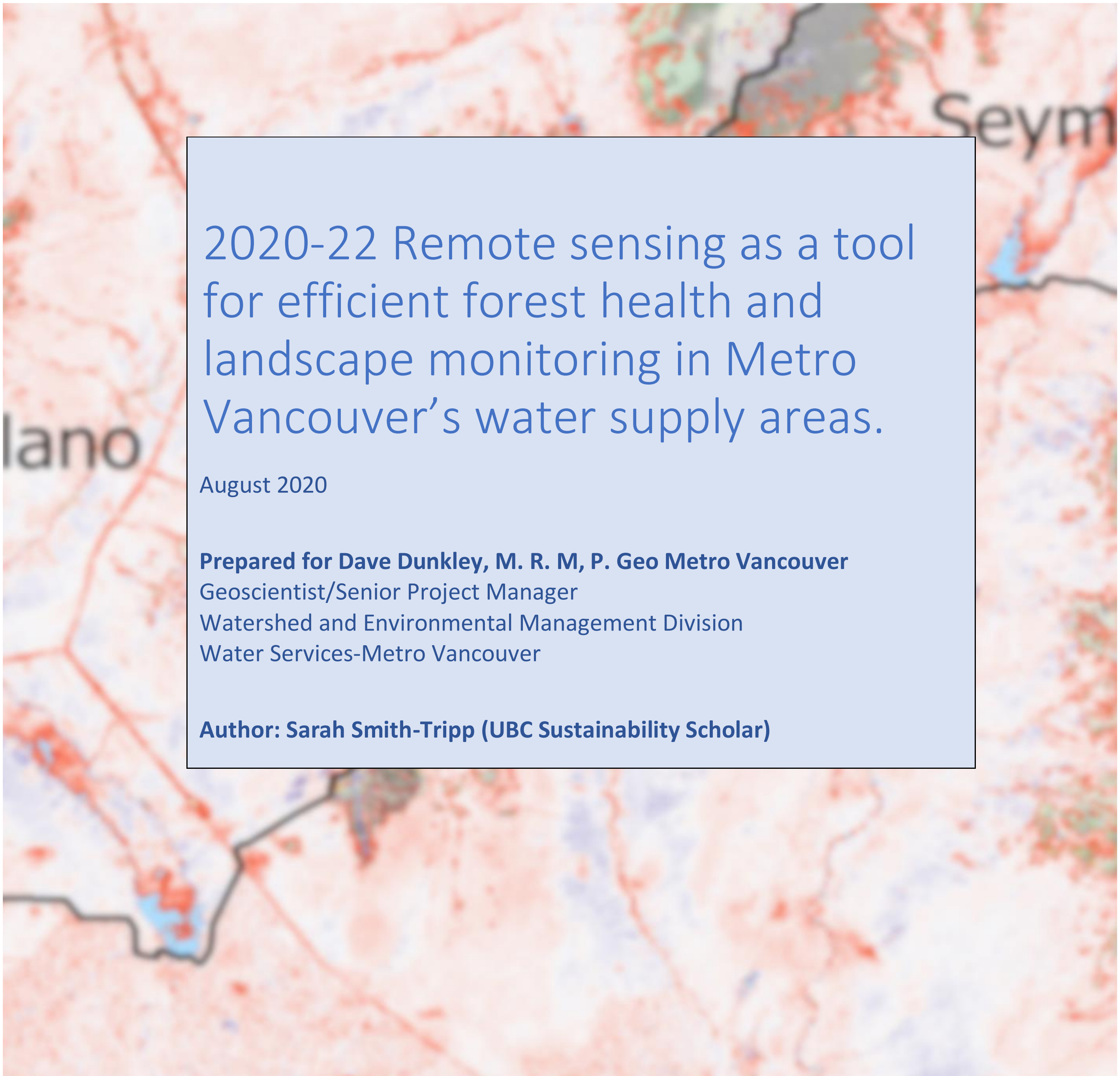

# 2020-22 Remote sensing as a tool for efficient forest health and landscape monitoring in Metro Vancouver's water supply areas.

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**Prepared for Dave Dunkley, M. R. M, P. Geo Metro Vancouver**
Geoscientist/Senior Project Manager
Watershed and Environmental Management Division
Water Services-Metro Vancouver

**Author: Sarah Smith-Tripp (UBC Sustainability Scholar)**

## List of Figures



**Sustainability Scholars Project Disclaimer**

This report was produced as part of the UBC Sustainability Scholars Program, a partnership between the University of British Columbia and various local governments and organizations in support of providing graduate students with opportunities to do applied research on projects that advance sustainability across the region.

This project was conducted under the mentorship of Metro Vancouver staff. The opinions and recommendations in this report and any errors are those of the author and do not necessarily reflect the views of Metro Vancouver or the University of British Columbia.

## Executive Summary

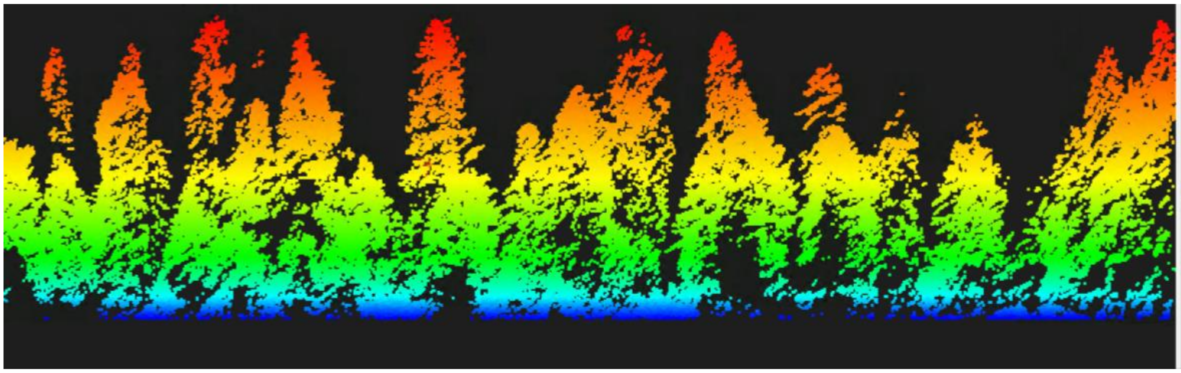
Forested watersheds are a critical component of healthy functioning water resources. Water quantity and quality is deeply influenced by upstream forest ecosystem health. Thus, a robust understanding of forest health is pivotal for understanding the current state of water resources and future threats.

This project represents an analysis of remote sensing techniques to monitor landscapes that could be integrated into Metro Vancouver monitoring efforts. The components of the analysis are (1) a review of techniques used by other natural resource managers; (2) a comparison of available remote sensing products used in watershed monitoring; and (3) a discussion of using existing data (Lidar) for ecosystem assessment. Section 1 is limited in application for Metro Vancouver, but a good overview of current remote sensing based management strategies. Section 2 gives a broadest overview of remote sensing including common remote sensing metrics, sources of remote sensing imagery, and which remote sensing product to select based on preferred conditions. Section 3 uses Metro Vancouver lidar to inform differences between ecosystems.

Each project component contributes key report deliverables that can be used by Metro Vancouver to implement a forest monitoring program that incorporates remote sensing. Key report deliverables include:

| Key Report Deliverables | |
|---|---|
| | ♦ Common remote sensing metrics for assessing forest health |
| | ♦ Sources of satellite imagery and associated costs |
| | ♦ Tools for choosing a remote sensing data product |
| | ♦ Application of satellite remote sensing to assess forest health in Coquitlam Watershed |
| | ♦ Application of Lidar to assess canopy and ecosystem characteristics in the Orchid Creek area |

Using the tools presented in this work, Metro Vancouver can create a more cost and time efficient monitoring strategy. This will help forest managers address disturbances as they arise and active plan forests for the future.



**Clip of Lidar Data from Orchid Creek area. Maximum tree height is 70 m**

## Introduction

Protected drinking watershed lands, and in particular the water supply areas (WSA), are the backbone of Metro Vancouver's multi-barrier approach to providing clean, safe drinking water to the 2.6 million residents in the Lower Mainland. These forested watersheds (Capilano, Seymour, and Coquitlam) directly impact water quality as they naturally filter water, regulate water flow, and help protect lands from erosion and landslides. The forested area also provides many other ecosystem services such as climate regulation, carbon storage, oxygen production, and habitat refugia for plants and animals. Given these benefits, it is of utmost importance that Metro staff monitor and protect forest health so that the forests that supply Vancouver drinking water continue to be resilient to disturbances (forest fire, insects, pathogens, drought, invasive species) that otherwise can impact water quality and other ecosystem services they provide. Forest monitoring has become particularly important with the increase in disturbance frequency associated with climate change.

An accurate understanding of forest health and forest disturbances in the Metro Vancouver watersheds is paramount to adaptive management. We must understand the effects of current strategies in ecosystem health in order to adapt and improve them. (McDowell et al., 2020; Thom & Seidl, 2016). Disturbances, when combined shifting climate conditions, have resulted in entirely novel ecosystems and unanticipated changes in associated ecosystem services (Millar & Stephenson, 2015).

This study provides an overview of recent monitoring work done by forest watershed managers and discusses cost and labor efficient approaches for monitoring forest health for both the short and long-term in Metro Vancouver watersheds. The study focuses on the use of remote sensing techniques employed to monitor and study forest health. These remote sensing techniques would complement existing monitoring strategies to improve understanding of forest health now and in the future.

Forest health monitoring is work designed to answer the five following questions:

- what is the condition of the forest?
- Where are the disturbances?
- How severe are the disturbances?
- Why are disturbances happening

- What is the probability of a future disturbance or problem in this area?
- Does the disturbance require a response and what would such a response look like? (Ciesla, 2000)

Remote sensing techniques can be a cost-effective and time-saving means to enhance knowledge of current forest conditions, location of disturbances, and the likelihood of future disturbance. The main objective of this study is to provide Metro Vancouver with tools to integrate remote sensing techniques into their forest health monitoring framework so that staff can respond to disturbances that pose risks to drinking water quality and important natural assets.

At the most basic level, remote sensing is information gained about an object based on energy either reflected or emitted from said object (Ciesla, 2000). For example, tree health can be evaluated based on color, where a tree reflecting mostly brown or red light is unhealthy. Differences in color are a component of spectral signature. Spectral signatures describe to what extent an object either absorbs or reflects a wavelength. An example spectral signature of healthy vegetation and unhealthy vegetation is included in figure 1. Remote sensing uses differences in spectra to assess forest health from a tree to a landscape scale.

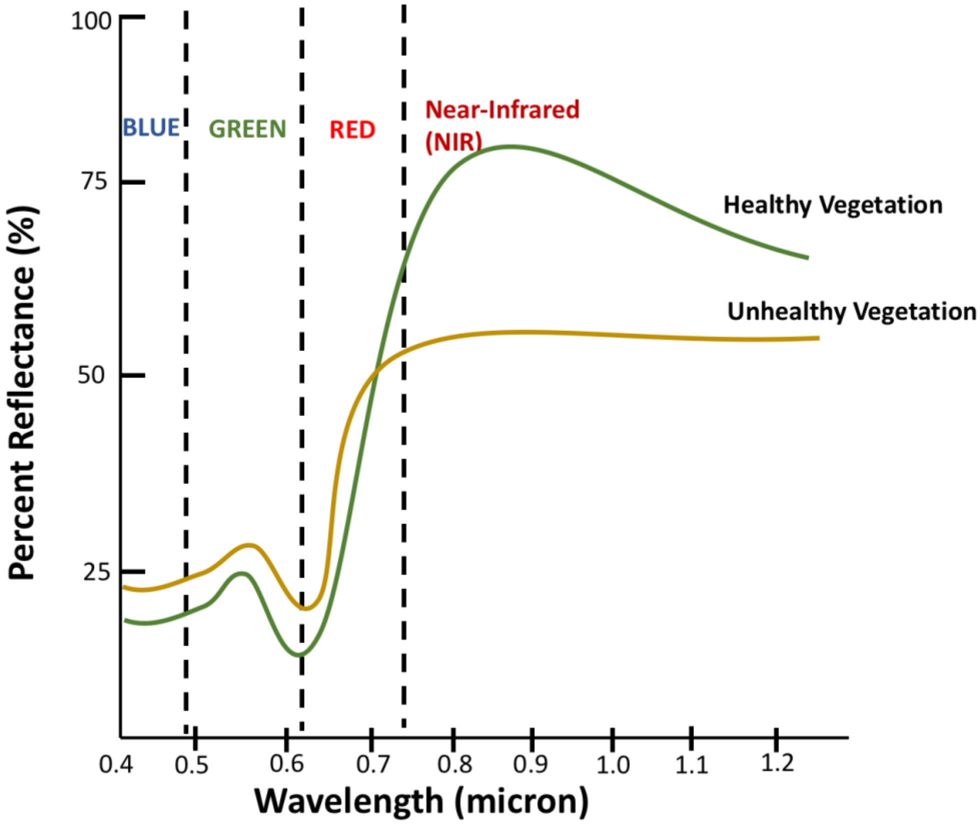



*Figure 1: Spectral signatures of healthy (green) and unhealthy (yellow) vegetation.* Locations on the electromagnetic spectra are included. Percent reflectance is approximate.

The report is divided into three components. The first component of this work lists forest resiliency plans prepared by municipal, provincial, or state agencies on the West Coast. The list focuses particularly on those plans that incorporate aspects of remote sensing, including aerial and Lidar surveys. The second component of this work discusses the aspects of remote sensing applicable to forest monitoring. This second component also includes workflows for analyzing satellite imagery and using Lidar for Forest Carbon estimates. The third component illustrates how existing data can be used for ecosystem assessment, using an example of using Metro Vancouver Lidar data to connect particularly dry-sites to landscape and forest components.

## 2.0: Summary of Water Managers' Approaches to Forest Monitoring

Iterative and adaptive planning is critical to achieve resilient forests. Natural resource management depends upon place; distinctive management techniques are required for the particular environments being managed. However, managers share tactics and strategies to allow each to build the most effective dynamic management model. This section summarizes monitoring policies of a few other water authorities and land managers. It also identifies the most promising strategies for Metro Vancouver to review.

Following a comprehensive literature review, two case studies from the Capital Regional District and the Washington State Department of Natural Resources (DNR) are highlighted as box text. (Knoth & Hooks, 2019). Capital Regional District (CRD) exemplifies how novel remote sensing components can augment existing data collection. DNR is highlighted for its integration of new research trends using a rating system outlined by the work plan of the Cooperative Monitoring, Evaluation and Research Committee.

### *1.1 Promising Strategies Based On Literature Review*

Water authorities are universally concerned with forest health. Forest monitoring strategies that include both temporal and spatial metrics can be used to show changes in forest function or new outbreaks. For example, the Capital Regional District has incorporated both temporal and spatial parameters to identify novel insect outbreaks. New forest monitoring plans frequently capitalize on the increased resolution of aerial imagery, Lidar, and satellite remote sensing assessments to improve management. However, even well-established monitoring plans are now incorporating such data. Case studies support use of iterative forest monitoring plans that integrate developing technology to better monitor and manage lands under their jurisdiction.

Effective remote sensing-based monitoring plans rely on available skills, capital, and the scale necessary to understand the problem. Most watershed managers are integrating remote sensing (primarily aerial imagery and Lidar) to improve knowledge of forest components. These remote sensing approaches are both cost and time effective but also represent a small subset of available remote sensing products.

### Box 1. Capital Regional District (CRD) Integration of High Resolution Aerial Imagery

The Capital Regional District is concerned about the increasing risk of forest disturbance from forest insects and pathogens (FIPs), as well as increasing wildfire risk. The have flown high resolution aerial flights (< 25 cm or 1:2500 scale) to outline areas of the forest with poor health. These flights are conducted annually, as opposed to the 2-year frequency of the BC Ministry of forest flights.

Using this high resolution orthoimages CRD has found several areas of the forest impacted by FIPs that were not identified with the Ministry of Forest Flights and were otherwise unknown to watershed managers. They used the extracted shape outlines of impacted forest to conduct ground assessments, where they found a novel outbreak of dwarf mistletoe (*Arceuthobium spp* ) on several lodgepole pines, the first recorded incident on the island.

Orthoimages and identified outbreak were used to create a targeted ground sampling strategy, where the impacts on forest health could be well documented. These orthophotos can be referenced from year to year to monitor spread and outline high risk areas.

*Figure 2. Example aerial photo showing drought stressed lodgepole pines in the Sooke Watershed.* Healthier crowns are Douglas fir and Western Hemlock. *Image source: (Hodge, 2018)*

Box 2. Rating System of Washington State's Cooperative Monitoring, Evaluation, and Research Committee Work Plan

The Forest Practices Habitat and Conservation Plan developed and published in 2005 by the Washington Department of Natural Resources established a Cooperative Monitoring, Evaluation, and Research Committee (CMER)Work Plan. The aim of this committee is to improve monitoring methods based on current and planned research.

*Capitalizing on Available Scientific Knowledge*

A major outcome of the CMER has been the continual adjustment of monitoring strategies and plans. Much of this work is focused on fish recovery, but in recent years has shifted to incorporate remote sensing to increase accuracy of habitat assessment. In the most recent iteration of the CMER work plan (Knoth and Hooks, 2019) remote sensing projects using Lidar were listed as urgent.

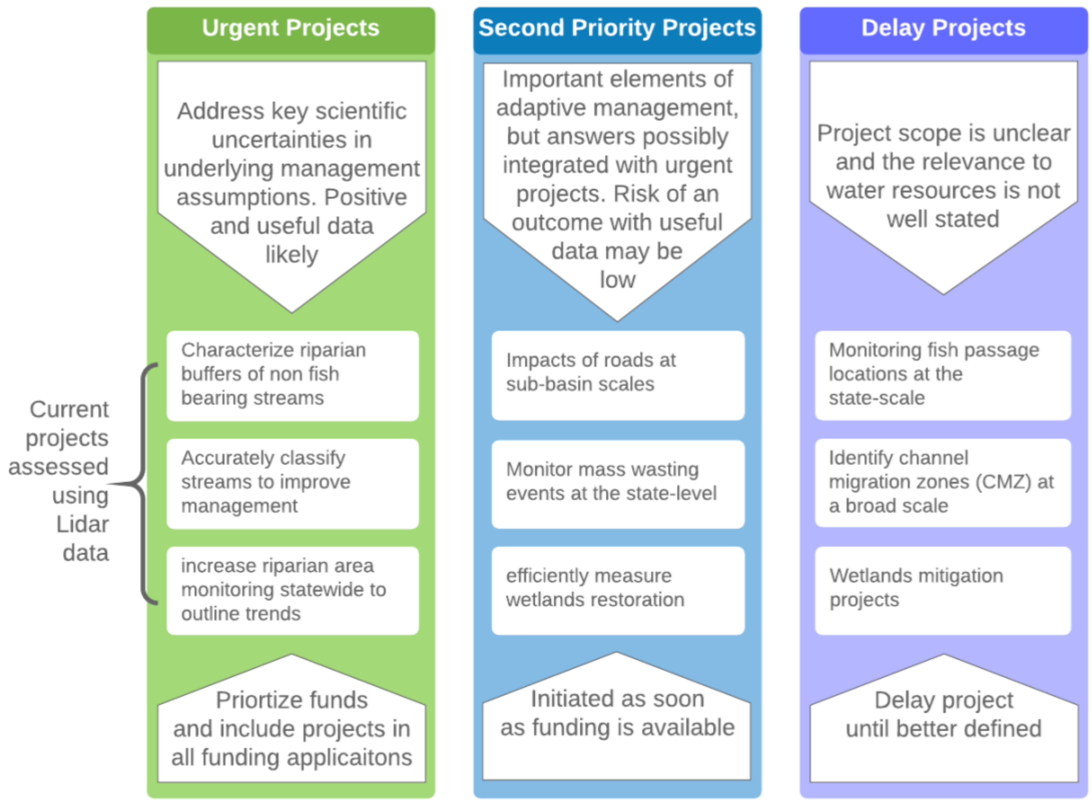



Figure 3. *Ranking system and current projects for Washington State's Cooperative Monitoring, Evaluation, and Research Committee*

*Application of Priority System for Metro Vancouver*

Classifying and outlining the projects that must be developed for management strategies can help a monitoring system that uses iteration to improve response. CMER and the associated ranking system have helped Washington state address large scale disturbance and gradually improve management tactics

## 2.0 Available Remote Sensing Products for Forest Monitoring

It is essential to provide watershed managers with an understanding and overview of available remote sensing approaches for monitoring forest health. Broadly, remote sensing can be divided into passive and active remote sensing. Passive remote sensing relies on external energy and then captures reflectance. Examples include satellites, aerial photography, and the human eye. Active remote sensing provides energy in the form of light (Lidar) or radio (Radar and Sonar) waves and then measures reflectance produced from it. Active remote sensing, including Lidar, is generally more expensive because of the technology associated with sending energy to objects. However, it has higher power and can assess below-canopy characteristics like terrain and canopy density.

This section provides an overview of passive remote sensing products because these products are often less expensive and readily available. The paper includes a decision tree to assist in selecting the correct remote-sensing tool for the job at hand. For assessing disturbance, an example of how to calculate and use vegetation indices, based on the normalized vegetation difference index (NDVI) is included. In addition, this section outlines the use of GEDI, a space-based Lidar remote-sensing platform for calculating carbon density.

### *2.1 Passive Remote Sensing Products and Indices*

Passive sensors or sensors that rely on external energy (like the sun) are the most frequently used in remote sensing because they the cheapest and best documented. The most well-known passive remote sensors are satellites. Satellites provide the capacity to monitor ecosystem change over different lengths of time and spatial scales. Other examples of passive remote sensing include aerial and remotely piloted photography.

Passive remote sensing measures the spectral reflectance of different objects. To identify trends, the science relies on differences in the spectral reflectances of vegetation in different conditions. For general forest-focused analyses, there are several commonly used indices help inform vegetation health. The most common of these indices is the Normalized Vegetation Difference Index (NDVI), which capitalizes on healthy vegetation's massive increase in reflectance in the near-infrared to differentiate between healthy (green) and stressed vegetation. The list of indices used to inspect vegetation health is exhaustive. The following table includes several commonly used vegetation indices for measuring forest health.

*Table 1. Indices Used to Monitor forest Health.* Most commonly used vegetation indices to monitor forest health, including a shortlist of advantages or disadvantages. Useful citations are the seminal paper for the index and provide an excellent overview.

| Index Name | Uses | Formula | Useful Citation |
|---|---|---|---|
| **Normalized Difference Vegetation Index** | Assessing vegetation greenness on a landscape can compare the seasonal or inter-annual change in greenness.<br>Can have issues with oversaturation if the canopy is very bright in the pictures<br>Has been used to model the probability to fire occurrence | $NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}}$ | (A. Huete et al., 2002) |
| **Normalized Difference Red-Edge** | Used to estimate vegetation stress, studies support that it can detect conifer stress about two weeks before traditional NDVI estimates. Requires red-edge bands (currently exclusive to RapidEye satellites) | $NDSI = \frac{\rho_{red-edge} - \rho_{red}}{\rho_{red-edge} + \rho_{red}}$ | (Eitel et al., 2011) |
| **Enhanced Vegetation Index** | Optimizes vegetation readings in areas with high brightness or high canopy biomass | $EVI = G\rho_{NIR} - \rho_{NIR}\rho_{red} + (C_1 * \rho_{red}) - (C_2 * \rho_{blue}) + L$<br>Where G = 2.5, $C_1$=6, $C_2$ =7.5, L = 1 | (A. R. Huete et al., 1997) |
| **Normalized Difference Snow Index** | Can estimate fractional snow cover, decreases issues with atmospheric reflection. Useful for classifying snow-cover | $NDSI = \frac{\rho_{NIR} - \rho_{SWIR}}{\rho_{NIR} + \rho_{SWIR}}$ | (Salomonson & Appel, 2004) |

## *2.2 Available Satellite/Space-Based Remote Sensing:*

There are several data repositories Metro Vancouver can use in remote sensing analyses. Thanks to government-supported research, many satellite products are free. Higher spatial and temporal resolution data often comes at a cost, but there are some exceptions for research purposes. The table below details the most prominent satellite services, including their general applications.

*Table 2. Available Space-Based Remote Sensing Products.* A list of available space-based remote products, including their applications and uses for Metro Vancouver. The resolution, including their spatial resolution (or pixel size), temporal resolution (or the frequency of visitation), start date, and costs are included. Available spectral bands can be used with indices listed in Table 2A.

| **Data Product** | | | **Spectral Bands** | **Applications** | **Uses for Metro Vancouver** |
|---|---|---|---|---|---|
| **Landsat 5-8** | *Spatial Resolution* | 30 m (starting 1984) | Blue, Green, Red, NIR, SWIR, Cirrus, Panchromatic. | Trend analysis, seasonal and yearly conditions and comparisons, Soil assessment | • Monitor disturbance severity by comparing to baseline conditions<br>• Analyze landscape changes over past ~50 years<br>• Monitor recovery of forest-based on past-recovery trajectories (e.g., how forest response to drought etc. in the past and now. |
| | *Temporal Resolution* | 16 Days | | | |
| | *Start Date* | 1972 | | | |
| | *Cost* | Free | | | |
| **MODIS** | *Spatial Resolution* | 250, 500, 100 m | Bands 1-2 (250 m)<br>Bands 3-7 (500 m)<br>Bands 8-36 (1000m) | Bands 1 – 7: spectral analyses, greenness by day.<br>Bands 20 and up: Climate modeling (surface and atmospheric temperature) | • MODIS first-level data includes 36 different bands that can be analyzed using a variety of indices<br>• Useful MODIS data products:<br>○ Land Surface Temperature (1km Resolution)<br>○ Thermal Properties (1km Resolution |
| | *Temporal Resolution* | Daily | | | |
| | *Start Date* | 1999 | | | |
| | *Cost* | Free | | | |
| **QuickBird** | *Spatial Resolution* | 2.62 m to 30cm | Band 1, 2,3, and NIR.<br>Panchromatic | Used for high-resolution mapping after a specific event (e.g., fire). Can give tree-level analyses. | • Useful for monitoring a specific event can be limited when imagery is available (based on cloudless days).<br>• High resolution can address issues of mountain shading on spectral analyses. |
| | *Temporal Resolution* | 2.4-5.9 days | | | |
| | *Start Date* | 2001 | | | |
| | *Cost* | ~$20 p/km$^2$ | | | |
| **SPOT** | *Spatial Resolution* | 2.5- 20 m | Bands 1,2,3, and NIR.<br>Panchromatic | Used frequently in urban planning, to assess growth.<br>Also used for surveillance | • Can show the development of features over time (e.g., the glacial retreat at high resolution)<br>• Also useful to enhance vegetation analyses at a high spatial resolution |
| | *Temporal Resolution* | 1-3 days | | | |
| | *Start Date* | 1986 | | | |
| | *Cost* | ~$6.45 p/km$^2$ | | | |
| **Planetscope** | *Spatial Resolution* | 3.7 m | Band 1,2,3, 4 | Developing programs mostly used to enhance the resolution of analyses similar to Landsat. Some problems with image distortion (images do not perfectly align with what is on a map). | • Highest resolution and possibly free spectral dataset available<br>• It can be used for vegetation analyses at the high spatial resolution, depending on data coverage.<br>• A parallel program called Skysat with 72 cm resolution and a temporal frequency of 2x per day. |
| | *Temporal Resolution* | Daily | | | |
| | *Start Date* | 2009 | | | |
| | *Cost* | *apply to use for free | | | |
| **RapidEye** | *Spatial Resolution* | 5 m to 50 cm | Blue, Green, Red, Red-Edge, NIR | The main advantage of Rapideye is the red-edge, which has been shown to help differentiate between healthy and unhealthy vegetation | • Can use imagery and temporal frequency of data to monitor forest-stress in near real-time at a resolution high enough for planning action. |
| | *Temporal Resolution* | 5.5 days | | | |
| | *Start Date* | 2009 | | | |
| | *Cost* | Min $7000 CAD purchase | | | |
| **GEDI** | *Spatial Resolution* | 25 m | Lidar Pulses | Unique technology aboard ISS. Used to model forest structure and canopy height on a global scale. Data is a 25-meter resolution and models are calibrated to field-based datasets | • Accurate coarse level monitoring of forest stands in watersheds (at 25-meter resolution).<br>• Data is updated to by ecosystem type<br>• Exploratory data can be combined with Lidar data for improved accuracy |
| | *Temporal Resolution* | Varying | | | |
| | *Start Date* | 2018 | | | |
| | *Cost* | Free | | | |

## *2.3 Selecting a Remote Sensing Product*

For best management practices, it is critical to have time-efficient and accurate forms of remote sensing available. The following section outlines a general decision tree for selecting a remote sensing product. This decision tree first asks if the monitoring is in response to a known disturbance, or if it is an element of long-term monitoring. For long-term monitoring, forests and landscape components (including slope stability, terrain, temperature, reflectance) are considered separately. Long-term monitoring components of this decision tree prioritize coarse resolution analyses - useful to understand watershed-level change and areas for further research. Watershed level analyses included trend analyses for forest change, ecosystem characteristics, and forest structural components. For decadal and general assessments of forest health, the most robust data repository is widely available and well-documented Landsat imagery. An example of the use of Landsat imagery to compare forest health between years is included in section 2.4.

Following the identification of forest health issues, the known-disturbance tree should be followed. The decision tree gives options based on site accessibility, available skills, and funding. Some analyses require complex ground-truthing or are still in development stages (e.g., soil moisture). These analyses would be most useful and time-efficient with someone already knowledgeable in remote sensing techniques. For accessible sites, Remotely Piloted Aircraft (RPA) imagery is cost and time-efficient alternative to aerial imagery that allows classification of forest health issues using both image and structural analyses. For more information on the use of RPAs for forest health issues, see Goodbody et al. (2019). However, if retrospective analyses are useful - high-resolution imagery is available for free from SPOT and Quickbird archives.

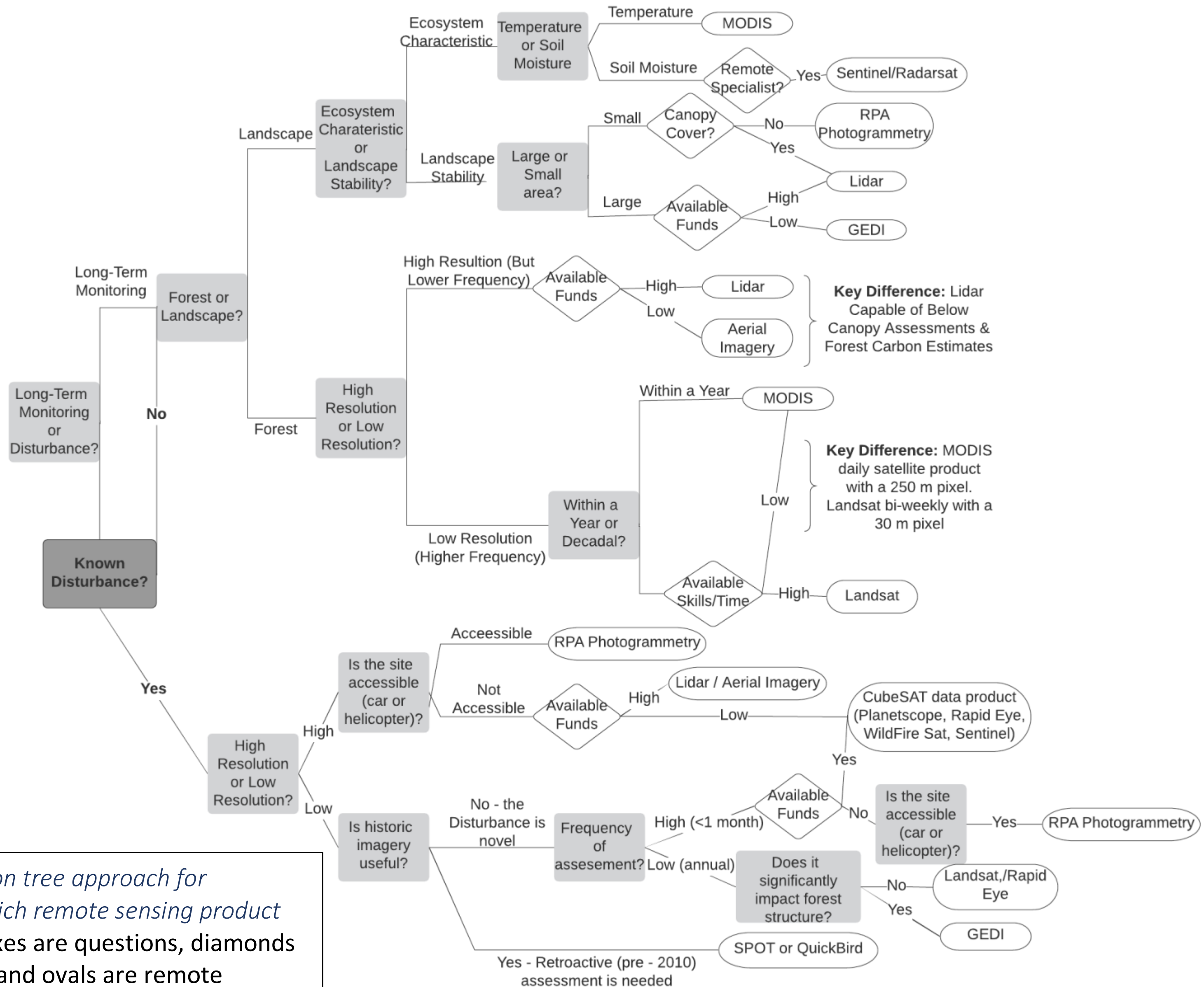



*Figure 4. Decision tree approach for determining which remote sensing product to use.* Grey boxes are questions, diamonds are conditions, and ovals are remote sensing products.

### *2.4 Applying Remote Sensing Products to Watersheds*

This section applies a selected subset of remote-sensing tools and demonstrates their use in the Metro Vancouver watersheds. Example 2A is an annual calculation of the Normalized Difference Vegetation Index (NDVI) using Landsat imagery. The code included in appendix C can be rewritten for different geographic areas and different periods. The coded can be altered for trend-based analyses and identifying problem sites at course resolution. Example 2B highlights peer-reviewed maps of forest disturbance based on Landsat imagery within the watersheds.

Given Metro Vancouver's interest in quantifying the carbon storage of the watersheds, it may wish to consider GEDI. GEDI is a freely available carbon storage dataset (Almeida et al., 2020). Example 2C describes the format and applications of GEDI data. Due to issues with the rGEDI program, examples provided by other institutions are included (Dubayah et al., 2020). Successfully downloaded data for most of the Coquitlam and Seymour watersheds are included in the metadata of this report.

#### 2.4.1 Landsat-based Annual NDVI of Coquitlam Watershed Using Landsat Imagery

LANDSAT temporal and trend-based analyses of forest health is Landsat. Landsat data spans over 50 years, many of which include eight spectral bands with 30 x 30-meter resolution. Google Earth Engine is a robust cloud-based computing platform that streamlines temporal analyses for Landsat and other satellite products, including MODIS. In this example, Landsat images are used to calculate median NDVI in 2017 and 2019 for the Coquitlam watershed. Here, pixels with a 40% likelihood of being clouds (based on spectral analyses) are removed before the NDVI is averaged. A percent difference between 2017 and 2019 is produced for the raster.

This analysis supports in 2019 Coquitlam watershed had a lower quality of forest health based on the calculated NDVI metric. However, these analyses can be biased by the number of cloud-free images available. Typically, Landsat imagery is best averaged over long periods (>5 years) to characterize changes within a given area.

*Figure 5. Median annual NDVI for the Coquitlam Watershed area in 2017 and 2019.* The percent difference from 2017 to 2019 is shown in red to blue at the bottom of the figure. In NDVI, values close to 1 are healthier vegetation, and values closer to -1 are considered an unhealthy or stressed plant. *Code for this figure is included in Appendix 2 of this document*

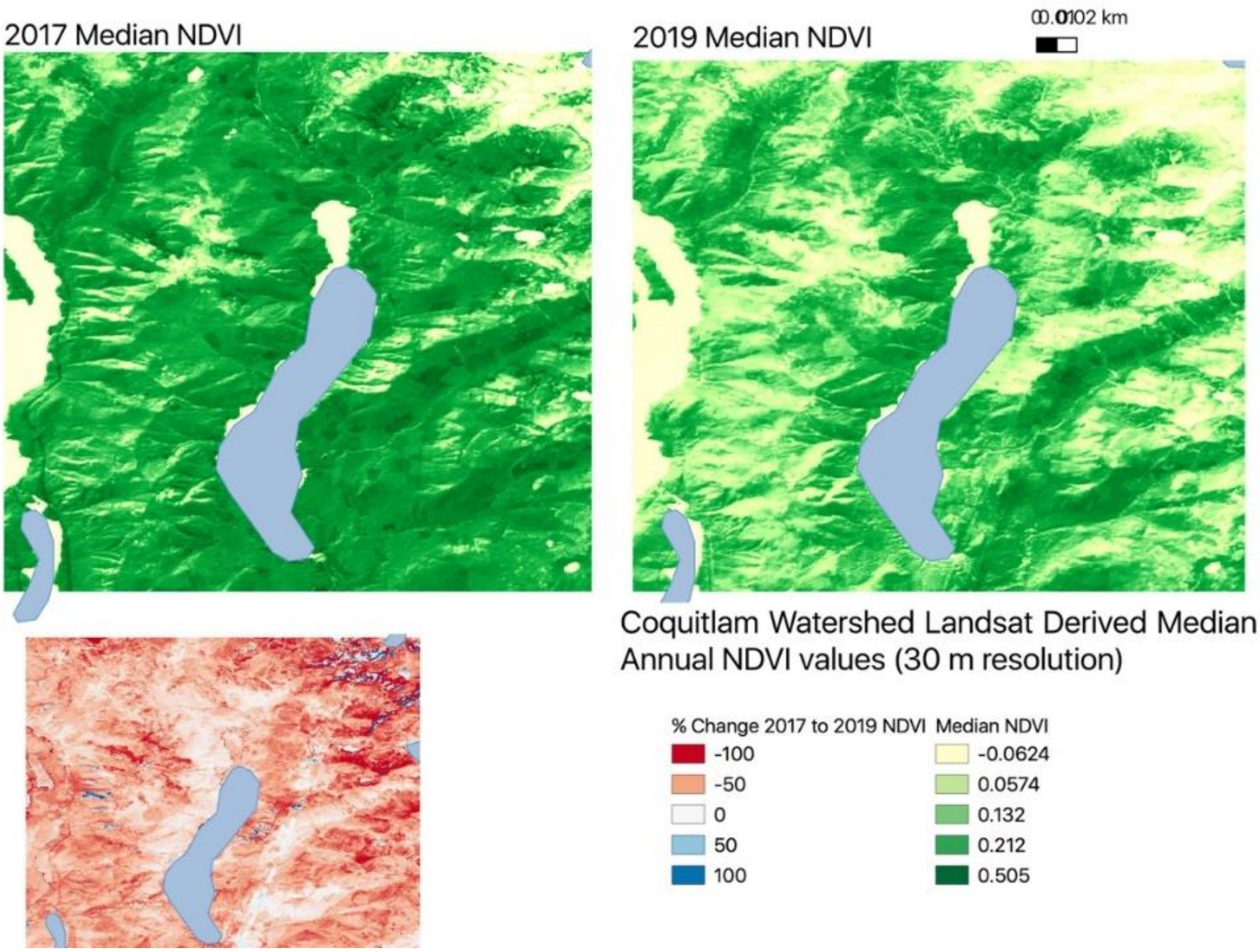



Figure 2B, an NDVI annual composite, can be used to assess forest stress during the year. Areas with lower annual NDVI are areas under pressure, possibly experiencing a disturbance. Additionally, multi-year composites can be used to identify forest composition shifts (Villarreal et al., 2016). NDVI can also be used to monitor forest for moisture stress (Pettorelli et al., 2005). It is the most used metric for assessing forest change.

Working with raw imagery and spectral reflectances requires increased time and expert knowledge. Understanding the limited time available to Metro Vancouver staff, this report also highlights free and downloadable Landsat products for Canada. Satellite Forest Information for

Canada includes many Landsat derived products that have been validated in peer-reviewed publications (Hermosilla et al., 2016). Products include basal area estimates, harvest year, landcover type, wetlands, and disturbance metrics at Landsat's 30 m resolution.
Large-scale peer-reviewed maps like Hermosilla et al. (2016) can be leveraged by Metro Vancouver to quantify disturbance within the watershed with minimal expert knowledge. The next section discusses freely available space-based forest structure data that expands on RGB based imagery alone.

### 2.4.2 GEDI for Carbon Storage Assessments

GEDI is a two-year space-based lidar mission which will cover 4% of the earth's surface. The mission will be complete in December of 2020. GEDI data are published at four levels. Level 1 is the location of the geolocated waveforms (with an accuracy of 10 m). Level 2 is canopy Height and Leaf Area Index (LAI) measurements. Tier 3 are gridded estimates of canopy height and LAI, and level 4 is 1 km estimate of carbon density. At the time of writing, level 1 and level 2 data are available for public download. Level 4 data will be available in early 2021.

Currently, the best tool for visualizing and working with GEDI data is the rGEDI package (Sylvia et al., 2020). This tool allows the user to download, plot, and visualize available GEDI data for any given area.

Coquitlam and Seymour reservoir data is downloaded and included with the information for this report. However, images used are based on example datasets because the rGEDI package has not been updated to reflect the latest GEDI data format.

**Visualizing GEDI data:**

In Lidar based estimates, canopy height is based on the difference in the last return height (the ground) and the first return ( the top of the canopy). Waveform lidar calculates returns over a 30-meter span and then returns an average for that area. For example, in figure 2C, the ground height is 775 meters, but the canopy height is 19.4 meters (RH100 – RH0).

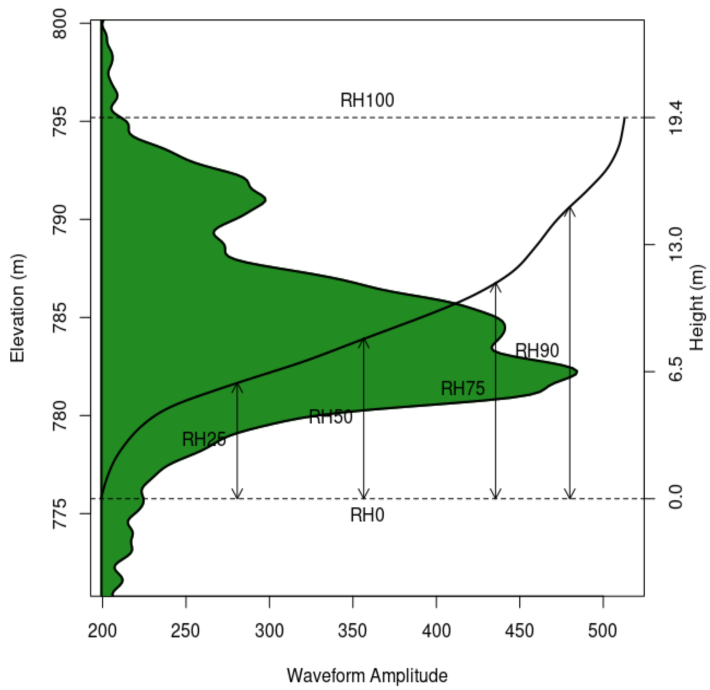



*Figure 6. Example GEDI pulse waveform.* Amplitude is the return strength, where most of the light is reflected. RH0 is considered ground, and RH100 is the top of the canopy. *Image source: Sylvia et al., 2020.*

**GEDI Data for Carbon Storage and Biomass Density Estimates**

Level 4 (carbon density metrics at a 1 km scale) data will be available in early 2021. Given the cost associated with ALS data, GEDI is a great option to increase the frequency of forest structural assessments at no extra cost to Metro Vancouver. Below is a comparison of forest biomass estimates made using ALS data, and GEDI pulse-waveforms in Teakettle Experimental Forest in the Sierra Nevadas. Qi et al. (2019) fuse TDX Satellite Aperture Radar (a free NASA satellite product) to increase the resolution from 1 km to 25 meters. These estimates of forest carbon biomass are within 15% of field derived estimates from the experimental forest (Qi et al., 2019).

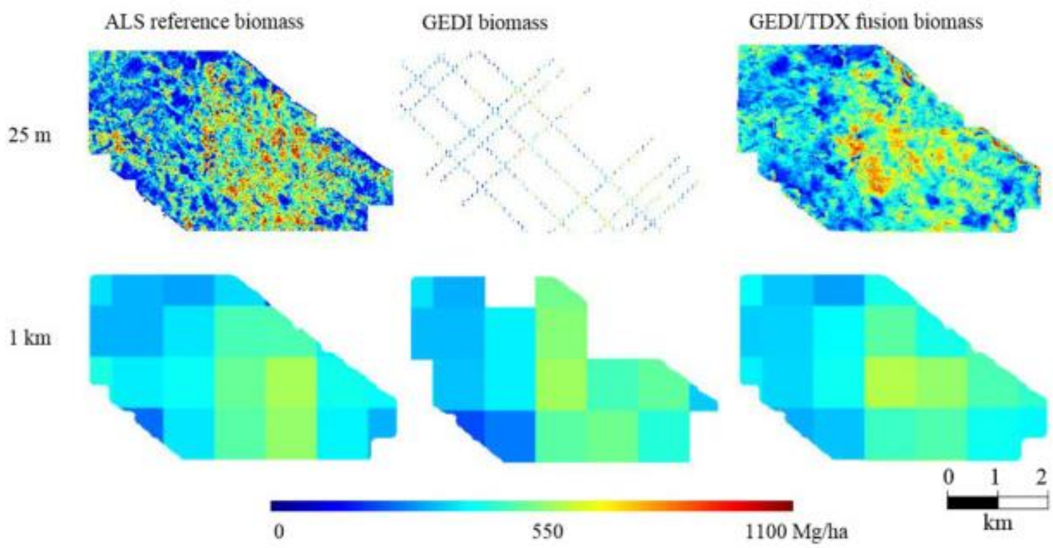



*Figure 7. Forest carbon estimates for Teakettle Experimental Forest* (a coniferous forest in the mid-slope of the Sierra Nevadas) based on ALS data, GEDI waveforms, and a fusion of GEDI and TDX satellite data.

GEDI data is a tool for Metro Vancouver to increase the frequency of forest structural assessments at no additional cost. Level 2 data, which includes height, plant area index measurements, and basal area, can be related to forest stand health (Meigs et al., 2011). Additionally, when level 4 data is available, forest carbon estimates will allow Metro Vancouver to assess better the role of the watersheds in climate mitigation and carbon storage.

### *2.5 Takeaways*

Metro Vancouver has many free or cost-effective remote sensing tools available to increase the spectral and structural assessment frequency of the forested watersheds. These tools can assist in identifying and monitoring problem areas that are either less apparent (e.g., slow drying and increased soil moisture stress) or are remote and require helicopter use.

## 3.0 Metro Vancouver Lidar Data as a tool for current Forest and Ecosystem Assessment – Applied in Orchid Area of Seymour Watershed

The final component of this paper uses available Lidar data to quantify current forest composition and ecosystem components. This research produces canopy metrics known to influence below-ground climate values. For this work, Lidar data is necessary because unlike satellite imagery or aerial photos, Lidar or light detection and ranging, uses a laser that can penetrate forest canopy to produce high-resolution topography and 3D forest structure models (Frolking et al., 2009). In this section, canopy variables, including density, coverage, and height, are used to model annual solar radiation received by a subset of Red Cedar dominant sites in the Seymour watershed.

Total solar radiation received by a surface determines thermal heating. Changes in thermal heating create site-specific microclimates. Total solar radiation is influenced by surrounding topography, including position, slope, and aspect (Oke, 2002). Typically solar radiation is estimated using topographic models. Yet, these estimates of solar radiation are limited because they do not include structural elements like forest canopy cover.

Canopy interference modifies the amount of light that penetrates to the forest floor as either direct of diffuse solar radiation (Fu & Rich, 1999). Light infiltration of a forest canopy can be defined as a function of the Beer-Lambert-Bouguer Law, shortened to Beer's Law (Oke, 2002). Beer's law states that below canopy light intensity is a function of initial radiation on canopy top as modified by a leaf extinction coefficient (a characteristic of vegetation type) and the leaf area index (Olpenda et al., 2018). The leaf area index (LAI) is a measure of canopy density, or the number of leaf layers before the forest floor (Brutsaert and York, 2005). Following the principle of Beer's law, a canopy with an LAI of 1 and an extinction coefficient of 0.6 will have 45% decrease solar radiation on the forest floor. Thus, canopy interference has a significant impact on the degree of solar radiation and thereby heating. Forest impacts on solar radiation directly alter the near-ground climate; a meta-study of in-forest and open-air temperature measurements found forests act as a buffer of regional climate, cooling maximum temperatures by an average of 1.7 ° C across the globe (De Frenne et al., 2019). Thus, accurately measuring solar radiation within the Metro Vancouver watersheds will help identify dry sites and those most at risk to drought pressure.

### *3.1 Approach*

This section describes the methodology to calculate solar radiation below the canopy using Lidar data compiled and analyzed at a 1-meter scale. Relative density is used to quantify the light penetration index (LPI). Similar to LAI, LPI represents the impact of vegetation (canopy) on the laser beam before it reaches the ground (Nyman et al., 2017). ArcGIS Solar Analyst estimates solar radiation on the canopy surface, which is then adjusted with LPI (Fu & Rich, 1999). Importantly, it quantifies the difference in the above-canopy solar radiation and the below-canopy solar radiation. This product allows managers to understand the role of the forest as a climate buffer and identify sites at risk to higher drought intensity (Asbjornsen et al., 2004).

Figure 3A shows the selected site for solar radiation analyses. Given the time-frame of this report, this section analyzes a subset of cedar dominant sites in the Seymour watershed. Dominant site-species are based on the 1997 ecological inventory mapping (*GRVD Watershed Ecological Inventory Program*, 1997). Cedar dominant sites were selected due to their increased risk of drought stress (Coops & Waring, 2011).

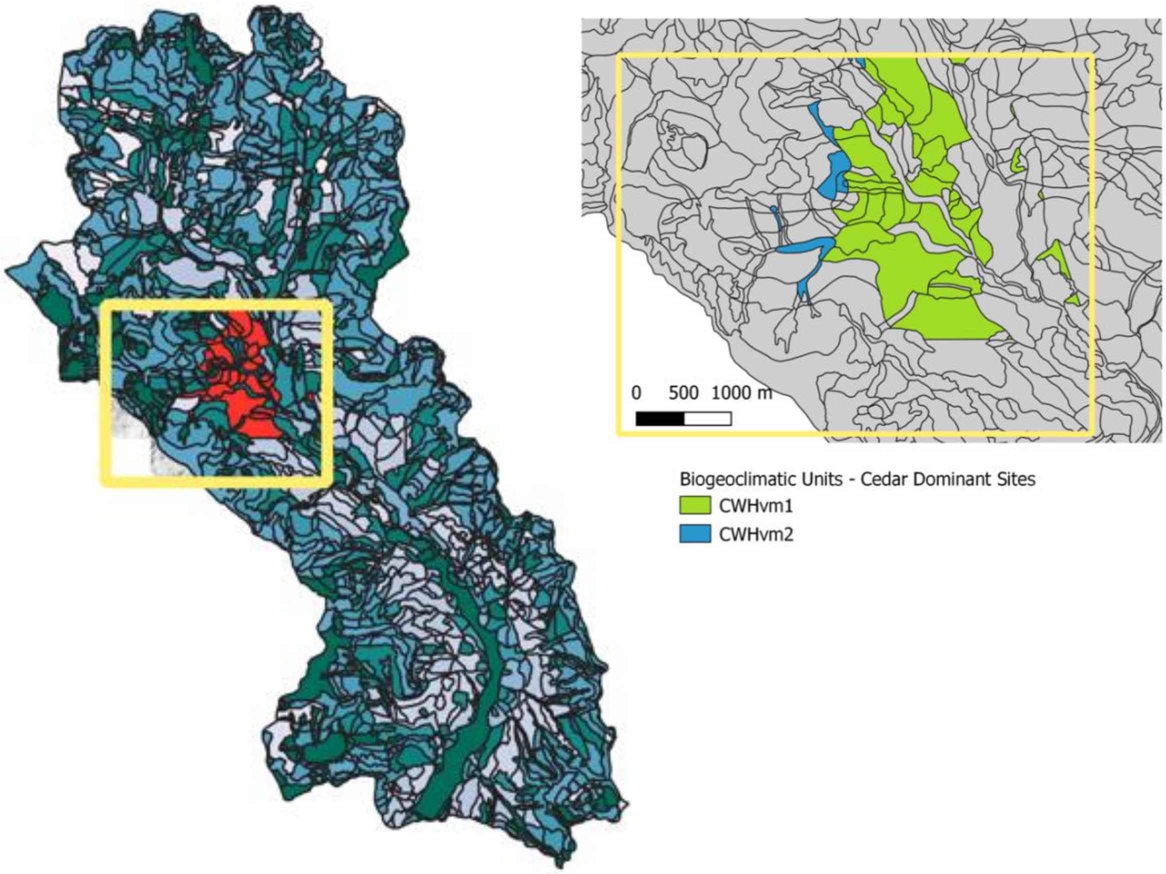



*Figure 8. Location of red cedar dominant sites near Orchid creek.* Left shows the Seymour watershed by species type and right study locations – which are variants within the Western Hemlock biogeoclimatic zone that are red cedar dominant.

*Figure 9. Overview of approach to calculate below canopy solar radiation using Lidar data.* Grey boxes show applied formulas, and bolded items are the software packages.

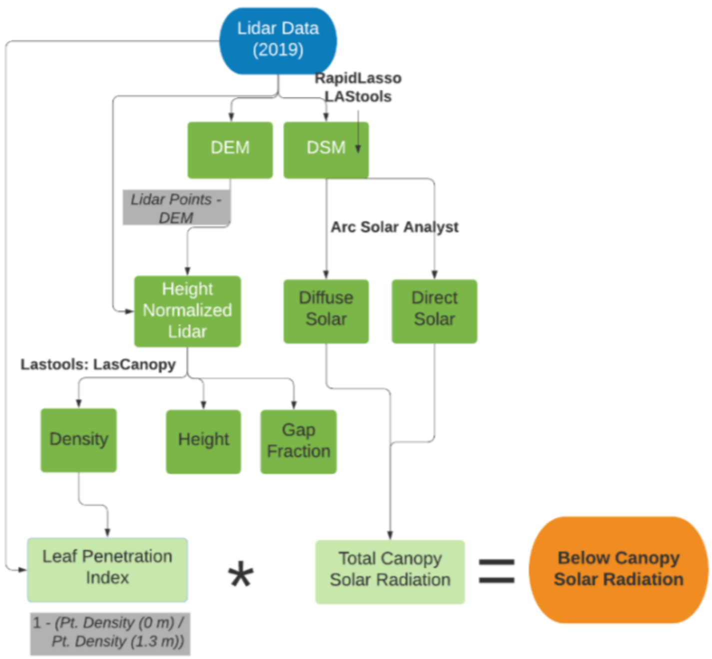



Figure 3B includes an overview of methodology for solar radiation estimates at cedar dominant sites. At these sites, Lidar point clouds were used to build a model of topography - digital elevation model (DEM), and canopy, including both a digital surface model (DSM) *and* a canopy height model. The lidar point cloud was normalized to topography to isolate lidar point returns associated with vegetation. Following normalization, canopy density, openness, and height are calculated at a 1 m spatial resolution (Isenburg et al., 2006). Accuracy for these point clouds is within centimeters (Tompalski et al., 2019). Canopy characteristics are compared among sites using zonal statistics, which are averaged over the site-level ecological inventory polygons.

Canopy density was used to assess the role of the canopy in total below-canopy solar radiation. Canopy density is a relative value of the number of returns (so the number of vegetative surfaces the laser passes through) and frequency of high returns nearby. Density scales from 0 to 100, where 0 is the most open, and 100 is the densest area. Following the methods of Bode et al. (2014), canopy density was used to calculate the Leaf Penetration Index (LPI) The formula for LPI is included in figure 3B.

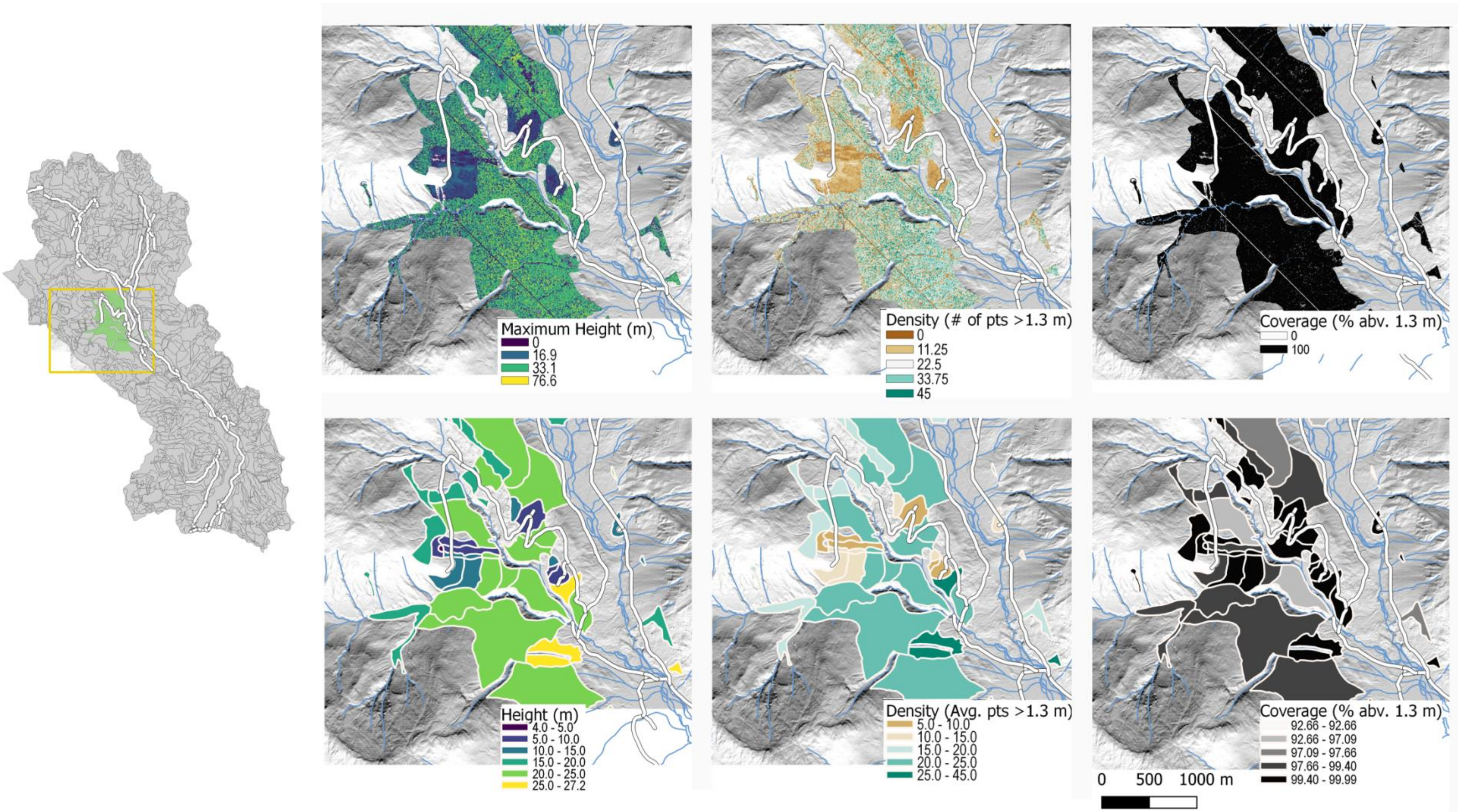
Total solar radiation at the canopy surface was estimated using ArcGIS solar analyst at both an annual and a monthly time-step (Fu & Rich, 1999). ArcGIS solar analyst calculates estimated solar radiation using a viewshed, which shows when the site is shaded based on the digital surface model. The output of this is total solar radiation at the canopy surface, which was then adjusted with LPI to produce and estimate of below-canopy solar radiation.

### *3.2 Output*

***Canopy Metrics***

Lidar canopy metrics can characterize forest structure. Figure 3C shows the output canopy metrics for the study area. General forest structural components can be easily assessed as past cut-blocks are clearly apparent, in addition to landslide deposits, and possible forest disturbances. Canopy cover for study area is very high, except for known landslide deposit in the north east portion of the plot.

*Figure 10. Canopy metrics for the Orchid Creek study area.* Top panels show 1 meter averages and bottom panel shows the average by BEC site. The white line is the location of the main road. Analyzed data is included in the meta-data of this report.



**Solar Radiation**

Solar radiation is a function of both canopy interference and topography. Figure 3D shows the total solar radiation for the study area and solar radiation adjusted with the Light Penetration Index. Solar radiation was calculated for at the canopy surface. Figure 3D supports that areas with shorter trees and ridges get the most sunlight. Other areas that receive high solar radiation include roads and water bodies. When adjusted for the impact of canopy, total solar radiation decreases by a factor of 2. This supports the impact of forest canopy on total solar radiation. Sites with less tree cover had higher average solar radiation values.

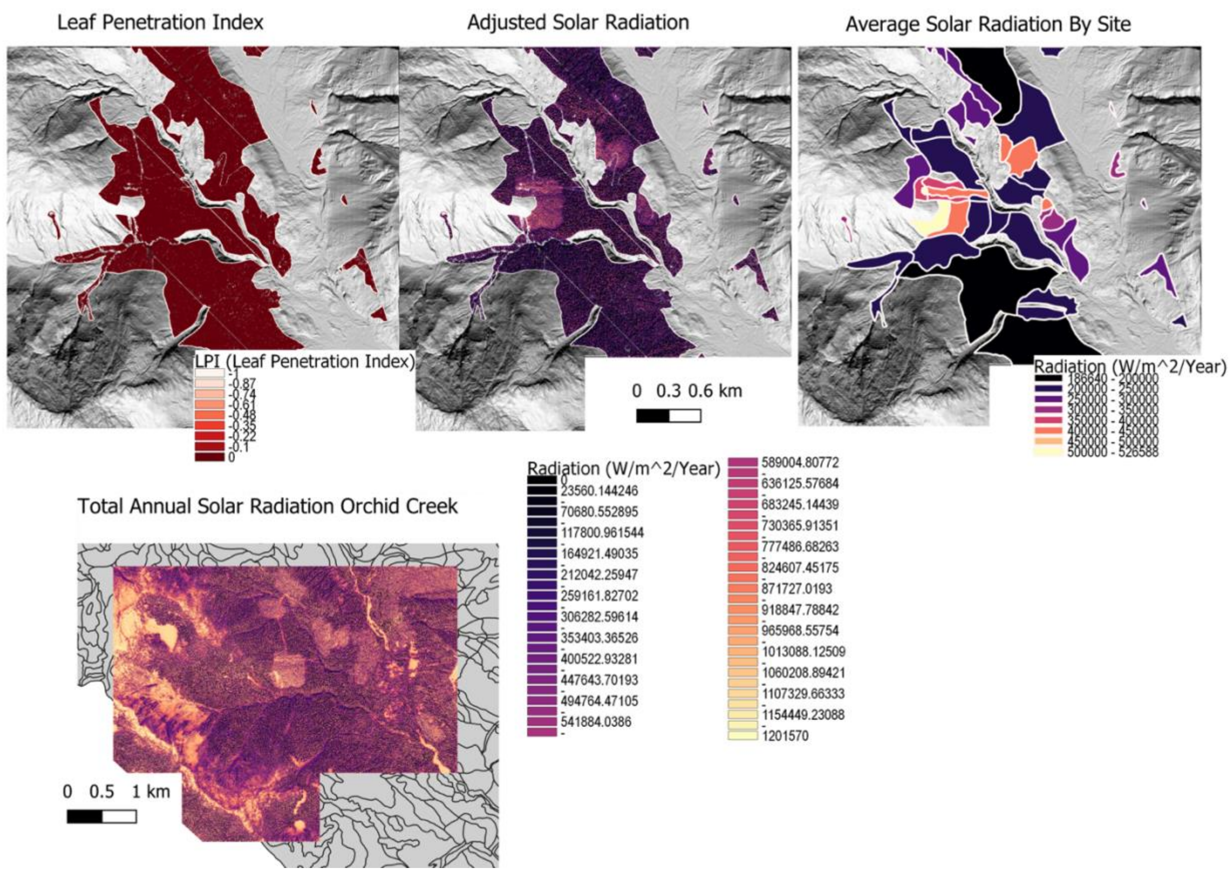



*Figure 11. Solar Radiation adjustments for below canopy.* The full image shows solar radiation for all areas near Orchid Creek. Subset is to the study area. Values are in Watt-hours/ m^2 over the course of the year.

## *3.3 Theoretical impact of Canopy on Site-Level Climate*

Topography influences the total amount of solar radiation, which in turn influences heating. Using the specific heat capacity of sandy soil (consistent with bedrock weathered soil of the Seymour watershed), we can roughly estimate how changes in solar radiation would result in a temperature shift. To contextualize the output of solar radiation, I convert differences in solar radiation to theoretical temperature shift for a shallow dry sandy soil with a density of 1.6 $g/cm^3$ and a specific heat capacity of 0.8 J/g °K (Oke, 2002). In the sites average solar radiation, the maximum site had annual average of 52687 $Wh/m^2$ over the course of the year. The minimum solar radiation a site is experiences is 186639 $Wh/m^2$ over the course of the year. This difference in solar insolation results in a estimated difference of 32 °C averaged over the year. However, this is highly dependent on the length of the day, which is highest in the summer and lowest in the winter. These estimates support that forest canopy plays an important role in surface temperature regulation, which in turn impacts forest health and the ecosystem services provide by the watershed. Additionally, solar radiation is more important when during the summer period because small differences in solar radiation amplify temperature change over the course of the day.

### *3.3 Takeaways*

Metro Vancouver's lidar data can be used to characterize forest structural components and improve models of the forest-ecosystem interactions. The section outlines the approach for processing lidar data to understand site-level climate due to different solar insulation values. Another possible use of Lidar is to calculate above-ground biomass and carbon sequestration (Margolis et al., 2015), or estimates of damage associated with windthrow, hemlock looper, or other forest disturbances (Bolton et al., 2015). Lastools is an easy and efficient tool to complete forest canopy analyses (Isenberg et al., 2006).

## Conclusions

By incorporating high resolution, low-cost remote sensing data, Metro Vancouver can increase the frequency and scale of forest assessments, while also improving overall efficiency. This report recommends increased use of Landsat for temporal assessments of change and a complete analysis of the Lidar data for both forest structure and carbon sequestration assessments. Fusing remote sensing data sources will allow Metro Vancouver to respond and adapt management plans as watershed ecosystems change and disturbances occur.

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## Appendix A

### *British Columbia Watershed Management Plans*

*Table S1 British Columbia Watershed Management Plans.* Prominent notes of plans reviewed are discussed by region provider (Capital Regional District and Okanagan). Only plans useful for Metro Vancouver are included in the table

| Region | Plan Document | Notes on Plan Components |
|---|---|---|
| **Capital Regional District** | (Cyr, 2017); Regional Water Supply Strategic Plan | • Ranks risk factors for water supply<br>*High Risk*: Wildfire, humans, and animals. *Medium risk*: forest health, dissolved oxygen depletion. *Low Risk:* Blowdown, erosion, contaminants.<br>• Annual aerial forest health monitoring for insect disturbance.<br>• Employed outside firm to model likely wildfire behavior in watershed (extent and severity). Identified areas with high fuel loads. Planned prescribed burning to reduce high-risk areas.<br>• 5 long-term monitoring plots for forest health and growth.<br>• Monitoring growth, composition, and health of disturbed and regenerating forest stands – including vegetation brushing to ensure seedling survival |
| | (Hodge, 2018); Summary of Forest Health Factors in the Greater Victoria Water Supply Area | • Report of 2017 forest health in the Greater Victoria Water District.<br>• Higher-resolution aerial imagery improved the ability to detect at-risk sites.<br>• Includes ground verification of at-risk sites |
| | (Taking Action on Climate Change: Capital Regional District - Regional Climate Action Strategy, 2017) | • 8-goal plan to address changes in planning associated with climate change.<br>• Goal 4: Manage natural assets to mitigate loss of ecosystem services.<br>• Goal 8: Manage natural assets to be resilient to climate change<br>• *Indicators of success:* completion of regional inventory of land cover, monitor % change in forest cover, and watershed evaluation with both environmental and hydrologic monitoring |
| | (Cyr, 2017); Regional Water Supply Strategic Plan | • Outlines 6 projects to protect water for Capital region including preparing for post-disaster water supply, and adaption and mitigation to climate impacts in forested watersheds<br>• Monitoring plans developed for watershed areas include parameters for when active forest management is needed |
| **Okanagan Basin Water Board** | (Pike et al., 2006); Key Points to Consider When Pre-Planning for Post-wildfire Rehabilitation | • Discusses the set-up of pre-planning and monitoring strategies for fire events<br>• Outlines key watershed components and monitoring strategies to assess health of components. This includes desired vegetation composition<br>• Prioritizes research on terrain monitoring and storm return intervals to better respond to mass movement events. |
| | (Neilsen & Guy, 2019); Okanagan Sustainable Water Strategy: Action Plan 2.0 | • Management guidelines for Okanagan water, discuss history and future of work.<br>• Use Lidar mapping to develop flood risk and forest change maps. The Okanagan Basin Board was awarded $1.45 Million for ongoing Lidar Based Research in 2018.<br>• Develop complete watershed assessments to assess snow storage and forest attributes<br>• Increase the density of weather stations to improve estimates of vegetation water needs |

## Appendix B

### *West Coast Examples Watershed Management Plans*

*Table S2 Broader West Coast Examples Watershed Management Plans.* Prominent notes of plans reviewed are discussed by region. Examples note differences in the US and BC approach to watershed monitoring and management.

| Region | Plan Document | Relevant Plan Components |
|---|---|---|
| Washington Department of Natural Resources | (*Forest Practices Habitat Conservation Plan*, 2005) | • Hallmark plan for Washington state compliance with (1) the endangered species act (2) fish habitat (3) water quality standards (4) timber economic needs<br>• Goals and management defined by the stream type, determined by fish in the system<br>• Plan success is assessed with fish stocks and hydrology changes<br>• Introduces Cooperative Monitoring, Evaluation, and Research Work Plan mandated with updating strategies for (1) Effectiveness and Validation Monitoring (2) Extensive Monitoring (3) Intensive Monitoring (4) Rule implementation tools |
| | (Rodger & Walters, 2012) | • Following 2007 windthrow enacted new monitoring scheme to measure slope stability, including follow-up measurements by the USGS<br>• Introduces an adaptive management strategy for plans to follow after a significant windthrow event.<br>• Includes funding for replanting and monitoring the growth of forested slopes impacted by disturbance events. |
| | (McNaughton et al., 2005) | • Develops a ranking system for adaptive management strategies combining the usability of the project with the cost-efficiency<br>• Describes active projects and how they fall within the ranking system |
| | (Knoth & Hooks, 2019) | • Two -year work plan for the CMER that states the hierarchy for upcoming monitoring and research activities<br>• High priority goal to use Lidar to classify stream types across the state |
| Skagit County | (*Cultus Mountain Watershed Management Plan 2013*, 2013) | • Plan to increase water security for Skagit County area, including the acquisition of private lands for public use.<br>• Plans for pre and post-fire response to limit sediment input.<br>• The monitoring plan focuses on active discussions with land managers because the majority of the watershed is privately owned. |
| Portland Public Utilities | (*Bull Run Water Supply Habitat Conservation Plan*, 2008) | • An adaptive management plan for the Bull Run water supply, which is now 100% owned operated by the city's public utilities<br>• Plans increasing canopy cover in near-riparian areas over the next 15 years, measured using aerial surveys<br>• Active forest management including planting if more than 20% of the forest is disturbed |
| Pacific Northwest Intensively Monitored Projects | (Hillman et al., 2019) | • Intensively monitored watershed projects in Oregon and Washington are primarily focused on monitoring fish populations, large woody debris, and stream habitat characteristics.<br>• None of these projects included an analysis of surrounding forest – relying on field-based descriptions of habitat type. |

**Appendix C**

*Code to Analyze NDVI in Google Earth Engine*

```
/// Code written by Sarah Smith-Tripp for Metro Vancouver, June 2020
/// This code calculates the median NDVI from cloud-free pixels in 2019
/// Here geometry is defined as a given watershed (the example is of coquitlam)
/// The year can be changed a timespan of interest, but beware of a data overload from the
///request

// Specify a location and date range of interest
// make a loop to get the dates for data download
var years = ee.List.sequence(2009,2019);

var start = ee.Date('2019-01-01'); //Define a start date for filter
var end = ee.Date('2019-12-31'); //Define a end date for filter
// Filtering and Sorting an ImageCollection
var bandNames = ee.List(['B2', 'B3', 'B4', 'B5']);
var collection = ee.ImageCollection("LANDSAT/LC08/C01/T1_RT")
//.select(bandNames)//import all Landsat 8 scenes
.filterBounds(point) //filter all scenes using point geometry from above
.filterDate(start, end) //filter all scenes using the dates defined above
.filterMetadata('CLOUD_COVER','less_than', 30); //sort all images within the ImageCollection by
cloud cover



//Add cloud scorings to the image as a layer
var cloudScore = function(image) {
  var cloud = ee.Algorithms.Landsat.simpleCloudScore(image);
  return image.addBands(cloud)
} ;
var collectionCloud = collection.map(cloudScore)

/*
// filter collection to fewer cloudy images
var cloud_thresh = 40;
var cloudLikelihood = collectionCloud.select('cloud');
var cloudPixels = cloudLikelihood.lt(cloud_thresh);

var cloudless = collectionCloud.updateMask (cloudPixels);
*/



// // explore the image collection
```

```
 print(collectionCloud);
// //var size = collectionClip.toList(100).length();
// //var count = collectionClip.size(); print(count); // print the numer of images
var image = collectionCloud.first();
print('Least cloudy image:', image);
//Map.addLayer(image)

//Map.addLayer(image, {bands:['B6','B2','B1']},'Natural Image'); // add least cloudy image to
the map

//function to calculate NDSI (Normalized Difference Snow Index) for the the images
var addNDVI = function(image) {
var ndvi = image.normalizedDifference(['B5','B4']).rename('ndvi');
return image.addBands(ndvi)
};



var collectionNDVI = collectionCloud.map(addNDVI).select('ndvi');
var ndviParams = {min: -1, max: 1, palette: ['brown', 'white', 'green']};

// reclassify NDSI to snow / non
//var level = -0.7; // define a level of NDVI to classify as unhealthy
// var train = random.filter(ee.Filter.lt('random', split));
//var unhealthy = collectionNDVI.gte(level);
//Map.addLayer(unhealthy)


// Map the function over the collection.
var ndviBand = collectionNDVI.select('ndvi');
var median = ndviBand.median();
//print('the max is', ndsiBand);

// Display the result.
//Map.addLayer(median, ndviParams, 'NDVI image');

var visParams = {
  min: 0.0,
  max: 9000.0,
  palette: [
    'FFFFFF', 'CE7E45', 'DF923D', 'F1B555', 'FCD163', '99B718', '74A901',
    '66A000', '529400', '3E8601', '207401', '056201', '004C00', '023B01',
    '012E01', '011D01', '011301'
  ],
```

```
};

var rgbVis1 = ndviBand.map(function(img) {
  return img.visualize(ndviParams).clip(geometry);
});

var gif1Params = {
  'region': geometry,
  'dimensions': 600,
  'crs': 'EPSG:3857',
  'framesPerSecond': 1
};

// Print the GIF URL to the console.
print(rgbVis1.getVideoThumbURL(gif1Params));

// Render the GIF animation in the console.
print(ui.Thumbnail(rgbVis1, gif1Params));
```