Forest health surveillance in New South Wales, Australia

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Summary

It has been over a decade since Forests NSW established a forest health survey unit (FHSU), with the first formal surveys beginning in January 1996. The unit was established due to a growing need for more formal detection, delineation and recording of pest and disease outbreaks, both endemic and exotic, and to ensure continuation of forest health expertise within Forests NSW. Forest health surveys are concentrated on eucalypt and *Pinus* plantations. For pine plantations (predominantly *Pinus radiata*), aerial and follow-up ground surveys are conducted of most of the plantation estate annually. For eucalypts (*Eucalyptus* spp. and *Corymbia* spp.) ground surveys have been the predominant methodology, due to the dispersed nature of the estate, with aerial surveys becoming a regular feature only in the past few years because of the importance of a new insect pest (a psyllid, *Creiis lituratus*). The FHSU provides advice on management of detected health problems, and data collected during surveys are used for national reporting requirements. There have been limited surveys of native forest, and no post-border[1] surveys for early detection of exotic incursions. Most private growers in NSW have been reluctant to conduct forest health surveys using trained experts. Aerial surveys have predominantly used typical sketchmapping procedures on hardcopy maps, but are now conducted using a digital aerial sketchmapping (DASM) system with a pen-based PC tablet. Efficiencies and accuracies gained with the DASM system have interested native forest managers and private eucalypt growers in cost-acceptable forest health surveys. The benefits of forest health surveys include early detection of pest and disease outbreaks, advice on operational management of health problems, identifying research priorities, providing data for annual reporting requirements, and detecting new and emerging pests and diseases.

Keywords: forest health; surveillance; methodology; plantations; native forests; cost analysis; returns; *Pinus radiata*; *Eucalyptus*; *Corymbia*; New South Wales

[1] Post-border surveys for early detection of exotic pests and diseases involve inspections of trees surrounding sea and air ports and in peri-urban environments to increase the chance of early detection of an exotic pest or disease incursion.

Introduction

Formal forest health surveys have been conducted annually in the United States since the 1940s, beginning with aerial surveys with fixed-wing aircraft (Ciesla 2000; McConnell *et al.* 2000; Johnson and Wittwer 2008). In Canada, annual aerial surveys for certain pests, such as mountain pine beetle, began in the 1950s (Simpson and Coy 1999; Taylor and Carroll 2003). In New Zealand, formal forest health surveys of exotic *Pinus* plantations were initiated in 1956 due to concerns over damaging outbreaks of *Sirex noctilio* and *Pseudocoremia suavis* (Kershaw 1989). Surveys initially concentrated on monitoring insect populations, but by the late 1960s the emphasis was on forest health problems in general, and by 1982 aerial surveys were a routine part of forest health surveys in New Zealand (Kershaw 1989; Bulman 2008).

Early forest health surveillance in Australia was also initiated for damage from a specific agent. Primarily this was for dieback caused by *Phytophthora cinnamomi,* for example in *Eucalyptus marginata* forests in Western Australia (Bradshaw 1974; Spencer 1984; Podger and Keane 2000; Robinson 2008). Surveys consisted of aerial photographic interpretation with some ground verification (Bradshaw 1974; Podger and Keane 2000; Robinson 2008). In contrast, the first formal forest health surveillance programs in plantations in Australia began in 1996, using both aerial and ground surveys for exotic *Pinus* plantations and ground surveys for eucalypt plantations (Carnegie 2007b; Lawson *et al.* 2008). These surveillance programs were initiated in part because damage from pests and diseases can significantly reduce return on the large investments in establishment and management associated with plantations. Several important pests and diseases already cause significant damage in *Pinus* plantations (e.g. *S. noctilio* and *Dothistroma septosporum*) and eucalypt plantations (e.g. chrysomelid leaf beetles and Christmas beetles) in NSW (Edwards and Walker 1978; Eldridge and Simpson 1987; Carnegie 2002; Carnegie *et al.* 2005a,b). There is also a recognised risk from the ingress of new forest pests and diseases into Australia, such as Asian gypsy moth (*Lymantria dispar*), pine pitch canker (*Fusarium circinatum*) and eucalyptus rust (*Puccinia psidii*) (Mireku and Roach 2000).

The historical mobility and turnover of field foresters within Forests NSW had resulted in loss of continuity in forest health expertise and management at the regional level[2] and there was, therefore, a need for consistent forest health expertise across the entire state. There was also no formal procedure in place to detect, delineate, monitor or record pests or disease outbreaks, either exotic or endemic. Furthermore, as the role of the planted forest sector continues to expand within a sustainable forest industry, the necessity to manage the health of these increasingly valuable resources grows. To this end the Forest Health Survey Unit (FHSU) was established in late 1995.

This paper details the operational procedures for forest health surveillance in softwood and hardwood plantations in NSW and describes the limited surveys that have been conducted in native forests.

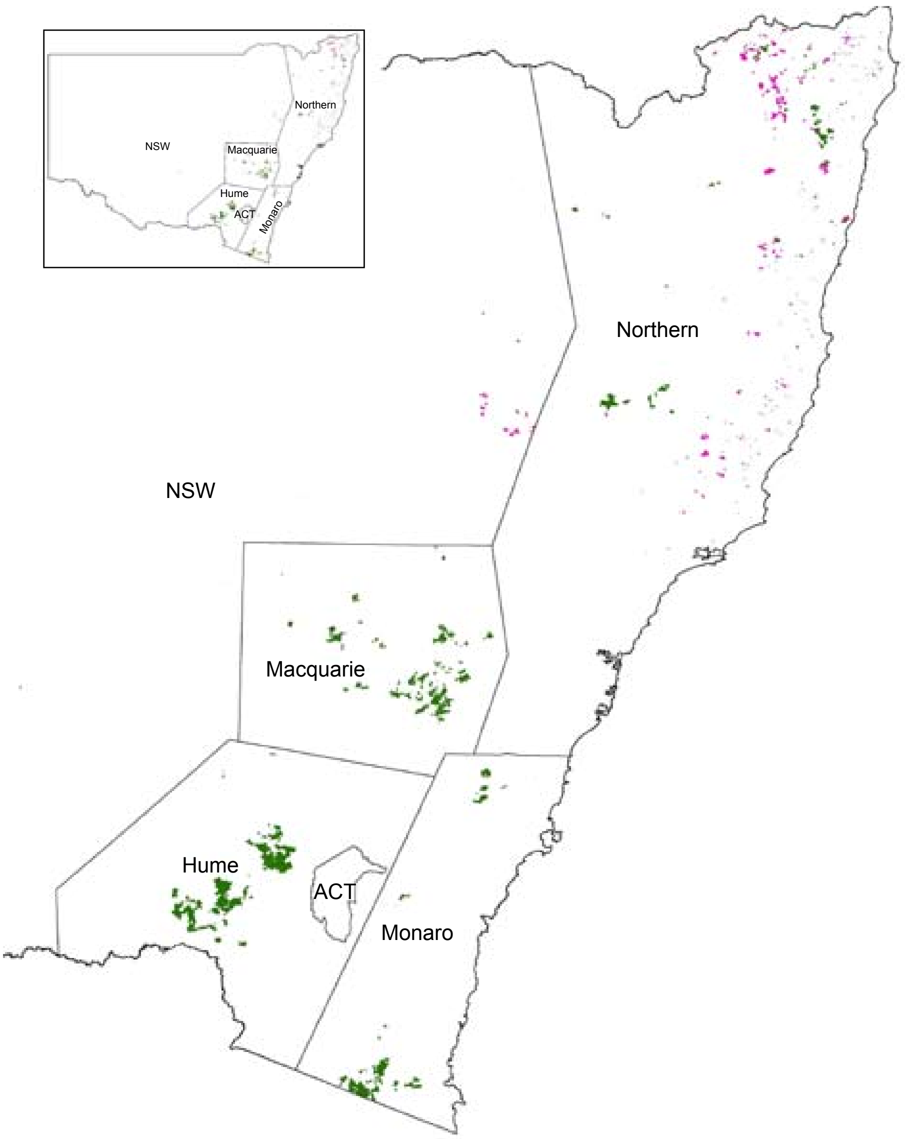

Figure 1. Map of NSW showing the four plantation regions, and softwood (green) and young hardwood (purple) plantations managed by Forests NSW

The Forests NSW's estate[3]

Forests NSW's plantation estate is divided into two forest types: softwoods and hardwoods. There are four softwood regions — Hume, Macquarie, Monaro and Northern — with hardwood plantations situated within Northern Region (Fig. 1). There are 196 821 ha of pine plantations (Forests NSW 2007a): the principal species is *Pinus radiata* (184 852 ha), with smaller plantings of *P. elliottii*, *P. taeda*, *P. elliottii* × *P. caribaea* hybrids, *Araucaria cunninghamii, A. bidwillii, P. ponderosa* and *Pseudotsuga menziesii.* Most softwood plantations are in large contiguous areas (Fig. 1). Additionally there are ~26 800 ha of young (planted since 1994) hardwood plantations (Forests NSW 2007a): the dominant species are *Eucalyptus dunnii*, *E. pilularis*, *Corymbia citriodora* subsp. *variegata* and *C. maculata*. Hardwood plantations range in size from 20 ha to 1000 ha, have multiple species per plantation and by 2006 there were over 350 separate plantations (Fig. 1). Over 20 000 ha of plantations are managed by Native Forests Operations Branch (Forests NSW 2006; R. Kirwood, Forests NSW, 2007, *pers. comm.*) where the main species include *E. grandis*, *E. pilularis*, *E. agglomerata* and *E. laevopinea.* Most of these were established in the 1960s and 1970s, and some areas are now being re-planted (second rotation). Forests NSW also manages about 2 million ha of native forest (Forests NSW 2007a).

Forest health surveillance pre-1996

There was no formal forest health surveillance program in NSW prior to 1996. Detection of new occurrences of pests and diseases, or outbreaks of known pests and diseases, was generally by chance by regional field staff during routine forest operations. Surveys by forest health experts were ad hoc, or on request by a region once a problem had been detected. There were, however, several pest-specific surveys pre-1996. Soon after *D. septosporum* had been detected in *P. radiata* plantations in NSW in 1975, aerial and ground surveys were conducted to map the extent and severity of the disease (Edwards and Walker 1978). In the 1980s, survey effort was aimed at the early detection of occurrences of established pests and diseases in new locations, such as ground and aerial surveys for *S. noctilio* (Carnegie *et al.* 2005a) and field inspections and pheromone baiting for *Ips grandicollis* (Eldridge and Simpson 1987). For many years management of established

[2] Forests NSW's planted forest estate is divided into four regions based on the distribution of plantations (see Fig. 1).

[3] Does not include plantations managed by private growers

pests and diseases, including monitoring and control procedures, was the responsibility of regional staff, who did not necessarily have all the relevant expertise.

Forest health surveillance 1996–2006

Due to the major differences in size and distribution of eucalypt and pine plantations and the pests and diseases that attack them, survey methods have been developed to suit each forest type. The methods for softwoods were mainly modelled on the New Zealand system, which are centred on aerial detection and mapping with supplementary ground surveys (Kershaw 1989; Ministry of Forestry 1992). Unlike New Zealand, however, port-environ (early detection) surveys are not conducted: the main objective of surveys in New Zealand is early detection of exotic incursions (Baddeley 1989; Ministry of Forestry 1992; Bulman *et al.* 1999), which is not the primary aim in NSW. Surveillance methods for the hardwood plantations, both young and old, were developed by the FHSU in consultation with plantation managers. The system for pine plantations and the young hardwood estate has been further developed and modified over the past decade. There are no routine surveys in native forests.

Objectives

The objectives of forest health surveillance in NSW are to:

- Provide accurate, timely and cost-effective forest health surveillance of planted forest resources for Forests NSW.
- Identify and record the extent and severity of outbreaks of both recognised and previously unrecorded pests and diseases in a timely manner with the aim of containing existing and new pest species (both endemic and exotic species) and managing the risk of unacceptable losses of plantation resources.
- Identify and record the extent and severity of vertebrate pest damage, weeds, nutritional imbalances and climatic disorders.
- Provide annual detailed reports on the health status of Forests NSW hardwood and softwood plantations to fulfil reporting requirements (including forest certification).
- Provide recommendations and technical advice on control and management operations to reduce the impact of insect pests, fungal diseases, vertebrate pests, weeds, nutritional imbalances and climatic disorders, and evaluate the effectiveness of control and management operations.
- Involve and train operational staff in active forest health surveillance and in pest and disease management.
- Collect data on forest health issues on a systematic and routine basis to facilitate planning, strategic development and research on forest health problems and aid in demonstrating sustainable forest management.
- Reinforce the communication channel that facilitates the flow of information in both directions between the Planted Forest Operations branch (Forests NSW) and Forests Resources Research (NSW DPI).

Personnel

The FHSU was established in late 1995, initially consisting of two professional officers, and has since varied from two to four officers. Forest health survey officers are trained and experienced forest health experts and have access to an extensive insect collection (FCNI) and fungal herbarium (NSWF) to assist in diagnosis. The FHSU also has some support from operational field staff in the regions who have been trained by the FHSU in pest and disease detection and surveillance.

Frequency and timing of surveys

Surveys of softwood plantations are conducted from May to September each year to coincide with the maximum expression of symptoms of the major pests and diseases in NSW (historically *S. noctilio* and *D. septosporum*), but also to allow regions to plan and budget for remedial or control operations that may occur from spring onwards. Between 9 and 12 days are spent in each region each year (including 2–3 days aerial survey). Surveys of hardwood plantations are conducted generally from January to April each year, again to coincide with the major activity or damage from the main insect pests and fungal diseases known in NSW. Three to four trips, of 12 days duration, are undertaken each year. In recent years (2003 onwards) surveys of hardwood plantations have extended into May and June due to the emergence of a new insect pest (*Creiis lituratus*) that is active during autumn–winter (Carnegie and Angel 2005). In total, each survey officer can be in the field for 60–80 days per year conducting surveys.

Liaison with operational staff

As the areas under surveillance by the FHSU are large and spread across the state, it is imperative that survey officers are assisted by regional staff who have good local knowledge. To this end, the role of Forest Health Liaison Officer was created and allocated to field staff in each softwood region, with field officers filling this role in the hardwood plantations. These officers are basically the ‘eyes and ears’ on the ground and assist the survey officers to plan and conduct the forest health surveys. The FHSU provides pest and disease training for these officers, as well as in-field training during surveys, and has produced field guides to aid in pest and disease identification (e.g. Carnegie 2002). Each region also has a designated ‘Forest Health’ forester, who is the initial contact with the FHSU and with whom results of surveys and recommendations on management options are discussed.

Survey planning

When the FHSU was initiated, maps used for surveys in softwood plantations were black-and-white photocopies of dye-line maps. Now, however, detailed geographic information system (GIS) maps of all forested areas to be surveyed are produced by the FHSU. Shapefiles (digitised boundaries) of these forests are now also down-loaded onto laptop computers or iPAQ© (Hewlett-Packard Development Company, L.P.) palmtops. These are connected to global positioning system (GPS) units via cable, or now Bluetooth, for navigation during aerial and ground surveys. The automated real-time mapping software Map*master*© (Cipher Systems, Australia) was initially trialled in the early days (from 1997), but now ArcPad© (ESRI, USA) is used for the GIS–GPS interface. These programs increase navigation accuracy and therefore increase the accuracy with which disorders are mapped.

Surveys in softwood plantations

Aerial surveys

An aerial survey is an ideal technique to provide a broad overview of forest health, allowing large areas, often difficult to access on the ground, to be viewed by the surveyor. The objective of the aerial survey is to detect any symptoms of ill health and plot their location accurately on the map using typical sketchmapping techniques (see McConnell *et al.* 2000). These locations may later be checked on the ground and hence accuracy of plotting is important. Skill and experience is needed to be able to relate ground position to map position ('tracking' or 'flight path navigation') and simultaneously record the position of trees displaying symptoms of ill health. GIS–GPS interface programs, such as described above (ArcPad®) greatly assist in this process.

The FHSU uses the Forests NSW Squirrel helicopter for aerial surveys. Aerial surveys are ideally carried out by a team of two survey officers: one in the front acting as navigator as well as sketchmapping, the other in the rear and on the opposite side of the helicopter. Aerial surveys are generally carried out at 100–300 m a.g.l. at a speed of 60–80 knots. Flight lines generally follow geographic features (ridge tops, gullies) or the shape of the plantation and are commonly 1 km apart. On average it takes about 12 h to conduct an aerial survey of each of the four softwood regions, including ferrying time.

Generally, all softwood plantations in a region are aerially surveyed each year. Forest health symptoms observed from the air are hand-sketched onto hardcopy maps with the size, shape and location of the affected area recorded as accurately as possible. Standardised symbols for each disorder have been developed which are used when annotating maps (Appendix I). In many cases the causal agent of the symptom can be identified from the air with an experienced eye (Fig. 2). If required, the GIS–GPS interface can be used to produce a shape file of the boundary of a disorder (e.g. large patch of dead trees): the pilot flies as close as possible along the boundary while the GPS records the position.

At the completion of the aerial survey the survey officers will review the survey results, and disorders will be stratified for possible ground surveys. A selection of disorders will be identified for ground survey, based on the number of disorder types and or causal agents, any history of previous problems (e.g. an increase in *S. noctilio* the previous year) and also on regional priorities. Not all disorders observed from the air are ground-truthed, but experienced survey officers can identify the amount of ground-truthing required. For example, some disorders such as boron deficiency and needle damage by *Essigella californica* or *D. septosporum* do not require ground verification, while tree mortality does require ground-truthing to determine the causal agent(s).

Ground surveys

This element of the survey has three objectives: (1) to diagnose disorders observed from the air, (2) to further quantify the extent, incidence and severity of disorders, and (3) to increase the chance of detection of new emerging pests or diseases (either exotic or endemic), pest outbreaks or cryptic disorders. The intensity of the ground survey is dependent mainly on results from the aerial survey, but also on road access within the forest. The survey officers drive to the locality of the disorder noted from aerial surveys and record specific information from a walked transect. Survey officers also observe the forest for disorders while driving (i.e. drive-through surveys). The size and shape of the transect vary according to the conditions or the disorder, but there are generally two 100–200-tree transects. Trees within the transect are examined for any signs of ill health, irrespective of the cause (i.e. insect, fungal, environmental, browsing animals, etc.). Each survey officer conducts ground surveys in a separate vehicle (4WD) so as to cover more forest per trip.

Initially ground transects were also conducted at 'random' locations where no disorders had been observed from the air. This was to ensure that non-cryptic symptoms were not being missed during aerial surveys. After several years we became confident that we were detecting the major problems during aerial surveys, and so now these random surveys are rarely carried out.

Data on the incidence (number of trees affected) and severity (damage on affected trees) of damage is collected. A table of codes and severity classes has been developed to assist in standardising notation and assessment of damage severity during ground surveys. Samples of organisms suspected of causing damage to trees are collected, and photographs and notes are taken to support the samples and for inclusion in written reports. All data are entered in an Access database and the majority spatially captured in ArcView©/ArcGIS© (ESRI, USA).

Reporting

At the completion of the survey and prior to leaving the region the survey officers meet with regional staff to discuss the results of the survey. Reports, generally supplied to the region within three months, contain both textural and spatial data collected during surveys, as well as recommendations on management of disorders. GIS maps are provided showing the extent and incidence or severity of the main disorders observed, and shapefiles of these maps and or data are also sent to the region when requested.

In 2006 we started using a new reporting procedure to assist forest managers in prioritising management of forest health disorders. A risk rating matrix allocated a risk rating to each disorder, based on the likelihood of its occurrence and its impact (Table 1). From

Table 1. Risk rating matrix used to allocate priority classes for forest health disorders based on the likelihood of an occurrence of a damage event and the impact on trees by such an event

Likelihood of occurrence	Impact			
	Tree death	Significant growth loss	Minor growth loss	Limited impact
Very likely	1	1	2	3
Likely	1	2	3	4
Possible	2	3	4	5
Unlikely	3	4	5	6

Figure 2. Examples of typical forest health disorders in plantations observed during aerial surveys: (a) dead *Pinus radiata* trees associated with drought and *Ips grandicollis* attack (causal agents confirmed during ground survey); (b) needle blight caused by *Dothistroma septosporum* in lower to mid-crowns of *P. radiata*; (c) chlorosis of *P. radiata* associated with *Essigella californica*; (d) boron deficiency (associated with poor drainage) in *P. radiata*; (e) purple-brown discolouration of *Eucalyptus dunnii* foliage associated with early outbreak of *Creiis lituratus* psyllid; (f) severe damage to *E. dunnii* following outbreak of *C. lituratus*

these we developed forest health disorder management tables (Table 2) that illustrated the risk rating of disorders, the timing and type of surveys necessary to detect damage, the threshold by which management intervention is required, and any management options available. Future reports will be streamlined, with maps and GIS shapefiles and a table with disorders given a priority class for action. This table (as an Excel spreadsheet) can then be used by regions to more formally identify and monitor: (1) who will manage the operations; (2) the budget; (3) the timing of the operation; (4) whether the operation was conducted, and if not, why not; and (5) the effectiveness of the operation, which can be assessed by the FHSU the following year(s). This system allows for more transparency during auditing (either internal or external) for certification (e.g. under the Australian Forestry Standard and the ISO 14001 Environmental Management System).

Surveys in young hardwood plantations (planted post-1994)

Aerial surveys

Initially, aerial surveys were not routinely conducted in the hardwood plantations due to the small size and disparate nature of the estate. However, specific aerial surveys were conducted between 2000 and 2005 for *C. lituratus* psyllid damage. Since 2006 a selection of plantations has been surveyed aerially for all types of damage, covering about half the young hardwood estate. Aerial sketchmapping is conducted in a manner similar to that used in pine plantations.

Ground surveys

As aerial surveys were not routine, ground surveys needed to be more intensive to increase the chances of detecting damage. Surveys were conducted along plantation roads by 4WD vehicle and within the plantation by walking transects. Generally all host species were surveyed (up to four per plantation) as well as all landscape positions (e.g. flats, gullies, ridge tops) in each plantation. Where possible, vantage points (ridges and hilltops) were used to gain a greater view of the plantation. In most cases, each plantation was visited only once per year. From 1996 to 1998 75–95% of plantations were surveyed annually; but after this period, due to the increasing size of the estate, 25–75% were surveyed. Plantations for surveillance each year were selected so as to include the main hosts and a range of age classes in each geographic area, as well as plantations with damage that were identified by field officers following routine operational visits.

Data were collected on the extent, incidence and severity of all disorders observed within the plantation. Data were collected separately for each disorder where the causal agent was known, or as a disorder class (e.g. stem canker, leaf spot fungus, herbivorous insect). Samples of insects or fungi were collected during most visits to a plantation and photographs taken where necessary.

The Crown Damage Index (CDI) is a new damage assessment method recently developed to standardise crown damage in young eucalypt plantations (Stone *et al.* 2003). This procedure enables the extent of crown damage in young eucalypt plantations to be quantified in an objective, rigorous and consistent manner. It requires up to eight 6-tree plots to be assessed within a plantation. This procedure was regularly used for forest health surveys from 2003 to 2005, but due to the greater time required for this survey method surveys have now reverted to the original methods.

In 2004 an Indicator Plantation Program was established whereby plantations were selected to be surveyed by field officers on a regular basis. Selection was based on a particular plantation being indicative of most plantations in a field officer's area. Each field officer, trained by the FHSU, surveyed a plantation every one to two months using the CDI methodology and sent data to the FHSU. The main idea of the Indicator Plantation Program was that data could be collected on pest and disease activity and damage on a regular basis throughout the year, not just at a single occurrence or event (as occurs with the FHSU surveys). However, due to competing priorities of field officers the Indicator Plantation Program ran only for one year. Furthermore, the program had not been running long enough to fully quantify any benefits to support this as a procedure in future.

Reporting

On completion of the survey the survey officers discussed observations with relevant regional staff. A separate report was

Table 2. Example of forest health disorder management table, for *Pinus radiata* in Northern Region, illustrating risk rating of disorders (see risk rating matrix, Table 1), timing and type of surveys necessary to detect damage, the threshold by which management intervention is required and management options available

Disorder	Risk rating	Surveillance		Threshold	Management
		Timing	Method		
Sirex noctilio	1	Winter	Aerial and ground	>0.1% tree mortality	Biological control — trap tree program
Dothistroma septosporum	1	Winter	Aerial	>30% crown severity	Aerial application of copper oxy-chloride
Diplodia pinea (associated with drought)	1–2	Winter	Aerial and ground	>1% tree mortality	Consider thinning compartment
Armillaria nova-zealandiae	1	Winter	Aerial and ground	>1% tree mortality	Plant non-susceptible tree species
Essigella californica	1–2	Winter	Aerial	>10% severity in >25% trees	Currently none (biological control program initiated)

written for each plantation surveyed, providing data on the major health problems observed and recommendations on remedial or control action where appropriate. Maps of affected areas, and those requiring control, were produced using ArcGIS© where appropriate. In 2006, a new reporting format was developed which included a priority class, allocated using the risk rating matrix, for observations and or recommendations of each plantation surveyed, as indicated above for softwoods.

Surveys in mature eucalypt plantations (generally > 20 y old)

Annual forest health surveys were conducted in a selection of the older eucalypt plantations, which are mostly located within native state forests, from 1996 to 1998. Surveys of these plantations in each region were stratified depending on geography (e.g. coastal plantations, high elevation plantations), species, age class and proportion of overall plantation estate (i.e. sampling in proportion to area planted). Plots were selected within these compartments by walking about 30 m into the plantation and selecting the 10 nearest trees. These 10 trees were then assessed, often with the aid of binoculars, for the severity of damage from pests and diseases in the crown and bole. Observations, mainly relating to stem damage, were reported.

Surveys in native forests

In NSW there have been few systematic surveys of forest health in native forests. The FHSU has conducted several surveys for specific forest health issues in the past decade. In 1999 and again in 2001, aerial surveys were conducted over about 60 000 ha of native forest in the Southern Highlands to map defoliation by phasmatid stick insects (*Didymuria violescens*). These were as a result of a request from the native forest manager in the region after significant defoliation was observed by ground crews. The area of damage mapped in 1999 was 8500 ha, and in 2001 a similar amount was evident. In 2004 the FHSU conducted an aerial survey of over 300 000 ha of native forest (including privately and publicly owned, and production and conservation-managed forests) in north-eastern NSW to map bell-miner associated dieback (BMAD) (see http://www.bmad.com.au). This was as a result of a request from the BMAD Working Group (http://naturalresources.nsw.gov.au/nr/joint_programs.shtml). About 20 000 ha of dieback were mapped.

Jurskis (2004) estimated that 120 000 ha of native forests were in decline in coastal NSW. This was based on extrapolation from limited observation (compared to total forest cover) of dieback and its association with stand age and geology. Similarly, Jaggers (2004) estimated 100 000 ha were in decline in south-eastern NSW, using data from limited ground and aerial surveys to predict decline risk based on forest type and forest structure (stand age), then extrapolating this over about 525 000 ha. Both authors discuss the limitations of this methodology, including the small number of observations (only 0.5% of state forest ground-surveyed), the bias of road-side surveys, and the poor predictability of some decline risk categories, which predicted areas of decline that were not declining and visa versa (Jaggers 2004; Jurskis 2004). This methodology does, however, have some merit, if at the very least to begin to identify potential factors associated with forest dieback or decline. Inclusion of more ancillary spatial data (e.g. soil type, plot-based canopy condition indices, and topographic and climatic indices), as well as many more observations, in the spatial analysis would greatly improve the accuracy of prediction of dieback in native forests (Stone and Haywood 2006).

The cost of surveys

In the United States, aerial surveys can cost as little as US\$0.003 ha^{-1} due to the large areas covered with fixed-wing aircraft (Ciesla 2000), with the cost in 2004 to cover over 180 million ha being US\$0.025 ha^{-1} (USDA-FS 2004). These surveys are designed mainly to detect landscape-scale outbreaks that can be mapped at a relatively small scale. Aerial weed mapping in the United States using helicopters, in contrast, can cost US\$0.50–\$1.70 ha^{-1} (Schrader-Patton 2005). In New Zealand, aerial surveys of pine plantations using fixed-wing aircraft cost NZ\$0.02–0.08 ha^{-1} (Carter 1989). A comparative cost to conduct just the aerial survey component over 90 000 ha of *P. radiata* plantation in NSW, including helicopter hire and the two surveyors' costs, is about \$0.15–\$0.30 ha^{-1}. Compared to the United States, the New Zealand and NSW aerial surveys are designed to detect problems at a much higher resolution (compartment scale) using larger-scale mapping. However, none of these costs include the cost of map production pre- and post-flight, or the cost of having a competent survey officer 'on call' to conduct the surveys (i.e. employing them full time). The aerial survey (in a helicopter) to map bell-miner associated dieback in native forests in northern NSW, described above, cost about \$0.05–0.10 ha^{-1}.

The cost of forest health surveillance in pine and eucalypt plantations in NSW has varied over the past decade, due mainly to the varying number of survey officers in the FHSU. In 1996 the cost was around \$0.77 ha^{-1}, which included the cost of employing two full-time forest health survey officers, plantation surveillance (aerial and ground), diagnostics, technical and GIS support, and year-round pest and disease management advice. In 2005, with three survey officers, this cost was about \$1.54 ha^{-1} and in 2006, with two officers, \$1.15 ha^{-1}. These costs are comparable to those of plantation surveillance in Queensland (Speight and Wylie 2001). A similar cost for forest health surveillance was also reported for New Zealand in the late 1980s (about NZ\$1.00 ha^{-1}, Baddeley 1989). Following 'privatisation' of forest health surveillance in New Zealand, however, costs for surveys now are around NZ\$0.50–0.80 ha^{-1}, which includes aerial and ground surveys, diagnostics, database and administration, although not technical advice or 'call outs' for specific problems outside the designated survey periods (P. Bradbury, SPS Biosecurity, New Zealand, 2008, *pers. comm.*).

Speight and Wylie (2001) calculated the cost of forest health surveys of pine plantations in Queensland, including aerial and ground surveys, diagnostics and written reports, at \$1.14 ha^{-1}. In contrast, the cost of hardwood plantation surveys was almost ten-fold (about \$10 ha^{-1}), due to the small and disparate estate requiring more detailed ground surveys and the larger number of pests and diseases requiring processing (diagnosis) in this forest type. A similar trend was observed during the early years of surveys in NSW. However, with an increasing and more consolidated estate enabling aerial surveys, and subsequently more targeted ground surveys, and a greater understanding of the main pests and diseases present (thus requiring less diagnosis), the overall cost per unit area of hardwood surveys has decreased.

What are the benefits of forest health surveillance?

Wardlaw (2008) discussed the benefits and outcomes of a decade of forest health surveillance in Tasmania. Similarly, we can outline the benefits in NSW along the same themes of strategic, tactical and operational management. Under strategic management, research priorities have been developed to address new and emerging health issues identified during forest health surveys. These include research on the biology and impact of the psyllid *C. lituratus* in *E. dunnii* plantations, including management options (Carnegie and Angel 2005; Carnegie *et al.* 2005b); management of shoot blight in spotted gum plantations caused by *Quambalaria pitereka* (Carnegie 2007b; Pegg *et al.* 2008), including tree improvement; and research trialling insect pheromones and plant compounds to protect *S. noctilio* trap trees from attack by *I. grandicollis* (so as to maintain the effectiveness of the *S. noctilio* biological control program) (Carnegie 2008).

Accumulation of information from surveys enables trends to be identified as well as risk factors that may determine the location and timing of pest outbreaks (Wardlaw 2008). The annual forest health surveillance program has helped to identify risk factors associated with the susceptibility of *E. dunnii* to *C. lituratus*, whereby the planting of *E. dunnii* has been postponed by Forests NSW. Another major strategic benefit of surveys is the data on damaging agents required under annual reporting requirements, such as for social, environmental and economic performance (Forests NSW 2007b), and for certification for sustainable forest management (Carnegie *et al.* 2005b; Australian Forestry Standard Limited 2007; Forests NSW 2008).

Still on strategic management, but at a national level, forest health surveys have detected an exotic pest and discovered new endemic fungi. In 1997, the FHSU detected the Douglas-fir adelgid, *Adelges cooleyi,* an insect native to North America, in a trial planting of Douglas-fir (*Pseudotsuga menziesii*) in Macquarie Region. *Adelges cooleyi* is a biosecurity threat to New Zealand's large Douglas-fir plantations (J. Bain, Scion, New Zealand, 2006, *pers. comm.*). This pest had not previously been reported from mainland Australia (CSIRO 2004), and as we were unable to confirm its reported presence in Tasmania by a validated specimen (Plant Health Australia 2007; D. Bashford, Forestry Tasmania, 2008, *pers. comm.*), we believe that our detection was in fact the first for Australia. However, further surveys determined that *A. cooleyi* was widespread in Douglas-fir plantations in Hume and Monaro Regions, indicating that it had been established in NSW for some time. Over the past decade more than 13 new species of eucalypt foliar fungi have been described, and new records of known fungi discovered, from collections in plantations and native forests during surveys, adding to our knowledge of the suite of endemic fungi in Australia and assisting in identifying potential emerging threats (e.g. Andjic *et al.* 2007; Carnegie 2007a; Carnegie *et al.* 2007).

Tactical management (the deployment and implementation of particular management prescriptions — Wardlaw 2008) has been assisted by information from forest health surveys. For example, data collected during surveys, and collaborative research by members of the FHSU, have lead to the registration of new insecticides that are now being used to control *C. lituratus* psyllids in *E. dunnii* plantations in northern NSW.

One of the main objectives of forest health surveillance in NSW is to assist with operational management of plantations. Surveys over the past decade have detected problems early enough for management prescriptions to be applied to reduce adverse economic impacts. For example, surveys in 2006 and 2007 identified an increase in levels of *S. noctilio* damage early enough for inoculation with the biological control nematode to be conducted as an emergency measure. Aerial surveys were used from 2003 to 2006 to identify areas where *C. lituratus* was active in *E. dunnii* plantations, followed up by ground monitoring of insect populations levels and life stages to optimise control spraying (Carnegie and Angel 2005). Other management prescriptions recommended by the FHSU following annual surveys, and implemented by operational divisions, include spraying copper oxy-chloride for *D. septosporum*; treatment of boron deficiency in young trees with boron fertiliser; locating extra trap tree plots in areas of increasing *S. noctilio* damage; and salvage logging hail-damaged stands to reduce further degrade from *Diplodia pinea*-associated blue-stain and top death.

Future technology for forest health surveillance

The United States Department of Agriculture Forest Service (USDA-FS) and other forest agencies in the United States now conduct aerial forest health surveys using the Digital Aerial SketchMapping (DASM) system (Morris 2001; Schrader-Patton 2003; Johnson and Wittwer 2008). This system utilises a PC tablet linked to a GPS (via cable or Bluetooth), with shapefiles, digital topographic images, satellite-based imagery or ortho-photos as background maps. The system enables the aerial observer to collect digital data (points, lines or polygons) directly onto the tablet screen with a pen and quickly enter attribute data (e.g. host, causal agent, incidence and or severity rating) using a 'one touch' keypad. An icon displays the locality of the aircraft on the screen 'live', so the observer can spend more time identifying and mapping damaged area than attempting to track their position on a map. The DASM software, GeoLink©(Michael Baker Jr Inc., USA), also has a feature that allows for automated background map rotation following screen regeneration, whereby the background map rotates so that the direction the aircraft is heading is orientated to the top of the tablet screen. The sketched features are later translated into ESRI shapefiles for download into a GIS, thus reducing the lengthy process of post-processing the maps into a digital format, ensuring rapid turn-around of data.

In 2007 the FHSU purchased a PC tablet (IBM Lenovo ThinkPad X60) and the GeoLink® software, which has been used to conduct aerial and ground surveys in both pine and eucalypt plantations since mid-2007. The PC tablet has a daylight-readable, antiglare screen and some 'tough' features, such as shock protection for the computer's hard drive and some water resistance of the keyboard. GIS maps of plantations are converted into geo-referenced TIFF files for use in GeoLink®. Other background maps are also loaded for areas outside plantation boundaries (if required), such as 1 : 25 000 topographic maps, digital mapping aerial photography (DMAP) images or geo-referenced project ('touring') maps. GeoLink® has a SplitTiff utility that reduces screen regeneration time when large, or multiple, images are used by dividing large map files into tiles and then loading only those tiles neighbouring the current GPS position (Schrader-Patton 2003).

A project is built for each flight mission, which includes the relevant background maps, the virtual keypad and quick buttons for data entry, and logging features on the toolbar (Fig. 3). During a mission, the position of the helicopter (or vehicle if on the ground) is displayed by an icon (Fig. 3a) as are flight lines (Fig. 3b). Background maps can be turned on or off by a toolbar button (Fig. 3c), which can extend battery life on long missions. The toolbar also has buttons to zoom in and out, and pan the screen (Fig. 3d). Quick buttons are used to select a feature so as to collect data, and include Area, Multi-Point and Lines (Fig. 3e). Area is the same as a polygon in a GIS; with multi-point the surveyor can either put a single point on the map or many points; lines can either be drawn for attribute data collection, or used to write notes on the map/screen (Fig. 3f). The virtual keypad enables the entry of attribute data at a single touch of the pen following the drawing of a feature (area, line or multi-point), and we have included disorder codes (Fig. 3g), incidence categories (Fig. 3h) and severity classes (Fig. 3i). For example, the Area feature is used to locate a stand with *D. septosporum*, which is then attributed with 'Dothi_' and a severity class (Fig. 3j), or the MPoint feature is used, with 'D-tr_', to locate a single dead tree (Fig. 3k).

At the completion of a mission the collected data are translated into ESRI-compatible shapefiles for integration into ArcGIS©. Once in ArcGIS©, the shapefiles and attributes require some post-processing for editing and data quality control, and several extensions have been developed to assist with this process (Schrader-Patton 2003). We are currently developing systems to streamline this process within our GIS environment, which at present uses 'heads up' digitising. Traditionally we have used 'heads-down' digitising, where the GIS operator digitises shapefiles from hardcopy maps (i.e. the operator continually looks 'down' to the hardcopy map). The DASM system collects data digitally, therefore digitising becomes 'heads-up' as the operator now digitises or re-draws while always looking 'up' at the data on the computer screen. These shapefiles can also be re-loaded onto the PC tablet–GeoLink® system, or PC tablet with ArcPad®, for use during ground surveys. This increases efficiency when locating disorders observed from the air, and attributes can also be edited, or new attributes captured, during the ground surveys. As such, our system could be called a Digital Aerial and Ground Sketchmapping (DAGS) system. This system has increased efficiencies and accuracy in data collection during surveys of plantations, and its possible use for fire mapping and mapping of forest health in native forests in NSW is currently being investigated.

The development of remote sensing technologies for application in forest health surveillance and interpretation is proceeding rapidly, with the capability for processing and analysis of imagery from airborne and satellite sensors constantly improving. The pressure to reduce costs associated with monitoring and reporting on plantation condition must eventually lead to a hierarchical system of spatial resolution to effectively stratify survey and assessment effort (Stone *et al*. 2008). Further, significant effort is now going toward combining assessments of forest health with inventory and growth information to improve management decision-making for the allocation of resources to forest health management (see www.crcforestry.com.au).

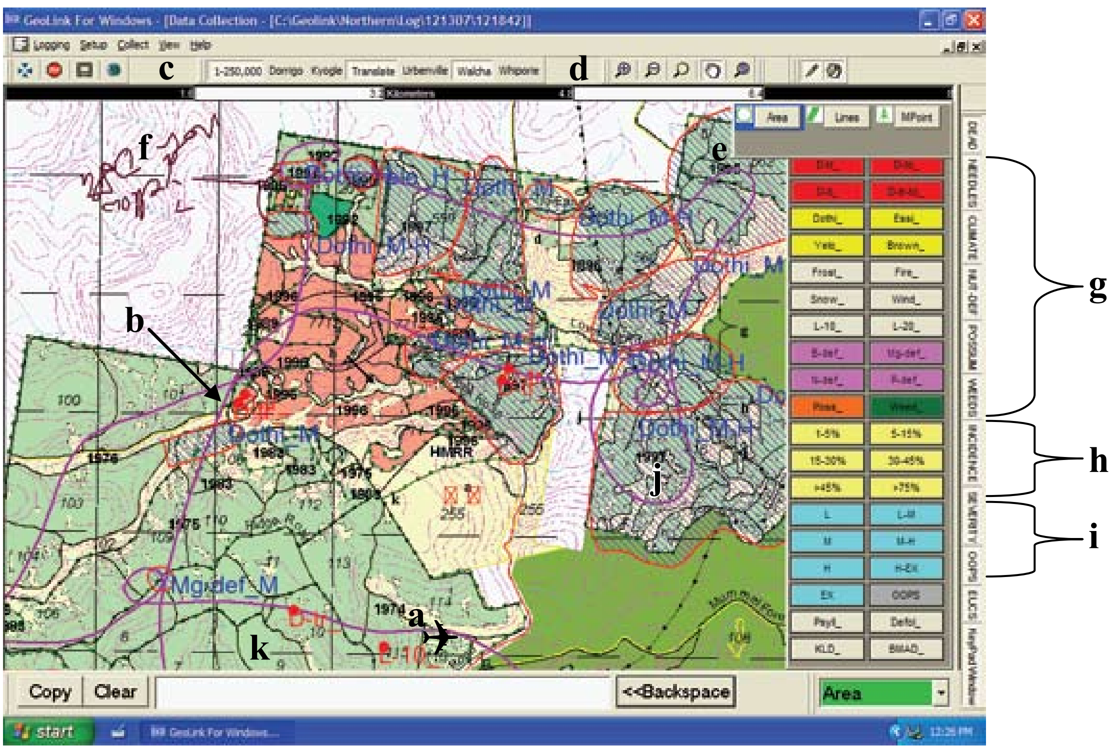

Figure 3. PC tablet–GeoLink® system screen used for digital aerial sketchmapping: (a) airplane icon for position location during flying; (b) flight lines drawn while flying; (c) various background maps can be toggled on or off during the mission; (d) zoom-in, zoom-out and pan buttons; (e) quick buttons for drawing features; (f) note written on screen using Line feature; (g–i) virtual keypad: (g) disorder codes, (h) incidence categories, (i) severity classes; (j–k) mapped damage: (j) area with *Dothistroma septosporum* (Dothi_M-H), (k) isolated dead tree (D-tr)

Discussion

Forest health surveillance is an integral part of sound forest management and an acceptable method by which forest managers may address several criteria under forest certification schemes, such as the Australian Forestry Standard and the Forest Stewardship Council (Carnegie *et al.* 2005b). Prior to 1996, forest health surveys in NSW were ad hoc or pest-specific (e.g. for *S. noctilio*, *D. septosporum*). Ad hoc forest health surveys by non-specialists are considered to be an ineffective survey method (Carter 1989). Furthermore, those who are solely in the forest to survey forest health and who have specific expertise and skill in recognising health problems will be better able to detect damage and damage agents than those in the forest for other reasons (Carter 1989; Bulman *et al.* 1999; Wardlaw 2008). It was recognised in NSW, by both forest health experts and forest managers, that there was potential for both the detection and management of major health issues to be delayed.

The main aim of forest health surveys in NSW is to map damage agents with the objective of reducing the risk of unacceptable losses through early detection of an outbreak and by providing recommendations on pest management. Detection of an exotic incursion is a small component (unlike in the New Zealand system — Baddeley 1989; Bulman *et al.* 1999), for two main reasons. Firstly, recent research has shown that the routine surveillance methods employed by state agencies in Australia are unlikely to detect an exotic incursion early enough for eradication (Wardlaw *et al.* 2008). Such early detection would require surveys of significantly greater intensity and cost. Secondly, the distance of the plantation estates from a probable entry point (ports of entry), which is generally greater than 100–200 km in NSW, suggests that any detection in a plantation would be of an insect or pathogen that is already well established (e.g. *A. cooleyi*). In NSW there is very limited urban and peri-urban surveillance for forest pests. This is a significant gap in our early detection and biosecurity program. Several other states (e.g. Queensland and Tasmania) have established post-border surveys for identified exotic forest pests, including hazard site surveillance and static trapping (Bashford 2008; Wylie *et al.* 2008).

In the United States, the forest health monitoring program provides 'accurate baseline and forest health trend information to determine detrimental changes or improvements in the forest over time' (Bennett and Tkacz 2008). A large proportion of the nation's approximately 304 million ha of forested lands is surveyed annually, either from the air or via the plot-based monitoring system (USDA-FS 2004, 2007; Bennett and Tkacz 2008; Johnson and Wittwer 2008). In contrast, a very small proportion of Australia's forested lands are surveyed, with most surveys concentrating in plantations, which represent 1% of Australia's forests and woodlands (National Forest Inventory 2007). In the United States, legislation requires that surveys and monitoring of forests be conducted (Burkman and Hertel 1992) and provides for significant Federal funding: over US$72 million in 2006 for the National Forest Inventory program, which includes forest health monitoring (USDA-FS 2007), with US$5 million just on aerial surveys in 2004 (USDA-FS 2004). No such legislation requires native forest owners in Australia to collect similar data, although there are 'agreements' to collect data for ecologically sustainable forest management, such as the Montreal Process (Commonwealth of Australia 1997). As such, most native forest owners in Australia, both public and private, and commercial and conservation management, have not put a high priority on forest health surveys.

The perceived high cost of surveys may also explain why native forest managers have not taken up forest health surveillance. Surveys in Australia are mainly focused on plantations. Due to the high establishment and management costs associated with plantations, many plantation managers understand the benefit of reducing their risk by employing a FHSU that can identify threats sufficiently early to significantly reduce impact. However, as there is rarely any active management of forest health disorders in native forests, the objectives of surveys are quite different to those in plantations. The main objective of forest health surveys in native forests in NSW is likely to be mapping of significant damage, to (1) quantify the area affected, (2) follow trends over time, and (3) collect data to gain an understanding of the process(es) causing the damage. This can be achieved mainly by aerial surveys. Because of the relatively low cost of conducting aerial surveys for BMAD in native forests reported here ($0.05–0.10 ha^{-1}), managers in Forests NSW are interested in conducting stratified aerial surveys over their commercial native forest estate.

Forest health surveillance in New Zealand has primarily focused on protection of exotic plantations, and plantation managers accept this cost (Baddeley 1989). The vast majority of plantation owners in New Zealand pay for forest health surveillance (Carter 1989; New Zealand Forest Owner's Association 2005). In contrast, in NSW only the state grower (Forests NSW) conducts forest health surveillance or has any forest health expertise. Private growers have been reluctant to conduct surveys, or employ forest health expertise, even though forest health surveillance is an acceptable method of meeting several criteria under forest certification (Carnegie *et al.* 2005b; Australian Forestry Standard Limited 2007). One of the main reasons for this reluctance is that the benefits have not been fully articulated to private growers, nor has the cost-benefit been quantified (Wardlaw 2008). Thus the onus is on forest health experts to provide appropriate information and analysis to ensure that most forest owners are paying for forest health protection rather than only the larger growers, with the remainder getting a free ride. Recently, however, private eucalypt plantation growers in NSW have shown interest in hiring forest health expertise to conduct aerial surveys.

Aerial surveys are an integral part of the forest health surveillance program in NSW. However, aerial sketchmapping is highly subjective due to the speed of the aircraft; variation in the knowledge, experience and skill of the sketchmapper (Ciesla 2000; McConnell *et al.* 2000; Johnson and Wittwer 2008); and variation in the signature of damage agents. This can lead to an element of error in both the location and size of a mapped area. Furthermore, there is an element of error in estimating the incidence and severity of damage agents during an aerial survey. The advent of digital aerial sketchmapping has reduced much of the error in mapping the location and size of a damage event. Only experience, however, can improve the accuracy of incidence and severity estimates. Even with this error, aerial surveys are still recognised as the most cost-effective technique for general forest health surveillance, and at present are sufficient for the current management objectives of forest health surveys in Australia.

Aerial photographs and subsequent photo-interpretation are used for mapping native forest dieback in Australia (Robinson 2008), and have been used on a small scale in pine plantations. This method of surveillance, however, is more expensive than aerial sketchmapping (Ciesla 2000) and so is not used for routine plantation surveillance. Aerial digital videography has been researched and used in the United States and other countries (Ciesla 2000), but has not been considered in Australia. Laser rangefinders, linked to palmtop computers with integrated GPS, are used to enhance aerial surveys of pine plantations in fixed-wing aircraft in Queensland (Ramsden *et al.* 2005). Advances in remote sensing technologies have great potential to improve the accuracy of the location and incidence of dead trees in plantations (Stone *et al.* 2008). However, these new technologies are unable to diagnose the causal agents of tree damage, or detect a wider range of tree disorders, and so there is still a real need for manned aerial surveillance. Both techniques, however, require some follow-up ground surveys by forest health experts.

In the decade since formal forest health surveys began in NSW, data collected by annual surveys and technical expertise within the FHSU have been of direct benefit to Forests NSW for strategic, tactical and operational management of pests and diseases in both pine and eucalypt plantations. The efficiency and accuracy of disorder mapping have improved through increased surveyor experience and the use of the DASM system, with further improvements on the horizon via remote sensing technologies. Close collaboration between the FHSU and Forests NSW managers and operational foresters, as well as private growers in recent years, has increased efficiencies in forest health reporting and pest and disease management at a state level. Further work is planned to quantify the impact of certain pests and diseases and the cost-benefit of pest management, and ultimately forest health surveillance.

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Appendix 1. Codes used by survey officers annotating disorder details onto maps during aerial surveys of softwood plantations (the survey officer hatches or circles an area of plantation affected and writes the corresponding code)

Mortality* (*Diplodia*/drought/*Sirex*/*Ips*)	Fungi/insects/vertebrates	Nutrition	Weeds/climate
Dead tips: Ti1 = 1–5% incidence Ti2 = 5–15% incidence Ti3 = 15–30% incidence Ti4 = >30% incidence **Dead tops:** To1 = 1–5% incidence To2 = 5–15% incidence To3 = 15–30% incidence To4 = >30% incidence **Dead trees:** Tr1 = 1–5% incidence Tr2 = 5–15% incidence Tr3 = 15–30% incidence Tr4 = >30% incidence	***Dothistroma*:** D = 1–15% severity D1 = 15–30% severity D2 = >30% severity ***Cyclaneusma*/yellowing:** Y1 = 1–5% incidence Y2 = 5–25% incidence Y3 = >25% incidence **Possums:** P = <1% incidence P1 = 1–5% incidence P2 = 5–15% incidence P3 = >15% incidence **Wallabies:** W = <1% incidence W1 = 1–5% incidence W2 = 5–15% incidence W3 = >15% incidence ***Essigella*:** L = 5–10% crown severity M = 10–25% crown severity H = 25–50% crown severity Ex = >50% crown severity	**Boron deficiency:** B1 = rounded, multi-stemmed trees B2 = tip dieback **Nitrogen deficiency:** N def = Moderate N def H = High **Phosphorus deficiency:** P def = Moderate P def H = High **Magnesium deficiency:** Mg def = Moderate Mg def H = High	**Weeds:** Ww = wattle We = eucalypts Wg = grass  = Low levels  = High levels **Snow / Wind:** S1/W1 = Flattened whorls/young trees (should recover) S2/W2 = Broken limbs or tops S3/W3 = Broken or felled trees **Frost:** F1# = Burnt foliage + incidence F2# = Mortality + incidence **Lightning:** L # (Number of trees) **Fire:** Fire # (Number of trees) or circle area affected

*Confirm causal agent during ground inspection