Potential effects of climate change on forest health in Metro Vancouver's water supply area: An investigation of biotic disturbances and management strategies

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1. Introduction

The Pacific Northwest is home to an incredible array of diverse landscapes-from dense coastal forests to alpine meadows. For Metro Vancouver, the forests of the three drinking watersheds found within the Pacific Ranges of the Coast Mountains are not simply a resource to be preserved for their natural beauty, but more importantly for the environmental services they provide. The approximately 60,000 hectares of watershed lands Metro Vancouver oversees assist in providing clean, safe drinking water to over 2.5 million people in the region (Metro Vancouver, 2019). But concern is growing over the ability of this ecosystem to withstand climate change through the end of the 21st century. Climate projections for the greater Vancouver area estimate average daily temperatures will increase by 3° by 2050. Precipitation is expected to increase by 5%, but the timing of precipitation across the year is projected to be much more sporadic, increasing drought occurrence and extreme weather events (Metro Vancouver A, 2016). This is expected to have wide ranging impacts on forest health across the region, as the biodiversity of natural and modified forest ecosystems are expected to be adversely affected by changes in temperature and precipitation (Allen et al., 2015).

Though some dangers of climate change seem straightforward, indirect consequences on forest health could be even more concerning-as they are difficult to predict in advance. The term 'forest health' has meant many things to the diverse groups of people who interact with forests. Through the 20th century, forest health was often defined by a forest or manager's ability to function in the absence of disturbance. This led to management practices such as fire suppression and insect sanitation logging in British Columbia. But in the last few decades, there has been a growing consensus that disturbance is a critical part of ecosystem functioning, promoting biodiversity and heterogeneity across landscapes. As this term is so critical to this report, we are defining forest health as a forested environment which experiences and successfully recovers from disturbance

(Raffa et al., 2009). However, in the coming century, where frequency and severity of disturbances such as fire, insect and pathogen outbreaks are predicted to cross critical recovery thresholds, forest managers should be concerned that these 'megadisturbances' could severely impact forest health in BC (Millar and Stephenson, 2015).

2. Report Objective

Metro Vancouver relies on the Capilano, Coquitlam and Seymour watersheds to provide "clean, reliable and affordable…drinking water" to a growing urban population (Metro Vancouver, 2019). The uncertainties associated with future climate change have the potential to endanger water quality and availability in the coming decades (Dunkley and Bonin, 2004). The goal of this report is to examine the state of current literature on coast forest ecosystems and how they are expected to be impacted by climate change. We will begin by reviewing the current Water Supply Areas (WSA) managed by Metro Vancouver and discussing short- and long-term climate projections for South-Western BC. This will be followed by a discussion of forest health-discussing examples of natural disturbance in these ecosystems and addressing how these could become threats for future forest health. This will culminate in the possible impacts this could have on water quality and availability for Metro Vancouver. This report concludes by summarizing current forest management practices used by other watershed groups across the Pacific Northwest, and how these could be applied to the Metro Vancouver WSA's to adapt for future climate variability.

3. Overview of Metro Vancouver's Water Supply Area

Metro Vancouver is supplied water from three sources-the Capilano, Seymour and Coquitlam watersheds (Figure 1). The three drinking watersheds, situated in the Pacific Ranges of the Coast Mountains, cover close to 60,000 hectares (includes both on-draining and off drainage lands). Most of the year, water is supplied approximately one-third from each of the tree

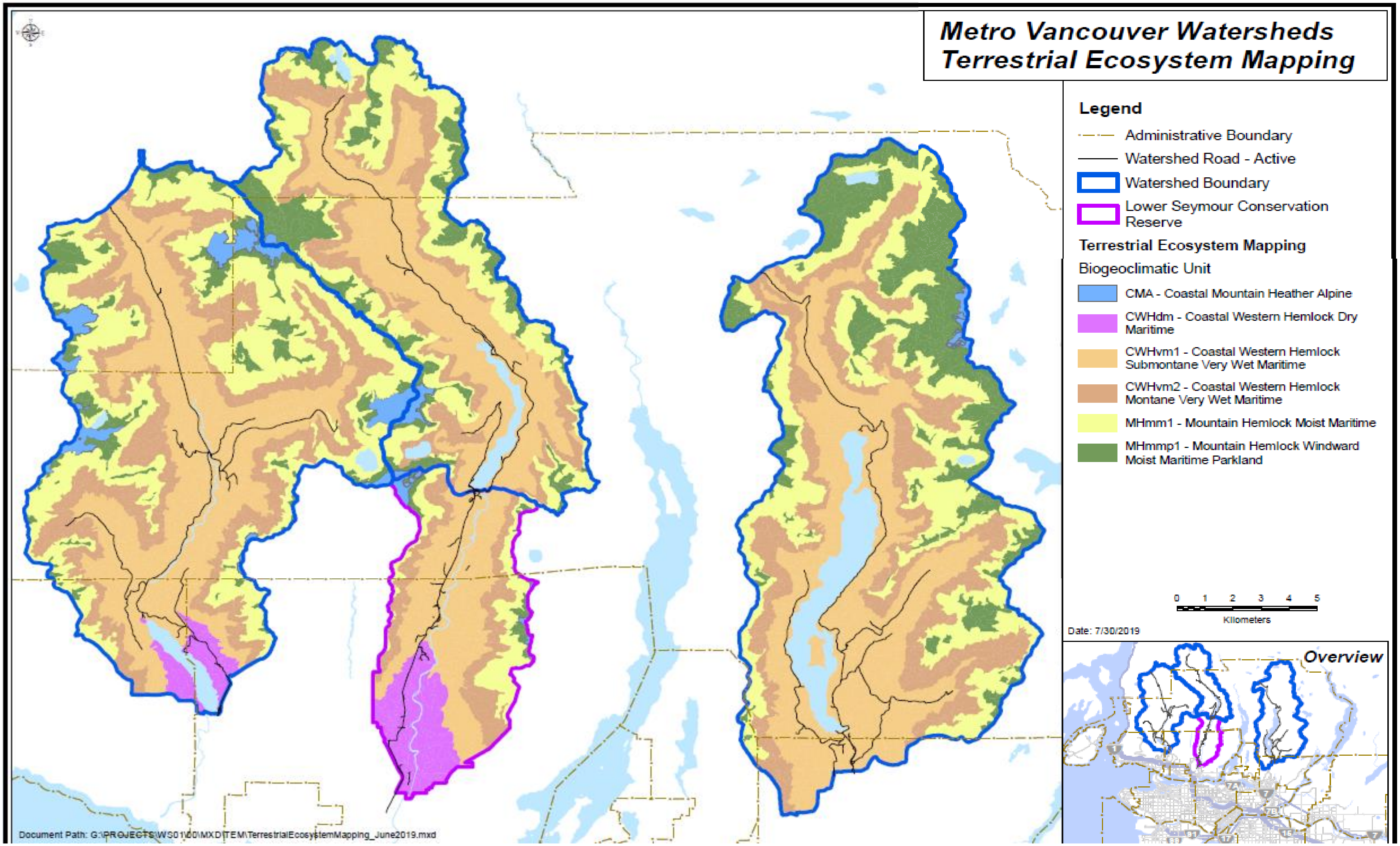

Figure 1: BEC Zone Distribution of Metro Vancouver Water Supply Areas. Supplied by Dave Dunkley (Metro Vancouver).

WSAs, however, the Coquitlam WSA can be responsible for supplying up to half of all drinking water to the region. Two Drinking Water Treatment Facilities-the Seymour-Capilano Filtration Plant (SCFP) and the Coquitlam Water Treatment Plant (CWTP) are owned and operated by Metro Vancouver to treat source water from the WSA (Metro Vancouver, 2019).

The WSA is primarily a diversely forested region found at elevations between 150 to 1800 meters above sea level (masl). The WSA can be broadly categorized into two BEC zones-the Coastal Western Hemlock (CWH) and the Mountain Hemlock (MH) zone. In addition, the Coastal Mountain Heather Alpine zone (formerly called the Alpine Tundra ecosystem) occupies less than 2% of the WSA. On average, the CWH is the rainiest BEC zone in British Columbia, and has a cool mesothermal climate, characterized by cool summers and mild winters. In contrast, the MH zone gets longer colder winters and cool wet summers.

CWH stands make up over 60% of the WSA forests and grow from 150 to 800 masl. The CWH is dominated by conifers-namely western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*). Pacific silver fir (*Abies amabilis*) and yellow cedar (*Cupressus nootkatensis*) are common on wetter, higher elevation sites in this region. Douglas-fir (*Pseudotsuga menziesii*) often appears on warmer, southern facing slopes. Many deciduous trees such as red alder (*Alnus rubra*), black cottonwood (*Poplus trichocarpa*), big leaf maple (Acer macrophyllum), and vine maple (Acer circinatum) also occupy these stands (Biogeoclimatic Ecosystem Classification Program, 2019; Green and Klinka, 1994).

From 150 to 400 masl, the forests can be classified further as the Coastal Western Hemlock Submontane Very Wet Marine subzone (CWHvm1), or at higher elevations, from 400-800 masl, as the Montane Very Wet Maritime (CWHvm2). The Dry Maritime (CWHdm) variant is found in the southern portion of the Capilano WSA bordering the Capilano Reservoir and in the Lower Seymour

Conservation Reserve (LSCR). Over 30% of the forests in the WSA are situated above 800 masl, and are classed as the Mountain Hemlock Windward Moist Maritime Variant (MHmm1). These forests are dominated by mountain hemlock (*Tsuga mertensiana*), Pacific silver fir, along with some yellow cedar and western hemlock. These areas then eventually give way to open meadow in the Mountain Hemlock Windward Moist Maritime Parkland (MHmmp) zone, which typically encompasses the elevational tree line corresponding to the MHmm1 (Green and Klinka, 1994; Biogeoclimatic Ecosystem Classification Program, 2019).

Old growth forest makes up close to 60% of all stands across all three water supply areas. Together with other stand structural age classes the forest provides four important environmental services for the Metro Vancouver WSA. These include:

- acting as a natural filter for water inside the WSA
- providing slope stability
- protecting some of the last examples of pristine or near pristine BEC zones, including and are rare and endangered habitat within the Lower Mainland
- acting as an important carbon storage sink for the region

Preserving the integrity of current stand structure, while letting natural disturbances prevail (under most conditions) may not be possible in an era of climate change. But any management that helps the resilience of these forests is in the interest of Metro Vancouver's future watershed goals.

4. Overview of Future Climate Trends

Though global climate change projections have been published since the early 2000s, more regionalized projections are needed to understand exactly how climate change will affect the Metro Vancouver region. To answer this, Metro Vancouver released a report in 2016 projecting future change by 2050 and 2080 for the region. In broad terms, the Metro Vancouver region is expected to have warmer temperatures, decreased snowpack, longer dry spells, higher precipitation overwinter and an increasing number of extreme events (Metro Vancouver A, 2016). In the following section, we will discuss the most pertinent of these projections and how they relate to the forest health of the Capilano, Coquitlam and Seymour WSAs.

Daytime summer temperatures for the region are expected to rise by 3.7 °C; and 6 °C by 2050 and 2080 respectively, for the Metro Vancouver region. Winter temperatures are also expected to change, with average winter lows above 2 °C, rather than the 20th century averages below 0 °C. This temperature increase could mean summer days above 25° may double with a 60% decrease in frost days in winter. In addition, future projections estimate there could be a loss in the relatively temperate climate Metro Vancouver currently experiences. There is an increasing likelihood there will be less certainty from year to year than has been observed in the past (Metro Vancouver A, 2016).

Precipitation for the region is only expected to increase by 5% in 2050, but to 11% in 2080. The major concern is that the current pattern of rainfall is projected to dramatically change in the 21st century. Currently, the most rainfall occurs in the winter months for the Metro Vancouver area. By 2050 and 2080, the most rainfall will occur in the fall season, with both winter and spring precipitation increasing over these time periods. Summer, already the driest season, is projected to get drier by 19% in 2050 and a staggering 29% by 2080 (Metro Vancouver A, 2016).

These changes impact several indicators for forest health in the region. Historically, the growing season has averaged approximately 250 days, depending on elevation. Lower sites are expected to increase from the current 301 days, to about 350 between 2050 and 2080. In contrast, high elevations are expected to change more rapidly-rising from 217 days to 281 by 2050, and 325 by

2080-which surpasses the current number of days seen at low elevations. Growing degree days are also expected to rise by almost 50% by 2050 and 82% by 2080. Both changes could have huge effects on the health of current tree species and biodiversity of the CWH and MH ecosystems of the WSA.

5. Forest Health and the Role of Biotic Disturbance

Climate change is expected to increase the frequency and severity of abotic and biotic disturbances in the forests of the lower mainland. As weather patterns begin to change more significantly in the 21st century, forest health is expected to be compromised in direct and indirect ways. After 2 record setting fire seasons for British Columbia, natural resource managers across the region are concerned about the relationship between changing precipitation patterns, rising temperatures and wildfire. Though these abiotic disturbances are important issues to discuss, we will only briefly focus on them in this paper, as our focus is the biotic. The role of fire and drought was examined in another Sustainability Scholar Initiative entitled "Drought, wildfire, and climate change in Metro Vancouver's water supply area" published in 2016. This current report builds on the conclusions made there and we hope these papers, when read together as companion pieces, will provide a comprehensive overview of future disturbance in the Vancouver WSAs.

Though this report's focus is how biotic disturbance-insects and pathogens-will affect forest health in the future, these events are often closely linked with abiotic change. Well-established stands can often withstand acute stressors to their environment, such as 1-2 years of drought or unusual heat stress, but not without sacrifices to their physiological condition. In any sustained period of stress, tree vigor will be compromised. When this happens, insects and pathogens are given an opportunity to overwhelm a trees ability to maintain its energy intensive defenses (Millar and Stephenson, 2015; Eyles et al., 2010). Under the projections discussed in the previous section, the stands of the Metro Vancouver WSA are predicted to experience not just acute, but chronic stress over the next 80 years.

This problem is only magnified by the relationship of insects and temperature. As climate warms, trees will become more heat and moisture stressed. As many stages of an insect's life cycle are thermoregulated, an increase in heat accumulation results in increasing diversity of insects in novel areas of latitude and altitude. In areas where these climatic changes have already begun to stress tree hosts, these stands become flash points for outbreaks of phytophagous insects and the pathogens they vector (Dale et al., 2001; Bentz et al., 2010; Woods et al., 2010). In recent years, this relationship has become abundantly clear in the interior of British Columbia. Recent outbreaks of the mountain pine beetle (*Dendroctonus ponderosae*) and North American Spruce beetle (*Dendroctonus rufipennis*) have killed billions of trees in outbreaks that have expanded in temporal and spatial variability unparalleled in recorded history (Bentz et al., 2010, Carroll et al., 2003). However, studying the exact links between insect success and climate change is complex, and though much work has been conducted, there are still uncertainties related to specific insect species and success on a warming planet. As observations have shown in Europe with the collapse of larch budmoth (*Zeiraphera diniana*) outbreaks in recent decades, not all insects become more successful with increasing temperatures (Esper et al., 2007).

The future of pathogens under climate change is less certain. As pathogens are able to evolve to changing climate much more quickly than their hosts, they are generally projected to become more common under climate change projections. Pathogens that cause needle diseases are expected to be directly influenced by changing temperature and moisture. In the following section we will detail some specific examples of insect and pathogen threats to the Metro Vancouver WSAs.

6. Insect Disturbance in the Vancouver Watershed Supply Area

6.1 Western Hemlock Looper

Western Hemlock Looper (*Lambdina fiscellaria lugubrosa*) is a moth native to the lower mainland of British Columbia. It is one of the most destructive defoliators in the province, and feeds on most conifer species found in the CWH zone, but prefers western hemlock (Koot, 1994). Typically, populations exist in low, sub-outbreak conditions, always causing some amount of defoliation in mature and over-mature western hemlock stands. However, populations in the lower mainland outbreak every 20-30 years for a period of 1-4 years (Gray and Daniels, 2006; Furniss and Carolin, 1977; McCloskey, 2007). These outbreaks are characterized by large amounts of defoliation in a stand leading to high mortality rates. Outbreaks like these can occur in young, vigorous stands, which result in growth reductions, tree mortality, and even defoliation of understory plant species (Koot, 1994).

Like all defoliators, the life cycle of the western hemlock looper is critically synchronized with phenology. This insect is an early season defoliator, synchronizing egg hatch within days of its host tree bud burst (Furniss and Carolin, 1977). What makes these larvae particularly destructive is their wasteful feeding pattern-before finishing one needle, it switches to another, consuming new and old foliage in the process. Unlike other common defoliators, this results not simply in top kill, but whole tree mortality. Typically, a western hemlock will be able to recover from less than 50% defoliation of needles, but if defoliated past this threshold, especially for more than 1 season, mortality is likely (Acres International, 1999).

The most recent outbreaks of western hemlock looper in the Metro Vancouver WSA occurred in the early 1960s and 2000s. These outbreaks caused defoliation across all watersheds for approximately 3 years, causing stand-wide mortality in the Coquitlam watershed in particular (Bonin, 2004). From a management perspective, these outbreaks caused widespread concern, and continue to be an area of future anxiety for Metro Vancouver. During the 2000-2003 outbreak there were concerns tree mortality and high levels of frass would cause a negative impact on water quality, and Metro Vancouver worked to determine if this was the case. After looper populations returned to normal levels, it was determined elevated levels of frass did not have any significant impact on water quality in the Coquitlam watershed (Bonin, 2004). This most recent research suggests that, though current looper outbreaks are alarming, they are not harmful enough to interfere with watershed output. However, as a potential damaging agent to western hemlock and other conifers in the lower mainland, it is only natural to wonder if climate change could create more severe western hemlock looper outbreaks.

Tree ring constructions of historic outbreaks found no evidence for an increase in outbreak frequency from 1911-2004 (McCloskey and Daniels, 2009). Further analysis in McCloskey et al., 2009 explored the relationship between climate variables and outbreaks. They determined early season moisture deficits often preceded significant defoliation, but the authors were not able to make a significant link between drought and outbreaks. These results are consistent with long held conclusions about the population dynamics of the western hemlock looper-that its population dynamics are driven cyclically. Outbreaks occur on the coast approximately every 24 years as a result of a 'predator-prey' relationship. After outbreaks reach high population thresholds, they are brought into check by a combination of parasites, predators, and diseases (U.S. Forest Service, 2005; Myers, 1988). Though broad scale climate drivers have not been found to solely influence outbreak dynamics of the western hemlock looper, this does not mean the system is not influenced by climate. Abnormal weather patterns, such as heavy rain in early summer can seriously impact moth flight and egg laying-decreasing population numbers (Koot, 1994; McCloskey et al., 2009). As mentioned previously, climate also affects flowering phenology and temperature, two things the western hemlock looper critically depends on for survival.

Studies conducted on the western hemlock looper's response to Pacific silver fir bud burst indicated egg hatch needed to occur within 4 days of bud burst for larval survival (Butt et al., 2010). It is increasingly clear that, as bud burst continues to move earlier due to climate change, this phenological asynchrony could prove devastating to looper populations if they cannot adapt quickly. Though there do not appear to be any studies investigating these consequences for the western hemlock looper specifically, there have been studies elsewhere. Approximately 70% of 23 butterfly species in California have advanced their first flight date 24 days in the last 30 years (Forister & Shapiro 2003; Parmesan, 2006). As this study, and recent outbreaks of bark beetles across North America indicate, insect species are more than capable of quickly adapting to climate changes-often faster than their tree hosts. At this point there does not appear to be any evidence showing western hemlock looper outbreaks becoming worse on their own. However, if Metro Vancouver's WSA forests become more stressed in the next century, as they are predicted to do, even the same amount of disturbance could have a more significant impact on forest health and water quality. Like most insect systems, the western hemlock looper's population dynamics are a complex series of trophic interactions and predicting how this species will react to changing climate is difficult. But continued research and monitoring will help Metro Vancouver understand these potential threats, and management strategies for loopers will be discussed in the following section.

6.2 Balsam Woolly Adelgid

The balsam woolly adelgid (*Adelges piceae*) is an invasive species, and since its introduction to Canada in 1910 it has become one of the most concerning pests to true firs (*Abies* spp.) in Canada and the Unites States. Though European firs are resistant to the adelgid, the North American fir growing in the Metro Vancouver WSAs, the Pacific silver fir, is susceptible. This insect can infest its host in two ways-through branch defoliation and bole attacks. Branch attacks, while damaging to long term growth, are not usually fatal. The balsam woolly adelgid injects toxic saliva into host branches while feeding, causing branch nodes to swell. Infested trees will suffer from yellow needles, needle loss, and terminal buds. Branches infected by this toxic saliva will also experience inhibited future bud formation, and the entire tree can suffer from top kill and radial growth loss (Balsam Woolly Adelgid, 2019; Turnquist and Harris, 1993). When the balsam woolly adelgid attacks boles, it does so in great numbers, swarming bark fissures and causing significant stem swelling. Though it often takes 2-3 years for the tree to die, these attacks are concerning because they open the host up to fatal secondary pests after being weakened by the balsam woolly adelgid (Turnquist and Harris, 1993).

Like the western hemlock looper, balsam woolly adelgid typically attacks older stands (over 40 years old). However, during a period of high infestation in the 1970s, all ages of Pacific silver fir were attacked in the Seymour watershed (Acres International, 1999). Because this is an invasive species, mitigation efforts must be strictly followed to maintain population levels and the current quarantine zone in BC. Pesticides, biological controls, selective thinning (and sanitation logging) all appear to be relatively ineffective at controlling populations (Turnquist and Harris, 1993; Balsam Woolly Adelgid, 2019). However, in recent years, the Aerial Overview Survey (AOS) of British Columbia has not detected any significant levels of this species causing damage in the Coastal Mountains (Westfall and Ebata, 2018).

Though currently not causing widespread damage in BC, the balsam woolly adelgid poses a significant threat to coastal forests in Washington. The 10-year average for infestation of balsam woolly adelgid in western Washington is approximately 36,000 acres of coastal forest (Flowers et al., 2013). Long term monitoring plots established near Mt Saint Helens in the 1950s illustrate damage and mortality is most severe at lower elevations with high concentrations of Pacific silver and grand fir (*Abies grandis*) as well as high elevation pioneer species such as subalpine fir (*Abies lasiocarpa*). Tree damage was most severe in the first decade of attack, but infestation and mortality has stayed consistent in the same sites more than 40 years later (Mitchell and Buffam, 2001). In Mt Rainier National Park, long term monitoring has also suggested the range of balsam woolly adelgid is constrained by low temperatures, keeping most heavy infestations at lower elevations below 2,000m. As climate models predict warmer winters, forest managers and the U.S. Forest Service are concerned this insect could not only cause more mortality at low elevations but persist in high elevation forests. This has been confirmed by long term plots established in 2006, documenting increasing crown infestations and predicting the balsam woolly adelgid could become a much larger problem for Washington as climate warms (U.S. National Park Service, 2018). This should be noted by forest managers in the lower mainland as a potential problem for British Columbia, not simply in terms of keeping the quarantine of the lower mainland intact but being prepared for potential increases of balsam woolly adelgid infestations occurring within the quarantine zone as temperatures warm.

6.3 Swiss Needle Cast

Swiss needle cast is a foliar disease caused by the *Phaeocyptopus gaeumannii* affecting Douglas-fir. Though first discovered in European plantations, the pathogen is native to the Pacific Northwest, across the native range of Douglas-fir in Oregon, Washington and British Columbia. Until the late 20th century, this disease seldom caused widespread damage, typically being associated with young tree plantations outside the native range of Douglas-fir (Oregon State University, 2008). However, when outbreaks on Douglas-fir plantations in the 1970-1980s began to spread to forest plantations along the coast. By 1999, over 3.5 million hectares along the Oregon-Washington coastal forest was infected (Flip et al., 2000). Until it was noticed in the lower mainland in 2012, swiss needle cast was not recognized as a forest pest in British Columbia, and therefore was not actively researched or surveyed. In the most recent mapping survey, roughly 1,100 ha were classed as infected in the Fraser TSA near Chilliwack (Westfall and Ebata, 2018).

Swiss needle cast causes yellowed needles and premature needle loss in trees it infects. The fungus accomplishes this by producing small fruiting bodies in the stomates of needles, plugging them and reducing growth rates or, in severe cases killing trees (Oregon State University, 2008). Impaired gas exchange has been observed to reduce radial growth up to 50% (Shaw et al., 2011). Though swiss needle cast typically infects younger trees, recent increases in severity and incidence of the disease is concerning as temperatures warm. Swiss needle cast has been shown to strongly correlate with winter temperatures across the world, accounting for 77-78% variation of infected young trees. The 0.2 -0.4 °C increase in winter temperatures since 1970 has been argued as the reason for increasing infection across the Pacific Northwest (Stone et al., 2008). The epidemic beginning in Oregon in the 1990's typically occurs at low elevations with a heavy coastal influence. Persistence in these high rainfall areas has been positively correlated to an increase of 0.7-1.5cm of rain from 1970 in addition to temperature increases (Stone et al., 2008; Sturrock et al., 2011).

Thus far in British Columbia, swiss needle cast is not as severe as the epidemic plaguing Oregon and Washington. In addition, outbreaks of the disease in the lower mainland are more concentrated inland than elsewhere in the Pacific Northwest, suggesting that the disease might be reacting to different climatic drivers in the Lower Mainland. What is troubling about the outbreaks observed in Chilliwack is that these are occurring in areas where Douglas-fir naturally regenerates, highlighting how, as temperatures warm, this disease could severely impact natural regeneration of a key and economic species (Oregon State University College of Forestry, 2017). Presently, it is not known whether this disease exists within the WSA, nor whether it has caused significant damage to the forests. This is a disease that should be monitored as climate continues to warm in the coming decades.

6.4 Western Hemlock Dwarf Mistletoe

Western hemlock dwarf mistletoe (*Arceuthobium tsugense*) is a parasitic seed plant that affects coniferous trees such as western hemlock, Pacific silver fir, subalpine and noble fir (Shaw et al., 2011). The mistletoe infests a tree, absorbing water and nutrients of its host, and causes radial growth loss and abnormal clumps of branches, called 'brooms'. Small tress can be killed and large trees experience such growth loss that they stagnate in a stand. Severely infected trees also become susceptible to secondary pests and pathogens (Province of British Columbia, n.d.). As a parasitoid, the dwarf mistletoe only survives if its host survives, which is why it often does not result in mortality.

Western hemlock dwarf mistletoe is heavily influenced by stand dynamics, rather than climate. Dwarf mistletoes depend on multi-aged; complex stands to promote its own longevity; stand replacing events such as wildfires, clear-cuts and landslides can remove mistletoe from a cohort (Province of British Columbia, n.d.). By jumping through a mixed canopy of species and ages, the mistletoe ensures its own survival in a forest. Though this was previously considered a pest, research in the last decade has suggested western hemlock dwarf mistletoe serves an important function for forest health through natural brooming, canopy dieback and vertical reorganization (Shaw et al., 2008). As climate change begins to affect the Metro Vancouver WSA forests, keeping these native parasites will be important for preserving ecosystem functions and promoting succession. If stand replacing events like fire or landslides become more common, as new research is suggesting could occur in the WSA, forest agents like this could be lost (Van der Kemp, 2016;

Dunkley in comm). Conversely, if warming temperatures or species compositions shift to include more susceptible host species, western hemlock dwarf mistletoe could begin to have negative effects on forest health. If infection were to spread it could open up some of the most critical conifer species in the watersheds to attack from further damaging agents. There does not appear to be much existing research on what will happen to this pathogen as climate warms, but to forest managers it could pose an interesting question about how helpful western hemlock dwarf mistletoe truly is to the WSA.

7. Implications on Water Quality

As outlined above, future changes in temperature and precipitation have the potential to be negative for forest health, but the 'knock-on' effects this could cause in water quality is a concern. Metro Vancouver operates two treatment and filtration plants which work to clean and provide safe drinking water to the greater Vancouver area. The Seymour-Capilano Filtration Plant (SCFP) was opened in 2009 and at maximum operating capacity could produce 1.8 billion liters of water a day. The SCFP is more complex than the Coquitlam Treatment Plant (CPT), sending raw water through 5 key processes before reaching taps. Flocculation begins the process, attaching to naturally occurring micro-organisms, organic matter and particles. A filtration step removes this floc and subsequent UV disinfection inactivates any remaining organisms. Water is then run through the clearwells, chlorinating water to kill any harmful micro-organisms before it is cleared for municipal distribution (Metro Vancouver B, 2016). Since raw water from the Coquitlam reservoir is much lower in turbidity, it is pre-treated with ozonation, removing micro-organisms and improving water quality and clarity. It then enters the UV disinfection facility, where UV light inactivates micro-organisms such as cryptosporidium and giardia before being chlorinated and distributed like the SCFP (Metro Vancouver, 2014). The complexities of water treatment and prevention of pathogenic and microbial growth could be dealt with in a report of its own. However, they are brought up here because of their relationship to forest health. Currently, Metro Vancouver would only intervene in the forest ecosystems when there is a risk to human safety or water quality (Metro Vancouver, 2011). If abiotic and biotic disturbances become more common in the Metro Vancouver watersheds, the organization may have to consider proactive intervention in the interests of protecting water quality and ecosystem integrity.

Should disturbances like western hemlock looper, balsam woolly adelgid and swiss needle cast become more severe, it could weaken stands and cause higher mortality of the WSA forest. In the event of stand-wide death there likely would be more total organic carbon (TOC) entering the WSA reservoirs. If present in high enough amounts, this could affect water treatment processes. In addition, a massive death of hemlock and balsam fir on steep slopes (>60%) could also result in a loss of shear strength and lead to slope failures-putting stress on Metro Vancouver's ability to treat water. Increasing abiotic disturbances such as drought stress, wildfire, windthrow and cedar die-back could have a similar effect in increasing landslides and erosion. New climate change research suggests landslide events are likely to increase, making this a pressing concern for future management (Dunkley, in comm.). Should a major decline in forest health result while frequency of extreme events like drought or extreme precipitation occur, it could have a significant impact on water quality and availability.

8. Future Adaptations and Opportunities

As stated above, Metro Vancouver attempts to intervene as little as possible with the natural forest ecosystems it manages (Metro Vancouver, 2011). More than anything, the most major threat to future watershed management is the unknown. Predictive climate modelling inherently deals with errors, but when looking at biotic disturbances, there are often large knowledge gaps. In recent years, much attention and research has been focused on abiotic disturbances such as wildfires and drought, and many news-worthy insect outbreaks occur in the interior of the province. As such, there appears to be less published literature on biotic disturbances in the Lower Mainland and how they will react to climate change. Therefore, the most important strategy, whether it is for the long or short term, is to implement monitoring programs and encourage further research into the WSA.

8.1 Short Term Recommendations (<50 years)

All forests in the Vancouver WSA exist with some level of healthy, inherent disturbance. In the era of climate change, short term monitoring will likely be the key to understanding disturbance over short timescales and to establish a baseline dataset for the future. Metro Vancouver has already done this successfully with the schemes implemented during the last western hemlock looper outbreak. Recording infestations and providing the opportunity for researching a disturbance in real time yielded valuable information for future outbreaks (Bonin, 2004). Short term monitoring would also be beneficial for the balsam woolly adelgid, as infestations in Washington were able to make significant progress within the last decade. As temperatures rise and precipitation changes, this system and many others are predicted to become problematic for forest managers (U.S. National Park Service, 2018). If this is also the case for British Columbia, short term monitoring to keep Metro Vancouver informed on the situation could be useful for adaptive management strategies.

Though infestations of western hemlock looper don't appear to be currently growing worse, monitoring through the pheromone trapping program should continue to be able to respond and adapt to any new outbreak within the WSA. However, like any pheromone trapping, this is not the 'silver bullet' of pest management. As useful as pheromones can be, they often need to be used in concert programs such as tree thinning, removal of infested trees, and active monitoring. The pesticide Bacillus thuringiensis kurstak (BTK) was also shown to be effective for western hemlock looper in 1993 and was used for aerial sprays outside the WSA's 2003 outbreak. Though this is effective against western hemlock looper and safe for humans, it can extremely harmful for other moths and butterfly species.

Setting up plots in the WSA to record data for future problems like swiss needle cast could also be an asset. Though swiss needle cast is native to BC, it is still only a problem for plantations in the lower mainland. However, outbreaks in Oregon and Washington jumped from plantations to native forests in a matter of decades (Stone et al., 2008). In the lower mainland, inside the native range of Douglas-fir, this type of monitoring has significance not only for Metro Vancouver but for forest managers and researchers across the province (Oregon State University College of Forestry, 2017).

In the short term, reaching out to more research groups and strengthening ties with local universities could be very beneficial to Metro Vancouver. A workshop held every two or three years with the relevant government and university researchers could be beneficial to coordinate studies and gain insight into the latest research. Many research labs within the faculty of forestry at the University of British Columbia and Simon Fraser host graduate students looking for field sites to collect data. Opening up and advertising the watershed as an area of further research to universities could be a more cost-efficient way to conduct climate change research in the coming years and promote relationships with other institutions.

8.2 Long Term Recommendations (>50 years)

It is a relative certainty that climate change will continue to stress the conifer forests of North America in the next 50-100 years. Even if forest managers decrease homogeneity on the landscape by increasing stand age class and species diversity, these forests will still be vulnerable to infestation and infection due to warming temperature and changing precipitation patterns. As insects and pathogens often reproduce yearly, these forest agents are not only capable of evolving more quickly than tree species, but they are doing so in an environment that appears increasingly advantageous for them.

The forests of the WSA are relatively diverse in age class, stand structure and species. This biodiversity has been the asset of the WSA in recent disturbance history and preserving this ecosystem resilience is one of the most important long-term goals for Metro Vancouver. As climate change related disturbances become more frequent and severe, dominant tree species shifts are likely to become more prevalent. In the aftermath of stand replacing disturbances like fire or insect outbreaks, this can be quite common. In 2003, Metro Vancouver proactively replanted multiple species in stands killed by western hemlock looper, increasing the likelihood of stand heterogeneity (Bonin, 2004). These types of actions may become more common if stand replacing disturbance become more frequent in the long term.

These insights present forest managers with an interesting prospect for replanting in the aftermath of future outbreaks. Though the success of tree species was out with the scope of this report, this is an important aspect of climate change to consider. Depending on forest health, future forest managers may have to decide whether to fight for original species composition or to proactively plant for future warming. In addition, insect and pathogen systems rely on such a complex set of trophic interactions for success, it is difficult to predict how they will react to long-term climate change and future management practices.

In the event of insects or pathogens becoming more damaging to water supplies, Metro Vancouver might need to be more invasive in their management approach. If swiss needle cast becomes a larger problem in natural forests due to shifting climate patterns, active planting of juvenile Douglas-firs might be needed to ensure propagation of the species. Conversely if a native pathogen like western hemlock dwarf mistletoe becomes less prevalent, selective thinning of over mature western hemlocks and firs might be required to keep stands healthy.

Long-term monitoring plots, like those established on Mt Saint Helens for balsam woolly adelgid in the 1950s, can be invaluable for managing a host of issues (U.S. National Park Service, 2018). Establishing a long-term dataset which captures low frequency disturbance trends, the cycles of native populations and the introduction of invasive species or decline due to climatic changes are all reasons to maintain these collections. Metro Vancouver already has plots set up by Professor Daniels out of the University of British Columbia. Metro Vancouver should consider expanding other related research into its long-term strategies, if it hasn't already.

Other watershed groups around the Pacific Northwest are beginning to discuss long term management goals in place with respect to climate change. The city of Seattle has implemented the Cedar River Watershed Habitat Conservation Plan-a 50-year ecosystem conservation plan for their old growth upland forest. This plan centers around monitoring and encouraging previously logged second growth forests to more quickly become old growth to encourage native fish and wildlife species (Seattle.gov, 2019). Though this plan does not specifically address climate change, the knowledge and data they will collect through this ongoing conservation effort could be beneficial to Metro Vancouver in the next decade.

Overall, this report agrees with the conclusions made in the LSCR Forest Management Plan (Oikos, 2001) that the most important long-term strategy Metro Vancouver can implement is the 'learn-by-doing' approach. As more is learned about climate change this should affect management around natural disturbance in the watershed supply areas, this way new information is always incorporated into management strategies and goals.

9. Conclusions

Published research to date comes to a consensus that the current rate of warming puts forests across the world at risk. Rising temperatures and changing precipitation patterns alone would be a great concern for the future, but these conditions are putting pressure on ecosystems in ways that are not yet understood. Native and invasive insects and pathogens alike are already being affected by climate change and present a complex suite of management problems for Metro Vancouver. Abiotic and biotic disturbances are expected to have a significant effect on forest health and water quality in both the short and long term in the WSA. It is unlikely that Metro Vancouver can prevent all negative effects of future disturbance, however, there is an opportunity in the next decade to minimize these ramifications on water quality. By investing in relationships with researchers and local governments, greater understanding of these complex ecosystem interactions is possible. Encouraging future climate research and strategic plans to consider these disturbances more carefully, it may be possible to mitigate frequency, severity and scope of events which could negatively affect water quality in the future.

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