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An ecological approach to climate change-informed tree species selection for reforestation

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ABSTRACT

Accounting for climate change in reforestation practices has the potential to be one of the most efficacious adaptation strategies for maintaining future forest ecosystem services. There is a rich literature projecting spatial shifts in climatic suitability for tree species and strong scientific evidence for the necessity of assisted migration. However, there has been limited translation of this research into operational reforestation, due in part to mismatches to the information needs of practitioners. Here, we describe a practitioner-focused climate change informed tree species selection (CCISS) model to support reforestation decisions in British Columbia (BC). CCISS projects the climate change redistribution of bioclimate units from the multi-scaled Biogeoclimatic Ecosystem Classification (BEC) system with machine-learning for 90 modelled futures. It leverages the reforestation knowledge from BEC to make site-specific species projections of reforestation feasibility with climate change uncertainty metrics. We present 21st-century feasibility projections for a comprehensive set of tree species native to western North America. Some general trends are evident: augmentation of the number of feasible species in sub-boreal regions due to the rapid expansion of feasibility for temperate species; attrition at low elevations in southern BC due to declines in the feasibility of native species with little compensation by non-native species; and turnover at mid-elevations as declining feasibility for subalpine species is compensated by uphill expansion of climatic feasibility for submontane species. Edaphic (soil) factors are important; feasibility declines are higher on relatively dry sites than on wetter sites for most species. Our analysis emphasizes that changes in feasibility are species-specific, spatially variable, and influenced by edaphic site factors. By employing the multi-scaled BEC system that currently informs operational reforestation, CCISS facilitates translation of research into actionable guidance for practitioners.

1. Introduction

Reforestation of harvested and naturally disturbed land is a common requirement of forest management and is practiced over vast areas of North America's temperate and boreal forest. Given the longevity of trees and their place as the keystone species of forested biomes, reforestation decisions have important economic and ecological implications that extend over many decades. Current reforestation practices on public forest land generally follow a conservative "local-is-best" approach for selecting appropriate species (Ying and Yanchuk 2006, Havens et al. 2015). Given current and predicted climate change, locally sourced trees may lead to higher risks of plantation failure, declining tree vigor and suboptimal forest conditions (Aitken and Bemmels 2016). Reforestation decisions informed by climate change projections are recognized as one of the most efficacious climate change adaptation strategies to improve forest ecosystem resilience and economic values (Williams and Dumroese 2013).

There is increasing evidence that climate change has already begun to affect forest ecosystems. Recent climate anomalies are associated with growth rate changes (Charney et al. 2016, Pedlar and McKenney 2017, Babst et al. 2019), increased forest health effects (Woods et al. 2005, Chapin et al., 2010, Weed et al. 2013, Agne et al. 2018) and mortality (Allen et al. 2010, Daniels et al. 2011, Michaelian et al. 2011, Westfall and Ebata 2018). The migration of tree species to newly suitable climate space in the post-glacial period is well documented (Davis 2001, Aitken et al. 2008, Petit et al. 2008, Gonzales et al. 2009). Evidence of natural range adjustment by some tree species in response to a modern changing climate has been observed in North America (Mathys et al. 2018) but is

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shown to lag the climate (Zhu et al. 2012, Renwick and Rocca 2015). Well-adapted provenances and species cannot naturally migrate at pace with projected climate change (Huntley 1991, Iverson et al. 2004, Aitken et al. 2008). Consequently, many authors have recommended the assisted migration of species and populations into areas of future climate feasibility to maintain the long-term health and productivity of managed ecosystems (McLachlan et al. 2007, Chmura et al. 2011, Lazarus and McGill 2014, Koralewski et al. 2015, Aitken and Bemmels 2016).

The necessity for operational implementation of assisted migration imposes a strong demand for scientific guidance on species-specific responses to climate change. There is a long tradition of spatial projections of future tree species suitability using a variety of methods including climate envelopes (McKenney et al. 2007), ecoregion associations (Gray and Hamann 2013), statistical niche models (Ledig et al. 2012), and process-based models (Coops and Waring 2011). These projections are complemented by extensive ecophysiological knowledge (Chmura et al. 2011) as well as observations from vegetation plot chronosequences (Hember et al. 2017), cohort analysis (Mathys et al. 2018), tree ring analysis (Charney et al. 2016, Babst et al. 2019), and remote sensing (Beck et al. 2011). This literature provides multiple lines of evidence for spatial climatic suitability shifts for a growing suite of tree species. However, there has been limited translation of these findings into reforestation practice, with the exception of the assisted range expansion of western larch (*Larix occidentalis*) (Rehfeldt and Jaquish 2010). Implementation has been restricted by barriers in forest policy (Lieffers et al. 2020) and practitioner capacity (Nelson et al. 2016). However, there also are important mismatches between the literature—coarse in scale, dominated by regional climatic drivers, and policy-agnostic—and the local, site-driven, policy-constrained context in which species selection decisions are made (Williams and Dumroese 2013). These types of mismatch between research and practice are pervasive in ecology and have motivated the field of translational ecology (Enquist et al. 2017)

The gap between science and reforestation practice can be bridged with operationally oriented models of species' responses to climate change. Several features are essential to such models. First, guidance on tree species selection for reforestation must be available at the local scale while also being consistent across the entire jurisdiction over which the model is applied. Second, it must account for topo-edaphic site factors (Rajakaruna and Boyd 2018) such as soil moisture and nutrient regime that are responsible for large variations in environmental suitability within regions of suitable climate (Bertrand et al. 2012, Winder et al. 2020). Third, guidance must be available for all operationally feasible species, including deciduous species that are not traditionally planted for timber objectives. This imperative stems not just from the expectation that diverse forests are more resilient to climate change (Vyse et al. 2013, Morin et al. 2014, 2018, Grossiord 2019), but also from the potential of non-commercial species to contribute to emerging management objectives such as fire hazard mitigation (Bernier et al. 2016). Fourth, guidance must be embedded within the relevant legal, policy, and corporate contexts (Williams and Dumroese 2013). Fifth, guidance should communicate the large uncertainties in modeling near-future climates (Goberville et al. 2015) to emphasize the necessity for a risk-management rather than optimization approach to reforestation decisions. Sixth, site-specific species selection knowledge must be available for climate analogs from outside the jurisdictional boundary to reduce the potential for erroneous feasibility inferences due to novel climates (Mahony et al. 2018). Finally, the model should use an adaptive management approach with ongoing integration of scientific research, expert judgement, and operational experience (Walters and Holling 1990).

The Government of British Columbia is developing an operational climate-change informed species selection (CCISS) tool that satisfies these conditions. The CCISS tool is a web-based decision support application tailored to reforestation practitioners. CCISS builds on the long-standing foundation of forest management in British Columbia: the Biogeoclimatic Ecosystem Classification (BEC; MacKenzie and Meidinger 2018). BEC defines and maps 211 biogeoclimatic (BGC) units within British Columbia and describes, for each of the mapped BGCs, site-level ecosystem units reflecting different soil moisture and nutrient conditions (1525 site series). Over the past several decades, each of these site units has been populated with tree species suitability ratings by provincial ecologists based on native vegetation plots, experimental trials, and operational experience (Klinka and Feller 1984). To accommodate cross-border climate analogs in CCISS (Klassen and Burton 2015), the BC Government has recently developed draft biogeoclimatic classification, mapping, and tree species feasibility ratings for northwestern United States and adapted existing Natural Subregion information for Alberta. CCISS uses a bioclimatic model to project a range of future spatial distributions of biogeoclimatic units based on an ensemble of downscaled global climate models (sensu Wang et al. 2012). CCISS is designed to facilitate integration of climate change into the existing reforestation policy and practice framework in BC. In doing so, it leverages decades of accumulated site-specific ecological and silvicultural knowledge. CCISS also serves as a structured knowledge system (Haeussler 2011) for integrating the scientific literature and future operational experience into reforestation decisions.

This paper explains the CCISS model and presents provincial-scale results of the model based on the current CCISS input data. The core questions of our analysis are: (1) What are the rates, types, and uncertainties of projected bioclimatic shifts for British Columbia? (2) Which types of species are projected to decline *vs.* expand in overall feasibility? (3) Where are risks to *status-quo* species selection practices the greatest, and where are there opportunities for innovative species selection? (4) What is the role of site factors (soil moisture and nutrient regimes) in the rate and spatial pattern of these changes? Finally, (5) how important to future regeneration options are tree species from outside BC's borders? The intent of this overview is to provide to practitioners a broader context for site-specific decisions, and to researchers a benchmark for validation both in the field and across the literature on species-specific responses to climate change.

2. Methods

2.1. Input data

2.1.1. Historic and future projected climate data

All climate data for this study were accessed through ClimateBC/NA v6.22 (Wang et al. 2016) a free software program that downscales a PRISM historical climate surface (Daly et al. 2002, 2008, Pacific Climate Impacts Consortium, and PRISM Climate Group., 2014) and provides CMIP5 projections of 21st-century climates (Taylor et al. 2012). PRISM surfaces are gridded at 800-meter resolution and ClimateNA downscales these surfaces using bilinear interpolation and elevation adjustment. ClimateNA downscales CMIP5 global climate models using a simple "delta" method: for each model projection, monthly changes are converted to anomalies relative to the model's historical 1961–1990 normal climate, and these anomalies are added to the PRISM climate surface. The 1961–1990 normal period was chosen because it is a relatively data-rich period of weather station data, covers a positive and negative Pacific-Decadal Oscillation period, and occurs primarily before the period of contemporary climate change. We used ClimateBC for British Columbia because it interpolates from a higher-resolution grid (800 m) than does ClimateNA (4 km).

2.1.2. Spatial maps of the biogeoclimatic subzone/variant distribution

Biogeoclimatic classification involves delineating ecologically equivalent climatic regions, classifying site-level ecosystem variation within each of these units, and relating their environmental space by relative soil moisture and nutrient regime using site/soil features characteristic of these types (Appendix A). We used version 11 of the biogeoclimatic classification and mapping (Province of British Columbia 2018) for the Biogeoclimatic Ecosystem Classification of British

Columbia (Pojar et al. 1987, MacKenzie and Meidinger 2018), with 211 *biogeoclimatic subzone/variants* as the biogeoclimatic map units and 1525 *site series* as the site units; and the Ecological Classification of Alberta (e.g., Archibald et al. 1996), with 21 *natural subregions* (Natural Regions Committee 2006) as the biogeoclimatic map units and 167 *ecological sites* as the site units. There is no equivalent, published biogeoclimatic classification and mapping for the United States. We used a modelled approximation of biogeoclimatic units for Washington, Idaho, Montana, Oregon, northern California, and northwestern Wyoming to provide potential future climate analogues for British Columbia (MacKenzie *et al.,* in prep). There are 130 prospective biogeoclimatic subzones and 655 site-level units delineated in this draft biogeoclimatic classification for the western USA. Fig. 1 shows the distribution of biogeoclimatic zones in western North America. A full list of modelled biogeoclimatic

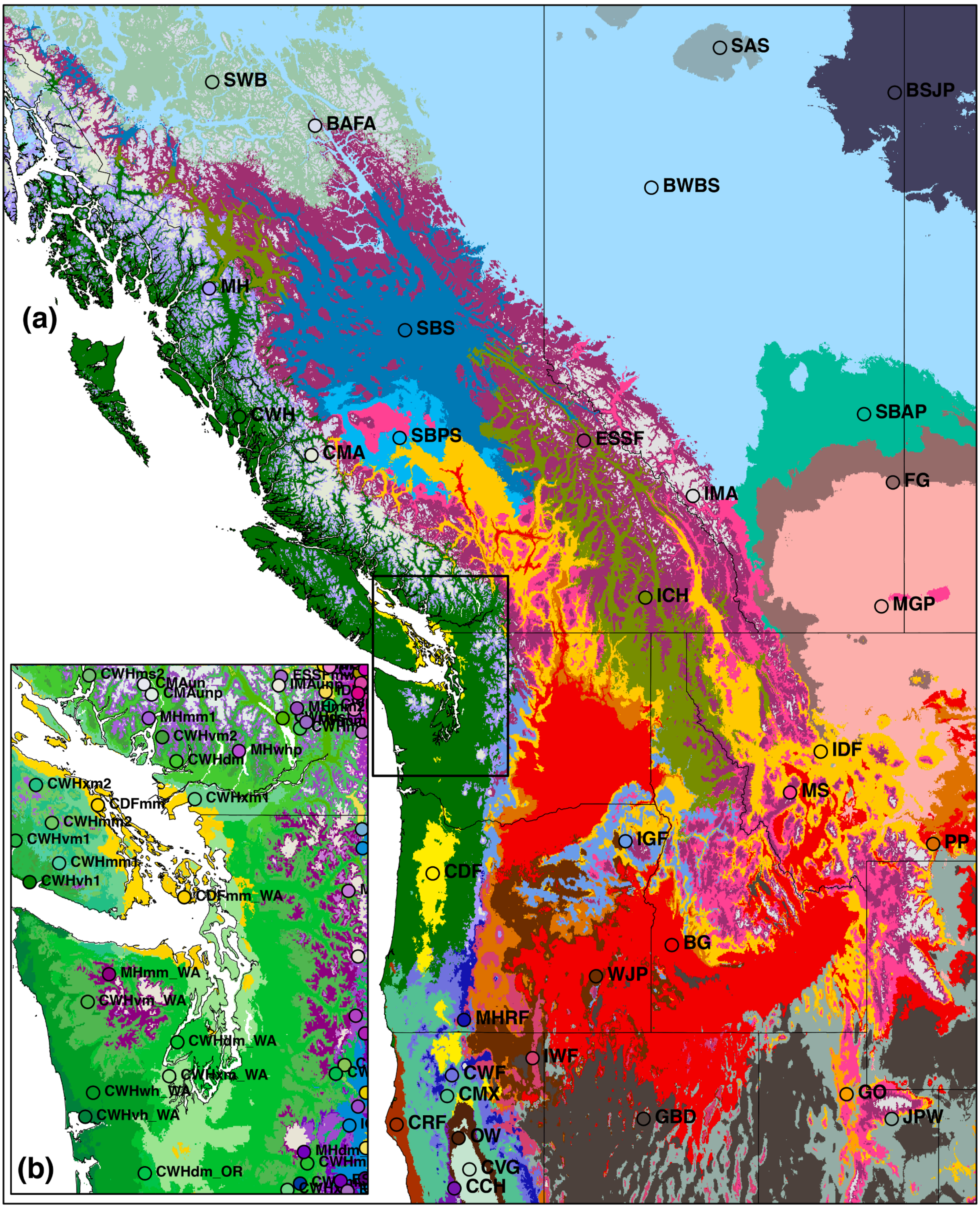

Fig. 1. Baseline biogeoclimatic zones of British Columbia and adjacent jurisdictions, inferred from 20th-century ecosystem observations. (a) Biogeoclimatic zones are the highest level of the biogeoclimatic classification. (b) Each zone comprises several subzones and subzone/variants. Zone and subzone/variant names are provided in Table 1 and Appendix B: Table B1, respectively.

subzone/variants is presented in Appendix B: Table B1.

2.1.3. Site-level equivalency

The site series in BEC describes the site-level ecological variability within each BGC unit. The environmental relationship between site series within a BGC unit is commonly displayed on an edatopic grid showing the relative soil moisture and nutrient position of site series in each BGC unit. Such relative placement allows equivalent site series concepts to be aligned between BGC units as the relative position is independent of climate; i.e. a subxeric site remains subxeric regardless of the climate regime (Appendix A: Figure A1). The CCISS decision aid uses this attribute of BEC to align site series concepts through a two-way comparison of edatopic space for the focal current site series with the edatopic space of all future predicted BGCs. Alignment of concepts is rarely exact, so a weighted overlap of edatopic space is used to adjust for the most probable match as well as less likely (but possible) equivalent site series.

2.1.4. Rating tree species environmental feasibility for reforestation

In British Columbia, the suitability of tree species to specific edaphic conditions is assessed by Klinka et al. (2000) using a three-class rating system. Similarly, government and industry foresters and ecologists have identified tree species that are ecologically suitable for each site series in the timber harvesting land base and applied a three-class suitability rating system based on crop reliability, reforestation feasibility, and timber (saw log) production (Klinka and Feller 1984, B.C. Ministry of Forests 2000). For this paper, we reassessed current tree species suitability ratings for 29 species native to British Columbia and adjacent jurisdictions to reflect only the feasibility of species for reforestation based on species prominence in natural stands, observed plantation success, and autecological characteristics (Table 2). Site-level variation in species feasibility within each biogeoclimatic unit for Alberta and the USA was similarly approximated using the plot data located in the modelled climate areas, descriptions available in publications describing forest associations or ecosites, and available autecological interpretations. We defined reforestation feasibility using five categories:

- F1 – High feasibility: species having no environmental limiting conditions for establishment and growth across the entire range of site series conditions. The species is typically widespread in natural stands. >90% survival of planted trees is observed across all site conditions in most years. Site index is average or greater compared to other species feasible for the site.
- F2 – Moderate feasibility: species occurring towards the outer range of the species environmental tolerance but occurs commonly in natural stands. High feasibility only on certain portions of site series range; or, may demonstrate relatively slow growth rates across all site conditions. Mortality rates of planted trees > 10% occurs in some portions of the sites series or during establishment years with extreme climatic conditions.
- F3 – Low feasibility: species is generally infrequent to sporadic in natural forests and has significant environmental limitations to establishment on large portions of the site series; or demonstrates markedly curtailed growth rates. >10% establishment mortality can be expected across all but the most favorable sites. Climatically extreme years may lead to very high mortality rates in establishing stands.
- F4 – Possible feasibility: species does not occur in natural forests in the site series but may be suitable for the climate and site conditions (i.e., areas within the species fundamental niche). Entries with this rating were not applied in the current models.
- F5 – Species is not feasible or only minimally feasible for the climate and site conditions.

Table 1
Names and codes of biogeoclimatic Zones referenced in this paper.

Zones within BC		Zones external to BC	
Zone	Zone Name	Zone	Zone Name
BAFA	Boreal Altai Fescue Alpine	**BSJP**	Boreal Spruce and Jack Pine
BG	Bunchgrass	**CCH**	California Chaparral
BWBS	Boreal White and Black Spruce	**CMX**	Coastal Mixed Evergreen
CDF	Coastal Douglas-fir	**CRF**	Coastal Redwood Forest
CMA	Coastal Mountain-heather Alpine	**CVG**	California Valley Grassland
CWH	Coastal Western Hemlock	**CWF**	Coastal White Fir
ESSF	Engelmann Spruce - Subalpine Fir	**FG**	Fescue Grassland
ICH	Interior Cedar - Hemlock	**GBD**	Great Basin Desert
IDF	Interior Douglas-fir	**GO**	Gambel Oak
IMA	Interior Mountain-heather Alpine	**IGF**	Interior Grand Fir
MH	Mountain Hemlock	**IWF**	Interior White Fir
MS	Montane Spruce	**JPW**	Juniper - Pine Woodland
PP	Ponderosa Pine	**MDCH**	Madrean Chaparral
SBPS	Sub-Boreal Pine - Spruce	**MGP**	Mixed-grass Prairie
SBS	Sub-Boreal Spruce	**MHRF**	Mountain Hemlock - Shasta Red Fir
SWB	Spruce - Willow - Birch	**MSSD**	Mojave - Sonoran Semi-Desert
		OW	Oak Woodland
		SAS	Sub-Arctic Spruce
		SBAP	Sub-Boreal Aspen Parkland
		SGP	Shortgrass Prairie
		WJP	Western Juniper - Pine

Table 2
Names and codes of tree species referenced in this paper.

Code	English Name	Scientific Name	Climate affinity
Acb	balsam poplar	*Populus balsamifera*	boreal
Act	black cottonwood	*Populus trichocarpa*	cool temperate
At	trembling aspen	*Populus tremuloides*	boreal
Ba	amabilis fir	*Abies amabilis*	maritime subalpine
Bg	grand fir	*Abies grandis*	cool temperate
Bl	subalpine fir	*Abies lasiocarpa*	continental subalpine
Cw	western redcedar	*Thuja plicata*	mesothermal
Dr	red alder	*Alnus rubra*	mesothermal
Ep	common paper birch	*Betula papyrifera*	boreal
Fd	Douglas-fir	*Pseudotsuga menziesii*	cool temperate
Hm	mountain hemlock	*Tsuga mertensiana*	maritime subalpine
Hw	western hemlock	*Tsuga heterophylla*	mesothermal
Lw	western larch	*Larix occidentalis*	cool temperate
Mb	bigleaf maple	*Acer macrophyllum*	mesothermal
Pa	whitebark pine	*Pinus albicaulis*	continental subalpine
Pj	jack pine	*Pinus banksiana*	boreal
Pl	lodgepole pine	*Pinus contorta*	boreal
Pw	western white pine	*Pinus monticola*	cool temperate
Py	ponderosa pine	*Pinus ponderosa*	warm temperate
Sb	black spruce	*Picea mariana*	boreal
Ss	Sitka spruce	*Picea sitchensis*	mesothermal
Sx	Interior hybrid spruce	*Picea glauca* × *engelmannii*	boreal
Yc	yellow-cedar	*Chamaecyparis nootkatensis*	maritime subalpine
Non-native Species			
Bb	balsam fir	*Abies balsamea*	boreal
Bc	white fir	*Abies concolor*	maritime subalpine
Bp	noble fir	*Abies procera*	maritime subalpine
Oc	coast redwood	*Sequoia sempervirens*	mesothermal
Ps	sugar pine	*Pinus lambertiana*	warm temperate
Yp	Port Orford-cedar	*Chamaecyparis lawsoniana*	mesothermal

2.2. Projections of future tree species feasibility

We project future tree species feasibility in four steps: (1) create a statistical climate model of biogeoclimatic units in western North America using machine-learning; (2) predict future biogeoclimatic unit redistribution within British Columbia for each of 90 modelled climate futures; (3) align site series in the current BGC with equivalent site series from projected future biogeoclimatic units for the same location based on relative edatopic position; and (4) cross-reference the site-series-specific species feasibility ratings for each of the 90 projected biogeoclimatic units in each grid cell.

2.2.1. Step 1: Biogeoclimatic model

We use a ranger implementation (Wright and Ziegler 2017) of random forests (Breiman 2001) to build a classification model of the climatic conditions that define biogeoclimatic units following the approach of Wang et al. (2012). A raw training point set is created by spatially joining a 2 km hex point grid to a western North America BGC map with 362 biogeoclimatic subzone/variants from British Columbia, Alberta, and the western USA. Because BGC units vary widely in spatial extent, this produces a highly imbalanced training set (range of 9–78722 points per BGC unit) that we resample to create a more balanced training point set with minimum sample size of 50 and a maximum of 2000. For, subzone/variants with less that 250 training points, we rescale a log10 transformation to create a sample size between 50 and 250 points and add points via a Synthetic Minority Over Sampling Technique (Chawla et al. 2002). For large BGCs with>1000 grid points, we rescale a log10 transformation of the raw count to create a sample set between 1000 and 2000 points and remove points from each oversampled BGC via conditioned Latin Hypercube Sampling (Minasny and McBratney 2006). The 1961–90 normal period was selected as the baseline climate period as it is the time period within which much of the information sources on BEC and tree feasibility were constructed. Each training point is attributed with 1961–1990 normal period data for 35 climate predictor variables from ClimateBC/NA 6.22.

The 35 predictor variables are selected by filtering the annual and seasonal variables for biological relevance and then excluding variables with both high spatial and temporal correlation (Appendix C: Table C1). Spatial correlation between variables is calculated from 1961 to 1990 normal period in a sample of grid cells across BC. Temporal correlation is calculated from projected change to the 2041–2070 normal period in the sample of grid cells across all GCMs. Variables are removed where the product of spatial and temporal correlation is > 0.8.

2.2.2. Step 2: Biogeoclimatic projections

We project recent and future geographic shifts in biogeoclimatic map unit distribution by submitting future period climate data for BC to the random forest model and predicting future BGC unit membership for each 2 km grid point in BC. We project to two recent periods —1991–2018 and 2001–2018—and three future time periods: 2011–2040 (for brevity, the “2020 s”), 2041–2070 (the “2050 s”), and 2071–2100 (the “2080 s”). We include projections for RCP4.5 and RCP8.5 global greenhouse gas emissions scenarios (van Vuuren et al. 2011) in all three future time periods. The RCP4.5 scenario roughly corresponds to the 2.7 °C (2.1–3.2 °C) global mean temperature rise by the year 2100 consistent with national commitments under the Paris Agreement, and the RCP8.5 scenario roughly corresponds to the 4.1 °C (3.1–4.8 °C) temperature rise consistent with extreme expansion of anthropogenic greenhouse gas emissions in the absence of emissions policies (Rogelj et al. 2016). We predicted the future BGC unit for each of the 15 CMIP5 climate models (Taylor et al. 2012) available in ClimateBC (Appendix D: Table D1). This range of models was chosen to represent the major clusters of CMIP5 GCMs identified by Knutti et al. (2013), and based on the validation statistics of their CMIP3 equivalents (Wang et al. 2016). Our use of 15 GCMs, 2 emissions scenarios, and 3 future time periods produced a total of 30 future biogeoclimatic map unit trajectories through a 90-year span for British Columbia. The ratio of BGC units predicted from the 30 projections in each 30-year normal period gives a metric for the uncertainty in biogeoclimatic futures.

2.2.3. Step 3: Align edaphically equivalent site units

Tree species feasibility is rated by site series in each biogeoclimatic unit. Site series commonly occupy multiple edatopic positions. For this paper, we chose a single representative site series for each of three edatopic positions from the 40 potential edatopic positions (see Appendix A): medium soil nutrient regime and mesic soil moisture regime (C4 edatope; zonal sites with medium textured soils and midslope positions), poor-subxeric (B2 edatope; moisture-shedding positions with coarse or thin soils and low water holding capacity), and rich-hygric (D6 edatope, moisture-receiving positions with active seepage and good aeration). The site series representing these three positions differ in abundance on the land base: the C4 edatope is the widespread zonal ecosystem and occupies over 50% of land base in most biogeoclimatic units; the site series representing the azonal B2 and D6 positions are common in most BGC units but typically occupying less than 10% of the land base. Where more than a single site series occupies an edatopic position, we selected the more common site series to represent that edatopic space.

2.2.4. Step 4: Cross-reference the site-series-specific species feasibility ratings

Tree species feasibility ratings are assigned to 29 tree species for each site series used in this model (Table 2). Each grid point in British Columbia has 90 projected biogeoclimatic futures (15 models × 2 RCPs × 3 time periods), and therefore 90 projected feasibility ratings per species per site series. Because many of the projected climatic futures are biogeoclimatically equivalent, and many closely related biogeoclimatic and site units may have similar species suitability ratings, the ratio of feasibility ratings for an individual species in a site series represents a species-specific measure of future uncertainty. These values are the basic working units used to calculate the metrics for feasibility change in this study.

2.3. Metrics of feasibility change

We summarize the results of the feasibility projections using several metrics: relative feasible area, feasibility persistence, feasibility expansion, and feasibility richness. To calculate these metrics, we have assigned the following fractional feasibilities to each feasibility rating: F1 = 1 (highest feasibility); F2 = 0.75; F3 = 0.5; and F4 & 5 = 0. The fractional feasibility for species j in grid cell k at time period t is $\boldsymbol{f}_{jkt}$. The 1961–1990 reference period is signified by t_o.

The *relative feasible area* of species j in time period t, $\boldsymbol{A}_{jt}$, is the sum of the projected feasibility divided by the sum of the reference feasibility across all N grid cells, k, in British Columbia:

$$\boldsymbol{A}_{jt} = \frac{\sum_k^N \boldsymbol{f}_{jkt}}{\sum_k^N \boldsymbol{f}_{jkt_0}} \tag{1}$$

Feasibility persistence across the study area for a single species, $\boldsymbol{P}_{jt}$, is the sum of projected feasibilities within the subset of n grid cells, i, that are feasible (i.e., $\boldsymbol{f}_{jkt} > 0$) for species j in time period t, divided by the sum of reference period feasibilities for species j:

$$\boldsymbol{P}_{jt} = \frac{\sum_i^n \boldsymbol{f}_{jit}}{\sum_k^N \boldsymbol{f}_{jkt_0}} \tag{2}$$

Feasibility expansion across the study area for a single species, $\boldsymbol{E}_{jt}$, is the sum of feasibilities across all grid cells with no historical feasibility for that species, divided by the sum of historical feasibilities for that species. It is calculated as above for $\boldsymbol{P}_{jt}$, using an altered definition of i and n. It also is equivalent to relative feasible area minus feasibility persistence:

$$\boldsymbol{E}_{jt} = \boldsymbol{A}_{jt} - \boldsymbol{P}_{jt} \tag{3}$$

Relative feasibility richness—analogous to species richness—within each grid cell, $\boldsymbol{R}_{kt}$, is the sum of the projected feasibilities for all m

species, j, divided by the sum of the reference period feasibilities for all species:

$$R_{kt} = \frac{\sum_j^m f_{jkt}}{\sum_j^m f_{jkt_0}} \quad (4)$$

Finally, *overall feasibility persistence* within each grid cell, P_{kt}, is similarly calculated for the set of u species, l, that were feasible in grid cell k in the reference period:

$$P_{kt} = \frac{\sum_l^u f_{lkt}}{\sum_l^u f_{jkt_0}} \quad (5)$$

Summaries of expansion, richness, and persistence in this paper exclude biogeoclimatic units that do not currently support commercially harvestable forest (Appendix B: Table B2). These exclusions are made because the intent of this study is to indicate risks and opportunities for reforestation, which in British Columbia is generally limited to harvested or productive disturbed sites. However, the calculations still include area of non-commercially harvestable forest within BGC units that do support commercially harvestable forest.

The degree of species feasibility ratings agreement between the 30 BGC predictions within each time period represents a measure of certainty in model agreement.

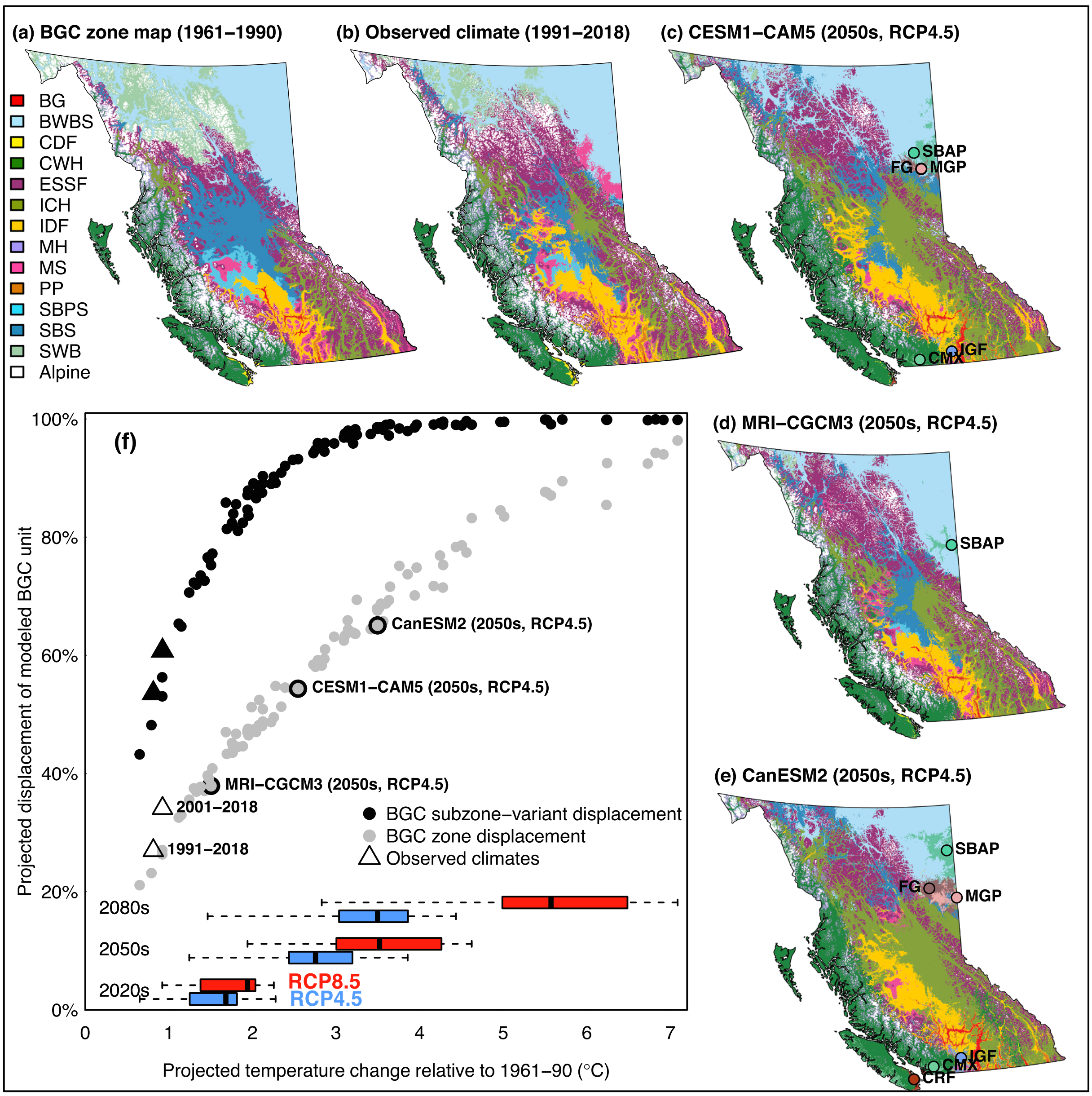

Fig. 2. Projected mid-century geographic shifts in biogeoclimatic zones within British Columbia. (a) Mapped biogeoclimatic zones, which encompass the 211 biogeoclimatic subzone/variants used to model tree species feasibility. (b) Biogeoclimatic projection of the recent period (1991–2018). (c-e) Biogeoclimatic projections of the 2041–2070 period (RCP4.5) for two GCMs with medium (CESM1-CAM5), low (MRI-CGCM3) and high (CanESM2) regional climate sensitivity. Inset labels indicate occurrence of extra-provincial BGC zones. (f) Biogeoclimatic displacement relative to the change in the BC-mean temperature change for each of 90 model projections. Biogeoclimatic displacement is the proportion of grid cells across BC that have a different projected biogeoclimatic unit than their model-predicted biogeoclimatic unit of the 1961–1990 reference period. Boxplots show the full range and 25th-75th percentile range of the temperature change projected by the 15-GCM ensemble in each RCP/time period combination. Zone names are provided in Table 1.

3. Results

3.1. Biogeoclimatic projections

Fig. 2 indicates the overall percent displacement of current BGCs under the 90 modelled climate scenarios (i.e., 15 GCMs for three time periods and two emissions scenarios) that underpin the projections of species feasibility. The RCP4.5 projection by the CESM1-CAM5 model for the 2041–2070 period (Fig. 2c) has a mean warming across BC of 1.3 °C, which is intermediate within the 15-GCM ensemble. The dominant zone-level trends for this projection include: the expansion of the Interior Douglas-fir (IDF) zone northward into the current Sub-Boreal Pine – Spruce (SBPS) zone and into higher elevations in the current Montane Spruce (MS) zone; the expansion of the Interior Cedar – Hemlock (ICH) zone northward into the current Sub-Boreal Spruce (SBS) zone and into higher elevations in the current Engelmann Spruce – Subalpine Fir (ESSF) zone; the expansion of the Coastal Western Hemlock (CWH) zone into higher elevations in the current Mountain Hemlock (MH) zone and eastward into the current SBS zone; and the near-complete displacement of the current Spruce – Willow – Birch (SWB) zone by the ESSF zone. These biogeoclimatic shifts correspond to a 61% and 88% displacement of the historical (1961–1990) biogeoclimatic zones and subzone variants, respectively, by the 2011–2040 period (Fig. 2f). The character of these shifts is generally matched by the other models in the ensemble, though at varying rates (Appendix D: Figure D1), for example the least-warming MRI-CGCM3 (Fig. 2d) and most-warming CanESM2 (Fig. 2e) models. Inter-model differences in precipitation changes are reflected in the biogeoclimatic projections, such as in the expansion of ICH into the central interior in the wetter CanESM2 model instead of IDF climates in the drier CESM1-CAM5 model. However, the tight relationship between warming and climatic displacement (Fig. 2f) suggests that inter-model differences are primarily driven by the amount and regional pattern of warming.

The biogeoclimatic projections for the 2011–2040 period include the incursion of exotic biogeoclimatic zones into the province; e.g., the Sub-Boreal Aspen Parkland (SBAP) zone from Southeastern Alberta and the Interior Grand Fir (IGF) zone from Northwestern Oregon. In addition to these exotic biogeoclimatic zones, the projected future climates of BC also include exotic subzone/variants of familiar zones (Appendix E: Figure E2). The largest area of projected exotic subzone/variants is in the boreal northeast of the province, where Albertan subzone/variants of the Boreal White and Black Spruce (BWBS) zone dominate. In later periods (2050 s and 2080 s), exotic units are also projected in the major valley systems of southern BC and on the south coast (Appendix E: Figure E3)

Regional warming and biogeoclimatic displacement for recent observed climates (1991–2018 and 2001–2018) are already within the range of modeling uncertainty for the 2011–2040 period (Fig. 2f), suggesting that the lower end of the ensemble uncertainty for the near future is underestimated. The dominant trends of the biogeoclimatic projections for the recent period (Fig. 2b) are generally similar to those of the ensemble projections, namely the northward expansion of the IDF and southern ICH subzones and the displacement of the SWB zone by the ESSF. However, there are some trends that are unique to the observed climates, such as the expansion of Alberta variants of the MS zone into Northwestern British Columbia. These unique trends reflect aspects of observed climate change that are not represented in the 15-GCM ensemble (Appendix D: Figures D1, D2), such as observations throughout Northern BC of strong winter warming coupled with weak summer warming (Appendix D: Figure D3).

3.2. Species-specific feasibility projections

Fig. 3 summarizes near-future RCP4.5 feasibility projections *on medium-mesic (C4) sites* for three major commercial tree species representing boreal, cool temperate, and mesothermal (rainforest) climates: lodgepole pine (*Pinus contorta* – Pl), Douglas-fir (*Pseudotsuga menziesii* – Fd), and western redcedar (*Thuja plicata* – Cw), respectively. Lodgepole pine is currently the predominant reforestation species in the interior of BC. It has high environmental feasibility (F1) throughout the central interior, the Thompson-Okanagan plateau of southern BC, and the boreal plain of northeastern BC (Fig. 3a). It has moderate feasibility (F2) at lower to middle elevations throughout the remainder of interior BC and on the hypermaritime portions of coastal BC. Fig. 3b shows the proportion of the 15-GCM ensemble that projects binary loss or gain of lodgepole pine as a reforestation option. The ensemble projections for the 2041–2070 period under RCP4.5 indicate both contraction and expansion of the areas where lodgepole pine is feasible for reforestation (Fig. 3b). A majority of GCM projections indicate expansion into higher altitudes for the feasible reforestation range of lodgepole pine into montane zones of the Columbia, Omineca, and Skeena Mountains and the leeward slopes of the Coast Range (see Fig. 1 for place names). These gains are balanced by the loss of this species as a reforestation option in the Peace River region of northeastern BC, the outer coast, portions of the Bulkley-Skeena, Cariboo-Chilcotin and Thompson-Okanagan plateau regions, and several other low-elevation areas. Despite these losses, lodgepole pine persists as a reforestation option in much of its historically feasible range, but with changes in site series/feasibility relationships. Fig. 3c provides further nuance by showing the mean change in the feasibility rating of this species across the 15 projections in the ensemble. Lodgepole pine is demoted to moderate feasibility in the eastern Omineca lowlands. Elevational gains are generally only by one rank (i.e., from unfeasible to low feasibility). The strongest gains in feasibility rating are in the SWB zone, and the biggest losses are in the IDF zone (Fig. 3d). Many of these trends are substantially underway in projections for the 2011–2040 period (Appendix F: Figure F1 a-d).

In contrast to lodgepole pine, for which projected gains in feasibility are generally balanced by losses, Douglas-fir is projected to have a large northward and elevational expansion of its feasible range, with losses limited to small areas in the valley bottoms of the Okanagan and Kootenay-Boundary regions of southern BC (Fig. 3f). Western redcedar is also projected to undergo a major expansion of its feasible range, both to higher elevations and into the central and southern-interior British Columbia (Fig. 3j). Projected losses of western redcedar are limited to the valley bottoms of the West Kootenay region—which are projected to transition to hot-dry climates characteristic of the IDF, Ponderosa Pine (PP), and Bunch Grass (BG) zones—and to the south and west coasts of Vancouver island, which are projected by some models to transition to the CRF(Coastal Redwood Forest) and CMX (Coastal Mixed Evergreen) zones characteristic of coastal northern California (Fig. 2). Feasibility projections for other ecologically and commercially important tree species are provided in Appendix F: Figures F2 through F5.

3.3. Site-specific feasibility projections

We choose the example of interior spruce (*Picea glauca* × *engelmannii* – Sx) to demonstrate how site and soil factors have an important role in projected changes of tree species feasibility (Fig. 4). The near-future RCP4.5 feasibility projections for interior spruce differ substantially between the three featured site types—the B2, C4, and D6 edatopes representing nutrient-poor/moisture-subxeric, medium/mesic, and rich/hygric soils, respectively. Interior spruce is projected to lose much of its historically marginal feasibility on relatively dry (B2) sites, balanced by gains of low feasibility in upslope and northern areas (Fig. 4a-d). In contrast, feasibility of interior spruce is projected to persist across much of its historically feasible range on relatively moist (D6) sites (Fig. 4i-l). Changes in feasibility on mesic (C4) sites are intermediate: the ensemble projects a downrating of interior spruce by one feasibility rank over most of its historically feasible range in the central and southern interior, although this species generally persists as a reforestation option (Fig. 4e-h). Ponderosa pine (*Pinus ponderosa* – Py) also shows strong site specificity (Appendix F, Figure F6), with a large

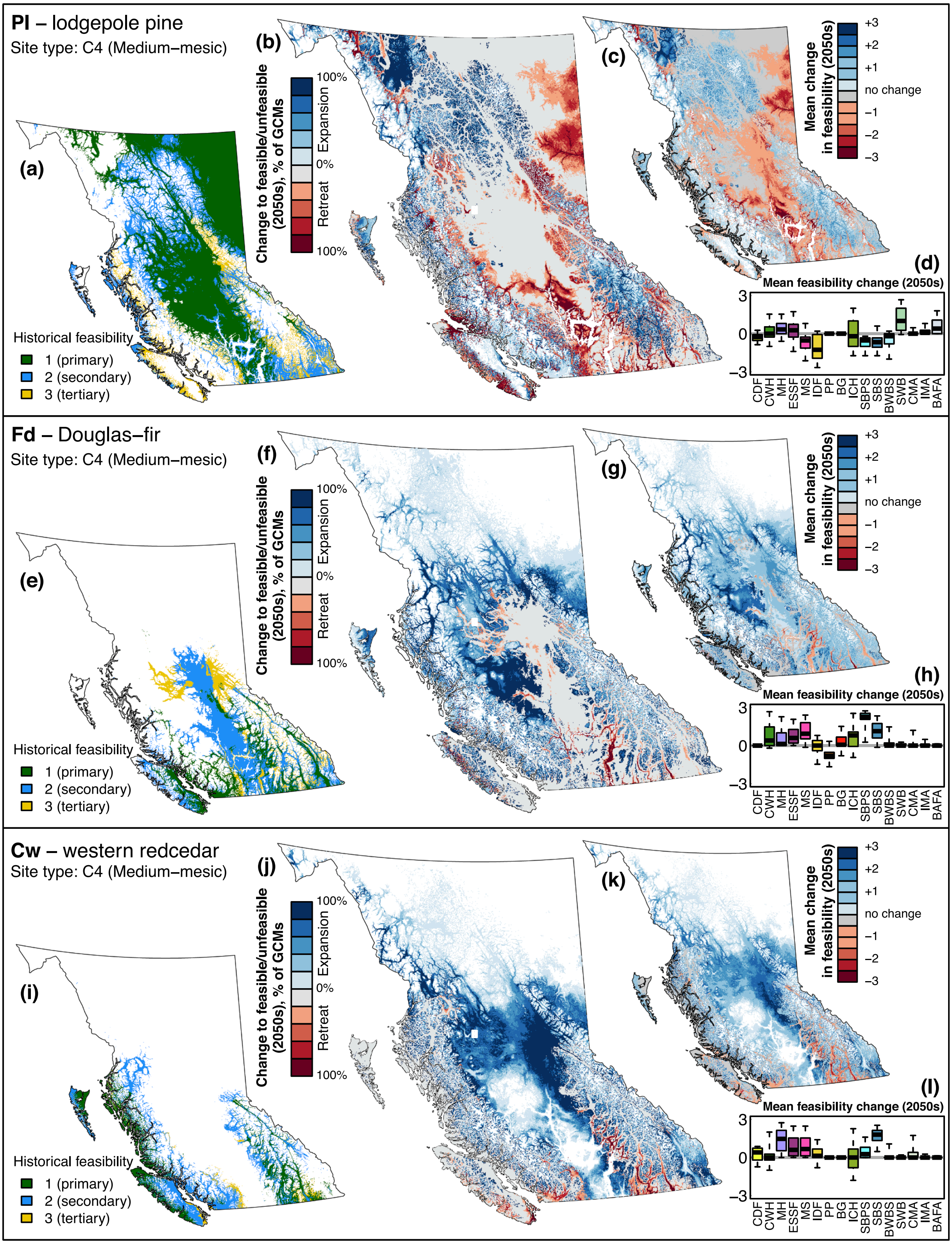

Fig. 3. Change in feasibility on medium-mesic (C4) sites for three major commercial tree species: (a-d) lodgepole pine, (e-h) Douglas-fir, and (i-l) western redcedar. (a,e,i) The historical environmental feasibility rating for each species. (b, f, j) Proportion of the 15-GCM RCP4.5 ensemble projecting the retreat (historically feasible but projected unfeasible) or expansion (historically unfeasible but projected to be feasible) of the species in the 2041–2070 period. (c, g, k) mean change in feasibility across the 15-GCM RCP4.5 ensemble by the 2041–2070 period. (d, h, l) The distribution of mean feasibility change within each biogeoclimatic zone; boxplot whiskers extend to the 5th and 95th percentiles.

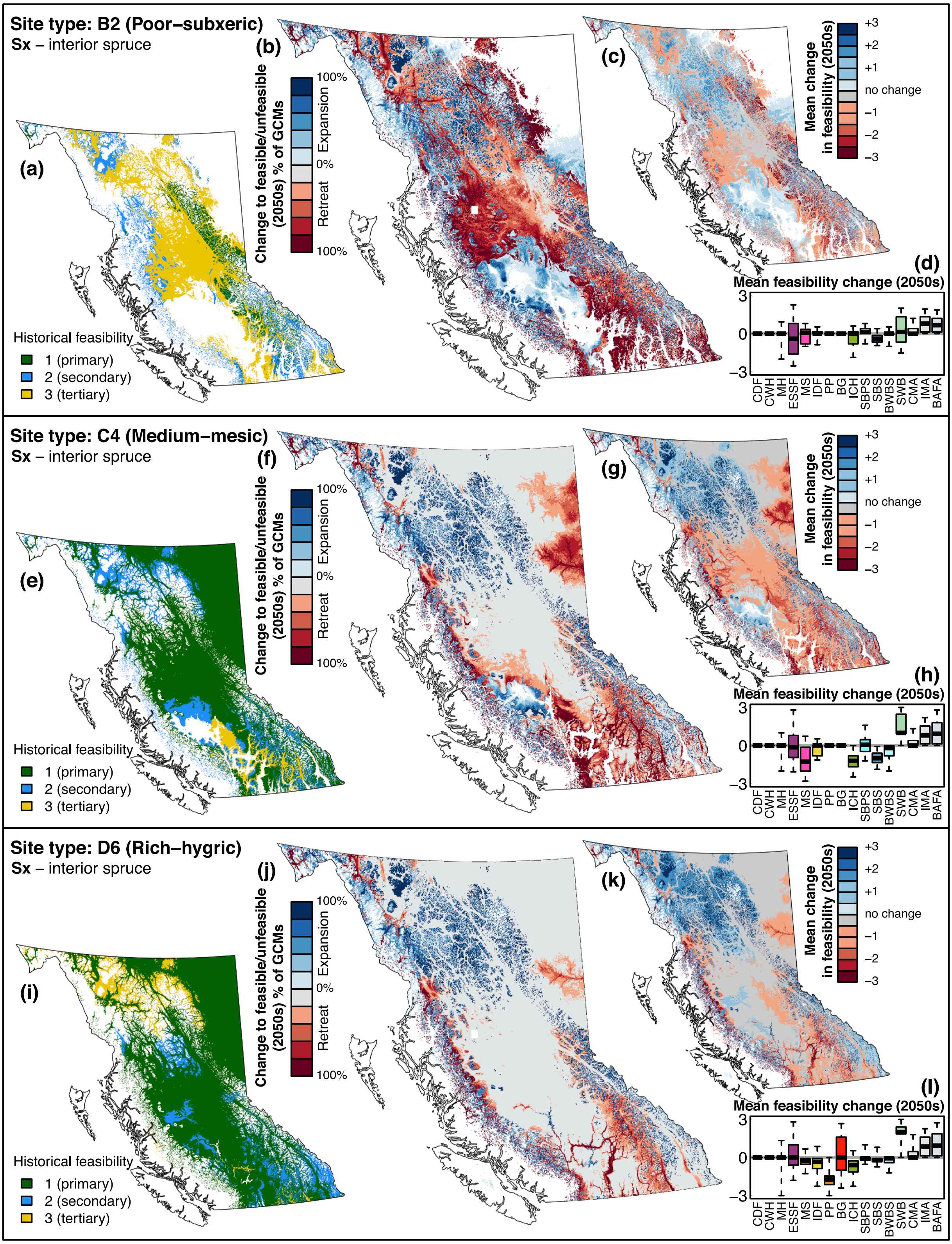

Fig. 4. Change in feasibility for interior spruce across three distinct site types: (a-d) B2 edatope (nutrient-poor, moisture-subxeric sites), (e-h) C4 edatope (nutrient-medium, moisture-mesic sites), and (i-l) D6 edatope (nutrient-rich, moisture-hygric sites). Panel descriptions are equivalent to Fig. 3.

projected expansion of climatic feasibility on relatively dry (B2) sites and minimal expansion on relatively moist (D6) sites. Site specificity of climatic feasibility is less pronounced for many other species, such as lodgepole pine (Appendix F, Figure F7) and Douglas-fir (Appendix F, Figure F8).

3.4. Trajectories of native and non-native tree species feasibility

At the provincial scale, tree species with similar climatic affinities (Table 2; Klinka et al. 2000) show similar feasibility responses to projected temperature increases (Fig. 5). Subalpine species and boreal

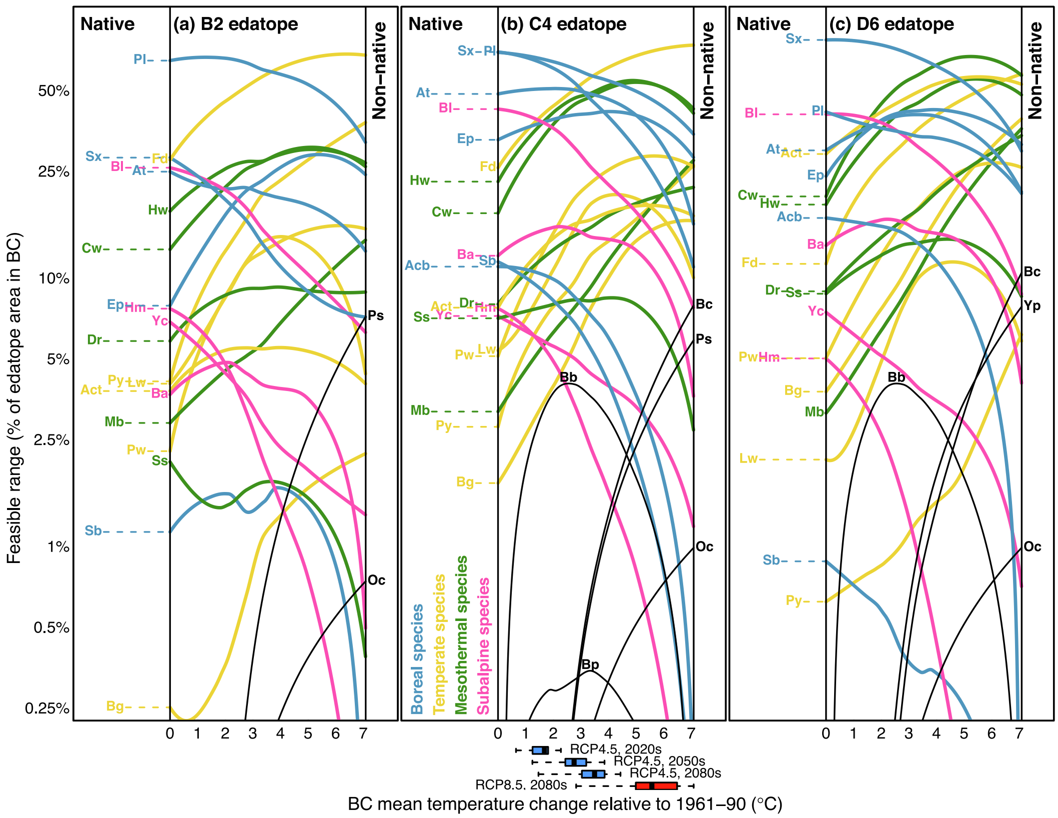

Fig. 5. Projected trends in the feasibility of native and non-native tree species relative to BC-mean MAT change. Trend lines are locally weighted regressions of 90 biogeoclimatic projections (2 RCPs × 3 time periods × 15 GCMs). Tree species names are provided in Table 2. This analysis excludes biogeoclimatic units that do not currently support commercially operable forest.

species, except for paper birch (*Betula papyrifera* – Ep), have accelerating declines of feasible area with increasing projected temperature. In contrast, cool and warm temperate species are projected to increase rapidly in feasible area with increasing temperature, though western larch (*Larix occidentalis* – Lw) declines at temperature increases of > 4 °C. Mesothermal species of the coast and interior rainforests generally increase in feasible area at moderate to high projected temperature increases (1–4 °C) and decline at the extreme temperature increases (>4°C) projected under RCP8.5. The trends of these species groups generally hold across the three site types, though their magnitudes differ.

The projected incursion of exotic bioclimates into BC during the 21st century (Appendix E: Figures E2, E3) suggests some potential for increasing climatic feasibility of non-native species from Alberta and the Pacific Northwest USA. Our analysis projects climatic feasibility for several non-native tree species (Fig. 5), ordered by the RCP4.5 ensemble-mean proportion of BC's area over which the species is feasible in the 2071–2100 period on any of the three featured edatopes: balsam fir (*Abies balsamea*), 3.5%; Port Orford-cedar (*Chamaecyparis lawsoniana*), 1.1%; white fir (*Abies concolor*), 0.8%; sugar pine (*Pinus lambertiana*), 0.7%; noble fir (*Abies procera*), 0.3%; and coast redwood (*Sequoia sempervirens*), 0.2%. At projected MAT changes of less than 4 °C, none of these species have a feasible area equivalent to the historical feasibility of minor native commercial tree species such as western white pine (*Pinus monticola* – Pw), ponderosa pine, and western larch. In other words, non-native species do not have significant feasibility in any of the RCP4.5 projections and are only a minor presence in the more extreme RCP8.5 projections for the end of the century.

3.5. *Persistence and expansion of tree species feasibility*

Changes to the total spatial area on which each species is feasible (A_{jt}) are a balance of two factors: (1) the persistence of feasibility within the historically feasible range (P_{jt}) and (2) the expansion of feasibility beyond the historically feasible range (E_{jt}) (Fig. 6). These factors are illustrated using the example of Sitka spruce (*Picea sitchensis* - Ss) in Fig. 6a-c. Feasibility persistence is an indicator of risk to *status quo* species selection: low persistence indicates a higher likelihood of adverse outcomes from planting the species in climates where it is historically feasible (Fig. 6a). Feasibility expansion is an indicator of opportunity for novel species selection (Fig. 6b). The sum of feasibility persistence and expansion is the change in the area over which the species is feasible (Fig. 6c). Plots of expansion against persistence provide a summary of the relative risks and opportunities for reforestation of BC's native commercial tree species (Fig. 6d-f). The dashed line in these plots indicates whether the total area of feasible climate is increasing or decreasing for each species. Spatial feasibility projections for all species depicted in Fig. 6d is provided in Appendix F: Figures F1 through F5.

3.6. *Persistence of the historical species feasibility profile*

The mean persistence of all historically feasible species at a location (P_{kt}; Equation (5)) is an indicator of the climatic risk to *status quo* species selection for reforestation. In general, mean feasibility persistence declines due to climatic displacement of locally adapted tree species for most BGCs (Fig. 7). The exceptions to this decline are in the SWB zone and in the higher elevations of the Purcell and Rocky Mountains where interior spruce and subalpine fir are promoted from low/moderate to high feasibility (Fig. 7a). Elsewhere, declines in feasibility persistence

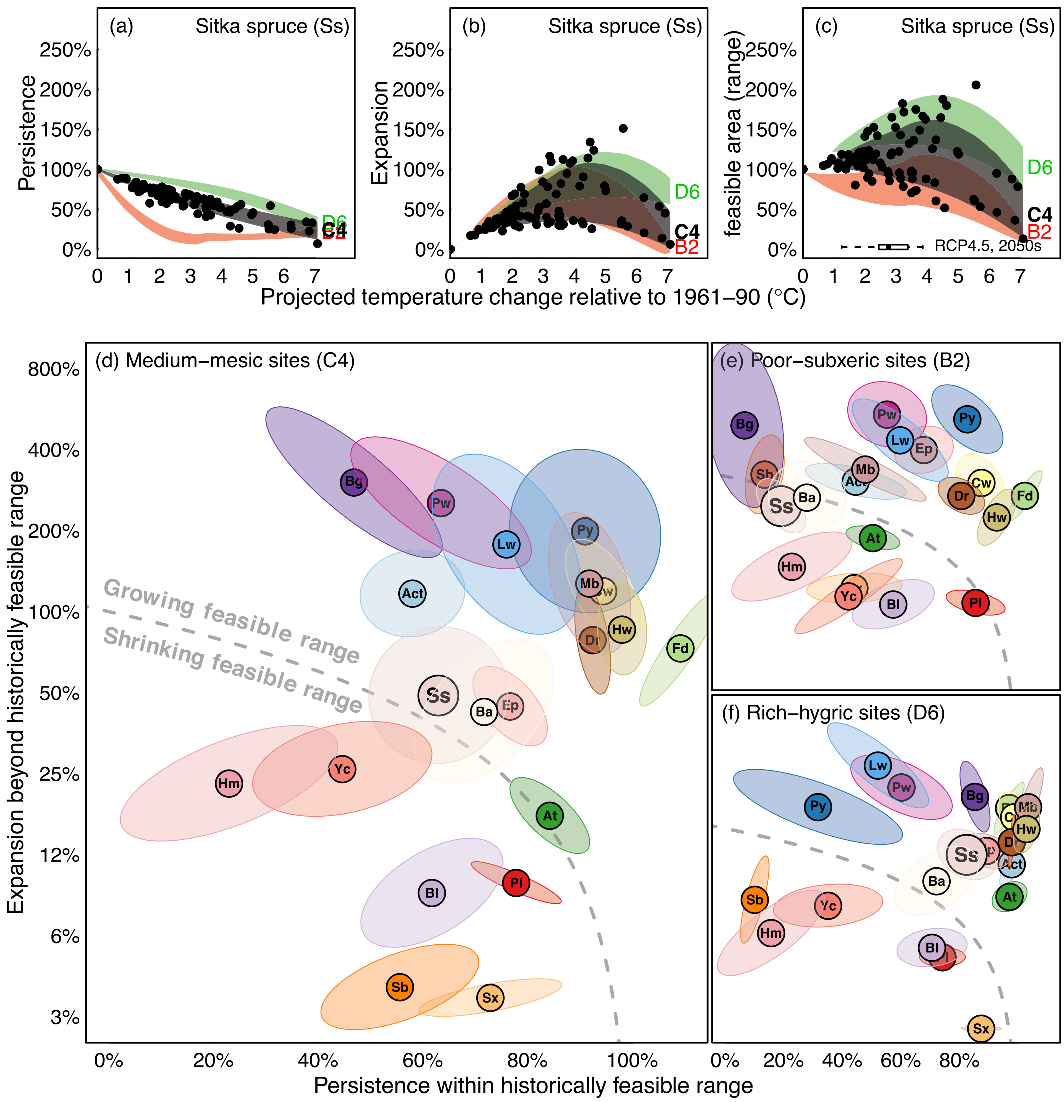

Fig. 6. Projected persistence and expansion of the feasibility of BC's native tree species relative to their historically feasible range. Panels a-c illustrate the concepts of feasibility expansion and persistence using Sitka spruce (Ss) as an example. Points for each GCM projection are shown for the C4 edatope, plus the corresponding 1-standard deviation prediction interval calculated from these points. Only the prediction interval is shown for the other edatopes. (c) The total feasible area (A_{jt}) declines with increasing temperature. This overall decline is the sum of (a) the *persistence* of feasibility within the historical species range (P_{jt}) and (b) the *expansion* of the species into new locations for which it was historically unfeasible (E_{jt}). Contributions of each grid cell to area are weighted by feasibility rating: 100% for feasibility rating of 1, 75% for a rating of 2, and 50% for a rating of 3. Panels D-F plot persistence and expansion of all of BC's major tree species for the C4, B2, and D6 edatopes, for the 2041–2071 time period under RCP4.5. Labelled points are the mean of the 15-member GCM ensemble, and shaded ellipses are the 1-standard deviation probability ellipse for the ensemble. The grey dashed line divides areas of the plot for which total feasible area is either growing or shrinking. All results exclude biogeoclimatic units that do not currently support commercially operable forest. Tree species names are provided in Table 2. Note that expansion (the y-axis) is log-scaled.

are highly uneven. The Boreal plains, Central plateau, and Chilcotin plateau have high persistence on mesic (C4) sites. The lowest feasibility persistence is projected for the Peace River Valley, the Chilcotin River, the Okanagan Valley, and the major valleys of the Kootenay-Boundary region. It is notable that reforestation is not a major activity in most of these areas of very low mean feasibility persistence. The greatest risks to current species selection practices therefore are in the areas of moderate persistence in the Thompson-Okanagan Plateau, the Cariboo, and the southern Skeena region. At the level of biogeoclimatic zones, the greatest persistence risks to operational reforestation are in the IDF zone (Fig. 7b).

At the provincial level, feasibility persistence is highly correlated with the projected change in mean annual temperature (Fig. 7c). Modeled persistence to the observed climate of the 2001–2018 period is 90%. The BC-mean feasibility persistence projected for the 2041–2070 period under RCP4.5 is 85%. Increasing projected temperatures produce a slightly accelerating decline in persistence, such that the BC-mean feasibility persistence projected for the 2071–2100 period under RCP8.5 is 59%. Nutrient-poor, relatively dry (B2) sites decline more rapidly than the other site types, particularly at lower magnitudes of warming. Fig. 7d illustrates the calculation of mean feasibility persistence for a single location (see Appendix F for explanation). Maps of mean feasibility persistence in the 2020 s and 2050 s for the three focal site types are provided in Appendix F: Figure F9.

3.7. Relative feasibility richness

Relative feasibility richness—the sum of projected feasibilities divided by the sum of historical feasibilities for all species at one location for one time period (R_{kt}; Equation (4))—is an indicator of the

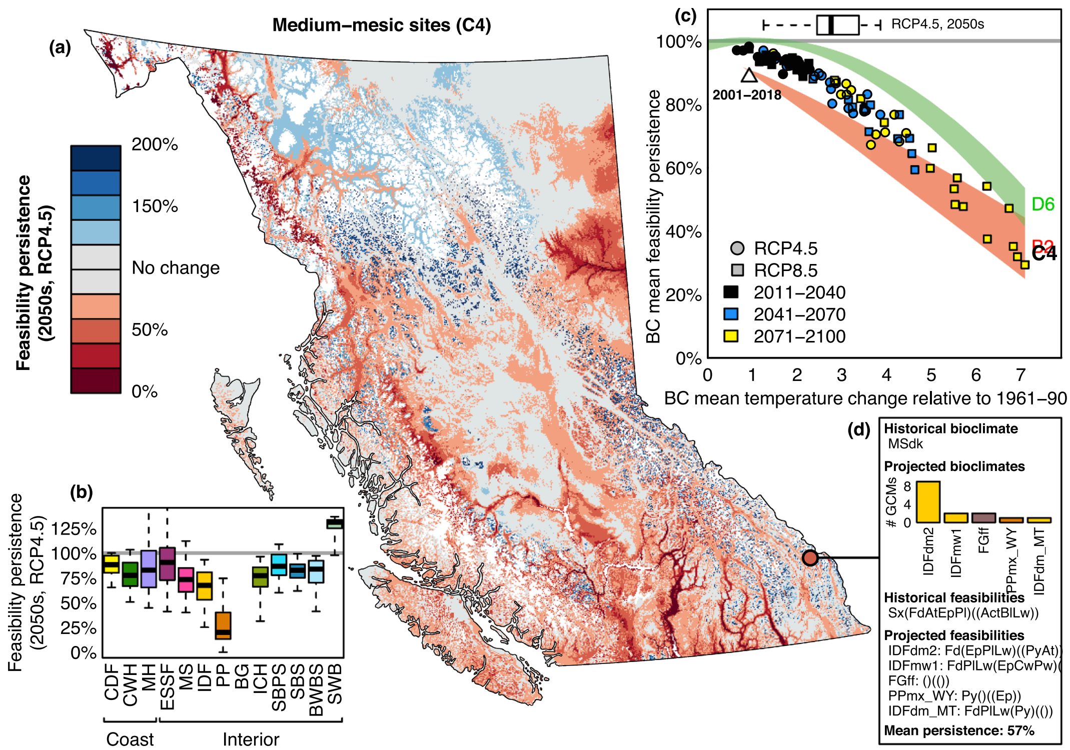

Fig. 7. Declines in the feasibility of historically feasible tree species are spatially uneven. (a) Projected mean persistence (P_{kt}) in the 2050 s (RCP4.5) of the historically feasible tree species on zonal sites (C4 edatope) at each location. (b) Mean feasibility persistence within the historical distribution of each biogeoclimatic zone. (c) The BC-mean feasibility persistence for each GCM projection in each time-period/RCP combination declines in response to the amount of warming. Points are shown for the C4 site type; shaded 1-sd polygons are shown for the B2 and D6 site types. (d) The species feasibility projections for an example location, using the convention High(Moderate)((Low)), illustrate the derivation of mean feasibility persistence. Zone and subzone/variant names are provided in Table 1 and Appendix B: Table B1, respectively.

change in species selection options available for reforestation. Relative feasibility richness is projected to increase on medium-mesic (C4) sites over most of the interior of the province by mid-century under RCP4.5 (Fig. 8a; maps for the three focal site types in the 2020 s and 2050 s are provided in Appendix F: Figure F10). This general increase is due to trends evident in Fig. 6, namely the moderate persistence of the boreal and subalpine tree species that dominate the interior plateaus (lodgepole pine (Pl), interior spruce (Sx), subalpine fir (*Abies lasiocarpa* – Bl), and trembling aspen (*Populus tremuloides* – At)) combined with the expansion of temperate and mesothermal species that were previously confined to the southern valley systems (Douglas-fir (Fd), western redcedar (Cw), ponderosa pine (Py), western larch (Lw), grand fir (*Abies grandis* – Bg), western white pine (Pw), western hemlock (*Tsuga heterophylla* – Hw)). However, each location has multiple projected bioclimates due to the model variation in the ensemble, and ensemble-mean feasibility richness can be reduced as a result of this uncertainty. This dynamic is evident in the three locations featured in Fig. 8b-d (see Appendix F for explanation). The large declines in feasibility richness in the Peace River valley and southeastern BC are due to the projection of non-forest climates at these locations. This is illustrated by the case of a location near Castlegar (Fig. 8e) with a historical ICHxw bioclimate that is predominantly projected as BGmw_WA, the grassland climate of the Columbia basin in Washington State. Although two of the 15 GCMs project forested climates at this location, this is not enough to bring the average feasibility of any one tree species to low-feasibility status, resulting in an ensemble-mean relative feasibility richness of 0%.

4. Discussion

Our results indicate distinct regional trends in the suite of climatically feasible tree species: (1) In the central interior plateaus, *augmentation* of persistent sub-boreal species by the rapidly expanding feasibility ranges of temperate species; (2) at lower elevations in the southern interior, and to a lesser extent on the coast, *attrition* due to declines in the feasibility of local species with little compensation by the addition of feasible non-local species; and (3) in montane climates, *turnover* of the suite of adapted species as declining feasibility for subalpine species is compensated by uphill expansion of climatic feasibility from submontane species. While individual climate model projections broadly indicate improving feasibility of the overall suite of adapted species in most regions, disagreement among climate models about the rate and the character of climatic changes can produce declines in overall feasibility in some scenarios. We find differential climate change effects on the spatial pattern and rate of feasibility change for many species between sites with different edaphic characteristics. In particular, the rate of overall feasibility decline on relatively dry (subxeric) sites is double the rate projected for mesic and relatively wet (hygric) sites.

4.1. Risk and opportunity in species-specific trends

On medium-mesic (C4) sites, which dominate the area of most forested bioclimates, there are clusters of species with distinct risk-opportunity profiles evident in Fig. 6d. Maritime subalpine species — mountain hemlock (*Tsuga mertensiana* – Hm) and yellow-cedar (*Chamaecyparis nootkatensis* – Yc) — are high-risk/low-opportunity species: their home-range feasibility is reduced by>50%, but they expand by less than 25% of area of their home range. The major factors in this trend are likely that these coastal species are bounded uphill by commercially inoperable forest and northward by the Alaskan border. There is substantial disagreement within the GCM ensemble about the trajectories of these species, signified by the size and orientation of their uncertainty

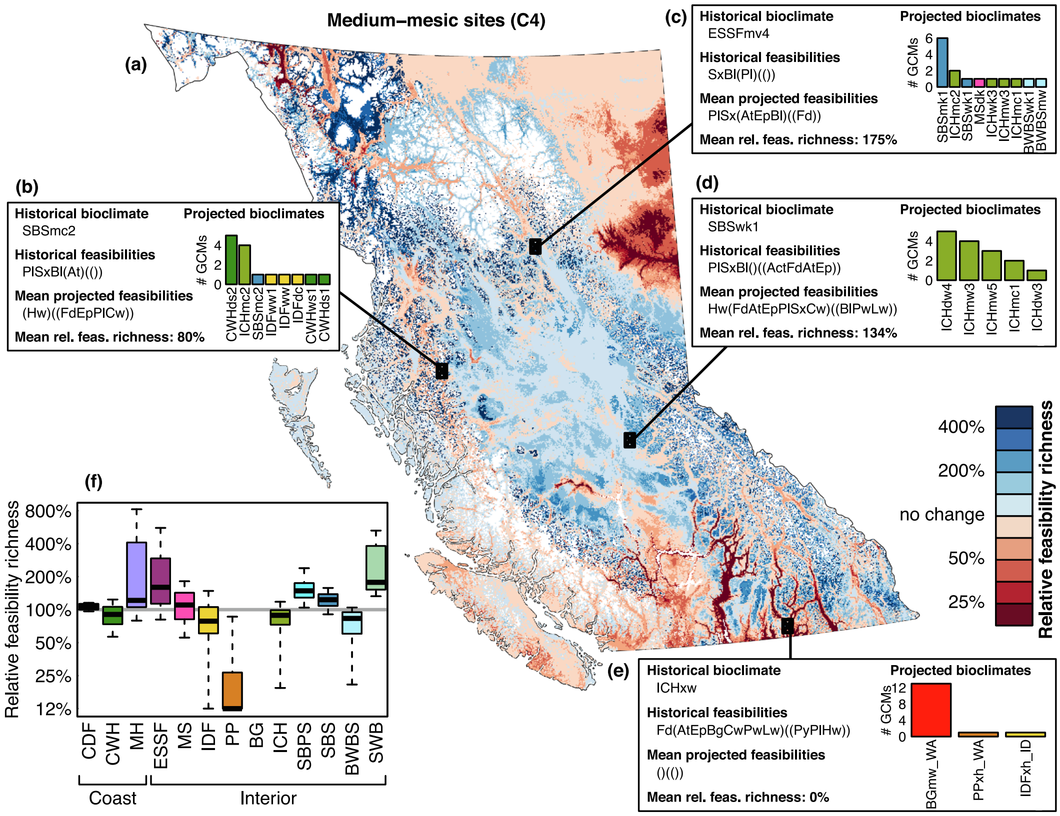

Fig. 8. Overall species feasibility is projected to increase, excepting declines at low elevations in some regions. (a) Relative feasibility richness (R_{kt}) at each location—analogous to species richness—is the sum of projected fractional feasibilities for all species divided by the sum of all historical fractional feasibilities. Values presented are the relative feasibility richness of the 15-GCM ensemble mean species feasibilities for the 2041–2070 period (RCP4.5) on zonal sites (C4 edatope). Species with ensemble mean species feasibility less than 0.375 are excluded from this calculation. (b-e) callout boxes for individual locations provide the historical and ensemble-mean projected feasibilities based on the distribution of biogeoclimatic units projected by the ensemble for that location, using the convention High(Moderate)((Low)). Ensemble-mean projected feasibilities are for illustrative purposes only: relative feasibility richness is calculated for each GCM prior to taking the mean. (f) Distributions of relative feasibility richness within historical biogeoclimatic zones. Zone and subzone/variant names are provided in Table 1 and Appendix B: Table B1, respectively.

ellipses. Interior spruce (Sx), black spruce (*Picea mariana* - Sb), lodgepole pine (Pl), and subalpine fir (Bl) are low-risk/low-opportunity species. Pl, Sx, and Bl have low expansion primarily because they are historically feasible on a majority of the productive land base of interior BC; they do not have latitudinal expansion opportunities and their uphill expansions are small in proportion to their historical area. Sb has low expansion primarily because it is a boreal species bounded by the northern border of BC, and its expansions are primarily into non-operable forest. Douglas-fir (Fd), western Hemlock (Hw), western redcedar (Cw), red alder (*Alnus rubra* – Dr), and bigleaf maple (*Acer macrophyllum* – Mb) are low-risk/moderate-opportunity species. These temperate low-elevation species can expand both uphill and northward into commercially operable forest and are at least somewhat climatically adapted to warmer and drier climates found in adjacent southern jurisdictions. Ponderosa pine (Py), western larch (Lw), western white pine (Pw), and grand fir (Bg), are moderate-risk/high-opportunity species. These species historically are restricted to the warm/dry valleys of the southern interior but are projected to be climatically feasible on the expansive plateaus of south- and central-interior BC, producing a doubling to quadrupling of their feasible area. Finally, Sitka spruce (*Picea sitchensis* – Ss), amabilis fir (*Abies amabilis* – Ba), paper birch (Ep), and trembling aspen (At) are moderate-risk/moderate-opportunity species. Feasibility for Ss and Ba is projected to contract in the southern portion of their ranges but expand northeastward into the Skeena region east of the Alaskan panhandle. Ep and At are historically feasible over large areas of interior BC. They are downrated by only one or two feasibility categories within this range and their feasible range expands geographically and to higher elevations in many areas of interior BC where they are not currently feasible.

It is important to consider historical feasibility when evaluating the opportunities and risks associated with changes in climatic feasibility. For example, there is a notable contrast between the projected losses of interior spruce on dry sites in the central interior, where it historically has low feasibility, and gains in the adjacent Chilcotin plateau to the south, where it is historically unfeasible (Fig. 4b). This contrast is due to variation in the ensemble. Majority losses in the central interior are likely associated with warmer conditions in which interior spruce is unfeasible for dry sites. The gains in the Chilcotin plateau are likely associated with the minority of models projecting substantially greater summer precipitation (Appendix D: Figure D1). This example highlights the importance of considering historical feasibility when interpreting ensemble projections of feasibility change: even though the central interior and Chilcotin plateaus have opposing feasibility trajectories, they both are high-risk regions for reforestation with interior spruce on dry sites.

4.2. Comparable research

4.2.1. Projected climate feasibility

The spatial pattern of enrichment and attrition of species climatic ranges in our bioclimate envelope model is generally corroborated by results from other research. Based on time series observations of mortality in a large suite of North American tree species, Hember et al. (2017) inferred a similar spatial pattern of changes in the rate of mortality over the 1951–2014 period; i.e. increasing tree mortality in southern British Columbia, the coast, and the northeast boreal, and neutral or declining mortality in the sub-boreal regions of the province. The attrition of the climatic feasibility for tree species in the southern interior is also apparent in projections of species distribution models for the full suite of North American tree species (McKenney et al. 2011).

Charney et al. (2016) and Babst et al. (2019) used tree ring analysis to infer that the northern sub-boreal region of BC was transitioning from a temperature-limited tree growth regime to a moisture-limited regime due to climatic warming in the 20th century. This observation is consistent with our projection of northward expansion of the climatically feasible ranges of dry- and warm-adapted temperate tree species.

Douglas-fir is featured in many comparable studies. Ecoregion projections informed by plot inventories (Gray and Hamann 2013) closely match the scale and pattern of northward expansion that we projected for this species, as well as the attrition in the southern interior valleys. 21st-century trends in Douglas-fir productivity projected with a process-based model (Coops et al. 2010) generally match the direction of the feasibility trends we projected, and also corroborate the expansion of feasible climates into northwestern British Columbia and Haida Gwaii. A genecological study (Rehfeldt et al. 2014) projected a more limited expansion into the subboreal region, with no expansion into the central coast and Haida Gwaii, and no attrition in the southern interior.

4.2.2. Projected site feasibility

While climate is a primary control describing the range of plants (Woodward and Williams 1987), topo-edaphic factors are needed to explain the distribution of species at the local level within regions of suitable climate (Rajakaruna and Boyd 2018) and to implement climate adaptation (Bolte et al. 2010). Differences in species feasibility between edaphically distinct site series is clearly documented in suitability ratings assigned by reforestation specialists in British Columbia (e.g., B.C. Ministry of Forests 2000) and our analysis at this level indicates that climate change effects on species feasibility is unequal between edaphic positions. Where topo-edaphic factors have been included in climate change modelling they generally improve model robustness (Mbogga et al. 2010, Bertrand et al. 2012, Mathys et al. 2014, Rehfeldt et al. 2014) but these studies do not provide specific feasibility metrics or site level units that allow direct comparison to our analysis. By employing a comprehensive ecological classification system which integrates climate, topo-edaphic factors and vegetation across the entire land base, our analysis projects species feasibility across a wide range of specific site conditions currently not presented in the literature.

4.3. Tree species feasibility

4.3.1. Accounting for migration lag

A “local-is-best” species selection approach is widely applied as a successful, though conservative, method of matching tree species with their appropriate normal range of environmental variability. The expert-defined list of feasible species at the basis of our study is determined largely based on this premise. However, the mature ecosystems used to define biogeoclimatic subzone/variants were established in an earlier, cooler time period. The current distribution of species (realized niche) is unlikely to represent the actual suitable range (fundamental niche) (Roberts and Hamann 2012, Park et al. 2014) due to a lag between species distributions and climate (Zhu et al. 2012, Renwick and Rocca 2015) as a result of slow migration rates (Lazarus and McGill 2014). The existence of very successful range expansion species trials established prior to 1991 (i.e. within or before the baseline normal period) provides evidence that additional suitable habitat is available for some species (LePage and McCulloch 2011). For this reason, the range of temperate species feasibility is likely already greater than the current species distribution and our bioclimate envelope model is conservative in identifying areas of future feasibility. Species-specific range modelling and reassessment of existing off-site species trials in areas outside of the historic range would help establish a proper baseline for modelling future species feasibility. In contrast, the CCISS model may not adequately account for pre-existing heat and drought stress for *in situ* stands established at warmer or drier edges of the species distribution. Research comparing the occurrence of drought mortality or growth reductions during recent climatically extreme years with CCISS predictions of declining feasibility could provide supporting evidence that the model is accurately forecasting future risks.

4.3.2. Accounting for contemporary climate change

In addition to a historical lag between climate and species distribution, there has been some shift in biogeoclimatic unit climate space since the end of the baseline normal period (1990 to 2018) from contemporary climate change, which is not reflected in BGC mapping but has corresponding effects on species feasibility (Fig. 3b). These areas of new feasibility are more likely to have establishment success in the current period and would provide important evidence for supporting the operational application of the climate-change informed species selection at the feasibility frontier (Mbogga et al. 2010). The results of CCISS analysis can act as a guide for identifying locations with higher likelihood of establishment success for range-extended species and prioritize locations for evaluation or establishment of additional field feasibility trials.

4.3.3. Species feasibility ratings

Our employment of a three-category rating system for species feasibility mirrors the rating system employed in operational reforestation but removes forest health and timber management considerations such that feasibility ratings reflect primarily environmental limitations to establishment of new plantations. The feasibility ratings assigned to species in every site series used in this model is based on regional assessments by different groups of individuals and variation in how criteria are applied are inevitable. In addition, there is more information and experience with commercially valuable conifer species in areas of active harvesting; feasibility ratings are less supported by operational experience for non-timber producing species and in areas of the province with no active forest management. A more objective assessment of environmental tolerances of species within the BEC framework through species specific site-level modelling, incorporation of other tree physiology and silvics research, and over expansive operational planting trials would help standardize and substantiate ratings.

4.4. Bioclimate envelope models

Bioclimate envelope models are widely used to identify the climatic space of species and ecosystems (Araújo and Peterson 2012) and to identify how that bioclimate space redistributes under different climate scenarios (Hamann and Wang 2006, Schneider et al. 2009, Mbogga et al. 2010, Wang et al. 2012, Roberts and Hamann 2012, Wogan and Wang 2018). Bioclimate envelope models are correlative and do not directly identify the underlying mechanisms that lead to the observed species distribution and are insufficient to predict how *in situ* species and ecosystems will respond during a period of climate transition (Guisan et al. 2006, Botkin et al. 2007). However, for guiding climate change reforestation strategies where the primary task is to match planting stock to anticipated future climate conditions, bioclimate envelope modelling approaches are well suited (Pearson and Dawson 2003, Mbogga et al. 2010, Gray and Hamann 2013). We have attempted to expand the defined climate space within our model by including climates of adjacent jurisdictions to account for future analogue climates in British Columbia. However, some novel combinations of climatic parameters which are not represented by historical climates may occur in some areas and should be considered as an additional cautionary uncertainty in application of CCISS. The biogeoclimatic subzone/variant is the ideal climate unit to employ in bioclimate envelope modelling in topographically complex terrain as the unit represents ecologically equivalent climate space and identifies the climatic thresholds of species.

Integration of the results from other research and modelling approaches can be employed to validate and inform the projections in the CCISS model.

4.5. Closing the gap between science and practice

4.5.1. An ecosystem-based operational decision-making framework

Even with a plethora of relevant literature on climate change effects on tree species, there has been limited application of the science into operational practice with few exceptions; (e.g. Rehfeldt and Jaquish 2010). Impediments to integration occur because of lack of sufficient specificity or scale, difficulty aligning findings with current guidance or accounting for policy limitations (Williams and Dumroese 2013), or simply through use of language or concepts not employed in the decision making apparatus. The urgent need to conduct research in a way that facilitates uptake in practice is a central motivator for the field of translational ecology (Schlesinger 2010), which tailors research to the needs of practitioners (Enquist et al. 2017).

This study demonstrates an approach to translational ecology that uses a practitioner knowledge system to bridge the gap between science and practice. Our adoption of the Biogeoclimatic Ecosystem Classification to supply the working units and feasibility ratings is pragmatic; the climate-site integration and hierarchical characteristics of the system are well suited to climate change forecasting. But more importantly, BEC's status as a knowledge framework for many land use decisions in British Columbia, one of which is tree species suitability, allows us to leverage decades of management experience and provide actionable results. The investment required to understand and make linkages to practitioner knowledge systems such as BEC is not trivial (Haeussler 2011). However, researchers that do so are more likely to see their science put into practice.

4.5.2. Status quo reforestation in climate change: Implications for ecosystem services

Maladaptation of species to future environmental conditions will lead to stressed forests with declining productivity, more susceptible to forest health issues. This has strong implications for future timber supply, wildlife habitat, carbon management and other ecosystem services provided by forests. Our analysis highlights that for most areas, some portion of the future adapted species list are local species. In these cases, our analysis provides information to promote or demote species in selection decision-making. For local species that become unsuitable in future climates, while there may be successful establishment of the species now, higher levels of mortality during the period of forest maturation caution against extensive continued use of the species in reforestation. In localities where the decline applies to many species or the predominant reforestation species, the continued application of *status quo* tree species selection guidance represents a high-risk strategy with increased probability of plantation failure within the period of forest maturation.

Simply removing species with declining feasibility from the suite without replacement by other new climate change adapted species would lead to declining species diversity and reduce future forest resilience. In these situations, assisted migration is an opportunity to increase diversity and fully account for changing environmental conditions with implications for future forest resilience and productivity. However, where species range is expanded several factors must be considered.

4.5.3. Some range expansion considerations

A bioclimate envelope modelling approach can only project the climate space included in the model. Our analysis includes only defined biogeoclimatic units from western North America and focusses on range extension of tree species native to this area; no long-range introductions of species are modelled. In contrast to intercontinental introductions, where tree species may express invasive behavior, limited invasive behavior is observed where species are translocated within western North America (Mueller and Hellmann 2008, Winder et al. 2011). Where ectomycorrhizal forests are widely distributed there appear to be few impediments to trees planted beyond their current range to obtain mycorrhizal colonization (Winder et al. 2020), which may assist tree species adaptation to new environments (Pickles et al. 2015).

Wildlife habitat will be impacted by climate-mediated changes to disturbance and forest health regimes and environmental stresses to *in situ* tree species and ecosystems. Maintaining healthy future forest ecosystems by selection of best adapted species in reforestation will be an important aspect of maintaining habitat quality. Many forest-dwelling species are not dependent on specific tree species but rather differentiate between conifer and deciduous dominated habitats; any reforestation decisions leading to widespread conversion of forest composition should consider implications to wildlife (Hashida et al. 2020)

4.5.4. Addressing uncertainty through diversification

Most bioclimate-based climate change studies employ a majority-vote ensemble future climate, implying a single known future, or they choose a select few models to represent the range of future climates (Mathys et al. 2017). These approaches do not properly account for the uncertainty in future climate condition, which is an important factor in reforestation investments. The variance in climate futures predicted across GCM-carbon emission scenarios explains the majority of future climate uncertainty (Goberville et al. 2015); other factors such as modelling algorithm or climate surface selection are relatively unimportant (Mbogga et al. 2010). The uncertainty in future climate trajectories and associated ecological interactions mean that optimizing species selection to a single known set of future environmental conditions is not valid. For this reason, we use a wide range of GCM futures and use model agreement on tree species feasibility to account for uncertainty in future environmental constraints. In addition to direct environmental stresses, the occurrence and severity of forest health outbreaks will also interact with changing climate and may have large species-specific impacts that can be ameliorated through stand and landscape level tree species diversification (Heineman et al. 2010, Woods et al. 2010). Reforestation activities represent long-term investments and accounting for uncertainty through the entire period of forest maturation is a prudent strategy (Radke et al. 2017).

Maintaining a diversity of tree species and provenances that will respond differently to environmental perturbations can stabilize ecosystems, preserve a range of management options (Hooper et al. 2005), and minimize risk. A species mix that finds an optimum balance of risk-minimization and long term productivity can be used to maximize the use of the entire range of suitable species at the stand and landscape scales (Vyse et al. 2013) for reforestation. The CCISS analysis identifies specific suites of species tailored to environmental conditions in current and future climates.

Our projections indicate that the effects of climate change on the environmental suitability of tree species is species-specific, spatially variable, and influenced by edaphic site factors. By employing a multi-scaled ecological classification system that currently informs operational reforestation and a broad suite of climate model scenarios, this analytic approach can identify specific areas of climate and site condition where changes in species feasibility are expected. The information allows climate change factors to be integrated into reforestation decisions and improve future forest ecosystem resilience and economic values.

CRediT authorship contribution statement

William H. MacKenzie: Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing. **Colin R. Mahony:** Formal analysis, Visualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2020.118705.

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