Monitoring the seasonal growth impact of foliar pathogens – an ideal sensor network

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Resilient Forests Research Programme

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Executive summary

The problem

The primary objective of this study was to develop a technical design for monitoring foliar pathogens in forest plantations and characterizing their impact on productivity and wood properties. Needle diseases cause needle dysfunction (blight) and/or induce premature partial crown defoliation (cast). Both phenomena are associated with a decrease in photosynthetic capacity. How that decrease translates to productivity losses is complex to characterize from a physiological standpoint. The production and utilization of photosynthates by trees varies seasonally. Wood formation is also under the influence of intra-annual cycles. Pathogen infection and reproduction follow specific dynamic patterns. The loss of foliage does not cause a proportional decrease in growth. Instead, it triggers a chain of events involving active defence response to infection, disruption to basic physiological functions such as water transport, and mobilization of internal carbohydrate reserves. Monitoring the dynamics of foliage, pathogen and radial growth is of critical importance to understand both short-term and long-term effects of needle disease on tree productivity and resilience. It is also essential to determine to what extent tree genotypes are resistant to pathogen infection and/or the physiological consequences of defoliation, and to identify which variables can be acted on to mitigate productivity losses.

Often, the many different tools for investigating epidemiology and tree physiology are used in isolation to address specific questions. The overarching aim of this study was to provide an integrated approach using inter-disciplinary methods to host-pathogen monitoring. This should lead to new insights on pathogen development and impact and allow a more holistic approach to control in forest ecosystems.

Client initiatives

Past work in forest pathology has allowed identification of new pathogens, such as *Phytophthora pluvialis*, cause of red needle cast (RNC), and the development of new methods and models to detect and predict disease expression in single trees and across the landscape (Dash, Watt, Pearse, Heaphy, & Dungey, 2017; Gommers, Tan, Ng, & Williams, 2018; Wake, Williams, & Pleasants, 2017). Pathogen impact on host physiology has highlighted new paths for future research on host resistance (Gomez-Gallego, 2019). Growth impact of RNC has been quantified for a single site (Beets et al., 2013). Scion has also deployed a sensor network to monitor forest ecophysiology and productivity in a forest trial (Meason, Segura, Sellier, & Lad, 2018).

This project

An ideal sensor network for monitoring the growth impact of foliar diseases in commercial forestry plantations is proposed. A pathway to implementation is provided and a trial site for deployment is suggested. The sensor network is designed to continuously monitor and link crown status (crown morphology and health, needle capacity and associated pathogens) to growth rates in individual trees. The aim is to understand the mechanisms of tree response to defoliation and identify pathways for resilience.

Key results

We describe an ideal sensor network which consists of:

- Airborne lidar, sub-canopy lidar, multispectral imaging supported by visual scoring, cast needle trapping, spore trapping, and foliage sampling to monitor the canopy changes throughout the seasons. This enables the study of dynamics of disease expression, crown health, foliage growth and turnover.
- Automated electronic sensors and carbohydrate and nutrient sampling to quantify the impact of disease on productivity and the physiological mechanisms by which it is impacted.
- Align work on tree growth to ongoing development of epidemiological models of needle diseases (Resilient Forests RA3.2).
- The combination for the first time of epidemiology and physiology monitoring in a single sensor network. We have made provisional costings that will be revised depending on best sensor and equipment options available closer to time of deployment.

Implications of results for the client

This work outlines the data and methods required to establish a trial that will allow clients to understand the impact of foliar pathogens on forest growth and hence economic value. This information will allow forest managers to understand cost-benefit trade-offs for management practices, allow optimal deployment of genetic material and prioritise future work to mitigate growth impacts.

Further work

A trial area has been selected for deployment of a proof-of-concept sensor network to validate the design and methods outlined in this report.

Introduction

Foliar diseases are a common occurrence in New Zealand commercial softwood plantations. Red needle cast, caused by *Phytophthora pluvialis*, is a recent addition having been recognised since 2008 and adding to dothistroma needle blight, cyclaneuesma needle cast and 'physiological needle blight' as the key drivers of foliar disease. So far, the focus has been on disease detection, management and control. Those have a socio-economic and environmental costs, especially control which relies on chemical application which needs to be both cost effective and socially acceptable.

Foliar diseases impair the function of the carbon production organ of trees, foliage, by blight or cast. It is critical to quantify losses of wood production resulting from diseased foliage to allow full cost-benefit analyses for management activities. The relationship between photosynthetic production and growth is physiologically complex:

- Carbon is the central currency for most metabolic processes in the plant (respiration, turgor control, translocation, resistance to embolism, immune defence). Carbon is also consumed by pathogens. Carbon availability also plays a large role in drought-induced mortality.
- Growth is driven by growing tissues demand in carbon rather than its supply, carbon storage pools buffer temporary effects in carbon imbalance, and defoliation can in some cases have little to no effects on growth.

Very few studies in New Zealand address the consequences of infection for the host (tree). Only one study in New Zealand has characterised the impact of *P. pluvialis* on radial growth, with losses of up to 40% observed the year after infection but lower to non-existent losses noted after this (Beets et al., 2013). The impact on growth quality is uncertain. More importantly, such studies do not establish the causal relationships between pathogen action and the growth response, instead documenting growth impact after the fact.

There exists a need for detailed, on-site, long-term monitoring of growth dynamics of foliage, pathogen, and wood. Each of these components follow a different seasonal cycle and is subject to distinct environmental influences. An improved theoretical knowledge will enable better predictive tools to quantify the economic losses associated with foliage disease cycles. This knowledge is also needed to understand if and what any pathway to host resilience may be. This will allow key questions such as what makes a tree resistant to pathogen infection or what makes a tree more tolerant to defoliation to be addressed. To understand resistance and susceptibility, the effect of timing of infection on host physiology in relation to phenology and acute stress events (e.g., droughts) must be considered.

Many experimental methods have been used to monitor needle diseases, tree growth and tree function; however, they are typically used in isolation. If combined, we could form an integrated picture of pathogen growth impact and identify the underlying mechanisms and key drivers. Here, we propose to combine the current state-of-the-art sensors with new approaches to form an ideal sensor network. We suggest a site and an experimental design for the first deployment, estimated costs, design rationale and expected outcomes. The data collected can be used for statistical analysis, but an important objective is collecting enough data to simulate defoliation to inform process-based or mathematical models (tree growth, carbon transport, SIR).

Sensor Network Design

We describe all the components of the ideal sensor network to monitor the growth impact of foliar diseases. Those components are experimental approaches to survey the status of the host (tree) and the pathogen as a function of time

An overview of the proposed sensor network design is shown in Figure 1.

Network components

Components of the sensor network consist of four main types: visual assessment, remote sensing, real-time monitoring, and field sampling. These components allow seasonal characterisation of disease expression or severity as well as tree structure, function and growth.

Costs are expressed as percentage of total Cost Per Year (CPY) and UC (Upfront Cost), respectively. CPY is linked to running the network and UC is linked to deploying the network. This gives an indication of the relative cost of each operational setup for task prioritisation.

For all measurements listed below for which costing is starred (*), the cost is already covered in the current field trial suggested for deployment of the sensor network. For deployment of the sensor network at another site, those costs would need to be added.

Field measurements

Foliage visual scoring

Description	On-site scoring of crown fraction of discoloured (symptomatic) needles by ground visual assessment.
Rationale	Measure the amount of disease in the field using established methods. Identify the timing of the symptomatic phase.
Measured variables	Disease score (0-100%) of crown affected.
Links	Compare and validate with disease scoring done using Vegetation Indices derived from multispectral imaging.
Sampling frequency	Monthly
Projected cost	(5.4% CPY) *

Tree mensuration

Description	Permanent Sample Plot (PSP) measurement of tree height, crown height and diameter at breast height.
Rationale	Standard practice to obtain generic morphological traits. Ground-proofing LiDAR-based growth metrics.
Measured variables	Height, Crown height, DBH.
Links	Compare to LiDAR-derived height and growth metrics as well as dendrometer-derived radial growth rates.
Sampling frequency	Yearly
Projected cost	(0.3% CPY) *

Digital hemispherical photography (DHP)

Description	Ground-based photography of canopy and light environment.
Rationale	Reference Leaf Area Index (LAI) values. Calibration and validation data set for developing LiDAR-based estimation of LAI and Leaf Area Density (LAD).
Measured variables	LAI
Links	LAI/LAD by LiDAR data (calibration/validation) and litter traps.
Sampling frequency	Seasonally
Projected cost	4.7% UC

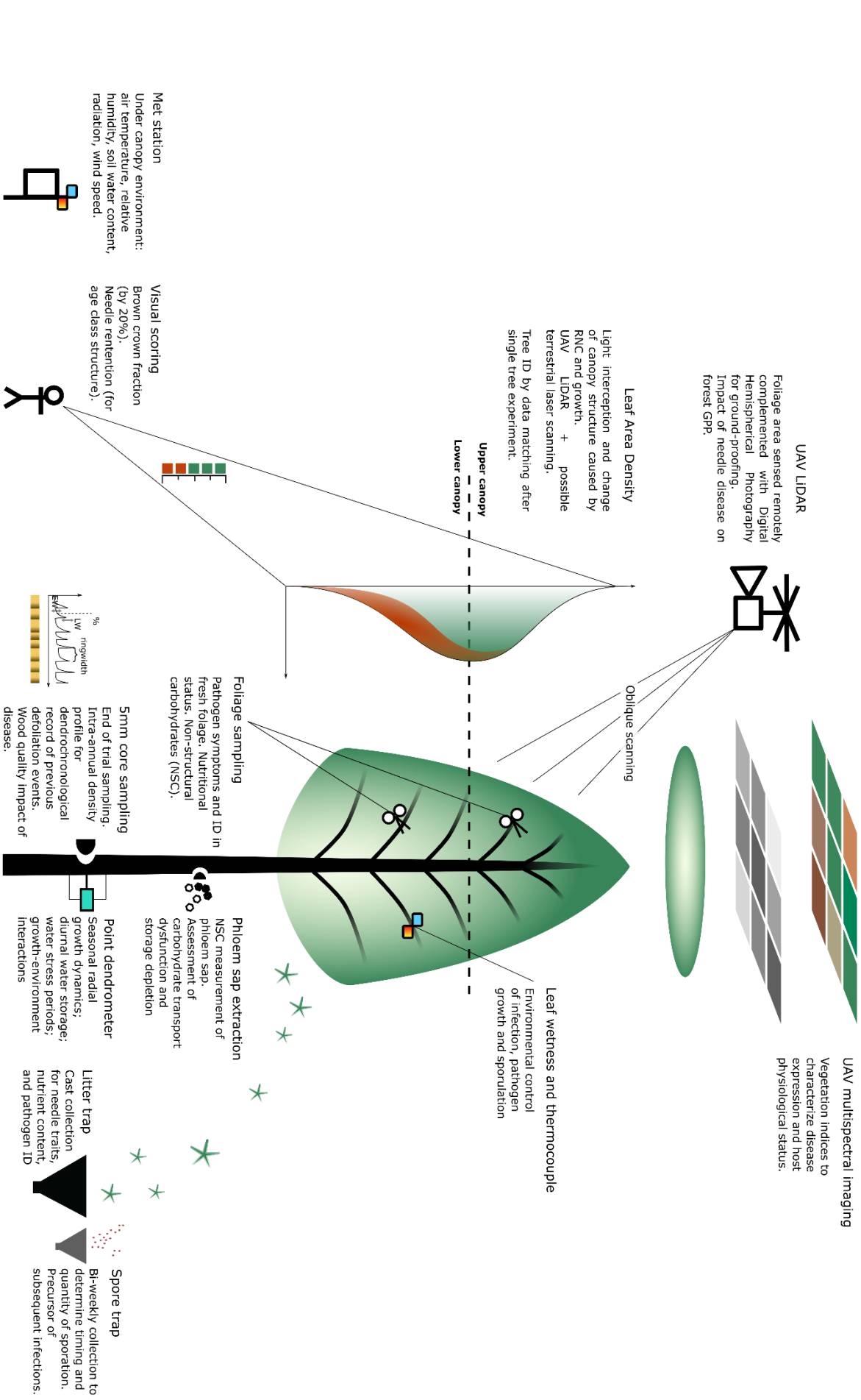

Figure 1: Overview of the ideal sensor network to monitor needle disease growth impact

Remote sensing

UAV and terrestrial LiDAR

Description	Laser scanning of tree and crown by UAV (LidarUSA Snoopy V-series) and by a ground operator (Zeb1). Fused aerial and terrestrial data set. Aerial data collected at single forest block scale. Terrestrial data collected at single plot scale.
Rationale	Construct a digital 3D model of tree crown associated with the different phases of pathogen expression and primary (shoot) growth. Terrestrial LiDAR is required to properly characterize the lower canopy region where RNC is preferentially expressed. Measure foliage biomass/area cyclic growth. Evaluate light interception/absorption to determine functional levels of photosynthesis.
Measured variables	LAI, LAD, tree height, canopy attributes.
Links	DHP measurement to calibrate LAI/point cloud metrics relationships. Dendrometer data to correlate foliage mass to wood formation. Phloem sampling for gross photosynthate production at single tree scale. Single tree LiDAR identification.
Sampling frequency	Seasonally
Projected cost	ULS: 4.7% CPY Sub-canopy LiDAR: 6.2% CPY Validate LAI code: 4.1% UC Develop LAD extraction code: 12.6% UC

UAV Multispectral imaging (MS)

Description	Data collected by multispectral camera (Micasense Red Edge 3) over the forest canopy by UAV.
Rationale	Determine Vegetation Indices from five-band data to detect needle disease symptoms and tree physiological indicators.
Measured variables	Vegetation Indices (especially NDVI), disease score
Links	Compare to visual disease score
Sampling frequency	Seasonally
Projected cost	5.3% CPY

UAV Oblique imaging

Description	Data collected by oblique camera mounted on UAV flown over study trees scored during ground assessments.
Rationale	Visual assessment of mid-to-upper canopy obscured from ground-based scoring to develop complete picture of needle disease symptoms and tree physiological indicators.
Measured variables	Visual disease score from imagery and video
Links	Compare to visual disease score and multispectral VIs
Sampling frequency	Seasonally
Projected cost	(5.7% CPY)* + 1.4% CPY (5th flight)

Real-time monitoring

Point dendrometers

Description	Automated point dendrometers (linear potentiometer technology, INRAE design) attached to tree stems measuring stem radial displacements at high temporal and spatial resolution.
Rationale	Measure radial growth dynamics, especially seasonal growth cycles, and level of tree water deficit.
Measured variables	Radial Growth Rate (RGR), Tree Water Deficit (TWD) and Maximum Daily Shrinkage (MDS).
Links	Relate wood formation to foliage growth and crown status
Sampling frequency	5 minutes

Projected cost	13% UC assembly & installation 2.4% CPY maintenance and data processing

Band dendrometers

Description	Automated band dendrometers attached to tree stems measuring girth increase at high temporal resolution.
Rationale	Provide the mean value of radial growth over stem circumference to avoid bias due to position of point dendrometer. Band dendrometers cannot be used alone as they are not as sensitive to radial displacement as a point dendrometer.
Measured variables	Mean radial growth rate
Links	Compare point and band dendrometer data
Sampling frequency	5 minutes
Projected cost	6.9% UC (first year) prototype 8.9% UC (second year) assembly & installation (if on same data logger as point dendrometers) 1.6% CPY maintenance and data processing (if combined with point dendrometers)

Leaf wetness

Description	Leaf wetness sensor (237, Campbell Scientific) positioned at one third of crown height in two opposite directions: north and south. Ideally, each sensor is placed on a branch away from the stem and towards the edge of the crown, but still in the shade. The sensors should be angled similarly to the general orientation of neighbouring needles. If that angle cannot be determined, sensors will be oriented north- and south-facing at a 10-degree angle. Sensor position is recorded.
Rationale	Leaf wetness is a key environmental factor in pathogen development and spread. Sensor location at one third of crown height corresponds to lower canopy region, which functionally different from the upper, sunlit region and is susceptible to needle disease such as RNC. A second sensor at two thirds of crown height would be ideal to study the upper region. However, installing sensors at that height is not recommended due to safety concerns for the climbing personnel (securing to tree stem top section is possibly unsafe).
Measured variables	Leaf wetness
Links	Relate wetness to other environmental variables in single tree lower crown and to the environment measured at larger scales (plot/block/forest).
Sampling frequency	5 minutes
Projected cost	29.2% UC (first year) assembly & installation 2.5% CPY maintenance and data processing (if no climbing involved)

Lower crown environment

Description	Air temperature and relative humidity logger (iButton Hygrochron, maxim integrated) installed in lower crown region (one third canopy height). Ideally, the sensor is placed close to LW237 sensor.
Rationale	The sensor provides intra-canopy environmental conditions to relate with foliage growth and pathogen development. This sensor has integrated logging capability and does not require cabling. Determine variation of canopy conditions between individual trees.
Measured variables	Temperature (T), Relative Humidity (RH)
Links	Degree of cross-correlation with other environmental data.
Sampling frequency	15/60 minutes depending on environment
Projected cost	1.6% UC sensors (first year). Assembly and installation included with leaf wetness sensors.

Met station

Description	Met station (Campbell scientific) recording local weather and soil environmental variables on site.
Rationale	Continuous monitoring of physical environment needed to understand growth patterns of both tree and pathogen. Key inputs to process-based models.
Measured variables	Air temperature, photosynthetically active radiation, soil water content, relative humidity, precipitation, soil water content probe.
Links	Relate sub-canopy conditions to intra-canopy conditions
Sampling frequency	15/60 minutes (depending on sensors)
Projected cost	5.2% UC (first year)

Field sampling and laboratory analyses

Live foliage collection

Description	Live foliage is sampled at 1/3 and 2/3 of crown height of individual trees. 3 samples are taken at each height: • Sample 1 is used for symptom inspection and prepared for qPCR at Slipstream (cf. Fraser et al. 2019) • Sample 2 is used for nutritional status. • Sample 3 is used for non-structural carbohydrates (NSC, cf. Gomez-Gallego, Williams, Leuzinger, Scott, and Bader (2020)). Specific Leaf Area (needle area per unit weight) is measured on at least one sample (sample 3 preferred).
Rationale	Determine presence and type of inoculum in foliage (sample 1) in relation to time, environment, and crown position. Upper and lower crown regions in tall trees are a) functionally different from a physiological standpoint and b) with a distinct susceptibility to pathogenic infection. Determine foliage nutritional status for foliage productivity and health (sample 2). Determine seasonal levels of photosynthate availability in foliage and levels of carbohydrate reserves (sample 3).
Measured variables	Quantity of inoculum and symptoms, needle chemistry (N concentration), NSC, SLA.
Links	Relate nitrogen content in live foliage and cast foliage. Relate NSC in foliage to stem NSC. Combine SLA information with LAI to determine foliage biomass.
Sampling frequency	Seasonally
Projected cost	20.8% CPY

Cast foliage collection

Description	Cast foliage is collected in a litter trap for symptom detection and pathogen identification. A subset of the cast needles is used for nutrient content analysis, fresh if requirements for qPCR analysis are met, dry otherwise.
Rationale	Determine presence and type of pathogen in freshest needles. Determine quantity of nutrients lost to pathogen-induced defoliation and ability of genotype to remobilize nutrients towards healthy regions when infection occurs. Calculate rates of foliage turnover and the impact of pathogen on carbon cycling towards ground pools.
Measured variables	Pathogen ID. LAI decay rate. Foliage mass. Dry weight. Litter turnover rate (derived). Nutritional status.
Links	Use for LAI dynamic model
Sampling frequency	Monthly (seasonally for leaf nitrogen)
Projected cost	(12.9%CPY)* (cast disease) 4.3% CPY (cast nutritional status)

Spore trapping

Description	Dedicated traps to collect pathogen spores
Rationale	Assess timing and magnitude of pathogen development. Predict inoculum mass for subsequent infections cycles.
Measured variables	Spore biomass
Links	Relate to foliage biomass availability in the forest.
Sampling frequency	Fortnightly
Projected cost	(10.6% CPY)*

Phloem sampling

Description	Micro-coring of inner bark tissue on the tree stem near breast height. Two samples are taken each collection. Sample 1: phloem sap is extracted and sent for NSC analysis. Sample 2: phloem tissue is embedded in resin and sent for anatomical analysis.
Rationale	Determine carbon transport capacity of individual tree and an estimate ground carbon flow in the stand. Determine carbohydrate reserve seasonal dynamics. Determine levels of pathogen-induced reserve depletion and degree of transport dysfunction.
Measured variables	Phloem hydraulic conductivity. Sugar compounds and starch concentration in the tree stem.
Links	NSC levels compared to those in foliage and in roots. Phloem transport capacity linked to total photosynthetic production (LAD) to calculate functional carbon budget of individual trees.
Sampling frequency	Seasonally (NSC, phloem 1st year). Annually (phloem 2nd year onwards)
Projected cost	13.8% UC (first year) 9.8% CPY (every year from 2nd)

Live roots

Description	Sampling of inner bark tissue on coarse roots collected for NSC analysis. 2 samples per tree are collected.
Rationale	Determine soluble carbon allocation to the roots in relation to time, environment, and disease expression. Determine seasonal levels of photosynthate allocated to the roots and levels of carbohydrate reserves.
Measured variables	Quantity NSC allocation to the roots.
Links	NSC levels compared to those in foliage and in stem.
Sampling frequency	Seasonally
Projected cost	4.6% CPY

Wood sampling

Description	A 5 mm core sample is collected at the end of the monitoring period. The sample is taken at the location where point dendrometers are attached on each tree. The sample is sent for densitometry analysis
Rationale	Determine the ring width (yearly radial growth) and the intra-annual density profile within tree rings to characterize the impact of crown status on growth and wood quality.
Measured variables	Ring width, intra-annual density fluctuations, earlywood-latewood ratio, basic density.
Links	Radial growth measured by dendrometers (validation).
Sampling frequency	Once (end of experiment).
Projected cost	1.4% UC

Maintenance and lifetime

The question of sensor lifetime and maintenance to ensure correct data collection is a critical aspect of the sensor network. Only sensors and electronic equipment staying in the field continuously are expected to have maintenance requirements.

- Leaf wetness sensors need to be regularly wiped, at least on a yearly basis after pollen season. This requires time and skill to do so and represents a supplementary cost as any

maintenance on sensors located in the tree crown involves climbing. This could be avoided using a pulley system with lightweight rope to allow lowering the leaf wetness sensor to ground level for cleaning by a ground operator. The pulley system needs to be designed and implemented.

- It has not been decided whether to power the sensors using batteries that will be replaced during the regular site visits or by solar panels. In a mature forest, the sub-canopy is dark enough to limit the power output of a solar panel. An option would be to place the panels on the top section of the stem top in the crown itself. They would also need to be cleaned of pollen.
- A protective foam is placed over the electronic parts of the dendrometers. It limits the effects of radiation and changes in ambient temperature and humidity. As a result, the overall lifetime of sensors is increased. Despite the low price of the electronic component, a fault requires an intervention and a downtime.
- The lifetime of the iButton hygrochron sensors is directly dependent on the sampling frequency. This is discussed in the relevant section. The value of protecting sensors using a radiation shield is unclear in the shaded region of the tree crown.
- Met stations and data loggers are encased in protective casings that are sufficient for normal temperature conditions in NZ.

Sampling strategy

Time is a critical variable as both pathogen and tree follow cycles. Discrete measurements are carried out and repeated at a frequency that depends on the measured variable.

Seasonal sampling (five times a year)

Some measurements are carried out several times a year to capture seasonal variation in key phenological stages of tree growth. We recommend carrying out seasonal measurements five times a year. Ideally, measurements would occur with greater frequency, but this strategy represents a cost-effective compromise to capture key cyclical patterns. Because the three main components (foliage, pathogen, wood) of the host-pathogen system follow different developmental dynamics (figure 2), it is critical to select sampling times carefully. We suggest carrying out seasonal sampling at the start of each of these months: June, August, October, December, and March. By subtracting crown states between two sampling events, it is possible to identify structural canopy changes resulting from pathogen action and primary growth.

The June sampling captures the tree in the initial state of the current year, prior to new spring growth or new disease expression. It provides a reference for crown status. During late Winter and Spring, peak disease expression is highly variable depending on the year of observation and prevailing environmental conditions. It is during the same period that primary growth rates (shoot elongation, foliage flushes) increase up to a maximum (Jackson et al. 1976). For these reasons, it is suggested to have a higher sampling density and do measurements late Winter (August), mid-Spring (October) and early Summer (December). A sampling event is done in March to capture post-disease crown growth and renewed shoot elongation: the ‘autumn growth’ (Burdon, 1993). The autumn sampling event also allows monitoring the impact of pathogens with different seasonal activity (e.g. *Dothistroma*).

If five seasonal sampling events every year is too expensive with respect to operational cost and data processing, an alternative approach is possible, albeit far from optimal. It is possible to sample four times a year (June, September, December, March). Using information relative to current rate of disease expression obtained by monthly monitoring (aerial imagery, visual scoring, needle cast qPCR analysis), one could adjust the timing of *spring* and *summer* seasonal sampling to account for yearly variation in pathogen peak expression (see figure 2). Some years, peak disease expression is Aug-Sep whereas it occurs later (Oct-Nov) in other years.

Seasonal measurements: UAV LiDAR+MS+Oblique, ground LiDAR, DHP, live foliage collection, phloem sampling, dendrometer maintenance.

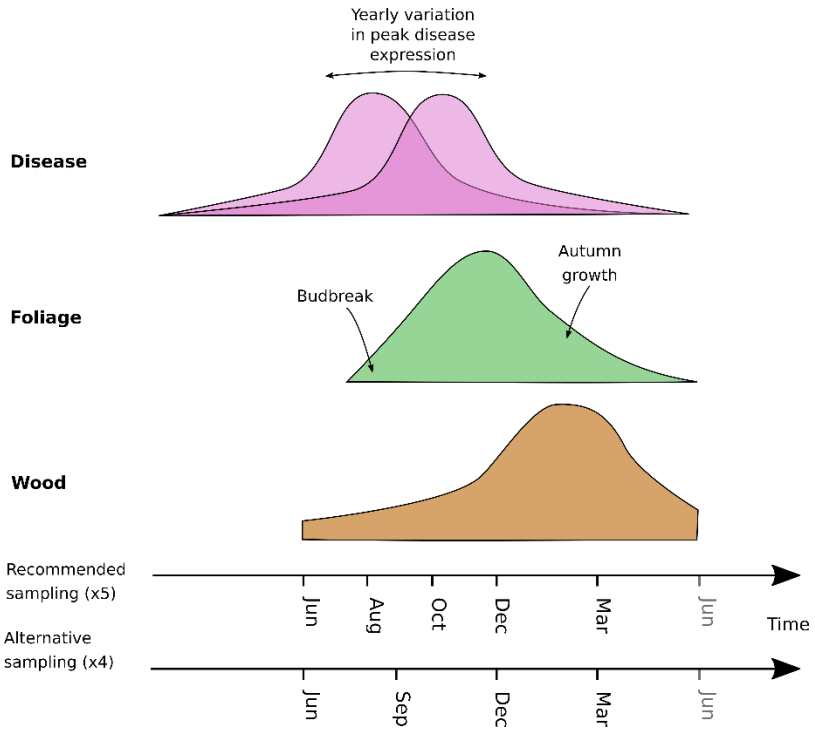

Figure 2: Typical seasonal patterns of disease expression, annual foliage growth and wood formation. In the alternative sampling option, the Sep/Dec samplings can be adjusted based on current disease monitoring.

Other discrete sampling

Spore trap monitoring will be carried out at least fortnightly. Spore traps are currently under development. Early prototypes are not suitable for the task; however, future designs would be deployed as part of the ideal sensor network to precisely determine sporulation dynamics. With staff visiting the site regularly, they will also attend to the maintenance of the sensor network and data downloads from dataloggers while there. They can also detect eventual material faults early and help minimise down time and data gaps. Cast needles collected within needle traps will be harvested on a 4-weekly basis in coordination with the spore trapping to describe the dynamics of disease expression (Fraser et al., 2020).

PSP measurements are done annually. They provide a reference for other growth measurements done in the sensor network. More frequent measurements are not required as height measurement error is large compared to the seasonal variation in tree height growth.

High-resolution sampling

Point and band dendrometers can be sampled at arbitrary frequencies. That frequency is set when programming the data logger. The point dendrometers are sensitive to very small changes in stem radial displacements (typically 1 µm). As those changes evolve rapidly depending on the time or environmental conditions during the day, we recommend a sampling frequency of 5 minutes. A datalogger has enough internal memory to store one year of data for 24 sensors at that frequency. It is possible to smooth the signal via processing to resample to a larger sampling time and compared with other sensors. Those dendrometers would be connected to the same data logger as the point dendrometers and, thus, sampled at the same frequency (5 mins). Band dendrometers are not as sensitive to small-scale displacement as point dendrometers but it is easy to degrade the signal frequency to the physically relevant time scale.

Leaf wetness sensors are connected to dataloggers in a similar wiring scheme to the automated dendrometers. The sampling period is programmed during the experimental setup. We recommend a 5-minute sampling for leaf wetness sensors as well for compatibility with dendrometer recordings. It is possible that daily patterns of surface wetness in the foliage do not justify such a high resolution but there is disadvantage in selecting it.

Environmental probes (iButton Hygrochron, Maxim Integrated, USA) in the lower crown have a lifetime dictated by the chosen sampling frequency. Hourly sampling is necessary to describe the daily patterns of relative humidity and temperature as well as day-to-day fluctuations in those patterns. Hourly sampling would ensure a sensor lifetime equal to 6 to 7 years, depending on prevailing temperature conditions within the canopy. For a 10-minute sampling interval, the sensor lifetime would drop to approximately 5 years. Changes of temperature and humidity are not expected to be rapid in the lower canopy. A 15-minute sampling offers a good trade-off between resolution and lifetime. If lifetime is prioritised, then hourly sampling should be chosen.

Work packages

To be deployed and useful, some of the suggested measurement techniques will require specific work to take place in support of the sensor network's objectives. Here, we present the main tasks associated with implementing the sensor network.

LiDAR-based LAI estimation

To calculate LAI values from laser scanning, it is necessary to calibrate the values derived from remote sensing against values obtained by a reference method. As part of the sensor network, it is suggested to send a trained operator on site at the same times as the UAV and ground laser scanning operations are carried out for the first year. The operator will measure LAI by digital hemispherical photography or similar instrument. Ground-truth LAI measurements will also provide estimates of measurement error and sensitivity of LiDAR-LAI. This is essential to determine to what extent the yearly fluctuations in foliage dynamics and pathogen defoliation events can be captured by this method. We will build on previous methods developed at Scion to improve and automate LAI calculation from remote sensing data.

LiDAR-based LAD profile

To understand the functional role of the tree crown, i.e. how much carbohydrates it can produce or store and how much water it transpires, it is essential to determine the spatial distribution of foliage area. Without a spatial representation of tree crown and how it is modified by pathogen infection, it is difficult to predict both short- and long-term consequences of the pathogen action on tree stem formation. An important aspect is how much needle area per unit volume of space varies vertically. That property is defined as Leaf Area Density ($m^2\ m^{-3}$). It determines to what extent light is attenuated with canopy depth, the amount of rainfall interception, the vertical wind speed profile, and ultimately, the environmental conditions in the lower crown region.

It is possible to build voxelised 3D models of foliage and shoot density using fused LiDAR point clouds (Béland, Widlowski, & Fournier, 2014; Hopkinson et al., 2013). These models can be processed to determine the LAD profiles of individual trees (Béland, Baldocchi, Widlowski, Fournier, & Verstraete, 2014). From the generated profiles, it is possible to predict crown carbon and water budget using process-based modelling. New algorithms must be developed to perform these steps. They must be validated and, in a later phase, automated. This represents the creation of new knowledge that would advance the state-of-the-art in interfacing remote sensing and ecophysiology of real biological systems. This approach will also require single tree identification to segment the LiDAR point clouds into individual crowns. This is expected to be done by digitally matching the air-borne and sub-canopy LiDAR data sets supported with field GPS measurements (Wright 2020). Accurate geolocation of individual trees within a forest stand for linking with remote sensing data is an important scientific and technical challenge.

Carbon flow analysis

Carbon translocation is the process by which photoassimilates are distributed within plants. At the forest stand level, carbon translocation needs to match canopy photosynthesis and carbohydrate requirements to sustain growth, respiration and immune responses (Epron, Dannoura, Ishida, & Kosugi, 2019). Depletion of carbohydrate production, e.g. as caused by partial defoliation, can result in translocation dysfunction and tree mortality (Sala, Woodruff, & Meinzer, 2012). Such a

dysfunction can be directly induced by pathogen action or occur because of drought-pathogen interactions (Oliva, Stenlid, & Martínez-Vilalta, 2014).

We suggest using a variant of Epron et al. (2019)'s method to calculate carbon translocation as an estimate of the stand's capacity to transfer carbon belowground. The method is based on measuring the concentration of sugar compounds in the conductive tissue at the source (foliage) and near the base of the stem. Sugar concentration is used to determine the osmotic pressure gradient driving the assimilate flow down the tree stem. Anatomical samples of the conductive tissue (phloem or inner bark) will be collected to be embedded in resin, imaged by fluorescent microscopy and analysed to compute the hydraulic conductance of samples using a microfluidic model. The key steps of the methods have been previously developed at Scion, but the chain of methods and processing will need automation and time efficiency to be applied on the number of samples suggested in this study. The model to extrapolate stand capacity from single tree behaviour will need to be developed as part of this work package. NSC levels in foliage and phloem sap (stem, roots) will be measured seasonally and analysed in relation to pathogen.

NSC model calibration

The concentration of non-structural carbohydrates is determined using the near-infrared spectrum of samples (Ramirez et al., 2015). This method is high throughout and has been applied to study pathogen impact on host physiology before (Gomez-Gallego et al., 2020). NIR spectra data needs to be calibrated against direct chemical measurements. We suggest doing this calibration phase using a subset of live foliage samples sent for chemical content analysis to Veritech and a subset prepared and imaged by NIR. This crucial step would allow to have a tested photochemical model of NSC for radiata pine and to deploy NSC measurements at large scale.

Band dendrometers

Radial growth is considerably more variable around the circumference of a conifer tree stem than is generally accepted (Sellier & Ségura, 2020). The use of a point dendrometer is valuable because it describes in detail the daily variation of stem displacement and water storage behaviour. On the other hand, it describes a localized behaviour and should not be extrapolated in mature trees without ground-proofing basal area dynamics. Band dendrometers serve that purpose by measuring the mean diameter growth increment. While some band dendrometers are commercially available, their cost is prohibitive for large scale deployment.

We recommend that experienced personnel at Scion develop a new sensor prototype using rotary linear potentiometer sensors. Besides the prototype development cost, each sensor should have a cost relatively close to the assembly cost of a point dendrometer. Scion personnel are already capable to assemble, calibrate and deploy the latter. Wiring, installation, data collection, and power usage aspects are also expected to be the same as point dendrometers.

Hyperspectral imaging

Hyperspectral imaging (HSI) is a promising remote sensing technology for monitoring plant physiology. HSI captures narrow band reflectance from a larger portion of the electromagnetic spectrum than multispectral imagery. These data can be used to accurately measure key plant physiological attributes remotely and at large scales. HIS has been successfully used to measure crown photosynthesis, foliar nutritional status and phenology in a range of contexts (D'Odorico, Besik, Wong, Isabel, & Ensminger, 2020; Hill, Buddenbaum, & Townsend, 2019; Watt, Pearse, Dash, Melia, & Leonardo, 2019). These measurements require the development of appropriate algorithms to extract that information from hyperspectral data.

The technology is currently being trialled at Scion's nursery in Rotorua. The HSI camera is mounted on a UAV and is heavy. Flights in the field have not taken place yet. It is planned to do test flights in a young forest stand, in an independent study, to develop the technology and operational handling further. It is premature to envision regular flights to capture HSI data in a mature forest canopy over 30+ m tall trees. The models for foliage photosynthesis and nutrients are also under development and in need of validation in mature canopies. While hyperspectral data collection should be part of an ideal sensor network to study the growth impact of foliar pathogens, we do not recommend its inclusion at this stage.

PATHWAY TO IMPLEMENTATION

Suggested trial site for deployment

We recommend deploying the ideal sensor network at Forest Protection's operational copper trial (Fraser, Tiemann, Baker, & Rolando, 2019). A long-term trial has been established at two sites at Kinleith in partnership with Hancock Forest Management NZ. The aim of the trial is aligned with the objective of the sensor network, which is to characterise the growth impact of needle disease. The trial consists of unsprayed forest blocks and copper treatments (two different times of application).

Deployment of the network at the operational copper trial would be supported by existing work with on-site disease scoring and monitoring, remote sensing, and PSP measurements that are already active or planned. Extending the trial at a specific location with a dense monitoring system would be more cost-effective than deployment at an entirely new site. The cost of running the sensor network at the Kinleith site would be 34% less expensive than any other sites where disease monitoring is not already set up. The setup cost would be the same at Kinleith as for any site close to Rotorua.

The proximity of Kinleith forest to Scion Rotorua office is also advantageous in terms of access and reactivity for all field operations (installation, maintenance, sampling, data collection). The Schnapper Road site had a higher recent incidence of disease as well as better access to field technicians. Additionally, there is remote sensing work already planned for the operational copper trials, including a proof-of-concept single tree identification study (Wright, 2020). Therefore, this site is the preferred option.

RNC elite clones (RPBC) have been established at Kinleith forest in 2017 (trial FR564). The trial is composed of individuals covering the full range of breeding values (estimated from detached needle assay phenotypes). That variation would be valuable to monitor and understand growth impact and disease resistance. However, trees currently are in the physiologically-different juvenile phase and before canopy closure. The priority at this stage is to study a mature forest stand to gain a more generic knowledge of host-pathogen interactions. Deploying automated dendrometers in young stands also increases the maintenance cost of those sensors. They need to be reset regularly because of the high radial growth rates. On the other hand, young stands provide a good line of sight for UAV flights.

Scion Forest Protection has RNC monitoring trials at Wharerata and Tauwhareparae on the east coast of the North Island. Those sites are good candidates for installing a sensor network because of the high disease expression and because of past and ongoing monitoring. On the other hand, those sites are relatively remote and would not be recommended for the first implementation of the proposed sensor network due to high transport and maintenance costs.

From sensor network to experimental design

This report only addresses designing an ideal sensor network. However, we have considered how it should be integrated in an experimental setup and how it could be upscaled.

Phase-in and implementation of the network sensor design

The sensor network is designed as an elementary unit to study the phenomenology of host-pathogen interactions. That unit aims to be representative of those interactions at the stand level by being deployed on typical sample plot size (0.04 to 0.08 ha, depending on stocking). By capturing the growth-disease dynamics at the scale of a clustered set of trees, it is possible to account for distance-dependent relationships between trees (competition) while limiting effects of microsite variability. Selecting of spatially random set of trees in a given forest block would introduce a severe bias.

The anticipated phase-in of the sensor network is described below. This is provisional, and implementation is subject to approval. It also assumes adequate funding and personnel availability

from October 2020 onwards. The phase-in only applies if the sensor network is deployed as suggested at the operational copper trials in Kinleith forest.

2020-2021:

- Aerial LiDAR data collection starting
- PSP, disease visual scoring ongoing
- Terrestrial LiDAR and single tree identification being tested
- Sampling collection and analysis being tested. Processing times being evaluated and potential issues being identified for scaling up to regular seasonal sampling
- Finalising spore trapping prototype
- Purchase of equipment, assembly and calibration of point dendrometers
- Purchase of equipment, determination of power usage and calibration of canopy sensors
- Developing and testing a band dendrometer prototype

2021-2022:

- Remote sensing, field measurement, and field sampling becoming operational as per this document on site
- Point dendrometers, canopy sensors, solar panels, data loggers being deployed on site
- Purchase of equipment, assembly and calibration of band dendrometers.

2022-2027:

- Network fully deployed and collecting data
- Ongoing maintenance and sampling

Constraints, lifespan and capacity

The deployment of the sensor network is constrained by cost and practicalities. All electronic equipment must be connected to a data logger (except for iButton sensors with individual logging capability). The most cost-effective approach is to minimize the number of locations being surveyed. While there is a cost associated with the absolute number of trees being monitored, that cost is small compared to the number of monitoring locations. There is also a maximum number of electronical channels that a datalogger can scan (48 in this case). Beyond that limit, more data loggers are required. In the suggested setup, monitoring more than 24 for trees per location would be equivalent cost-wise to monitoring more than one location. Monitoring all trees of a permanent plot (c. 20 trees) is optimal. This builds on the growth inventory and disease scoring already in place. Alternately, one could employ data loggers with less channels and more locations with less monitored trees. The cost reduction would be small, field crew time would increase. Additionally, competition effects would not be captured and those of microsite variability would be increased.

UAV flights over a closed-canopy forest have their own constraints (e.g. line of sight). Operational procedures for this study have not been fully decided yet. They may depend on final site/plots selection.

The sensor network is expected to remain on site for 5 to 6 years. This would allow the network to capture 2 cycles of disease expression. Kinleith operational copper trials are expected to end in 2024. Monitoring would need to extend for another 3 years based on the proposed phase-in. The equipment is weather protected and is expected to remain in good conditions during the period.

All equipment and personnel costing are given for deploying the sensor network at two plots for a total of 40-50 trees. The cost is expected to scale linearly with the number of plots unless those are located on different sites.

Suggested experimental design

We recommend to first implement the sensor network at the operational copper trials in two plots. One plot will be sprayed with copper as per the workplan (Fraser et al. 2019); it will act as control in this study to determine growth and other attributes under minimum pathogen impact. The other plot will not be sprayed and will act as treatment. In each plot, it will be required to monitor $n \geq 20$ trees. The plot will be chosen in adjacent blocks to limit the distance between the monitored plots. A distance between plots of less than 400 m is needed to minimize spatial variance and

environmental variance. In the case of the latter, topographical features will also be considered. Albeit it is critical that the treatment here is applied, it is difficult to anticipate the occurrence and location of the needle disease. To lower the risk of monitoring healthy trees at two plots, prior data will be analysed to find area particularly susceptible to disease development.

Future integration in landscape management plan

It can be envisioned to deploy multiple monitoring units to study, for example, host-pathogen interactions on contrasted sites simultaneously. However, scaling should be considered carefully because of the increased cost. A streamlined version of the sensor network, limited to measuring key variables only, could be deployed at a large scale after new knowledge has been gained. Once validated, it may be possible to extend monitoring through increased use of remote sensing to reduce cost.

Remote locations are still problematic for monitoring (both seasonal sampling and continuous monitoring). It is important to proceed to the first implementation at an accessible location.

Experimental trials equipped on the sensor network need to consider the potential for statistical inference and data extrapolation. A large number of sites with contrasting environmental and silvicultural attributes should be studied. It is too early to discuss this option until the deployment and maintenance costs of sensor networks are mitigated. However, it is possible to envision versions limited to UAV laser scanning and point dendrometers after our knowledge of defoliation impact is improved. Alternately, landscape modelling results could be tested and validated against small scale but precisely documented results.

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