University of Alberta

Conservation planning for forests, tree species, and their genetic populations under climate change: a case study for western North America

by

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Abstract

Approximately 34% of the 8.4 million km² landbase of western North America is covered by forests, which provide critical habitat for the majority of the flora and fauna. About 18% (or 1.5 million km²) of this landbase is set aside as protected areas to ensure the *in situ* conservation of biodiversity, but this mandate is shared by 17 states and provinces that have a variety of conservation policies and objectives. This study provides an overview of how different jurisdictions protect forests, tree species, and their genetic populations. I also assess the vulnerability of populations, species, and the protected area systems of different jurisdictions to climate change. The analysis relies on the statistical species distribution maps generated from 250m resolution remote sensing data in conjunction with species frequency estimates from 50,000 forest inventory plots. The vulnerability of tree populations to climate change is assessed by means of a required migration distance to matching climate habitat in the future, using a multivariate climate change velocity approach. Rather than evaluating the protected area status of species as a whole, I evaluate putative genetic population within major ecological zones. The results indicate, that forests are generally well represented, with only four jurisdictions protecting less than 10% of their forested land base (OR, SK, YT, NT). Jurisdictions differ markedly in their responsibility for protecting forest genetic resources. By far the highest combination of species and ecological zones occur in BC, followed by CA, OR, WA, and AB. From a total of 54 tree species, I identified populations of Western white pine, Whitebark pine, and Limber pine as least protected *in situ*. Under climate change, the protected area status decreases most for interior and boreal tree species. In this case study, I show how conservation efforts can be prioritized across multiple jurisdictions and provide data for resource managers that pinpoint the least protected tree populations as well as their relative vulnerability to climate change.

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This study builds on data I obtained from previous work on predicitive modeling of western North American tree species distributions (Gray and Hamann 2013), and also uses velocity of climate change data from Hamann et al (2014).

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1. Introduction

On a global scale forests are known to be critically viable habitats rich in biodiversity, providing many ecosystem services while regulating local and global climate, aiding in climate change mitigation (CBD 2001). Approximately 30% of the Earth is forested (Schmitt et al. 2009) with North America containing approximately 17% of the world's most diverse forest area (FAO 2011). In North America, land-use changes, forest pests, diseases and climatic change are major threats to the forest tree species and their genetically distinct populations (Lipow et al. 2004). The forest industry is vital to western North America therefore adequate protection of forest resources at the species and population level is needed for the industry's continued success (Hamann et al. 2005). Not only is it important to conserve forests as a whole but the conservation of their genetic resources is imperative for the longevity of forest tree species under changing climate conditions. This study focuses on the forest tree species of western North America and the protected area status of their populations under current and future conditions under climate change.

1.1 Protected areas, conservation of forests & gap analysis

The International Union for Conservation of Nature (IUCN) has suggested that countries set aside at least 10% of their land into protected areas (Dudley & Parish 2006). The Convention on Biological Diversity (CBD) has set a target of 17% of the world's terrestrial ecosystems to be protected by the year 2020 (CBD 2011). A protected area is defined as "A clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (Dudley 2008).

Protected areas are recognized as an important tool for conserving biodiversity (Mansourian et al. 2009). The twentieth century was a period of rapid growth in protected areas, however, it still does not fulfill the global biodiversity commitments, leaving a large number of species and populations inadequately protected with conservation gaps occurring within the current protected area network (Dudley & Parish 2006). The Convention on Biological Diversity has called for parties to “assess the representativeness of protected areas relative to forest types” and to “establish biologically and geographically representative networks of protected areas” to deal with forest loss (Schmitt et al. 2009).

Trees are keystone species in forest ecosystems (Koskela et al. 2013) and forest protected areas are extremely valuable in conserving forest resources and providing ecosystem services, such as non-timber forest products, as well as conserving biodiversity (Mansourian et al. 2009). This study takes a coarse-filter approach combined with a fine-filter approach to conservation of native forest trees and their populations which is suggested as the most beneficial for their conservation (Tingley et al. 2014). A coarse-filter approach focuses on the conservation of representative samples of ecosystems resulting in the conservation of the majority of biodiversity, while a fine-filter approach focuses on the conservation requirements of individual species and prioritizing them, such as disjunct populations of a tree species that requires a particular environment (Tingley et al. 2014) combining both approaches as this study has done results in conservation of species and their environments.

The protected areas in this study are ranked from International Union for the Conservation of Nature protected management category Ia to VI. Protected area category Ia is referred to as a strict nature reserve and are strictly protected areas with biodiversity conservation as its main goal. Category Ib is referred to as a wilderness area and is generally large and unmodified, managed to preserve its natural condition. Category II is a national park and is set aside to protect natural biodiversity while also promoting education and recreation. Category III is an area set aside to conserve a national monument or feature, these areas are generally quite small and visitors are encouraged. Category IV is called a habitat/species management area with the priority obviously being protecting and/or restoring particular species and habitats, these areas will often have active management. A protected landscape/seascape is considered category V, these areas are the result of human intervention with the environment, often are actively managed with management interventions and are sometimes uses as buffers around higher category protected areas or as corridors between protected areas. The least strict of these is category VI which is a protected area with sustainable use of natural resources, these areas are generally large with only a portion of it under natural resource management (IUCN 2014a).

Gap analysis is a widely used tool for conservation assessment and planning (Lefèvre et al. 2013). A gap analysis was performed in this study, it is a well-developed conservation method which identifies areas where species or populations are adequately represented as well as identifies those species or populations that require additional protection in the existing *in situ* protected area network (Maxted et al. 2008). *In situ* conservation is generally the preferred approach for maintaining genetic diversity among forest tree species (Koskela et al. 2013). A protected area network should contain sufficient coverage of species' populations to maintain genetic diversity (Lefèvre et al. 2013).

1.2 Impact of climate change on species and populations

Climate change is recognized as one of the largest challenges to forest conservation (Bodegom et al. 2009). Climate change is expected to alter the species composition of protected areas, which will have major effects on conservation decisions (Hannah et al. 2005). As the climate changes, the amount of suitable habitat under protection will also change, depending on the changes in the species' range and whether or not they remain inside protected areas (Hannah et al. 2005)

The Intergovernmental Panel on Climate Change (IPCC) has concluded that forests are extremely sensitive to climate change, with the largest impacts of climate change expected to occur earliest in the boreal forest (Easterling et al. 2007). It is becoming evident that effective conservation strategies are needed for protected areas to mitigate the effects of climate change on biodiversity (Araújo et al. 2011). Climate change and forests are dependent upon each other. Climate change is a threat to forests in terms of loss of habitat and slow adaptation, while protecting forests from conversion and degradation helps moderate the effects of climate change (Bodegom et al. 2009). Protected areas are important to forest conservation, providing a refuge to allow for adaptation to changes in climate. Under future climate change scenarios much of the current protected area network is expected to be unable to fulfill their role of protecting habitat for species that require conservation (Mansourian et al. 2009).

Species and their populations respond differently to changes in environments. However, based on past observations the typical response of species' to climate change on a large scale has been to shift their geographical range to match new climate conditions and track suitable habitat (Hole et al. 2011). In western North America there is an expectation of general northward and increased elevational shift in forest tree species' ranges (Gray & Hamann 2013). Past rates of migration are believed to be insufficient to maintain species and populations in the face of impending climate change (Gray & Hamann 2013; Noss 2001). If species are unable to track suitable habitat they are likely to grow more slowly, become more vulnerable to pests and diseases, fail to reproduce, ultimately leading to extirpation of local populations affecting all levels of the forest ecosystem (Corlett & Westcott 2013).

Conservation strategies generally focus on protecting rare species that are thought to be at the greatest risk, more recently it has been acknowledged that it is imperative to conserve common species as well, as they are essential to the structure of most ecosystems (Gaston & Fuller 2008). Diverse gene pools should be maintained within populations of forest tree species (Noss 2001). The loss of genetic diversity within a species may compromise the potential of a population to adapt to new and changing environmental conditions (Hamann et al. 2004). Species and their populations require the opportunity to adapt, acclimatize and migrate to suitable sites in order to minimize the possibility of extinction or loss of genetic diversity of forests under climate change conditions (Noss 2001). It has been suggested that developing networks of protected areas and corridors for migration between protected areas will help conserve species as they shift in response to climate change (Mansourian et al. 2009). To improve conservation planning for native forest tree species and populations of western North America it is important to address climate change as a factor in their potential future location, determining if these species and populations will be adequately protected.

1.3 Velocity of climate change

Since the beginning of the 20th century, the global mean annual temperature has risen by approximately 0.8°C which has been accompanied by other changes such as rising sea levels, seasonal changes and extreme temperatures (Diffenbaugh & Field 2013). Ecosystems and species have already experienced substantial changes in climate over the past century and the rate at which climate change is expected to continue will challenge the ability of species to survive (Diffenbaugh & Field 2013). The ability of species to survive and thrive under current climate change has been a matter of debate (Dobrowski et al. 2013).

The capacity for plants to adapt themselves to changes in climate has not been well documented (Corlett & Westcott 2013). Plant populations migrate when they are able to establish themselves beyond their current range by dispersal of seeds and pollen flow, therefore, species that are unable to migrate to suitable climate conditions are likely to become extinct. Tree provenance trials have shown that the ability to adapt to climatic change varies among species as well as among the locally adapted populations of those species, it is more probable that they will migrate rather than adapt in response to climatic changes (Aitken et al. 2008; Corlett & Westcott 2013).

It is important to consider the rate at which climate change is occurring when evaluating how vulnerable species and their populations will be to the impacts of climate change (Dobrowski et al. 2013). The velocity of climate change is defined as the velocity or rate at which an organism must move to maintain constant suitable climatic conditions, and is in turn a measure of the climate change exposure of a species (Corlett & Westcott 2013). A method to calculate velocity of climate change was first developed by Loarie et al. (2009), in a study that focused on the rate at which species would have to move to maintain suitable habitat based on climatic change in the form of mean annual temperature (°C) and total annual precipitation (mm) and using an average of 16 General Circulation Models for each emissions scenarios to predict future climate conditions. The velocity of climate change is calculated by dividing the rate of climate change through time (°C per year) by the spatial gradient in climate at that location (°C per kilometer), resulting in an estimate of climate displacement describing the direction and velocity that a species would need to migrate to maintain suitable habitat (Dobrowski et al. 2013).

Topography is an important factor to consider when determining the velocity of these climate changes, there is a strong correlation between topographic slope and velocity of temperature change. Relatively low velocities are required to maintain suitable habitat in mountainous regions, provided that the climate does not disappear altogether, referred to as a climate sink by Burrows et al. (2014). High velocities have been found to be required in flatter areas where large geographic shifts are required to maintain the preferred climate (Loarie et al. 2009). It is also important to consider that in habitats that have not yet been fragmented the migration capacity of plants, which can limit their movement, will be in the range of 1.7-1500 meters per year, with most species dispersing much less than a kilometer per year (Corlett & Westcott 2013).

However, species are most often faced with obstacles and barriers to their migration due to human development such as land cover changes (Loarie et al. 2009). Fragmentation of suitable habitat is expected to substantially reduce the velocities of plant movement (Corlett & Westcott 2013). It is suggested that protected areas where the land cover is less fragmented are the optimal space for species to be able to shift to maintain suitable climate conditions (Loarie et al. 2009). According to Loarie et al. (2009) only 8% of protected areas globally will maintain their present climate in excess of the next 100 years. Failure to track suitable climate can result in species and population extinction (Diffenbaugh & Field 2013).

To assess the future conservation status of the forest tree species and populations in this study, a velocity of climate change has been adapted from the methods developed by Loarie et al. (2009) calculated under a representative range of climate change scenarios (Hamann et al. 2014). Due to it being most probable that forest tree populations will adapt with the help of pollen flow from well adapted nearby populations in the face of climate change, it is important to determine how far and how quickly species and populations need to migrate to maintain suitable climate in western North America. This in turn allows for the determination of whether or not a protected area remains a "safe" reserve in the future for each species. Species and populations that are not adequately represented in the current protected area network can be considered conservation gaps and those that no longer remain adequately protected in the network under future conditions are potential future conservation gaps. These gaps in conservation will require attention, possible action, and are informative for conservation management and planning. As calculating the velocity of climate change also results in the direction of displacement it allows for planning of migration corridors in the protected area network to ensure conservation of species and populations into the future under changing climate.

1.4 Purpose of study

This study provides an overview of how different jurisdictions protect forests, tree species, and their genetic populations. I also assess the vulnerability of populations, species, and the protected area systems of different jurisdictions to climate change. Specifically, the following questions were addressed:

- How well are forests protected in western North America? Are the particular states or provinces where forest resources are under-protected? Is the protected land base proportional to the protected forest base, or do some jurisdictions over- or under-emphasize forest areas in their protected area network?
- Where lies the responsibility in protecting western North American forest resources? Not all states or provinces have an equal share of the forested landbase, cover the same number of species, or contain a variety of ecological zones that result in unique locally adapted tree populations.
- Which are the tree species that are best and least covered by the current protected area network?
- What states or provinces provide the relative best or worst protection of unique tree populations that fall under their responsibility?
- How do populations rank in their need of in situ protection, implying conservation gaps? And what are the most valuable reserves in the current protected area network?
- How do the ranks of protection for population change under projected climate change? And what are future-proof reserves that maintain habitat for species populations in the future?

2. Methods

2.1 Study area and GIS data

The study area includes the western United States and Canada, west of the 100°W parallel, not including those jurisdictions that were only partially contained within the 100°W parallel. The study area includes 17 jurisdictions: 3 Canadian provinces, 2 northern Canadian territories, 11 of the contiguous American states as well as the state of Alaska in the north (Figure 1). Throughout the study area a total of fifty-four native forest tree species were analysed.

A polygon terrestrial protected areas dataset was used to conduct the analyses in this study (CEC 2010). This dataset contains all International Union for the Conservation of Nature classifications of protected areas. For the purposes of this study all those protected areas ranking from International Union for the Conservation of Nature level I-VI were included and those that are unclassified were excluded. A land cover dataset of North America developed by the Canadian Centre for Remote Sensing (CCRS) from Moderate Resolution Imaging Spectroradiometer (MODIS) data at 250m resolution was also used to define forested areas and uninhabitable areas (CCRS 2010). We have defined forested areas as being land cover classes: Temperate or sub-polar needleleaf forest, Sub-polar taiga needleleaf forest, Tropical or sub-tropical broadleaf evergreen forest, Tropical or sub-tropical broadleaf deciduous forest, Temperate or sub-polar broadleaf deciduous forest and Mixed forest.

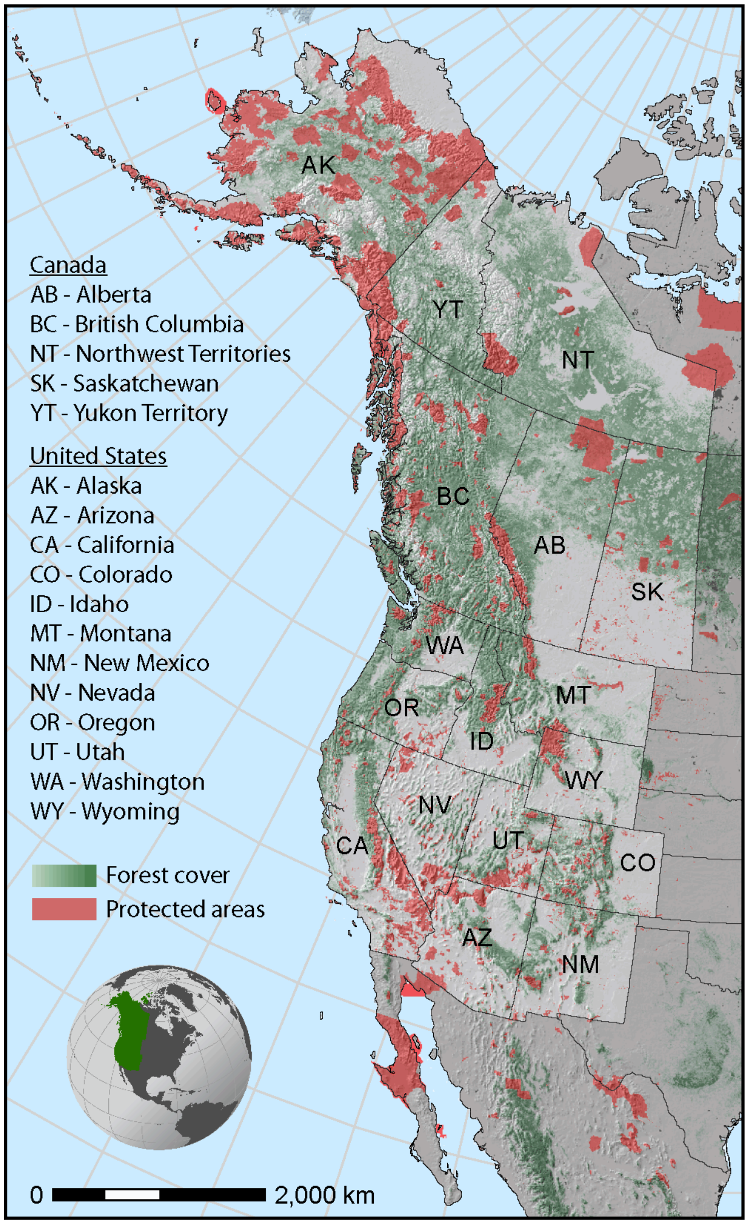

Figure 1. Study area showing forests and protected areas in the 17 states and provinces that were evaluated in this case study.

2.2 Statistical species distribution modeling

Species-level forest inventory data is not available for all jurisdictions, and is incomplete for most jurisdictions therefore, statistical species distribution models were used to assign local species frequencies to areas that were identified as forested through remote sensing. Species distribution modeling was carried out according to methodology described by Gray & Hamann (2013). Briefly, data from 50,000 forest inventory plots were used to establish statistical relationships between environmental predictor variables and percent basal area (for the US), or percent crown cover (for Canadian plot data). The ensemble classifier technique RandomForest (Breiman 2001) was used to predict the quantitative dependent variable.

We included the fifty-four most common western North American tree species based on their overall abundance in forest inventory plots: Pacific silver fir (*Abies amabilis* (Douglas ex J.Forbes)), White fir (*Abies concolor* ((Gordon) Lindley ex Hildebrand)), Grand fir (*Abies grandis* ((Douglas ex D. Don) Lindley)), Subalpine fir (*Abies lasiocarpa* ((Hooker) Nuttall)), California red fir (*Abies magnifica* (A.Murray)), Noble fir (*Abies procera* (Rehder)), Big leaf maple (*Acer macrophyllum* (Pursh)), Red alder (*Alnus rubra* (Bong.)), Pacific madrone (*Arbutus menziesii* (Pursh)), Paper birch (*Betula papyrifera* (Marshall)), California incense cedar (*Calocedrus decurrens* ((Torr.) Florin)), Alaska yellow cedar (*Cupressus nootkatensis* (D.Don)), Giant chinquapin (*Chrysolepis chrysophylla* ((Douglas ex Hook.) Hjelmqvist)), Pacific dogwood (*Cornus nuttallii* (Audubon ex Torr. & A.Gray)), Oregon ash (*Fraxinus latifolia* (Benth.)), California juniper (*Juniperus californica* (Carr.)), Alligator juniper (*Juniperus deppeana* (Steud.)), Western juniper (*Juniperus occidentalis* (Hook.)), Utah juniper (*Juniperus osteosperma* ((Torr.) Little)), Rocky mountain juniper (*Juniperus scopulorum* (Sarg.)), Tamarack (*Larix laricina* ((Du Roi) K. Koch)), Subalpine larch (*Larix lyallii* (Parl.)), Western larch (*Larix occidentalis* (Nutt.)). Tannock (*Lithocarpus densiflorus* (Hook. & Arn.)), Engelmann spruce (*Picea engelmannii* (Parry ex Engelm.)), White spruce (*Picea glauca* ((Moench) Voss)), Black spruce (*Picea mariana* ((Mill.) Britton, Sterns & Poggenburg)), Sitka spruce (*Picea sitchensis* ((Bong.) Carr.)), Whitebark pine (*Pinus albicaulis* (Engelm.)), Bristlecone pine (*Pinus aristata* (Engelm.)), Jack pine (*Pinus banksiana* (Lamb.)), Lodgepole pine (*Pinus contorta* (Douglas)), Pinyon pine (*Pinus edulis* (Engelm.)), Limber pine (*Pinus flexilis* (E.James)), Jeffrey pine (*Pinus jeffreyi* (Balf.)), Sugar pine (*Pinus lambertiana* (Douglas)), Western white pine (*Pinus monticola* (Douglas ex D. Don)), Ponderosa pine (*Pinus ponderosa* (Douglas ex C.Lawson)), Trembling aspen (*Populus tremuloides* (Michx.)), Bitter cherry (*Prunus emarginata* ((Dougl. ex Hook.) Eaton)), *Pin cherry* (Prunus pensylvanica (L.f.)), Douglas-fir (*Pseudotsuga menziesii* (Mirb. Franco)), Canyon live oak (*Quercus chrysolepis* (Liebm.)), Blue oak (*Quercus douglasii* (Hook. & Arn.)), Emory oak (*Quercus emoryi* (Torr.)), Gambel oak (*Quercus gambelii* (Nutt.)), Oregon white oak (*Quercus garryana* Douglas ex Hook.)), California black oak (*Quercus kelloggii* (Newb.)), Redwood sequoia (*Sequoia sempervirens* ((D. Don) Endl.)), Pacific yew (*Taxus brevifolia* (Nutt.)), Western redcedar (*Thuja plicata* (Donn ex D.Don)), Western hemlock (*Tsuga heterophylla* ((Raf.) Sarg.)), Mountain hemlock (*Tsuga mertensiana* ((Bong.) Carr.)), and California laurel (*Umbellularia californica* ((Hook. & Arn.) Nutt.)).

Predictor variables included the climate variables used by Gray and Hamann (2013): mean annual temperature, mean warmest month temperature, mean coldest month temperature, continentality, mean annual precipitation, growing season precipitation (May to September), the number of frost free days and the number of growing degree days above 5°C), generated at 1km resolution with the ClimateWNA software package (Hamann et al. 2013; Wang et al. 2011).

In addition, static predictor variables that are not normally included for habitat projections under climate change, but that improve predictions for present species habitat were used. This includes two topographic predictor variables, a relative radiation index as a proxy for exposure due to slope, aspect and shadowing by adjacent topography (Pierce et al. 2005), and a compound topographic index to describe soil water accumulation resulting from topography (Gessler et al. 1995). Further, six soil variables were included as predictors, available from the International Geosphere-Biosphere Programme at relatively low resolution of 5 arcminutes (GSDT 2000): soil-carbon density (kg/m^2), total nitrogen density (g/m^2), field capacity (mm), wilting point (mm), profile available water capacity (mm), and bulk density (g/cm^3).

2.3 Defining tree species populations

Locally adapted populations of tree species were approximated by ecological delineations as in Hamann and Aitken (2013). Previous work has shown that these delineations roughly correspond to seed zone delineations that reflect locally adapted genotypes identified in genetic field tests (Hamann et al. 2005). Ecosystem delineations include "Zones" of the biogeoclimatic ecological classification system for British Columbia (Meidinger & Pojar 1991), "Natural Subregions" of the Alberta Natural Region classification system (NRC 2006), "Ecoprovinces" of the National Ecological Framework for Canada (Selby & Santry 1996), and the "Level 3" delineation of the United States Ecoregion System (EPA 2007).

For the purpose of this conservation gap analysis, the core habitat of the fifty-four most common tree species of western North America is the focus. Therefore a number of conservative adjustments are made that reduce the number and size of populations that may require *in situ* protection: (1) habitat projections were intersected by remote sensing data, so only pixels remain within which the majority of landcover is forests, (2) the resulting species distributions were further trimmed using Little's range maps (Little 1971), removing any potential over-projections, and (3) the populations that resulted from intersecting the trimmed species distributions and the ecological zones had to contain at least 1% of the total species abundance measured in cumulative cover (% frequency x area). Consequently, we err on the side of missing low frequency populations that may actually be present in the landscape, and can be confident that putative populations included in this analysis truly represent major tree populations in the landscape.

2.4 Gap Analysis

In this study the gap analysis methods developed in previous studies such as Hamann et al. (2005) are built on and expanded to include the large study area of western North America. GIS has been used to conduct a gap analysis, spatially modeling the fifty-four forest tree species and their populations' distributions and frequencies within protected areas and outside of the protected area network. This data was then used to assess their protected status by jurisdiction, species and population. This analysis provides an assessment of the effectiveness and status of current protected areas for the *in situ* conservation of native forest tree species.

To assess the current protected status of species and populations an overlay analysis of multiple spatial layers was performed. This was completed using a combination of ArcGIS (ESRI 2012) and R programming with the SDM tools package facilitating importation and exportation of ASCII files between GIS and R environments (R Core Development Team 2013). The protected area status of species and their populations (defined by the species-ecosystem combination) under current conditions was assessed by overlaying the spatial layers of the study area, protected areas, land cover, ecosystems with each species distribution. Non-forested areas were removed from the analysis.

The cumulative cover of each species and its populations that fell within each jurisdiction and its protected areas was then calculated. For a protected area to qualify as a safe reserve for a population it was required to be large enough to ensure adequate genetic variability and functioning of mating systems of tree species, a cumulative cover of 10 hectares (ha) is likely to contain a population size large enough for this (Hamann et al. 2005). For a species or population to be considered protected in this study it had to have at least a 10 ha cumulative cover (percent crown cover) in at least three protected areas throughout its range. To avoid placing responsibility on jurisdictions that only contain very small amounts of populations the total hectares of the population was calculated for each species range, this was then expressed as a percentage of the total range and values beyond 99 percent were not included in further analysis.

The hectares of species' populations were then summed by each protected area. The proportion (percent) of the population that is protected was calculated by dividing the sum of hectares by the total hectares, allowing for determination of how many protected areas meet the 10 ha standard for protection of the population. Populations that had three or more protected areas meeting the standard of 10 ha were considered to be protected. Those with less than three meeting this standard were not considered to be protected and are considered to be conservation gaps. Populations protected compared to the number of those unprotected have been determined by jurisdiction and by species.

2.5 Climate change exposure analysis

An algorithm for calculating the velocity of climate change (Loarie et al. 2009) was built upon for future time period analysis of species and population protection under climate change conditions. This algorithm measures from within protected areas for each species, returning a velocity and distance to their nearest most suitable habitat. To represent current climate conditions, the 1961-1990 climate normal period is used. Future climate data for the 2011-2040, 2041-2070, and 2071-2100 period, hereafter referred to as the 2020s, 2050s, and 2080s, were based on A2 emissions scenarios implemented by 7 GCMs of the CMIP3 multimodel dataset: CCMA CGCM3.1, CSIRO MK3.0, IPSL CM4, MIROC3.2 HIRES, MPI ECHAM5, NCAR CCSM3.0, UKMO HADGEM1, referenced in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007). Similar to Fordham et al. (2011) poorly validated GCMs were excluded, and ensemble velocity estimates based on individual runs for each future scenario were used for analysis.

Climate change velocities, or required migration distances were calculated for each pixel of the 1km gridded dataset was overlaid with the trimmed and filtered species distribution maps to evaluate the populations' future protected area status provided the current protected area network remains as it is. For a species to be considered safe in the future it must have 10 ha total cumulative coverage amongst three protected areas with a low velocity, allowing for migration within a protected area and to other protected areas. This analysis allows for prediction of populations that will experience low exposure to climate change compared to those that are expected to experience high exposure to climate change.

3. Results

3.1 Evaluation of the current protected area network

Of the 17 jurisdictions analyzed in this study, 16 are protecting 5-20% of their total area (Figure 2a). These 16 jurisdictions are split equally with 8 protecting 5-10% (New Mexico, Idaho, Montana, Oregon, Wyoming, Colorado, Saskatchewan and the Northwest Territories) and the remaining 8 (Washington, Utah, Arizona, Nevada, California, Yukon Territory, Alberta and British Columbia) protecting 10-20% of their land. Alaska is an exception to this, having an area of approximately 1,400,000 km^2 and protecting approximately 50% of that land at just less than 700,000 km^2. The majority of the jurisdictions are meeting the International Union for the Conservation of Nature's suggestion of protecting at least 10% of their land however many are protecting below the CBD's future goal of 17% land protected by 2020 (CBD 2011).

In comparison, of the 17 jurisdictions the vast majority are protecting more than 10% of their forests with 10 jurisdictions protecting between 10-20% of their forests, Washington, California, Montana, Colorado, Idaho, New Mexico, Arizona, Utah, Nevada and Alberta (Figure 2b). There are exceptions to this, Alaska is protecting approximately 40% of its forest and the Yukon Territory is protecting less than 5% of its forest even though it has a large area of forested land. British Columbia being the jurisdiction containing the most forested land at 640,000 km^2 is protecting 12% of their forest. Some jurisdictions that do not necessarily contain large areas of forest are protecting quite well the forests they do have, an example of this being Wyoming protecting 30% (9,000 km^2) of its 30,000 km^2 of forest.

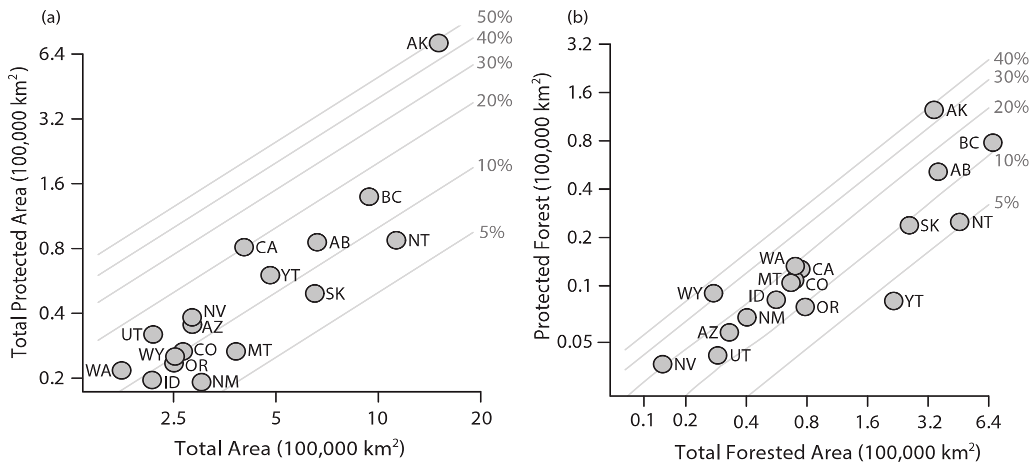

Figure 2. Protected land area (a) and protected forest area (b) by US state or Canadian province in western North America.

3.2 Identifying current conservation gaps by jurisdiction

Conservation gaps under current conditions were determined first by jurisdiction (Figure 3). These results showed that jurisdictions with high diversity and large number of populations require better protection for these populations. Those jurisdictions with smaller population numbers generally protected these populations well. British Columbia is the most genetically diverse jurisdiction, having 28 species and the most populations of any of the jurisdictions included at 182, it is protecting 123 of these populations but has 59 populations still requiring protection. California and Oregon contain the highest number of major forest tree species, 31 and 29 respectively and are protecting 40-50% of their populations. There were five jurisdictions that are protecting less than 50% of their populations, Montana, Idaho, Oregon, Washington and Yukon Territory. Those populations still requiring protection are considered to be conservation gaps. The Northwest Territories is the only jurisdiction protecting 100% of its populations, however it does have the smallest number of populations (5) in the study.

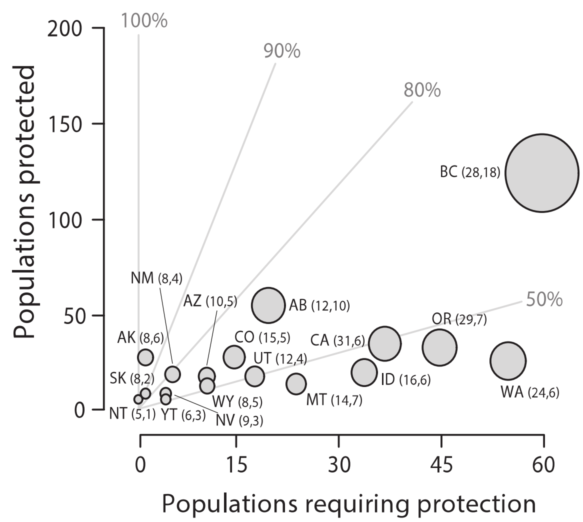

Figure 3. The number of tree species populations that are protected versus those that require additional protection by US state or Canadian province. Species populations were defined by major ecosystem delineations. The number of species and ecosystems in each jurisdiction is given in parenthesis, and the size of the circles is proportional to the number of species populations in ecosystems. Criteria for sufficient protection were at least three reserves with a population size of 10ha cumulative cover each. Corresponding conservation priorities are shown in Table 1 and Appendix I.

3.3 Identifying current conservation gaps by species

Conservation gaps were then summarized at the species level (Figure 4). Twenty-five of the 54 species in the study have less than 50% of their populations protected. Many of the species requiring the most protection have smaller and sparser ranges than those that have more protection such as the Pacific yew. The majority of the species that have many populations protected, indicating adequate conservation of genetic diversity, such as lodgepole pine, Douglas-fir, trembling aspen, as well as white and black spruce are those that have widespread ranges in the study area. Although there are some species with relatively small ranges that are 100% protected such as the Redwood sequoia, which is an endangered species (IUCN 2014b).

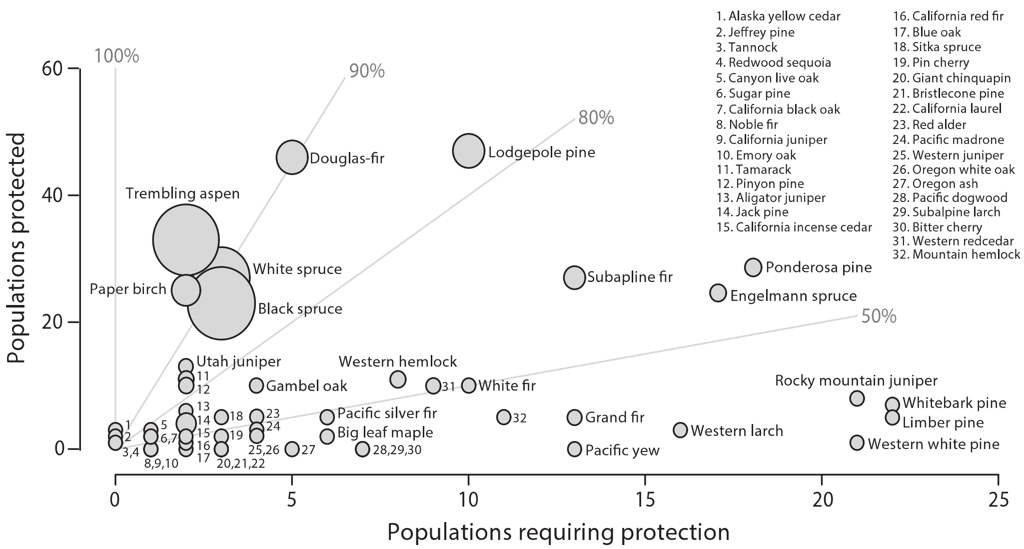

Figure 4. The number of tree species populations that are protected versus those that require additional protection. The size of the symbols is proportional to the species abundance measured in cumulative hectares of canopy cover. Species populations were defined by major ecosystem delineations, and criteria for sufficient protection were at least three reserves with a population size of 10ha cumulative cover each. Corresponding conservation priorities are shown in Table 1.

The top 25 conservation priorities for populations (Table 1), ranked by the largest population areas (ha) having no protected areas meeting the 10ha requirement, are spread across many jurisdictions in the study area. The number one priority population requiring protection is Jack pine in the Lower Boreal Highlands ecosystem of Alberta with 197,000ha left unprotected. Amongst the top priorities are boreal species such as white spruce and black spruce, both of which occur in the subalpine ecosystem of Yukon Territory as well as a population of tamarack in British Columbia. Among the priorities are also populations of subalpine fir (AB, WA), Engelmann spruce (WA, MT, UT) as well as lodgepole pine (WY), all of which are species with interior populations and generally grow at higher altitudes. Oregon's top priorities are western juniper and Oregon white oak, constituting 61 and 50% of their ranges respectively, left virtually unprotected. Wet transitional forest, transitional deciduous forest, dry conifer and ecosystems that pertain to the boreal forest tend to be prevalent amongst the top priorities.

Table 1. Top 25 population conservation priorities, ranked by population size (ha), all populations have no protected areas meeting the 10ha requirement for a safe reserve.

Jurisdiction	Species	Ecosystem	Population (ha)	Proportion of species range (%)	Population protected (ha)	Population protected (%)
AB	*Pinus banksiana*	Lower Boreal Highlands	197288.4	21.8	0	0
MT	*Pseudotsuga menziesii*	Wet Transitional Forest	35997.8	1.4	3.3	0
YT	*Picea mariana*	Subalpine Forest	21427.3	0.3	0	0
AB	*Abies lasiocarpa*	Central Mixedwood	17898.8	1.6	0	0
YT	*Picea glauca*	Subalpine Forest	13236.1	0.2	0	0
ID	*Larix occidentalis*	Wet Transitional Forest	6350.3	26.8	11.1	0.2
WA	*Picea engelmannii*	Dry Conifer	5912.9	1.5	0	0
OR	*Juniperus occidentalis*	Dry Conifer	5637.5	61.1	0.7	0
WA	*Abies lasiocarpa*	Dry Conifer	5219.2	0.5	0	0
OR	*Thuja plicata*	Transitional Deciduous Forest	4675.6	2.9	9.2	0.2
UT	*Picea engelmannii*	Dry Conifer	4489.3	1.2	2.7	0.1
WY	*Pinus contorta*	Dry Conifer	3933.4	0.1	23.6	0.9
BC	*Larix laricina*	Boreal White And Black Spruce	3812.2	1.6	3.3	0.1
AB	*Pseudotsuga menziesii*	Lower Foothills	3460.9	0.1	0	0
WA	*Abies lasiocarpa*	Wet Transitional Forest	3304.3	0.3	1.6	0.1
OR	*Abies concolor*	Dry Conifer	3086.5	8	0	0
MT	*Picea engelmannii*	Wet Transitional Forest	3040.9	0.8	0.2	0
OR	*Quercus garryana*	Transitional Deciduous Forest	2960.3	26.2	3.8	0.1
WA	*Alnus rubra*	Transitional Deciduous Forest	2904.4	8.7	12.2	0.4
OR	*Tsuga heterophylla*	Transitional Deciduous Forest	2833.5	0.9	1.1	0
OR	*Quercus garryana*	Wet Transitional Forest	2719.5	24	0	0
MT	*Pinus ponderosa*	Wet Transitional Forest	2622.0	0.6	0	0
WA	*Thuja plicata*	Wet Transitional Forest	2541.4	1.6	3.1	0.1
MT	*Abies grandis*	Wet Transitional Forest	2540.9	2.1	0	0
OR	*Arbutus menziesii*	Transitional Deciduous Forest	2369.7	8.1	0	0

3.4 Identifying future conservation gaps

The results of the climate change exposure analysis correlated with that of Loarie et al. (2009). The mountain slopes have low velocity, species generally don't have to migrate far distances to keep pace with suitable climate as these short distances can result in large changes in temperature on mountains. However, high velocities are required to maintain suitable climate on mountains in those cases where the climate disappears completely from the mountain top and species are forced to move northward or migrate to new mountain ranges to maintain their climate, or in cases where higher velocities result from projected precipitation changes, such as in Banff National Park (Figure 5). Overall, the interior plains have much higher velocities than mountainous areas resulting in the need for larger migration to maintain constant climate. Consequently, the species inhabiting this area can be assumed to be more vulnerable to climate change.

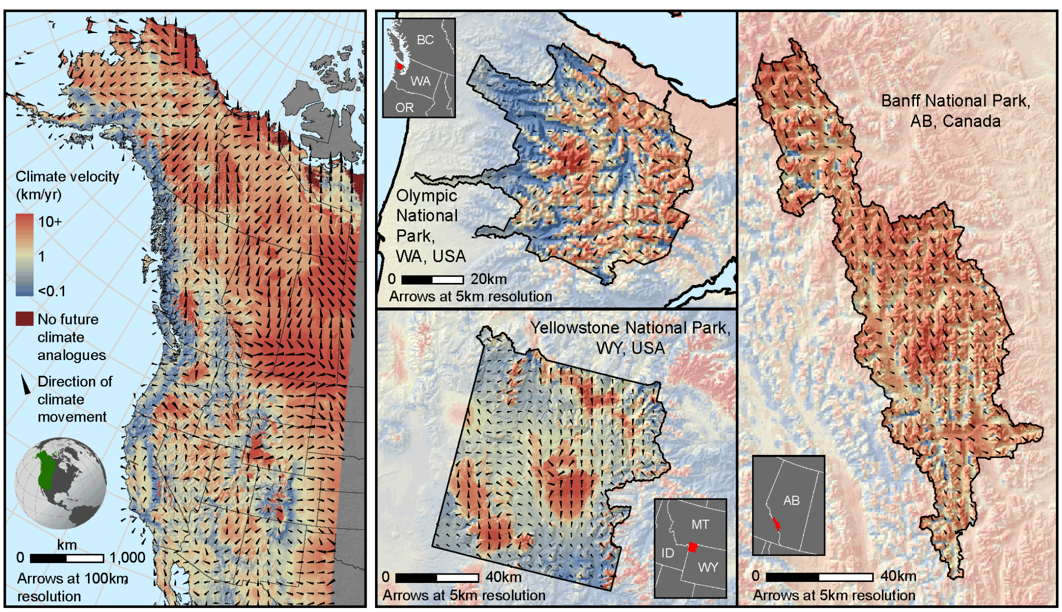

Figure 5. Visualization of required migration distances and directions for populations to maintain constant climatic conditions. A tree population in a protected area is classified as "safe" if at least 10 ha of its cumulative cover have to migrate less than 2km/year, this value seems high however some species have a tolerance to climate change (Burrows et al. 2014), by the 2050s relative to the 1961-1990 climate normal period. Those areas that remain blue and yellow are considered "safe", while those areas in red are not. The resulting changes to conservation priorities are shown in Table 2 and Appendix I. An example showing the data produced for the above protected areas and their vulnerability to climate change is shown in Appendix II.

Protected areas were evaluated to determine if they are safe reserves under climate change conditions. Under current conditions the boreal species that are expected to have the largest conservation gaps in the future are considered safe in Wood Buffalo National Park (AB) with very large areas. Jack pine has almost 70,000 ha among two populations in this reserve, however, by the 2020s it is projected to have 0 ha coverage in this reserve and no other safe reserves. Black spruce, white spruce, and trembling aspen's highest ranking safe reserves under current conditions are Wood Buffalo National Park as well and Yukon Flats National Wildlife Refuge (AK). Just as with Jack pine, these species deplete quickly from these safe reserves under climate change conditions with Wood Buffalo National Park again containing 0 ha of these species' populations by the 2020s and the Yukon Flats National Wildlife Refuge containing much smaller coverages. However, other reserves become higher ranking safe reserves for these populations, in the case of white spruce, Jasper National Park (AB) and Kenai National Park (AK) become important safe reserves, and for black spruce Wood-Tikchick State Park (AK) becomes its most important safe reserve by the 2080s. The highest ranking safe reserves for western white pine, one of the least protected species, are Three Sisters Wilderness Area (OR), Yosemite Wilderness Area (CA) and Glacier National Park (MT), all have approximately 35-55 ha cumulative habitat coverage. Under climate change these highest ranking reserves remain safe. The same outcome is expected for the other two least protected species, whitebark pine and limber pine, both of which remain "safe" in Yellowstone National Park (WY) and North Absaroka Wilderness Area (WY) with a lesser coverage than under current conditions.

Populations of species were evaluated for vulnerability to climate change (Table 2). Species that maintain protection under climate change conditions are redwood, Alaska yellow cedar, alligator juniper, Utah juniper, lodgepole pine, pinyon pine, Jeffrey pine and sugar pine. Coastal species such as Douglas-fir, western redcedar, western hemlock, mountain hemlock and Sitka spruce, all maintain adequate protection. There are also many species that are currently lacking protection with that protection becoming even less so under climate change conditions. Western white pine has only 1 of 22 populations protected which remains protected in the future, jack pine has 4 of 6 populations protected, however, this drops to 0 by the 2020s. Limber pine is also lacking protection and has less than 1% protected populations by the 2080s. Overall the spruce species lose 56 protected populations by the 2080s, the pines lose 135, and the fir species lose 60 protected populations. There are also species that are already of conservation concern that are major conservation gaps. Under future conditions it is estimated that Whitebark pine, which is currently endangered, will only have 2 populations left in protection as well as Pacific yew has 0 populations protected under current and future conditions. The full species and their populations vulnerability to climate change is shown in Table 2.

The largest conservation gaps were evaluated showing that under climate change conditions the populations most vulnerable are those of the boreal species. Throughout the 2020s, 2050s and 2080s, trembling aspen, black spruce, white spruce and jack pine continuously show up as conservation priorities. Interior populations of lodgepole pine and Douglas-fir are also priorities. The ecosystems that show up as priorities most often are Boreal, Central Mixedwood, Dry Mixedwood, Northern Mixedwood, Lower Boreal Highlands and the Lower Foothills. The jurisdictions that are mainly responsible for these populations are Alberta and Saskatchewan, with a few populations requiring protection in Montana, British Columbia and Yukon Territory. The full list of top 25 conservation priorities for each future time period is shown in Appendix I.

Table 2. Population protection by species under current and future climate change conditions.

			Populations Protected			
Species	Total Range (ha)	Populations	Current	2020s	2050s	2080s
Abies amabilis	36064	11	5	5	5	5
Abies concolor	38123	20	10	8	7	5
Abies grandis	121450	18	5	5	5	4
Abies lasiocarpa	1129172	40	27	24	20	18
Abies magnifica	653	3	1	1	1	1
Abies procera	80	1	0	0	0	0
Acer macrophyllum	22910	8	2	2	2	2
Alnus rubra	32831	8	4	4	4	4
Arbutus menziesii	28866	6	2	2	2	2
Betula papyrifera	2197684	27	25	18	14	12
Calocedrus decurrens	4873	4	2	2	2	2
Cupressus nootkatensis	10501	3	3	3	3	3
Chrysolepis chrysophylla	480	3	0	0	0	0

Continued on next page

Table 2 continued

Species	Total Range (ha)	Populations	Populations Protected			
			Current	2020s	2050s	2080s
Cornus nuttallii	4565	7	0	0	0	0
Cornus nuttallii	4565	7	0	0	0	0
Cornus nuttallii	4565	7	0	0	0	0
Fraxinus latifolia	1224	5	0	0	0	0
Juniperus californica	57	1	0	0	0	0
Juniperus deppeana	19535	8	6	6	6	6
Juniperus occidentalis	9095	5	1	1	1	1
Juniperus osteosperma	108754	15	13	13	12	11
Juniperus scopulorum	51163	29	8	8	6	5
Larix laricina	236372	13	11	6	4	4
Larix lyallii	148	7	0	0	0	0
Larix occidentalis	23468	19	3	3	3	3
Lithocarpus densiflorus	11435	1	1	1	1	1
Picea engelmannii	380992	42	25	25	24	20
Picea glauca	6206514	30	27	22	16	14
Picea mariana	7712075	26	23	18	14	11
Picea sitchensis	18626	8	5	5	5	5
Pinus albicaulis	20386	29	7	5	2	1
Pinus aristata	57	3	0	0	0	0
Pinus banksiana	891120	6	4	0	0	0
Pinus contorta	2597588	57	47	42	37	33
Pinus edulis	210662	12	10	10	10	9
Pinus flexilis	11743	27	5	4	3	2
Pinus jeffreyi	2639	2	2	2	2	2
Pinus lambertiana	2521	3	2	2	2	2
Pinus monticola	1907	22	1	1	1	1
Pinus ponderosa	451710	47	29	27	24	23
Populus tremuloides	7489455	35	33	27	21	18
Prunus emarginata	334	7	0	0	0	0
Prunus pensylvanica	20292	5	2	0	0	0
Pseudotsuga menziesii	2554250	51	46	45	38	36
Quercus chrysolepis	23260	4	3	3	2	2
Quercus douglasii	462	2	0	0	0	0
Quercus emoryi	372	1	0	0	0	0
Quercus gambelii	36550	14	10	10	9	9
Quercus garryana	11154	5	1	1	1	1
Quercus kelloggii	16576	3	2	2	2	2
Sequoia sempervirens	3931	1	1	1	1	1
Taxus brevifolia	1870	13	0	0	0	0
Thuja plicata	158610	19	10	10	9	9
Tsuga heterophylla	307554	19	11	11	11	10
Tsuga mertensiana	16539	16	5	5	5	5
Umbellularia californica	5777	3	0	0	0	0

Conservation gaps under climate change conditions were also summarized by jurisdiction (Table 3). Alberta and British Columbia both contain relatively large numbers of populations and prove to be quite vulnerable to climate change with Alberta only having 2 of its 73 populations remaining under protection by the 2080s and British Columbia having 97 of its 182 populations protected. The Northwest Territories, Saskatchewan and the Yukon Territory all have small numbers of populations and have major conservation gaps by 2020s due mainly to the vulnerability of the boreal species in these jurisdictions. There are many jurisdictions in the United States that are protecting 40-60% of their populations, they do seem to be relatively less vulnerable to climate change and maintain higher numbers of protected populations through future climate change conditions. Alaska is the least vulnerable to climate change maintaining 96% protection through the future time periods. Idaho, Utah and Oregon are the most vulnerable to climate change losing the largest numbers of protected populations by the 2080s.

Table 3. Population protection by jurisdiction under current and future climate change conditions.

				Populations Protected			
Jurisdiction	Species	Ecosystems	Populations	Current	2020s	2050s	2080s
Canada							
AB	12	10	73	54	26	9	2
BC	28	18	182	123	122	108	97
NT	5	1	5	5	1	0	0
SK	8	2	9	8	0	0	0
YT	6	3	9	5	4	0	0
United States							
AK	8	6	24	23	23	23	23
AZ	10	5	27	17	15	14	14
CA	31	6	70	34	34	33	33
CO	15	5	41	27	27	27	25
ID	16	6	52	19	19	16	12
MT	14	7	36	13	13	11	10
NM	8	4	23	18	18	16	16
NV	9	3	12	8	7	5	5
OR	29	7	76	32	31	28	26
UT	12	4	34	17	15	12	9
WA	24	6	79	25	24	24	24
WY	8	5	22	12	11	11	9

4. Discussion

4.1 The need for more effective protection of species and populations

For diversity within forests to be conserved, the conservation of the genetic diversity within species needs to be improved (Geburek & Konrad 2008), with conservation strategies put into place to fill the conservation gaps. Forest tree populations are high in genetic diversity and species with large ranges tend to have many populations throughout their vast ranges. The species with larger ranges tend to be relatively better protected. Many of these species are also economically important such as Douglas-fir and lodgepole pine, however they still have conservation gaps in particular ecosystems such as the Douglas-fir population in the wet transitional forest ecosystem of Montana and the lodgepole pine population in the dry conifer ecosystem of Wyoming. Due to their economic importance it is essential that their populations are protected to conserve the genetic variability within the species.

The results indicate that forest tree species with scattered and sparse distributions in western North America are particularly in need of increased conservation measures. Many of these species have less than 50% of their populations protected. Within this group of species requiring protection are some species of interest, particularly Pacific yew and Western white pine, both of which are listed as near-threatened on the most recent International Union for the Conservation of Nature Red List of Threatened Species (IUCN 2014b). According to the results, Pacific yew has a total of 13 populations in the study area, all of which are considered unprotected. This species is important for use in production of anti-cancer medicines such as Taxol and has been heavily exploited due to this (IUCN 2014b). These populations exist mainly on the coast within British Columbia, Washington, Oregon, and California as well as in the interior in the state of Idaho. This is a major conservation gap that needs to be addressed by these jurisdictions.

Western white pine is mainly threated by pine blister rust, a non-native fungal disease invading North American forests. This species has 22 populations in the study area and only one of these populations located in California is considered protected. Another species in this study, whitebark pine, has been listed as endangered and is threatened by the same disease. This disease is expected to spread and worsen as climate change progresses. Unfortunately in these cases, protected areas where this disease has already taken hold cannot protect these species and the focus should be put on the protected areas that are still free of this disease to protect these species.

Every jurisdiction within the study area has some level of population conservation gaps apart from the Northwest Territories which currently does not but is expected to have conservation gaps in the near future. The results also indicate that in some cases where jurisdictions are protecting adequate amounts of their forests they are still not adequately protecting their species and populations therefore putting the genetic diversity and potential for adaptation at risk. The jurisdictions with the highest number of populations still requiring protection, British Columbia, Alberta and Washington, are also the jurisdictions with the greatest forest diversity. These jurisdictions are protecting a fair amount of their forests but when looking at the population and species level it is apparent that there are still conservation gaps such as the Lower Boreal Highlands population of jack pine in Alberta, the dry conifer population of Engelmann spruce in Washington and the boreal population of Tamarack in British Columbia under current conditions. It is imperative to recognize and develop conservation strategies for these gaps as conserving genetic populations within species is vital to their continuation and ability to adapt under climate change conditions (Hamann et al. 2004). Strategic placement of additional protected areas may be required to provide corridors to achieve this and ensure possible migration. It is also important to ensure those protected areas that contain multiple populations remain highly protected to provide more efficient conservation for genetic variation of forest trees.

4.2 The need for cross-border conservation strategies

Forest tree species and their populations are naturally distributed and differentiated by ecological boundaries rather than the political borders of jurisdictions. Forest tree conservation is overwhelmingly complex because of differences among jurisdictions and the lack of unified conservation goals as well as differences in forest management. This complexity hinders effective conservation of species and populations. There is a recognized failing in the conservation of forest genetic diversity due to the lack of cross-border conservation strategies (Geburek & Konrad 2008).

This study has broken down the protection needs for populations and species' by jurisdiction in an effort for these jurisdictions to recognize where their greatest conservation gaps exist. Once these gaps are recognized, conservation strategies can be planned for and implemented. Most often conservation planning is done on a regional basis and more in depth at an individual protected area level to achieve specific goals. As climate change progresses and species' ranges shift there is going to be an even greater need for regions, jurisdictions and nations to work together (Hannah 2010) on the conservation of forest tree species in western North America. Unified short and long-term conservation goals that benefit the whole of the western North America region are required as species and populations migrate across borders into new jurisdictions. It is evident that there is a need for jurisdictions to work together to protect the genetic diversity that exists among boreal and interior species. In the lack of cross-border strategies it is expected that there will be inconsistent strategies for managing species and populations under climate change conditions, potentially leading to the loss of genetic variability among species (Hannah 2010).

4.3 Implications of climate change for conservation management and planning

Climate change is predicted to result in migration and changes in the distribution of forest tree species in western North America. In the future, conservation management and planning will have to be adapted continuously and quite swiftly to ensure the longevity of these species. It has been confirmed that forest tree species are lagging due to current changes in climate and expected to lag further in the future under predicted climate change scenarios, there is a northward shift in their distributions as well as a shift to higher elevations predicted to find suitable habitat (Gray & Hamann 2013). Modeling which reserves will remain safe for each species' populations is a good start to identifying where conservation plans may need to be adjusted to mitigate for climate change. The results indicate that the top conservation priorities in the future will be the boreal and interior species' populations and it would be proactive to begin planning how best to protect those populations most vulnerable to climate change. Being aware that the current safest reserve for these species, Wood Buffalo National Park, will no longer be a "safe" reserve in the future suggests that conservationists and natural resource managers will have to shift their focus to other areas to continue the conservation of these species rather than relying on this reserve to ensure the survival of these populations.

An accepted conservation strategy for this challenge is to ensure the possibility of connectivity to enable species' to maintain suitable habitat under climate change conditions (Hannah et al. 2002). By determining how far and how quickly populations of species are expected to migrate, effective corridors for their movement may be determined and planned for. It is suggested that the current habitat be maintained as a reserve until the population is re-established in the new locations for populations that may be able to reach suitable habitats (Hansen et al. 2001). Smaller protected areas may need to be added to the network, particularly on the edge of a species range, to provide safe reserves for the conservation of genetic diversity of species as well as locally adapted populations while migration is occurring (Hannah et al. 2002). The results of this study provide the date necessary to determine where migration corridors and protected areas may need to be added to the current protected area network to "future proof" population protection, knowing where the most important reserves for populations currently are and where they are expected to be in the future allows for this planning and implementation to occur. For example, knowing that there are no future safe reserves for Jack pine implies it is necessary for those jurisdictions where this species exist to add protected areas to their network to ensure the conservation of its genetic diversity for the future.

For populations that are not predicted to safely migrate to suitable habitat it may be appropriate to strictly protect them and consider *ex situ* conservation strategies (Hansen et al. 2001). This may be especially necessary for those species that are already considered at conservation risk. The impending threat of climate change particularly emphasizes the need for cross-border and cross-jurisdictional conservation strategies (Hannah 2010), the conservation of forest tree species will not succeed without the cooperation of nations and jurisdictions.

5. Conclusions and Recommendations

This study has provided information necessary to address conservation gaps by species, populations and jurisdictions under current and future climate change conditions as well as the determination of safe reserves, allowing for conservation planning of migration corridors and a more efficient protected area network. It is essential to ensure that current conservation gaps are recognised and mitigated at the species and population level to ensure conservation of genetic diversity. Forests are for the most part well represented in the current protected area network in western North America, with all but four jurisdictions protecting more than 10% of their forested land. Alaska and Saskatchewan are currently doing the best job of protecting their populations. Those jurisdictions with large numbers of unique tree populations, British Columbia, Alberta, Washington, Oregon and California need to safeguard these populations. Alberta faces many challenges to this under climate change conditions with only two populations protected by the 2080s and is facing a large number of conservation gaps.

The large distribution of forest trees poses many challenges for conservation of forest genetics, particularly for conservation planning and implementation across many jurisdictions (Lefèvre et al. 2013). The responsibilities for conservation of populations fall on many jurisdictions in the study area, reiterating the need for cross-border conservation strategies. Coastal species seem to be relatively safe and the majority of the conservation gaps fall on boreal and interior species. In the future it is expected that boreal species will be the most vulnerable to climate change and will for the most part be unprotected by the 2020s. The provinces and territories of Canada, particularly Alberta and Saskatchewan will need to work together to develop conservation strategies to ensure that populations of White spruce, Black spruce, Trembling aspen and Jack pine are adequately protected to ensure their chances of survival.

Interestingly, the species most represented in the current protected area network are also those that have the largest conservation gaps in particular under future climate conditions, Black spruce, White spruce, Trembling aspen and Lodgepole pine. It is important to recognize that although a species may be represented well, its unique populations may not be, genetic diversity is vital for a species adaptation, migration under future climate change conditions. To reduce the loss of species and populations it will be necessary to increase the size of protected areas and to add protected areas to the network to function as migration corridors (Loarie et al. 2009). *Ex situ* conservation may be necessary for those populations that are major conservation gaps and conservation concerns such as Western white pine and Pacific yew which are underrepresented in the current protected area network. It is absolutely imperative that jurisdictions work together to ensure the protected area network represents adequate levels of populations and addresses conservation priorities, as well as develops strategies to ensure continued protection of genetic resources of these tree species and their populations under current and future climate change conditions.

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Appendix I. Priority population conservation gaps under climate change conditions

Appendix I, Table 4. Expected top 25 population conservation priorities for the 2020s, all with no protected areas meeting the 10ha requirement.

Jurisdiction	Species	Ecosystem	Population (ha)	Proportion of species range (%)	Population protected (ha)	Population protected (%)
SK	*Populus tremuloides*	Boreal	1834814	24.2	0	0
SK	*Picea mariana*	Boreal	1435797	18.4	0	0
SK	*Picea glauca*	Boreal	1040100	16.6	0	0
SK	*Pinus banksiana*	Boreal	411517	45.4	0	0
AB	*Picea mariana*	Northern Mixedwood	229584.4	2.9	0	0
AB	*Pinus contorta*	Lower Foothills	199098.8	7.6	13.2	0
AB	*Pinus banksiana*	Lower Boreal Highlands	197288.4	21.8	0	0
SK	*Betula papyrifera*	Boreal	186603.7	8.4	0	0
AB	*Pinus banksiana*	Central Mixedwood	179592.8	19.8	0	0
AB	*Populus tremuloides*	Northern Mixedwood	170347.7	2.3	0	0
AB	*Betula papyrifera*	Central Mixedwood	149021.5	6.7	6.8	0
AB	*Picea glauca*	Northern Mixedwood	135916.1	2.2	0	0
AB	*Picea mariana*	Boreal Subarctic	130157.9	1.7	0	0
SK	*Larix laricina*	Boreal	97443.9	40.7	0	0
AB	*Populus tremuloides*	Upper Boreal Highlands	91875.2	1.2	0	0
AB	*Populus tremuloides*	Boreal Subarctic	86718.8	1.1	0	0
AB	*Abies lasiocarpa*	Lower Foothills	72096	6.3	5.5	0
AB	*Picea glauca*	Boreal Subarctic	66469.3	1.1	0	0
AB	*Picea mariana*	Upper Boreal Highlands	63420	0.8	0	0
AB	*Picea glauca*	Upper Boreal Highlands	61753.9	1	0	0
AB	*Pinus banksiana*	Northern Mixedwood	48483.4	5.4	0	0

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Appendix I, Table 4. Continued

Jurisdiction	Species	Ecosystem	Population (ha)	Proportion of species range (%)	Population protected (ha)	Population protected (%)
AB	*Pinus banksiana*	Upper Boreal Highlands	36548.9	4	0	0
SK	*Pinus contorta*	Boreal	29079.3	1.1	0	0
MT	*Pseudotsuga menziesii*	Wet Transitional Forest	28586.9	1.1	3.3	0
AB	*Betula papyrifera*	Lower Boreal Highlands	26312.5	1.2	2.8	0

Appendix I, Table 5. Expected top 25 population conservation gaps for the 2050s, all with no protected areas meeting the 10ha requirement.

Jurisdiction	Species	Ecosystem	Population (ha)	Proportion of species range (%)	Population protected (ha)	Population protected (%)
SK	*Populus tremuloides*	Boreal	1834814	24.2	0	0
SK	*Picea mariana*	Boreal	1435797	18.4	0	0
AB	*Picea mariana*	Central Mixedwood	1170806	15	6.1	0
AB	*Populus tremuloides*	Central Mixedwood	1045734	13.8	3.5	0
SK	*Picea glauca*	Boreal	1040100	16.6	0	0
AB	*Picea glauca*	Central Mixedwood	671555.7	10.7	1.6	0
SK	*Pinus banksiana*	Boreal	411517	45.4	0	0
AB	*Picea mariana*	Lower Boreal Highlands	405030.6	5.2	0	0
AB	*Populus tremuloides*	Dry Mixedwood	301882.3	4	0	0
AB	*Populus tremuloides*	Lower Boreal Highlands	287742.3	3.8	0	0
AB	*Picea mariana*	Northern Mixedwood	229584.4	2.9	0	0
AB	*Picea mariana*	Dry Mixedwood	217226	2.8	0	0
AB	*Picea glauca*	Lower Boreal Highlands	216167.2	3.4	0	0
AB	*Pinus contorta*	Lower Foothills	199098.8	7.6	6.7	0
AB	*Pinus banksiana*	Lower Boreal Highlands	197288.4	21.8	0	0
SK	*Betula papyrifera*	Boreal	186603.7	8.4	0	0
AB	*Pinus banksiana*	Central Mixedwood	179592.8	19.8	0	0
AB	*Populus tremuloides*	Northern Mixedwood	170347.7	2.3	0	0
AB	*Picea glauca*	Dry Mixedwood	169971.6	2.7	0	0
AB	*Picea glauca*	Lower Foothills	163995.8	2.6	6.3	0
AB	*Betula papyrifera*	Central Mixedwood	149021.5	6.7	2.7	0
AB	*Picea glauca*	Northern Mixedwood	135916.1	2.2	0	0
AB	*Picea mariana*	Boreal Subarctic	130157.9	1.7	0	0
BC	*Pinus contorta*	Sub-Boreal Pine And Spruce	107043	4.1	9.8	0
SK	*Larix laricina*	Boreal	97443.9	40.7	0	0

Appendix I, Table 6. Expected population conservation priorities for the 2080s, all with no protected areas meeting the 10ha requirement.

Jurisdiction	Species	Ecosystem	Population (ha)	Proportion of species range (%)	Population protected (ha)	Population protected (%)
SK	*Populus tremuloides*	Boreal	1834814	24.2	0	0
SK	*Picea mariana*	Boreal	1435797	18.4	0	0
AB	*Picea mariana*	Central Mixedwood	1170806	15	0	0
AB	*Populus tremuloides*	Central Mixedwood	1045734	13.8	0	0
SK	*Picea glauca*	Boreal	1040100	16.6	0	0
AB	*Picea glauca*	Central Mixedwood	671555.7	10.7	0	0
SK	*Pinus banksiana*	Boreal	411517	45.4	0	0
AB	*Picea mariana*	Lower Boreal Highlands	405030.6	5.2	0	0
AB	*Populus tremuloides*	Dry Mixedwood	301882.3	4	0	0
AB	*Populus tremuloides*	Lower Boreal Highlands	287742.3	3.8	0	0
AB	*Populus tremuloides*	Lower Foothills	284756.2	3.8	0	0
BC	*Picea mariana*	Spruce-Willow-Birch	270216.1	3.5	0	0
BC	*Picea mariana*	Boreal White And Black Spruce	248079.3	3.2	0	0
AB	*Picea mariana*	Northern Mixedwood	229584.4	2.9	0	0
YT	*Picea glauca*	Boreal	223624.7	3.6	0	0
AB	*Picea mariana*	Lower Foothills	218084	2.8	0	0
AB	*Picea mariana*	Dry Mixedwood	217226	2.8	0	0
YT	*Picea mariana*	Boreal	216898.9	2.8	0	0
AB	*Picea glauca*	Lower Boreal Highlands	216167.2	3.4	0	0
BC	*Populus tremuloides*	Boreal White And Black Spruce	201561.8	2.7	0	0
AB	*Pinus contorta*	Lower Foothills	199098.8	7.6	0	0
AB	*Pinus banksiana*	Lower Boreal Highlands	197288.4	21.8	0	0
SK	*Betula papyrifera*	Boreal	186603.7	8.4	0	0
AB	*Pinus banksiana*	Central Mixedwood	179592.8	19.8	0	0
BC	*Populus tremuloides*	Sub-Boreal Pine And Spruce	174442.1	2.3	0	0

Appendix II: Example of protected area data accumulated. The following tables show the data accumulated for Banff National Park (Alberta, Canada), Olympic National Park (Washington, US) and Yellowstone National Park (Wyoming, US). All of these protected areas are classified as IUCN protected area category II. These tables are shown as examples of the data created through this study for the approximately 130,000 protected areas within the study area. These tables show the coverage of each population under current and future climate change conditions. All of this data will be made available through online appendices if published with the version of this thesis that has been submitted to a peer reviewed journal: Russell, E.J., Gray, L.K., Roberts, D.R. and Hamann, A. (2014). Conservation planning for forests, tree species, and their genetic populations under climate change: a case study for western North America.

Appendix II, Table 7. Banff National Park population coverage under current and future climate change conditions.

		Time period (hectares of population)			
Species	Ecosystem	Current	2020s	2050s	2080s
Abies lasiocarpa	Subalpine	474.2	241.4	32.9	0
	Upper Foothills	33.2	6.9	1	0
Betula papyrifera	Alpine	3.1	3.1	1.5	0
	Montane	4.3	4.3	4.3	0
	Subalpine	109.1	102	60.8	3
	Upper Foothills	0.3	0.3	0	0
	Alpine Tundra	0.3	0.3	0.3	0
	Engelmann spruce-Subalpine fir	0.4	0.4	0.4	0
Picea engelmannii	Subalpine	249.2	171	35.8	0
	Engelmann spruce-Subalpine fir	0.2	0.2	0.2	0

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Appendix II, Table 7. Continued.

Species	Ecosystem	Time period (hectares of population)			
		Current	2020s	2050s	2080s
Picea glauca	Alpine	99.1	69.8	24.2	0
	Montane	1549.5	962.9	144.5	29.5
	Subalpine forest	3022.5	2345.5	1022.2	84.5
	Alpine Tundra	5.8	5.8	5.8	0
	Engelmann spruce-Subalpine fir	4.3	4.3	4.3	0
Picea mariana	Montane	100	78.3	51.4	10.2
	Subalpine forest	564.7	507	429.4	62.8
Pinus albicaulis	Subalpine forest	3.9	3.8	0	0
Pinus contorta	Alpine	1.8	1.8	0	0
	Montane	5.4	1.5	0	0
	Subalpine forest	320.2	191.5	90.6	2.4
	Engelmann spruce-Subalpine fir	1.3	1.3	1.3	0
Populus tremuloides	Alpine	97.1	97.1	68.2	0
	Montane	1893.1	1443.3	130.4	20.8
	Subalpine forest	4948	4191.7	1944.7	113.4
	Alpine Tundra	16.1	16.1	16.1	0
	Engelmann spruce-Subalpine fir	11.1	11.1	11.1	0

Appendix II, Table 8. Olympic National Park population coverage under current and future climate change conditions.

		Time period (hectares of population)			
Species	Ecosystem	Current	Species	Ecosystem	Current
Abies amabilis	Subalpine forest	109	109	109	109
	Transitional deciduous forest	153	143.2	143.2	153
	Wet transitional forest coastal	396.5	396.5	396.5	396.5
Abies grandis	Transitional deciduous forest	0.2	0.2	0.2	0.2
	Wet transitional forest coastal	0.8	0.8	0.8	0.8
Abies lasiocarpa	Wet transitional forest coastal	8.1	0	0	0
Acer macrophyllum	Transitional deciduous forest	0.6	0.6	0.6	0.6
	Wet transitional forest coastal	5.8	5.8	5.8	5.8
Alnus rubra	Wet transitional forest	2.2	2.2	2.2	2.2
	Subalpine forest	6.9	6.9	6.9	6.9
	Transitional deciduous forest	2.6	2.6	2.6	2.6
	Wet transitional forest coastal	66.2	66.2	66.2	66.2
Betula papyrifera	Subalpine forest	1.6	1.6	0	0
	Wet transitional forest coastal	0.1	0	0	0
Cupressus nootkatensis	Subalpine forest	3.4	3.4	3.4	3.4
	Transitional deciduous forest	1.5	1.5	1.5	1.5
	Wet transitional forest coastal	2.4	2.4	2.4	2.4
Cornus nuttallii	Wet transitional forest	1	1	1	1
	Subalpine forest	0.2	0.2	0.2	0.2
	Transitional deciduous forest	0	0	0	0

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Appendix II, Table 8. Continued.

Species	Ecosystem	Time period (hectares of population)			
		Current	2020s	2050s	2080s
Cornus nuttallii	Wet transitional forest coastal	7.6	7.6	7.6	7.6
Picea engelmannii	Wet transitional forest coastal	25.8	0	0	0
Picea glauca	Subalpine forest	14	11.1	0	0
Picea mariana	Subalpine forest	11.5	8.8	0	0
Picea sitchensis	Wet transitional forest	2.9	2.9	2.9	2.9
	Subalpine forest	14.8	14.8	13.4	13.4
	Transitional deciduous forest	1.9	1.9	1.9	1.9
	Wet transitional forest coastal	34	34	34	34
Pinus albicaulis	Wet transitional forest coastal	6.0	0	0	0
Pinus contorta	Wet transitional forest	121.4	121.4	116	121.4
	Subalpine forest	30.9	30.9	30.9	30.9
	Transitional deciduous forest	177	177	176	177
	Wet transitional forest coastal	545.7	521	521	529.1
Pinus monticola	Wet transitional forest	0.7	0.7	0.7	0.7
	Transitional deciduous forest	2.3	2.3	2.3	2.3
	Wet transitional forest coastal	6.7	6.7	6.7	6.7
Populus tremuloides	Wet transitional forest coastal	32.7	32.7	32.7	32.7

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Appendix II, Table 8. Continued.

Species	Ecosystem	Time period (hectares of population)			
		Current	2020s	2050s	2080s
Prunus emarginata	Transitional deciduous forest	1.5	1.5	1.5	1.5
	Wet transitional forest coastal	1	1	1	1
Pseudotsuga menziesii	Wet transitional forest	96.3	95.7	92.9	96.3
	Subalpine forest	117.3	117.3	117.3	117.3
	Transitional deciduous forest	735.7	702.2	702.2	735.7
	Wet transitional forest coastal	2576.6	2544.1	2539	2556.4
Taxus brevifolia	Wet transitional forest	1.6	1.6	1.6	1.6
	Subalpine forest	0.4	0.4	0.4	0.4
	Transitional deciduous forest	0.4	0.4	0.4	0.4
	Wet transitional forest coastal	21.7	21.7	21.7	21.7
Thuja plicata	Wet transitional forest	57.8	56.9	43.1	57.8
	Subalpine forest	43.6	43.6	43.6	43.6
	Transitional deciduous forest	165.1	149.6	149.6	165.1
	Wet transitional forest coastal	804.7	803	788.8	804.7
Tsuga heterophylla	Wet transitional forest	119.1	119.1	119.1	119.1
	Subalpine forest	171.8	171.8	171.8	171.8
	Transitional deciduous forest	427.8	397	397	427.8
	Wet transitional forest coastal	1645	1631.7	1630	1640.4
Tsuga mertensiana	Subalpine forest	74.4	70.8	73.1	73.1
	Wet transitional forest coastal	100.9	100.9	86.3	86.3

Appendix II, Table 9. Yellowstone National Park population coverage under current and future climate change conditions.

		Time Period (hectares of population given for each time period)			
Species	Ecosystem	Current	2020s	2050s	2080s
Abies amabilis	Alpine Tundra	0.9	0.9	0	0
	Subalpine forest	1466	1425	1136	221
	Steppe	0.4	0	0	0
Juniperus scopulorum	Subalpine forest	97.5	97.5	94	1.3
Picea engelmannii	Alpine Tundra	0.8	0.8	0	0
	Subalpine forest	2354.5	2211.4	1623.7	224.2
	Steppe	15.4	0	0	0
Pinus albicaulis	Alpine Tundra	0.6	0.6	0	0
	Subalpine forest	1535.6	1467.9	1176	268.4
Pinus contorta	Alpine Tundra	2.1	2.1	0	0
	Subalpine forest	8323.7	8037.6	5837.3	780.5
	Steppe	39	0	0	0
Pinus flexilis	Alpine Tundra	0.1	0.1	0	0
	Subalpine forest	921.9	846.4	574.9	44
	Steppe	31	0	0	0
Populus tremuloides	Subalpine forest	409.6	393.8	308.3	112.3
Pseudotsuga menziesii	Alpine Tundra	5.1	5.1	0	0
	Subalpine forest	9812.7	9689.1	8350.5	3559.9
	Steppe	50.2	0	0	0