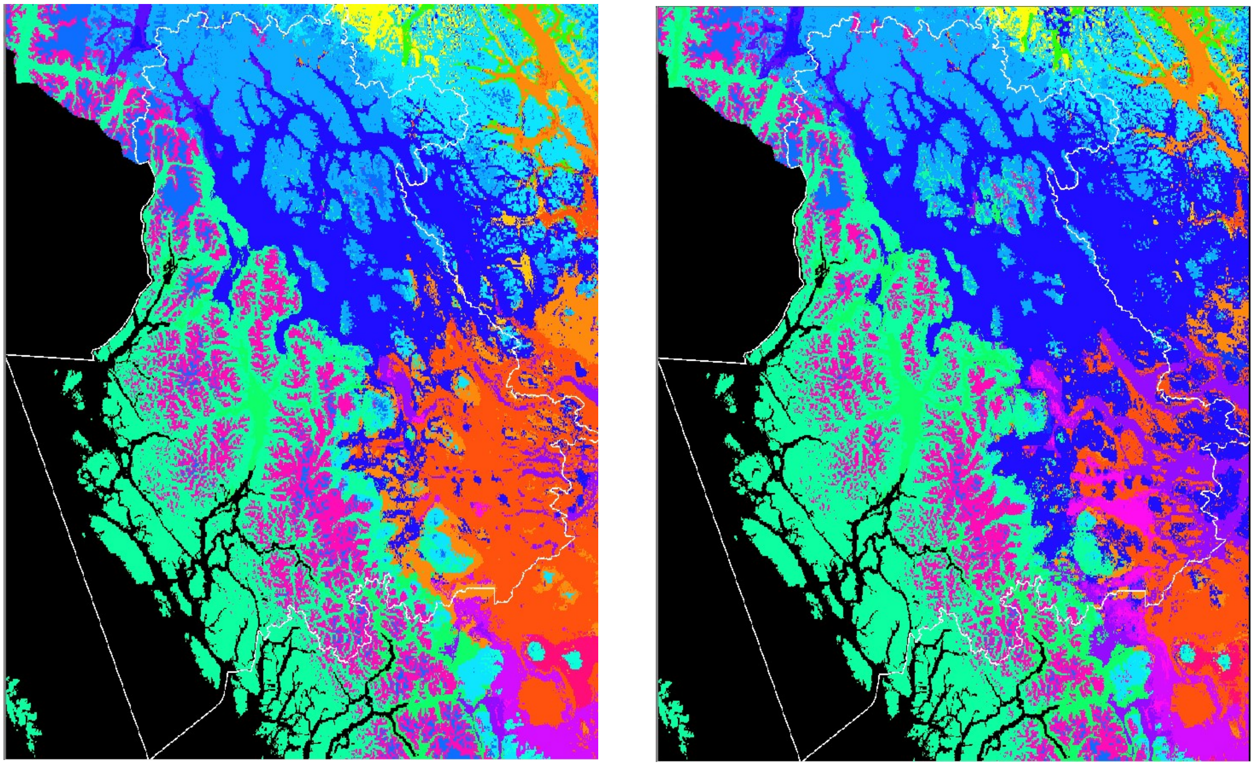


Figure 7. BGC subzone groupings at 2050 (left) and 2080 (right) (derived from Wang et al. 2012). Same legend as in Figure 6.

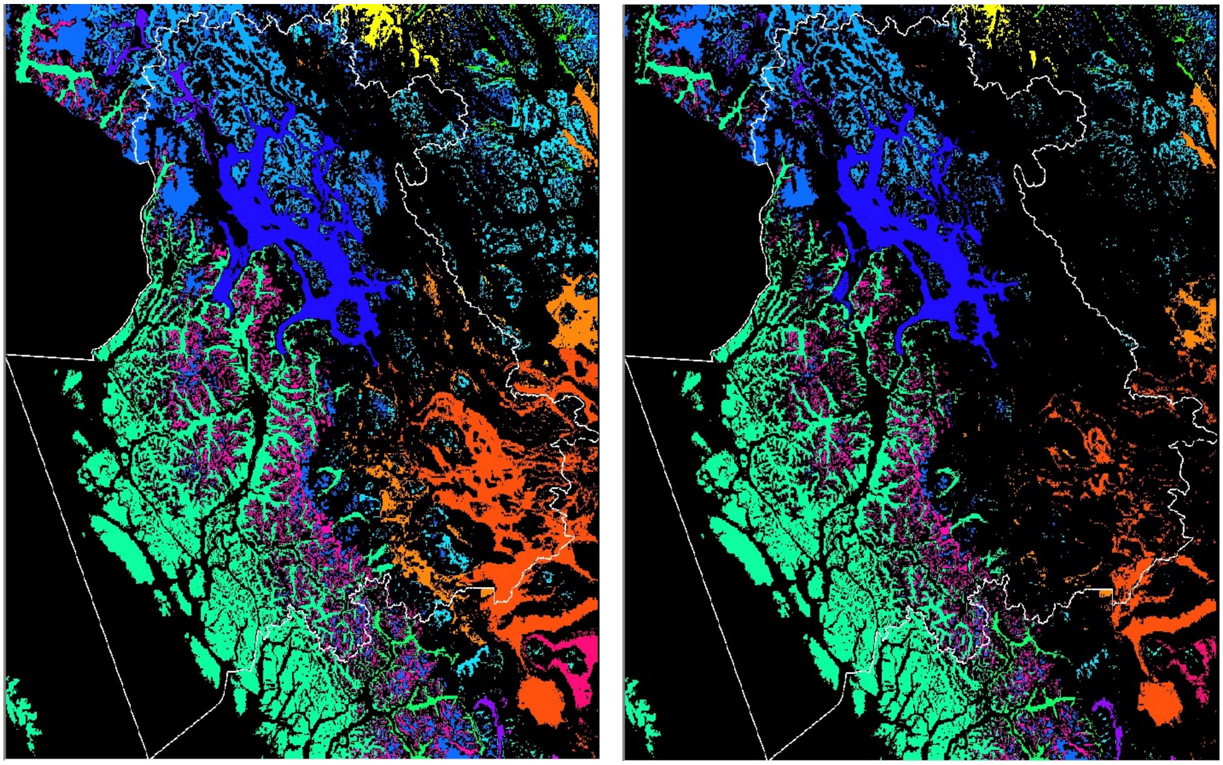


Figure 8. Stable (non-changing) BGC subzone groupings at 2050 (left) and 2080 (right) derived from BGC subzone groupings. Legend same as for BGC subzone groupings in Figure 6.

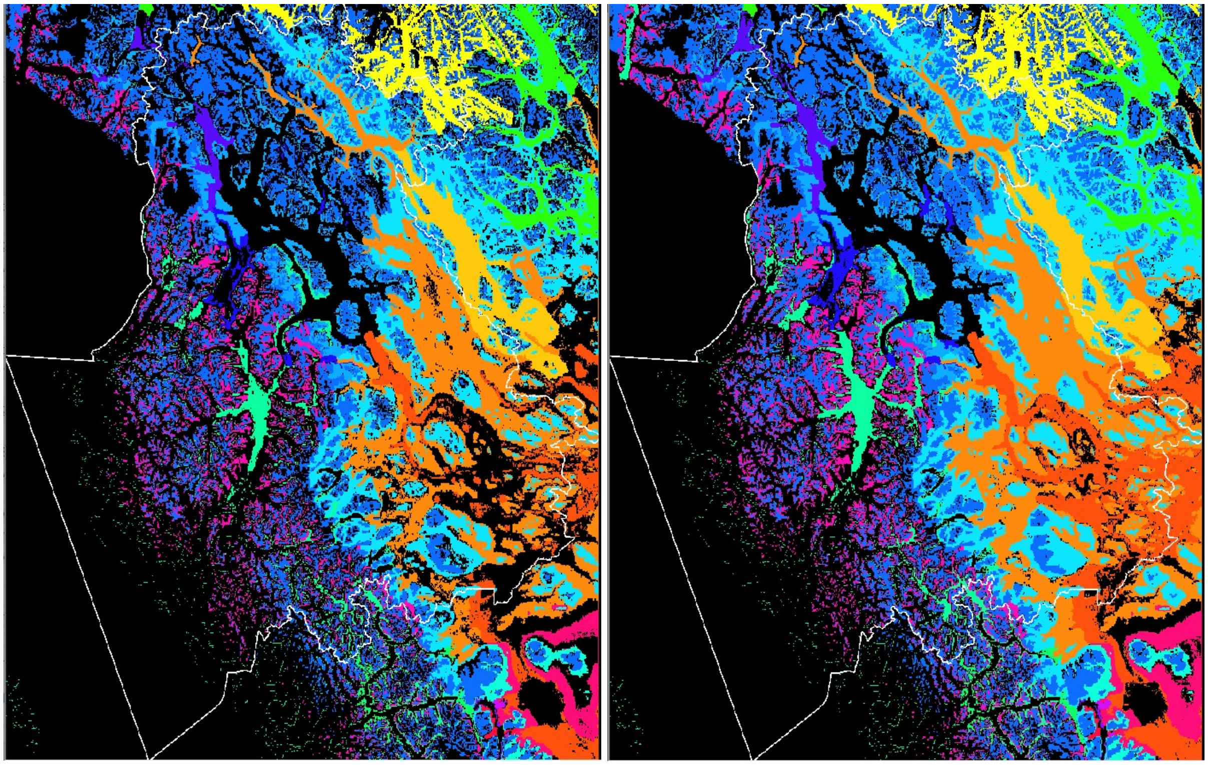


Figure 9. Unstable (changing) BGC subzone groupings at 2050 (left) and 2080 (right) derived from BGC subzone groupings. Legend same as for BGC subzone groupings in in Figure 6.

Based on the projected BGC layers, about 44% of the land remains in a stable, non-changing BGC grouping by 2050, and about 31% by 2080. Areas with more topographic complexity (e.g. mountains) and areas with strong coastal influence tend to be more stable than plateaus, consistent with other research and climate projections. However, there seems to be a risk of loss of high elevation habitat. Currently wet coastal subzones seem to provide some candidacy as macro-refugia, as does the ICH-Moist grouping, and some areas of the ESSF-Wet grouping. The ICH-Wet grouping has a potential refugium in the upper Nass River. In the areas of gentler terrain, the SBS-Moist grouping seems to have few options for refugia, but there are a few areas in the SBS-Dry grouping, in particular near some of the large lakes (Francois, Tetachuk).

5.2.3 Potential uses for Conservation Planning and Assessment

This method can be used to

(a) Identify BGC subzone groupings that are expected to decline significantly in extent as being at risk due to climate change.
(b) Within an at risk BGC subzone grouping, identify areas expected to remain stable – these may be considered *in situ* climate refugia.

5.2.4 Future improvements

- Use updated BGC subzone projections, with separate assessments for different RCPs and GCMs.
- Incorporate "novel" subzones (subzones that are not present in the study area, or more generally in BC, but expected to exist in the future)

5.5 Analog Refugia Class and Analog Climate Condition

5.5.1 Method

Eng (2020) recommended to focus on *in situ* refugia. That is, areas where the current and future climate analogs match. However, in some situations this may be overly limiting, since it does not give guidance on how to deal with areas too small to be functional. However, the *in situ* (stable) areas can provide anchor points for identifying nearby areas that may be of conservation value in a heating climate.

Analog Refugia Class

Figure 10 illustrates a new method I developed to classify the landscape for each analog (BGC subzone group) into "*Analog Refugia Classes*" (representing decreasing likelihood of being macro-refugia):

- *Stable* (*in situ*) (Class 1, Figure 10): areas where the current and future analogs are the same.
- *Near Stable*: areas within a prescribed distance (buffer) from stable areas (1 km was used in this analysis) that have the same analog as the stable area: either a current analog (Class 2, Figure 10) or a future analog (Class 3, Figure 10). [2]
- *Near Analog*: areas within a prescribed distance (again 1 km is used here) from any analog areas where the current and future analogs do not overlap. In Figure 10, Class 4 areas are current analogs that are close to, but do not overlap, future analogs; Class 5 areas are the reciprocal.[3]
- *Not Refugia*: includes current analogs that are further than the buffer distance from any future analog (Class 6, Figure 10), and future analogs that are further than the buffer distance from any current analog (Class 7, Figure 10).

Rationale for including these "nearby *ex situ*" areas as potential conservation candidates include:

(a) Due to uncertainty in the delineation of the current climate envelopes these areas may be more 'overlapping' that climate projections might indicate;
(b) Due to uncertainty in climate projections, stable areas may be larger than projected;
(c) Due to proximity, dispersal uncertainty is relatively low compared with more distant areas; and
(d) Due to time lags in system changes, such areas may provide ongoing habitat (current) or near future opportunity (future).

Note that this method must be applied separately for each analog (BGC subzone group) because of overlap between current and future analogs in changing areas. That is, a given cell may have a current BGC subzone group *b1* and a different future subzone group *b2*. In this case, this cell will have one refugia class for b1 and a different class for b2 (neither of which, by definition can be stable).

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[2] These areas represent areas of relatively low 'forward' and 'backward' climate velocity, described in Appendix A. That is, Class 2 areas may 'provide' immigrants to bolster the existing community in the stable area, Class 3 areas may 'receive' emigrants that might develop into a community similar to the stable area.

[3] As with Near Stable areas, these classes represent areas with relatively low 'forward' and 'backward' climate velocity, respectively.

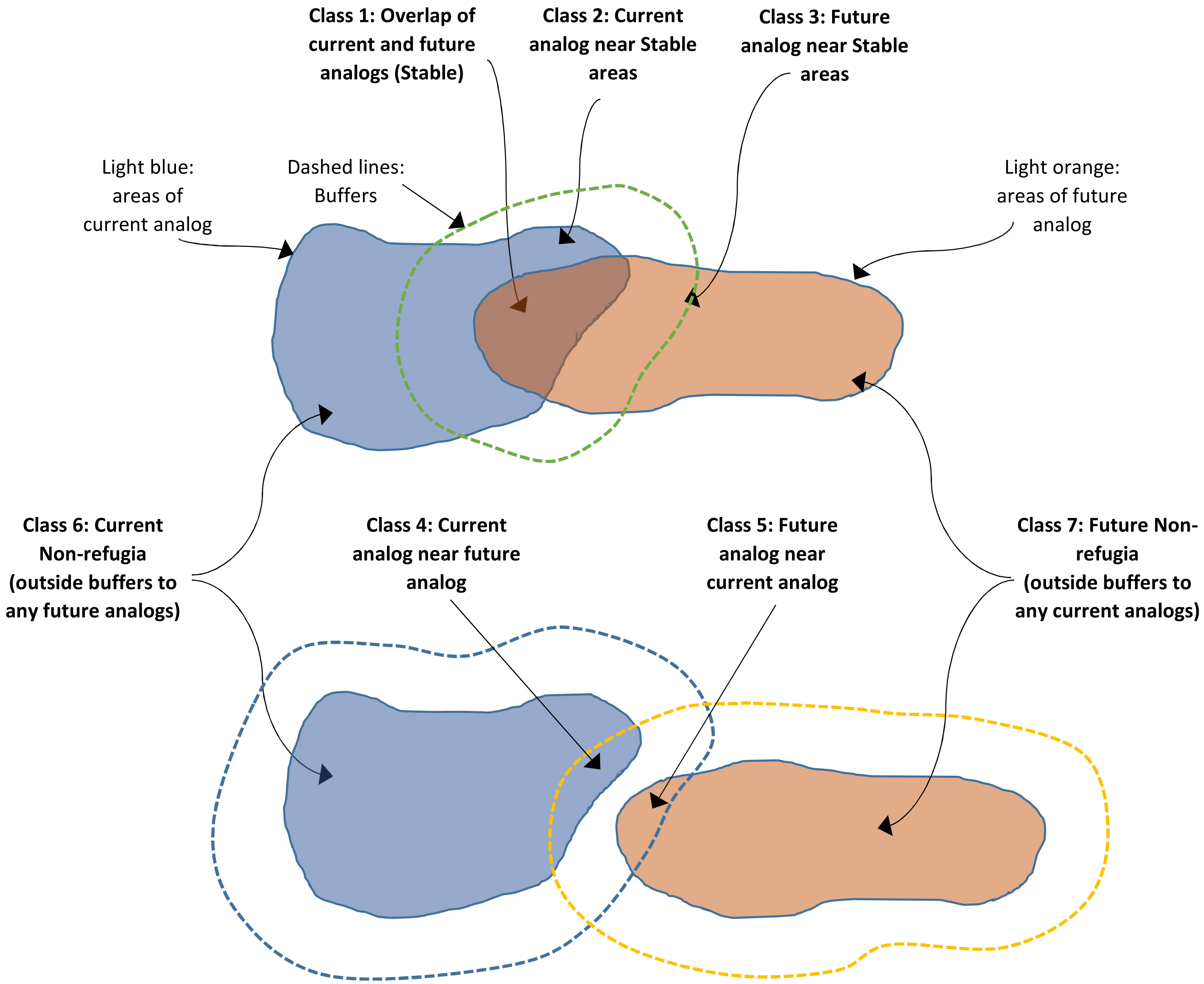


Figure 10. Conceptual diagram showing Refugia Classes for an analog (BGC subzone group): Class 1: Stable areas. Classes 2 & 3: current and future analogs near stable areas. Class 4: current analog near future analog. Class 5: future analog near current analog. Classes 6 & 7: not refugia (not close to stable or non-stable analogs).

<u>Analog Climate Condition</u>

The Analog Refugia Class method was used to derive an overall "*climate condition*" for each analog (BGC subzone group), defined as the general degree to which *in situ* and nearby areas contribute to potential macro-refugia. Results are shown stratified by Ecosection. The *Climate Condition* types are as follows:

- *Sufficient stable* (proportion Stable/Current is "sufficient"; I used > 50% for "sufficiency" for the proof-of-concept)
- *Sufficient near stable* (proportion NearStable/Current > 50%, where NearStable includes Stable)

- *Sufficient near analog* (proportion NearAnalog/Current > 50%, where NearAnalog includes NearStable and Stable; could alternatively be considered as "*Insufficient – high*" since there are insufficient *in-situ* and near *in-situ* areas)
- *Insufficient - moderate* (proportion NearAnalog/Current ≤ 50%, but not too low, defined as > 10% for the proof-of-concept)
- *Insufficient - low* (proportion NearAnalog/Current ≤ 10%, but > 0%)
- *Disappearing* (NearAnalog = 0)
- *Novel* (Current area = 0, future area > 0)

To provide additional information for conservation planning and assessment, I expanded this method to classify the analog climate condition for each Ecosection to show how the conditions vary in different areas of the landscape.

5.5.2 Results

Results are shown for selected "characteristic" BGC subzone groups. In addition to the spatial outputs, the area in each analog refugia class and the analog climate condition were summarized for each BGC subzone group, and output as a table, stratified by Ecosection (not shown).

<u>Analog Refugia Class</u>

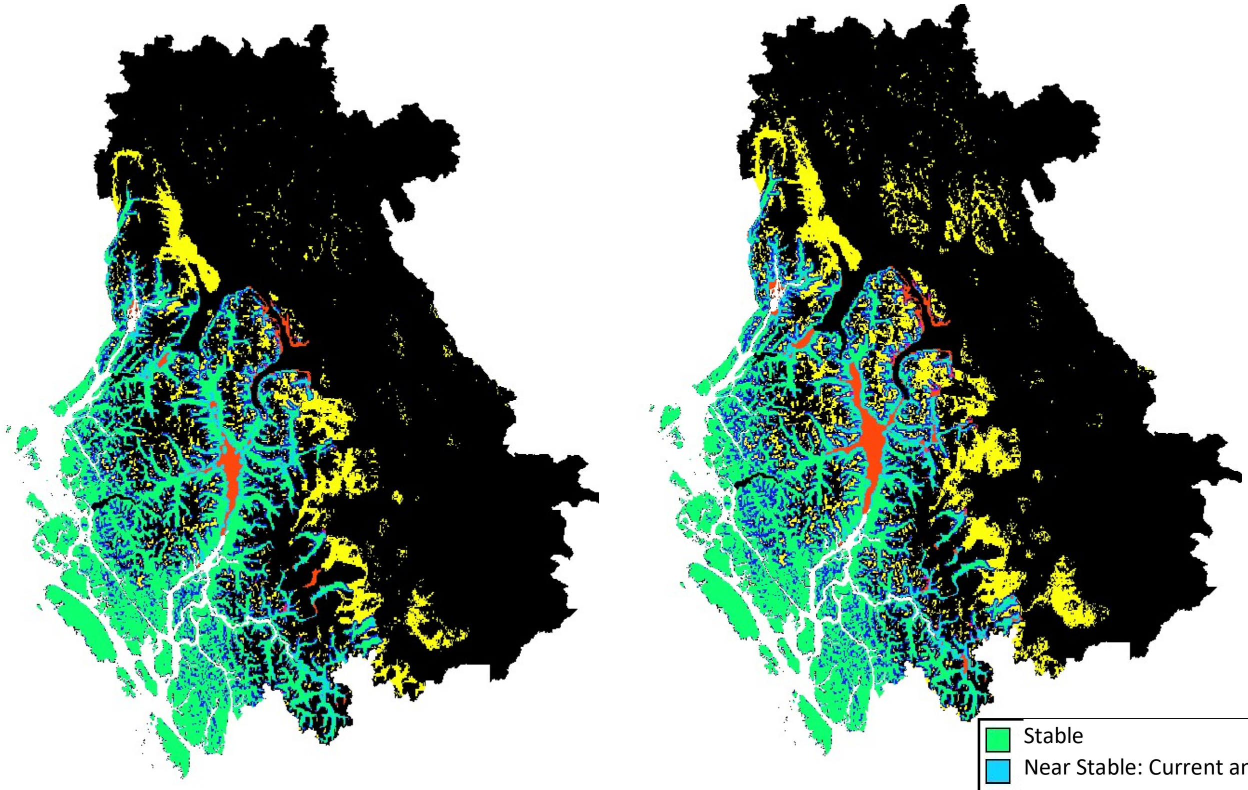


Figure 11. Analog Refugia Class for Coast – Wet BGC subzone group using a 1 km maximum distance for 2050 (left) and 2080 (right).

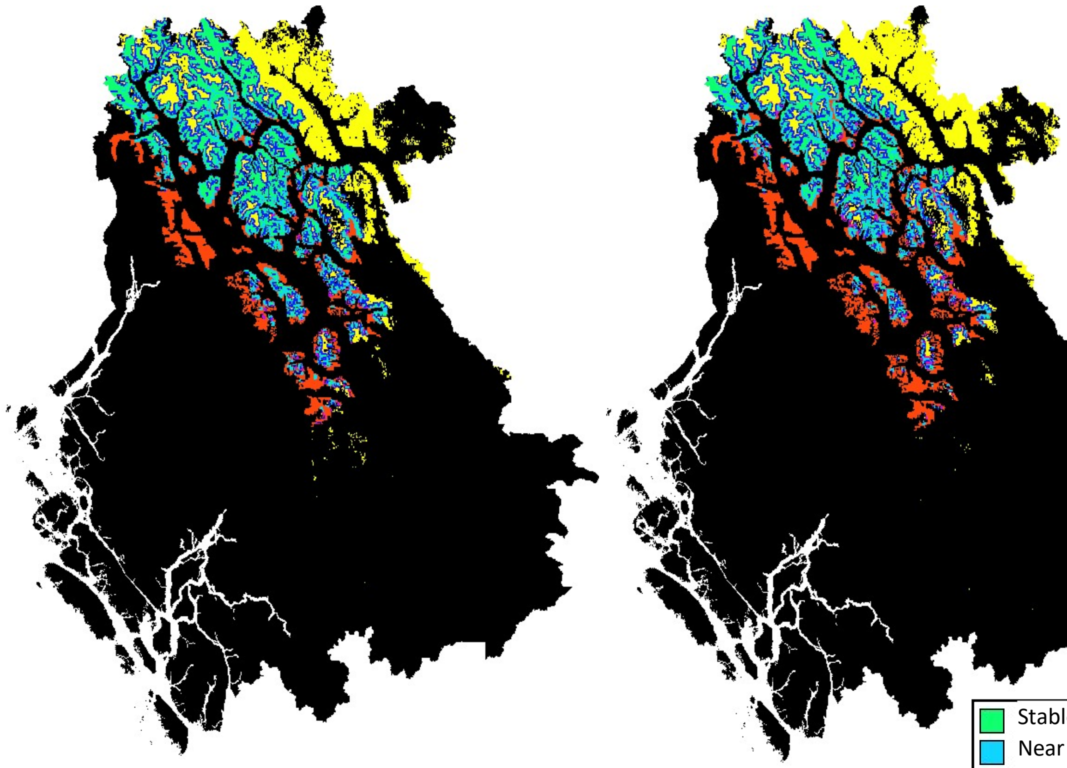


Figure 12. Analog Refugia Class for ESSF – Wet BGC subzone group using a 1 km max. distance for 2050 (left) and 2080 (right).

🟩 Stable
🟦 Near Stable: Current analog
🟦 Near Stable: Future analog
🟪 Near Analog: Current near future
🟥 Near Analog: Future near current
🟧 Not Refugia: Current (disappearing)
🟨 Not Refugia: Future (expanding)

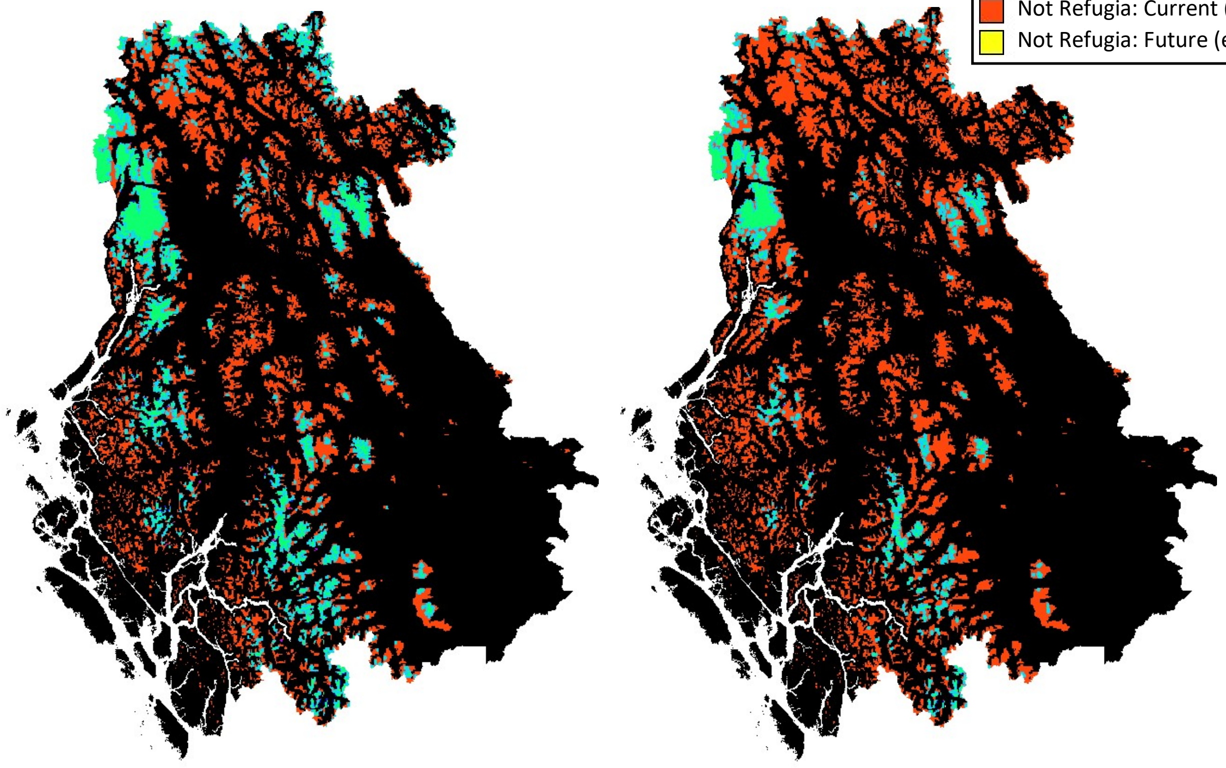
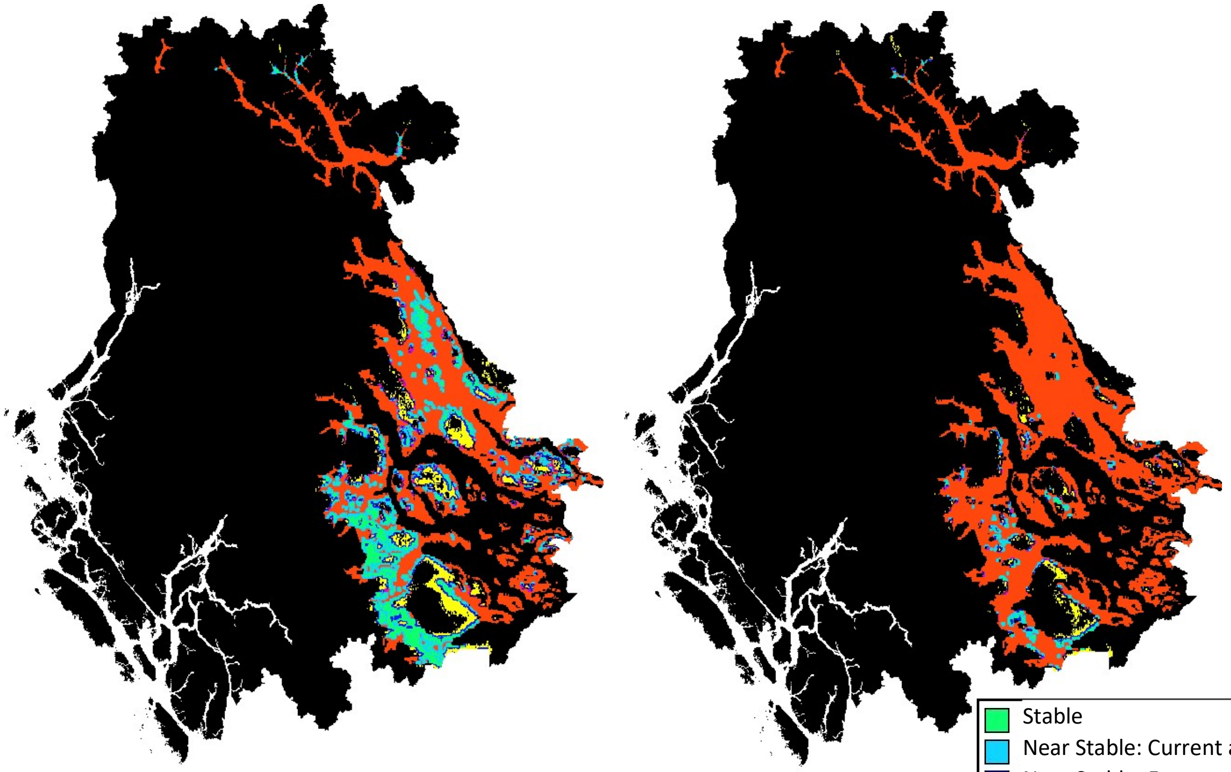


Figure 13. Analog Refugia Class for High Elevation BGC subzone group using a 1 km max. distance for 2050 (left) and 2080 (right).



🟩 Stable
🟦 Near Stable: Current analog
🟦 Near Stable: Future analog
🟪 Near Analog: Current near future
🟥 Near Analog: Future near current
🟧 Not Refugia: Current (disappearing)
🟨 Not Refugia: Future (expanding)

Figure 14. Analog Refugia Class for SBS – Moist BGC subzone group using a 1 km max. distance for 2050 (left) and 2080 (right).

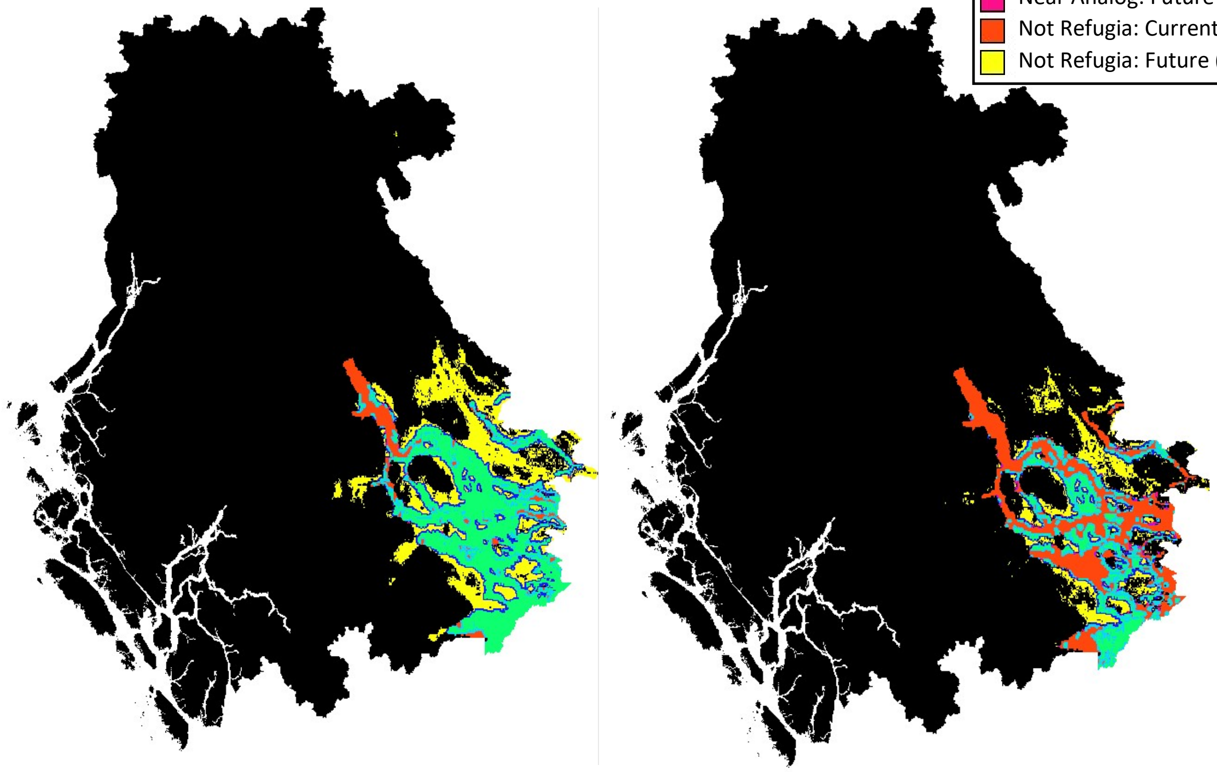


Figure 15. Analog Refugia Class for SBS – Dry / SBPS BGC subzone group using a 1 km max. distance for 2050 (left) and 2080 (right).

Analog Climate Condition by Ecosection

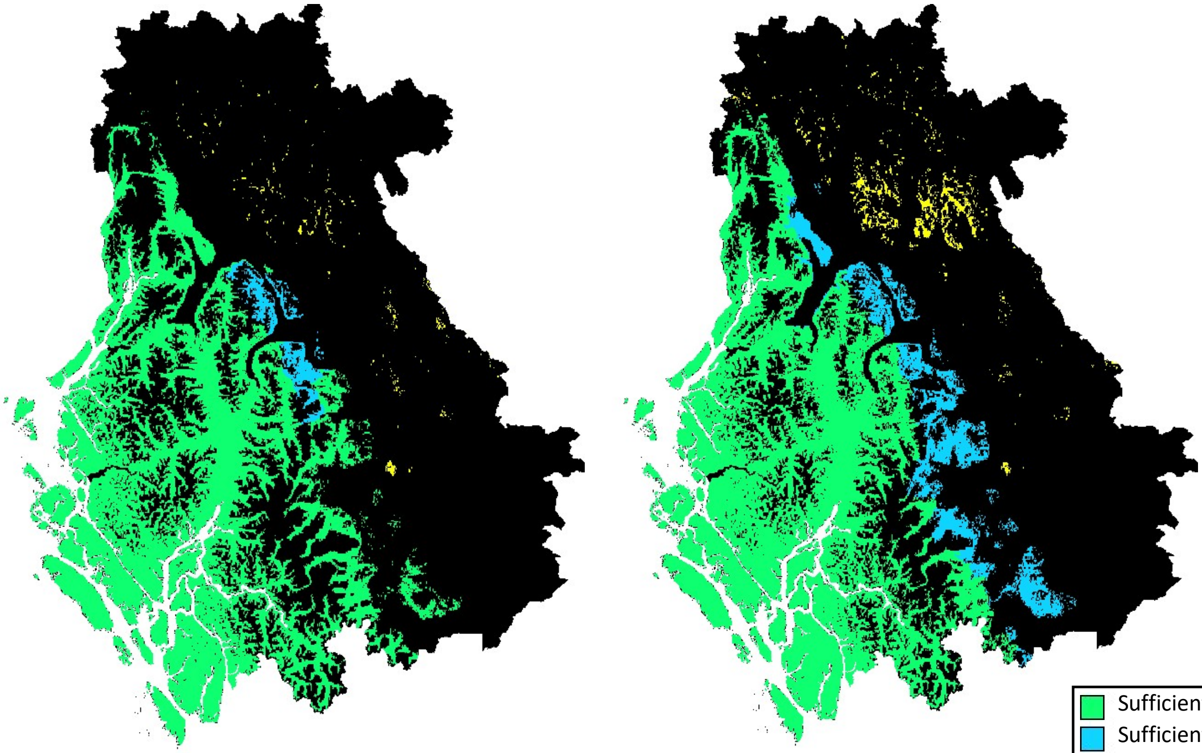


Figure 16. Analog Climate Condition by Ecosection for Coast – Wet BGC subzone group using a 1 km max. distance for 2050 (left) and 2080 (right).

- 🟩 Sufficient Stable
- 🟦 Sufficient Near Stable
- 🟦 Sufficient Near Analog
- 🟪 Insufficient - moderate
- 🟥 Insufficient – low
- 🟧 Disappearing
- 🟨 Novel

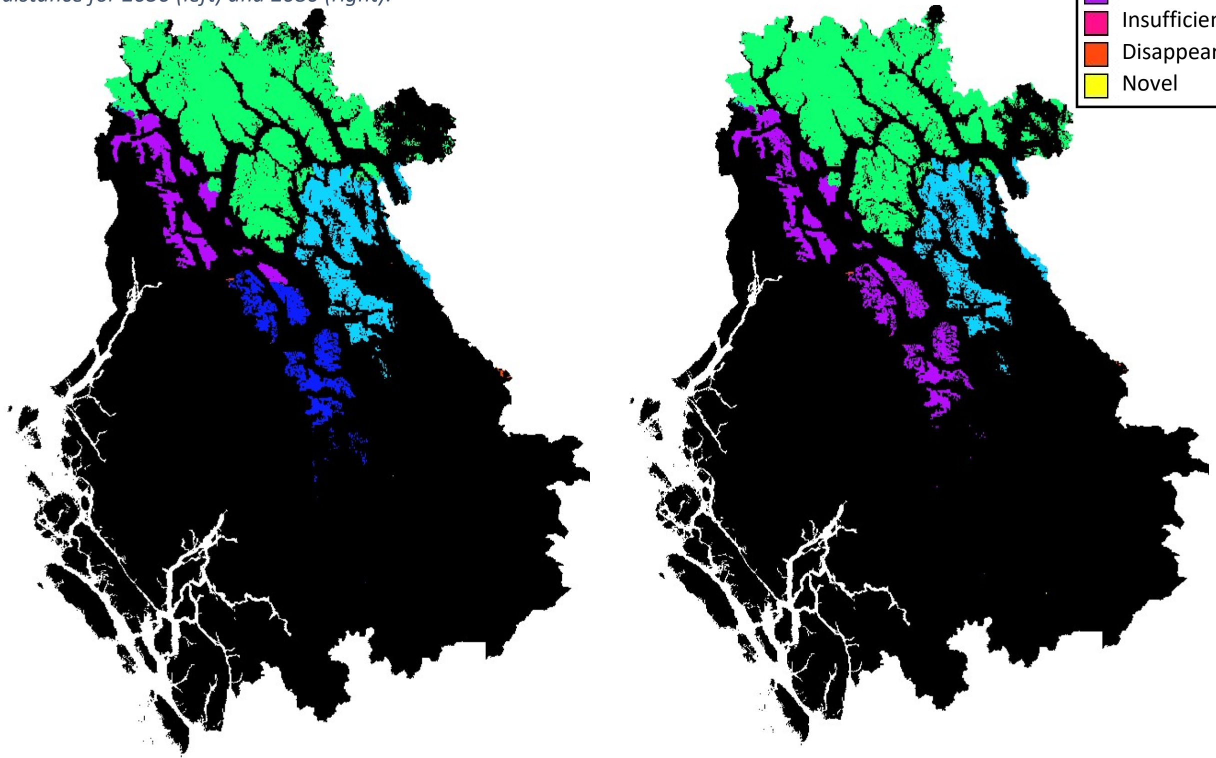


Figure 17. Analog Climate Condition by Ecosection for ESSF – Wet BGC subzone group using a 1 km max. distance for 2050 (left) and 2080 (right).

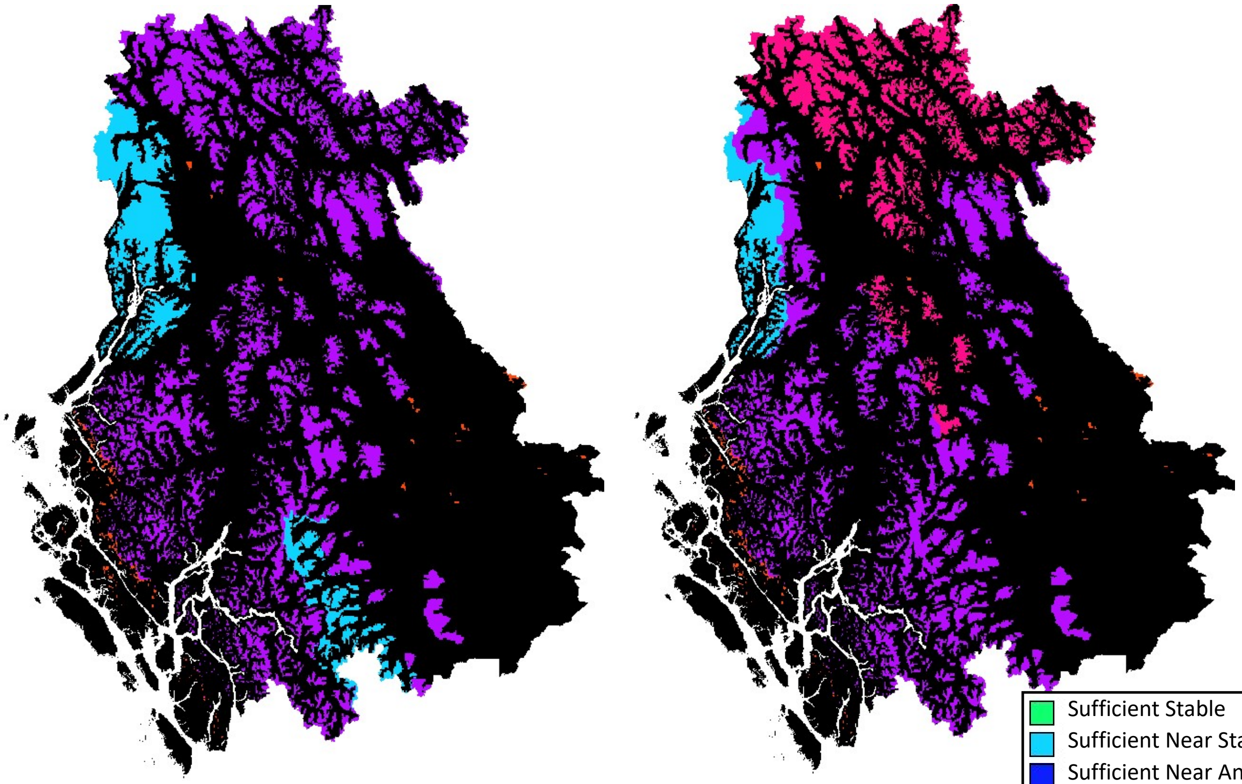


Figure 18. Analog Climate Condition by Ecosection for High Elevation BGC subzone group using a 1 km max. distance for 2050 (left) and 2080 (right).

🟩 Sufficient Stable
🟦 Sufficient Near Stable
🟦 Sufficient Near Analog
🟪 Insufficient - moderate
🟥 Insufficient – low
🟧 Disappearing
🟨 Novel

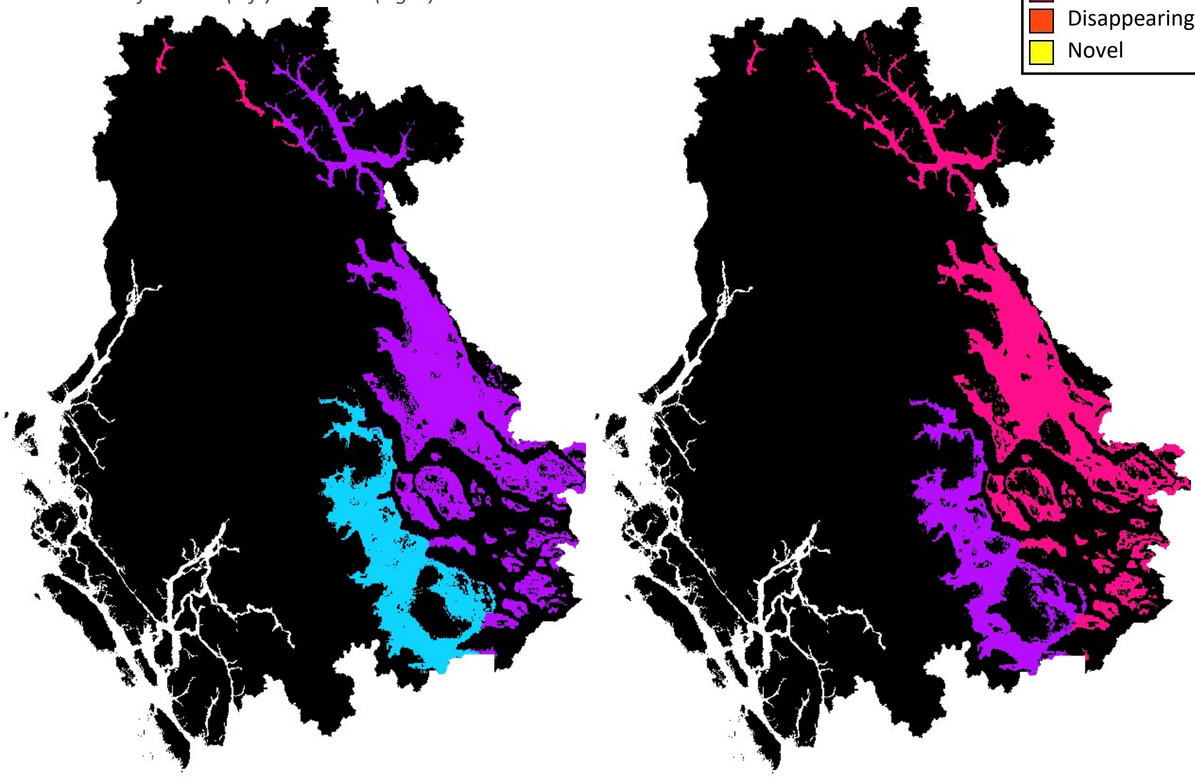


Figure 19. Analog Climate Condition by Ecosection for SBS – Moist BGC subzone group using a 1 km max. distance for 2050 (left) and 2080 (right).

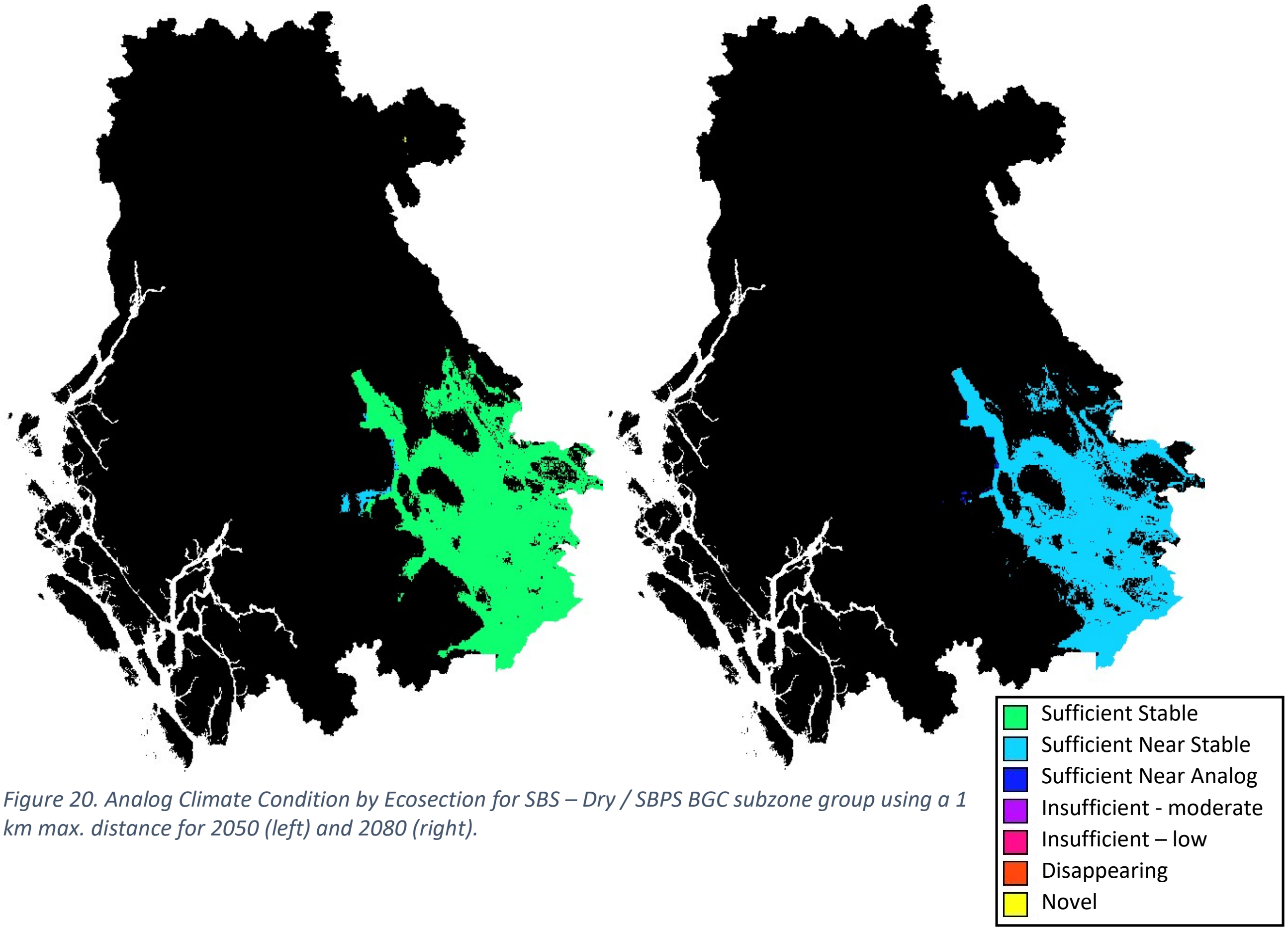


Figure 20. Analog Climate Condition by Ecosection for SBS – Dry / SBPS BGC subzone group using a 1 km max. distance for 2050 (left) and 2080 (right).

5.5.3 Potential uses for Conservation Planning and Assessment

Conservation planning and assessment in BC often focuses on representation issues (e.g. adequate old forest by site series or BGC variant). Using grouped ecosystem types can reduce some of the uncertainty of climate projections downscaled to regional analysis by joining areas with similar historic climates, providing some balance between precision of ecosystems uses for analogs and accuracy/uncertainty of being able to map changes over time. Focusing on BGC subzone groupings, or similar units, seems an appropriate place to start.

Focusing on individual analogs (BGC subzone groups) allows identifying specific conservation needs and challenges for each. A focus only on macro-refugia over an entire study area risks missing opportunities to protect certain analogs that may have small areas of climate refugia.

Computing results separately by Ecosection could help prioritize BGC subzone groupings in specific Ecosections for management depending on the climate condition of the analog overall, as well as variation among Ecosections. Analog Climate Condition provides a high-level perspective on the BGC subzone group conditions to be used in conjunction with the details in the Analog Refugia Class.

5.5.4 Future improvements

These new methods should be further explored, which would be particularly useful in the context of a pilot project involving collaboration with experts to refine and adapt the method and parameters.

6.0 Conservation Class

6.1 Method

Table 1 in Eng (2020) defines a recommended set of conservation classes and actions based on the characteristics of an area in terms of macro-refugia, intactness and density of enduring features. I developed a new method to integrate the previous methods in this report in order to provide spatial outputs based on these conservation classes.

The enduring features and intactness aspects require parameters to define:

- "high density of enduring features" (I used 25% “full value equivalent cells” of a 1 km circular window for the proof-of-concept), and
- "intact" (I used 50% for the proof-of-concept).

Areas were classed as potential macro-refugia (for the purpose of defining conservation class) using Analog Climate Condition by Ecosection to select areas of applicable Analog Refugia Classes according to a series of tests (Table 3):

- All areas of Stable refugia class (*in-situ*) were classed as potential macro-refugia.
- If the Analog Climate Condition is not “*Sufficient stable*” (i.e. there is a relatively low amount of Stable areas for the analog in the Ecosection), then areas of Near Stable refugia class were additionally classed as potential macro-refugia (*ex-situ* close to *in-situ*).
- If the Analog Climate Condition Class is also not “*Sufficient near stable*” (i.e. there is a relatively low amount of combined Stable + Near Stable areas for the analog in the Ecosection), then areas of Near Analog refugia class were additionally classed as potential macro-refugia (*ex-situ* not close to *in-situ*, but close to analogs).

Table 3. Analog Refugia Classes used to classify areas as potential macro-refugia based on Analog Climate Condition by Ecosection, for the purpose of defining a conservation class.

Analog Climate Condition by Ecosection	**Refugia Classes defined as macro-refugia**
Sufficient stable	*Stable*
Sufficient near stable	*Stable* and *Near Stable*
Sufficient near analog	*Stable, Near Stable and Near Analog*
Insufficient (moderate and low)	*Stable, Near Stable and Near Analog*
Disappearing	*n/a*
Novel	*n/a*

A grid cell was classed as a potential macro-refugia if it was a classed as a potential macro-refugia, according to the above tests, using either the current or future analog (BGC subzone group) of the cell.[4]

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[4] In stable areas, the future and current analogs (BGC subzone group) are identical by definition. In non-stable areas, the future and current analogs are different, and their respective Analog Climate Condition and/or Analog Refugia Class may be different.

Conservation Class is then identified using a simple step-wise decision process based on Table 1 of Eng (2020) (assigning the first class that is satisfied):

- *Resistant 1a*: if potential macro-refugia, intact and high density of enduring features
- *Resistant 1*: if potential macro-refugia and intact
- *Resilient 2a*: if potential macro-refugia and high density of enduring features
- *Resilient 2*: if potential macro-refugia
- *Susceptible 3*: if intact and high density of enduring features
- *Sensitive 4*: if high density of enduring features

6.2 Results

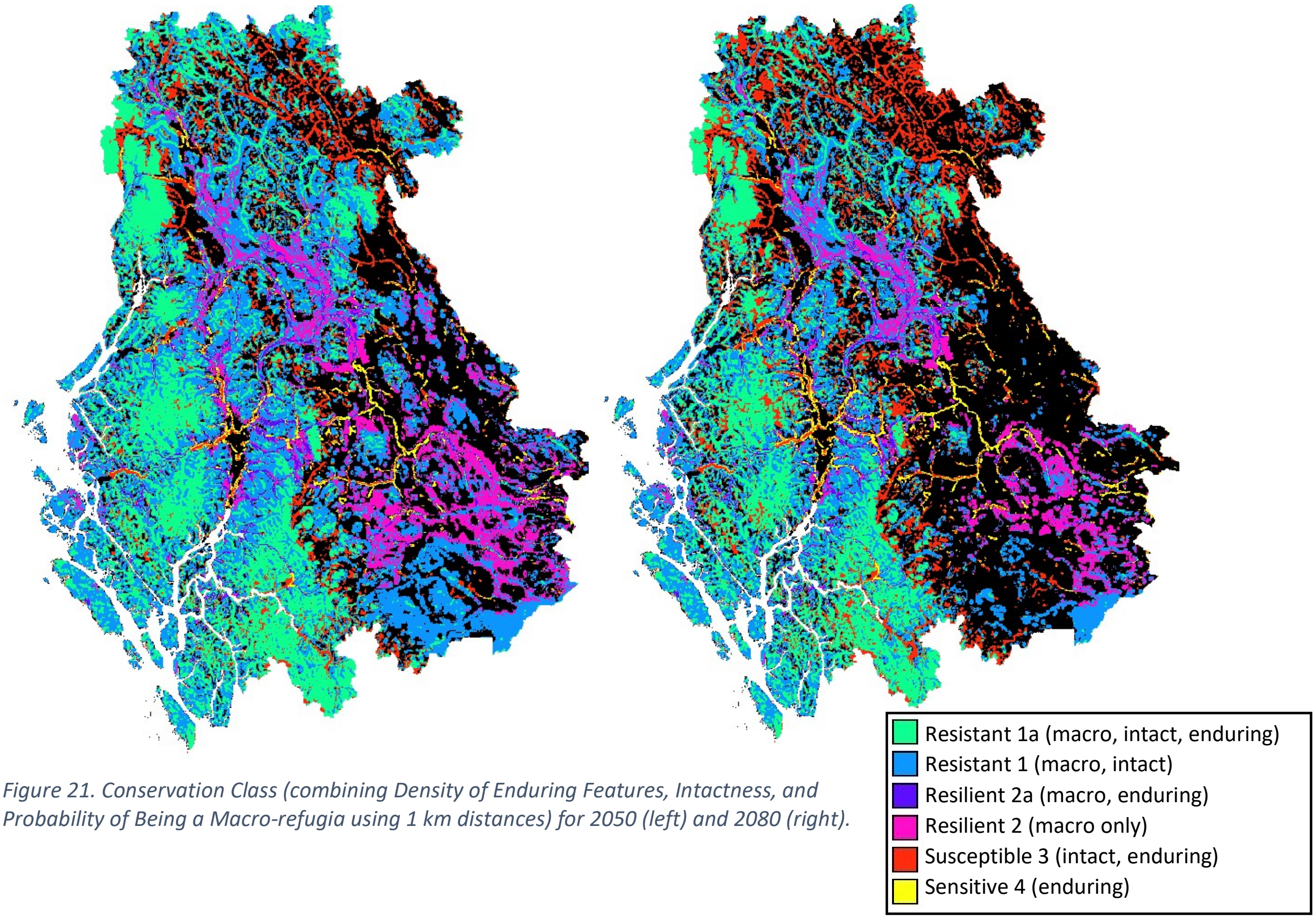

Figure 21. Conservation Class (combining Density of Enduring Features, Intactness, and Probability of Being a Macro-refugia using 1 km distances) for 2050 (left) and 2080 (right).

6.3 Potential uses for Conservation Planning and Assessment

This metric provides high level information for a coarse filter assessment of management actions that may be most relevant in different areas of a landscape. It could provide a start point for more detailed assessment of different sub-areas, climate analogs, ecosections, etc.

6.4 Future improvements

This method is in preliminary development and should be refined in collaboration with experts.

7.0 General Future Directions

7.1 Assess Role of Current Protected Areas

Current protected areas could be overlain on climate refugia metrics to obtain information on the degree to which the protected areas network protects intact areas, enduring features and macro-refugia. This could potential help identify gaps.

7.2 Comparison with Results from Other Research

It could be informative to compare results from these methods with those from Stralberg (2018) on Ecoregion shifts, Mahony et al. (2017), and other related work (e.g. methods on the AdaptWest site).

7.3 Connectivity

Connectivity between habitat is important for dispersal, especially in relation to shifts in climate analogs (Carroll et al. 2018; Harrison and Voller 1998, Fall et al. 2007, and many others). Connectivity assessments often explore clusters of connected patches at different scales and movement corridors across landscapes (based on graph and circuit theory).

It could be useful to develop methods that integrate connectivity of selected enduring features with climate refugia metrics. For example, a connected network of wetland complexes could be identified, with cost preference weighted to links along waterways. This network of wetlands and links between wetlands could be overlain on the Analog Refugia Class layers to identify areas where connections have higher/lower risk of being impacted by climate change. Alternatively, Refugia Class could be used was part of the cost surface to identify links between wetlands that minimize climate disruption.

7.4 Dynamic Projections

The climate metrics developed in this study could be integrated with dynamic projections of landscape conditions. For example, the Skeena-Nass Cumulative Effects Assessment (CEA) modelling framework includes modelled projections under a range of management scenarios based on the Shared Socio-economic Pathways (SSPs) used in the IPCC assessments. The CEA modelling framework includes dynamics for management (logging, roading, pipelines, etc.), land use change, and natural disturbance, and can be applied under different RCPs. Other dynamic projection opportunities include strategic planning (timber supply review process, land use planning, etc.).

Some options for such integration include:

- Simple summarization of projected changes in conditions related to intactness, or on/near enduring features over time.
- Integration of human footprint and intactness metrics with dynamic models to project changes over time under different scenarios.
- Use of intactness, enduring features, macro-refugia and/or conservation class to develop new scenarios for dynamic assessment (e.g. avoid activities in intact areas, areas with high density of enduring features or in macro-refugia).

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Appendix A Additional Macro-refugia Methods

This appendix includes some additional methods to identify the probability of being a macro-refugia, but were not used as part of the conservation class recommended by Eng (2020). These methods may have some utility in conservation planning and assessment in BC, especially with further adaption, and so are included with the similar format to the methods documented in Section 5.0.

A.1 Climate Velocity and Refugia index

A.1.1 Method

Adapt methods of Carroll et al. (2015) and Stralberg (2018, 2019) to

(a) compute the "*climate velocity*" of BGC subzone groupings; and
(b) compute a refugia index using a log transform of backward climate velocity.

A first step is to compute:

- the distance from a focal cell to the nearest location (if any) with the same BGC subzone group in the future as is current in the focal cell (forward) and
- the distance from a focal cell to the nearest location (if any) with the same BGC subzone group currently as the focal cell is expected to have in the future (backward)

Climate velocity is then simply these distances divided by the number of years between time periods. As discussed by Eng (2020) and others, backward velocity is more practical for identifying climate refugia.

An efficient means of computing the "distance to nearest analog" layers is via diffusion to compute nearest distances simultaneously with a single pass over the study area (starting from the feature to which distance is being computed). However, such diffusion can only be done for a single feature type at a time (e.g. a single BGC subzone grouping). Hence, I ran one diffusion for each BGC subzone group (i.e. 22 runs), each producing a layer with distance in metres to the nearest cell with the subzone group. For backward velocity, this only needs to be done for the current time period. For forward velocity, it needs to be done for each future time period (2050, 2080).

Backward velocity is then computed by loading all the "distance to current BGC subzone group" layers as well as the future BGC subzone layer (future analog). The future subzone is used to select the value from the corresponding distance layer, which is then divided by the number of years (30 or 60). The model outputs velocity values in metres/year. Forward velocity is calculated the same way, but single distance to future BGC subzone groups, indexed by the current BGC subzone group layer (current analog).

The refugia index of Stralberg (2018, 2019) is computed as -1 * LOG(velocity). In this function, velocity is km/year. Since LOG(0) is undefined, I assigned cells with velocity of 0 to a base index of 7. This is because the lowest non-zero velocity represented is 1m/year, and -1*LOG(1) is a bit less than 7. Since values higher than 1 km/year are negative (i.e. since LOG(x) crosses the y-axis at x=0), I set values larger than 1 km/year to 0. Finally, values were normalized to a range from 0 to 100 (where 0 is a low probability of being a macro-refugia, and 100 is a high probability).

A.1.2 Results

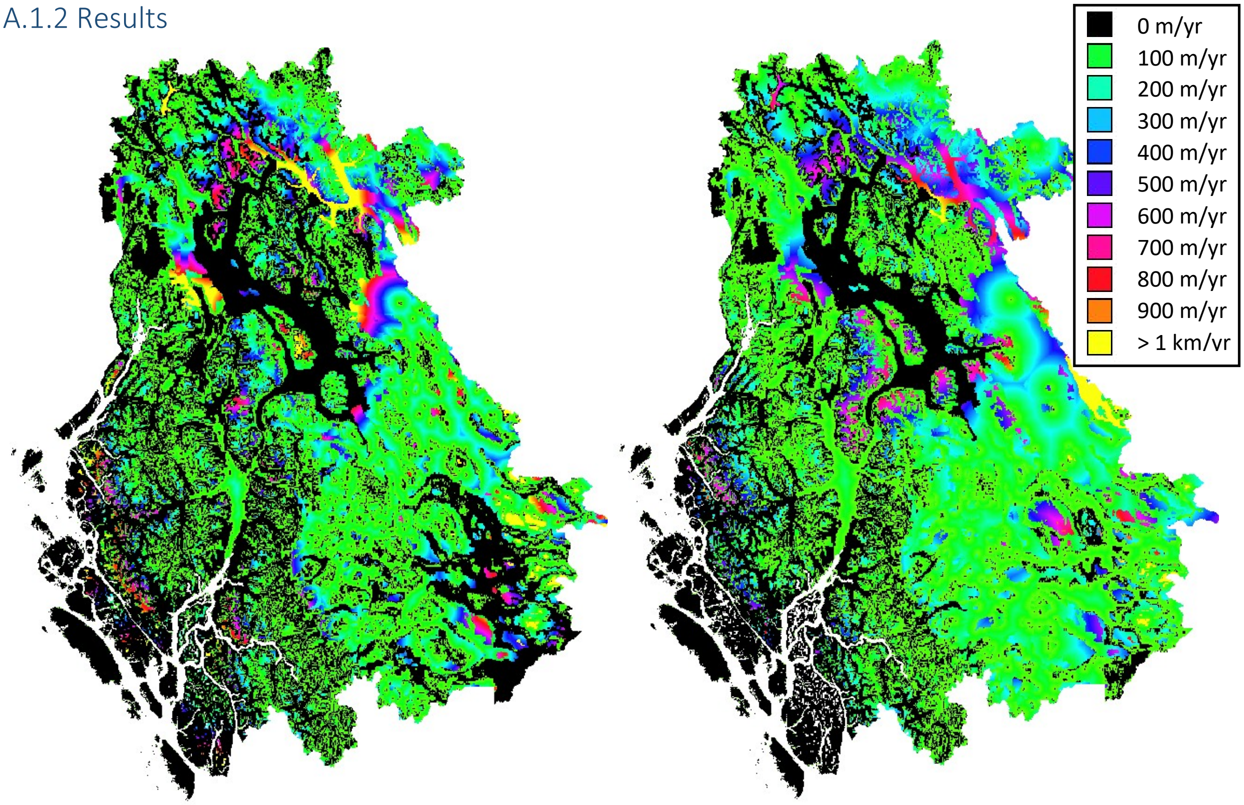

Figure 22. Forward climate velocity (km/year) for current to 2050 (left) and to 2080 (right). White means no matching analog.

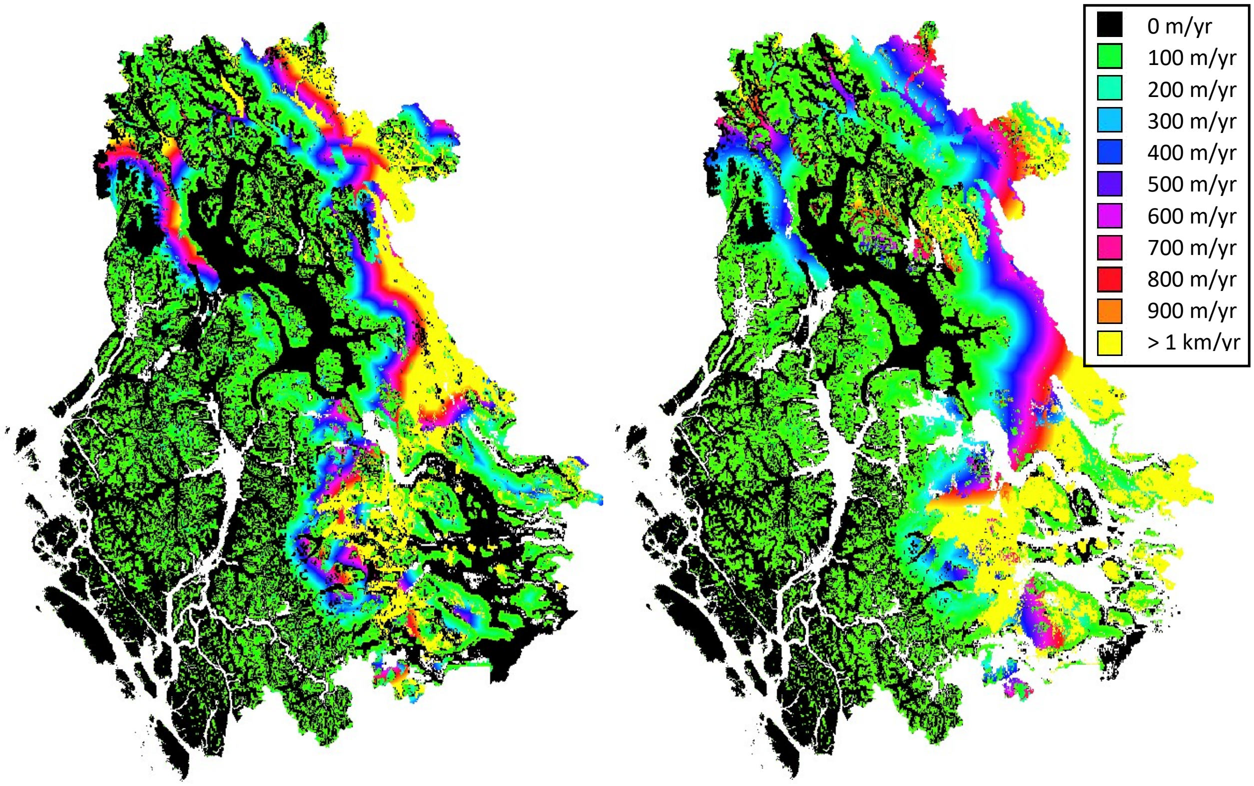

Figure 23. Backward climate velocity (m/year) for 2050 (left) and to 2080 (right) to current. White means no matching analog.

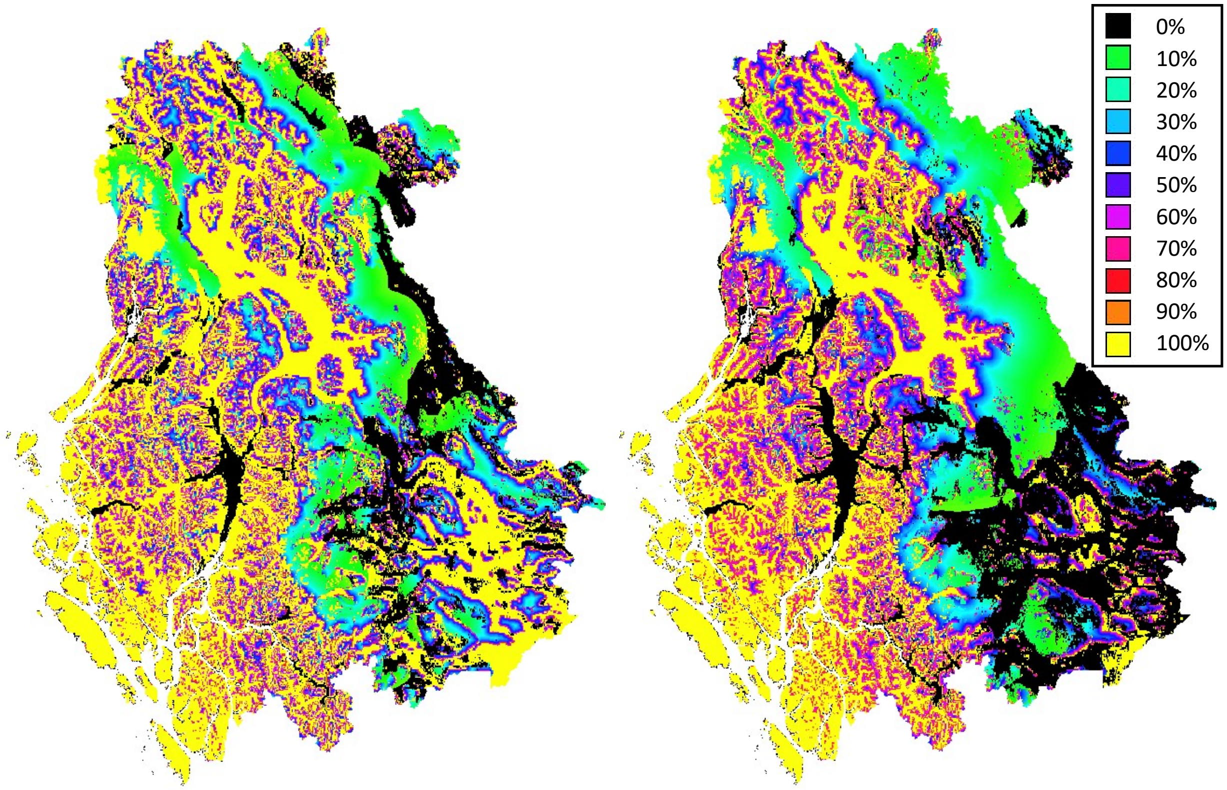

Figure 24. Refugia index based on backward velocity for 2050 (left) and 2080 (right).

A.1.3 Potential uses for Conservation Planning and Assessment

In situ refugia will have, by definition, a velocity of zero. Since velocity is directly linked with distance, this indicator can be used to identify *ex situ* refugia that are sufficiently close to existing analogs to have a high likelihood that most species may reach the future habitat. Velocity and the refugia index provide a high-level view of where change is expected to be most or least dramatic, and could be useful for to identify areas for broad-scale management (e.g. regional corridors). One drawback of these methods is that they do not take into account the density of current or future analogs (just the distance to the closest one), and so low velocity could be due to short distances to a large patch or a single cell.

A.1.4 Future improvements

Climate velocity is effectively a function: Forward velocity is a function from current analog locations to a future analog location (the closest one, if any); backward velocity is a function from future analog locations to a current analog location (the closest one, if any). Put another way, velocity is a mathematical graph that links cells at one time period with cells at another. Density/concentration of current or future analogs are not considered. This method could be enriched by linking each focal cell to multiple cells at the other time period (e.g. not just the closest cell, but the 2nd closest), and use graphs to weight links. This could give more of a distribution of velocities.

A second improvement could be to use a cost surface instead of straight-line distances. For example, relative difficulty of moving could be related to intactness or to differences in BGC subzone groupings.

A.2 Shrinking Analogs

A.2.1 Method

Methods of Michalak et al (2018) were adapted to

(a) compute the density of current and future analogs in moving windows of a given radius; and
(b) identify areas with shrinking analogs as potential macro-refugia

The following diagram illustrates how the density of current and future analogs is calculated for a given focal cell. If the focal cell is a current analog, then the process is "forward"; if the focal cell is a future analog, then the process is "backward"; and if the focal cell is stable, the results are identical in either direction.

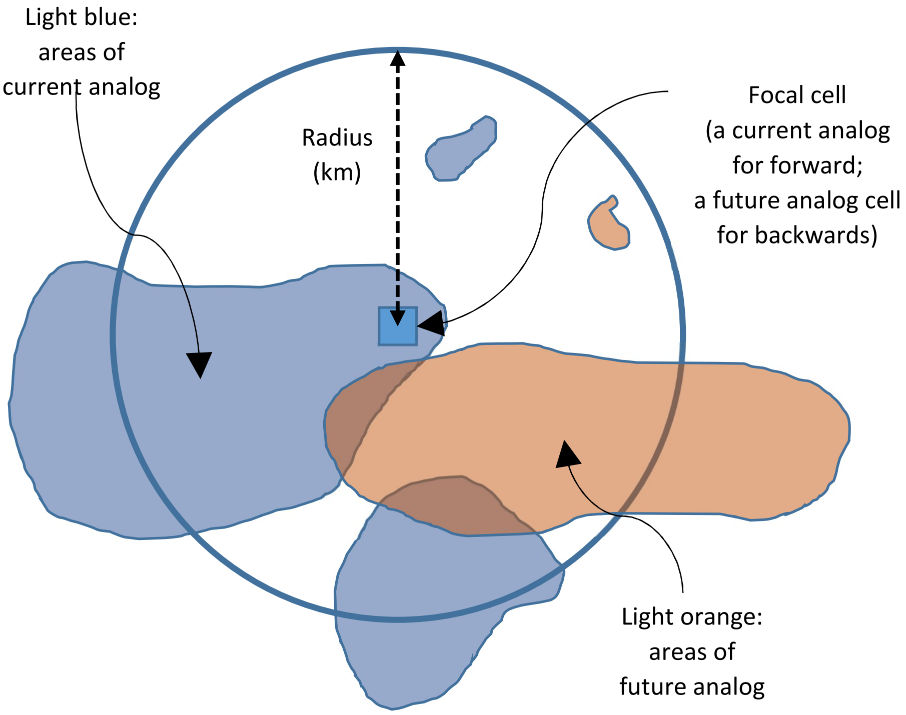

Figure 25. Computing number of current and future analog cells in a moving window centred on a current analog (forward) or future analog (backward). Values for forward and backward are identical in stable areas (where current and future analogs are the same).

A straight-forward computation of large circular moving windows over a large landscape is computationally intensive (e.g. a window radius of 30 km on a 1-ha grid has about 270,000 cells for each window; the Skeena-Nass study area has about 12.5 million cells in which the moving window needs to be calculated). For computational efficiency, an efficient circular moving window algorithm was adapted, which only needs to compute changes in the perimeters of the circular moving window windows (reducing computations to be a function of window diameter rather than area).

This required the steps to be restructured because the efficient moving window algorithm can only compute values for a single attribute (i.e. climate analog) at a time:

- For each radius and each time period to assess (current, 2050, 2080), and for each analog type, compute grids of the number of cells in the moving windows (nCurr, nFut at 2050 and at 2080).
- Load an array of the resulting grids and merge results for each analog, index by the selected focal analog (current analog for forward or future analog for backward).

A.2.2 Results

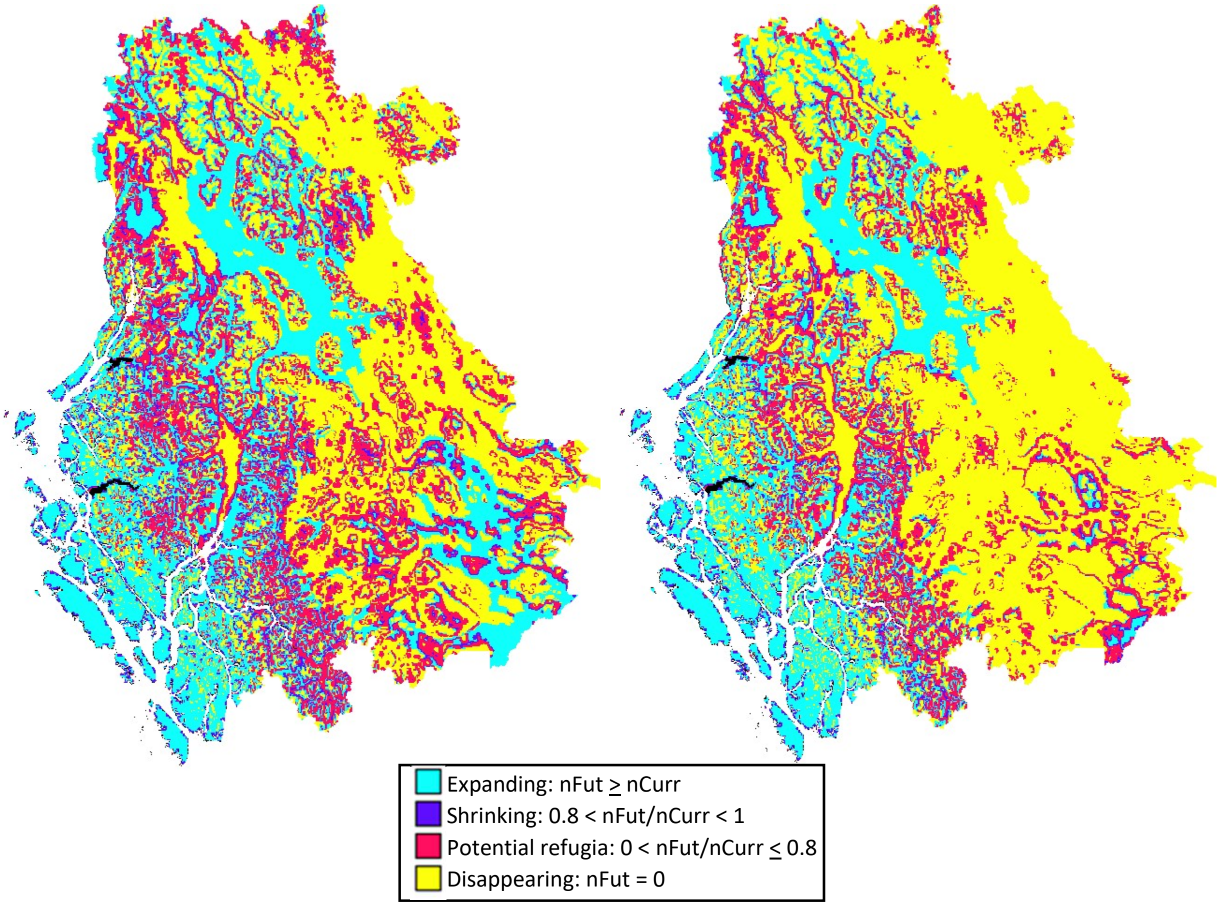

Figure 26. Analog change class (forward) using a 1 km radius moving window for 2050 (left) and 2080 (right).

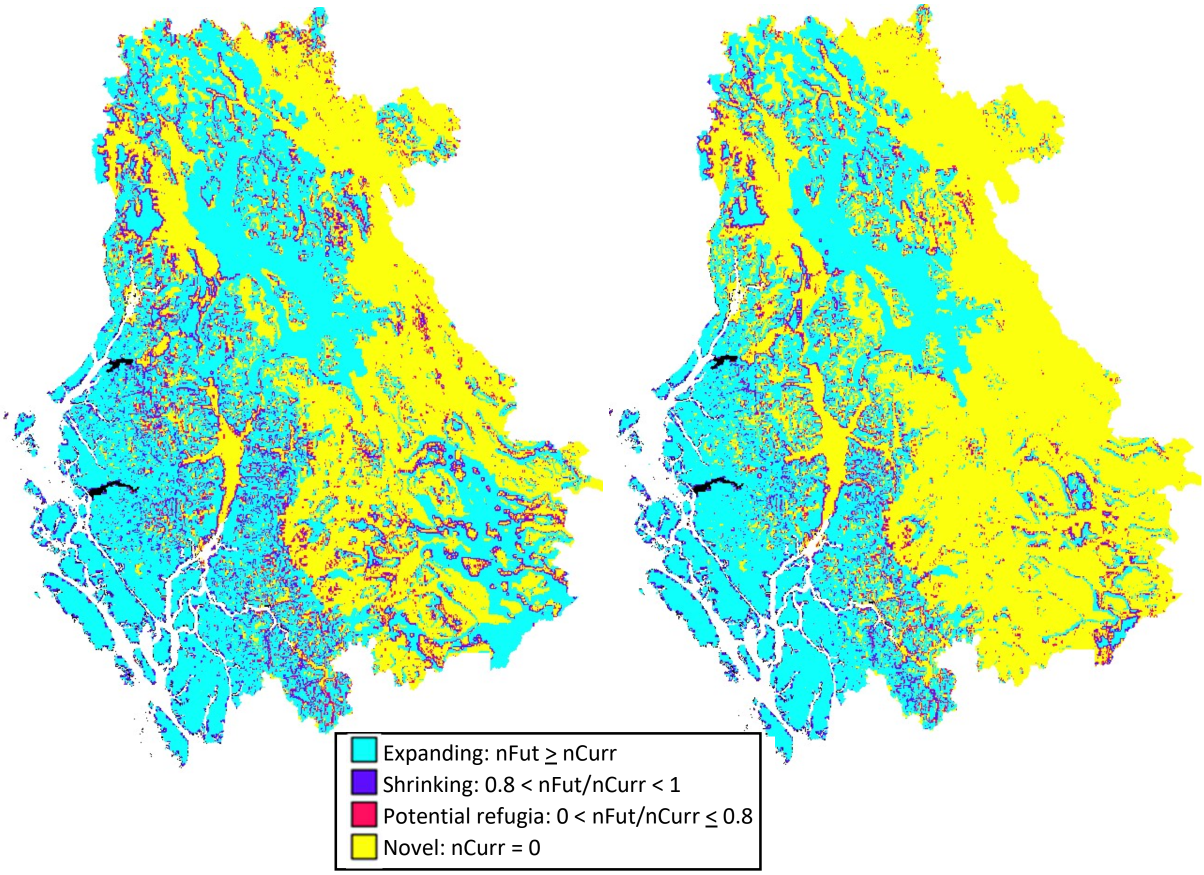

Figure 27. Analog change class (backward) using a 1 km radius moving window for 2050 (left) and 2080 (right).

A.2.3 Potential uses for Conservation Planning and Assessment

This method may be most suitable for a specific species or species guild, with a well-defined potential dispersal distance. As a general conservation planning and assessment tool, it may overly focus on fine-grained detail and on ratios of analog areas rather than magnitude. For example, a moving window with 2 future analog cells and 1 current cell will have the same class (expanding) as a moving window with 200 future analog cells and 100 current cells.

A.2.4 Future improvements

This method may be adapted for use with specific species of concern, especially dispersal limited species, as part of a more fine-filter process following a coarse filter approach to conservation in the context of climate change.

Appendix B Key Parameters

The list summarizes the key parameters that are recommended should be estimated by experts to apply the methods described in this document:

Degree of Intactness

- Impact intensity scores for each human footprint factor (Section 3.1)

Density of Enduring Features

- Relative value ratings for each enduring feature (Section 4.1)

Probability of Being a Macro-refugia

- "*Sufficiency*" thresholds for defining for analog climate condition classes (Section 5.5.1)

Conservation Class

- Density threshold for defining "areas with high density of enduring features" (Section 6.1)
- Intactness threshold for defining "intact areas" (Section 6.1)