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Examining climate-biome ("cliome") shifts for Yukon and its protected areas

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ABSTRACT

Protected area networks are the foundation of conservation, even in northern Canada where anthropogenic impact on the landscape is currently limited. However, the value of protected areas may be undermined by climate change in this region where the rate and magnitude is high, and shifts in vegetation communities and associated wildlife species are already underway. Key to developing responses to these changing conditions is anticipating potential impacts and the risks they pose. Capitalizing on an existing modeled dataset for Yukon from Scenarios Network for Alaska and Arctic Planning (SNAP), we examine projected shifts in the distribution of 18 clusters of climate parameters, and the vegetation communities currently associated with them (collectively termed "cliomes") across three 30-year time steps, from the present through the 2090s. By the 2090s, Yukon may lose seven cliomes and gain one. Three regional changes, if accompanied by vegetation redistribution, represent biome shifts: complete loss of climate conditions for arctic tundra in northern Yukon; emergence of climate conditions supporting grasslands in southern Yukon valleys; reduction in climates supporting alpine tundra in favor of boreal forests types across the mountains of central and northern Yukon. Projections suggest that, by the end of the 21st century, higher elevations in southern Yukon change least when compared to the turnover in cliomes exhibited by the high latitude, arctic parks to the north. This analysis can assist with: planning connectivity between protected areas; identifying novel conservation zones to maximize representation of habitats during the emerging changes; designing plans, management and monitoring for individual protected areas.

1. Introduction

The challenge of conserving the world's ecological systems and biodiversity is amplified by the numerous and significant biophysical changes occurring, and expected to occur, under changing climate conditions. In many countries conservation strategies are anchored on protected area (PA) networks that will be affected as individual species and ecosystems track climate changes into the future (Araújo et al., 2004; Chen et al., 2011; Lemieux and Scott, 2005; Hole et al., 2009). As species distributions shift in and out of PAs with the potential for creating novel communities, the ecological representation on which protected designations were based may be altered and potentially undermine their conservation values

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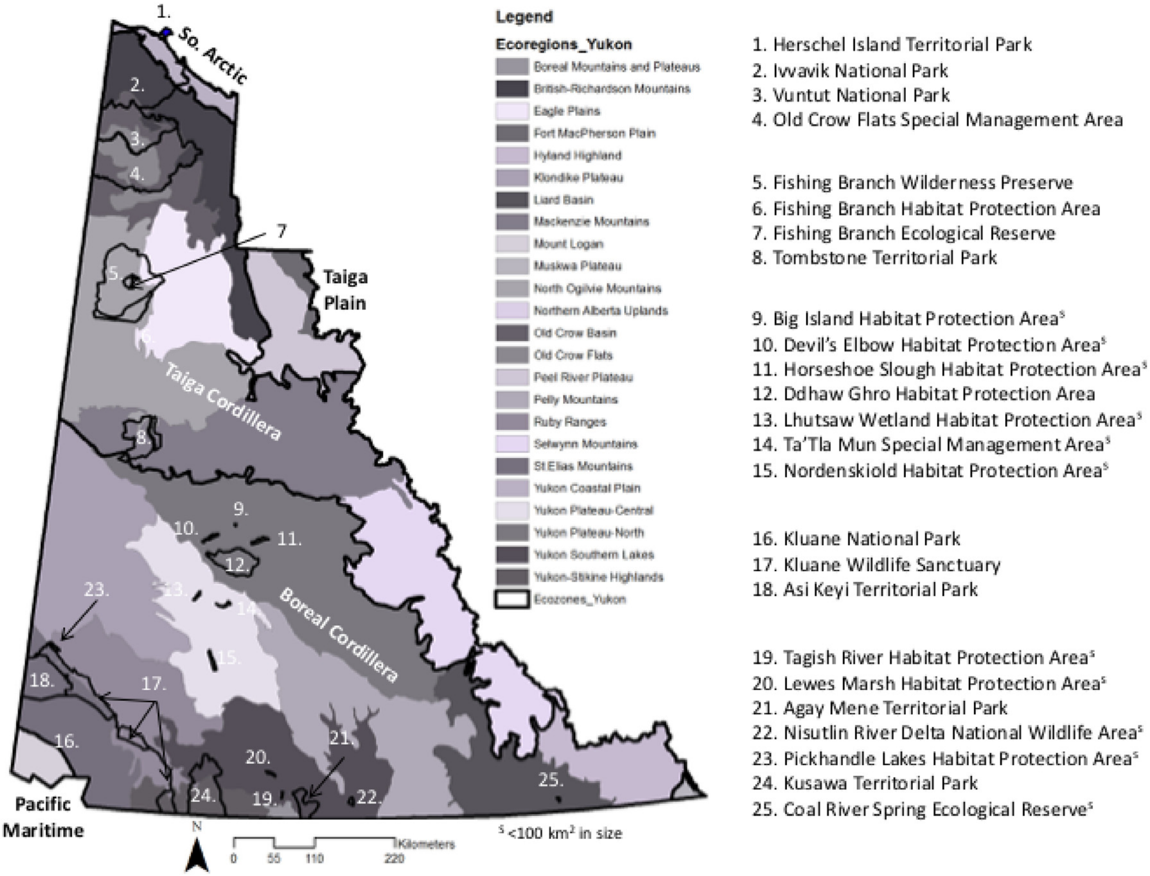

Fig. 1. The protected areas of Yukon, Canada, including National Parks, Territorial Parks, Habitat Protection Areas, Special Management Areas, Wildlife Sanctuaries, Wilderness Preserves, Ecological Reserves, and National Wildlife Areas. The backdrop includes the 23 ecoregions and 5 ecozones occurring in the territory.

(Scott and Lemieux, 2005; Hannah et al., 2007; Beale et al., 2013). Conservation planners and PA managers need to understand the potential responses of ecological systems both inside and outside reserves to develop proactive approaches to achieve conservation goals and strengthen the effectiveness of entire networks (Hannah et al., 2007; Lawler et al., 2008; Hole et al., 2011; Lemieux et al., 2011; Garcia et al., 2014).

Canada's boreal and arctic regions have already experienced warming and associated ecological change. In northwest Canada, Yukon's mean annual surface temperature has risen by between 1.0 and 2.5 °C from 1901 to 2012 (Stocker et al., 2013). Documented changes in Yukon's environment and PAs include decreases in glacier volume with increasing melt (Flowers et al., 2014), increasing permafrost melt (Lyon and Destouni, 2010), alpine tree line advance (Danby and Hik, 2007), shrub expansion on the arctic tundra (Myers-Smith et al., 2011), range expansion of some butterflies (Leung and Reid, 2013), and earlier egg-laying in arctic passerines and shorebirds in response to earlier snow melt (Grabowski et al., 2013).

Yukon's system of PAs is comprised of 26 management units representing a variety of land designations, including National Parks (NP), Territorial Parks (TP), Wilderness Preserves (WP), Ecological Reserves (ER), National Wildlife Areas (NWA), Habitat Protection Areas (HPA), Special Management Areas (SMA), and Wildlife Sanctuaries (WS) (Fig. 1; see Lemieux et al., 2010, p. 55 for descriptions). Ranging in area from ∼5 to 22,000 km^2, Yukon's PAs cover ∼65,000 km^2 or 13.4% of the total Yukon area. The PA network is currently incomplete in terms of representation of Yukon ecoregions (12 of 23 in the network), which is the basis for conservation planning in Canada's PA network (Lemieux and Scott, 2005). However, Yukon's boreal and arctic landscapes are relatively intact with a minimal human footprint, and thus retain significant ecological and conservation value (Sanderson et al., 2002; Schmiegelow et al., 2006; Schindler and Lee, 2010). Understanding potential changes in Yukon's ecological systems under climate change will facilitate management of the existing PA network and planning for conservation across the broader region.

There are multiple approaches for assessing the potential impacts of future climate conditions to ecosystems, their components, and associated conservation values (Araújo and Luoto, 2007; Morin and Thuiller, 2009; Lawler et al., 2009; Dobrowski et al., 2013). Many are species-based efforts, relying on climate envelope or distribution modeling, sometimes integrated with other modeling approaches. Such efforts describe species distributions based on climate and other habitat variables, and project these distributions into the future using the outputs of climate models (e.g., Global Circulation Models or GCMs) (e.g. Hannah et al., 2007; Beale et al., 2013). Process-based models that project vegetation types associated with particular climatic conditions are another option (e.g., Scott et al., 2002). It is well recognized that these efforts make certain assumptions (e.g., coincidence of realized and fundamental niches) and do not clearly account for other processes (e.g., varied dispersal abilities, dependence on biotic interactions) that may well influence future species distributions (e.g., Pearson and Dawson, 2003; Wiens et al., 2009). Also, while climate is ultimately a key determinant of biome characteristics, biomes are also shaped by physiography and hydrology. Models are inherently limited in their representations of ecological systems, and it is difficult to predict the effects of climate change on vegetation, biomes and ecosystems.

Species- and process-based models are data intensive, requiring detailed, accurate, and high-resolution information on distributions of species and ecosystems. An alternative approach, that circumvents the data requirements and caveats of species distribution models, considers the rate and magnitude of projected changes in climate parameters themselves (i.e., climate change exposure) as a proxy for understanding potential biodiversity impacts (Loarie et al., 2009; Davison et al., 2012; Watson et al., 2013; Garcia et al., 2014). Although such an approach cannot be expected to predict responses by any one species, it may be appealing in high latitude landscapes, such as Yukon, in which limited empirical data on species distributions are available, many key ecological processes are linked to climate conditions, such as snow depth and the timing of snow melt, and where the rate of warming and ecosystem response, particularly arctic regions, is greater than many other parts of the world (McLennan et al., 2012).

Capitalizing on a dataset available for Alaska and northwest Canada, we examined the projected shifts in the distribution of 18 clusters of climate parameters and their associated ecological biomes (collectively termed "cliomes") in Yukon across three, roughly 30-year time steps, from the present through the 2090s. Previous work evaluated potential biome shifts in Canada's National Park system using global biome maps and climate scenarios derived from older GCMs (Scott et al., 2002; Lemieux and Scott, 2005). For this study we used more recent climate projections to examine projected changes across Yukon's entire PA network. We explored (1) the potential rate and magnitude of change in cliomes across Yukon and its PA network; (2) the future effectiveness of Yukon's PA network in conserving ecological diversity; and (3) the implications for climate change adaptation and conservation planning in the region.

2. Methods

2.1. Study area

Yukon covers approximately 483,450 km^2 of arctic and subarctic northwest Canada, bordered on the west by Alaska (USA), and south by British Columbia (Canada). Ranging from sea level, on the Arctic Ocean coast in the north, to the highest elevation in Canada (Mt. Logan, 5959 m), the region is primarily a complex of mountain belts and plateaus resulting from the ongoing tectonic activity along the west edge of the North American plate (Smith et al., 2004).

Yukon's climate is classed as subarctic continental. Mean annual temperatures range from −2 °C in southern valleys to −10 °C along the arctic coast. The continental climate is most noticeable in the interior where mean daily temperatures range from −20 to −30 °C in January and from 10 to 15 °C in July (Wahl, 2004). A sequence of parallel, northwest to southeast trending mountain ranges act as orographic barriers to moist air pushing inland from the south. The north and east slopes of each interior mountain range lie in precipitation shadows, with some interior valleys receiving as little as 250–300 mm annually (Wahl, 2004). The great majority of Yukon (98%) supports boreal forests ranging from closed canopy stands in southern valleys to more taiga forests with sparse tree coverage and shrub lands in northern lowlands and also in subalpine zones where the forests merge into alpine tundra. Lowland tundra (1% of the land) is found along the arctic coast. Yukon is strongly influenced by proximity to the Pacific Ocean to the southwest. The coast range, lying closest to the Pacific, captures the largest amounts of precipitation (2000–3500 mm annually) and is covered in alpine glaciers (Wahl, 2004). However, only a small portion of this range lies within the southwest corner of Yukon.

2.2. Cliome projections

We applied the existing Alaska–Canada Climate Biome Shift outputs prepared by Scenarios Network for Arctic Planning (SNAP) (SNAP-EWHALE, 2012) to address questions about Yukon and its PA network. Climate-biomes or "cliomes" were initially created as part of a collaborative effort between multiple agencies in Alaska and Canada (SNAP-EWHALE, 2012). The original project combined progressive clustering methodology, existing land cover classifications, and historical and projected climate data to identify areas likely to undergo ecological pressure as climate regimes change.

The cliome information was developed by first identifying 18 clusters of climate space using the historical baseline period (1961–1990) for Alaska and Canada west of Hudson Bay (SNAP-EWHALE, 2012). The cliome classifications were created from 24-climate variables that included mean monthly temperature and total monthly precipitation for all twelve months to capture variations in seasonality. Values for climate variables in the baseline period were derived from gridded Climatic Research Unit (CRU) data at 10' latitude/longitude (∼18.4-km grid resolution) (New et al., 2002). Finer-scale climate data were not available for the entire Alaska–Canada study area. Clustering of the 24 climate variables used Partitioning Around Medoids methodology (Breiman, 1998; Breiman, 2001; SNAP-EWHALE, 2012). The machine-learning system created a central value (medoid) for each cluster, and assigned all data points to a cluster such that the sum of the dissimilarities between all points and their designated medoid was minimized, offering a robust means of grouping values into an optimal

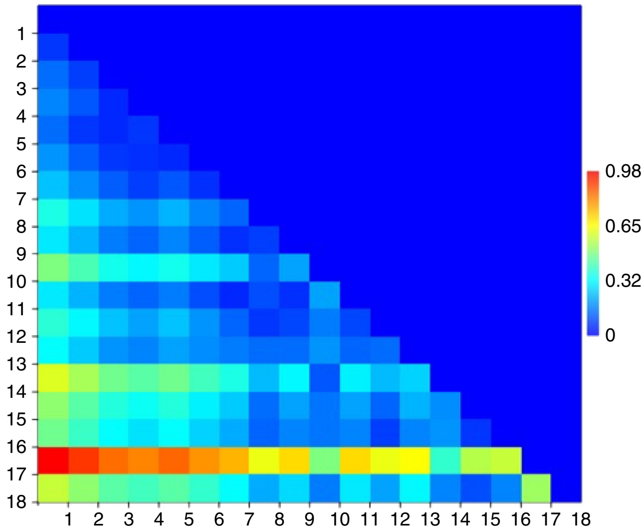

Fig. 2. The relative distance between the 18 cliome clusters from the Partitioning Around Medoids methodology. Distances between medoids for each cluster are standardized so as to create a potential range between 0 and 1, with larger values indicating greater dissimilarity (orange to red end of color gradient) between medoids. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

number of categories. Silhouette analysis was used to test the mathematical strength of the clusters and the meaningfulness of biome descriptions for management applications.

As in any clustering of this nature, some categories are relatively similar to one another, and some are extremely distinct. Fig. 2 illustrates the relative distances (i.e., differences) in climate conditions between all possible pairings of cluster medoids, standardized to a range between zero and one. If the underlying assumption of the analysis holds, these differences in climate conditions provide a meaningful estimate of differences in ecological conditions. Although in some cases, ecological responses may be non-linear, due to thresholds such as prevalent temperatures below or above freezing, there is no indication that such thresholds occur disproportionately between any two particular cliomes. The distance values allow interpretation of which shifts between cliomes represent potentially profound ecological changes. However, the metric does not take into account threshold differences between cliomes.

The 18 cliomes are characterized by their defining seasonal climate parameters (Table 1). Each cliome is also described based on the dominant features of land cover categories in five existing classification systems and associated datasets: North American Land Change Monitoring System 2005 land cover map (NALCMS, 2005); Advanced Very High Resolution Radiometer 1995 land cover dataset (AVHRR, 1995); GlobCover, 2009 land cover map (GlobCover, 2009); and Alaska Biomes (Nowacki et al., 2001) and Canadian Ecozones (Ecological Stratification Working Group, 1996). The analysis used spatial overlay techniques to examine the degree of overlap between each cliome and extant ecological biomes. Descriptions were created from the details of the dominant land cover categories associated with each climate cluster (Table 1; SNAP-EWHALE, 2012).

SNAP-EWHALE (2012) produced projected spatial configurations of the 18 cliomes across Alaska, Yukon and Northwest Territories using Random Forests™ (Breiman, 2001) based on climate model outputs from five CMIP3 GCMs selected for their accuracy in northern regions (ECHAM5, MIROC, CCCMA, GDFL, MIROC; (Walsh et al., 2008)). Model outputs were averaged for 2010–2019 (2010s), 2030–2039 (2030s), 2060–2069 (2060s), and 2090–2099 (2090s). Decadal averages were assessed, as opposed to data for single years, in order to reduce error due to the stochastic nature of GCM outputs, which mimic the true inter-annual variability of climate. For Alaska and Yukon, the projected cliomes, as well as those for the historical baseline (1961–1990), were generated at 2-km resolution, based on downscaling using the finer-resolution PRISM data (Parameter Regression on Independent Slopes Model) (PRISM Climate Group, 2015) available for these regions. Cliome outputs were produced for three emissions scenarios, as defined by the IPCC (B1, A1B and A2) (Nakicenovic et al., 2000), and the 5 CMIP3 GCMs. While some differences in the magnitude and spatial configuration of projected change in cliome outputs exist between model and emission scenario combinations, the overall patterns of northward shifts and the loss of arctic cliomes are consistent (SNAP-EWHALE, 2012). In addition to the projected cliomes, the SNAP dataset includes a map of cliome resilience, which depicts the number of cliome shifts (ranging from 0 to 3) experienced by each 4-km^2 cell between the three time steps (2010s to 2030s, 2030s to 2060s, 2060s to 2090s; SNAP-EWHALE, 2012).

The full SNAP methodology is described in detail at www.snap.uaf.edu.

2.3. Yukon analysis

For our Yukon analysis, we used the cliomes generated with the five-model composite (average) climate projections of the A2 emissions scenario (Nakicenovic et al., 2000) and compared changes in the distribution of cliomes across three time

Table 1
Climate and vegetation-based (cliome) descriptions of the 18 cliome clusters developed for the Alaska–Canada Climate-Biome Shift project (from SNAP-EWHALE 2012). Cliome descriptions are based on similarities between the conditions represented by the climate clusters and existing land cover classifications and techniques which are mainly vegetation types: NALCMS (*), AVHRR (*), GlobCover (2009), Alaska Biomes and Canadian Ecozones. Note that these land cover or vegetation types, currently associated with climate-based clusters, may not have the same composition in the future. Climate descriptions include mean seasonal temperature and mean annual precipitation for 1961–1990. Cliome 2 is not found in Yukon under present or future climate conditions.

Cliome	Biome/Land cover-based description	Mean seasonal temperatures				Mean annual precipitation (mm)
		Spring (°C)	Summer (°C)	Fall (°C)	Winter (°C)	
1	Northern Arctic sparsely vegetated tundra with up to 25% bare ground and ice, with an extremely short growing season.	−21	3	−14	−31	117
3	More densely vegetated arctic tundra with up to 40% shrubs but no tree cover.	−15	6	−9	−26	198
4	Arctic tundra with denser vegetation and more shrub cover including some small trees.	−12	8	−9	−26	206
5	Dry sparsely vegetated southern arctic tundra.	−16	8	−9	−30	243
6	Northern boreal/southern arctic shrubland, with an open canopy.	−14	9	−7	−28	274
7	Northern boreal coniferous woodland, open canopy.	−9	12	−7	−27	281
8	Dry boreal wooded grasslands–mixed coniferous forests and grasses.	−4	11	−4	−19	355
9	Mixed boreal forest.	−5	12	−6	−24	284
10	Boreal forest with coastal influence and intermixed grass and tundra.	−2	11	0	−12	561
11	Cold northern boreal forest.	−8	12	−5	−26	390
12	More densely forested closed-canopy boreal forest.	−3	13	−3	−22	420
13	Sparsely vegetated boreal forest with elevation influences.	−7	8	−8	−21	586
14	Densely forested southern boreal.	1	12	1	−10	857
15	Southern boreal/aspen parkland.	1	16	2	−17	474
16	Southern boreal, mixed forest.	−2	15	0	−20	545
17	Coastal rainforest, wet, more temperate.	2	11	3	−4	2249
18	Prairie and grasslands.	4	17	4	−11	443

* NALCMS: North American Land Change Monitoring System.
* AVHRR: Advanced Very High Resolution Radiometer.

steps: the historical baseline period (1961–1990) to the 2030s; 2030s–2060s; and 2060s–2090s (SNAP, 2015). A comparison of cliome outputs between the A1B and A2 scenarios for the Yukon PAs showed some differences. However, because output from different emission scenarios does not diverge greatly until after mid-century (Knutti and Sedláèek, 2013), we used output from the A2 scenario only in our analyses. Moreover, studies show this to be the most consistent with respect to current emission trends (Fussel, 2009; Peters et al., 2013), and thus may accurately reflect changes at the end of the 21st century. Although the IPCC's most recent report, the fifth Assessment Report, refers to four Representative Concentration Pathways (RCPs) rather than the scenarios described in the Special Report on Emissions Scenarios published in 2000, the slightly older CMIP3 model outputs used in this analysis are still relevant within the new framework (Knutti and Sedláèek, 2013).

We converted Yukon Parks and Protected Areas shapefiles (Geomatics Yukon, 2013) to raster formats using ArcMap 10.1 (ESRI, 2012) to make the output resolution (cell size) consistent with the cliome dataset. Cliome representation was determined for each PA, and for Yukon as a whole, for the baseline and three projected time periods. We converted the cell counts of each cliome to percent area to describe the cliome composition of each PA, the entire PA network, and the entire Yukon in each of the time periods.

Finally, we used linear regression to examine relationships between the magnitude of change based on the cliome projections for the Yukon's ecoregions and PAs and a set of potential explanatory characteristics (ecoregional elevation, PA size and PA latitude). We described the magnitude of change by the end of the 21st century for each unit (PA or ecoregion) with a "cliome shift index" (CSI). The CSI was calculated for each unit from the sum of the % area multiplied by the number of shifts (0, 1, 2, and 3) experienced (i.e., $50\% * 0 + 25\% * 1 + 10\% * 2 + 15\% * 3 = 90$). Thus, units with large areas experiencing multiple cliome shifts would exhibit larger CSI values than units with less area experiencing multiple shifts.

3. Results

3.1. Cliomes of Yukon: baseline conditions

In the historical baseline period (1961–1990) 16 cliomes occur in Yukon (Fig. 3(a)). The Boreal Cordillera ecozone is dominated by Cliomes 8, 9, and 12 at moderate elevations (800–2200 msl). Together these cliomes capture a moisture gradient from 284 mm to 420 mm of total annual precipitation (Table 1), and associated land cover may range from dry boreal wooded grasslands to more densely forested closed-canopy boreal communities. Sparse open boreal forest and

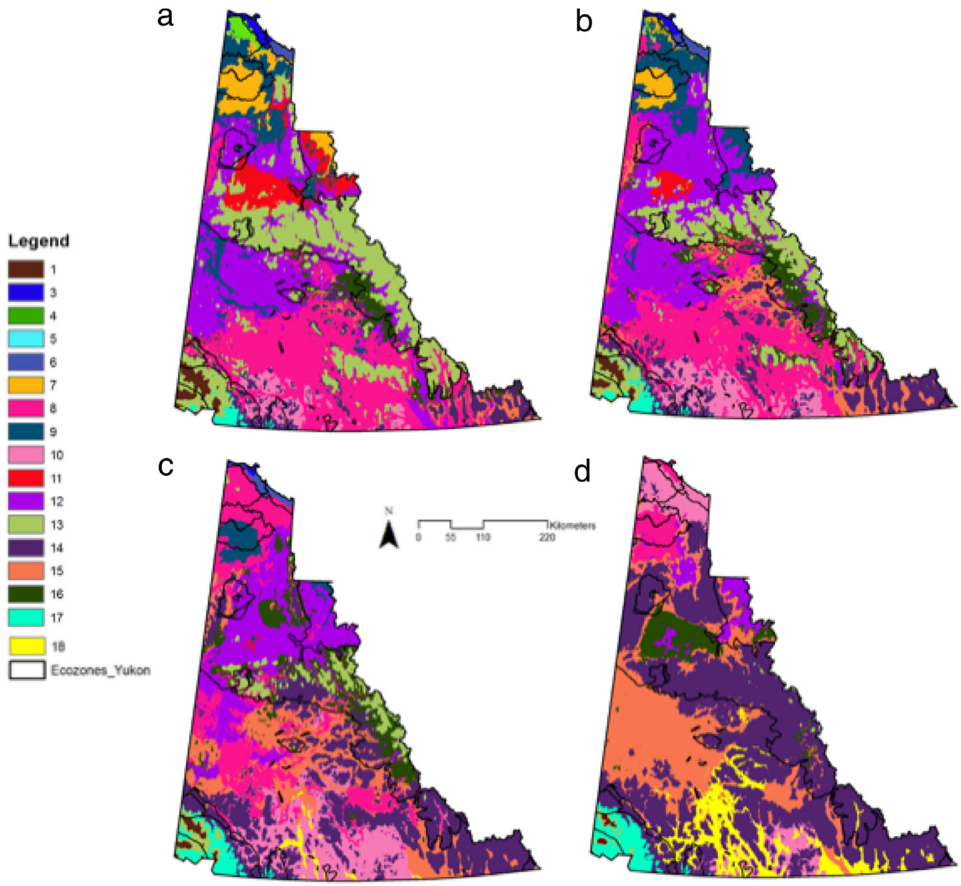

Fig. 3. Cliome representation in Yukon, Canada during (a) the baseline period (1961–1990) and projected for (b) the 2030s, (c) the 2060s, and (d) the 2090s based on the 5-model composite projections and A2 emission scenario (SNAP-EWHALE, 2012). Numbers in the legend refer to cliomes in Table 1.

tundra vegetation of Cliome 13 prevail at higher elevations, particularly the St. Elias Mountains in the southwest, the Pelly Mountains in southcentral Yukon, and the Selwyn and Mackenzie Mountains that mark the transition of Boreal to Taiga Cordillera (see Figs. 1 and 3(a)). The cliomes analysis indicates that some of the harshest winter conditions (Cliome 1; −31 °C) and relatively high precipitation regimes (Cliome 13; 586 mm MAP) are found in the southwestern corner of Yukon. While these conditions can be associated with vegetated land cover when categorized across the entire cliome modeling region, this area of southwest Yukon is predominantly glaciated (Smith et al., 2004; Strong, 2013). Cliomes 7 and 11, which are characterized by open northern boreal forests (Table 1), dominate the Taiga Cordillera and Plains ecozones (Fig. 3(a)). Cliome 11 has similar winter temperatures to Cliome 7 but greater annual precipitation (380 mm). Moving northward, cliomes associated with arctic influences (3, 4, and 6) dominate, and modern open tundra and shrub tundra communities are common on the landscape. With similar winter and fall temperatures and moisture regimes, Cliomes 3 and 4 are distinguished by the length of their growing season, which supports denser shrubs and scattered trees in the latter (Table 1).

3.2. Cliomes of Yukon: projected changes

The number of projected changes in cliomes over the next century is generally greater in the northern regions of Yukon than in the southern parts, and at least half of Yukon is projected to undergo two or more shifts in cliome by the 2090s (Fig. 4). By century's end seven cliomes (3, 4, 5, 6, 7, 9, and 11) found in the historical baseline period are no longer present in Yukon and one (18) is gained; four cliomes (1, 8, 12, and 13) show key declines in Yukon and two others (14 and 15) expand dramatically (Fig. 3(d)). The dominant cliomes by the end of the century (8, 10, 12, 14, 15, 16, 18) are those found in Alberta, British Columbia, and southern Yukon during the 1961–1990 baseline period (SNAP-EWHALE, 2012). Compared with the historical baseline, temperatures are projected to increase by 3.9 °C to 6.9 °C through the 21st century for the A2 scenario (Fig. 5).

Over the three time steps, the majority of the Boreal Cordillera, Taiga Cordillera and Taiga Plains are projected to experience one or two cliome shifts (Table 2). Results suggest that a greater percent area in the southern ecozones (Boreal Cordillera and Pacific Maritime) may undergo one shift whereas two or more shifts more often occur in the three northern ecozones (Taiga Cordillera and Plains, Southern Arctic). Of all ecozones, the Taiga Cordillera has the greatest percent area

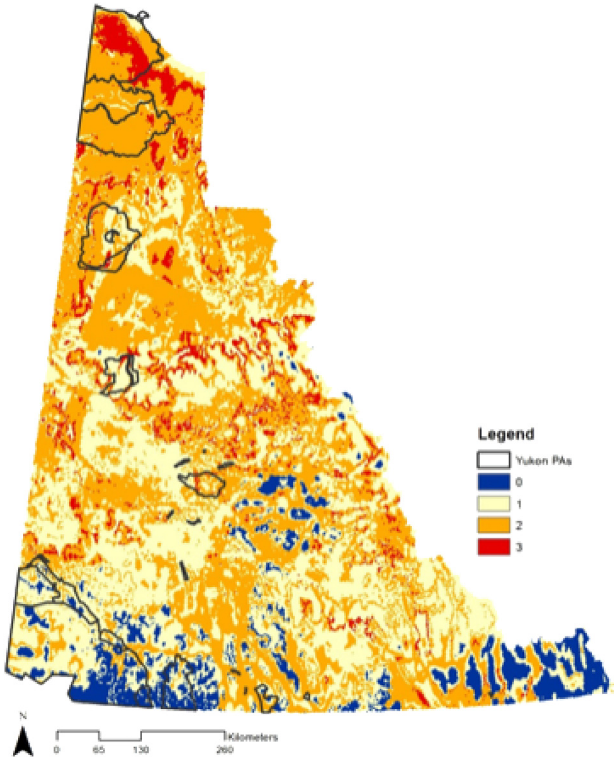

Fig. 4. The total number of shifts in cliomes that any given pixel undergoes across all time periods (2000s–2090) in Yukon. The climate projections for this figure are based on the 5-model composite (average) using the A2 emissions scenario (Data from SNAP-EWHALE, 2012). Note that this is an original output of the SNAP-EWHALE (2012) analysis, and the baseline time step (2000s) for this analysis differs from that used (1961–1990) in all other figures focused on Yukon.

experiencing three shifts (Table 2). In the southwest, 11% and 7% of the Boreal Cordillera and Pacific Maritime, respectively, are projected to experience no cliome shifts. The pattern of greater change in the northern than southern parts of Yukon corresponds to the pattern of warming for mean annual temperatures (Fig. 5).

Compared to areas with >1 cliome shift, the percent ecoregion area with zero and one shifts tends to increase with mean ecoregion elevation (Fig. 6). Although linear regression between mean elevation and the CSI suggests this relationship is significant, it is not strong (Fig. 7; $t = -2.44, P = 0.02, r^2 = 0.22$). The only ecoregions with at least some area experiencing no cliome shifts by the end of the century all have mean elevation at or above 950 m (Fig. 6). The mean elevation of an ecoregion is strongly correlated with its elevational range ($r^2 = 0.83$). Thus, the percent ecoregion area with one cliome shift also increases with increasing range in elevation across an ecoregion, while the percent ecoregion area with two cliome shifts decreases.

Compared to the baseline period, the cliome composition of Yukon remains nearly the same in the 2030s (Fig. 3(b)). Differences include the expansion of Cliome 9 at the expense of other northern cliomes, the retreat of Cliome 13 to higher elevations in the southwest Yukon, and the incursion of Cliomes 14 and 15 into Yukon from the southeast.

By the 2060s, the higher winter, spring and fall temperatures associated with Cliome 8 have expanded as far north as the Southern Arctic ecozone (Fig. 3(c)). Cliome 10 has joined 8 to dominate the northern parts of Yukon by the 2090s (Fig. 3(d)). The 7 cliomes that are projected to disappear by century's end currently occur throughout the north, extending as far south as the Boreal Cordillera (Fig. 9). Projections of warmer temperatures, especially in winter, coupled with increasing precipitation suggest growing conditions that will support the expansion of deciduous and conifer forest into vegetation communities that are now arctic tundra, subarctic boreal forest (taiga), and subalpine shrublands toward the end of the century (Fig. 3(d)).

Cliomes currently associated with mixed boreal forests and aspen parkland of southern Canada (14 and 15) are suggested to move north and west into Yukon in the 2060s. By the 2090s these two cliomes, representing 4% of the landscape and relatively novel climates in the historical period, may expand to 71% of the Yukon (Table 3) and occupy nearly all of the Boreal Cordillera (Fig. 3(c)–(d)). Upper elevation Cliome 13, which retreats to higher elevations in the 2060s, is reduced to a couple of small patches in Yukon's southwest corner by the 2090s. In west-central Yukon, the conditions associated with southern boreal forest and aspen parkland (Cliome 15) will replace those that support the denser, mixed boreal forests that currently occur (Cliomes 9 and 12).

The current conditions and dry, open forests (Cliome 8) of south-central Yukon are projected to be replaced in 2090s by climates that support denser boreal forests, potentially of different species composition, at higher elevations (Cliome 14) and climates that foster prairie and grasslands at lower elevation (Cliome 18). Cliome 18, which has no analog climate in the

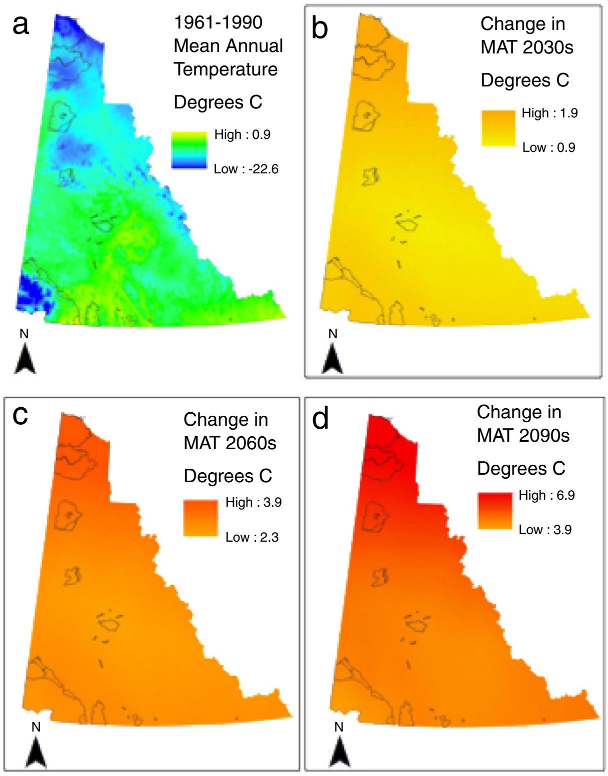

Fig. 5. Mean annual temperature (MAT) for the baseline period (1961–1990) and projected temperature increases for the 2030s, 2060s, and 2090s time steps based on the 5-model composite projections using the A2 emissions scenario. Protected areas are displayed in black outline.

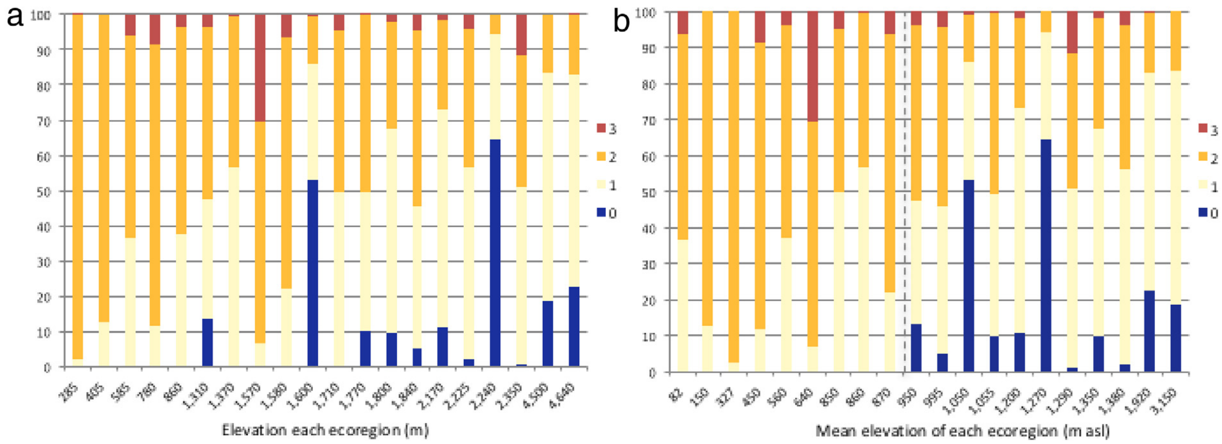

Fig. 6. Percent of the area of each ecoregion with 0–3 projected cliome shifts by the end of the century: (a) displayed by the elevational range (m) within the ecoregion and (b) displayed by mean elevation of the ecoregion in meters above sea level (m asl). Only ecoregions with >1000 km^2 of their area in Yukon are shown.

historical period, may occupy as much as 8% of the Yukon landscape (Table 3). The expansion of Cliome 14 from 3% to 49% of Yukon's entire landbase in the 2090s (Table 3) is associated with increases in precipitation across nearly all the mountain blocks (including Pelly, Selwyn, Mackenzie, Ogilvie and Richardson Mountains) and reflects improved growing conditions for forests where orographic precipitation is best captured. In contrast, higher temperatures during the spring, summer, and fall in many southern and central valley bottoms may counteract any potential increases in precipitation and create more drought-like growing conditions.

Two cliomes nearly lost by the end of the century (1, 13) are characterized by some of the coldest spring and fall temperatures and short growing seasons (Cliome 1, in particular) and are associated with ice, bare ground, and sparsely vegetated tundra (Table 1). These cliomes currently cover the glaciated portion of Kluane NP and the higher elevations

Table 2
Projected number of cliome shifts and percent area affected for each ecoregion across the three time steps, combined with elevational parameters of ecozones and ecoregions. For example, projections suggest that the 37% of the Southern Arctic undergoes 1 shift, 57% undergoes 2 shifts, and 6% undergoes 3 shifts. *Text in italics: ecoregion with <1000 km^2 total area within Yukon. Text in bold font: ecoregions with ≥50% area affected in a time period.

Ecozone	Ecoregion	Elevation				# Cliome Shifts (% area)			
		Low	High	Range	Mean	0	1	2	3
Southern Arctic	Yukon Coastal Plain	0	585	585	82	0	37	**57**	6
	Total					0	37	57	6
Taiga Plains	Fort MacPherson Plain	35	440	405	150	0	13	**87**	0
	Muskwa Plateau	*255*	*1115*	860	*570*	*64*	*34*	*2*	*0*
	Northern Alberta Uplands					*0*	*0*	***100***	*0*
	Peel River Plateau	*45*	*1470*	1425	*455*	*0*	*38*	**60**	*2*
	Total					2	34	62	1
Taiga Cordillera	British–Richardson Mountains	40	1610	1570	640	0	7	**62**	31
	Eagle Plains	250	1110	860	560	0	37	**59**	4
	Mackenzie Mountains	400	2750	2350	1290	1	**50**	37	12
	North Ogilvie Mountains	280	1860	1580	870	0	22	**72**	6
	Old Crow Basin	300	1080	780	450	0	12	**80**	9
	Old Crow Flats	325	610	285	327	0	2	**98**	0
	Selwyn Mountains	745	2970	2225	1380	2	**54**	40	4
	Total					1	33	56	10
Boreal Cordillera	*Boreal Mountains and Plateaus*	660	*1700*	1040	*1050*	*6*	*44*	*50*	*0*
	Hyland Highland	300	1900	1600	1050	**53**	33	13	1
	Klondike Plateau	290	2000	1710	850	0	**50**	46	5
	Liard Basin	580	1890	1310	950	13	34	49	4
	Pelly Mountains	600	2400	1800	1350	10	**58**	31	2
	Ruby Ranges	575	2745	2170	1200	11	**62**	25	2
	St.Elias Mountains	580	5220	4640	1920	22	**60**	17	0
	Yukon Plateau-Central	490	1860	1370	860	0	**56**	43	0
	Yukon Plateau-North	320	2160	1840	995	5	41	**50**	4
	Yukon Southern Lakes	610	2380	1770	1055	10	40	**50**	0
	Yukon–Stikine Highlands	460	2700	2240	1270	**65**	30	6	0
	Total					11	48	39	2
Pacific Maritime	Mount Logan	1500	6000	4500	3150	19	**65**	16	0
	Total					19	65	16	0
ALL	Total					7	42	46	5

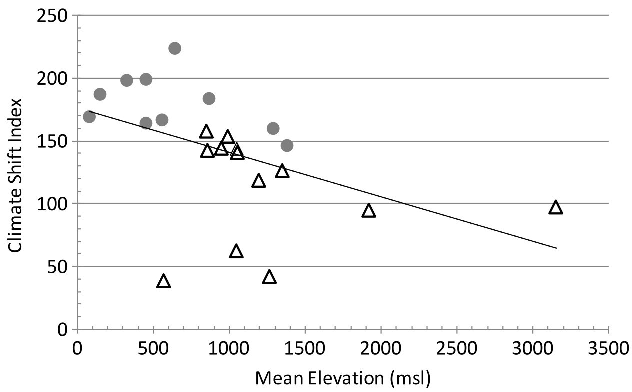

Fig. 7. Linear regression showing the (significant) relationship between the Climate Shift Index (CSI) of Yukon's ecoregions and the mean elevation of each. The black triangles indicate ecoregions found in the Maritime and Boreal Cordillera Ecozones, while the gray circles indicate ecoregions found in the higher latitude Tiaga Cordillera, Tiaga Plains, and Southern Arctic Ecozones.

across Yukon. Very southwest Yukon (i.e., Kluane NP) may be the only place retaining the climate conditions represented by these cliomes at the end of the 21st century. Much of the area lost from the colder cliomes transitions to Cliomes 17 and 14, which are the two wettest clusters, the former of which is currently characteristic of temperate, coastal rainforest (Table 1).

3.3. Cliome conditions and changes in Yukon's protected areas network

All of the 17 cliomes occurring in Yukon in the baseline period also occur within the PA network (Table 3, Fig. 8). This pattern generally holds through the 2030s and the 2060s (Table 3), and, even by century's end, all cliomes projected to occur

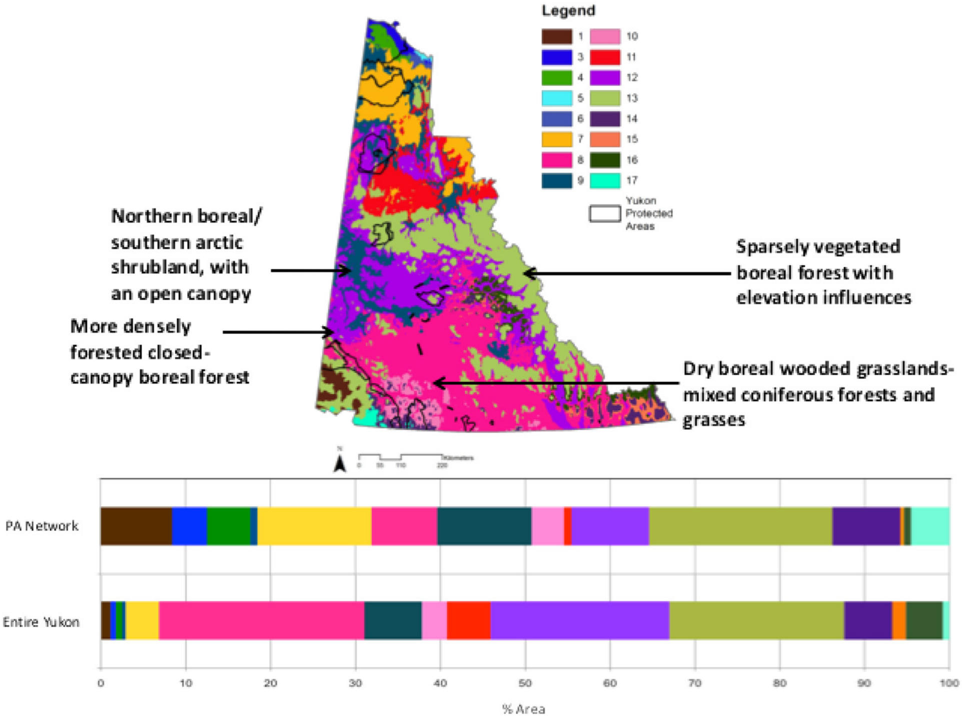

Fig. 8. A composite graphic showing a map of the distribution of cliomes in Yukon for the baseline (1961–1990) time period and two bar charts representing the cliome composition of the entire Yukon (bottom) and PA network only (top) in the same time period.

Table 3
The proportional representation (%) by area of cliomes in the Protected Areas (PA) network of Yukon relative to their representation across the entire Yukon land base (Yukon area = 483,450 km^2). Land area of the entire PA network is ∼13.4% of the total land area of Yukon. * indicate instances when cliome representation in the PA network is less than half of its Yukon-wide proportion.

Cliome #	% Cliome area—Baseline		% Cliome area—2030s		% Cliome area—2060s		% Cliome area—2090s	
	Yukon	PA network	Yukon	PA network	Yukon	PA network	Yukon	PA network
1	1.3	9.3	0.9	6.6	0.5	4.0	0.2	1.5
3	0.8	4.8	0.4	3.1	0.2	1.2	0.0	0.0
4	0.9	5.5	0.1	0.8	0.0	0.0	0.0	0.0
5	0.1	0.0*	0.1	0.1	0.0	0.0	0.0	0.0
6	0.3	0.0	0.6	1.1	0.7	2.6	0.0	0.0
7	6.8	16.7	2.0	10.7	0.0	0.0	0.0	0.0
8	25.8	9.1*	22.3	7.8*	16.0	22.5	3.0	15.3
9	8.7	9.8	6.6	14.5	2.2	8.8	0.0	0.0
10	2.5	4.1	5.9	5.8	11.0	5.4*	6.5	15.3
11	6.3	0.9*	1.1	0.0*	0.1	0.0*	0.0	0.0
12	19.0	7.7*	24.6	9.1*	16.1	5.0*	3.1	0.6*
13	20.9	21.4	11.7	17.1	4.9	10.3	0.5	2.7
14	2.7	6.0	10.5	11.9	24.9	19.9	48.7	33.1
15	1.2	0.2*	6.0	2.4*	13.3	3.9*	22.6	4.9*
16	2.5	0.2*	6.0	1.3*	7.4	1.1*	4.4	0.5*
17	0.6	4.4	1.1	7.8	2.1	15.0	3.1	22.5
18	0.0	0.0	0.0	0.0	0.8	0.2*	7.9	3.0*

across Yukon will still be represented within the PA network (Table 3, Fig. 8). Of those cliomes that comprise at least 1% of the total area in protection in the baseline period (11 of 17), only 2 (9, 13) have representation in the network at a proportion that equals or exceeds representation across the whole Yukon (Table 3). Four of the coldest cliomes (1, 3, 4, and 7) constitute <10% of Yukon but comprise 36% of the PA network during the historical period. In contrast, two cliomes (8 and 12) occupy ∼45% of Yukon in the baseline period while accounting for only 17% of the PA network. Other cliomes under-represented during the baseline period include Cliomes 11, 15, and 16 (Table 3).

By the end of the century (2090s), low elevation areas outside the PA network are projected to be dominated by cliomes currently associated with southern boreal forests, aspen parkland, and grasslands (Cliomes 12, 15, 16, and 18), whereas PAs are projected to be dominated by dry open boreal forests currently occurring in southern Yukon (Cliomes 8 and 10; Table 3, Fig. 9). Cliome 14 is projected to dominate at higher elevations both regionally and in PAs. By the 2090s, Cliomes 1, 8, 10, 13,

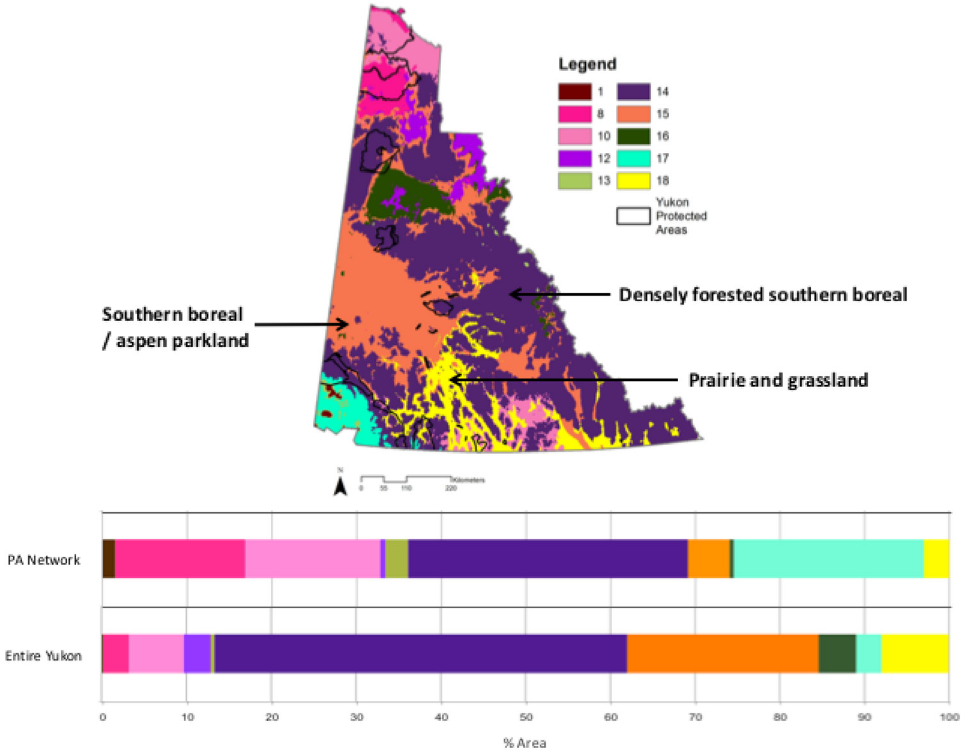

Fig. 9. A composite graphic showing a map of the distribution of cliomes in Yukon for the 2090s time period and two bar charts representing the cliome composition of the entire Yukon (bottom) and PA network only (top) for the same time period.

and 17 are almost exclusively within individual PAs (Fig. 9). Interestingly, some cliomes, such as Cliome 8, decrease in extent across the four time periods but increase in representation in the PA network as they shift northward (Table 3, Fig. 9). The individual PAs in the north (i.e., Herschel Island TP, Vuntut NP, Ivvavik NP, and Old Crow Flats SMA) become more similar to one another over time in terms of climate conditions.

Individual PAs vary in the proportion of their land base that transitions to a different climate regime between each of the periods examined (Table 4). In each time step, projections suggest that approximately half of the PAs experience less than 50% area turnover in cliome and half experience greater than 50% area turnover. However, for some (e.g., Nisutlin NWA and Nordenskjold HPA), the rate of cliome turnover is at its lowest in the initial time step. Others, such as Agay Mene TP and Lewes Marsh and Lhutsaw Wetland HPAs, experience nearly complete shifts in the initial time step (Table 4). Several PAs (e.g. Ddhaw Ghro HPA, Kluane NP and WS, and Asi Keyi and Kusawa TPs) retain some representation of cliomes from the previous time period at each time step.

All but five PAs (Herschel Island TP, Big Island HPA, Nordenskjold HPA, Kusawa TP, and Kluane NP) experience cumulative changes that represent more than 100% of their land area by the last time step, indicating multiple shifts by individual cells (Table 4). For five PAs (Pickhandle Lakes, Lewes Marsh, and Lhutsaw HPAs; Fishing Branch WP; Vuntut NP), shifts in the cliomes of 50%–100% of the management unit occur at each time step. While PAs located at the highest latitudes (e.g., 5 of 8 in the northernmost group) tend to record the greatest area exhibiting 2 and 3 cliome shifts and those in the south record the greatest area exhibiting 0 and 1 shift (Table 4), linear regression indicates no significant relationship between latitude and CSI ($t = 1.32$, $P = 0.2$, $r^2 = 0.07$).

4. Discussion

4.1. Projected changes to Yukon's cliomes and protected area network

Our analysis projects major shifts in cliomes across Yukon over the next century. Results suggest the disappearance of cliomes characteristic of arctic tundra biome at high latitudes; reductions in subalpine and alpine conditions in mountain ranges; expansion of southern Yukon boreal systems across northern Yukon, and of southern boreal cliomes across much of Boreal Cordillera; and the conversion of southern Yukon valley-bottom forests to cliomes indicative of grassland biomes in southern Canada. The biome shifts projected for the entire Yukon will, in part, be reflected in the PA network. Arctic tundra may be lost from Herschel Island TP and Vuntut NP by 2100. Projections suggest that alpine and subalpine systems could be much diminished in Kluane NP. Drier boreal forests of central and southern Yukon may replace cold northern boreal forests

Table 4
Proportion (%) of the area of each Protected Area (PA) in Yukon experiencing a cliome shift quantified for the three time steps: baseline to 2030s, 2030s to 2060s, and 2060s to 2090s. The final "total" column represents the cumulative change. In many cases, the total is >100%, which indicates that some pixels had >1 cliome shifts. PAs are sorted roughly south to north, as in Fig. 1. Acronyms: NP = National Park; TP = Territorial Park; WP = Wilderness Preserve; ER = Ecological Reserve; NWA = National Wildlife Area; HPA = Habitat Protection Area; SMA = Special Management Areas; WS = Wildlife Sanctuaries.

Protected area	Area (km^2)	Cliome Shifts (% area per period)				Total # Cliome Shifts (% area)			
		Baseline-2030s	2030s–2060s	2060s–2090s	*Total*	0	1	2	3
Kluane NP	22 243	26	33	34	*93*	30	55	15	0
Kluane WS	3 492	44	41	20	*105*	27	53	20	0
Asi Keyi TP	2 974	58	40	18	*116*	0	10	76	14
Kusawa TP	3 061	27	15	19	*61*	55	38	7	0
Pickhandle Lakes HPA	56	57	86	71	*214*	0	33	67	0
Coal River Spring ER	14	100	0	75	*175*	0	25	75	0
Agay Mene TP	703	94	15	55	*164*	13	32	55	0
Lewes Marsh HPA	22	100	50	50	*200*	0	0	100	0
Nisutlin NWA	52	0	100	44	*144*	0	73	27	0
Tagish River HPA	7	100	100	0	*200*	0	0	100	0
Horseshoe Slough HPA	87	29	100	5	*134*	0	52	48	0
Ddhaw Ghro HPA	161	63	76	48	*187*	0	38	55	7
Big Island HPA	6	0	100	0	*100*	0	0	100	0
Lhutsaw HPA	32	100	86	71	*257*	0	24	63	13
Devils Elbow HPA	70	6	100	0	*106*	0	100	0	0
Ta Tla Mun SMA	36	12	62	37	*111*	0	100	0	0
Nordenskjold HPA	90	0	100	10	*110*	0	90	10	0
Tombstone TP	2 004	10	46	77	*133*	0	76	14	9
Fishing Branch HPA	977	83	46	88	*217*	0	13	72	15
Fishing Branch WP	5 346	59	56	78	*193*	0	35	61	4
Fishing Branch ER	174	95	7	100	*202*	0	84	16	0
Vuntut NP	4 333	58	92	67	*217*	0	9	92	1
Herschel Is TP	117	0	0	100	*100*	0	100	0	0
Old Crow SMA	12 085	41	94	78	*213*	0	5	92	2
Ivvavik NP	9 702	68	41	100	*209*	0	8	54	38

of Old Crow Flats SMA, Ivvavik NP, and Fishing Branch WP, ER and HPA. And, the central and southern Yukon boreal systems of Lhutsaw Wetland HPA, and Kusawa and Agay Mene TPs may be occupied by climates conditions that support parkland, grassland, and southern boreal forest biomes.

Three of the four potential shifts in climate conditions are quite compelling because genuine biome shifts may be the outcome. Conversions of boreal forest to grassland, arctic tundra to shrubland and forest, and alpine areas to forest represent major shifts in vegetation composition and structure, which will likely drive shifts in animal distributions. For example, arctic tundra now supports barren-ground caribou (*Rangifer tarandus*), nesting shorebirds, and resident lemmings (*Dicrostonyx* and *Lemmus* spp) (Burn, 2012). These could largely disappear and ultimately be replaced by moose (*Alces alces*), snowshoe hare (*Lepus americanus*), northern red-backed vole (*Myodes rutilus*), and boreal songbirds. Such shifts are already underway as evidenced by the rapid expansion of erect willow shrubs (Myers-Smith et al., 2011) and expanding ranges of some boreal butterflies (Leung and Reid, 2013) on Herschel Island TP.

Tree line expansion into the alpine and densification of open forest stands is also occurring in southwest Yukon (Danby and Hik, 2007). Such colonization has a strong stochastic component and tends to lag behind changing climate conditions. Elevational shifts in forests may also be limited by absence of soils, by cryosols, or by generally poor soil development, all of which are prominent factors in various Yukon landscapes (Smith, 2004).

The gradual press of climate change may be enough to trigger the shift from boreal forest to grassland in southern Yukon (Smith et al., 2009). Because evaporation rates are primarily energy limited at northern latitudes, warming temperatures can overwhelm moisture increases and also lead to increased drought stress in some parts of the landscape (Cook et al., 2014). Thus, areas of central and southern Yukon now occupied by mixed-coniferous forest and grasslands (Cliome 8) may become better suited to structurally similar but drought-tolerant southern boreal–aspen parkland vegetation (Cliome 15) or the prairie-type grasslands of Cliome 18.

Many cliome shifts projected for the end of the 21st century involve conversions among boreal forest types, and at least one field study confirms a projected transition (Conway and Danby, 2014). Lower elevations in southwest Yukon are projected to shift between baseline and 2030s from a dominance of Cliome 8 (dry boreal wooded grasslands) to Cliomes 9 (mixed boreal forest) and 10 (boreal forest with coastal influence). Conway and Danby (2014) have found encroachment of aspen stands into grasslands in this region (near Kluane and Ashihik Lakes) correlated with warmer springs, which are also a feature of the projected cliome shifts.

Shifts among boreal forest cliomes might be interpreted as being less significant ecologically than the projected biome shifts. However, changes in boreal forest structure may be more important to some species than changes in composition. Boreal songbirds, for example, have specific fine-scale habitat requirements that may have higher availability, altered distribution, or become absent entirely in forests with comparable composition but altered structure (Stralberg et al., 2015).

When shifts in tree species composition are involved, pulse-type disturbances (e.g., fire, floods, insect outbreaks) may be required to overcome inertia and competition (Jackson et al., 2009; Johnstone et al., 2010). But, new disturbance agents, like the mountain pine beetle (*Dendroctonus ponderosae*), recently epidemic in central British Columbia, are moving north and threaten to invade Yukon (YFMB, 2013). Coupled with lengthened growing season and increased annual precipitation, disturbances like these may enable expansion of denser, southern boreal forests characterized by Cliome 14, or other shifts in dominant tree species. Other geographic shifts in trees may primarily depend on more stochastic dispersal and germination opportunities. For example, lodgepole pine (*Pinus contorta*) expansion is already lagging behind the Holocene climate warming in its colonization of boreal Yukon (Johnstone and Chapin, 2003; McKenna et al., 2004).

Existing abiotic and ecological conditions associated with cliome units (i.e., adaptive capacity), and the rates and magnitude of climate change within those units (i.e., exposure), can assist in determining their vulnerability and relative need for adaptation (e.g., Magness et al., 2011). Results suggest a greater number of cliome shifts in ecoregions with lower average elevation and a lower range in elevation (Table 2). Ecoregions with higher mean elevation and greater range in elevation may experience less change. PAs at higher latitudes show the most dramatic changes in cliome composition compared to large PAs and more southerly PAs in Yukon. Yukon's mountains, especially in the south, may provide climate refugia for some boreal species while experiencing less cumulative change in cliomes. These findings about the potential for mountains to serve as refugia for some species are supported by other studies (e.g., Loarie et al., 2009; Dobrowski et al., 2013), although projections from bioclimatic models for upper elevations can also show high species turnover due to the presence of steep environmental gradients over short distances (Lawler et al., 2009).

Studies of future changes of climate space and biomes or vegetation communities in North America at coarser resolutions than the cliomes show patterns consistent with the potential for major change at high latitudes. Applying a global vegetation model under 3 emissions scenarios, Gonzalez et al. (2010) found that boreal conifer forest, along with alpine and arctic tundra biomes, have among the greatest exposures to change globally. They also projected that by 2100 boreal forests would expand at the expense of tundra and alpine habitats through most of Yukon, and temperate grasslands could occur in the southern regions. Looking specifically at North America and using similar methods, Rehfeldt et al. (2012) projected the northward expansion of climates associated with prairie grasslands and montane forests, coupled with a loss of those associated with taiga and tundra habitats by the end of the 21st century. Finally, loss of tundra and taiga and gains in boreal biomes are consistent with projections focused on Canada's national park system (Scott et al., 2002).

Langdon and Lawler (2015) projected climate space at a finer resolution for the same set of vegetation communities used by Rehfeldt et al. (2012) for PAs in western North America, south of our study area. Their analysis found that the magnitude of projected climate change, biome shifts, and species turnover increased along a longitudinal gradient, from lowest along the Pacific Coast to highest in the northern Rocky Mountains and the Boreal Plains ecozone (Langdon and Lawler, 2015). The low biome turnover projected through the Pacific coastal mountains corresponds with that suggested by our study for the coastal ranges of southwest Yukon. In contrast, our study found a tendency for higher turnover with latitude. These differences may partly be explained by patterns of precipitation (highest along the Pacific coast and decreasing to the east across boreal British Columbia /Alberta, but decreasing northwards across Yukon) and prevalence of continental climate regimes (highest in interior British Columbia/Alberta and northern Yukon). Projected annual increases in precipitation are higher along the Pacific Coast in boreal latitudes than in the interior continental regions of the two study areas (Wang and Kotamarthi, 2015). This might stabilize drought stress related to increasing temperature regimes, but only if the seasonality of the precipitation and temperature increases coincide.

4.2. Implications for planning and management of Yukon's protected area network

Over the next century, Yukon is projected to lose seven cliomes and gain one, to possibly experience biome shifts in some regions, and to undergo cliome transitions across its PAs that could affect 50% or more of the network's land area. This raises questions about what can be managed, feasibly and within current or, potentially, altered stewardship mandates. The adaptive capacity of the region with its predominantly intact natural vegetation may be high (Hole et al., 2011; Watson et al., 2013). Regardless, managing PAs in the face of this considerable reorganization will likely require multiple strategies (Millar et al., 2007; Hole et al., 2011; Groves et al., 2012; Lemieux et al., 2010). For existing PAs, the primary decision is whether or not to try to intervene (active vs. passive management) in the future trajectory of change in vegetation or other species' distributions. Additional decisions would need to be made regarding best options for augmenting or modifying the PA network to represent cliomes and related ecosystems, and to facilitate range shifts.

Resources will be limited for active management, and require careful choices about investments. The lowest priority will likely be the PAs projected to experience the least change in climate conditions (Langdon and Lawler, 2015). It may be prudent to consider active intervention for those showing greatest extent of near-term change (2030s), depending on the relative magnitude of shift in climate space and vegetation types (Table 1), and the uniqueness of the PA and its cliome(s) and ecological composition in the PA network, as well as in the broader ecoregional context. Risk to PAs and their conservation values could be assessed in greater detail with vulnerability analysis (Rowland et al., 2011; Magness et al., 2011; Young et al., 2015) to identify management interventions that might influence species distributions and adaptive capacity (Lemieux et al., 2011).

Active management requires an experimental approach that can help improve understanding about ecosystems' direct and indirect responses to climate, such as the factors currently limiting growth and reproduction in key species, postdisturbance regeneration constraints, and the colonization rates of different vegetation types. Options could include planting novel species or novel genotypes of extant species (e.g., canopy trees; dominant ground plants such as grasses) suited to projected future conditions. For example, although shrubs are growing more erect and expanding on arctic and alpine tundra (Myers-Smith et al., 2011), conifer tree line advance is much slower (Danby and Hik, 2007) and might be enhanced by experimental planting. Experiments could also include prescribed burning to stimulate novel successional pathways. Monitoring of key ecosystem elements or processes (e.g., vegetation condition, disturbance regime) will also be an ongoing tool for assessing the need to intervene. For example, the mountainous terrain of Ivvavik NP may provide refugia for some arctic vegetation (McLennan et al., 2012), which our results indicate may be greatly diminished by 2100.

Most PAs will be left to change at rates driven by ongoing climate shifts, disturbances, and extreme events (i.e., passive management). In what could be emerging novelty of ecological assemblages, the continuation of most ecosystem processes will require shifts in species' distributions in response to their principal limiting factors. Maintaining connectivity of the focal PAs to neighboring landscapes with suitable conditions into the future is one important approach to facilitating adaptation and providing the necessary environmental benchmarks upon which to base monitoring, research, and evaluation of appropriate adaptive management actions (Lemieux et al., 2011; Hannah et al., 2014). Our results suggest that expanding the current PA network in Yukon may be necessary to ensure aquatic and terrestrial connectivity into the future, but additional analyses would be required to demonstrate how to do this. Mapping those ecosystem conditions minimally influenced by climate (e.g., bedrock, physiography, surficial geology), also known as enduring features or geodiversity (Beier et al., 2015), can provide an important basis for connectivity planning.

Yukon, as a whole, is still relatively intact, with multiple opportunities to plan for change through designation of new PAs and corridors of connectivity (see Hole et al., 2009; Groves et al., 2012), unlike highly modified landscapes where fragmentation or degradation of suitable habitat constrains wildlife movement (Mawdsley et al., 2009). With frequent east–west trending mountain ranges, distribution shifts for some species in Yukon may be limited by topography which results in patchy suitable habitats separated by inhospitable habitat barriers. However, reserve networks can be laid out along gradients of climate and/or enduring features, thus providing 'stepping stones and corridors' of suitable abiotic and bioclimatic conditions for species to spread (Davison et al., 2012; Hannah et al., 2014; Beier et al., 2015). As well, the matrix, - the area outside reserves-, can be managed to promote functional connectivity and minimize barriers to movement (Mawdsley et al., 2009; Hunter et al., 2010). Further, if Yukon is pro-active in planning for conservation and climate change simultaneously, the overall costs of conserving biodiversity, whatever the constituent species and ecosystems may be, will presumably be lower in the long term (Hannah et al., 2007).

4.3. *Potential limitations and considerations*

Any climate modeling exercise has inherent limitations. The cliomes of the baseline period were developed from historical climatology, and assigned vegetation-based descriptions reflective of current land cover in the associated climate space. However, the current land cover and vegetation classification systems that SNAP-EWHALE (2012) used to describe the cliomes have specific limitations. Each of the three land cover maps SNAP used is robust in separating shrublands, grasslands, deciduous, and coniferous forests, but none clearly distinguishes boreal, temperate, and coastal forests. The ecozone and ecoregion mapping assisted in differentiating boreal, temperate, and coastal forests was limited to separating boreal forest into two broad regions across Yukon (Boreal vs. Taiga Cordillera).

Another important consideration in interpreting and applying our results is that cliomes are not equivalent to ecoregions or biomes. Cliomes are distinct from ecoregions in that they are based on climate parameters alone, while ecoregion categories capture landforms, climate, soils and vegetation communities (Smith et al., 2004). The cliome descriptions correspond roughly with ecoclimate regions mapped for Yukon by Strong (2013), but include a greater number of designations and finer scale classification. The glaciated areas of Kluane NP are a notable exception because clustering occurred at a relatively coarse scale, and thus did not always account for elevational detail (SNAP-EWHALE, 2012). Cliomes also may not correspond with biomes, especially when projected, because shifts in species distribution can incorporate significant and variable lag times, as well as factors not directly linked to climate. However, "results serve as indicators of potential change and/or stress to ecosystems, and can help guide stakeholders in the management of areas of greatest and lowest resilience (i.e., resistance) to changing climate". (SNAP-EWHALE, 2012).

There is uncertainty associated with the projections from climate models. In general, cliome shifts driven by warming temperature are likely robust, as there is little inter-model disagreement. There is greater variability in the inter-model projections of precipitation, although comparisons of cliome projections from all 5 models show that the broad patterns in the number and character of cliome shifts hold (SNAP-EWHALE, 2012). Our choice of the A2 emissions scenario restricts us to only one set of projected outcomes, but this scenario is a frequent choice in other studies (Lawler et al., 2009; Wiens et al., 2011; Langdon and Lawler, 2015). The interaction of temperature and precipitation to affect moisture balance and drought will likely have strong influence on future Yukon ecosystems as is occurring in boreal Alaska (Beck et al., 2011; Dobrowski et al., 2013; Cook et al., 2014).

The actual pace of change in biomes may well deviate from our projected timeline of change in climate space. Factors other than climate, some of which were noted above, will mediate biotic responses, particularly at the scale of the individual species and PAs (Hole et al., 2009; Chen et al., 2011). Future communities living in a certain climate regime will likely differ from current communities supported by the same regime and often with novel species assemblages (Williams and Jackson, 2007). Three key factors that are difficult to model but have the potential to significantly alter projected future ranges of species are interspecific interactions (e.g., competition and predator–prey relationships), natural disturbance regimes (e.g., fire and floods), and anthropogenic land use change (Lawler et al., 2009). Projected cliome distributions should be interpreted as projected climate space, which is associated with the respective land-cover designations and ecological communities in the baseline period. An emerging research focus then needs to be the identification of the particular combinations of climate, disturbance, and biotic conditions at which thresholds of biome shift can be anticipated.

The cluster analysis method that generated the cliomes started with a pre-defined and fixed number of categories derived from current climate parameters. Future climate regimes were 'forced' into the most similar category even if they were not always well captured by it. In addition, the robustness or degree of sharp division between some cliome pairs is low (Fig. 2; SNAP-EWHALE, 2012). Thus, novel climate regimes, not recognized by this analysis, may occur in Yukon in the future (Saxon et al., 2005).

Our projections suggest an overall homogenization in climate and reduction in diversity of cliomes across the region, especially toward the second half of the century. This outcome is most evident in the northern region where five dominant cliomes are converted to two. Homogenization may be a realistic circumstance biologically if climate regimes become less distinct. However, there are some potential explanations based on properties of the modeling process. First, future novel combinations of monthly temperature and precipitation may not be adequately captured by cliome clustering, which is conducted using present combinations of climate variables. Second, homogenization may be an artifact of identifying cliome clusters using 18.4-km resolution data, and then projecting them at a 2-km resolution. This may be particularly relevant for the mountainous Yukon where climate conditions, and associated biomes, can change dramatically over short distances, especially with aspect and elevation (Smith et al., 2004). Davison et al. (2012) note that the use of climate models to assess and plan PAs is limited in areas with high topographic diversity and a lack of ground-based monitoring, both of which are relevant in Yukon. Third, the cliomes projected to expand into Yukon currently are large, homogenous regions across British Columbia, Alberta, Saskatchewan, and Manitoba (SNAP-EWHALE, 2012). They are projected to shift north and northwest into Yukon until they cover almost the entire landbase by the 2090s. As currently mapped, these cliomes may also be a homogenization of their respective biomes. For example, Cliome 14 captures at least 3 different biogeoclimatic zones in British Columbia (B.C. Ministry of Forests, Lands and Natural Resources Operations, 2014) and 3 natural regions and 8 natural subregions of Alberta (Natural Regions Committee, 2006). Thus, the apparent homogenization of Yukon's boreal forest may reflect the relatively homogenous climate space mapped for central and southern Canada in the baseline period. Fourth, several cliomes dominant in the baseline period (8, 9, 11, 12) are relatively indistinct from each other (distance-between-medoids <0.1; Fig. 2). Collectively these cliomes cover ∼60% of Yukon (Table 4). In contrast, several of the dominant cliomes in the 2090s (14, 15, 16, 18) have more distinct clustering (Fig. 2), which probably makes their differences more robust. Thus, the baseline period may, in fact, be more homogenous than suggested by the SNAP-EWHALE (2012) discrete cliome mapping.

Finally, the cliomes analysis is only one approach for identifying the potential impacts of climate change and associated conservation challenges. The projected results we present here do not tell us exactly what will happen in terms of ecosystem re-distribution. Its applicability and value can be assessed and complemented by using other coarse-filter approaches based on climate (Wiens et al., 2011; Davison et al., 2012) and geophysical features (Groves et al., 2012; Beier et al., 2015), as well as fine-filter approaches focused on species (Hole et al., 2009; Beale et al., 2013). In combination, species-based and climate-based (Nuñez et al., 2013) approaches can be applied to better understand the factors influencing the shifts in distribution of key species (e.g., forest canopy trees) that are projected to occur as cliomes shift.

4.4. Conclusion

Despite the uncertainties, it is clear that rapid changes in climate are underway and expected in Yukon. Given the intimate link between ecosystem distribution and climate, we can expect major changes in ecosystems to track the climate changes but with uncertain time lags and species responses. The research and management communities can put more effort into refining projection models. However, we see an immediate need and opportunity to relate these projected changes to the composition and layout of the existing network of protected areas and to their specific management goals. In addition, we see a need to concertedly track ongoing changes with monitoring programs, with research focused on specific mechanisms of change, and with experimental management.

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