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NATIONAL INSTITUTE FOR FOREST PRODUCTS INNOVATION

Development and implementation of forest health and biosecurity systems and protocols based on quantitative pest risk and economic

Implementation of a cooperative forest health and biosecurity surveillance system

2025

Mount Gambier Centre
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NATIONAL INSTITUTE FOR
FOREST PRODUCTS INNOVATION
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Development and implementation of forest health and biosecurity systems and protocols based on quantitative pest risk and economic impact assessment

Implementation of a cooperative forest health and biosecurity surveillance system

Prepared for

National Institute for Forest Products Innovation

Mount Gambier

by

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Executive Summary

The NIFPI project, Innovative Forest Health and Biosecurity for the Green Triangle aimed to establish a cooperative forest health monitoring and surveillance system in the Green Triangle (GT) and build capacity in forest health and biosecurity. The key initiative has been to develop a standardised forest health program for the GT forest industry to provide tools to better understand the risks pest and pathogens pose on their plantations and provide information where management actions can be undertaken through a range of efficiencies and ultimately a more effective forest health system.

This has been accomplished through the establishment and assessment of more than 200 plot monitoring sites across approximately 293,000 ha in both Pine and Eucalypt plantations, a collaborative aerial surveillance program followed up by diagnostic surveys and sampling to detect pest and pathogens. A result of this project is consistent data collection methods, standardised systems and reporting for Forest Health have been developed across multiple forest growers in collaboration. Along with the forest health monitoring and surveillance system, support for a local role to develop and implement a forest health and biosecurity program for the GT into the future has been initiated by industry.

In the current National Forest Biosecurity Surveillance Strategy, it is acknowledged that accurate and up to date understanding of the distribution of forest pests and pathogens is important to support and assist state and federal governments with claims of pest area freedom (both endemic and exotic) which supports the forest industry with market access. This system, developed and installed into the GT will assist in the early detection of endemic and exotic pest issues and supports biosecurity activities.

This report is in memory of

Dr Charlma Phillips

Charlma was a highly respected forest entomologist who will be remembered for being a mentor, colleague, practical thinker with an exceptionally positive attitude to everything she put her mind to.

Charlma was instrumental in the development of forest health in the Green Triangle and supported not only the South Australian State Government but the entire forest industry and the wider forest health community across Australia.

This project and its findings would never have come about without her input and generous support and guidance.

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Introduction

What is forest health and vitality?

Forest health and vitality can be difficult to easily define as it is often dependent on the main objectives on which a forest is being managed. A healthy forest is usually able to sustain its unique species composition and the vitality of the ecological processes that exist within it. Biotic agents (pests), that can affect forest health and vitality include animal browsers, invertebrates (mainly insects), pathogens and weeds. Abiotic agents such as drought, fire, floods and other weather events such as windstorms and hailstorms can also have a significant impact on forest health and vitality as can soil factors (e.g. structure, nutrition and salinity), on which a forest is growing. Climate change may also be impacting on the frequency of both biotic and abiotic events and extent of the damage (Percy 2002).

Why forest health in the Green Triangle?

The Green Triangle (GT) is one of Australia's highest production plantation forestry regions, spanning 300km through south eastern South Australia and south western Victoria. Soil types, groundwater and topography make this region's forestry assets a significant contributor to the local and national economy. The ability to better manage pest risk will improve consumer confidence and social license, maintain and expand the forestry industry and reduce economic, environmental impacts associated with pest incursions.

Regular and systematic monitoring and surveillance of forest health provides information on any change in condition of forests due to threatening processes and agents such as insects, pathogens as well as climatic, edaphic, and atmospheric factors (fire, soil fertility, salinity, flooding, pollution). Such information is crucial to reporting requirements of the forest industries, and state and national reporting. The status of forest health and vitality is recognised as an important criterion under the Montreal Process of Criteria and Indicators of sustainable forest management (Criterion 3: *Maintenance of Ecosystem Health and Vitality*, Indicator 3.1 *Scale and impact of agents and processes affecting forest health and vitality*) adopted by Australia (Montreal Process Implementation Group for Australia 2008). It also forms part of the framework of the Forest Stewardship Council Principles and Criteria for international accreditation of sustainable management of forests (FSC, 1996).

Predicting pest population dynamics supports effective and efficient systems for monitoring, surveillance, eradication, containment and management. Any significant delay in pest detection increases the management response for endemic pests and potential emergency response for exotic often making eradication unfeasible, therefore early detection through surveillance activities significantly contributes to the effectiveness of forest health. An understanding of pest biology, phenology, dispersal, population ecology and mitigation techniques can reduce spread of pests and determine management actions. Modelling the likely spread of outbreaks and incursions can assist in risk mitigation for the plantation estate.

This understanding supports the design of scientific monitoring and surveillance programs for both endemic and exotic pests and pathogens, while reducing costs in the event of an incursion through earlier detection and faster deployment of control/eradication strategies. The establishment of this forest health system supports the Australian forestry industry and the GT region.

Why was this project needed?

Historically the forest industry relied on forest entomologists, pathologists, nutritionists, and wood scientists working in state forest departments or CSIRO for specialist services. The number of experts is now much reduced and those that remain are at capacity and some are considering retirement. The national availability of plant health scientists with forestry specific training is also very low. Capacity building and succession planning is required to re-establish a network of forest health and biosecurity experts to serve the industry. Placing a dedicated resource in the GT with a requirement to conform to and participate in national standards, will help to re-establish past capacity.

Located within the GT Region is the Port of Portland, Victoria, which is legislated as a first points of entry under section 229 of the Commonwealth Biosecurity Act 2015. This means that the port is also a high-risk area for potential pest and pathogen incursion.

While the consequences of exotic incursions are notionally understood, better quantification of epidemiological and economic impacts of exotic pests and pathogens (collective called pests) is required (Bailey, 2012; Carnegie et al., 2017, Weiss et al. 2019).

A lack of information regarding the potential spread of and economic impacts of high-risk pests in the GT, impedes government and industry planning and response to any future incursion. This reduces the ability to quantify the potential spatio-temporal spread of pests through the region making the design, establishment, and costing of effective surveillance and monitoring programs difficult. This project initiated the process of collecting this information so better operational decisions can be made.

Recent publications present methods for the integrated bio-economic assessment of forestry pests internationally and in Australia (Carnegie et al., 2018b; Carnegie et al., 2006; Soliman et al., 2015; Soliman et al., 2012b, Weiss et al. 2019). The forest industry has developed a National Forestry Biosecurity Surveillance Strategy 2018-2023 and has entered into funding and cost sharing agreements with state and federal governments.

In the GT, forest health has been coordinated in house within individual companies. The GT was historically supported by a forest health expert within the South Australian government but since this expert retired, ad-hoc support has been provided through short term contracts. The development of a forest health and biosecurity surveillance capacity within the GT will provide a dedicated forest health advisory service. This will also help to upskill local plantation companies field staff awareness of forest health and biosecurity issues and is an important aim of this project.

Forest Health Monitoring and Surveillance

Forest health monitoring and surveillance programs (FHP) are established to determine the status, changes, and trends in tree health on an annual basis at different spatial scales. The focus of this report is on monitoring and surveillance of potential effects on forest health from biotic stress impacts, with some scope to detect abiotic stress effects.

Regular and systematic monitoring and surveillance of tree health provides:

- Information on the change in condition of forests due to threatening processes and agents such as insects and pathogens, as well as climatic and edaphic factors (fire, soil fertility, salinity, flooding).
- Indicators for the maintenance of productivity and the long-term sustainability of forests managed for both wood and non-wood products.

- An early warning system for the management of insect/pathogen (pest) incursions threatening the health and productivity of plantations.

What's the difference between monitoring and surveillance?

Monitoring and surveillance both play a role in a forest health system. They provide data at different spatial scales which can lead to different operational outcomes.

Monitoring

Forest health monitoring (FHM) refers to an ongoing, continuous, routine observation on health and productivity of tree health and carried out at the branch and tree scale. It is a structured process of collecting data through routine measurements, aimed at detecting changes in pest / pathogen status in the environment over a defined time period. FHM can assist in understanding pest and pathogen phenology and impacts and aims to identify minor changes in forest health that may not be identified in a surveillance program that can have a much broader focus.

FHM constitutes on-going programmes directed at the detection of changes in the prevalence of pests through routine recording of observations on health, productivity and associated environmental factors.

Surveillance

Forest health surveillance (FHS) is undertaken at a compartment or forest spatial scale. FHS is systematically collected data, generally using practical and rapid methods, rather than by detailed accuracy or completeness. Surveillance can collect data in a timely, systematic, and orderly form and analysis and interpretation aims to report on changes in distribution of health problems, to recommend measures to prevent and control pests.

Spatial scales (fine, medium, coarse)

Within a FHP, there are different spatial scales of assessment, and appropriate recording is necessary to adequately describe changes in forest condition that vary in magnitude. These scales are:

- branch/leaf scale (fine),
- crown/tree scale (medium)
- and stand scale (coarse) (Spetich and He 2008).

The different spatial scale measurements are dependent on the focus and reasons for undertaking the assessments. Assessments at the stand scale are generally carried out using aerial or remote sensing methods and can give a general overview of forest health which is important for determining overall trends in forest health and delineating the area affected. However, assessment of the causes may be weak, and early detection of changes in condition unlikely, especially where they occur in lower canopy locations or in a closed canopy environment.

Monitoring at a medium spatial scale (tree scale) can more accurately identify the amount of damage within a tree's canopy and provide an indication of the variability of health within a stand, an important indication of the resilience of a forest to damaging agents (USDA Forest Service 2007).

Fine scale assessment including foliar, insect and pathogen samples are important for identifying potential causes of observed damage and effects of abiotic stress e.g. changes in nutrition. Where research has been undertaken into pest life cycles and epidemiology, a prognosis as to future forest health issues and management actions may then be made and undertaken.

Measurements at the medium and fine scale are generally undertaken using ground assessment techniques, and while they can be more time consuming, give a greater level of tree assessment accuracy compared to the stand coarse scale. A combination of the three spatial scales is required to balance the needs of extent (area affected), and accuracy (including potential determination of causes and prognosis), within a comprehensive and effective FHP.

Timing of Assessments (temporal scale)

The timing of canopy assessments is dependent on the aim of the FHP and requires careful consideration as often the maximum expression of defoliation events occurs once the causal agent disappears, leading to subsequent difficulties in attributing causes.

When considering the potential adverse impacts of abiotic and biotic agents within a tree canopy, the timing of canopy assessments is important to:

i) provide assessment activities to indicate the potential maximum expression of a defoliating/discolouring event to accurately quantify its impact,
ii) time an assessment activity to potentially avoid the overlaying defoliation impacts of potential agents or,
iii) determine the possible cause of a recent/past defoliating/discoloration episode where damage is still present, but the pest associated with the damage is absent.

The definition of the FHP is essentially the identification of agent-based processes and their impact on stand productivity and vitality through assessment of the forest canopy. It is important to consider when assessing the health of tree canopies, the likely damaging agent complexes operating at particular times of the year, so that their impacts can be factored into any assessment metric produced.

A possible complication in assessing tree canopy health using stand scale methods is with the flushes of new immature foliage growth (particularly in eucalypts), usually experienced in spring and following rain in autumn (‘autumn break’). These ‘flushes’ are sometimes difficult to interpret for eucalypts because ‘discoloured’, ‘red’ or ‘non-green’ foliage can be the result of the presence of immature foliage or natural senescence within foliage, rather than due to damaging agents. This emphasises the need to undertake all three spatial scales in a FHP.

Ideally where the aim of FHM is to evaluate long-term changes over time, assessment timings should be undertaken preferably when maximum health is expressed in regions being evaluated. This would enable trends to be measured outside of fluctuations due to seasonal defoliation events that may distort a particular assessment. However often due to budget restraints, timing of assessments will generally be timed to match available resources and timing of other survey activities.

In terms of pest complexes operating in other bioregions, data indicates that the majority of insect pest complexes operate during the summer period, and pathogens during the wetter spring period. However, it should be noted that the ‘optimal’ monitoring periods indicated are approximate and based on a history of previous observations and outbreaks. These timings are subject to change dependent upon prevailing climatic variables such as rainfall and temperature and as such, can vary from year to year. Even within the time period the pest species operates, the timing of any surveillance can influence the results obtained. For example, assessments made early in the damaging period of the lifecycle may not capture the full defoliation impact, although identification of the causal agent(s) is generally easier. However, an early assessment aids in the potential implementation of a control program. Conversely, while a late assessment may capture the full defoliation impact, it may fail to accurately identify a causal agent(s) which may no longer be present and render any control program ineffective.

As most pest complexes will have potentially run their course in terms of damage caused by late autumn, it is most probable that late autumn/winter (i.e. May to July) represents an optimal period for canopy assessments to be conducted when little new growth is expected, and when insect and pathogen activity is minimal. However, it is unlikely a definitive diagnosis of the causal agent(s) will be possible, especially in the case of insect pests as most pests will have completed the damaging phase of their lifecycle. However, research has been conducted to associate foliage damage symptoms with a particular pest species, to be able to subsequently identify the causes of defoliation in tree canopies (Collett 2001).

Another aspect to a FHP is undertaking pest specific surveys. These surveys are complementary to the base program and allow for specific operational outcomes in relation to timing, damage thresholds and treatments.

Aims

The Innovative Forest Health and Biosecurity for the Green Triangle (GT) project is a two-part design run in parallel resulting in an iterative and applied outcome of understanding and developing a better understanding of forest pests through collaboration with the GT forest industry.

Part A is the further development of calibrated pest spread models Agriculture Victoria has created. This model is a spatially explicit species spread model that combines fine meteorological data, host location data, life-cycle models and dispersal/wind models for the greater Melbourne region of Victoria. The model provides illustrative and quantitative data on the rate of spread of forestry pests at 100 m to 10 km grid cell resolutions. This model combined with an economic overlay, provides a great opportunity for application to the GT forestry region to provide ongoing decision support to forest health managers and policy makers. However, the model is uncalibrated for the GT region and specific to only one pest (i.e. *Monochamus*). The model has potential to be used as a decision support tool for forest health managers designing surveillance and monitoring activities. This project aims to address several areas identified by Bailey (2012) and Carnegie et al. (2017) in further understanding the epidemiology of high-risk exotic pests.

Part B, which is the focus of this report, aims to implement a cooperative forest health and biosecurity surveillance system. The aims of Part B of the project are to:

- Coordinate surveillance activities and reporting with similar roles elsewhere in Australia, integrated with national initiatives.
- Introduce a forest health system standardised across all growers with training provided to interpret the results of surveillance and to understand the management options and responses resulting from the analysis.
- Provide training, awareness and capacity building with companies and contractors employing forest industry staff to improve their forest health and biosecurity expertise e.g. improved detection of forest health and biosecurity issues.
- Develop a forest sector biosecurity surveillance capacity to provide a dedicated diagnostic, emergency response and advisory forest health and biosecurity service for the GT region.
- Develop a standardised plantation industry wide reporting system designed to provide compliant reports to a centralised local body in both soft and hardcopies.

- Apply the forest health and biosecurity system to enable more informed preparedness planning and budgeting, and the integration into broader state and national reporting and preparedness structures and allows for determination of returns on different management scenarios.
- Contribute to the national goals of the National Forestry Biosecurity Surveillance Strategy 2018- 2023, namely;
    - Goal 1.2 - Develop sustainable funding mechanisms for surveillance that are equitable for all forest stakeholders;
    - Goal 3.1 - Update and review forest pest knowledge;
    - Goal 4.1 - Improve risk mitigation of exotic forest pests along the biosecurity continuum;
    - Goal 4.3 - Develop incursion preparedness plans for key forest pests

Methodology

Forest health methodology standardisation

Standardisation of method is the first step in co-ordinating both a FHS and standardising reporting both at a regional level and a national scale. This project used the same methodology for both Pine and Eucalypt surveillance activities (Aerial and ground-based monitoring plots). This allowed for:

- Measuring data consistently for reporting
- Comparison on FHS at a species level
- Centralisation of reporting to move to a real-time automated approach ensuring industry can respond to events

The proposed methods and parameters are based on both ground and aerial designs. Analogous to similar forest monitoring systems overseas and using experiences with Australian surveillance systems, the suggested parameters assess tree crown health using visual assessments of crown defoliation, crown discolouration, and other specific parameters. Methods consider the differences in tree species and are designed to be used by field crews.

Aerial surveillance and monitoring of ground plots using the proposed assessment methods is the basis of a robust forest health reporting system. It also delivers ground truthing for remote sensing signatures, and a basic data set for more detailed studies designed to identify particular stressors or develop better early detection methods.

Aerial surveillance methods

Aerial surveys are a remote sensing technique of observing forest change from an aircraft and recording them manually onto a map (McConnell et al 2000). McConnell (2000), describes this assessment as both an art form and a form of scientific data collection, and although the data can be a highly subjective skill, experience and assessor consistency is the key. Aerial observers generally hold an aircraft accreditation and training certificate. Surveys provides a broad picture of forest health, allowing large areas, often difficult to access on the ground, to be viewed by the assessor.

They are carried out annually and/or, ad hoc in response to observed tree health issues. The objective of an aerial survey is to detect any symptoms of damage or ill health and accurately locate on a map the position using typical sketch mapping techniques (Carnegie 2008). The data collection methods used by the forest health team within the aircraft and has been used over

Victorian forests since 2008. The data collected is collated so field staff are able to undertake the ground validation (Carnegie 2008). Aerial surveillance is undertaken to provide a broad assessment of plantation health when symptoms are at their peak. Surveillance is carried out at a flight height of approximately 1000-2000 feet, with speeds of 80-100 knots, depending on the aerial platform being utilised. The air observer pre-plans 4km transects allowing for 2km swathe of forest to be evaluated on each pass, though this can be adapted if dual observers are utilised. This gives the assessor approximately 18sec per km to recognise, classify, and record all the activity they observe and thus requires significant concentration. It is important that where possible fights are not more than 4 hours to reduce fatigue.

Air Operation plans are developed for each flight and approvals gained from the relevant agency. Flight plans/transects are created as part of pre-flight planning to ensure even coverage across the estate.

Experience is needed to relate ground position to map position (‘tracking’ or ‘flight path navigation’), and simultaneously record the position of trees displaying symptoms. GIS–GPS interface programs such as GeoLink and ArcMap running on a tablet computer, assist in collecting and locating the sketched location on the ground.

When symptoms of poor health such as crown discolouration or defoliation or abiotic factor is detected, its location is marked on the survey map using either an area, line or point feature. Large outbreaks are drawn as polygons while very small infestations usually less than 10 trees in a group, are designated as a point. Line features are used to delineate an edge of damage or separate a feature.

Data from an aerial survey needs careful ground-truthing of identified health problems to be undertaken where ‘abnormal’ stand conditions are observed. The objectives of the ground-truthing are:

1. to identify the pest organism;
2. to determine the severity of the damage;
3. to locate additional trees affected by the pest in the immediate vicinity before visible crown symptoms appear (e.g. Sirex).

It is possible, after obtaining this data, to correct the raw aerial survey data to more accurately reflect the pest conditions within the survey area.

Supplementary / roadside surveys

Supplementary / roadside surveys are used with the aerial and plot-based programs and strengthens the accuracy of the system. The three main objectives are:

- to diagnose damage/disorders observed from the aerial surveys,
- to further quantify the extent, incidence, and severity of the identified damage, and
- increase the likelihood of detecting new emerging pests, either exotic or endemic, pest outbreaks or cryptic disorders.

The intensity of the ground survey relies primarily on the data collected from the aerial surveys, along with pest reports provided by the plantation growers, and on general access throughout the forest.

Trained forest health surveillance staff also undertake roadside surveys while travelling to and from monitoring plots, and while performing ground truthing of aerial data. Data is recorded while performing these roles and walked transects (generally three 100-tree transects) are carried out when calculating the percentage of trees affected by a pest or pathogen. Roadside surveys are also carried out by plantation staff as part of normal duties and recorded as per company policy.

Ground plot monitoring

Assessments within ground-plot systems are generally based on the well-founded assumption that crown condition is a primary indicator of tree and overall stand health (Hosking & Anderson 2004). The health of the forest canopy is generally regarded worldwide as an effective indicator of both the health of the tree and more broadly on a collective scale, as an overall indicator of stand health (Stone and Haywood 2006, Innes 1993, Coulston et al. 2005, Hosking and Anderson 2004, Ferretti 1997).

Crown condition assessments are often relatively simple and therefore well suited for field crews to assess many plots. They can be undertaken at a relative intense sampling level both in spatial scale and time and form the backbone of the plot network.

Health monitoring plots

Whilst there are long-running forest monitoring programs overseas (e., the ICP Forest and ICP Integrated Monitoring plots in Europe for over 20 years, or the USDA Forest Service Forest Health Monitoring system), the new GT program is a significant expansion of the program, based on the plot-based system previous established for HVP Plantations and OFO plantations, in the region with now a wider systematic plot-based system standardised across all forest companies. A plot-based monitoring system can be expected to collect data in which early detection of forest health deterioration over time can be observed and used to trigger further research activities, pest identification measures or management interventions.

It is proposed to establish a forest health monitoring and surveillance program with a backbone of monitoring plots allocated at 1 per 1,500 ha and supported by aerial and diagnostic surveys. Table 1 describes the assigned age-classes categorised to best capture the onset of different damaging agents most efficiently for reporting. Many forest health conditions impact trees at different stages in their lifecycle and this grouping represents this susceptibility.

Table 1. Age-class grouping (years) for plantation species used to evaluate plantation health.

Pinus radiata	1-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40
Eucalyptus sp.	1-5	6-10	11-15	16-20	20+			
Each age-class is assigned a colour code as above for visual reference for field work/ digital aerial sketch mapping								

It is important to implement plots in a spatially uniform pattern across the plantation, accounting where feasible, species, age-class, topography and soil types. Within this distribution care is taken to also independently allocate plots to each company involved so that if the program is run independently the plot distributions will still be relevant at a smaller scale but also compatible within the larger project.

The methods used for the health monitoring plots by the forest health team in this project are outlined in detail in Smith et al 2022.

Plot based systems allow for accurate tree assessments to be carried out and allows for the analysis of trends within background populations of the pests. The principal components of the program include monitoring for pest insects and pathogens, animal browsing, weed infestation and abiotic factors (fire, drought, lightning etc).

There are also environmental and tree structural issues to consider when assessing trees as assessments were confined to the area of green crown present (assessable crown). Inherently as trees age, the size of the green crown can fluctuate depending on the abiotic environment that a tree is growing in, and the pests and pathogens it is exposed to. As a tree canopy closes and nutrient cycling occurs, the lower crown is discarded and the green crown height (distance from ground to the base of the green crown) increases, thus decreasing the assessable crown. This variation in assessable crown has implications for the way trees are assessed. If a tree had a large defoliation event in the lower crown in a particular year, and when the assessment was repeated in the next year, the crowns may appear healthier as the assessable crown size has reduced.

Stand information relating to the trees and plots were recorded at each plot site; this can include the aspect, slope, soil type, drainage, silviculture history (e.g. fertiliser application, thinning or pruning) and if the stand has reached canopy closure. Additional information regarding other factors that may impact on tree health such as weed invasion, animal browsing and physical factors (e.g. history of drought etc.) were also recorded.

These plot networks can generate baseline data to more specific measurements and investigations. In this study, assessments were carried out by experienced forest health scientists. However even though foliar assessments can be simple and efficient, assessor bias and error are always an issue, and when quantified, these biases can introduce errors of ± 15% in crown transparency (Metzger and Oren, 2001). To reduce these potential errors, the assessment team calibrated themselves by assessing many local references trees so that the scoring would remain consistent.

Crown assessments in the GT plantation estate are divided into upper and lower crown sections to differentiate pest and pathogens operating within the different sections of the crown. The system implemented is based on the assessment of crown condition where a tree is visually divided into upper and lower sections for assessment, giving both an upper and lower 'score' and distinguishing between the various pest agents operating in different sections of the tree crown. A 10% increment scale is used and a causal agent is assigned for the defoliation, discolouration and stem damage (Table 2.) (Smith *et al.* 2008, Smith et al, 2021).

Diagnostic surveys

Trained forest health surveillance staff undertake diagnostic surveys in response to observations of potential decline in health or 'abnormal' conditions of plantations found in other surveys or general field work.

Drive through / Ad hoc surveys

These surveys are conducted while survey and field staff move throughout the estate during normal operations. If 'abnormal' stand conditions are observed, records of the location and extent of the problems are noted and a health-surveillance plot may be established to determine level of damage and monitor any future increase/decrease in damage. Drive-through surveys are cost effective as they take advantage of staff presence in a plantation and can potentially detect early development of damaging agents with minimal effort. They also can act as a trigger for more extensive surveys. However, they are limited in accuracy as often only a few rows of trees are visible from a track or roadside.

Table 2. Criteria and attributes used in the forest health monitoring plot assessments

Health assessment criteria	Attribute
Tree status	Tree condition (living, dead <1 year, dead >1 year) Dominance (dominant, co-dominant, suppressed)
Crown condition (Upper 50% and lower 50% of the unsuppressed green crown assessed separately)	Foliage present (10% increments, 100% being a fully foliated tree) Foliage type (adult, transitional or juvenile) Cause of foliage loss (damaging agent) Discoloured foliage (10% increments, 0 being no discolouration) Colour of foliage (necrotic, chlorotic, purple) Distribution of discoloured tissue (edges, interveinal, spots, etc.) Cause of discolouration (damaging agent)
Stem and or branch condition	Part of tree affected (stem, branch, etc.) Location of damage (base, middle, top, etc.) Layer of tree affected (bark, sapwood, heartwood, etc.) Type of damage (scar, decay, etc.) Cause of damage
Other	Additional information regarding potential threatening processes such as weed invasion, animal browsing and abiotic factors is also recorded.

Recommended additional components important in the forest health system include those described below.

Establishment surveys

Recommended additional components important in the forest health system including post plant survival assessments can also be used to assess other plant health issues such as damage by insects, browsing or shoot ‘die-back’ that require a follow-up diagnostic survey.

Targeted / Pest specific surveillance

Targeted surveys, or pest-specific surveys, are undertaken to monitor development of known pathogen or pests. In surveys of this type, the aim is to have a proportion of plots within the health surveillance network that match the age class and site-specific factors that favour the particular damaging agent. These surveys may occur at several times during the year and can allow for an understanding of potential outbreaks. This information allows decision makers to enact management plans for those pests.

Centralised system for reporting

Data systems used for the collection and storage for the FHP

In Victoria, for the past 20 years digital data collection systems have been used for the collection, storage and processing of forest health data. Throughout the project the systems used for data collection and processing software were developed for multiuser and ease of access. Previous systems were based around an offline database that was maintained by one forest health officer and the programs used were not multiuser and required significant maintenance.

In the first year of the project, the previous systems of manual data entry via excel into a database was used and development was scheduled for Bioweb. The capability of the Bioweb system was limiting and therefore changes were made during the second year of the project.

Development of a data collection system that allows for multiuser entry is important and therefore the Esri ArcGIS products were selected and implemented for the second surveillance season.

The products used for the collection and analysis of the data during the project were:

- Microsoft Access
- Microsoft Excel
- DroidDB®
- GeoLink®
- QGIS 3.14.16
- Esri ArcGIS Desktop 10.5
- Esri ArcGIS Pro
- Esri ArcGIS Online
- Esri ArcGIS Field Maps
- Stata 16

Use of GeoLink® for aerial suveys

GeoLink® for Windows is a highly graphical, user-customisable, data collection tool which utilises GPS and GIS technologies to georeference feature data. It can output collected data to several GIS/CAD/text formats and can display a variety of GIS/CAD/Image formats as background maps. Other capabilities include the ability for sketch lines, points, and polygons to be drawn and automatically georeferenced onscreen, and the capability to input and output in many different user-selectable coordinate systems. GeoLink® has been specially modified for use with aerial sketch mapping as its primary purpose. These modifications allow faster data entry, expanded onscreen sketching capabilities, which make operation easier, faster and more user-friendly. Figure 1 shows the data screen used while collecting aerial data from the aircraft.

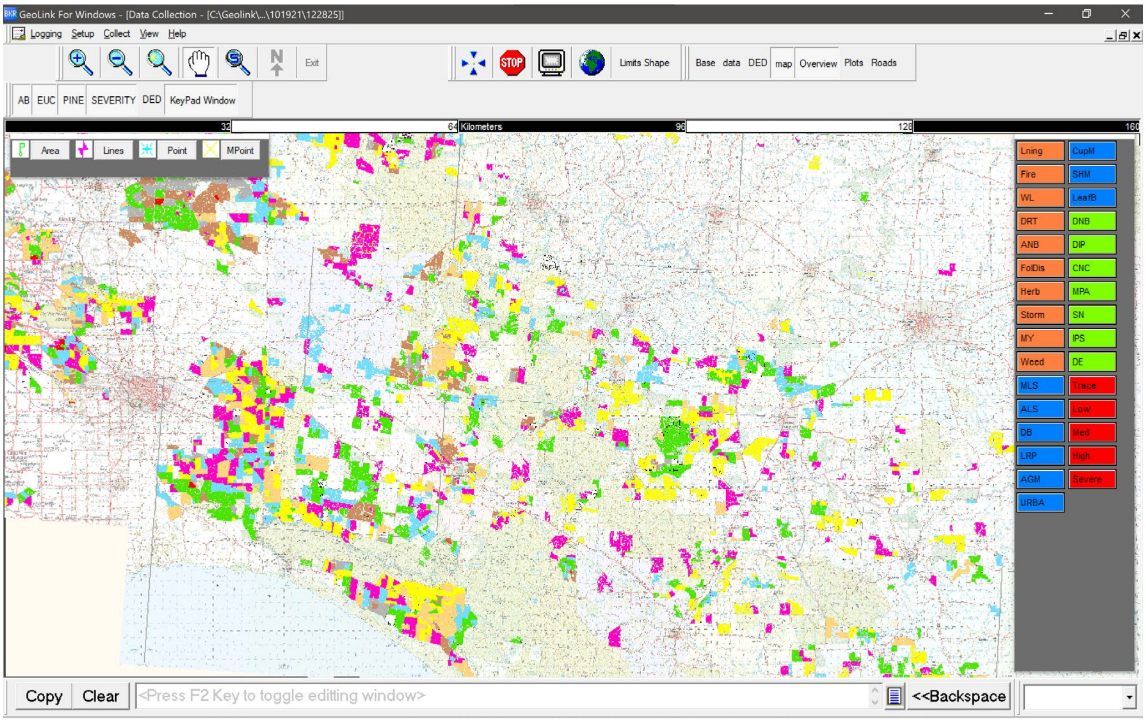


Figure 1. Screen shot of the GeoLink® Digital Aerial Sketch Mapping (DASM) program setup for aerial surveys in the GT.

Training

Training for both industry staff and a local forest health co-ordinator was hampered by COVID-19 restrictions. Agriculture Victoria biosecurity officers were only able to be present on the ground within South Australia for 2 weeks over the life of the project which required the field work to be split (SA/VIC). The project was fortunate to recruit a local forester with previous operational and research experience in Pine and Blue gum and responsibility and transition from the project could be initiated. Initial training was provided with regard to the on-ground components but unfortunately the digital aerial sketch mapping components could not be completed.

Methods for training local forest health role included:

- One on one in field training in both monitoring plots/ground identification
- FHaB observer to build understanding of national interests
- Online survey officer training (AgVic) to aid in sampling methodology
- Online Biosecurity preparedness training (PHA)
- Online training and networking via teams/zoom with Forest Health experts
- Access to literature and self-learning provided under UniSA
- Access and utilisation of industry knowledge and historic data (ForestrySA archive, IPMG, company protocols)

Methods for training industry:

- One on one in field training in monitoring plots
- Online presentations/mini-seminars via video conference
- Field visits

Results

The program was initiated in late 2019 to establish a standardised forest health program across seven forest companies in the GT. Approximately 296,000ha of plantation was included in the project with 170,000ha of *Pinus radiata* and 126,000ha of *Eucalyptus globulus*.

Forest Health methodology standardisation

Forest Health Monitoring Plots

Forest health monitoring plots were evenly distributed across the seven companies and based on hectares of plantation under their management and compartments put into the relevant age-class grouping. Plots were evenly distributed across the GT but effort was also made to evenly distribute the plots into the appropriate weighted age-class group and the companies spatial grouping. Soil type and typography was also a component of the final plot locations. These plots were allocated via a desktop study to reduce bias regarding their position and prior knowledge of current pest damage or outbreaks. Access to the plots (particularly in winter) was considered, and during selection of the 20 assessment trees no bias was given to healthy and dead standing trees.

In 2020, a total of 224 plots (4480 trees) were assessed and 140 new plots in the region were established; two companies had pre-exiting monitoring plots established that were utilised in the program, Table 3. The process of assigning plot numbers and company allocations is described in detail in Smith et al. (2021). After establishment of the plots the network was reviewed gaps in the network were identified within the eucalypt grid, especially to the youngest ages (1-2 year old).

In 2021, 237 plots (4740 trees) were assessed, and an extra 15 eucalypt plots established to target the younger age-classes and strengthen the plot network (Table 4). Both the 2020 and 2021 plot monitoring were completed in June/July.

Table 3. Health monitoring plots assessed in 2020.

Species	Age-class (years)								Total
	1-5	6-10	11-15	16-20	21-25	26-30	31-35	35+	
Pine	24	23	22	23	19	13	4	3	131
Eucalypt	25	11	31	26	0	0	0	0	93

Table 4. Health monitoring plots assessed in 2021.

Species	Age-class (years)								Total
	1-5	6-10	11-15	16-20	21-25	26-30	31-35	35+	
Pine	22	22	28	21	19	12	6	3	133
Eucalypt	33	13	30	19	9	0	0	0	104

Plot data analysis

Data collected within the monitoring plots was analysed using the damage index formula and trees were assigned one of six damage classes (Figure 2 and Table 5). The damage index is a formula to assist in understanding the true level of defoliation once the proportion of discoloured foliage as a percentage of the defoliation is added. Generally (depending on if it's an abiotic or biotic issue) discoloured foliage is shed by a tree, increasing the level of defoliation.

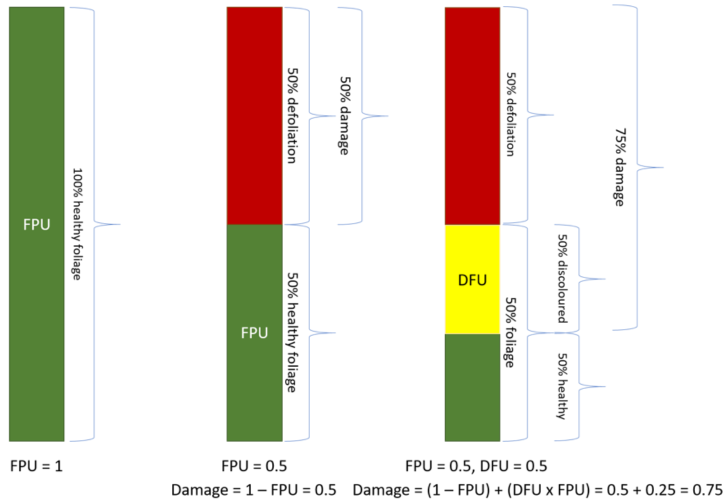


Figure 2. Examples of foliage presence upper (FPU) scoring, discoloration foliage upper (DFU) scoring and calculation of the resulting damage index in the upper crowns.

Table 5. Tree health scores and their relationship to forestry surveillance metrics

Tree health description	Tree health score	Damage Index score	FPU Class	DFU Class
Trace damage/stress	6	0.0-0.10	10	0-1
Low levels of damage/stress	5	0.11-0.20	9	2
Moderate levels of damage/stress	4	0.21-0.40	7-8	3-4
High levels of damage/stress	3	0.41-0.50	6	5
Severe levels of damage/stress	2	0.51-0.99	1-5	6-9
Dead tree	1	1.00	0	10

* FPU = Foliage presence Upper, DFU = Discoloured Foliage Upper.

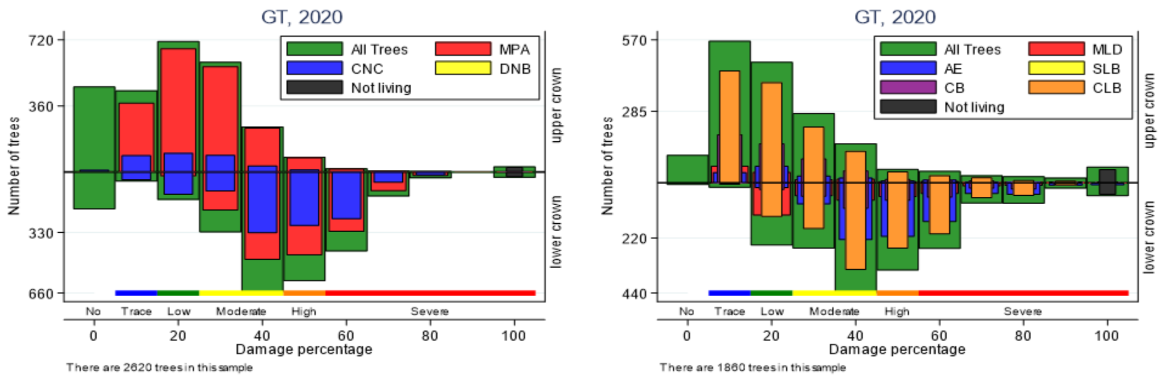
Once processed the data shows the levels and location of damage in the upper and lower crowns (Figure 3). The large, green bars in the figure are the total number of trees surveyed per damage class. The other coloured bars indicate which pests are involved and number of trees by damage class. Each tree can test positive for multiple pest issues. The black bar at the 100% damage percentage indicates trees that have died from causes such as Sirex, Diplodia or animal damage.

The data can be broken down further and analysis undertaken to look at the damage by a particular damaging agent relative to the part of the crown affected and within each age-class. Figure 4 and Figure 5 are examples of a pine and eucalypt pest impacting on plantations in the Green Triangle. Graph A in both figures describes the number of trees infested with MPA and AGM in both the upper and lower crowns, by age class. For MPA, the two older age-classes showed the same trend of damage, although had a significantly smaller sample sizes (Figure 4A). This graph also shows that in the 1-5 age-class a lower number of trees were affected, and the consistent damage was primarily in the upper crowns.

Figure 3B shows the MPA data as a proportion of trees infested. In the lower crown the damage was moderate or above for all age categories, except for the 1-5 age-class. The lower crowns in this situation were also showing significant damage, although understanding the lifecycle of the pest and the complexity of the lower crown damage with other pests and pathogens, it enables a focus on the upper crown damage which is the primary driver for tree growth.

For AGM, a significant number of trees in the 1-5 age-class were affected and although damage was also identified in the older age-classes it was mainly due to infested epicormic shoots and not mature leaves. (Figure 5A). It can also be observed that the pest primarily is caused damage to the lower crowns, although some damage was observed in the upper crowns. Graph B shows the data as a proportion of trees infested. In the lower crowns the damage was low to severe for all age categories.

Areas of white in both Figure 4 Figure 5 display parts of the crown that are unaffected. Trees with neither upper or lower crown damage were not included in the graphs.

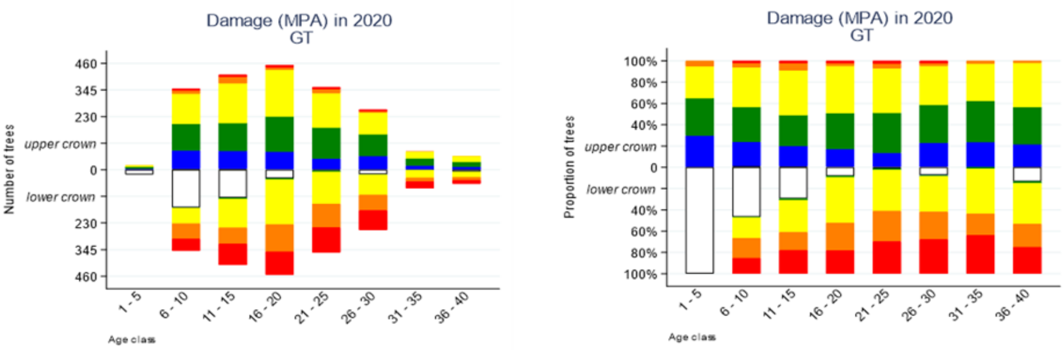


A. Pinus radiata

B. Eucalyptus

CNC = Cyclenusma needle cast, MPA = Monterey pine aphid, DNB = Dothistroma needle cast, AE = *Aulographina eucalypti,* CB = Christmas beetles, MLD = Mycosphaerella leaf disease, SLB = Septoria leaf blight, CLB = Chrysomelid leaf beetles

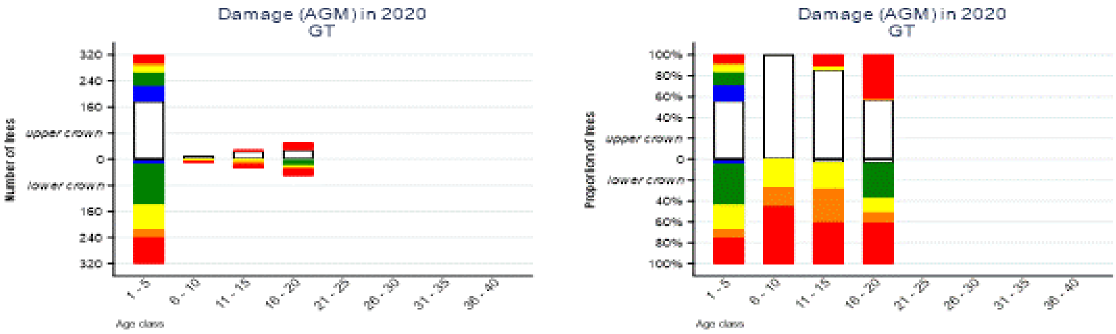
Figure 3. Damage class by plant pests in the upper and lower crowns of the Green Triangle estate in 2020.



A

B

Figure 4. Number of Radiata Pine trees and proportion of Monterey pine aphid (MPA) damage by age-class. Damage severity is indicated by colour and represents a percentage damage to the crown. White = Nil, Trace/Blue = 1-10%, Low/Green = 11-20%, Yellow/Moderate = 20-40%, Orange/High = 40-50% and Red/Severe = >50%.



A B

Figure 5. Number of *Eucalyptus globulus* trees and proportion of Autumn gum moth (AGM) damage by age-class. Damage severity is indicated by colour and represents a percentage damage to the crown. White = Nil, Trace/Blue = 1-10%, Low/Green = 11-20%, Yellow/Moderate = 20-40%, Orange/High = 40-50% and Red/Severe = >50%.

Aerial Surveillance and supplementary surveys

During the 2020 and 2021 survey period the entire plantation estate within the study area was flown. Transect flights were initially designed on the desktop using a Geographic information system (GIS) using the following criteria:

- 4km distance between transect. Visual range of 2km between runs
- Distance from airport and refuelling
- Efficient coverage limiting double flights
- Species

The analysis identified 10 separate transects that met the criteria (Figure 6). The aim was to utilise the two commercial airports in the region (i.e., Hamilton, Victoria and Mount Gambier, South Australia) for refuelling and efficiency. This was challenging over the past two years due to COVID19 restrictions. In 2020 operations were able to be conducted as proposed however in 2021 all flights operated out of Hamilton, Victoria.

Aerial Surveillance was undertaken at two different times of the year. In 2020 the aerial surveys were completed in October, whereas in 2021 softwood surveys were carried out in June and hardwood surveys in July. Figure 7 and Figure 8 show the tracklogs from transects completed in 2020 and 2021 respectively.

The aerial surveys in 2020 were undertaken over five days focusing on both *Eucalyptu*s and *Pinus* plantations together. However, in 2021, the aerial surveys were undertaken separately to evaluate the different scenarios and costings of coordinating separate aircraft flights.

Many observations were made during these surveys with 1107 locations mapped in 2020 and 1313 in 2021. The damage observed ranged from trace to severe levels of damage and tree death to widespread compartment level tree decline. Table 6 shows an example of the results of the ground truthed aerial data and the approximate area of damage recorded at the compartment scale across the region. The pests and pathogens identified following ground truthing from the aerial survey included Sirex wood wasp, Diplodia dieback, Ips damage, lightning strikes, Autumn gum moth damage, Mycospherella leaf disease, sawfly defoliation and individual tree deaths (e.g. associated with *Phorocantha* longhorn beetles) (Figure 9 and Table 6).

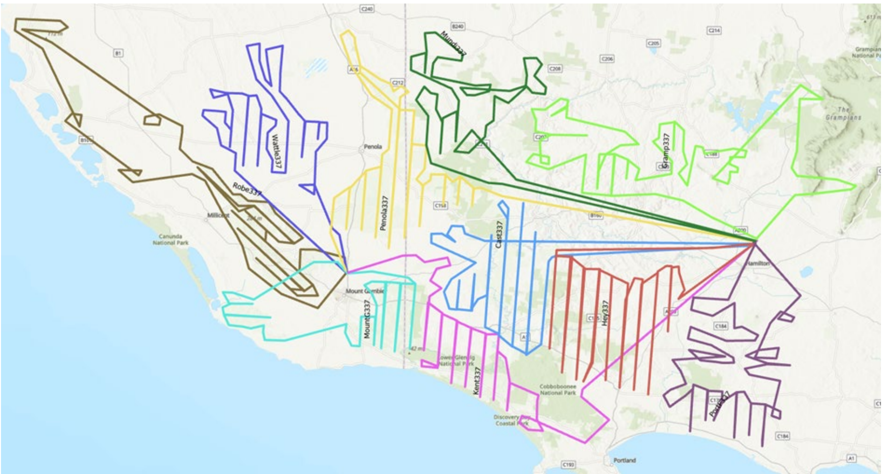


Figure 6. Flight Transect Route Planning 2020 for the Green Triangle estate

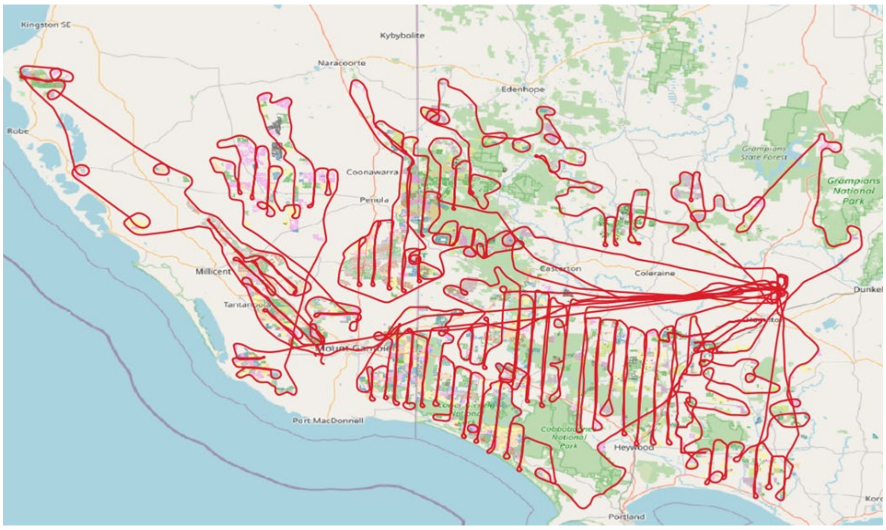


Figure 7. Transect flight paths of Green Triangle estate completed in the 2020 survey.

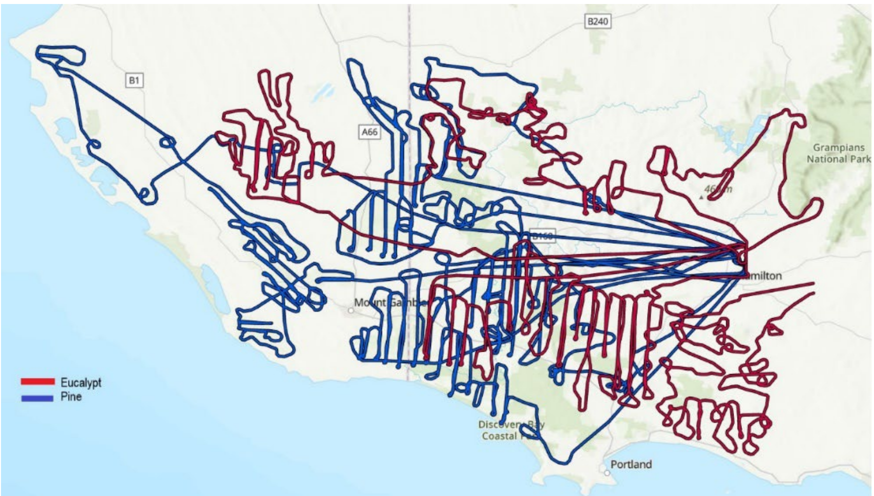


Figure 8. Transect flight paths of Green Triangle estate completed in the 2021 survey showing the differences between Eucalypt and Pine focused flights.

Figure 9. Mycosphaerella leaf disease in a eucalypt plantation in the Green Triangle as observed from air and ground truthed.

Table 6.. Approximate area of plantation damage (ha) by plant pest and pathogens in 2020 as assessed from aerial surveillance.

Code	**Common Name**	**Species**	**Approximate area of damage at the compartment scale (ha)**
SN	Sirex Wasp	*Sirex noctillio*	*2463*
IPS	Ips	*Ips grandicollis*	*2230*
MPA	Monterey pine aphid	*Essigella californica*	*3372*
DP	Diplodia	*Diplodia pinea*	*9763*
CNC	Cyclaneusma Needle Caste	*Cyclaneusma minus*	*577*
AGM	Autumn Gum Moth	*Mnesampela private*	6155
HET	Heteronyx Beetle	*Heteronyx spp.*	768
MLD	Mycosphaerella leaf disease	*Teratosphaeria spp.*	6669
SPRBET	Spring Beetle	*Liparetrus discipennis*	736
ALS/AE	Corky Leaf Spot	*Aulographina eucalypti*	45
CB	Christmas Beetle	*Anoplognathus spp.*	109
CLB	Eucalypt Leaf Beetles	*Paropsis and Chrysophtharta*	944
SHM	Shot hole minor	*Perthida sp*	3884

URBA	Gum Leaf Skeletonizer	*Uraba lugens*	389
BB/ITD	Wood borers/Individual Tree death	*Phorocantha spp*	1141
WEV	Eucalypt Weevils	*Gonipterus spp.*	229
SBWF	Defoliating Sawflies	*Perga spp*	198
CM	Cup Moth	*Doratifera oxleyi*	*142*
SGM	Splendid Ghost Moth	*Aenetus ligniveren*	*Trace*
AN	Animal Damage	*Animal Damage*	*843*

Time and cost required for operational delivery

The aerial surveillance requires approximately 2 days for both preparation (flight plans, approvals, etc.) and data analysis ready for ground truthing. Aerial surveys in 2020 were combined under the collaborative approach whereby in 2021 surveys were carried out separately for softwood and hardwood plantations. Table 7 shows that there was 8.77 hr difference between the 2 years. In 2021 the softwood and hardwood surveys took 21.3 hours ($33,178) and 20.26 hours ($31,558) respectively. When broken down the collaborative survey cost approximately $0.17 per hectare whereas individually the softwood survey cost $0.20 per hectare and hardwood $0.25 per hectare. The operational time and costs may change and will depend on the aircraft type used, time of the year and environmental conditions.

It needs to be noted though that these costs only include the cost of aircraft and do not include the cost of the air observer/trained aerial surveillance expert, pre-flight planning or data processing.

Table 7. Number of days and hours taken to perform ground and aerial surveys of the Green Triangle Plantations.

Year	Plot field days	Diagnostic field days	Aerial Surveillance	Total Days
2020	42	19	32.79hrs (6days) $51,076*	67
2021	47	10	41.56hrs (6days) $63,771*	63

*Costs are based on 2020/21 prices of approximately $1,500/hr and will change over time.

Ground based plot assessments vary in the time they can take to complete as the number surveyed in a day depends on travel time between sites, weather conditions and the age-class of the plantation the plots are located in. Generally, about 7 - 10 plots per day can be assessed depending on access and travel times. The number of days taken to complete the 2020 and 2021 surveys was 42 and 47 days respectively (Table 7). Approximately 9,000kms were driven in the GT in both the 2020 and 2021 surveillance periods. Three staff undertook plot surveillance and ground truthing in 2020 with two staff undertaking this component of the project in 2021.

Centralised system for reporting

Investigation into appropriate data collection system

As part of this project investigations were carried out to identify an appropriate system that would be suitable for the forest industry. The key criteria include:

- Secure system housed outside of industry but accessible to industry
- Allows multiuser access

- Flexibility in data capture
- Data systems flexible with linkages to a variety of mapping systems
- Ease of data export but security between different users
- Off the shelf product or product that could be adapted
- Opportunity for further development with the potential for automation of reporting.

During the project two systems were identified. The first is used for the National Sirex Coordination Committee for the delivery of the biological control program. The system includes the management of the trap tree program with automated reporting and is stored in the Victorian State Government (Bioweb). The second is an off the shelf GIS and Data management system. While this system has limitations of subscriptions and ongoing costs, it has benefits including that many of the forest growers use it.

In the first year of the project, the historical system was used which required much manual data transfer due to it being a single user interface with three surveillance staff. This project has enabled the continued development of the data structure and data recording with the investigation of the two new systems, now both allowing multiple users. The product that was implemented for the 2021 survey was based on Esri ArcGIS that included the use of ArcGIS, ArcGIS Online and ArcGIS Field Maps (Figure 10 and Figure 11).

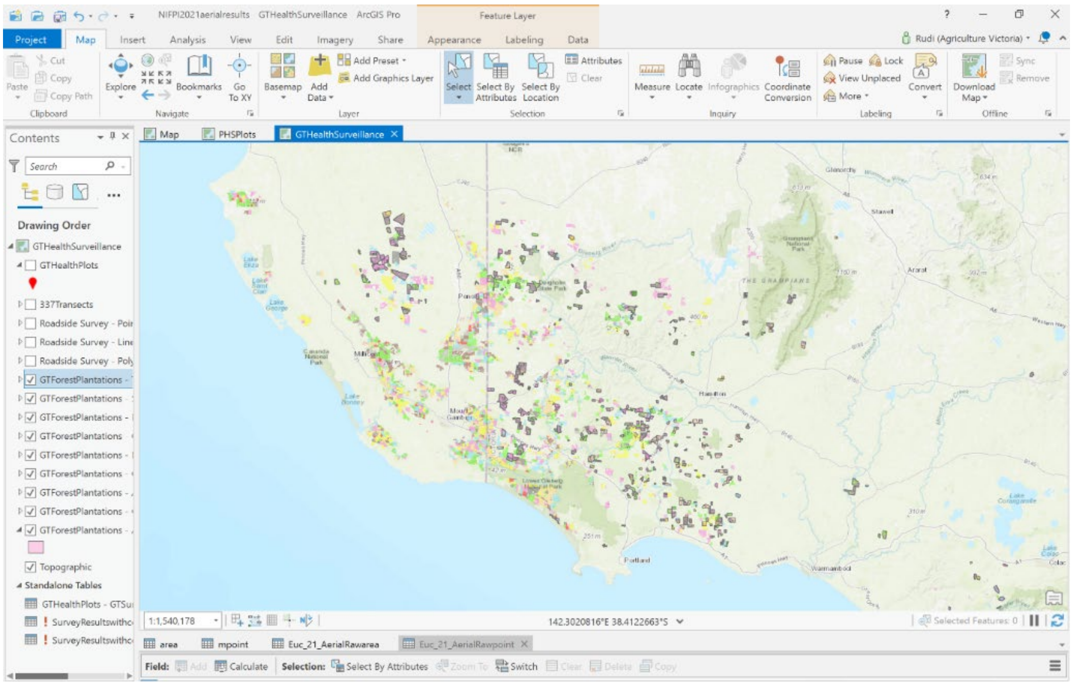


Figure 10. Screen shot of the user interface and plantation area within the current program displayed in Esri ArcGIS Pro.

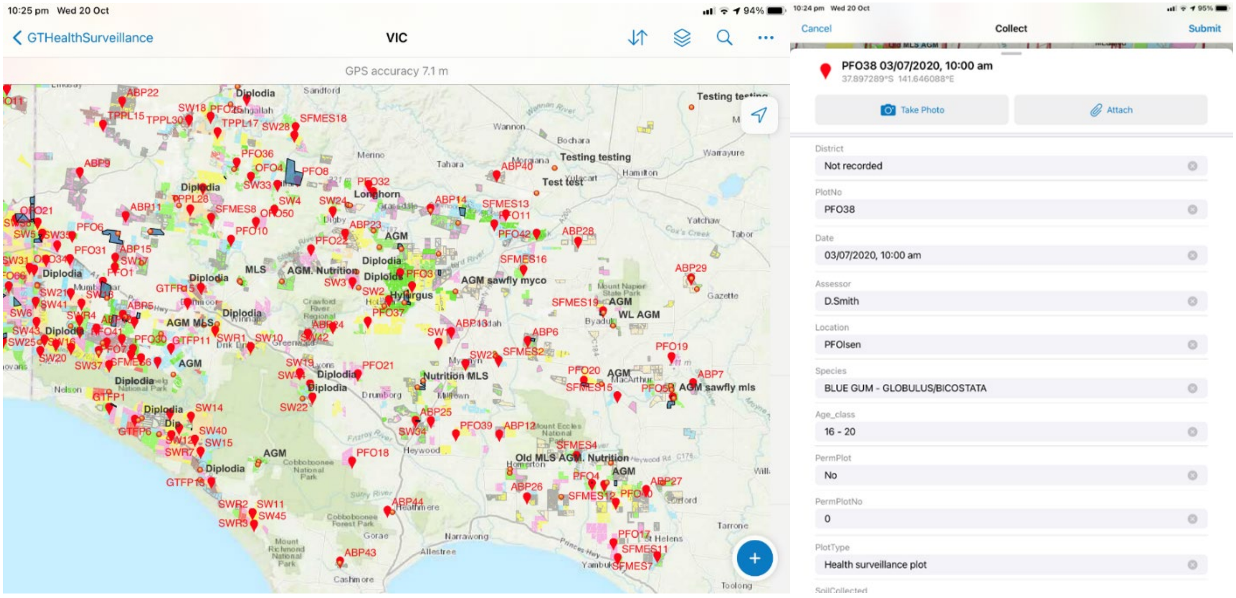


Figure 11. Screen shots of mobile device with the user interface setup for the project within Esri ArcGIS Field Maps.

Training

What engagement and communications have been delivered to industry

The project has delivered many opportunities for engagement and communication. Over the past two years, 14 individual company health reports and two regional reports have been delivered along with the raw plot data, corrected aerial data, and georeferenced images (Table 8).

Company health reports reported in 2020 were generated in Agriculture Victoria template and reporting structure as implemented in previous programs within individual companies. In 2021, company health reports were generated by local forest health role with assistance of Agriculture Victoria in a new template after investigation into alternative reports and feedback from industry for continuous improvement. This allowed for continued local training, transition, and responsibility to be transferred to the local forest health role.

Table 8. Project communication activities.

Activity	**Audience**	**Date**
Mt Gambier workshop and presentation	Steering Committee	Nov 2019
NIFPI Forest Health and Biosecurity Part B: Mini seminar on Forest health data and pest and pathogens.	Stakeholders	29 July 2020
Stakeholder online presentation	Stakeholders	30 July 2020
NIFPI Forest Health and Biosecurity Part A: Mini seminar 1	Stakeholders	2 Sept 2021
NIFPI Forest Health and Biosecurity Part A: Mini seminar 2	Stakeholders	30 Sept 2021
NIFPI Forest Health and Biosecurity Part A: Mini seminar 3	Stakeholders	2 Dec 2021
Individual 2020 Company reports and presentations	Stakeholder	5 Dec2020

Individual 2021 Company reports and presentations	Stakeholder	20 Aug 2021
Regional report 2020	Stakeholder	5 Dec 2020
Regional report 2021	Stakeholder	5 Oct 2021
Stakeholder online presentation	Stakeholders	Feb 2021
Newsletters - Introduction to Part B team	Stakeholders	16/3/2020
Newsletters - Introduction to Part A team	Stakeholders	21/09/2021
Monthly Forest Health Research Meeting with UniSA	Researchers	Monthly 2020/21

Forest Health Monitoring and Surveillance links to Plant Biosecurity

A further aim of the project was to link into State and National Biosecurity Programs. Biosecurity trap monitoring was implemented in the November 2020 program with ten insect traps containing pheromone lures installed around the Portland, Victoria area, a potential pathway for exotic pests (Figure 12). Pheromone lures installed included the Spruce Beetle and *Monochamus* spp. lure types (P408 and P333 respectively), both significant potential pests to forestry in Australia. The lures used are specific attractants for softwood beetles and implemented as a pilot to determine appropriate trap placement and strengthen the forest biosecurity program delivered by Agriculture Victoria.

Before traps were placed, planning and analysis was completed to assess the risk profile. The placement of traps was dependant on their proximity to high-risk areas or high-risk site clusters (clusters of Federal Approved Premises), accounting for factors such as the genera and number of host trees nearby, ease of access, likelihood of being vandalised or efficiencies gained by having other survey traps nearby i.e. from National Plant Health Surveillance program.

To locate adequate locations for the establishment of insect traps, host trees were selected through access to georeferenced council street tree databases and data acquired as part of this project (Smith et al. 2010). Traps were sited close to, or in host trees within parks, gardens roadside reserves and private property including near a private plantation and log holding yards.

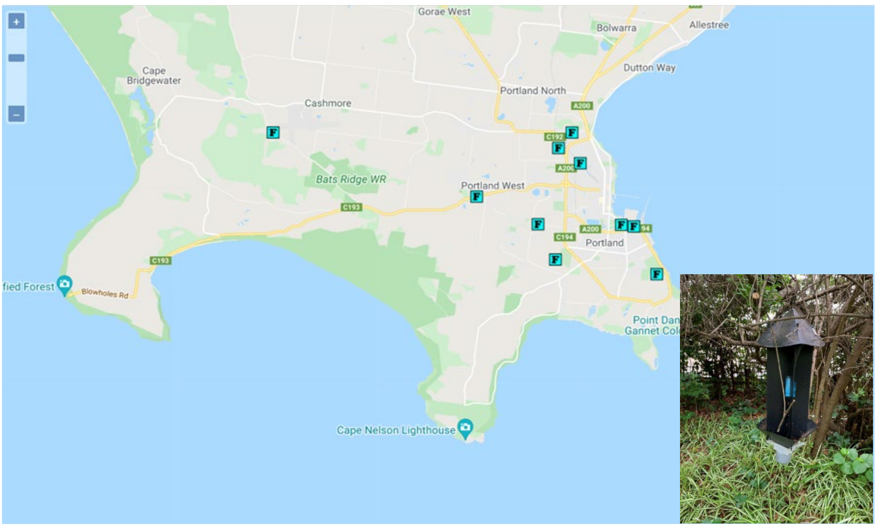


Figure 12. Placement of biosecurity traps around Portland, Victoria for detection of exotic forest pests and panel traps installed around Portland, Victoria for detection of exotic forest pests

Discussion

The Innovative Forest Health and Biosecurity for the Green Triangle NIFPI project comprises two parts. Part A of the overall NIFPI project will further develop an existing Victorian specific model (Weiss et al. 2019) and make it applicable to the GT. The model provides illustrative and quantitative data on the rate of spread of forestry pests and can accommodate user defined spatial extents and data scales (from 100 m to 10 km grid cell resolution). Full detail of this output can be found in Weeks et al. (2021).

The aim of Part B was to establish a cooperative forest health monitoring and surveillance system in the Green Triangle and build capacity in forest health and biosecurity. The key initiative was to develop a standardised forest health program across the Green Triangle forest industry which would allow for efficiencies and a more effective forest health system. Detecting and accurately diagnosing abiotic and biotic issues in plantations before they cause significant damage is vital if management actions are to be effective. Forest health monitoring and surveillance as part of a formal forest health program, enables forest managers to be proactive and to maximise survival, growth and productivity of their plantations.

The forest health monitoring and surveillance system was implemented on the establishment of a network of monitoring plots and supported by an estate wide aerial surveillance program. Results, discussion, and recommendations from the 2020 and 2021 program have been delivered through individual company reports.

The two components of the system provide differing levels of spatial and temporal scales which assist in supporting operational outcomes and provide an overall picture of forest health now and over time. The long-term monitoring can assist with understanding varying management decisions and practises and their impact on plantation productivity.

The established aerial surveillance programs and ground based monitoring program

Aerial surveys

With the use of aerial surveillance in the project, several factors must be evaluated to determine the level of accuracy required. Such factors include, but are not limited to, the intended end use of the data, method of data collection, type of GPS receiver, Datum and Projection, and skill and availability of staff. McConnell et al. 2000, describes the assessment as both an art form and a form of scientific data collection.

The data was recorded on a digital referenced map in a process called Digital Aerial Sketch Mapping (DASM). The digital system of sketch mapping reduces the error found with a manual paper-based system because the mapper does not have to struggle with orientating themselves, instead using digital raster images and background maps with live GPS positioning of the aircraft shown directly on the screen.

Although the data can be subjective, experience and assessor consistency is important. It requires time and understanding of the pest and pathogen lifecycles to be able to diagnose the symptoms from the air; a less experienced observer would require slower speeds and more transect overlap.

Supplementary on ground surveys (ground truthing) are important in correcting the raw aerial survey data to reflect the pest conditions more accurately within the survey area.

Why did we choose fixed wing over rotary wing aircraft for aerial surveillance?

The aircraft that was deemed the most suitable to complete the surveys was a high wing Cessna 337G Skymaster which followed the Victorian state government IAOP FO 2.04 Operational and Flight Planning procedures and IAOP AM 1.06 Obtaining Aircraft procedure. This aircraft is a twin-engine aircraft in a push-pull configuration providing unparalleled safety handling in the event of an engine failure in addition to exceptional all-round visibility for all crew members. Its engines are mounted in the nose and rear of the fuselage providing exceptional stability and controllability, especially over turbulent mountain terrain. Depending on conditions and tasking requirements the aircraft can loiter for up to 6.5 hours before requiring refuelling. It offers generous "go-to" speeds of 145kts and comfortable survey speeds as low as 80kts which makes this aircraft very versatile and cost efficient. There is provision for a pilot and 3 crew members with all crew having a separate observation window.

The use of rotary wing (i.e., helicopter), was examined, and also provides a good platform for the surveys. The benefits of rotary wing are the increased visibility and larger variability of speed, especially slower speeds. This aircraft type was not used during these surveys primarily due to operational complexities relating to shorter flight times between refuelling, increased hourly costs and during 2020/21 the effect of COVID 19 and border closures. To operate the rotary wing aircraft during this time across state borders was logistically too difficult as the situation did not allow easy of refuelling. Table 9 describes an operational comparison between the two aircraft platforms. Both aircraft are capable of undertaking the operation, but due to a number of factors (e.g. COVID 19 restriction) fixed wing was chosen. Depending on the rotary wing type there could be roughly 10 - 20% increase in costs per hour. During training rotary wing can be more appropriate because of the potential for slower air speeds but the increased costs will need to be acknowledged.

Table 9. Comparison between fixed wing and rotary wing aircraft

Attribute	Fixed Wing	Rotary Wing
Time between refuelling	6.5hr	3hr
Visibility	Good	Better
Go-to speeds	145kts (268.54 km/hr)	80-100kts (185.2 km/hr)
Loiter speeds	80kts	80kts but can slow down.
Passengers	3	3
Refuelling	Fixed to airports	Can be more flexible with approved Helicopter Landing Areas

As part of the project, it was important to look at the collaborative approach and the potential scenarios between running a joint aerial surveillance program across all companies and tree species against running the surveys separately between the different tree species. Table 7 shows that there was an 8.8hr difference between the two years. These costs take in all features of running an air operation including aircraft, pilot, and air observer's time.

Air operations are a significant and costly component of the FHP, but the correct timing of aircraft operations to determine pest presence and status is critical to avoid collection of inaccurate or incomplete data sets. Aerial surveys conducted at the correct time will potentially capture the major mortality events that might occur within the plantations.

Maximum pest and pathogen symptom expression in both hardwood and softwood plantations varies depending on abiotic (e.g. seasonal conditions) and biotic factors in the estate. In the hardwood estate for example, maximum symptom expression from AGM is primarily observed in early to mid-winter, whereas MLD symptoms are most prevalent in mid spring to early summer. In the softwood estate, Ips, Diplodia and Sirex show maximum symptomatic expression during winter. Such differences are important to recognise in surveillance programs, as there are points throughout the year where new damage from these agents has ceased, thus allowing for the seasonal end point surveys to be conducted. This understanding also highlights the need for pest specific monitoring to supplement the annual surveys. Consequently, winter is the best time to perform either hardwood or softwood surveys in the Green Triangle as it can be carried out for both the pest specific surveys, along with general annual health surveys.

Forest health monitoring plots

The primary goal of a forest monitoring program is the detection of fine to medium changes in tree health, and in particular the deterioration of trees, and ultimately assess the status of wider forest health issues. Innes (1993) describes the deterioration as forest decline which is manifested as symptoms such as reduced growth rate, loss of foliage or leaf discolouration, often eventually, but not necessarily, leading to tree death.

Data collected in monitoring plots is at the scale where initial stages of tree decline can be recorded, and over time analysis of changes in attributes such as defoliation or discolouration, may detect changes at the crown and canopy level. Decline can also be associated with chronic biotic or abiotic stress impacts, although establishing a causal relationship is not always easy or even possible (Schulze 1989).

Plot based systems allow for more accurate tree assessments at a fine to medium scale, allowing analysis of trends within background populations of pests. The principal components of the program include monitoring for pest insects and pathogens, animal browsing, weed infestation and abiotic factors such as fire, drought, lightning etc.

Assessments within ground-plot systems are generally based on the sound assumption that crown condition is a primary indicator of tree and overall stand health (Hosking & Anderson 2004). The health of forest and tree canopies are generally regarded worldwide as an effective indicator of both the health of the tree, and more broadly on a compartment scale, as an overall indicator of stand health (Stone and Haywood 2006, Innes 1993, Coulston et al. 2005, Hosking and Anderson 2004, Ferretti 1997). Crown condition assessments using defoliation and discolouration, are often relatively simple and efficient, with many trees and plots assessed with relative ease. The assessments can be undertaken at varying intensity.

Plot based monitoring provides the finest level of spatial scale and can be linked with other tree productivity metrics such as height and diameter. Linking these productivity metrics to health can help with modelling growth and production losses.

With a collaborative effort such as that made across the Green Triangle, resources and data can be shared to gain a better understanding of regional forest health through a wider plot network and allowing for joint management actions to be implemented.

Targeted / Pest specific monitoring / surveillance

Targeted surveys, or pest-specific surveys, are important tools in a monitoring and surveillance program because they aim to target a specific part of a pest's lifecycle whereby management options can be considered. The surveys are undertaken to monitor development of known pathogen or pests at locations highlighted by the aerial surveys.

Pest specific surveys can also be integrated into a general plot monitoring program where a proportion of plots within the network are matched to a set of criteria such as species, age class, site-specific factors, or specific damaging agent/s. Surveys may happen at several different times during a year and can allow for a greater understanding of pest's thresholds and critical times where management actions can be used to reduce the impact. These surveys have a specific outcome in mind and can use different monitoring techniques such as egg numbers, number of insects at different life stages in combination with defoliation and discolouration scores.

Comparison of aerial vs ground-based detection and single and separate surveys

The FHP is the identification of agent-based process and their impact on stand productivity and vitality through assessment of the forest canopy. It is important to take into consideration when assessing the health of tree canopies, the likely damaging agent complexes operating at particular times of the year so that their impacts can be factored into any assessment metric produced. Both hardwood and softwoods plantation have complicating factors like flushes of new immature foliage growth usually experienced in spring and following rain in autumn ('autumn break'). These 'flushes' are sometimes difficult to interpret for eucalypts because 'discoloured', 'red' or 'non-green' foliage can simply be the result of the presence of immature foliage, natural senescence or even nutritional issues within foliage, rather than due to damaging agents. Both aerial and ground surveys are impacted by these issues and appropriate timing is critical.

Ideally where the aim of FHP is to evaluate long-term changes over time, assessment timings should be undertaken preferably when maximum health is expressed. This would enable trends to be measured outside of fluctuations due to seasonal defoliation events that may distort a particular assessment. In terms of pest complexes operating, previous forest health data indicates that most insect pest complexes operate during the summer/autumn period and pathogens during the wetter spring periods. However, the 'optimal' monitoring periods indicated are approximate and based on a history of previous observations and outbreaks, with these timings subject to change dependent upon prevailing climatic variables such as rainfall and temperature, which will vary from year to year.

Within the monitoring and surveillance carried out in 2020 and 2021, damaging agents were identified in both the aerial surveillance and plot-based monitoring across both the hardwood and softwood plantations. Aerial surveys allow for a broad overview of damage caused to the plantation estate. The aerial surveys also enable plantation staff to identify small areas of damage not easily seen from tracks or roadsides. The annual monitoring plots allow for comparisons to be made between pest specific monitoring and end point surveys of particular pest/pathogen outbreaks and to determine potential recovery or decline.

There is a significant difference in time associated with coordinating one set of aerial and ground surveys per year across all growers compared to two separate surveys, one for softwood and one for hardwood or even a single company survey. Over the two years of the project a comparison was made between a single survey in 2020 and split species survey in 2021.

In 2020, approximately 32 hours of flight time was required to undertake a joint aerial survey which takes into account ferry repositioning and operational delivery. This time was spread over 6 days and cost approximately 17 cents per ha. This cost however only includes the cost of aircraft and do not include the cost of the air observer/trained aerial surveillance expert, pre-flight planning or data processing.

Whereas in 2021, 41 hours were required (Table 7). The time required to undertake the aerial survey for hardwood and softwood separately were similar at approximately 20 hours each (Table 7). The cost of the separate softwood survey was approximately $0.20 per hectare whereas the hardwood survey was $0.25 per hectare. As stated above though these costs do not include the entire operational delivery and prices are based on 2020-21 and may change.

The reason for the difference in costs and time is due to the spatial distribution of the plantation estate. In Figure 8 it can be observed that there were portions of the estate that required an overlap of the flight logs. Areas around Mumbannar and Lankoop had the largest amount of overlap and thus do benefit from a joint collaborative survey. By undertaking the aerial surveys as a joint effort similar to the 2020 scenario there is saving of close to 9 hrs which equates to approximately $13,000.

Undertaking the separate aerial surveys also duplicates the areas that needs to be assessed for damage as surveillance staff are having to revisit areas whereby, they had already attended in the first survey. Linking the ground truthing and the plot monitoring allows for efficient assessment and reduces the need for excessive doubling up.

Innovations, improvements and challenges

During this project there have been several key innovations and improvements made including development of a new data capture process and data structure that is available for multi-user and better data sharing capabilities. These new systems have increased the efficiency of plot assessments and the processing and ground truthing of aerially collected data. The new FHP has enabled the collection of forest health data in a consistent manner using the same metrics and attributes so that within company, and at a regional scale, the data can be analysed and compared. Regional reporting and data presentation allows all companies in the Green Triangle to understand the overall pest and pathogen issues and enables further collaboration through investigation into pest specific issues and sharing of resources to accomplish a joint outcome of increased productivity in the region.

Other companies across Australia have shown interest in the project and the FHP that has been implemented into the region. This is encouraging as this project may help with standardising some of the metrics used in forest health assessments across Australia.

Unfortunately, because of COVID-19 the original objectives for training and upskilling of the forest industry was not able to be accomplished to the level that was proposed although training was provided to a new forest health officer based in the Green Triangle. This has enabled capacity building through one-on-one training. Presentations were undertaken with individual companies through online meetings where their data was presented back to them outlining the key issues observed by the forest health team and discussions of the pests and pathogens identified. Individual forest health reports have been developed and delivered allowing more discussion and detail about the data and more understanding of the locations and severity of the issues identified.

There is a need for coordination of the future FHP in the GT and requirement for future training of foresters across all the companies so that they can better identify the common pests and pathogens in their plantations and importantly understand what is not normal and requires further investigation e.g. detection of a potential exotic.

Covid constraints/ border closure and capacity exposure for industry

The 2020-2021 COVID-19 restrictions impacted on the project through reduced engagement with project and industry staff. Training that had been planned as part of the project was not able to be completed to the levels planned, for example around aircraft where limitations on crew were made to only essential staff and in field company pests and pathogen identification.

South Australian and Victorian, cross border restrictions and closures are a significant issue, but the project was fortunate to have staff based on both sides of the border allowing for the work to remain on track and be completed. Agriculture Victoria were unfortunately only able to spend 2 weeks over the life of the project within SA and COVID restrictions hampered the University of South Australia staff to only traveling within the allowed border bubble. This has highlighted the requirement to develop a wider local expertise external and within the companies to ensure exposure for pest and disease are mitigated.

Exemptions were made for the use of aircraft within the project and both University of South Australia and Agriculture Victoria supported the program by issuing permits for staff to complete the work as essential travel required.

Investigations into a data collection platform

Historically, plot-based forest health data in Victoria has been collected using digital data collection and storage systems. The original system was based around a Microsoft Access database that was maintained by a forest health officer. This system contained limitations in being complex for data transfer and not multiuser compatible.

During the project two systems were identified as replacements to the historical system. One already being used by industry (i.e. for the National Sirex Coordination Committee for the delivery of the biological control program the management of the trap tree program with automated reporting) housed within the Victorian State Government (Bioweb) and the other an off the shelf GIS and data management system that has limitations of subscriptions and ongoing cost but has benefits including that many of the forest growers use this system.

Bioweb system development

At its core Bioweb is a 'Microsoft Share Point 2013' collaboration platform. The Victorian Government, Agriculture Victoria, extended the sharepoint product in a number of ways to support the business and branded this 'Bioweb'. Basically, Bioweb is a collection of websites used to store, organise and share information.

Bioweb is a single sign on platform that is used for:

- Document Management
- Team Collaboration
- Cross Business Collaboration
- Project Management
- Data Capture & Storage
- Reporting
- Business Automation

It also has a vital role in biosecurity emergency response and recovery operations through customised 'MAX' sites. A MAX site is a customised SharePoint (Bioweb) site, designed to capture and collate emergency response or routine project information. MAX site data elements are additionally stored and made available through a central data warehouse.

The name MAX derives from the ‘Maximum Disease and Pest Management’ software tool initially developed in a Microsoft SharePoint environment for emergency disease and pest responses.

MAX was originally conceived as part of the Victorian State Government response to equine influenza in 2007. Since then it has been remodelled, customised and applied to various Agriculture Victoria based emergency response campaigns, routine Biosecurity/Agricultural project work and has been adapted to support the forest industry for the management of Sirex Wasp through the biological control program. The MAX platform is now also being used by most of the state government biosecurity agencies.

Due to the relative success of the National Sirex Wasp project Bioweb and MAX was investigated for use in the GT data collection. Forms and attributes were created, and testing was in the final phase when significant limitations were found particularly within the spatial GIS analysis and integration of the aerial survey data and its ground truthing. There were also issues about long-term maintenance of the system and its further development.

Use of GeoLink® and ArcGIS suite for the data collection and benefits and challenges of this system

After the decision was made to move away from Bioweb, investigations were made into using an off the shelf product that many within the forest industry were already using. The ArcGIS Suite of products was selected because it met the criteria of being multiuser, flexible in data capture, the data outputs were compatible with other GIS systems, and it was easy to export the data but had a level of security that could be set between different user groups.

One of the benefits of the ArcGIS suite is the online portal where the data can be stored and kept secure. It is also a benefit to have the data in the cloud where it can be pulled down to a mobile device for data collection and viewing. The mobile device interface ArcGIS field maps is simple but powerful enough to be able to collect relationship data and include all the attributes required to accurately monitor the plots and undertake the supplementary surveys after the aerial flights were undertaken.

One downside of the system is the ongoing cost with licences ranging from around $500 per year for a field worker licence to a Creator ArcGIS Desktop Advanced licence at close to $6000. The structure of the licence could be that the forest health coordinator has an advanced licence that can manage the data and create relationships between tables and process photos into GIS layer and geodatabase and the field staff have a field worker licence to be able to collect the data.

The GeoLink® program was used in the collection of the aerial surveillance data. This program was designed by the U.S. Department of Agriculture, Forest Service, Remote Sensing Applications Centre with a commercial vendor, to develop a product that will meet the needs of forest health aerial surveyors. This program is now discontinued and only a small number of licences remain and are still supported by the private company. There is a need to develop a new program that will take the needs of aerial surveillance in Australia into the future as the GeoLink® program becomes more difficult to access, install and use on newer computer systems.

Forest health diagnostic/ advisory capacity and linkage to the National strategies and framework

In Carnegie et al. 2018, they described that even though there were inconsistencies in methods used across the forest industry in relation to forest health monitoring and surveillance, generally the base data collected is similar. They also describe that there is no national coordination or national industry/ technical body that oversees the forest health monitoring and surveillance activities across Australia. The baseline data collected across the country which may include attributes such as host and pest species recorded, distribution and severity, and management options of particular damaging agents. This program has attempted to standardise the approach used by forest growers in southeast South Australian and Victoria which is important for consistency of reporting and regional summaries. Data collected within this FHP is important in understanding the current pests and pathogen agents and their impact on the productivity of plantations. Within a recent industry survey, forest growers also indicated that they believe that routine forest operational activities have potential to help detect exotic pests (Department of Agriculture and Water Resources, 2018).

Diagnostic capacity, across Australia, for commercial forestry pests and pathogens was and still is primarily held within State Governments and Universities. This advice and laboratory support comes with set costs for individual samples and basic advice is provided depending on prior arrangement.

Forest pest diagnostics is essential to support surveillance activities. Good diagnostic capability in state government agricultural agencies could be enhanced and leveraged to identify forest pests. Improved communication and extension networks between these agencies and non-traditional stakeholders such as forest growers would improve capability and capacity for detection of suspect exotic forest pests.

In the current National Forest Biosecurity Surveillance Strategy, accurate knowledge of the current distribution of forest pests and pathogens is required to support and assist state and federal governments with claims of pest area freedom (both endemic and exotic). This will also assist with modelling the risks and spatial distribution of similar pest species absent from Australia. Both parts A and B of this project aim to assist with building a better understanding for both the current risks posed by endemic pests and pathogens and the ones that are still to arrive on our shores.

One of the aims of the project has also been to contribute to the national goals of the National Forestry Biosecurity Surveillance Strategy 2018- 2023, namely:

> 1.2 - Develop sustainable funding mechanisms for surveillance that are equitable for all forest stakeholders;
> 3.1 - Update and review forest pest knowledge;
> 3.3 - Improve surveillance capacity and capability across all forest stakeholders
> 4.1 - Improve risk mitigation of exotic forest pests along the biosecurity continuum.

During this program, the GT forest industry has been developing a funding model that will support a forest health position based in the region (Goal 1.2). Pest information sheets have been provided in the back of the individual company reports and also provided to Plant Health Australia for addition into the new My Pest Guide Trees app being developed in the national project (Goal 3.1). The establishment of the monitoring and surveillance system has increased the capacity and capability of the forest industry in the GT to identify pests and provide a more streamlined pathway of reporting to the biosecurity agencies if potential exotics are detected (Goals 3.3 and 4.1).

Conclusions

The key innovation delivered throughout this project is the development and implementation of a structured and systematic forest health monitoring and surveillance program that aims to provide forest managers with the tools to better understand the risks pest pose on their plantations and provide information where management actions can be undertaken. All plantation companies within this program aim to maintain the estate in a sustainable condition and their third party certification status require this. This project has provided a standardised structure that will allow for the analysis of data that will assist with the monitoring and treatment strategies of a particular forest pest or pathogen.

The rebuilding of a forest health monitoring and surveillance capacity within the Green Triangle has started with a dedicated position taking up a leadership position to coordinate the monitoring and surveillance activities locally. This position will assist industry partners with pest specific monitoring and will collaborate in the establishment and monitoring of the forest health plots and has undertaken the second-year company reports. This has meant that throughout the project there has been continual development and training activities even throughout the COVID-19 issues. Unfortunately, due to COVID-19, the proposed training that was to be provided by Agriculture Victoria to the new forest health officer and the industry partners was not completed in the way intended and training had to be undertaken remotely using more innovative methods. Pest guides were attached to industry reports to assist in the understanding of the pests identified and were discussed in the reports and mini seminars.

The use of ArcGIS suite of products has aided in the development of a data structure and system that allowed for efficient collection of forest health data. The system is flexible enough to cater for the different types of data collected (e.g. plot and aerial) and has aided in a reduction of transcription errors and sped up the data analysis. The system is efficient and secure, storing different types of data, from relationship data to aerial sketch mapped polygons, to georeferenced images for presentation to industry and assisting in ground truthing.

Nationally this project has contributed to the national goals of the National Forestry Biosecurity Surveillance Strategy 2018- 2023. During the program the GT forest industry has begun developing a funding model that will support a forest health position based in the region (Goal 1.2). Pest information sheets developed have been provided in company reports and also provided to Plant Health Australia for the national project (Goal 3.1). The establishment of the monitoring and surveillance system has increased the capacity and capability of the forest industry in the GT to identify pests and provide a more streamlined pathway of reporting to the biosecurity agencies if potential exotics are detected (Goals 3.3 and 4.1).

Recommendations

Need for an ongoing Green Triangle Forest Health coordinator

There is a need for a Green Triangle forest health industry coordinator that can organise the annual forest health surveillance program, perform the monitoring and surveillance, and undertake the analysis and reporting. This position can further assist industry in a co-ordinated approach to forest health for the region and assist in administration, operations and research functions. Industry have created this position (Forest Health co-ordinator) for the region to continue this capacity past this project.

Increased forest health and biosecurity capacity requirements within industry

There is a need to support the continuation of the training of the Forest Health coordinator and industry staff, that was not able to be delivered to the full extent envisaged as part of this project due to the COVID-19. Training needs to be provided on establishment of forest health monitoring plots and their assessment along with the identification of the major forest pest and pathogens regularly observed. Continued training has been highlighted as a key component of the Forest Health program into the future.

Digital monitoring and surveillance systems for the GT

The system developed, along with the geodatabase structure and domains, are currently being transitioned from the Victorian State Government ArcGIS servers to local servers to continue the work achieved in this project. This online system will continue in its development to allow access to individual companies and develop into a real-time system. There are also opportunities to house other monitoring programs to aid in co-ordinated pest specific monitoring and roadside opportunistic surveys throughout the region both at a company and regionally co-ordinated scale.

Development of an aerial sketch mapping program

There is a need for the development of a new aerial sketch mapping program to replace the now discontinued and unsupported GeoLink® program. A new application could be developed in the ArcGIS platform to collect the aerial surveillance data which would allow a more streamlined data transfer and data analysis. The program could be customised to Australian conditions and pests of significance.

Links to national biosecurity program AusPest Check

It is recommended to investigate linkages with Plant Health Australia (PHA) and the data requirement needs for effective data transfer to the national AUSPestCheck™ currently being developed with rollout of the National Forest Biosecurity Program and increases to the levy in July 2022. The initial phase would be to agree on the minimum data standards required and discuss the potential reporting functions. AUSPestCheck™ is a Virtual Coordination Centre, (VCC), which includes a data aggregation software system designed to collate and provide pest surveillance data for biosecurity and pest management stakeholders in Australia. It provides authorised users with a regional and national presentation of pest and disease activity and is designed to support existing surveillance programs and systems used by government jurisdictions and industry.

Research needs

Research into new remote sensing technologies to support operational delivery

Throughout the world, remote sensing technologies are used to detect and monitor forest health and the impacts of various forest pests. The range of remote sensing platforms available, including ground, aerial (both UAV and aircraft) and satellite provide substantial opportunities to develop complementary multi-scale surveillance approaches, capable of delivering a range of tailored spatial analytical tools in a timely manner for forest managers (Stone et al. 2008, Hall et al. 2016, Senf et al. 2017). The use of remote sensing to monitor mountain pine beetle damage in western North America provides an example of the utility of remote sensing, particularly at different spatial scales (Wulder et al. 2006).

Advancements in remote sensing, particularly in the past decade, have increased the diversity and availability of sensors including multi-spectral, hyper-spectral, radar and LiDAR. These technological developments, coupled with advancements in machine learning, deep learning, such as convolutional neural network analytics, and big data, provide a large potential for remote sensing to contribute to forest health surveillance programs moving forward (Stone et al. 2017). Long-term monitoring studies over large areas, utilising time-series of imagery provides an opportunity to monitor forest health trends and detect changes which may denote and issue requiring further investigation. Linked with predictive modelling capability, these technologies may expand a response capability in terms of a pest outbreak.

Potential student projects

Pest and pathogen damage thresholds

With an increased understanding of the pest and pathogens in the Green Triangle, it is important to put context around the amount of damage thresholds it takes to impact on productivity. Potential students may increase this understanding through studies of the insect pest biology and the spatial and temporal scales to develop damage thresholds that would direct management activities.

Developing the pest forecast models using degree day models for endemic pests

To be able to direct on time and preventative management activities, a pest forecasting model could be developed to predict the current lifecycle of the pest and conditions in which an outbreak may occur. The model could target key stages in the lifecycles where you might target management activities and use degree day models and accurate weather data to forecast insect development.

Exploring the use of Forestry pest dispersal model and configuring for endemic pests

With the development of the forest pest dispersal model there is an opportunity to investigate the extension of the model to incorporate some key pest and pathogens in the region. This forecast model could enable an understanding of current pests and their likely hood to spread across the landscape and their potential spread rates. This would help with collaboration within the industry in controlling and mitigating pest and pathogen damage.

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Appendix 1. Detailed domains/ lookup codes and data structure used.

Number	Code	Percentage
0	0	0
10	1	10
20	2	20
30	3	30
40	4	40
50	5	50
60	6	60
70	7	70
80	8	80
90	9	90
100	10	100

PartAffID	Code	PartAff
NR	0	Not recorded
B	1	Branch
N	2	Not affected
S	3	Stem
SB	4	Stem and Branch

LocaAffID	Code	LocaAff
NR	0	Not recorded
B	1	Base
M	2	Middle
T	3	Top
BM	4	Base and Middle
MT	5	Middle and Top
BT	6	Base and Top
A	7	Entire Tree

LayerAffID	Code	LayerAff
NR	0	Not recorded
A	1	All layers
B	2	Bark
BS	3	Bark and Sapwood
H	4	Heartwood
S	5	Sapwood
SH	6	Sapwood and Heartwood

TypeDamID	Code	TypeDam
NR	0	Not recorded
B	1	Break
Ca	2	Canker
Cr	3	Cracks
D	4	Decay
DS	5	Decay/Stain
L	6	Lesions
LN	7	Lean
R	8	Ringbarking
RE	9	Resin
RT	10	Root coiling
S	11	Swelling
SC	12	Scar
ST	13	Stem twisting (Growth wobbles)
B	14	Borer
LAD	15	Loss of apical dominance

AgeID	Code	Age_class
0	0	Not recorded
1	1	1 - 5
2	2	6 - 10
3	3	11 - 15
4	4	16 - 20
5	5	21 - 25
6	6	26 - 30
7	7	31 - 35
8	8	36 - 40

AspectID	Code	Aspect
NR	0	Not recorded
E	1	East
N	2	North
NE	3	North-east
Nil	4	Nil
NW	5	North-west
S	6	South
SE	7	South-east
SW	8	South-west
W	9	West

ColourID	Code	Colour
NR	0	Not recorded
C	1	Chlorotic
N	2	Necrotic
P	3	Purple

ColourLocID	Code	ColourLoc
NR	0	Not recorded
LM	1	Leaf margins
LB	2	Leaf base
LA	3	Leaf apex
IR	4	Interveinal regions
EL	5	Entire leaf

FolTypeID	Code	FolType
NR	0	Not recorded
J	1	Juvenile
B	2	Both (Transitional)
A	3	Adult

PlotID	Code	PlotType
0	1	Not recorded
1	3	Random survey
2	2	Diagnostic survey
3	4	Roadside survey
4	5	Health surveillance plot

ConditionID	Code	Tree Condition
NR	0	Not recorded
D<1	1	Dead <1yr
D>1	2	Dead >1yr
L	3	Living

DomID	Code	Dominance
NR	0	Not recorded
CD	1	Co-dominant
D	2	Dominant
S	3	Suppressed

CauseID	Code	Common	Scientific
NR	0	Not recorded	Not recorded
UD	1	Unidentified disease	Unidentified disease
UI	2	Unidentified insect	Unidentified insect
IM	3	Leaf Miner	Leaf miner
AWL	4	Water Logging	Water Logging
ALR	6	Awaiting lab result	Awaiting lab result
U	7	Unknown	Unknown
IGM	8	Autumn gum Moth	Mnesampela privata
ILS	9	Leaf Blister Sawfly	Phylacteophaga froggatti
AWT	10	Windthrow	Windthrow
IOB	11	Other Borers	Coleoptera and Lepidoptera
ILO	12	Longicorn Borers	Phorocantha spp.
BO	13	Biotic other	Biotic other
IOC	14	Other Caterpillars	Lepidoptera
BA	15	Animal damage	Animal damage
IO	16	Insect other	Insect other
IBL	17	Lace and Basket Lerps	Cardiaspina spp.
IGG	18	Gumtree Scale	Eriococcus coriaceus
ID	19	Cup Moth	Doratifera spp.
ICB	20	Christmas beetles	Anoplognathus spp.
ILB	21	Eucalypt Leaf Beetles	Paropsis and Chrysophtharta
ISL	22	Sugary Lerps	Glycaspis spp.
ISS	23	Steelblue Sawfly	Perga affinis affinis
IGS	24	Gumleaf Skeletoniser	Uraba lugens
DAS	25	Angular Leaf Spots	Seimatosporium/Vermisorium spp.
DO	26	Disease other	Disease other
DWS	27	Winter Leaf Spot	Piggotea eucalypti
DCF	28	Cinnamon Fungus	Phytophthora cinnamomi
DPS	29	Pin Spot Disease	Plectospaeria eucalypti
DM	30	Crinkle Leaf	Mycosphaerella spp.
AHE	31	Herbicide	Herbicide
AS	32	Salt	Salt
AND	33	Nutrient Deficiency	Nutrient Deficiency
AC	34	Competition	Competition
AO	35	Abiotic other	Abiotic other
AM	36	Mechanical damage	Mechanical damage
AF	37	Fire	Fire
AFr	38	Frost	Frost
AL	39	Lightning	Lightning
AH	40	Hail	Hail
DCS	41	Corky Leaf spot	Aulographina eucalypti
LS	42	leaf scale	leaf scale
BB	43	Bullseye borer	Bullseye borer
CO	44	Cossid	Cossid
DA	45	Armillaria root rot	Armillaria spp.
DAI	46	Armillaria root rot	Armillaria luteobubalina
DCL	47	Spring Yellows	Cyclaneusma & Lophodermium spp.
DCN	48	Cyclaneusma needlecast	Cyclaneusma spp.
DDC	49	Diplodia Canker	Diplodia pinea
DGM	50	Grey mould	Botryotinia fuckeliana
DLN	51	Lophodermium needlecast	Lophodermium spp.

DNB	52	Pine needle blight	Dothistroma septospora
DP	55	Phytophthora root rot	Phytophthora spp.
IAP	56	Painted apple moth	Teia anartoides
ICM	57	Leaf case moth	Hyalarcta huebneri
IFB	58	Fivespinned bark beetle	Ips grandicollis
IGB	59	Goldenhaired bark beetle	Hylurgus ligniperda
IGT	60	Greenhouse thrip	Heliothrips haemorrhoidalis
IPA	62	Monterey pine aphid	Essigella californica
IPB	63	Black pine bark beetle	Hylastes ater
IPP	64	Pine adelgid	Pineus pini
IS	65	Sirex wasp	Sirex noctilio
ISM	66	Bag shelter moth	Ochrogaster contraria
ITM	67	Pine tube moth	Lichenaula sp.
IW	69	Radiata pine shoot weevil	Merimnetes oblongus
IWG	70	Wingless grasshopper	Phaulacridium vittatum
RC	71	Root coiling	Root coiling
DKE	72	Septoria Leaf Blight	Kirramyces eucalypti
IEW	73	Eucalyptus Weevil	Gonipterus
ISHM	74	Shothole Miner	Perthida
IBGP	75	Blue gum Psyllid	Ctenarytaina eucalypti
IM	76	Moth	Moth sp
ISB	77	Spring Beetle	Heteronyx spp
ILH	78	Leaf Hopper	Cicadellidae spp

Data Structure

Field Name	Alias	Domain
OBJECTID	OBJECTID	
OID_1	OID	
LinkID	LinkID	
Location	Location	LocID
SurveyNo	SurveyNo	
TreeNo	TreeNo	
TreeHeight	TreeHeight	
TreeDiam	TreeDiam	
TSCond	Tree Condition	ConditionID
TSDom	Tree Dominance	DomID
FPU	Foliage Present Upper	PercentID
FTU	Foliage Type Upper	FolTypeID
CFLUP	Cause Upper Primary	GTSurveyResults_CFLUP
CFLUS	Cause Upper Secondary	GTSurveyResults_CFLUS
CFLUT	Cause Upper Third	GTSurveyResults_CFLUT
CFLUF	Cause Upper Forth	GTSurveyResults_CFLUF
FPL	Foliage Present Lower	PercentID
FTL	Foliage Type Lower	FolTypeID
CFLLP	Cause Lower Primary	GTSurveyResults_CFLLP
CFLLS	Cause Lower Secondary	GTSurveyResults_CFLLS
CFLLT	Cause Lower Third	GTSurveyResults_CFLLT
CFLLF	Cause Lower Forth	GTSurveyResults_CFLLF
DFU	Discoloured Foliage Upper	PercentID
ColourU	Colour Upper	ColourID
ColourLocU	Colour Location Upper	ColourLocID
CDUP	Cause Discolouration Upper Primary	CauseID
CDUS	Cause Discolouration Upper Secondary	CauseID
DFL	Discoloured Foliage Lower	PercentID
ColourL	Colour Lower	ColourID
ColourLocL	Colour Location Lower	ColourLocID
CDLP	Cause Discolouration Lower Primary	CauseID
CDLS	Cause Discolouration Lower Secondary	CauseID
PA	Tree Parts Affected	PartAffID
LT	Location in Tree	LocaAffID
LA	Layer Affected	LayerAffID
TD	Type of Damage	TypeDamID
CP	Stem Cause Primary	GTSurveyResults_CP
CS	Stem Cause Secondary	GTSurveyResults_CS
Epicormic	Epicormic Entire tree	YesNo
EpicormicB	Epicormic Below	YesNo