Drought, wildfire, and climate change in Metro Vancouver's water supply area

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Introduction

Periods of drought will inevitably occur in any region and will impact forests in a number of ways, ranging from direct physiological impacts to indirect influences on insect and pathogen populations and increased wildfire activity. Forested ecosystems are adapted to withstand a certain amount of drought. However, the combined influence of a changing climate, forestry, land use change, and fire suppression have acted, over the last century, to create forests that are not in balance with the climate. This adds further stress to ecosystems, and can lead to an increase in baseline mortality rates, large-scale die-off due to pest outbreaks, and severe megafires that can transform large forested areas (Allen *et al.* 2015).

These issues will increase the challenge of managing forests in the 21st century. Recently, there has been a call for increasing the resilience of forested ecosystems so that they can recover from disturbances, including wildfires and insect outbreaks. However, there is concern that particular thresholds may be reached, forests will transition to different ecosystems, and crucial ecosystem services could be compromised (Millar and Stephenson 2015).

These concerns are of particular significance to the Water Supply Area (WSA) of Metro Vancouver, which supplies drinking water to over 2.4 million people. Metro Vancouver has committed to "provide clean, safe drinking water and [to] ensure its sustainable use" (Metro Vancouver Regional District 2011). This goal will require a thorough understanding of how future trends in the climate will impact ecosystems within the WSA.

This report details the impact of climate on the forested ecosystems of the WSA. It examines disturbance and climate history in the area, as well as outlines possible future trends. It begins with a general discussion of how drought impacts forested ecosystem, both directly and indirectly, followed by a more detailed discussion regarding the history of wildfires, insect outbreaks, and drought within the WSA. The report also includes an examination of future trends within the region, including predicted shifts in species ranges, as well as changes in fire activity and the probability of insect outbreaks.

Overview of Metro Vancouver's Water Supply Area

The WSA is located on the southern slopes of the Pacific Ranges of the Coast Mountains, at the northern extent of Metro Vancouver. It consists of three separate watersheds: the Capilano, Seymour, and Coquitlam watersheds, which have areas of 198 km^2, 126 km^2, and 212 km^2, respectively. These watersheds are characterized by significant topographic relief, ranging in elevation from 150 to 1800 metres above sea-level. Figure 1 provides the location of the watersheds, along with the boundary of the southern portion of the Coastal Fire Centre, which will be the focus of this report. Figure 1 also provides a map of summer precipitation amounts across the region. The data used for this map was taken from the Climate North America interpolated climate dataset (http://cfcg.forestry.ubc.ca/projects/climate-data/climatebcwna/). Prevailing weather patterns, and a general increase in precipitation with altitude results in elevated precipitation within these watersheds, relative to the surrounding regions. The northeastern section of the Coastal Fire Centre is within the rain shadow of the Coast Mountains and sees significantly lower precipitation than the WSA.

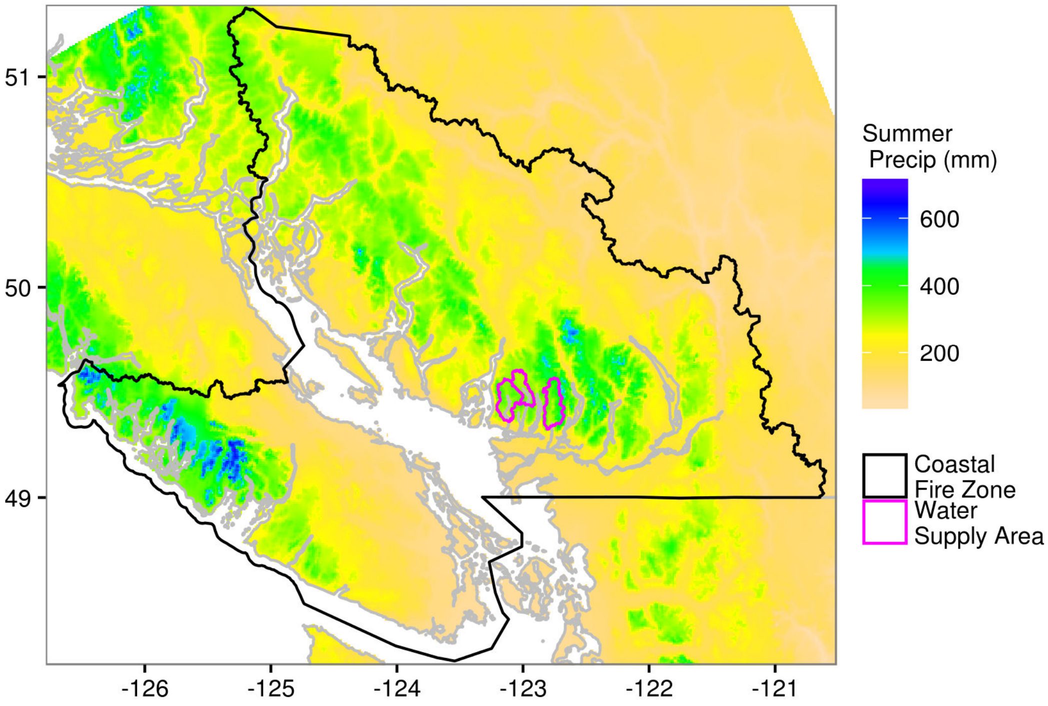

Figure 1: Location of the Water Supply Area the southern portion of the Coastal Fire Centre, and total summer precipitation in mm.

The wet forests of the WSA are dominated by Western hemlock (*Tsuga heterophylla*), western redcedar (*Thuja plicata*), Pacific silver fir (*Abies amabilis*), and Douglas-fir (*Pseudotsuga menziesii*). A number of deciduous trees including red alder (*Alnus rubra*), big leaf maple (*Acer macrophy1lum*), and black cottonwood (*Populus trichocarpa*) are also found in the area. 63% of the watershed is within the Submontane and Montane Very Wet Maritime variant of the Coastal Western Hemlock biogeoclimatic zone (CWHvm1 and CWHvm2) (Green and Klinka 1994). Western hemlock and Pacific silver fir are the dominant tree species within these areas, while western redcedar is a secondary species. Douglas-fir is found within the lower elevations and on warmer south-facing slopes. Above the Coastal Western Hemlock zones is the Mountain Hemlock zone (Windward Moist Maritime variant), MHmm1 which covers 30% of the WSA area. Here the forests are composed primarily yellow cedar, Pacific silver fir, and mountain hemlock (*Tsuga mertensiana*) (Green and Klinka 1994).

Drought and wildfire impacts on forest ecosystems

Reduced moisture availability and excess heat can impact forest health in a number of different ways that in turn can lead to crown die-back (or defoliation), or large-scale mortality (Allen *et al.* 2015). Such events can accelerate ecological transitions and species migration. Mature vegetation can withstand a certain range of climatic conditions; they will continue to grow but perhaps with less vigor as the climate changes. However, since seedlings are much more sensitive to climate variability (Littell *et al.* 2010), the resulting plant community following a large disturbance will likely shift to favour the new climatic conditions.

Drought and heat can have a number of direct physiological impacts on trees, although the details and relative importance of these processes are still being debated (Fettig *et al.* 2013). In extreme cases, the rate of evaporation from a tree's needles or leaves overwhelms the uptake of moisture from the roots, leading to a collapse of the water column that supplies moisture to the tree's canopy (Anderegg *et al.* 2015). To reduce the loss of moisture during periods of drought, trees often partially or fully close the pores or stomata that they use to exchange gases with the atmosphere. However, this also reduces rates of photosynthesis and the uptake of carbon. If drought conditions persist long enough, this "carbon starvation" can reduce plant growth and vigour. (McDowell *et al.* 2008)

These physiological impacts can also limit a tree's ability to develop and maintain energy-intensive defenses against insects and pathogens. Moreover, because many stages of an insect's life cycle are strongly dependent on temperature, increased temperatures and reduced moisture can benefit insect populations and pathogens (Bentz *et al.* 2010). For instance, during warmer periods, insects may complete their life cycle in one year instead of multiple years, and adults can live longer (Bentz *et al.* 2010). Consequently, higher temperatures can increase reproduction rates and the probability of an outbreak, although insect population dynamics are also driven by a complex mix of additional factors (Millar and Stephenson 2015). Insect populations also benefit from reduced moisture and precipitation

(Peterson *et al.* 2014). Compared to insects, the impact of climate on pathogens is more uncertain. Fungal pathogens can increase during warmer temperatures (Daniels *et al.* 2011), although they also benefit from moist conditions (Fettig *et al.* 2013).

Along with insects and pathogens, wildfire is the other major indirect impact of drought on forests. Obviously, periods of low moisture will reduce fuel moisture and increase the probability and severity of fires. Most ecoregions in western North America see increased fire activity during periods of low precipitation and high drought severity (Littell *et al.* 2009). Persistent drought can also pre-condition forests to burn by increasing mortality and the amount of dead fuels present (Millar and Stephenson 2015).The impact of fire on ecosystems can also be larger for drought-stressed forests.

As previously mentioned, periods of drought are inevitable. However, faced with a warming climate, increased attention has been paid to what's been termed “Hotter Droughts” or “climate-change type droughts” (Allen *et al.* 2015). Increased temperatures will exacerbate many of the drought impacts mentioned above. Indeed, damage to forest health is greater for warmer droughts, and increased temperatures can overwhelm the benefits of increased precipitation (Millar and Stephenson 2015). van Mantgem *et al.* (2009) found increasing background mortality rates in old forests across western North America. As these forests were found across a range of climates, fire regimes, and fire suppression histories, these results suggest that increased temperature was the primary cause of increases in mortality rates. Hotter droughts will also reduce snowpacks, extending the snow-free season and increasing the likelihood of early season fires (Westerling *et al.* 2006).

Allen *et al.* (2015) suggest that in the future these hotter droughts could have serious consequences for forest health, leading to wide scale mortality. The authors also warned that the scientific community have thus far underestimated the potential negative impacts of hotter droughts, especially for wetter forest such as those found in the Metro Vancouver WSA.

Drought, wildfire, pests, and forest health in Metro Vancouver's WSA

The forests within the WSA are “energy-limited” ecosystems. That is, their growth is limited by the amount of sunlight they receive, and, with over 2300 mm of mean annual precipitation (Aresenault

1995), there is more than enough precipitation to sustain their current growth rates. Moreover, unlike the drier forests of British Columbia, fire suppression has likely not increased stand density or fuel amounts within the WSA (Schoennagel *et al.* 2004). This is important because the most extreme examples of large-scale forest mortality generally occur in moisture-limited forests, which are closer to exceeding low-moisture thresholds that can lead to increased mortality, and in overly dense stands. It is therefore likely that the forests within the WSA are not in eminent danger of crossing ecosystem thresholds that would trigger massive die-offs or ecosystem transformations (Millar and Stephenson 2015). Indeed, no significant forest decline has been seen within old cedar-hemlock forests in southern coastal British Columbia (Arsenault 1995).

However, the WSA ecosystems do have a history of insect outbreaks and fire activity that could be exacerbated with future warming. For instance, outbreaks in the western hemlock looper (*Lambdina fiscellaria lugubrosa Hulst*), a native defoliating Lepidoptera, has led to localized reductions in canopy and tree mortality within the Coastal Western Hemlock biogeoclimatic zone. It is one of the most important defoliators in British Columbia, and likely the most significant defoliators on the southern British Columbia coast. The main host of the western hemlock looper is western hemlock. Outbreaks generally occur every 20 – 30 years (Gray and Daniels 2006) and last three to four years, after which there is a return to pre-outbreak levels (McCloskey 2007). Old-growth stands are the main target of defoliation, although 80 to 100 year old hemlock stands have been affected. Tree mortality often requires two consecutive seasons of defoliation (Gray and Daniels 2006).

Between 2000 and 2003, 5000 ha of forest on the British Columbia coast were impacted by the western hemlock looper. This is equal to just less than half the area of the city of Vancouver. Of this area, 20% saw high levels of mortality (Gray and Daniels 2006). Stands within the Capilano, Coquitlam, and Seymour watershed were impacted. The Coquitlam Watershed in particular has seen numerous looper outbreaks over the last century, with events occurring, on average, every 24 years. However, each successive event generally attacked different stands.

McCloskey *et al.* (2009) explored the connection between western hemlock looper outbreaks and climate variability. They determined that drought conditions during the growing period are associated with outbreaks. Specifically, late spring, early summer soil moisture deficit often occurred before significant defoliation occurred. They also found that warmer and drier conditions during the two previous growing seasons increased the probability of an outbreak. However, the authors stressed that the connection between outbreak events and climate were tenuous; not all droughts led to outbreaks, and other factors such as predation, parasites, and diseases can have a significant impact on the looper populations.

Although the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) has seen major outbreaks throughout western North America in the last 30 years, bark beetles outbreaks are less prevalent along the wettest regions of the British Columbia coast. The spruce bark beetle (*Dendroctonus rufipennis* (Kirby)) can be found throughout the drier regions of the Coast Mountains, within the ranges of Sitka spruce (*Picea sitchensis*). Its preferred habitats are windthrown trees, stumps, logging slash, and weakened trees (Gray and Daniels 2006).

Compared to other regions in western North America, pre-settlement fire activity within the wet coastal forests that characterize the WSA was relatively low. Ample amounts of precipitation, even during the summer months keep fuels relatively moist. Even during dry periods, a layer of moss and herbs act to retain much of the moisture within the forest floor, which, due to high rates of decomposition, is composed primarily of larger fuels that dry slowly. Moreover, lightning frequency is low in coastal British Columbia (Daniels and Gray 2006). Gavin *et al.* (2003) examined soil charcoal and tree rings within the Clayoquot Sound which is in the same biogeoclimatic zone as a portion of the WSA: CWHvm. They found median time-since-fire was 4410 years for terraces and 740 years for hillslopes. All south-facing and southwest-facing slopes had burned in the last 1000 years. When modelling carbon dynamics in Pacific Northwest forests, Raymond (2010) took the fire return interval to be 600 – 900 years in hypermaritime hemlock/redcedar forests. Rogers *et al.* (2011) assumed fire return intervals to be 200 – 500 years for Oregon and Washington forests west of the Cascade Range. Both studies assumed that all fires were stand-replacing.

Green *et al.* (1998) examined sites throughout the Capilano watershed with clear evidence of past fires. This restricted their analysis to primarily warmer slope aspects with Douglas-fir stands. By assessing the age of 306 trees, they found that the time since fire ranged from 320 to 850 years. They estimated the mean fire return interval to be 346 years. However, Gray and Daniels (2006) pointed out that these results were for some of the warmest stands in the watershed, which are more likely to experience fires. By examining the spatial pattern of stand structure within a sub-basin of the Capilano watershed, Arsenault (1995) found evidence for two overlapping severe fires in 1690 and 1100. From these data he estimated a fire return interval of around 600 years.

Daniels (2003) demonstrated that western redcedar stands within the WSA generally have a range of ages, suggesting that they did not initiate from a stand-replacing disturbance. Instead, it is likely that the disturbance regime for these stands are characterised by a range of disturbances intensities. Moreover, relatively old western redcedars can be found within younger, even-age stands. As redcedars are highly susceptible to fires, Daniels and Gray (2006) suggest that this points to a fire regime characterized by infrequent, low to moderate severity fires of small to moderate size.

Even though fires are relatively infrequent, historical records show that the WSA is capable of sustaining large fires, and recent dry conditions have brought fire to even the wettest coastal rainforests. Fire activity within and around the WSA during the last hundred years has been dominated by human activity. Figure 2 provides time series of annual area burned within the Coastal Fire Centre for all fires larger than 10 ha, and Figure 3 provides annual fire counts. Fire activity within the southern coast of British Columbia has diminished over the last 100 years. The large fire activity in the 1920's and 1930's was driven primarily by logging in the area (Green, 1999). However, this reduction in fire activity over the 20th century has occurred over most of British Columbia and has been linked, in part, to historical increases in summer precipitation (Meyn *et al.* 2012). It is also important to note that only a small portion of the fire activity has been located within the wet CWHvm BEC zone which comprises most of the WSA; most of the fire activity has occurred in drier regions further inland and within the rain shadow of the Coast Mountains

The geographical distribution of fires can be seen in Figure 4 and Figure 5 locations for fires larger than 10 hectares from1920 to 1955 and 1980 to 2015 are shown. During the earlier period fires occurred across the region, driven by logging activity. However, during the last 35 years, most fires have been located within the drier areas of the Coast Mountains. Indeed, no fires over 10 ha have been recorded within the WSA since 1980. However, a number of large fires burned in the WSA between 1920 and 1955. These fire locations are shown in detail in Figure 6. By far the largest fire burned on the eastern slope of the Capilano watershed in 1925. Many of these fires were likely escaped slash fires (Green et al., 1999).

The 2015 fire season saw elevated fire activity relative to recent history; more area burned in 2015 within the Coastal Fire Centre than in any other year since 1951. This total area was composed of a handful of larger fires located primarily on the dry lee-side of the Coast Mountains. From Figure 5 it is clear that these fires where unprecedented compared to recent history.

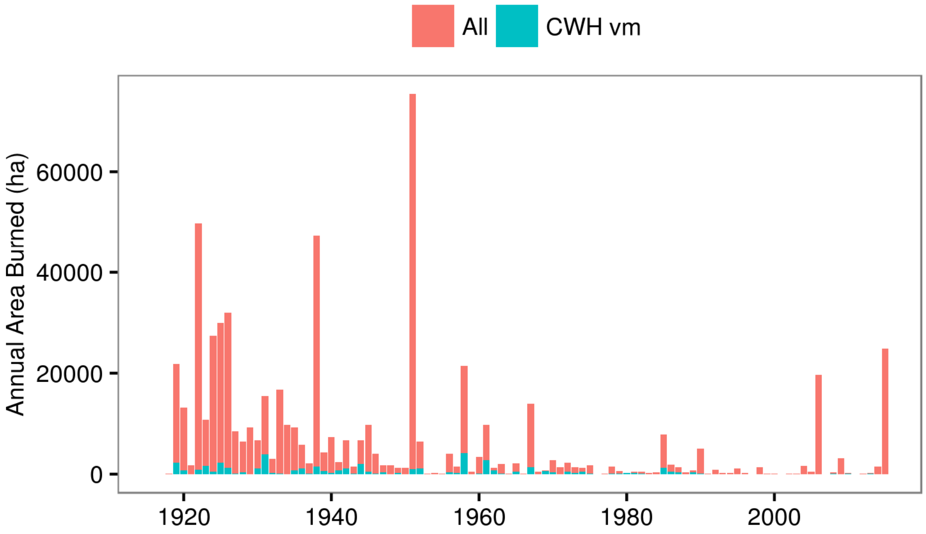

Figure 2: Annual area burned within the Coastal Fire Centre (see Figure 1 for location) by fires larger than 10 ha. Fires within the CWH vm biogeoclimatic zones are highlighted.

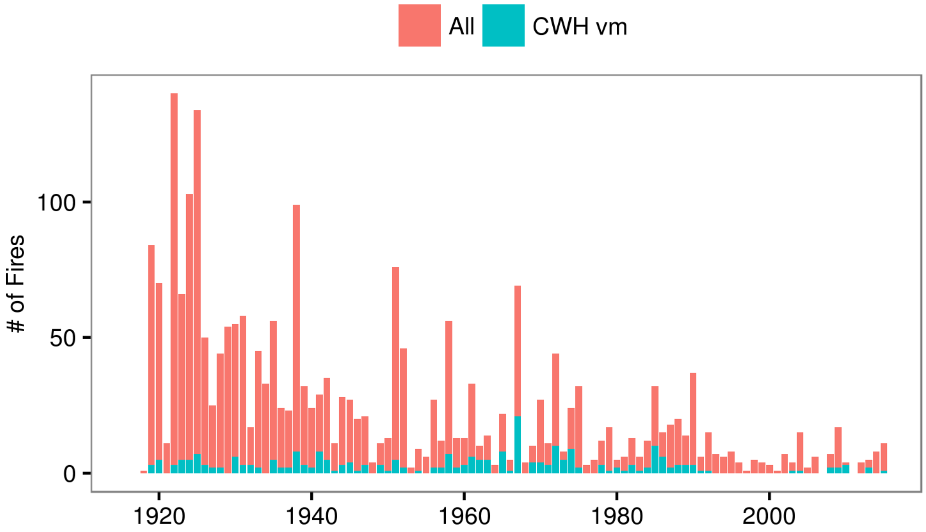

Figure 3: As in Figure 2 but for number of fires per year.

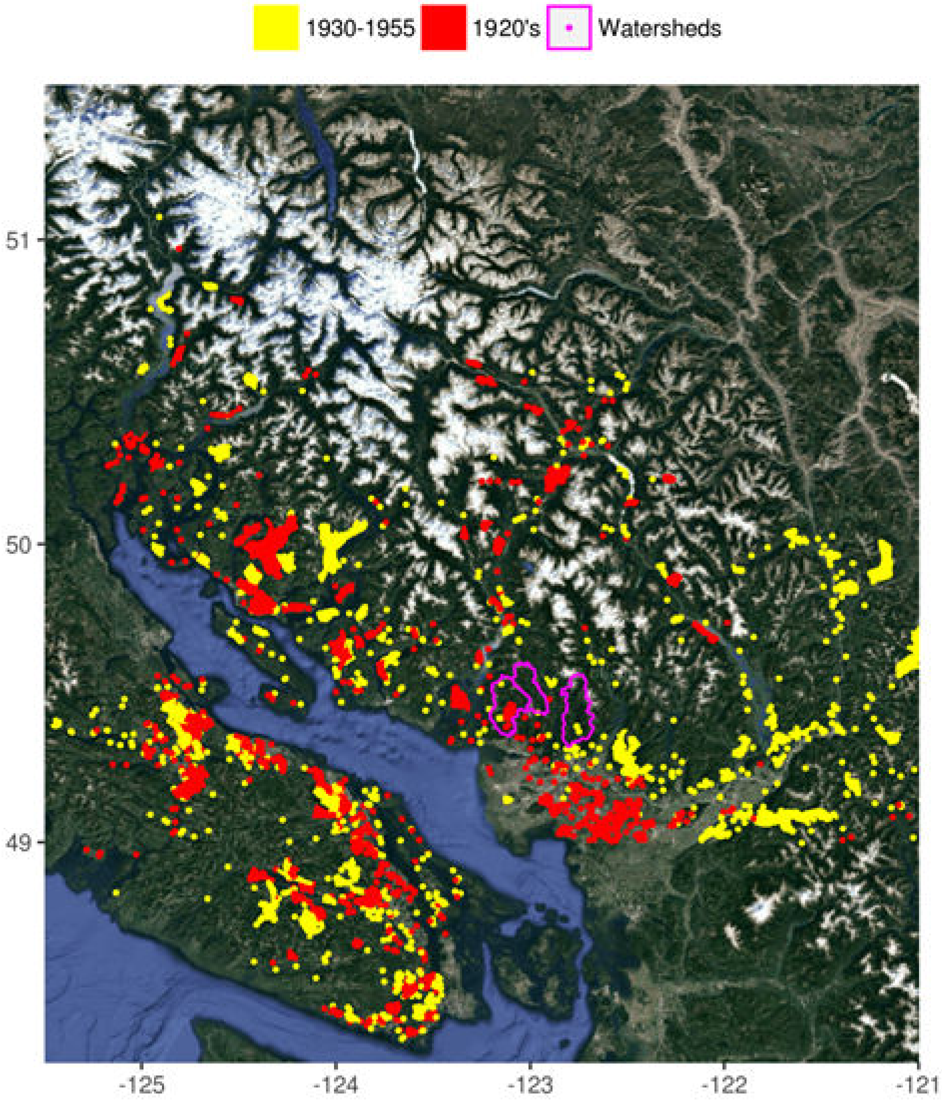

Figure 4: Fire locations within the Coastal Fire Centre for the years 1920 to 1955. Only fires larger than 10 ha are shown. All fires smaller than 500 ha are indicated with a point, while actual fire perimeters are shown for larger fires.

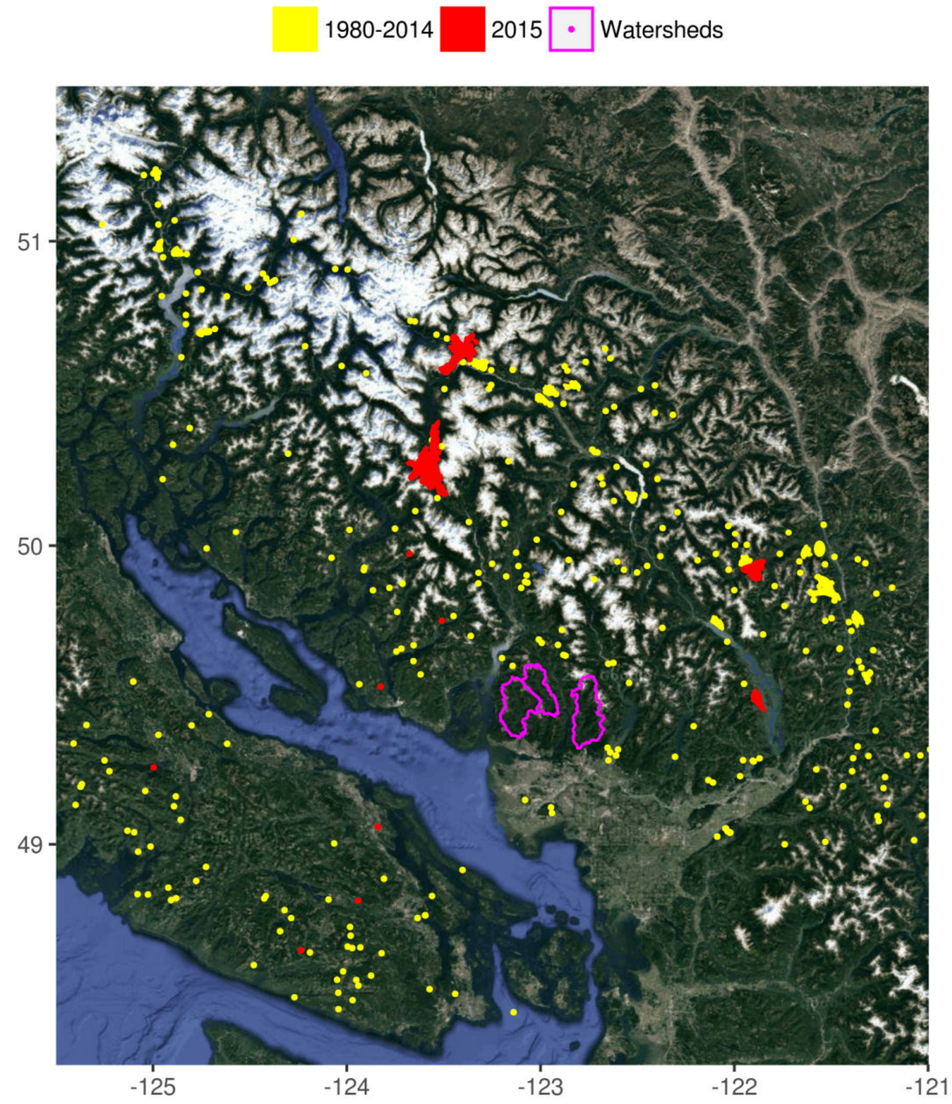

Figure 5: As in Figure 4, but for fires between the years 1980 to 2015.

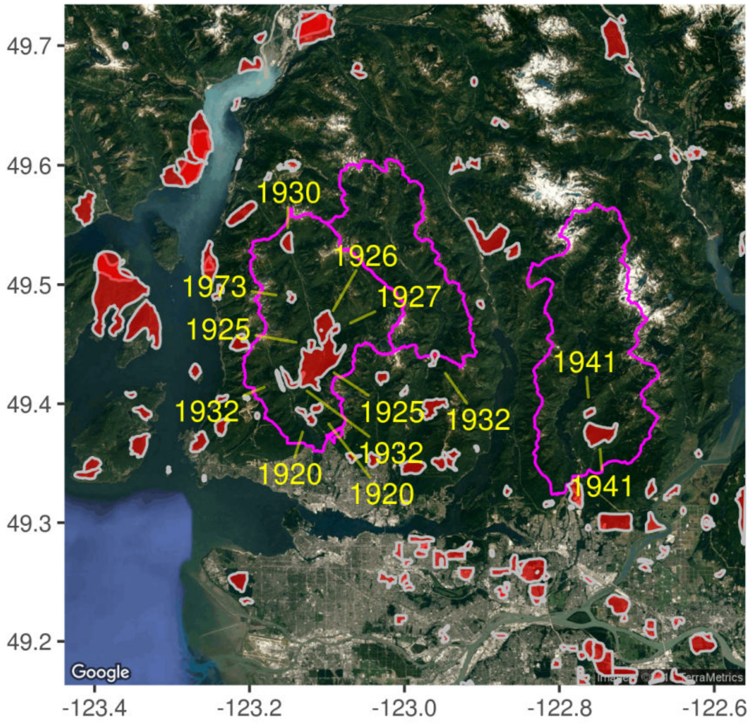

Figure 6: Fire locations since 1918 for the region surrounding the WSA. The year of all fires within the WSA are indicated.

The Elaho Valley fire was the largest fire within the Coastal Fire Centre with an area of 125 km^2. This is almost equal to the size of the Seymour watershed. Three other fires burned over 10 km^2 in 2015. The 2015 season also saw an unprecedented fire burn through 11 km^2 of hypermaritime rain forest in the Olympic National Park in northwestern Washington. As a comparison, in the last hundred years, the largest fire within the WSA burned 1.1 km^2 (see Figure 6).

2015 was also unusual in that the fire weather became extreme very early in the season. Figure 8 provides historical precipitation amounts for June and August. Because the dataset used from the WSA stations only date back to 2009, two additional long term fire weather stations maintained by the British Columbia Wildfire Management Branch have also been included. Like the WSA stations, the UBC Research station is located on the southern slope of the Coast Mountains at a similar elevation and experiences a similar climate to the WSA. The D'arcy station was chosen to represent the drier climate within the rain shadow of the Coast Mountains. The location of all these sites is provided in Figure 7. June precipitation amounts were extremely low at the UBC Research station. In fact, they were comparable to typical precipitation seen at the D’Arcy station.

We can also use the Canadian Fire Weather Index System to determine the level of fire danger at these stations. Three indices will be used here, the Drought Code, the Fire Weather Index and the Fire Danger Rating. The Drought Code is a slowly varying metric which is meant to represent the moisture of larger fuel elements and the deep compact organic soils. The Fire Weather Index represents the potential intensity of a spreading fire in a standard fuel bed. Finally, the Fire Danger Rating indicates the relative difficulty of fighting a fire (Van Wagner 1987).

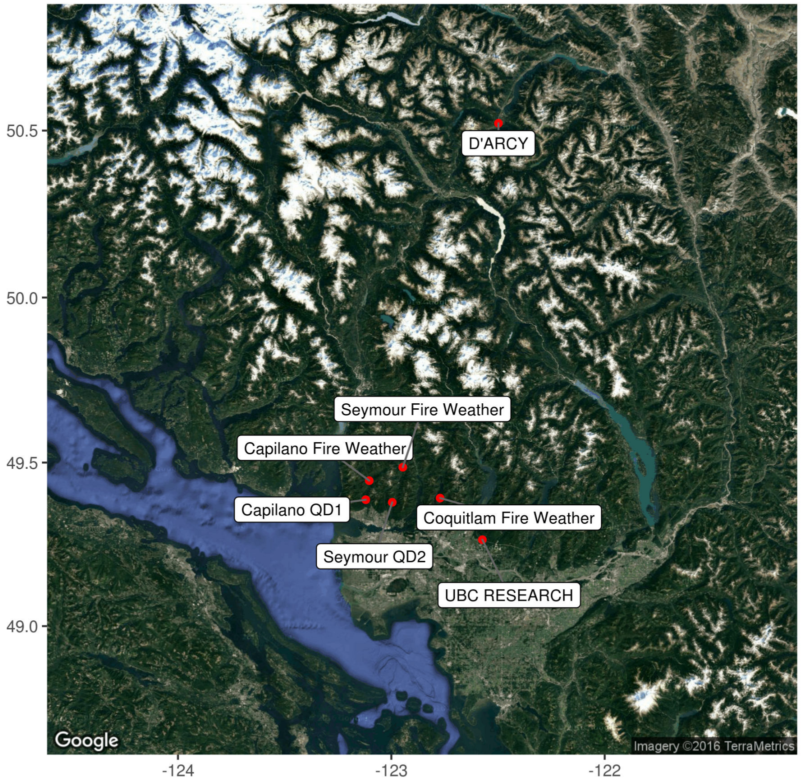

Figure 7: Fire weather station locations.

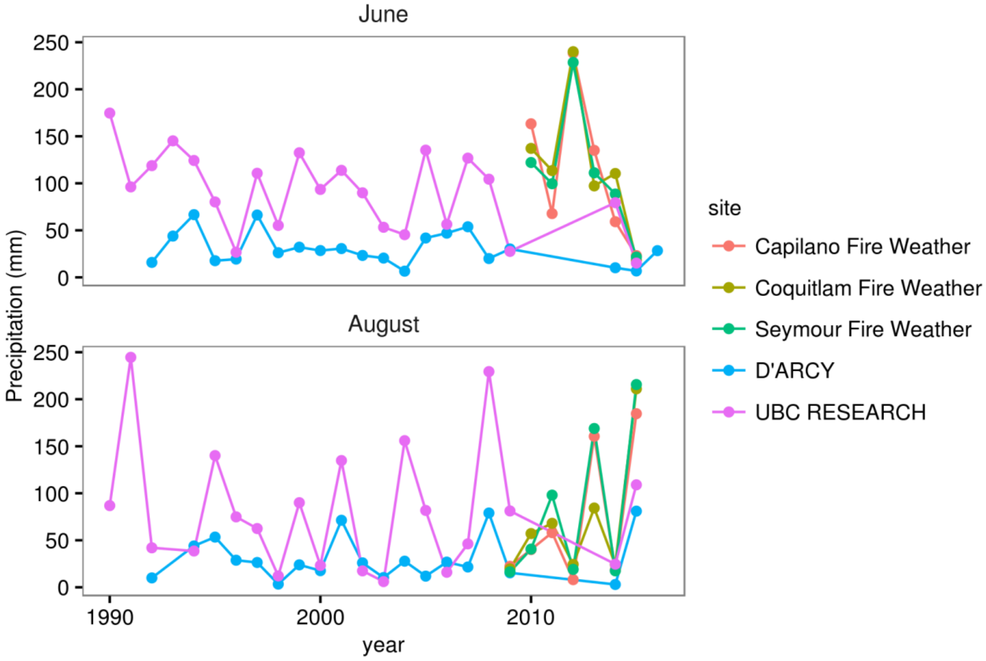

Figure 8: Precipitation for June and August for stations surrounding the WSA. See Figure 7 for locations.

Figure 9 and Figure 10 provide time-series of the 95th percentile of the Fire Weather Index and the Drought Code, respectively. The 95th percentile was used here to indicate the level of the most intense fire weather during each month. It is in these extreme conditions that most fire activity occurs (Wang *et al.* 2015). Both the Drought Code and the Fire Weather Index were anomalously high during June, and comparable to typical conditions observed at the D’Arcy Station. Moreover, at the UBC Research station, the number of days when the FDR was either “High” or “Extreme” during 2015 was higher by far than any other time in the station's 21 year record (Figure 11). The 2015 fire season was also extreme at the D'arcy station. The exceptionally dry conditions during 2015 led to the large fires seen in Figure 4 and Figure 5

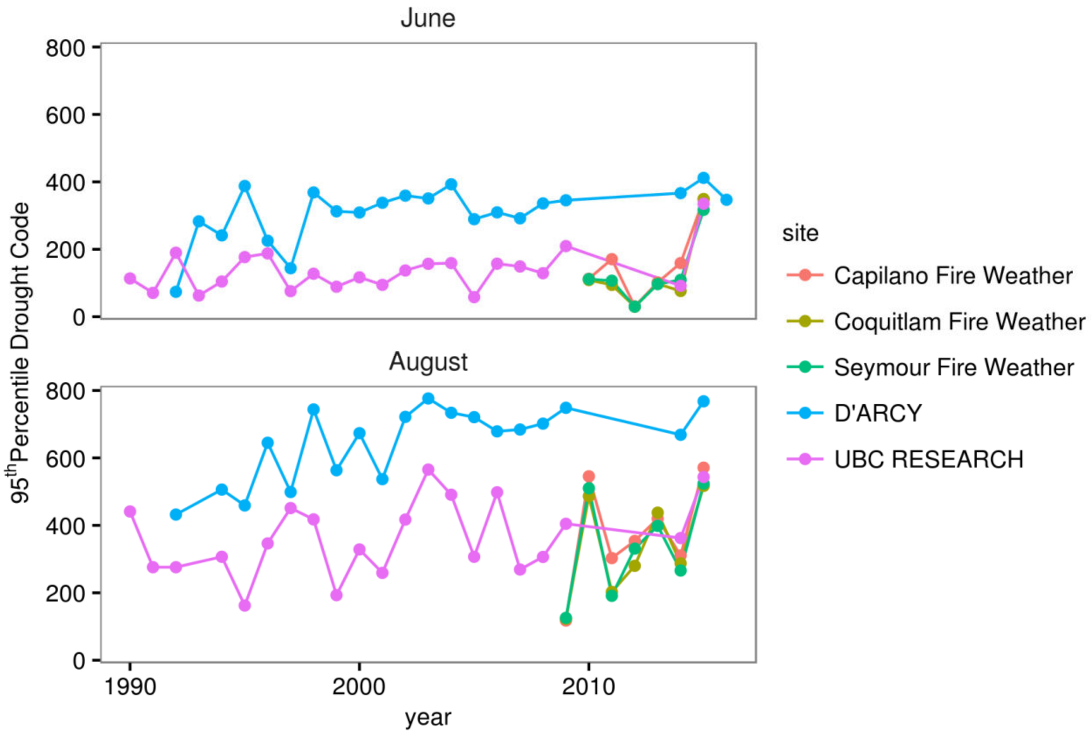

Figure 9: As in Figure 8, but for the 95th percentile of the Drought Code

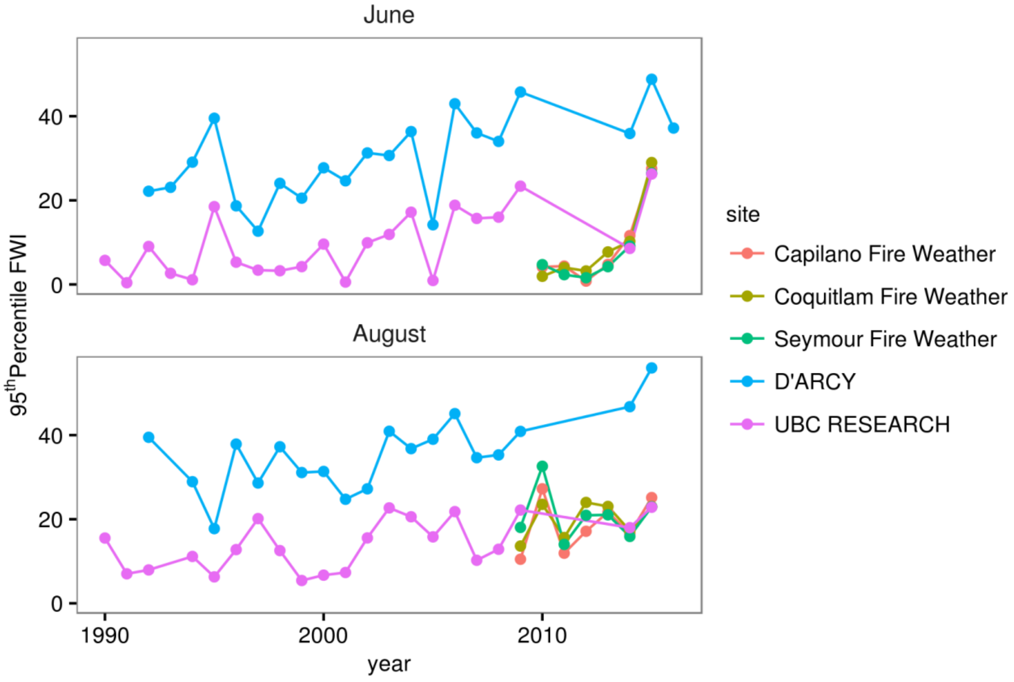

Figure 10: As in Figure 8, but for the 95th percentile of the Fire Weather Index

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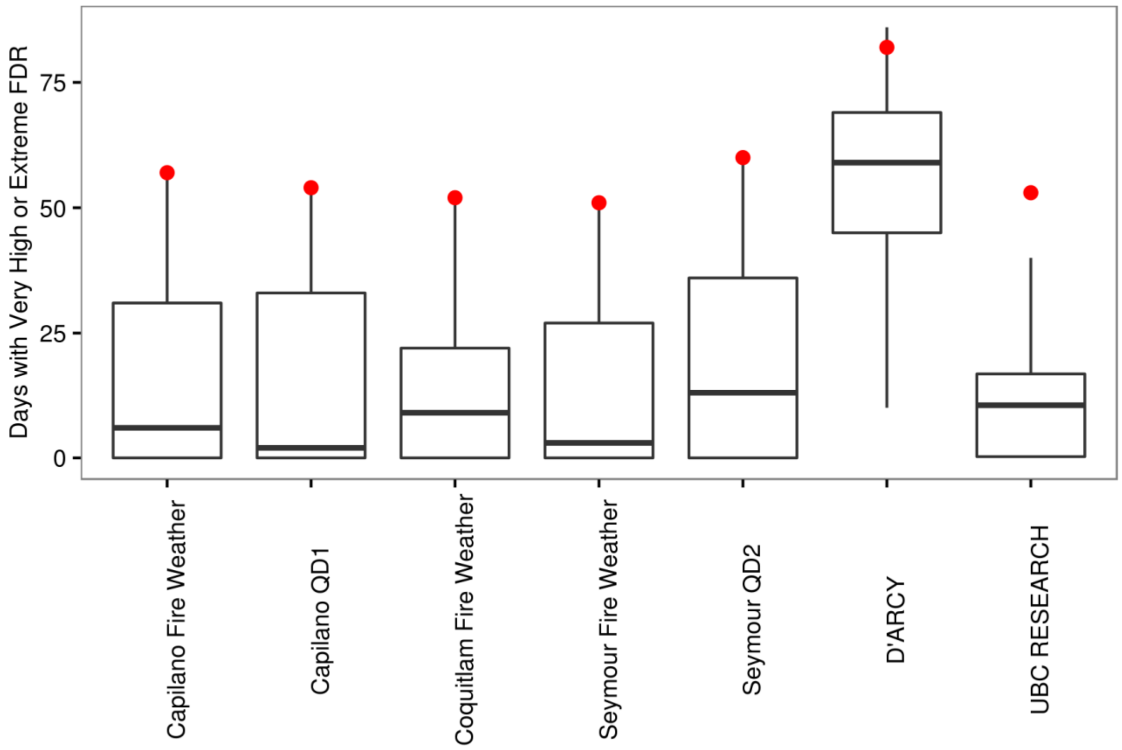

Figure 11:Boxplots of the number of days during the year that the Fire Danger Rating was at " High" or "Extreme." The Thick line indicates the median value, the extent of the boxes indicates the inter-quartile range (i.e., from the 25th to the 75th percentile). The ends of the outer lines indicate the 5th and 95th percentile. The values for 2015 are indicated by red points.

Future Trends

An important challenge is determining what a changing climate will mean for drought, wildfire and pest outbreaks in the WSA. As previously mentioned, a warming climate will bring “hotter droughts” which have been shown to have larger impacts of forested ecosystems than historically average droughts. It is also clear that the forest types of the WSA are capable of sustaining large fires, but historically, conditions were rarely dry and warm enough. However, these conditions will likely become more prevalent as the climate warms.

There are large uncertainties surrounding the projections of future changes in climate, due to uncertainties in future greenhouse gas emission trajectories and the details of environmental processes, and the inherent chaotic nature of the climate system. However, we can present a range of projections based on different future pathways and models used. By the 2050's, summer daytime high temperatures are expected to increase by, on average, 3.7 ºC with a range of 2.4 to 5.2 ºC. By the 2080's this will increase to 6.0 ºC above historical levels. Although annual precipitation is projected to increase by 5%

by the 2050s (-1% to 9%) and 11% by the 2080s (2% to 17%), summer precipitation is projected to decrease by 19% by the 2050s (Range: -41% to +1%) and 29% (-52% to -6%) by the 2080s. Spring precipitation is expected to increase by 8% (-4% to 15%) by the 2050s and 12% (3% to 25%) by the 2080s (Metro Vancouver 2016).

What these changes will mean for forest health and disturbance regimes within the WSA is difficult to ascertain. In the short term we can expect to see only gradual changes in forest density, structure, and age, but if certain ecological thresholds are crossed, there could be significant transformations in the vegetation types (Millar et al., 2015). However, it is generally accepted that the energy-limited wet maritime forests found within the WSA are less susceptible to a changing climate, and may benefit from higher temperatures. Wu et al. (2014) used an ecosystem model and forest inventory data to simulate the impact of a warming climate on forests within British Columbia. They found that increased temperatures have already led to growth enhancements within the province, especially within coastal regions. Indeed, temperature increases that have already been realized have led to increased growth rates of yellow cedar on the north coast of British Columbia (Daniels et al., 2011). Millar et al. (2015) pointed to the coastal forests of British Columbia as an example of a forest ecosystem which is currently resilient to disturbances and not in immediate danger of crossing any thresholds which would precipitate large-scale mortality or ecological shifts. Coops and Waring (2011) combined mechanistic and statistical models to determine where 15 different western North America tree species are stressed in their current geographical ranges due to historical warming. In the wet coastal forests, the authors found that western hemlock, western redcedar, Sitka spruce, and Pacific silver fir experienced little to no stress within their historical range. Moreover, most of these species have expanded their range in the last 30 years. Yellow cedar was the only species which did not experience optimal conditions within a portion of its range.

However, this does not preclude the possibility that significant shifts in the climate do not have the potential of triggering large-scale mortality and an ecological transformation within the WSA, leading to possible degradation in the quality of the water. Indeed, Millar et al. (2015) suggest that eventually all temperate forests will see a fundamental shift in their condition. Allen et al. (2015) have argued that the risk of significant future tree mortality has generally been underestimated, especially for wetter forests. As the climate warms, droughts will likely become more damaging due to the concurrent increase in evaporation rates. The also caution that the lack of significant historical mortality does not mean the wide-spread mortality is not possible in the future.

One change that is almost certain to occur in the WSA in a warming world is a reduced snowpack and an elevated snowline (Mote and Salathe 2010). Projections indicated that the average depth of the May 1st snowpack in the WSA will be reduced by around 66% in the 2050s and 82% in the 2080s (Metro Vancouver 2016). By the 2050s the snowline could rise by over 300 m (Cohen et al., 2012). A reduced snowpack will likely lengthen the fire season (Westerling *et al.,* 2006). Additionally, because snow acts to insulate the fine roots of yellow cedars from cold conditions, a reduced snowpack will likely lead to more root damage during late-season cold snaps (Daniels *et al.*, 2011).

A number of studies have attempted to forecast shifts in tree species' ranges over the next century. Coops and Waring (2011) projected that the ranges of Pacific silver fir, western redcedar, western hemlock, Sitka spruce, and yellow cedar will all expand over the 21st century. Wang et al., (2012) developed statistical models for predicting the future distribution of tree species in British Columbia. Their projections indicate that the wet coastal forests would remain relatively stable and that the southern Coast Mountains will remain within the Coastal Western Hemlock biogeoclimatic zone.

As mentioned above, insect outbreaks have been associated with high temperatures and low precipitation. Bentz et al. (2010) combined population models with future climate projections to assess the potential for increased outbreak probabilities of the mountain pine beetle and the spruce bark beetle. Their results suggest that the climate of the British Columbia coast will become more suitable for the spruce bark beetle in the future. However, bark beetles are dependent on a host of associates such as fungi, mites, and bacteria that aid in tree colonization. There is little information about how these associate communities will be impacted by a changing climate, which in turn limits our ability to predict how insect populations will change in the future (Littell et al., 2010). Based on the relationship between the western hemlock looper outbreaks and climate outlined above, McCloskey et al., (2009) suggested that outbreaks of the defoliator may increase in frequency, size, and severity. However, there is no evidence that the frequency of looper outbreaks have increased over the last 200 years of warming (Daniels *et al.* 2011). Moreover, Bentz et al., (2010) cautioned that elevated levels of carbon dioxide will likely alter the carbon to nitrogen ratio in trees, reducing the nutritional value for insect herbivores.

As previously mentioned, significant wildfire activity can lead to ecological transformations when severe fires are followed by the introduction of a novel ecosystem which is better aligned with a warmer climate. However, there is a large amount of uncertainty surrounding the future of wildfire activity in the moist forests that characterize the WSA due in part to the low amounts of historical fire activity as well as a lack of fire science research aimed specifically at these wet ecosystems. Littell et al. (2010) developed a statistical model connecting wildfire activity on the western slopes of the Cascade Range to climatic variables. Although the authors cautioned that the predictive strength of the model was weak relative to other drier regions, their projections of future fire activity did show the largest absolute and relative changes in area burned of any region in the Pacific Northwest. In their most extreme projection annual area burned increased by an order of magnitude, although these projections were still below the historical amounts seen in other forests east of the Cascade Range. Rogers *et al.* (2011) used a dynamic vegetation model to predict future fire activity for forests west of the Cascade Range in Oregon and Washington. They produced similar results to Littell et al., (2010) with significant increases in fire activity by the 2080's ranging from 162 to 1177%, depending on the global climate model used. Finally, Haughian et al. (2012) presented projections of the Seasonal Severity Rating for regions throughout British Columbia. In their projections the Seasonal Severity Rating was 30 to 60 % higher in the 2080's for July to September, but there were no projected increases for June.

The above projections are for larger regions within British Columbia, Oregon, and Washington. However, this region is characterized by significant climatic gradients. It would be useful, therefore, to have fire weather/activity projections for the specific region of the WSA. Here I present future projections of precipitation and the Drought Code for the UBC Research and D'Arcy fire weather stations in Figure 12 and Figure 13. Future projections of temperature and precipitation were taken from a dataset of global climate model output interpolated across North America to a resolution of 1 km. A suite of 15 global climate models were used to create ensemble, or average, future projections. Details of this dataset can be found in Wang *et al.* (2016).

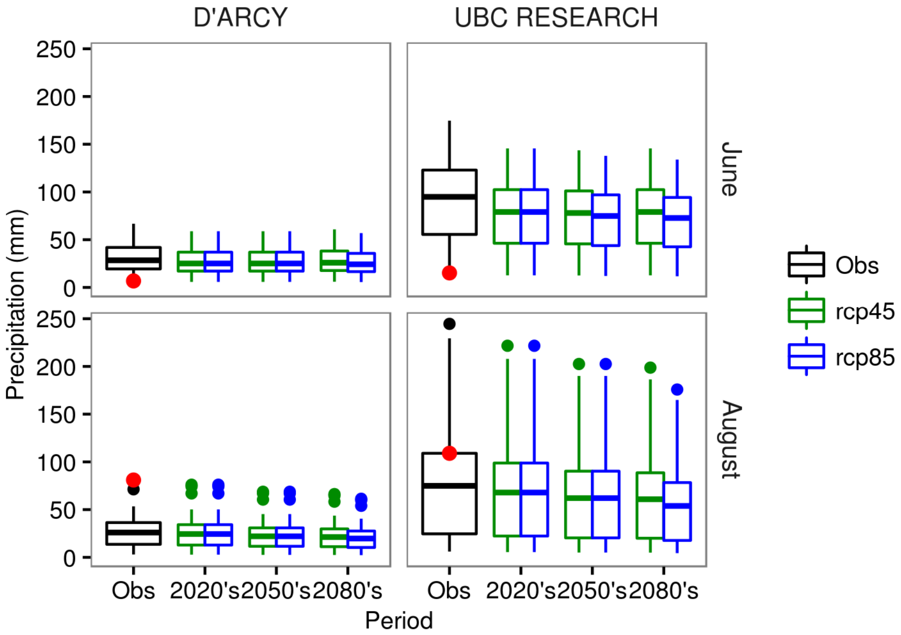

Figure 12: Boxplots of observed historical precipitation along with future projections for the 2050's and 2080's using the rcp4.5 and rcp8.5 scenarios (see Figure 11 for an explanation of the boxplots).

These projections suggest a number of interesting findings. Firstly, while the June Drought Code at the UBC Research station does increase over the 21st century, the extreme fire weather seen during the early summer of 2015 would still be an anomalously dry situation even in the 2080's. Secondly, the Drought Code is projected to see the largest increase during the last half of summer. This is a consequence of the projected changes in precipitation discussed above: spring precipitation is expected to increase while summer precipitation is expected to decrease. Consequently, June sees relatively moderate increases in the Drought Code. Thirdly, for all but the driest years in the 2080s, the Drought Code at the UBC Research station will not reach the historical levels recorded at the D'Arcy station.

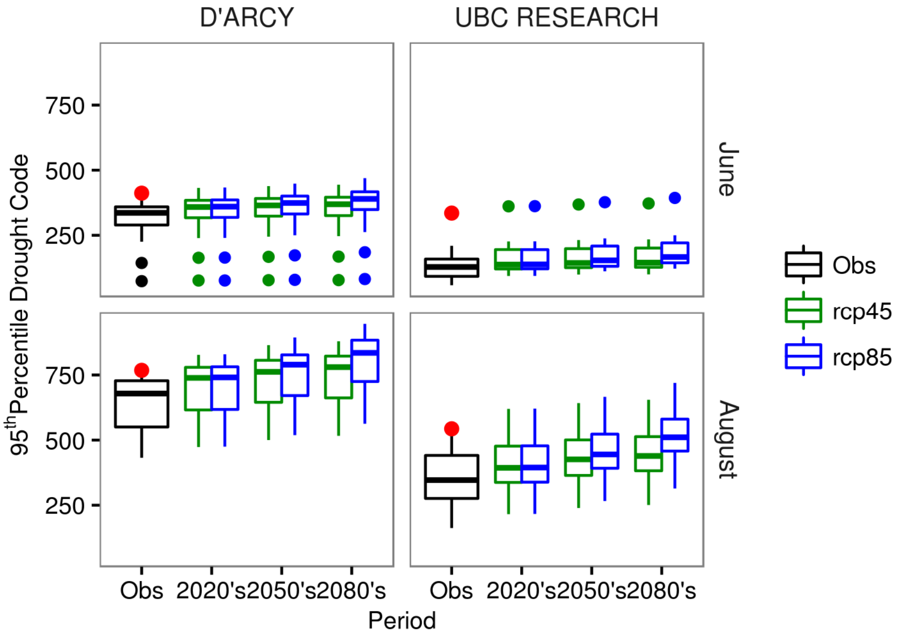

Figure 13: As in Figure 12, but for the Drought Code.

Conclusions

Maintaining the health of the ecosystems within the WSA is crucial for maintaining Metro Vancouver's water supply. A healthy forest is resilient to a host of different disturbances including fire, insect outbreaks, and windfall. Indeed, just such disturbances have historically been a natural part of the forests within the WSA. Periods of drought, which inevitably occur, are often catalysts for these disturbances. Severe drought can also have direct physiological impact of trees. Insect outbreaks and wildfires are likely the two processes that could lead to large-scale transformations of the forests within the WSA in the future.

Several lines of evidence suggest that the forests of the WSA are currently relatively resilient to disturbances and have benefited from increased temperatures. Most of the tree species in the region are not currently stressed by historical warming, and the southern Coast Mountains are expected to remain within the Coastal Western Hemlock biogeoclimatic zone during the 21st century. It should also be mentioned that although 2015 was a very active fire year within the Coastal Fire Centre, it was isolated to the drier regions of the coastal Fire Centre.

However, fire activity is expected to increase in the future. This is important as large forest fires within the WSA could impact water quality by increasing erosion and/or increasing the amount of organic materials and dissolved nutrients in the reservoirs. In two different studies the upper range of the projections suggest an order of magnitude increase in area burned within wetter coastal forests. However, these studies have necessarily focused on large coastal regions of western North America. Yet, the WSA is characterised by large amounts of precipitation relative to the larger coastal region, and consequently the reservoirs have seen very little historical fire activity, especially since the forestry industry has decreased its activity in the region and reduced its rate of accidental fires. As well, lightning frequency is relatively low within the WSA which may also maintain a lower fire activity. Yet the enhanced fire activity during the first half of the 20th century demonstrates that the WSA can sustain large forest fires given the right conditions and enough ignitions. It should also be re-iterated here that there is a large degree of uncertainty regarding projections of fire activity in coastal regions.

The most severe projections of the Drought Code produced for this report suggest that in the 2080's an average fire season will see August conditions that are comparable to some of the most extreme historical years. Yet, the extremely dry early fire season of 2015 will still likely be an outlier compared to future conditions. It is unclear how such dry conditions will translate into fire behaviour within the wet forests of the WSA. Increases in annual precipitation amounts will likely maintain the high rates of decomposition of litter on the forest floor, which skews the fuel bed to larger elements which dry slowly. Moreover, the floors of these wet forests are covered in a layer of herbs and mosses which can keep the fuel elements wet during drought. However, evidence from the Paradise Mountain Fire in Olympic National Park, which burned 1132 hectares of coastal rainforest, suggests that if conditions are dry enough mosses, herbs and lichen can become cured and act as fuels themselves.

The impact of climate change on insect outbreaks is also unclear. Overall, the literature suggests that as temperatures increase, the severity of drought impacts will increase, including the impact of insect outbreaks. However, insect populations are dependent on a set of complex interactions with associate communities, and not enough is known about these interactions to predict future population dynamics with any confidence. Yet, as has been pointed out by Allen *et al.* (2015), a lack of information regarding an ecological process does not preclude the possibility that it could lead to wide-spread mortality in the future.

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