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## Problems and Prospects

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Natural Resources Canada

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Cover photo: Coast redwood seedlings in a 'Styroblock' container. (Photo by R. Winder)

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AGRO SUP DIJON Institut national supérieur des sciences agronomiques de l'alimentation et de l'environnement

# Table of contents

# 1 Abstract

Climate change threatens coast redwood (*Sequoia sempervirens*) within the extent of its current range along the western coast of North America, from southern California to southern Oregon. We examined the potential for assisted migration of coast redwood to the western coast of Vancouver Island as an adaptation strategy to counter climate threats. While many coast redwood trees have been planted successfully throughout the Pacific Northwest, the ability of the species to establish successive generations of seedlings in this region remains questionable. To address this, we first plotted potential optimal habitat for self-sustaining populations of coast redwood on Vancouver Island using several key factors, including optimal annual fog frequency (> 200 h), optimal elevation above sea level (20-300 m), aspects not facing and adjacent to the ocean, optimal mean spring temperature (>6°C) and optimal biogeoclimatic zone. Within this optimal habitat, we also plotted the variation in three relevant parameters: mean annual precipitation, mean summer humidity, and cumulative annual frost-free days. This resulted in a prediction of narrow strips of optimal habitat along the central west coast of Vancouver Island, wherein the best environmental trade-offs were located midway along coastal inlets. To assess the capacity of Sequoia to recruit naturally in these stands, we evaluated the germination of coast redwood seeds at various salt concentrations reported to negatively affect coast redwood growth. NaCl had a slight negative influence on germination and $MgCl_2$ showed no influence at all. Germination was relatively insensitive to the levels of salts tested in these *ex-situ* experiments, with only a slight negative influence of NaCl. We also compared the germination of seeds on three different substrates: natural soil from the area of southwestern Vancouver Island subject to coastal fog (Fairy Lake), on natural soil collected next to an established coast redwood tree growing at the Pacific Forestry Centre (PFC), and on a paper substrate (control). The seeds on these three substrates were incubated in normal spring (13°C/6°C) or warmer future (+5° warming, 18°C/11°C) diurnal (day/night) temperature cycles applicable to the fog zone. After 21 d, germination was nearly absent in the natural soils from Fairy Lake and the PFC soil incubated in the lower diurnal temperature regime, and somewhat reduced in the higher regime, with the soil from Fairy Lake providing the best result (only ca. 15% reduction) vs. the paper controls (ca. 25% reduction). The potential for recruitment of coast redwood planted in this region appears to increase with rising temperatures. Assisted migration of sustainable populations would therefore need to consider the influence of continued warming, which is, however, complicated by the unknown future behaviour of shifting ocean currents in the region as it warms, and their impacts on atmospheric temperature and fog formation in the region. Modelling these factors with increased resolution, establishment of field trials, and assessment of the social context and acceptability of moving this species would improve our understanding of the potential for assisted migration of coast redwood to Vancouver Island.

Le changement climatique menace le séquoia côtier (*Sequoia sempervirens*) dans l'étendue de son aire de répartition actuelle le long de la côte ouest de l'Amérique du Nord, du sud de la Californie au sud de l'Oregon. Nous avons examiné le potentiel de migration assistée du séquoia côtier vers la côte ouest de l'île de Vancouver en tant que stratégie d'adaptation au changement climatique. Alors que de nombreux séquoias côtiers ont été plantés avec succès dans tout le nord-ouest du Pacifique, une question demeure concernant la capacité de l'espèce à établir des générations successives de semis dans cette région. Nous avons d'abord identifié l'habitat optimal potentiel pour les populations autosuffisantes de séquoias côtiers sur l'île de Vancouver en utilisant plusieurs facteurs clés, y compris la fréquence annuelle optimale du brouillard (> 200 h), l'altitude optimale au-dessus du niveau de la mer (20-300 m), les aspects sans vis-à-vis et adjacents, à l'océan, température printanière moyenne optimale (>6oC) et zone biogéoclimatique optimale. Au sein de cet habitat optimal, nous avons également tracé la variation de trois paramètres pertinents : les précipitations annuelles moyennes, l'humidité estivale moyenne et les jours annuels cumulés sans gel. Cela a abouti à une prédiction de bandes étroites d'habitat optimal le long de la côte centre-ouest de l'île de Vancouver, où les meilleurs compromis environnementaux étaient situés à mi-chemin le long des bras de mer côtiers. Afin d'évaluer la capacité du Sequoia à recruter naturellement dans ces peuplements, nous avons évalué la germination des graines de séquoia côtier à diverses concentrations de sel signalées comme affectant négativement la croissance du séquoia côtier. NaCl a exercé une légère influence négative sur la germination et $MgCl_2$ n'a montré aucune influence. La germination était relativement insensible aux niveaux de sels de Na et de Mg testés dans ces expériences ex-situ, avec seulement une légère influence négative du NaCl. Nous avons comparé la germination des graines sur trois substrats différents : sol naturel de la zone du sud-ouest de l'île de Vancouver sujette au brouillard côtier (Fairy Lake), sur sol naturel recueilli à côté d'un séquoia côtier établi poussant au Pacific Forestry Centre (CFP), et sur support papier (témoin). Les graines sur ces 3 substrats différents ont été incubés dans des cycles de température diurnes (jour/nuit) normaux de printemps (13$^{o}$C/6$^{o}$C) ou plus chauds (+5$^{o}$ de réchauffement, 18$^{o}$C/11$^{o}$C) applicables à la zone de brouillard. Après 21 jours, la germination était presque absente sur les substrats naturels (sols Fairy Lake et CFP) incubé dans le régime de température diurne inférieur, et quelque peu réduite dans le régime supérieur, le sol de Fairy Lake fournissant le meilleur résultat (environ 15 %) par rapport aux témoins en papier (environ 25%). Le potentiel de recrutement de séquoias côtiers plantés dans cette région semble augmenter avec l'augmentation des températures; envisager une migration assistée de populations durables impliquerait donc de considérer l'influence du réchauffement futur. Ces considérations sont compliquées par des inconnues dans le comportement futur des courants océaniques changeants dans la région à mesure qu'elle se réchauffe, et de leurs impacts sur la température atmosphérique et de leur impact sur la formation de brouillard dans la région. La modélisation de ces facteurs avec une résolution accrue, la mise en place d'essais sur le terrain et l'évaluation du contexte social et de l'acceptabilité du déplacement de cette espèce amélioreraient notre compréhension du potentiel de migration assistée du séquoia côtier vers l'île de Vancouver.

## 2 Introduction

The purpose of this document is to explore the potential use of assisted migration (AM) to extend the range of *Sequoia sempervirens* (D. Don) Endlicher (coast redwood, coastal redwood, or California redwood) northward to the Pacific Rim of Vancouver Island. Coast redwoods are well-known to be among the largest trees and are an important endemic component of forests occupying coastal zones in California and southern Oregon. However, the International Union for Conservation of Nature (IUCN) has designated this tree species 'endangered', with its current habitat reduced due to past logging and facing the threat of further human encroachment (Farjon and Schmid, 2013). As the Earth's climate changes, warmer temperatures and associated droughts are also threatening habitat in the current native range of the tree (Brunhuber, 2015; Earle, 2020). While the specific response of mature coast redwood trees to climate change is uncertain (Carrol *et al*., 2014) and the climate tolerance for many species often extends beyond their current fundamental niche (Bocsi *et al*., 2016), there is ongoing concern for conservation of the species as climate change proceeds. Assisted migration of coast redwood provenances is an adaptation strategy that might help counter the potential impact of climate change and loss of habitat (Libby, 2017).

Plant species have the natural capacity to disperse into new habitats and adapt to change, but ongoing climate change is so rapid that many species are unable to naturally keep pace (Aitken *et al.*, 2008). AM has been used by humans since historical times but is only now being considered as a deliberate forest management tool to counter the effects of climate change, albeit not without challenges and controversy. Risks and problems to consider include potential invasiveness of the translocated species, disease introduction and exposure, differences in soil environments (pH, soil biota, etc.), proportional differences in climate parameters (temperature and precipitation ranges and extremes), differences in herbivory, etc. AM may involve the human-assisted movement of provenances to more suitable habitat within the native range of a species (assisted population migration, APM), translocation just beyond the current range (although possibly within the historic range) of the species (assisted range extension; ARE), or migration to a point well beyond the current range (assisted long-distance migration; ALM). APM carries the lowest risk for unexpected or undesired outcomes and is usually considered in the context of managing commercial forest species. ARE is also considered within a forestry context but may involve slightly increased risks and challenges while ALM is a method employed as a 'last resort' method for conserving endangered species as it involves higher risks and challenges (Winder *et al*., 2011). AM of redwood has been proposed as a potential method to conserve this species (Mandel, 2015; Libby, 2017; O'Hara *et al*., 2017). The strategy might also contribute to sustaining the productivity of coastal BC forests as climate change progresses (Artz, 2010; Mandel, 2015) for other declining species such as yellow cedar (*Cupressus nootkatensis*) (Buma *et al*., 2016; Comeau *et al*., 2019).

This report will focus on the prospects of using ARE to extend the range of coast redwood northward in a changing climate regime, along with the associated issues. Our specific objectives were to use known habitat characteristics to map areas of Vancouver Island where *ex-situ* conservation of self-sustaining coast redwood populations might be possible in a changing climate, and to test the ability of Vancouver Island soils to support germination of *S. sempervirens* seedlings. The latter is an important aspect of successful *ex-situ* conservation, where a complete life cycle (from seedling recruitment to full-sized trees at maturity) is required. Natural recruitment proceeds in a forest environment where competition, pests, and other selective pressures are extant. We hypothesized that the germination of coast redwood seeds would be reduced in soil with relatively low organic content (within the range of soils existing on Vancouver Island), colder temperatures, and higher sodium and magnesium salt concentrations.

# 3 Background

## 3.1 Coast redwood habitat

Coast redwood is a North American conifer famed as one of the world's tallest tree species. It is currently distributed in a narrow (ca. 8-56-km wide) band of coastal areas that extend almost 725 km from just south of 46° N latitude in Big Sur, California to just north of 42° north latitude in the very southern portion of coastal Oregon, normally not more than 30 km (up to 80 km) from the Pacific Ocean (Fig. 1). A Late-Holocene disjunct population may have existed as far north as the central Oregon coast (Gavin *et al*., 2013). Until recently, old-growth coast redwood forests covered approximately 70,000 ha within their native range. Less than 5% of that amount remains after extensive logging and clear-cutting, much of it as homogeneous, dense, and even-aged stands (Lalemand, 2018). The extensive decline in habitat leaves populations of this species vulnerable to further losses. Unfortunately, there are concerns that coast redwood may also be declining within its range due to climate change and associated changes in fog regimes (Brunhuber, 2015; Earle, 2020). While cone and seed production is abundant in the northern part of the range, it is more variable elsewhere (Olson *et al*., 1990; O'Hara *et al*., 2017), and trees in the southern part of the range tend to be clustered in canyon bottoms susceptible to disturbance (Lorimer *et al*., 2009). Dynamic range models based on climate variables generally predict attenuation of the southern portion of the range with a concomitant expansion to the north in warmer, drier climates. DellaSala *et al*. (2015) have used climate models to project a 21% loss of habitat supporting baseline distribution for the species by the 2050s. Fernández *et al*. (2015) developed models incorporating historical climate trends that generally project contraction of suitable climate in the southern portion of the species range and expansion towards the north in anomalous (warmer and/or drier) climates, with some relatively stable areas (refugia) also occurring within the range. Hargrove (2016) modeled several climate scenarios for coast redwood that also generally follow the trend of a northward shift. In addition to all these concerning trends, the requirements for coast redwood to reach future climate refugia may present significant challenges (Roberts and Hamman, 2016).

## 3.2 Current range constraints

In the current epoch, higher elevation and mountainous terrain, which are above fog decks where habitat may be increasingly xeric and characterized by serpentine soils (Zinke *et al*., 1986), limit eastward distribution of coast redwoods. While fires can be damaging to coast redwood in the northern part of its range, the species nevertheless copes with natural fire regimes in this region (Viers, 1980; Olson *et al*., 1990). Zinke et al. (1986) point out that serpentine soils east of coast redwood habitat in southern Oregon limit spread in that direction. The species is also sensitive to cold temperatures and frost (Snyder, 1992) which poses another challenge to northern expansion. Competing vegetation could theoretically constrain range limits; however, coast redwood is classified as a shade-tolerant, dominant climax species. Within its range, it coexists with Douglas-fir (*Pseutotsuga menzesii*)—a tree that is also dominant throughout the coast of the Pacific Northwest (Olson *et al*., 1990). With potentially optimal terrain in much of coastal Oregon being a relatively narrow region between the Pacific Ocean and mountainous terrain, we theorize that this coastal corridor would allow disturbances such as storms, fire, and floods to have a relatively strong influence on northward spread, in effect constituting a 'bottleneck' terrain. For example, tsunamis and storms periodically inundate the lowest seaward elevations, exposing prime areas for northward expansion to salt water. Likewise, fires, winter storms, and other natural disturbances might block or slow expansion further inland along this confined area. However, there is evidence that a disjunct population of coast redwood existed further north along the Oregon coast (Fig. 2, Table 1) during the recent epoch (late Holocene) either as a relict community or the result of long-range movement of propagules (Gavin *et al*., 2013).

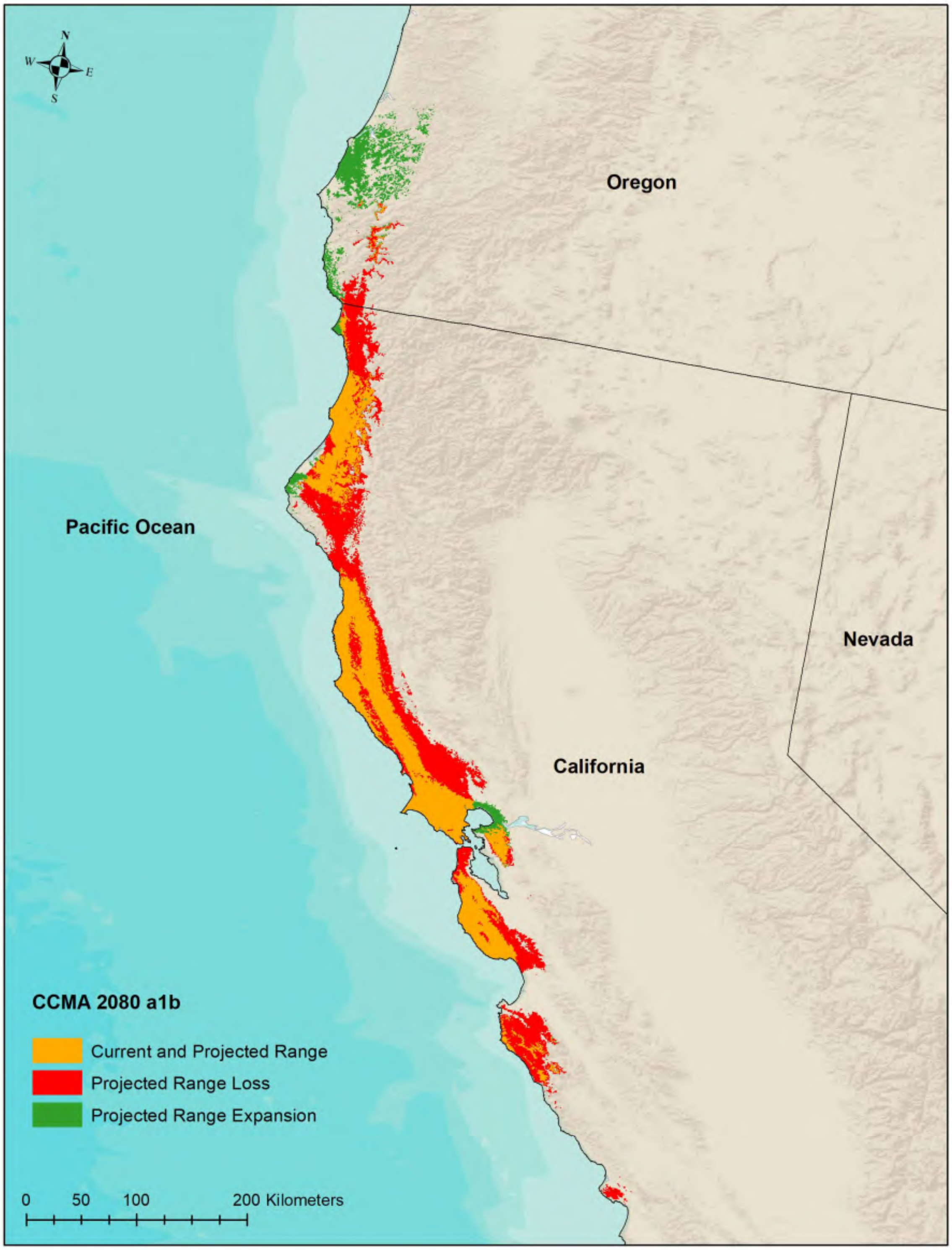

Figure 1. An example of projected shifts in distribution of coast redwood. The map shows the current range of the tree along with a 2080 projection of where it is anticipated to persist, using the CCCMA_2080_a1b climate model. It also shows where the model projects a loss or gain vs. the current range (per DellaSala *et al*., 2018). While a northward range expansion is projected, further northward extension of the range is not indicated within the timeframe and parameters considered by this particular model.

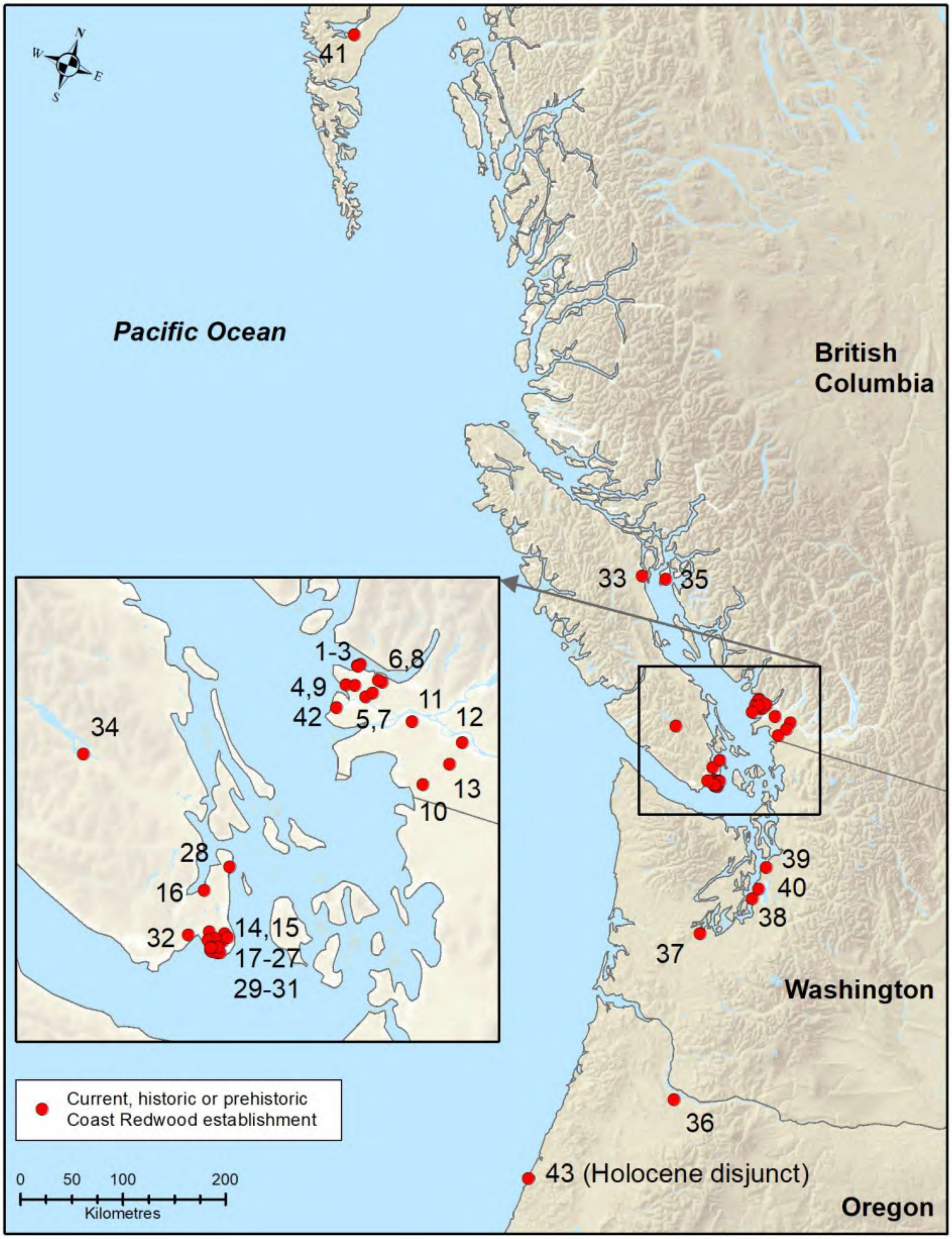

Figure 2. Forty-three documented coast redwood trees, groves, and plantations in the Pacific Northwest, from sources cited in Table 1. The southernmost marker indicates the potential northernmost extension of coast redwood in recent geological time; the remnants of an ancient stump there may correspond to a disjunctive Holocene population north of the current native range (Gavin *et al*., 2013).

Table 1. Sources of occurrence data used in Figure 2, for successfully planted coast redwood trees, groves, and plantations in the Pacific Northwest.

| Site(s) | Description | Source |
|---|---|---|
| 1-3 | Single trees, UBC Botanical Garden | UBC Botanical Garden, 2012 |
| 4 | Single tree, Private residence | " |
| 5-8 | Single tree, boulevard | City of Vancouver, 2021 |
| 10 | Grove >100 y-old, Redwood Park | UBC Botanical Garden, 2012 |
| 11 | Threatened mature tree | Diakiw, 2013 |
| 12 | 38 mature trees | UBC Botanical Garden, 2012 |
| 13-16 | Single tree, urban | Direct observation by R. Winder |
| 17 | Two trees, Butchart Gardens | " |
| 18-27 | Single tree, boulevard/park | City of Victoria, 2021 |
| 28 | Single tree, Sidney | Garman, 1949 |
| 29 | Single tree, urban | University of Victoria, 2020 |
| 30-31 | Single trees, urban | Anonymous, 2021 |
| 32 | Single tree, 47 y-old, removed | Seeman, 2017 |
| 33 | Single tree, urban | UBC Botanical Garden, 2012 |
| 34 | Research plot, Cowichan Lake Research Station | Direct observation (Figure 3) |
| 35 | Assisted migration plantation | Mandel, 2015 |
| 36 | 61 street tree records | City of Portland, 2021 |
| 37-39 | Single tree, urban | iNaturalist, 2021 |
| 40 | 66 street tree records[1], 26 > 30cm stem diam. | City of Seattle, 2021 |
| 41 | Species reported in 1964 survey | Calder and Taylor, 1968 |
| 42 | Vandalized mature street tree | Wood, 2018 |
| 43 | Relict (natural) Holocene stumps | Gavin *et al*., 2013 |

## 3.3 Climate

Redwoods are thought to be a relict species, a holdover from more diverse and widespread Mesozoic conifers. Since then, their distribution has changed considerably in response to changes in climate. During the Paleocene and Eocene Epochs (6.5-3.8 x $10^7$ y bp), they reached their widest and northernmost distribution, mixing with other conifers and ranging up 60°N latitude (Florin, 1963, Snyder, 1992). There is evidence of *S. sempervirens* occurring in Alaska, Eurasia, and Greenland. Cooler, drier temperatures during the Oligocene and Miocene (38-6 x $10^6$ y bp) accompanied a shift southward, until coast redwoods reached their present location during the Pliocene Epoch (Snyder, 1992). One study suggested that drought-induced limits to $CO_2$ availability might have been a factor involved with this range contraction (Quirk *et al*., 2013). Lack of drought tolerance has also been noted as a limiting factor in the post-glacial rebound in the distribution of conifer species in general (Elias, 2013).

### 3.3.1 Fog

The current core habitat of coast redwoods is characterized by cool summer temperatures and high humidity from fog. The occurrence of summer fog may be more important than precipitation in

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[1] Compilation of *S. sempervirens* data in the Seattle Street Tree Inventory provided by Roland Rundquist, City Arborist, Seattle Department of Transportation (Pers. comm. 2021)

delineating habitat because the area is also defined by the occurrence of summer droughts (Snyder, 1992). Fog interception is a key source of water for coast redwoods since it decreases water loss through evapotranspiration (Dawson, 1998; Burgess and Dawson, 2004; Simonin *et al*., 2009. In fact, coast redwood trees absorb as much as 40 percent of their water directly from coastal fog—an adaptation necessary in taller trees where transpiration stress might otherwise limit growth (Dawson, 1998; Burgess and Dawson, 2004; Simonin *et al*., 2009).

California's coastal fog has decreased significantly over the past century, associated with a decrease in atmospheric moisture and a lifting of the cloud deck (O'Brien, 2011). These changes have the potential to affect the entire coast redwood ecosystem (Hamilton, 2013), given that a cool coastal temperature regime and warm interior is one of the defining characteristics of California's coastal climate. Using a network of 114 temperature stations along the Pacific Coast, Johnstone and Dawson (2010) found that the coast-inland temperature contrast associated with fog has decreased substantially, not just in Northern California, but along the entire U.S. coastline (Sanders, 2010). Redwoods also depend upon deep, moist soils or ground water provided by rainfall during winter rainfall events. Mature coast redwoods are therefore unlikely to die outright with decreased fog, but there could be less recruitment of new trees, which would lack necessary water, high humidity, and cooler temperatures.

### 3.3.2 Temperature

Atmospheric temperature is an important characteristic of coast redwood habitat, currently bounded by monthly mean temperatures ranging between 2°C to 29°C and a mean annual temperature ranging from 10°C to 16°C. Proximity to the Pacific Ocean influences the degree to which temperature extremes are buffered, and by extension the suitability of areas for growth of coast redwoods (Snyder, 1992; Olson *et al*., 1990). Studies of coast redwood populations introduced to various parts of New Zealand have shown that about three quarters of the variability in growth rate (site index) is linked to differences in mean atmospheric temperatures and associated deficits in water vapor pressure. Site index was maximal (>45 m) above 15°C mean annual daily temperature, and minimal (<30 m) below 12°C (Palmer *et al*., 2012).

### 3.3.3 Elevation

Currently, coast redwoods occupy a range and habitat that generally includes irregular NW to SW ridges and deep, narrow valleys, with principal streams draining NW. The terrain is generally rough and steep, divided by both major streams and smaller drainages. Coast redwoods are distributed from approximately 0 to 915 m elevation (mostly 30-760 m). Growth of the largest trees occurs on flats and benches along the larger streams, on wetter coastal plains, river deltas, moderate westerly slopes, and valleys with seaward openings. Drier zones are less optimal for growth and seedling viability (Olson *et al*., 1990).

### 3.3.4 Soils and terrain

Soils are also an important component of coast redwood habitat. Distribution is sharply delimited by inland changes in bedrock and associated serpentine soils inhibitory to growth (Zinke *et al*., 1986). Areas directly adjoining the Pacific Ocean are also not necessarily favourable, as soils may accumulate deleterious concentrations of sodium and magnesium, and salt spray may cause foliar damage (Snyder, 1992; Wu and Guo, 2006). Within coast redwood habitat, predominant soils include Xerochrepts, Haploxerults, and Haplohumults (Hugo, Josephine, Melbourne, Empire, Sites, and Larabee series, orders Inceptisols and Ultisols), along with alluvial soils derived from these; the soils originate from consolidated or soft sedimentary rocks. The Hugo soil series (Typic Distrochrept, order Inceptisols) predominates in the natural range (Olson *et al*., 1990). Within coast redwood habitat, moisture ranges between 18-86% of soil storage capacity (62% being optimal) (Olson *et al*., 1990) and equivalents of replaceable calcium are reported to range from 4-80 or more, with 63 being optimum

(Zinke, 1964; Snyder, 1992). Coast redwood does not grow well on soils with high amounts of magnesium and sodium.

The aspect of coastal terrain is another factor that may constrain coast redwood habitat. Although most habitat borders the ocean, the species does not tolerate strong winds and is reported to be sensitive to salt spray carried inland during storms (Olson *et al.*, 1990, Wu and Guo, 2006). The soils of areas proximate to the ocean may also lack sufficient depth and fertility. With increasing altitude and slope, and decreasing moisture, coast redwoods have a smaller stature and other tree species begin to predominate. Habitat occurs in all aspects of terrain in its northern range, where the trees reach maximum growth and development. In the southern range of coast redwoods, its occurrence is limited to western or northern aspects; at the southern extreme the species almost exclusively occurs on narrow canyon floors in foothills adjacent to the ocean. At canyon mouths, the trees exposed to onshore winds frequently have flat tops with dead windward limbs—effects attributed to desiccation (Haasis, 1933). Coast redwoods reach their maximum size on alluvial flats where flooding generally limits competing species, resulting in nearly pure redwood stands (Olson *et al.*, 1990).

# 4 Potential AM of coast redwood to Vancouver Island

In the following sections, we use information from climate change models and environmental data to map potential areas where coast redwood populations might persist in a changed climate. We also describe seed germination experiments that examine the potential influence of Vancouver Island soils and temperatures on seedling recruitment

## 4.1 Distribution of *ex-situ* coast redwoods

*S. sempervirens* has been grown around the world, throughout the Pacific Northwest (Figs. 2-3, Table 1) and as far afield as New Zealand, for example (Palmer *et al.*, 2012). Could AM (the ARE mode) be used to conserve self-sustaining populations of coast redwood on Vancouver Island? By virtue of its northern location, Vancouver Island experiences cooler temperatures where coastal fog formation (and therefore suitable habitat for self-sustaining coast redwood populations) might persist.

Figure 3. Redwood plantation at Cowichan Lake Research Station (B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development) near Cowichan Lake, B.C.

## 4.2 Vancouver Island as potential future habitat

Plants are genetically adapted to prevailing climate conditions (Douhovnikoff and Dodd, 2011). However, genetic studies are needed to quantify these relationships. This is especially true for long-lived species like trees, where changes in climate can bring concerns about increased mortality, lowered potential growth rates, and increased susceptibility to insects and diseases. In this study, we considered habitat with a potential future climate similar to the contemporary climate of coastal California. We focused on coastal Vancouver Island, as it possesses the most optimal fog and temperature regimes for the growth of coast redwood.

## 4.3 The recipient ecosystem

The North Pacific Seasonal Sitka Spruce Forest (NPSSSF) occupies the hypermaritime zone along the Pacific Rim on Vancouver Island. Sitka Spruce (*Picea sitchensis*), the dominant or co-dominant tree species in this zone, can be associated with other conifers, including western hemlock (*Tsuga heterophylla*, often co-dominant), western redcedar (*Thuja plicata*), Douglas-fir (*Pseudotsuga menziesii*), shore pine (*Pinus contorta*) and yellow cedar (*Cupressus nootkatensis*), usually within 25 km of the Pacific Ocean (NatureServe, 2022).

### 4.3.1 Fog

Fog is also an important feature of the NPSSSF; it ameliorates the effect of summer droughts and therefore would be critical to recruitment and survival of coast redwoods. On Vancouver Island, maximum fog frequency occurs along the west coast, due to occurrence of a semi-permanent oceanic high-pressure cell (Fig. 4). Maximum fog frequency occurs during summer months (Pincock & Turner, 1955; Environment Canada, 2015). Diurnal fog also occurs, driven by daily temperature contrasts between air and water, fluctuating with daily heating and cooling. (Environment Canada, 2015). Coastal Vancouver Island also experiences advection fog, related to the movement of atmospheric waves ('stratus surges') that develop along the California coast and move northward along coastal Oregon and Washington to the west coast of Vancouver Island. (Environment Canada, 2015). Models also indicate a parallel increase in ocean upwelling and associated fog that may mitigate increased summer drought. However, current trends indicate a decrease in fog levels (NatureServe, 2022). The unknown future balance of summer drought intensity vs. fog intensity in this area may be an important caveat for any attempts to perform assisted migration of coast redwood in this region. If drought impacts increase along the Pacific Coast more generally, or if increased ocean upwelling and fog increases or maintains cooling and continues to favour Sitka Spruce forests rather than coast redwood, migration efforts may face barriers from both technical and conservation perspectives.

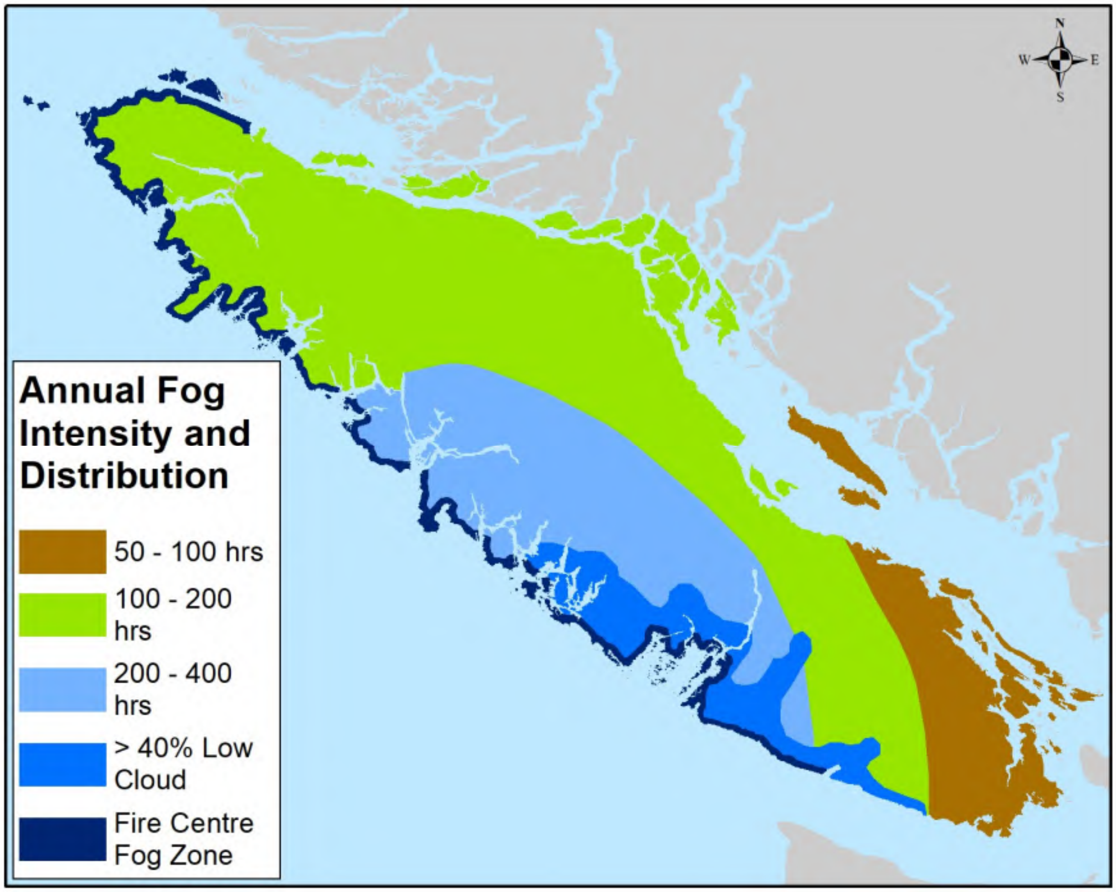

Figure 4: The annual intensity and distribution of fog and low cloud on Vancouver Island. Zones depicting annual hours of fog are derived from Toth *et al*. (2010). Low cloud incidence is derived from Dye *et al*. (2020). The official coastal fog zone defined by the B.C. Coastal Fire Centre is derived from B.C. Wildfire Service (2016).

### 4.3.2 Temperature

The mean annual temperatures found in most areas in Vancouver Island are colder than the 10°C-16°C range reported for current coast redwood habitat (Fig. 5). However, many species tolerate *ex situ* climates well outside their current niche; *in situ* temperature ranges may therefore be less suitable for modelling projected ranges (Bocsi *et al*., 2016). As there are many examples of coast redwood growing in the Pacific Northwest (e.g., Fig. 2, Table 1), it may be that mean annual temperature is a landscape characteristic of current habitat not directly responsible for biological limits to growth and survival. Considering the results of the germination experiment presented in section 6.3, the requirements of self-sustaining coast redwood populations might more directly involve mean spring temperatures above 6°C, as there was little germination detected at that temperature.

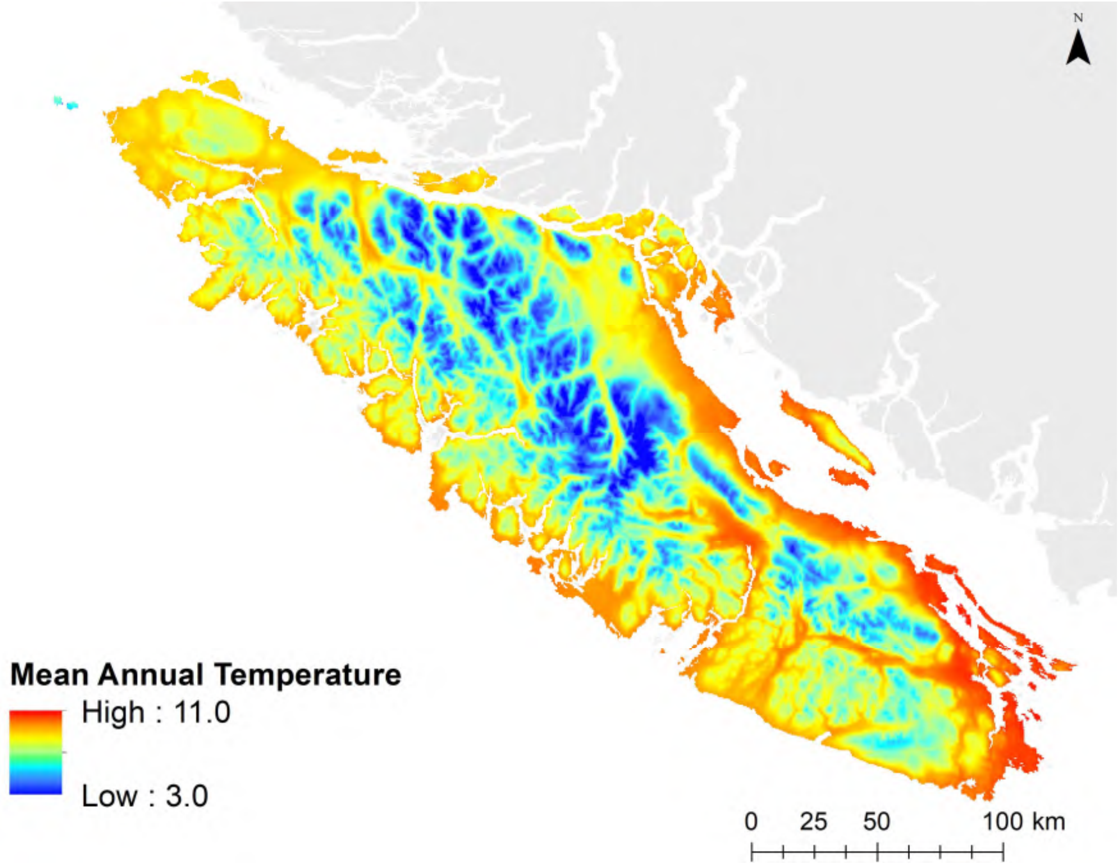

Figure 5. Mean annual temperatures (°C) for Vancouver Island, per data from the 'Climate NA Map' (University of British Columbia, 2019).

### 4.3.3 Precipitation

While winter rainfall is abundant in the NPSSSF, there is very little in the summer (Wolf *et al.*, 1995). Climate models for the area suggest that summer precipitation may decrease in this zone; this decrease could provoke shifts in vegetation in the region (NatureServe, 2022). Figure 6 illustrates the distribution of mean annual precipitation (mm) on Vancouver Island. We estimated that the most optimal habitat for coast redwood would occur in areas with moderate to high mean annual precipitation, which includes most of the western coast of the island but would exclude areas on the southwest coast southeast of the Jordan Plateau (the southwestern tip of the island). Snow falls during northerly Arctic outflow events, but accumulation is generally light along the west coast. Exceptionally, winds over water can pick up increased moisture and lead to more snowfall. This can be considerable when outflow winds move across the Strait of Georgia to the southern end of the Insular Mountain Range (Environment Canada, 2015).

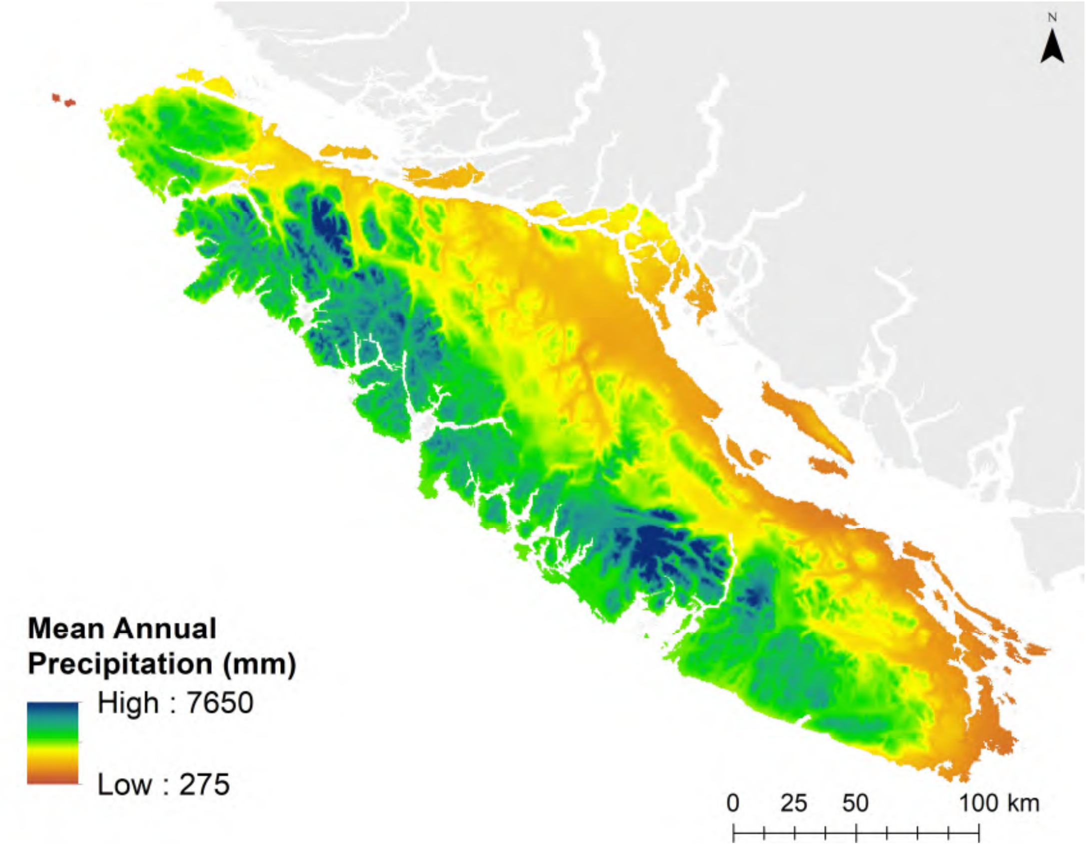

Figure 6. Vancouver Island Mean Annual Precipitation, per data from the ‘Climate NA Map’ (University of British Columbia, 2019).

### 4.3.4 Elevation

Elevations on Vancouver Island range from 0 to 1900 m above sea level (Fig. 7).

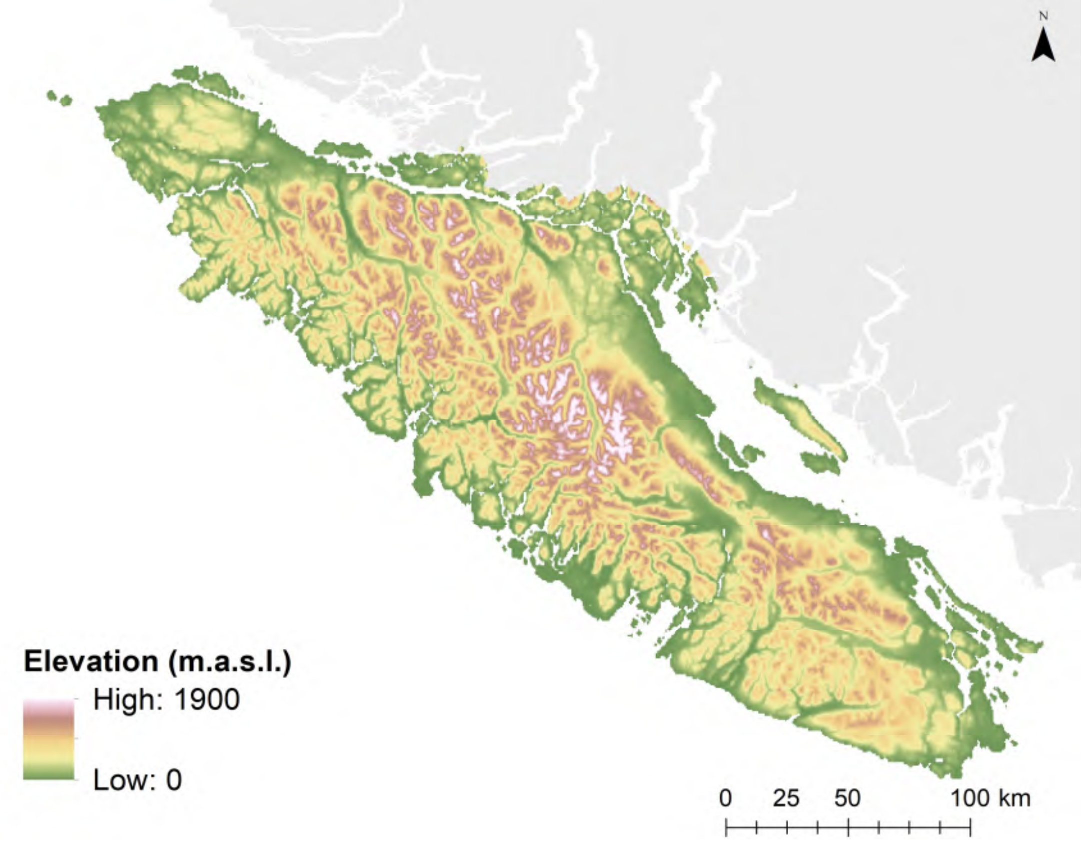

Figure 7. Elevations on Vancouver Island (1-1900 m above sea level) per data from Danielson and Gesch, 2011.

### 4.3.5 Soils & Terrain

Potential differences in soil characteristics are an important consideration in AM. For some tree species, soil physical properties and soil biota must be compatible with transplanted trees to ensure optimal seedling survival and the later growth of mature trees (Cleavitt *et al.*, 2011; Winder et al., 2020). There are ample examples of successful planting and growth of coast redwood trees throughout the Pacific Northwest (see Figs. 2-3, Table 1), suggesting that the species is compatible with a wide variety of soil types in the region.

Soils on the Vancouver Island predominantly include types of clay and silty clay, material from weathered metamorphic or volcanic rock, and layers with sand and gravel. They range from well-drained sandy brunisols to more developed, well-drained, sandy or gravel-laden podsolic soils on slopes. There are also thin upland and upper slopes soils, and organic/clay soils at the base of slopes and in depressions, especially in hypermaritime regions. Alluvial sites have high silt containing gravel and cobbles. (Semmelink *et al.*, 2012, B.C. Ministry of Agriculture and B.C. Ministry of Environment & Climate Change Strategy. 2018).

The Island's climate has a direct effect on soils, with temperature and moisture relatively cool and wet in the northwest and warm and dry in the southeast. This gradient affects soil composition, and the distribution and ecology of plant species. In the wettest parts of the Coastal Western Hemlock (CWH) biogeoclimatic (BGC) zone of coastal B.C., organic soil layers can accumulate to depths of 40 cm or more (Semmelink *et al*., 2012). Wetter subtypes include wet and very wet hypermaritime, maritime, and submaritime subzones (B.C. Ministry of Forests, 1991).

Natural recruitment of seedlings is a key life-cycle attribute that could be impacted by soils. Natural recruitment of coast redwood would be critical to completing the life cycle of the tree in a recipient habitat and maintaining sustainable populations without ongoing human intervention. There are anecdotal reports of natural recruitment occurring in coast redwoods planted at several sites in the Seattle, Washington area, although the degree of recruitment is uncertain due to confounding factors such as basal sprouting, 'guerrilla planting' by individuals, and deer browsing (Connie Barlow, Pers. Comm., 2020). The extent to which natural recruitment might be successful in this region is thus still unclear.

## 5 Mapping the potential for AM of coast redwood to Vancouver Island

To map potential habitat for self-sustaining populations of coast redwood on Vancouver Island, we overlayed several climatic, terrain, and ecological datasets to identify areas with optimal potential habitat using R software (R Core Team, 2020) and the 'Raster' package (Hijmans, 2022). A 500-m digital elevation model (DEM) was used to generate aspect and elevation layers. Recent climate data (2000-2010) from ClimateNA (Wang *et al.*, 2016) were also incorporated as layers in the model. We digitized a coastal fog-hours map and rasterized it, along with the Biogeoclimatic Zones of British Columbia, using the 500-metre DEM as a template. Consequently, the minimum mapping unit of the analysis was 25 ha. The environmental parameters described below were chosen to define and map the bounds of potential habitat on Vancouver Island.

We included areas of Vancouver Island experiencing 200 cumulative hours of fog or more. The southwest portion of the coast is reported to experience the greatest amount of fog on Vancouver Island (Environment Canada, 2015). This area approximately coincides with the 200-h+ fog zone estimated from Toth *et al*. (2010) portrayed in Fig. 4. It should be noted that our estimates of the fog zone derived from Toth *et al*. (2010) and Dye *et al*. (2020) are based on low resolution figures. The precision of our estimated potential habitat would improve with more detailed modelling and improved spatial resolution of the fog parameter.

Within the 200-h fog zone, we only included areas between 20-300 m above sea level. In its native range, the maximal elevation for the occurrence of coast redwood trees is 915 m (Olson *et al*., 1990). On Vancouver Island, however, fog normally occurs in low-lying areas (Pincock and Turner, 1955). The North Pacific Seasonal Sitka Spruce Forest occurring in this hypermaritime zone only extends 0-350 m above sea level (NatureServe, 2022); we therefore used 300 m above sea level as a conservative upper elevation limit for fog occurring within this zone. Areas lower than 20 m above sea level were excluded due to the potential for coastal flooding during extreme weather.

Coast redwoods are sensitive to sodium cations found, for example, in sea salt (Zinke, 1964; Snyder, 1992, Wu and Guo, 2006). Shoreline areas along the entire west coast of Vancouver Island can be exposed to rare but strong storm and tidal events that could inundate low-lying coastal areas and expose trees to relatively high levels of salt.

Areas likely to be exposed to winds carrying salt spray aerosols were also excluded from habitat. Again, this parameter accounted for the sensitivity of coast redwoods to salt as previously described. In their report on sea spray aerosol measurements and modelling, de Leeuw *et al*. (2000) found that the concentration of 10-m sea spray aerosols drops by roughly 90% at 5 km from the coast at an average wind speed of 2ms$^{-1}$ (7.2 kmh$^{-1}$). Additionally, the height of aerosol plumes did not exceed 55-60 m above sea level. Accordingly, areas were excluded from potential habitat if they were within 5 km of the coast, and below 55 m elevation with a south- to west-facing aspect (the direction of prevailing onshore winds).

Since the roots of coast redwood seedlings lack root hairs, the seedlings require ample soil moisture during their initial period of growth (Roy, 1966). Rapid establishment of root systems in moist soils during relatively abundant springtime precipitation and warmer spring temperatures is therefore a key factor for recruitment. Per the discussion in Section 4.3.5., soils in Coastal Western Hemlock very wet maritime (CWHvwm), or very wet hypermaritime (CWHvwh) BGC zones have the most humid soils in the region. Areas not in these BGC zones were excluded from potential habitat. Moreover, from our findings in germination experiments mentioned in Section 6, germination of coast redwood seeds is minimal below 6°C. We therefore excluded areas from habitat if their mean springtime (March-May) temperature during the past 10 years was less than 6°C.

Figure 8 shows 233,400 ha of coastal Vancouver Island matching all of the above criteria. This area would be our best estimate of potential habitat for establishment of self-sustaining populations of coast redwood. The mapped areas do not necessarily equate to current habitat in all respects. Differences in the previously discussed parameters will require further evaluation with field trials to understand how they may or may not limit growth and recruitment. Moreover, environmental parameters may improve or become more constraining as climate change proceeds. Evaluation of spacing, provenance, timing of planting, thinning, pest control, type of planting stock, competing vegetation, etc. would be necessary to truly refine this model.

Figure 9 shows a close-up map of the area containing potential habitat, wherein the current status of three important climate variables is shown on continuous scales. Mean annual precipitation is included for its impacts on soil moisture. Mean summer humidity is included for its correlation with summertime fog and amelioration of summer drought. 'Cumulative annual frost-free days' is an included parameter because increased frost frequency and colder temperatures would indicate longer periods of below-optimal conditions for seedling germination and growth. While the range of variation in these three parameters may not preclude the growth of coast redwood in the selected area, they would nevertheless serve as useful guides to consider in any selection of future test sites.

Regarding future test sites, the possibility of continuing climate change represents a complicating factor. To address this, we used two climate change scenarios to project potential changes in the three continuous variables within the habitat area. We generated climate projections with ClimateNA (Wang *et al.*, 2016), which we downscaled using a 500-m digital elevation model. The Canadian Earth System Model version 5 (CanESM5) and the Max Planck Institute for Meteorology Earth System Model version 1.2 (MPI-ESMI1.2) were selected for analysis, as among the global climate models (GCMS) in the Coupled Model Intercomparison Project phase 6 (CMIP6), these GCMs provide a strong contrast in projected temperature and precipitation changes in western North America (CanESM5 = warm, wet; MPI-ESMI1.2 = cold, dry). We acquired the projected seasonal and annual climate normals for 2040 and 2070 under Shared Socioeconomic Pathway (SSP) 245 (likely or intermediate greenhouse gas emissions scenario) and 370 (less likely or high greenhouse gas emissions scenario), outlined by Intergovernmental Panel on Climate Change (2022). For each GCM, SSP, and time period, the projected difference from the 2010-2020 (baseline, Fig. 10) mean annual precipitation (Figs. 11,12), summer relative humidity (Figs. 13,14) and annual cumulative frost-free days (Figs. 15,16) were calculated.

These figures may provide further insight into optimal locations that might be suitable for field tests. In general, areas midway along the length of coastal inlets are projected to experience mid-range values that might present the best trade-offs in view of fluctuations in the three variables.

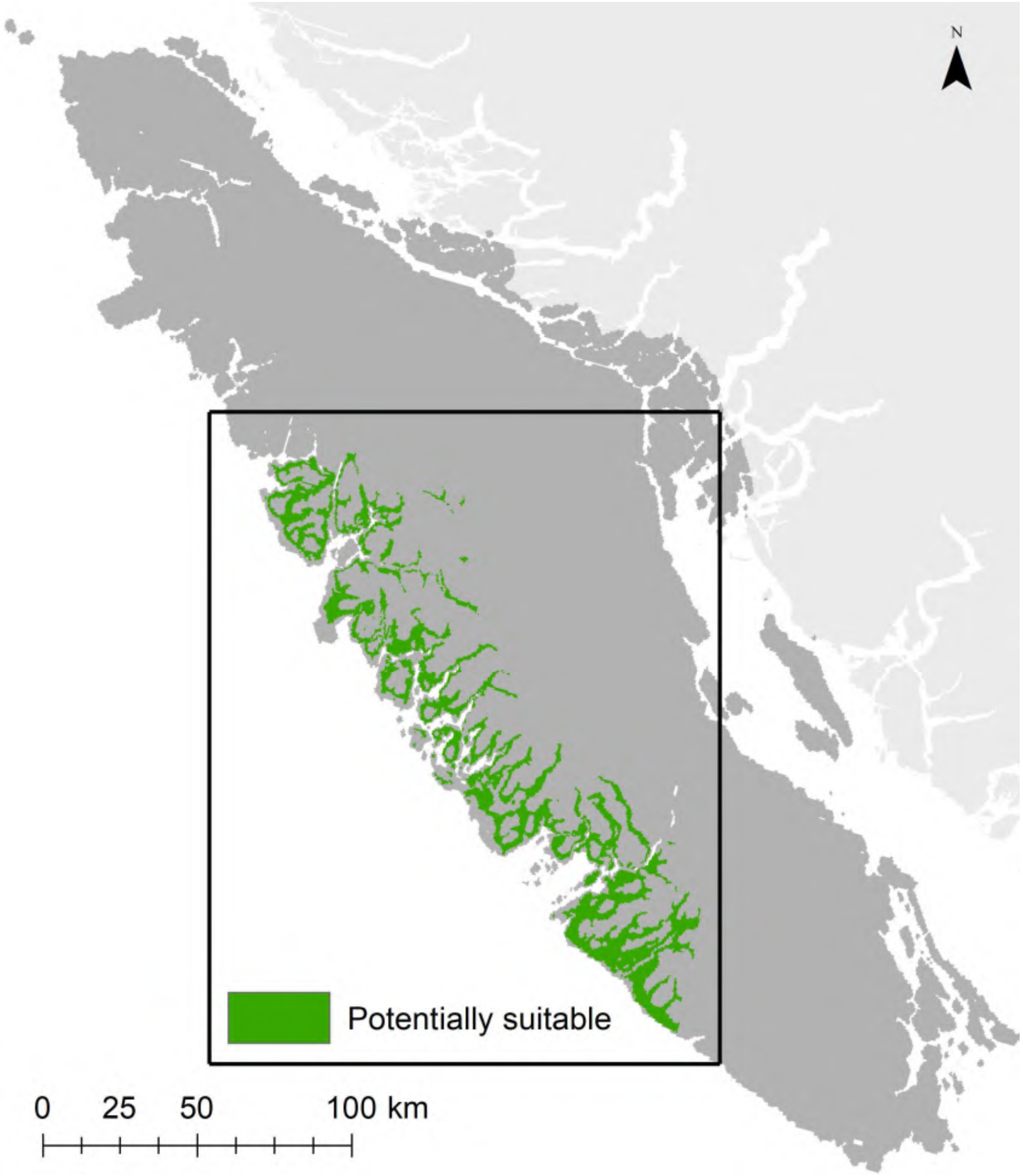

Figure 8: Current potentially suitable habitat (green areas) for assisted migration of self-sustaining coast redwood populations to Vancouver Island. The potential habitat corresponds to areas 20-300 m above sea level having an annual fog frequency of 200 hours or more. Areas were excluded if they were within 5 km of the coast and below 55 m elevation with a south to west-facing aspect (i.e., exposed to winds with salt spray). Areas were also excluded if they had mean spring temperatures less than 6$^{o}$C or were not in the very wet maritime (CWHvwm), or very wet hypermaritime (CWHvwh) BGC zones. The rectangular boundary indicates the specific area mapped in Figures 9-15.

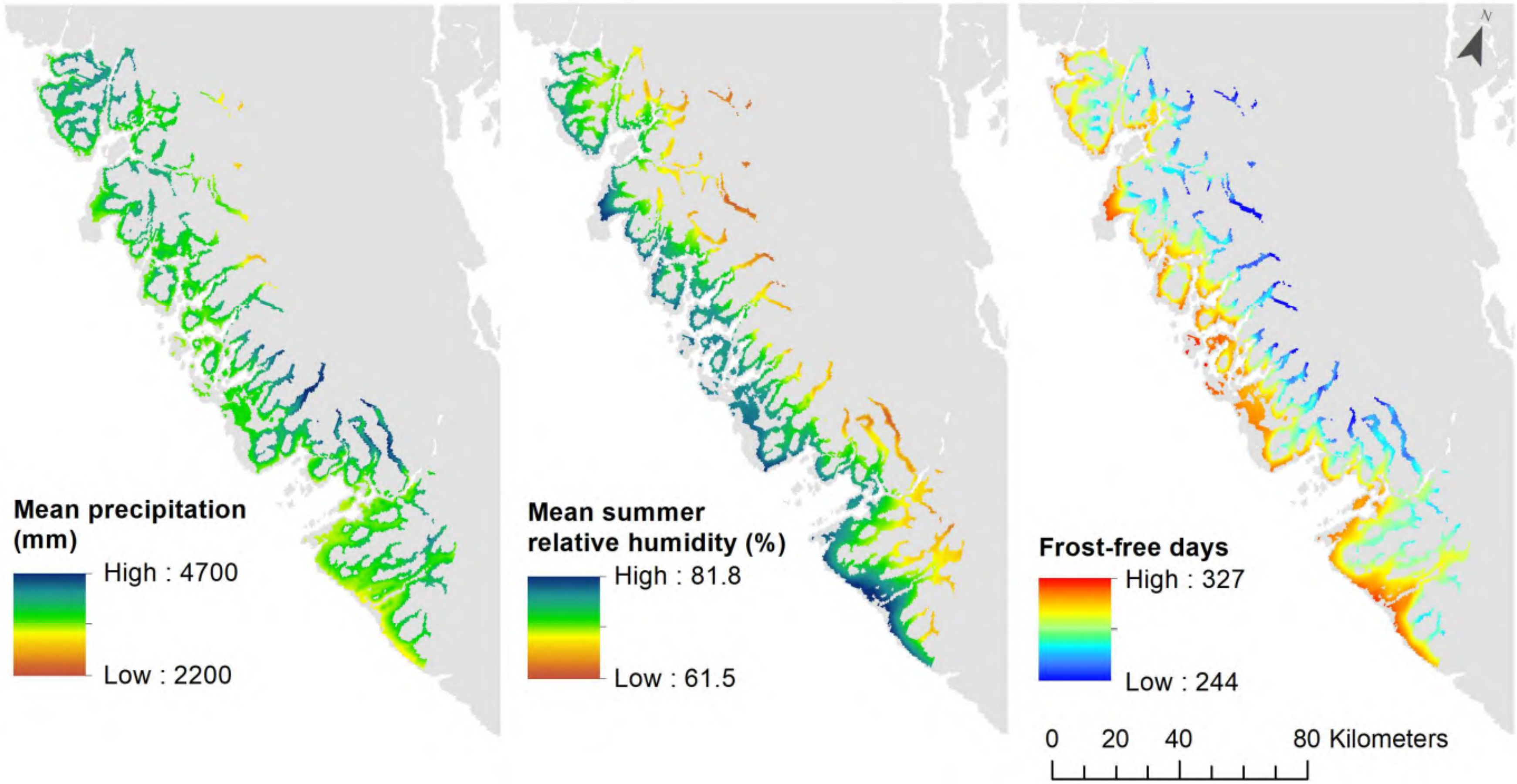

Figure 9. Baseline (current) environmental conditions within the potentially suitable habitat for self-sustaining coast redwood populations indicated in Figure 8. Mean annual precipitation (left), mean summertime relative humidity (centre), and cumulative annual number of frost-free days (right) are parameters pertinent to optimal recruitment of coast redwood seedlings.

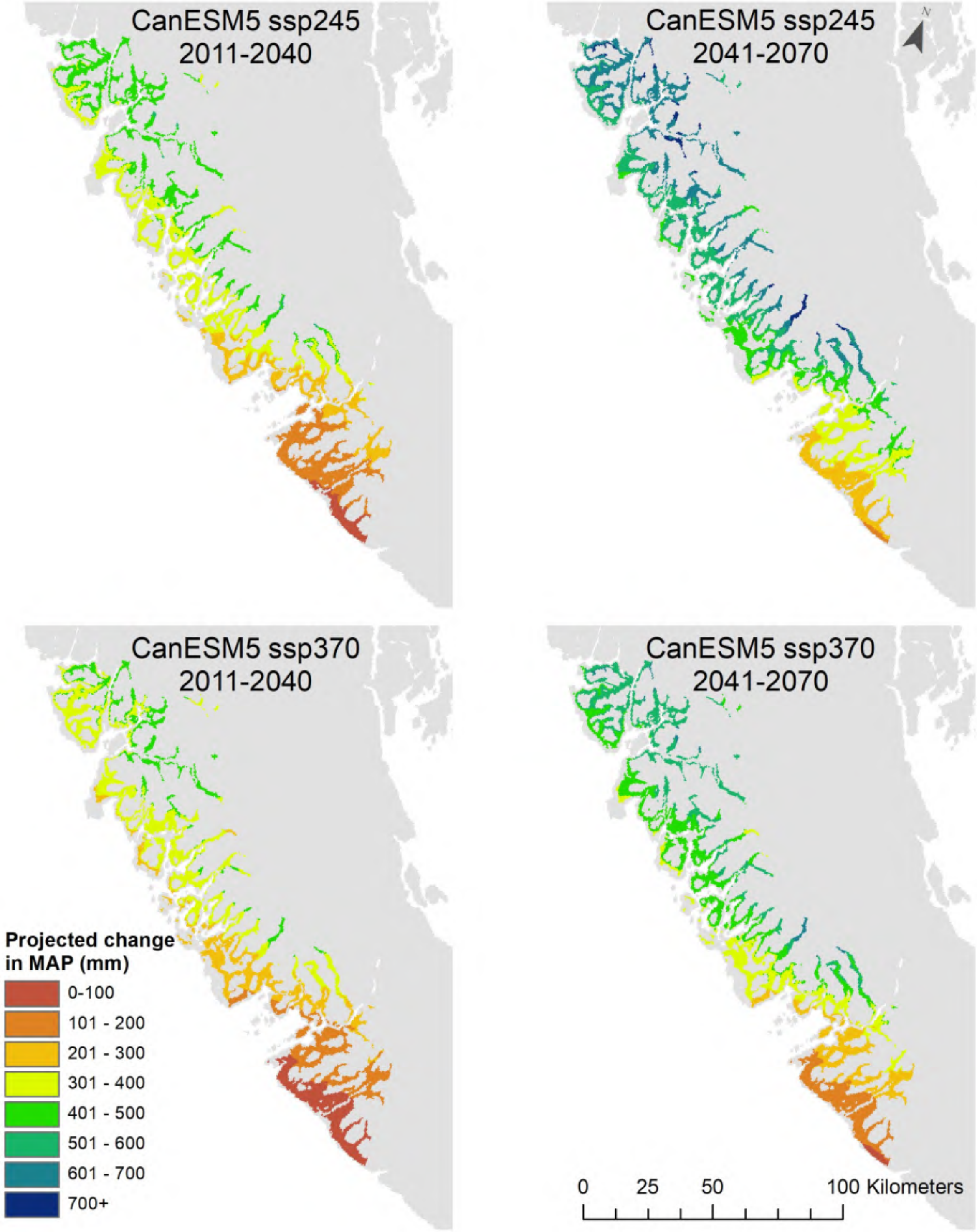

Figure 10. Projected change in future vs. current mean annual precipitation (2011-2040 period, left; 2041-2070 period, right) within the potentially suitable habitat for self-sustaining coast redwood populations indicated in Figure 8. Predicted changes are according to the CanESM5 ssp245 model (top) and CanESM ssp370 model (bottom).

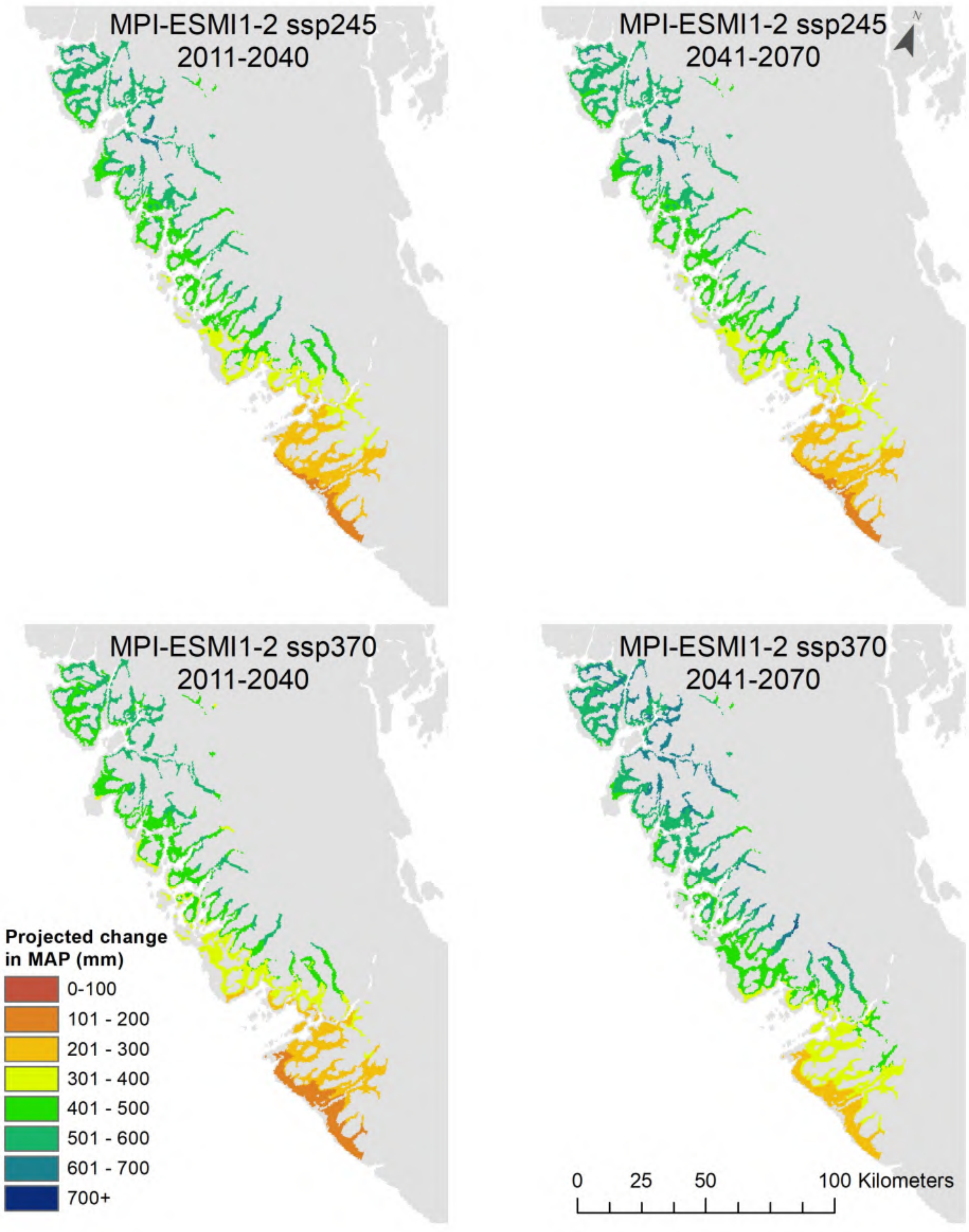

Figure 11. Projected change in future vs. current mean annual precipitation (2011-2040 period, left; 2041-2070 period, right) within the potentially suitable habitat for self-sustaining coast redwood populations indicated in Figure 8. Predicted changes are according to the MPI-ESMI1.2 ssp245 model (top) and the CanESM ssp370 model (bottom).

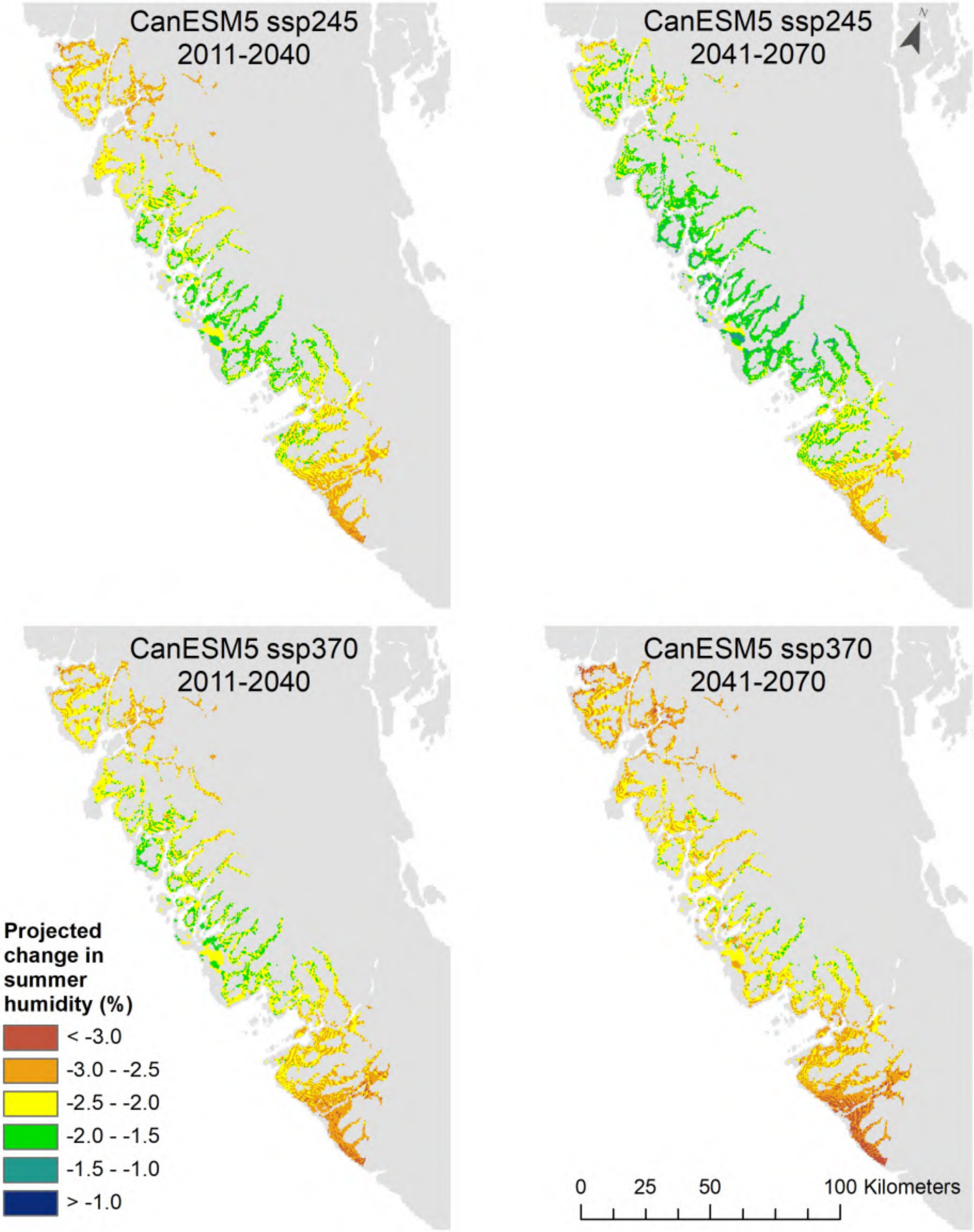

Figure 12. Projected change in future vs. current summertime relative humidity (2011-2040 period, left; 2041-70 period, right) within the potentially suitable habitat for self-sustaining coast redwood populations indicated in Figure 8. Predicted changes are according to the CanESM5 ssp245 model (top) and the CanESM ssp370 model (bottom).

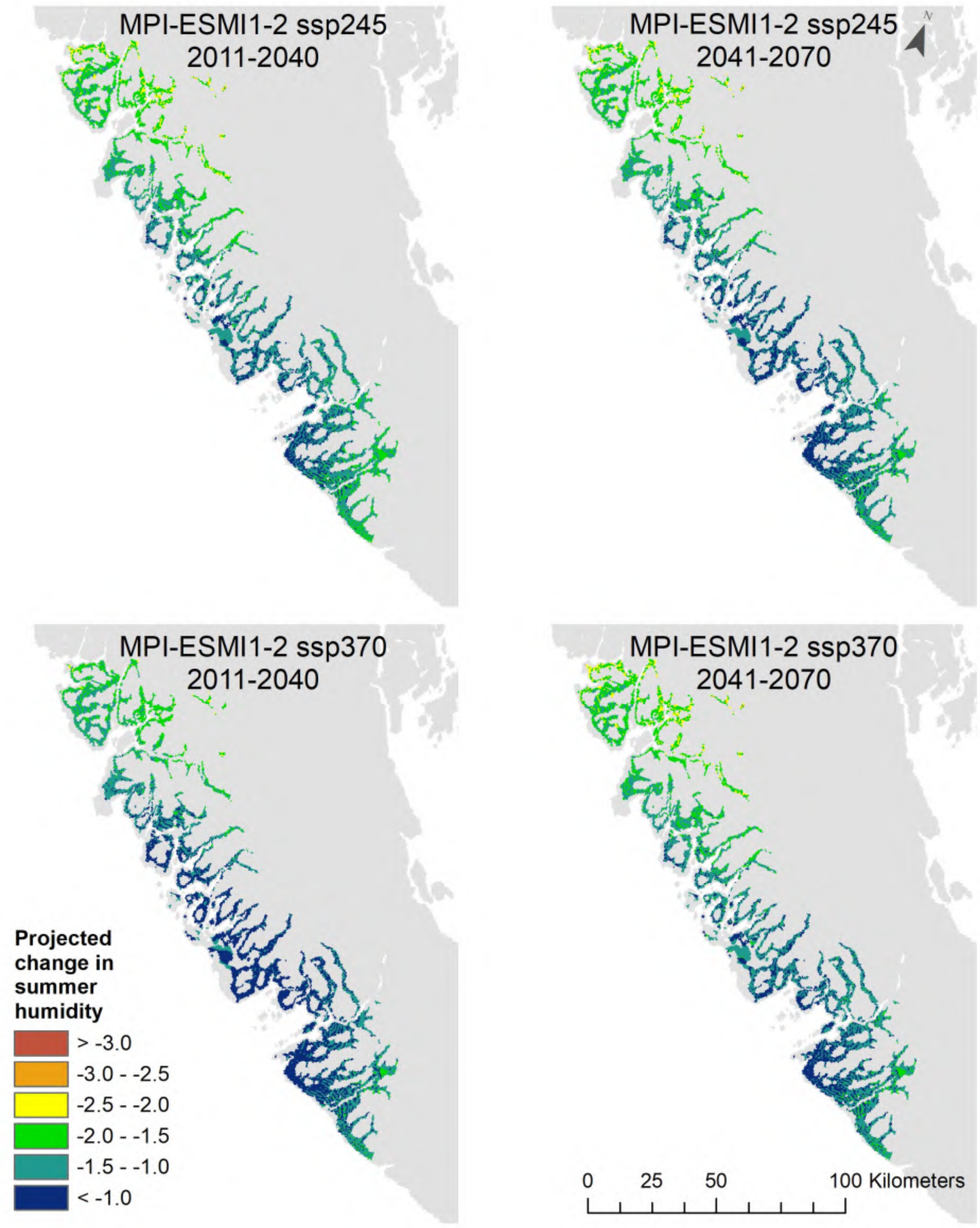

Figure 13. Projected change in future vs. current summertime relative humidity (2011-2040 period, left; 2041-70 period, right) within the potentially suitable habitat for self-sustaining coast redwood populations indicated in Figure 8. Predicted changes are according to the MPI-ESMI1.2 ssp245 model (top) and the CanESM ssp370 model (bottom).

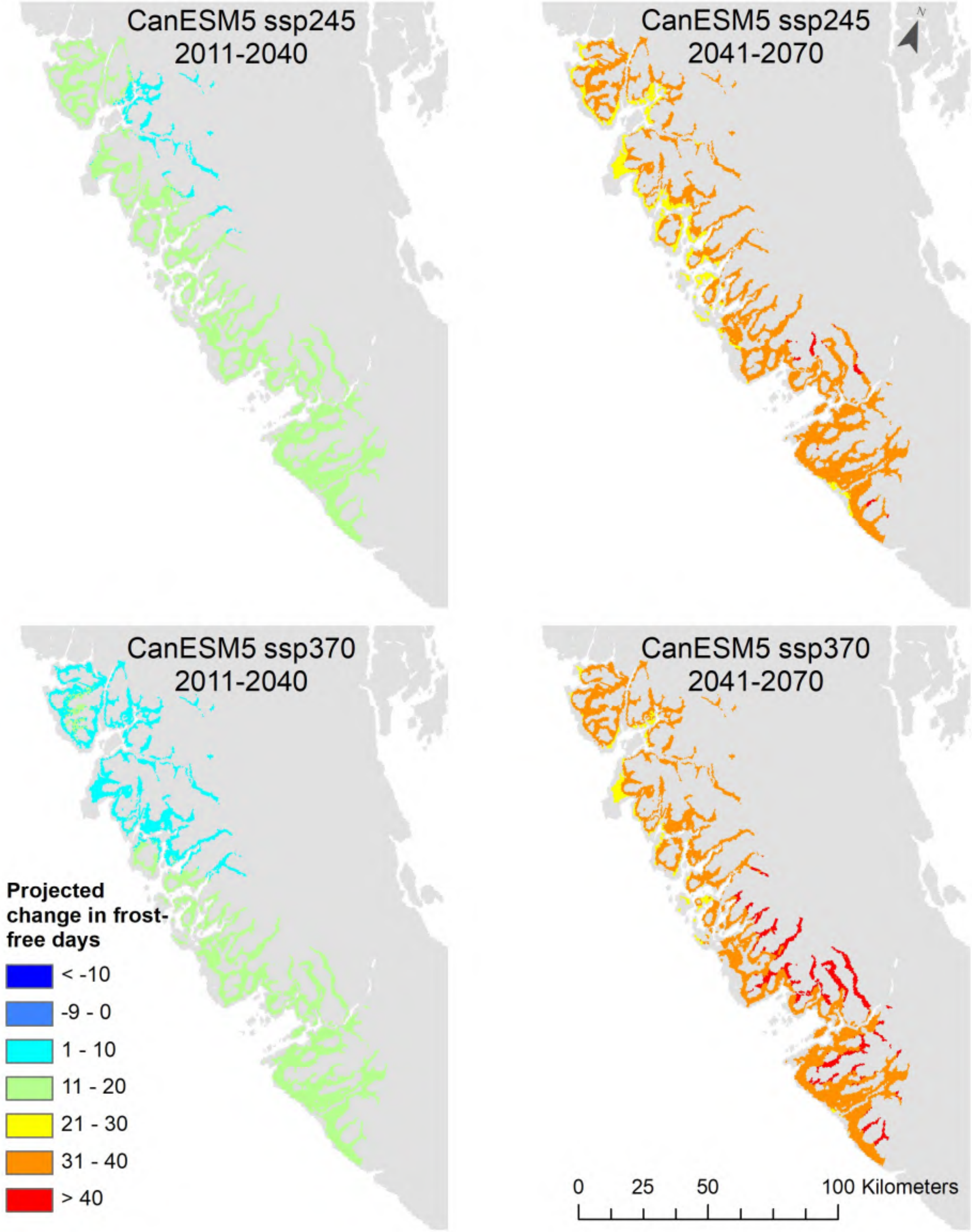

Figure 14. Projected change in future vs. current cumulative annual frost-free days (2011-2040 period, left; 2041-70 period, right) within the potentially suitable habitat for self-sustaining coast redwood populations indicated in Figure 8. Predicted changes are according to the CanESM5 ssp245 model (top) and the CanESM ssp370 model (bottom).

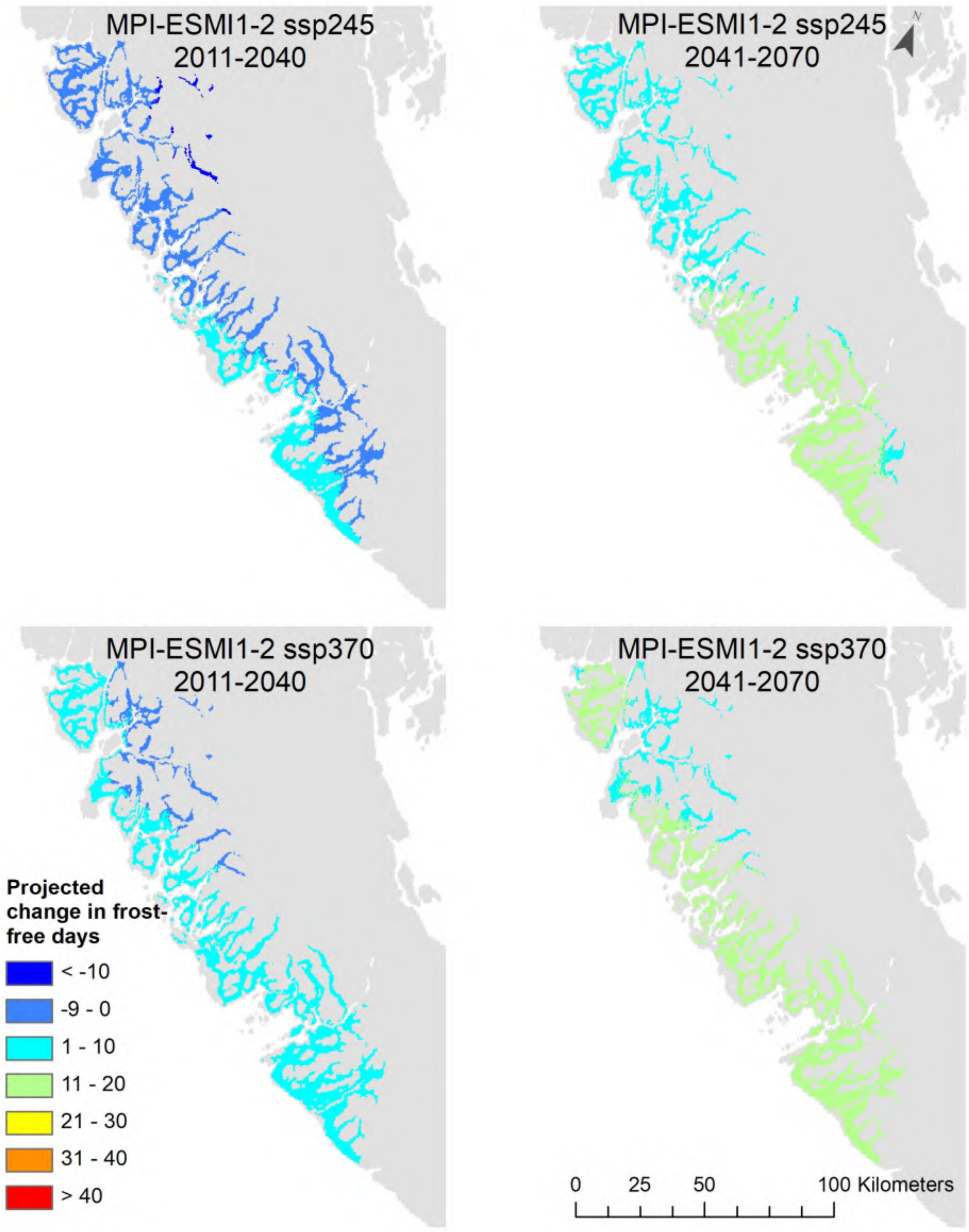

Figure 15. Projected change in future vs. current cumulative annual frost-free days (2011-2040 period, left; 2041-70 period, right) within the potentially suitable habitat for self-sustaining coast redwood populations indicated in Figure 8. Predicted changes are according to the MPI-ESMI1.2 ssp245 model (top) and the CanESM ssp370 model (bottom).

# 6 Seed germination trials

## 6.1 Viability check

Prior to their use in the germination tests described below, coast redwood seeds from California (Scheffield’s Seed Co., Inc., 269 Route 34, Locke, NY, 13092, USA, lot # 1819609, source FF-6-K, FB-3-C9) were stored and stratified at 5°C. To establish baseline viability, we incubated 25 seeds in distilled water at 20°C. Germination was 20% after 7 days, and 40% after several weeks, similar to the viability reported on the packaging (41%) and verifying that further cold stratification would be unnecessary.

## 6.2 Salt tolerance

### 6.2.1 Sodium chloride tolerance

We examined the effect of NaCl concentration on germination success, since coast redwoods are reported to be sensitive to the salt (Zinke, 1964; Snyder, 1992; Wu and Guo, 2006), and NaCl content in soils could therefore have an impact on successful natural recruitment of seedlings. Seeds were incubated at 20°C (14h diurnal photoperiod) in trays with one of six different unbuffered aqueous NaCl (ca. pH 7) solutions: 0 M (control), 0.0001 M, 0.0005 M, 0.005 M, 0.01 M and 0.02 M. HCl and NaOH were used to normalize unbuffered pH to 7.0 (for NaCl) or 6.0 (for $MgCl_2$), respectively, before preparing solutions. After 45 days, the number of germinated seeds was counted and germination versus salt concentration results were subjected to regression analysis using the data analysis tool of Microsoft Excel (Table 2). There was a slight but significant ($P<0.05$) trend to lower germination with increasing concentration of NaCl ($F<0.05$). However, the trend only accounted for less than 17% of germination variance (Fig. 16).

Table 2. Regression analysis of coast redwood seed germination (cumulative number out of 25 per experimental unit) incubated in solutions with increasing concentrations of NaCl.

| *Parameter* | *Value* |
|---|---|
| Multiple *R* | 0.409635771 |
| $R^2$ | 0.167801465 |
| Adjusted $R^2$ | 0.129974259 |
| *SE* | 1.775462525 |
| *N* | 24 |

ANOVA

| | *df* | *SS* | *MS* | *F* | *Significance F* |
|---|---|---|---|---|---|
| Regression | 1 | 13.98346 | 13.98346 | 4.435999 | **0.046825*** |
| Residual | 22 | 69.34988 | 3.152267 | | |
| Total | 23 | 83.33333 | | | |

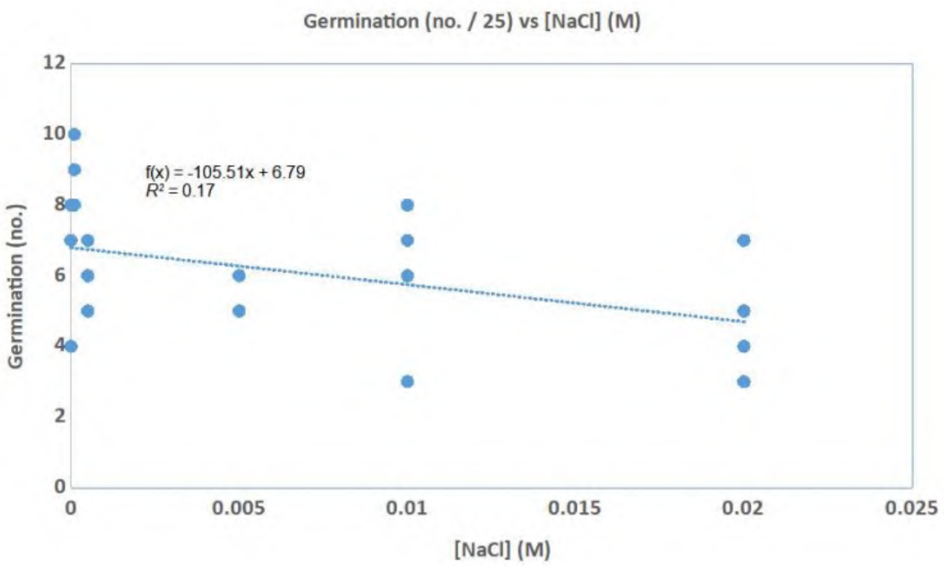

Figure 16. Regression plot for coast redwood seed germination (cumulative number out of 25 per experimental unit) incubated in solutions with increasing concentrations of NaCl. The regression trend was significant (*P*<0.05).

### 6.2.2 Magnesium chloride tolerance

Because coast redwood is also reported to be sensitive to magnesium chloride (Zinke, 1964; Snyder, 1992), we examined the effect of $MgCl_2$ concentration on germination success. Seeds were incubated at 20°C (14h diurnal photoperiod) in trays with one of six different unbuffered aqueous $MgCl_2$ (ca. pH 6.0) solutions: 0 M (control), 0.0001 M, 0.0005 M, 0.005 M, 0.01 M and 0.02 M. After 45 days, the number of germinated seeds was counted and germination versus $MgCl_2$ concentration and results subjected to linear regression analysis using the Data Analysis tool of Microsoft Excel (Table 3). Increasing concentrations of $MgCl_2$ did not produce a significant regression trend versus germination ($P>0.05$; Fig. 17).

Table 3. Regression analysis of coast redwood seed germination (cumulative number out of 25 per experimental unit) incubated in solutions with increasing concentrations of $MgCl_2$.

| *Parameter* | *Value* |
|---|---|
| Multiple *R* | 0.324058 |
| $R^2$ | 0.105014 |
| Adjusted $R^2$ | 0.064333 |
| Standard Error | 2.168816 |
| Observations | 24 |

ANOVA

| | *df* | *SS* | *MS* | *F* | *Significance F* |
|---|---|---|---|---|---|
| Regression | 1 | 12.14222 | 12.14222 | 2.581385 | 0.122386 |
| Residual | 22 | 103.4828 | 4.703763 | | |
| Total | 23 | 115.625 | | | |

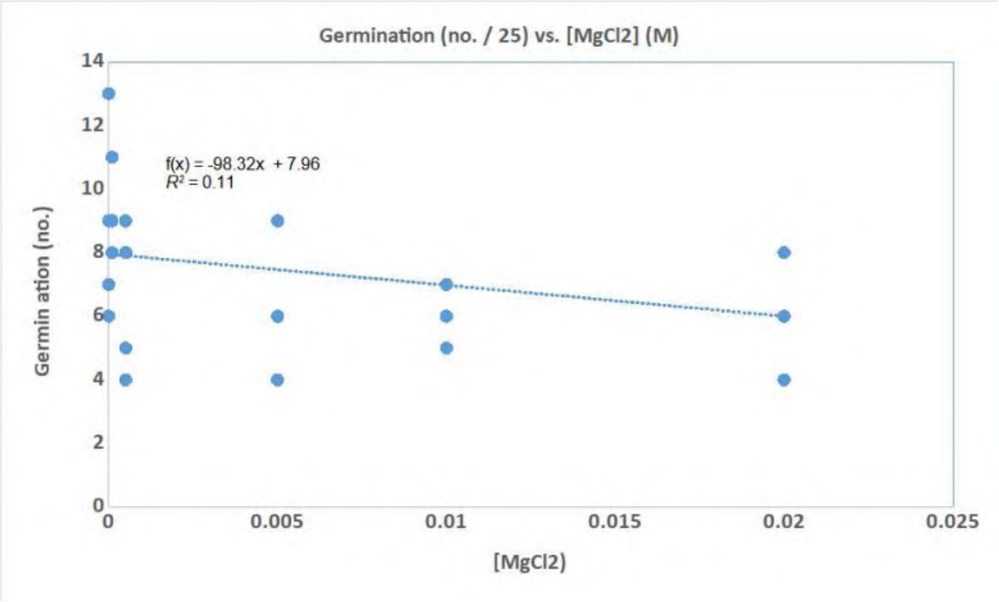

Figure 17. Regression plot for coast redwood seed germination (cumulative number out of 25 per experimental unit) incubated in solutions with increasing concentrations of $MgCl_2$.The regression trend was not significant (*P*>0.05).

## 6.3 Interactive effect of soil type and temperature on germination

To understand the potential impact of soil type and climate on germination success of coast redwoods, we designed an experiment that approximated contrasting spring conditions in Victoria, BC (southeastern Vancouver Island (drier Coastal Douglas-fir BGC zone) versus Fairy Lake (wetter western Vancouver Island Coastal Hemlock BGC zone).The experiment also compared contrasting soil types from these areas as a second factor. We altered the substrate used in prior experiments by instead using soil collected from deep organic layers at Fairy Lake (Fig. 18.) and sandy, gravelly clay collected under a redwood tree growing at Pacific Forestry Centre (PFC) in Victoria. (Fig. 19.). Soil samples were weighed, dried for 24 h in an oven at 80°C, and weighed again to determine their approximate moisture content. Samples were also evaluated on a dry weight basis (corrected for field moisture content) by the Chemical Services Laboratory at the Pacific Forestry Centre (D. Dunn) to determine pH, $[Na^+]$, and $[Mg^{2+}]$. The Fairy Lake soil samples were organic and had a relatively acidic pH of 4.2, while soil under the PFC coast redwood had a mineral component and its pH was 5.3. At Fairy Lake, water soluble $[Na^+]$ was 3.6 ppm vs. 5.0 ppm at PFC; $NH_4Cl$-extractable $[Na^+]$ was 20.6 ppm at Fairy Lake vs. 41.8 ppm at PFC. Water soluble $[Mg^{2+}]$ 7.8 ppm at Fairy Lake and 18.0 ppm at PFC; $NH_4^-$extractable $[Mg^{2+}]$ was 78.0 ppm at Fairy Lake vs. 609 ppm at PFC.

Assuming optimal soil moisture of >60% for germination of coast redwood seeds (Olson *et al*., 1990), distilled water was added to each soil to normalize all substrates to 62% moisture content. We compared incubation on the soil substrate using 30 x 20 cm trays, with 100 seeds placed equidistantly in a 10 x 10 grid. Instead of paper, germination substrate consisted of one of the two soil types. We conducted preliminary trials to vary humidity in open trays, using 40% (corresponding to the drier southeastern island conditions), or 90% (corresponding to the more humid western island conditions). However, the constant flow of air in growth chambers caused immediate drying of soils; humidity was therefore not included among the experimental parameters to be tested, and trays remained covered during incubation.

Figure 18. Soil collection site at Fairy Lake in western Vancouver Island. Large trees and deep (>3m) organic soils in the area are typical of sites in the fog zone.

Figure 19. Soil collection site at the Pacific Forestry Centre on Vancouver Island. The coast redwood pictured is growing in sandy, gravelly clay with a thin organic layer typical of the area.

Temperature was compared as a second factor in the experiment using a nested experimental design. Trays containing either one of the two soils or the control (paper) substrate were placed randomly in two different growth chambers, one set was incubated with a 13°/6°C day/night temperature, replicating spring-time temperatures on the west coast of Vancouver Island. The other set was incubated with an 18°/11°C day/night temperature, a 5°C increase corresponding to a 'High Emissions' global warming scenario for the year 2100 (United States Environmental Protection Agency, 2017). Germination status was assessed at the beginning of the germination period and throughout its peak (11, 13, 14, 15, and 21 days after the start of incubation). Data for final germination rate at 21 days were subjected to a two-way analysis of variance using Microsoft Excel (Table 4). Mean germination and *SE* was also graphed to compare germination rates throughout the incubation period (Fig. 20).

Table 4. Analysis of variance for effects of substrate and temperature on germination of coast redwood seeds in controlled environments after 21 days of incubation. Substrates consisted of soil from either Victoria, BC, Fairy Lake, BC, or paper (control). Temperature regimes corresponded to contemporary cold spring (13°/6°C day/night) or warmer spring (18°/11°C day/night).

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Substrate | 129.3333 | 2 | 64.66667 | 0.725686 | 0.497623 | 3.554557 |
| Relative temperature | 1734 | 1 | 1734 | **19.45885** | **0.000337*** | 4.413873 |
| Interaction | 484 | 2 | 242 | 2.715711 | 0.093168 | 3.554557 |
| Within | 1604 | 18 | 89.11111 | | | |
| Total | 3951.333 | 23 | | | | |

There was no significant effect of substrate, or interaction between substrate and temperature. Temperature regime, however, had a significant effect on germination success. This can be seen in Figure 20, where final germination in warmer temperature regimes was much closer to baseline viability in comparison to normal springtime temperatures. The implications of this result are that recruitment of migrated coast redwood populations may be relatively insensitive to different soil types on Vancouver Island, but it may be significantly reduced in colder temperatures. Temperature regimes may have to be warmer than current seasonal norms to ensure successful recruitment in migrated coast redwood populations.

Figure 20. Germination of coast redwood seeds (cumulative mean % ± *SE*) vs. incubation period, in different substrates (soils from Pacific Forestry Centre and Fairy Lake, BC, and paper (control) and different diurnal (day/night) temperature regimes (13°C/6°C vs. 18°C/11°C).

## 7 Discussion and Conclusions

Coast redwoods have been successfully planted throughout the Pacific Northwest (Figs. 2-3, Table 1). But can these trees complete their life cycle in this extended range and establish self-sustaining populations? The results of the seed germination experiments suggest that areas located within the fog zone of the western coast of Vancouver Island could provide habitat that would support natural recruitment, especially in a slightly warmer climate. Although exposure to sodium and magnesium cations is reported to be a limiting factor for redwood growth, the germination experiments did not establish salt exposure or soil type as a critical limitation to seed germination. Concerns about exposure to these salts may be more pertinent for later growth stages, or there may be other interactive factors such as soil pH or phosphorus concentration (Zinke *et al*. 1986), genotype (Wuo and Guo, 2006), or other parameters that could affect sensitivity.

With regard to self-sustaining populations, a salient point is the ability of coast redwood trees to regrow via stump resprouting. It is possible that migrated populations could be sustained via this mode of vegetative regeneration in the absence of seedling recruits. On the other hand, resprouting leads to a highly aggregated stand structure with sprouts clustered near older stumps (O'Hara *et al.*, 2017). Limited recruitment via seedlings in the current range already represents a limit to dispersion capacity (O'Hara *et al.*, 2017). Reliance on resprouting to maintain and sustain populations in the long term would be a constraint on further dispersion, genetic diversity, and adaptation of the species.

Notwithstanding planting success for individual trees and limited experimental stands, genetic studies have indicated that coast redwoods may have difficulty adapting to new climates or shifting to new habitats (Douhovnikoff and Dodd, 2011). New habitat may also be dynamic, rather than static and shifting temperatures may cause changes in soil microflora, with implications for nitrification rates and soil fertility in coast redwood habitat (Bradbury and Firestone, 2012). Increases in temperature, changes in ocean currents, and the current trend of reduced fog could lead to a decline of endemic species in the area, one that could be ameliorated through AM of more southern provenances or species such as coast redwood. On the other hand, severe reductions in fog might also limit recruitment of coast redwood seedlings.

In developing their models for climate impacts on the range of coast redwood, Fernández *et al*. (2015) highlighted the importance of considering oceanic effects in coastal regions. In the context of AM, changes in ocean currents and increased upwelling could lead to increased fog and cooler temperatures that would maintain the endemic forest type and make AM efforts counterproductive or shift these efforts to regions with more favourable conditions. On the other hand, there are troubling indications that flow of meso-scale ocean currents may diminish with increasing temperatures (Martínez-Moreno *et al*. 2021); thus, the implications for fog formation along the B.C. coast remain an open question. Consequently, successful AM of self-sustaining coast redwood populations would likely require higher resolution modelling and projection of future ocean upwelling and currents, and a better understanding of impacts of these factors on temperature and coastal fog formation.

Regarding terrestrial factors, it should be mentioned that a variety of existing models and computer programs can be used to help to address concerns about climate variables and the suitability of potential migration zones. These tools can support decisions on moving plant material across environmental gradients and provide a more quantitative approach to visualizing potential migrations. They could be applied to project the terrestrial parameters pertinent to migration of coast redwood and optimal habitat within the fog zone of the Pacific Northwest.

Setting aside the question of self-sustaining populations, it is already clear that coast redwood plantations can be established in the Pacific Northwest. Even so, data is still needed concerning suitability and mortality, competition with endemic flora, compatibility with soil microflora, and pest interactions within this region. The establishment of common garden trials per the suggestion of O'Hara *et al*. (2017), including translocation trials along Vancouver Island's Pacific Rim, would help to further understand those factors, along with climatic constraints on growth and recruitment. This would be particularly important if the regional climate change produced ca. 5°C warmer springtime soil temperatures, shifting mean annual temperatures from the lower end of the optimal growth range and potentially improving natural seedling recruitment by warming soils. Understanding the social context and acceptability of moving this species is also something that would need to be examined. Managed plantations are a potential venue for *ex-situ* conservation of the species and offer a way to study the potential for assisted migration efforts to conserve the species in the Pacific Northwest.

Figure 21. Close-up of foliage on a coast redwood seedling

## 8 Acknowledgements

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