# EFFECTIVENESS OF ROUTINE FOREST HEALTH SURVEILLANCE IN DETECTING PEST AND DISEASE DAMAGE IN EUCALYPT PLANTATIONS

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## ABSTRACT

Routine health surveillance of forestry plantations in Australia typically involves inspections from the air, roadside and ground to detect, identify and map health problems caused by pests and diseases. An often-cited objective of routine health surveillance is the early detection of new incursions of exotic pests and diseases. To be effective, this requires the incursion be detected when damage is often cryptic either because of low incidence or low severity. However, the reliability of routine surveillance in detecting damage when symptoms are still cryptic has not been tested.

We measured the efficiency of aerial, roadside and ground inspections to detect nine different types of damage symptom ranging from very obvious (mortality and dead tops) to very cryptic (stem cankers and stem borers), each occurring at a range of incidences among five 3-year-old *Eucalyptus globulus* Labill. plantations. Cryptic damage symptoms (stem borers, stem cankers and kino exudation) could not be reliably detected using any of the inspection platforms even when their incidence, within small patches, was as high as 2%. Conversely, dead tops were detected most efficiently by aerial inspection, at incidences as low as 0.1%. The crown symptoms produced by moderately severe insect

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defoliation or necrotic leaf lesions due to *Mycosphaerella* spp. infection could be detected with equal efficiency from roadside and ground inspections but could not be reliably detected from aerial inspection.

We conclude that the combination of aerial and roadside inspection provide sufficient resolution to detect operationally relevant damage, i.e. damage of sufficient severity to consider remedial treatment. The inclusion of ground surveys does little to enhance the capacity of routine health surveillance to detect the more cryptic damage symptoms that characterise the early stages of outbreaks by stem and branch-attacking pests and pathogens. Routine ground surveillance of plantations is unlikely to detect damage by new incursions at a sufficiently early stage when eradication may be feasible.

**Keywords**: *Eucalyptus*, surveillance techniques, arthropod pests, pathogens

# INTRODUCTION

The purpose of forest health surveillance is primarily to detect outbreaks of pests and diseases at an early stage while damage is confined to small areas or before severe adverse impacts occur. Early detection of outbreaks allows forest managers to consider a wider range of response actions, particularly in the case of new introductions of exotic pests or pathogens, where eradication or containment may be options.

It is important to know how reliable forest health surveys are in detecting different symptoms of damage. Forest certification in general, and the Australian Forestry Standard (Standards Australia, 2003) in particular, require that any survey and monitoring procedures used to meet the standard can document their power. As well, forest managers need information on the costs and benefits of various elements of forest management to optimally allocate resources. Health surveillance offers the potential net benefit of reduced costs associated with management to ameliorate losses from pests and diseases. However, achieving these benefits is dependent upon the surveillance method having sufficient resolution to detect pest and disease outbreaks early enough to minimise costs and maximise the success of subsequent management actions.

There are three main inspection platforms used in conventional forest health surveillance: aerial (or static observation from a high vantage point), roadside cruise and ground transects or plots. Aerial inspections, particularly those done from fixed-wing aircraft, can view large areas quickly and, hence, are relatively cheap to conduct. However, aerial inspections are only reliable in detecting obvious crown damage symptoms (Carter, 1989) although inspections done using helicopters flying at lower altitudes are effective in detecting more cryptic crown symptoms (Appleton, et al., 2000). At the other extreme, ground inspections have a higher resolution but are slow and hence expensive to conduct. Efficient health surveillance uses a mixture of all three inspection platforms at varying intensities of sampling to provide the optimum mix of detection resolution and cost.

Research done in the 1980s by the Forest Research Institute in New Zealand demonstrated the very low efficiency of forest workers in detecting pest and disease problems during the course of their normal field duties (Carter, 1989). This research apparently vindicated the New Zealand approach of using a structured health surveillance program undertaken by specially trained observers to detect pest and disease outbreaks. However, the benefit of the New Zealand system, in terms of detection efficiency, remained largely unquantified. Carter (1989) attempted to quantify the probability of detecting pest and disease outbreaks using trained observers conducting aerial, roadside and ground inspections. Although he used measured data on the detection efficiency of aerial surveys, he had to make informed guesses on the detection efficiency of roadside and ground surveys. Bulman et al., (1999) provided better measures of the detection efficiency of roadside and ground surveys based on actual detection rates from field simulations. However, they used decoys to simulate different types of damage symptoms rather than detecting actual damage caused by pests and diseases. It is not known whether the visual stimulus provided by decoys realistically reflected the visual stimulus of actual symptoms, particularly those more cryptic symptoms that do not produce obvious colour changes in affected host tissue.

In this study we aim to measure the resolution of each of the three main inspection platforms used routinely in forest health surveillance in detecting the range of damage symptoms commonly encountered in eucalypt plantations.

# MATERIALS AND METHODS

The trial was conducted within five *Eucalyptus globulus* Labill. plantations in Retreat Block, northern Tasmania, in May 2004. The five plantations were RT206D, RT233C, RT228B, RT228E and RT241F, but for the purposes of this study were denoted Plantation A, B, C, D, and E respectively. The plantations were each established at the normal density of 1100 stems/ha (spacing of 4.5 m between rows x 2 m along rows). At the time of assessment the trees were about 3 years old and had heights ranging between about 3–7 metres.

In each of the plantations, a 2.5 ha rectangular plot was mapped prior to commencing surveys. The shape (length-breadth ratio) of the plot was adjusted so that the length of road per unit area of plantation was the same in the plot as it was in the stand (Figure 1). Generally the plot was positioned so that its long axis ran parallel with planting rows.

Aerial inspections were done over each of the five plantations using a Bell Jet Ranger helicopter flying at an altitude of about 100-150 metres and an airspeed of about 80 knots. Inspections of each plantation were done twice, each using a separate three-person crew (exclusive of the pilot) comprising two observers and a navigator. The navigators had maps showing the location of the 2.5 ha plots that had been established in each plantation and ensured that the flight path of the helicopter was over the plots.

A roadside cruise survey was simulated in the 2.5 ha sample area within each of the five plantations. Each observer involved in the study walked along the section of road within each sample plot at a steady pace and inspected the adjoining plantation for damage symptoms.

Two types of ground survey were tested: a line transect survey and a 9-tree plot survey. For the line transect survey, each observer involved in the study selected a take-off point at a randomly chosen distance along the road abutting each of the 2.5 ha plots. Each observer then walked at a slow, steady pace down the planting row and inspected 20 consecutive trees for symptoms of damage. Each observer then moved across several rows and inspected a further 20 consecutive trees for damage on the return journey to the road. For the 9-tree plot survey each observer selected a take-off point at a randomly chosen position along the road and walked down a planting row into the plantation for a predetermined number of trees (i.e. decided before entering the plantation). Upon arriving at the predetermined point, each observer then inspected nine trees (3 rows x 3 trees) for damage symptoms. No account of symptoms seen *en route* was recorded for either of the two ground surveys.

For the aerial, roadside and line transect ground surveys, observers simply recorded damage symptoms seen plus a description of incidence and severity of that damage. For the 9-tree plot surveys, each of the nine trees was assessed for damage in the same systematic manner used for the blitz surveys. The time spent by each observer on each roadside and ground survey was recorded. Similarly, the time spent by each observer on the blitz survey done in each 2.5 ha plot was recorded.

For each of the five plantations the incidence-by-severity of each damage type within the 2.5 ha plot was calculated from the blitz surveys. These incidences together with the incidence of each of the artificial damage types defined the actual damage profile of each plantation against which the results of the detection surveys could be compared. For each of the nine damage types illustrated in Figure 2 the range of incidences recorded in the blitz surveys in each of the five plantations were compared with the results of the detection surveys and expressed as the proportion of observers who saw the particular damage symptom. In this manner a threshold level for detection of each damage type based on its incidence and severity was determined for each inspection platform (air, roadside and ground) of the detection surveys.

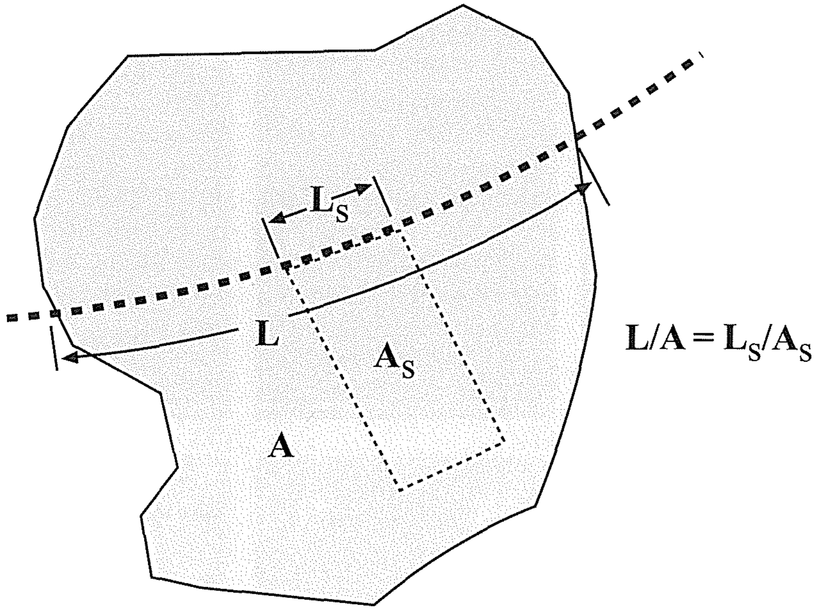


FIGURE 1: Diagram illustrating the configuration of the 2.5 ha sample plot within a plantation. The road is marked with a dashed line. The ratio of the length of road within the compartment (L) to the compartment area (A) was the same as the length of road $L_S$ within the 2.5 ha sample area $A_S$.

## Symptom description and assessment

Nine types of damage symptom were tested (Figure 2). These had differing degrees of visibility, ranging from very obvious (mortality) to very cryptic (exit holes of stem borers). Five of the damage symptoms (mortality, defoliation, discolouration and stem galls/swellings) were known to be common in eucalypt plantations based on an analysis of health surveillance records. We relied on their natural occurrence for the trial. The remaining four symptom types (borer, cankers, kino bleeding, and top death) are rare in plantations (Forestry Tasmania unpublished forest health surveillance records). These symptom types were simulated using artificial symptoms as detailed over page and in Figure 3.

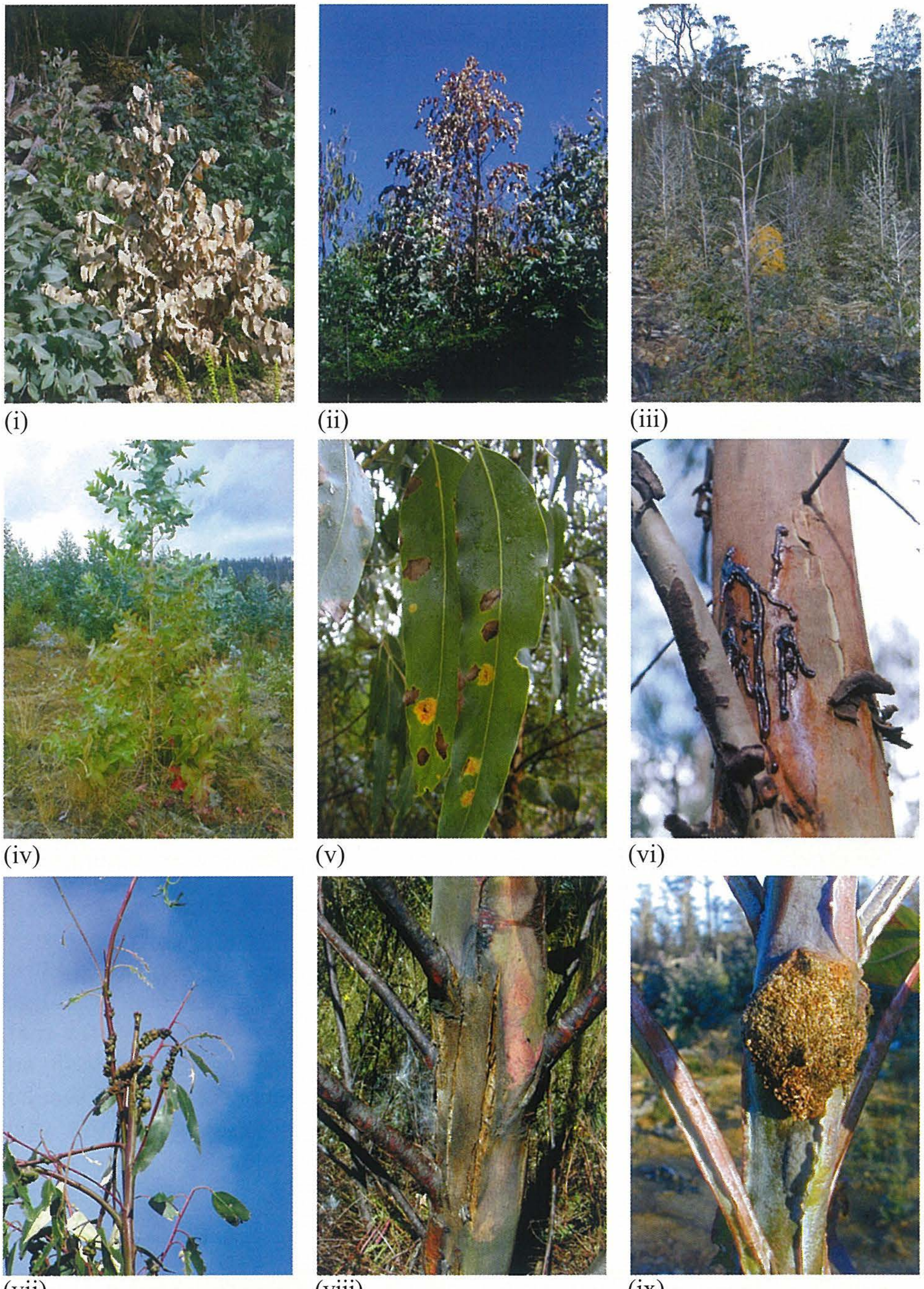


FIGURE 2: Symptoms recognised in the study and shown in order of decreasing visibility (most visible top left, least visible bottom right): (i) mortality; (ii) top death; (iii) defoliation; (iv) discolouration; (v) necrotic leaf lesions; (vi) kino bleeding;(vii) stem galls or swellings; (viii) stem wounds and cankers; (ix) stem borers.

FIGURE 3: Simulated damage symptoms: (i) frass-covered gallery of a wood-boring insect; (ii) stem canker; (iii) kino exudation; (iv) dead top (arrowed) about to be tied to the top of a lopped tree.

**Borer:** The frass-covered webbing over the gallery entrance produced by the cossid moth *Aenetus* spp. was simulated using a hemispherical, sawdust-covered foam block.

**Cankers:** Lenticular pieces of coarse, reddish-brown coloured sandpaper painted with orange flecks were used to simulate superficial stem cankers similar to those caused by *Endothia gyrosa.*

**Kino Bleeding**: A trail of reddish-brown coloured caulking compound, applied using a caulking gun, was used to simulate kino bleeding from stem wounds.

**Dead tops**: Dead tops were simulated by attaching 2-metre (approximately) lengths of lopped branches to the tops of subject trees using plastic ties. The branch lengths had been lopped from 2-year-old *E. globulus* trees two weeks prior to their deployment, and dried in the open. By the time of their deployment they were a dull olive-green colour.

Each artificial damage symptom was deployed in each of the five plots at one of five levels of incidence ("absent", 0.1%, 0.2%, 1%, and 2%). Incidences of 0.1 and 0.2% were achieved by deploying the artificial symptoms to two and five randomly-selected trees, respectively, in the 2.5 ha plot (approximately 2500 trees at an establishment success rate of 90%). Incidences of 1 and 2% were achieved by deploying the artificial symptoms to two and five randomly-selected trees, respectively, within a 0.5 ha subplot located at a randomly selected point inside the 2.5 ha plot. The 0.5 ha sub-plots were only allocated to plots that had artificial symptoms at the 1% and 2% incidence levels. In plots that were assigned two or more of the artificial symptoms at 1% or 2% incidence levels separate sub-plots were assigned to each symptom type. The level of incidence of each artificial damage symptom was randomly allocated among the plantations (Table 1). The observers did not have knowledge of the incidence of these damage symptoms at the time they undertook the field surveys, although they were shown what the artificial symptoms looked like before commencing surveys.

TABLE 1: Incidence of each of four types of artificial damage symptom deployed in five plantations.

| | Symptom type | | | |
|---|---|---|---|---|
| Plantation | Dead top | Borer | Canker | Kino |
| A | 0.2% | Absent | 1% | Absent |
| B | 2% | 1% | Absent | 0.2% |
| C | 1% | 2% | 0.2% | 2% |
| D | 0.1% | 0.1% | 2% | 1% |
| F | Absent | 0.2% | 0.1% | 0.1% |

## Detection surveys

A blitz survey, where every tree was inspected for damage, was done in the 2.5 ha plot in each of the five plantations. Between five and eight observers undertook blitz surveys in each of the five 2.5 ha plots, with each observer inspecting a separate section of the plot. Each tree was systematically inspected for about 20 seconds to record any damage present. Damage was classified according to the type of symptom and its severity (Table 2).

TABLE 2: Symptoms of damage and their associated measures of severity used in blitz and ground surveys.

| Damage symptom | Severity | | |
|---|---|---|---|
| | Low | Moderate | Severe |
| Mortality | | Present | |
| Dead top | <30 cm | 30 - 1 m | >1 m |
| | | *Length of dead top* | |
| Defoliation | <25% | 25 - 50% | >50% |
| | *Crown volume lost: spreading from bottom-up or top-down* | | |
| Leaf lesions (necrotic) | <25% | 25 - 50% | >50% |
| | *Crown volume with significant lesions (>25% of leaf area)* | | |
| Discolouration *(obvious red or yellow colours)* | <25% | 25 - 50% | >50% |
| | | *Crown volume affected* | |
| Galls and swellings | | Present | |
| Kino bleeding | | Present | |
| Borers *(Galleries extend into cambium or deeper)* | | Present | |
| Cankers, wounds and bark splits *(penetration to cambium)* | | Present | |

# RESULTS

## Mortality

Mortality in the five plantations ranged from 0.1 - 1.3% of trees (Table 3). In most cases the mortality was not recent and affected trees were generally shorter than neighbouring living trees and dull grey coloured rather than the stronger red-brown colour of recently dead trees. No mortality was detected by aerial inspection. By contrast, however, roadside inspection was moderately reliable in detecting mortality down to an incidence of 0.9% (Table 3). Ground inspection using line transects was less efficient in detecting mortality than roadside inspection. The 9-tree plot surveys, which sample a smaller number of trees than the line transects, were inefficient in detecting mortality at the incidences recorded (Table 3).

TABLE 3: Summary of the incidence of mortality in five *E. globulus* compartments measured from blitz surveys compared with the proportion of observers who detected the presence of mortality from aerial, roadside and ground inspections.

| Plantation | Incidence from blitz survey (%) | Inspection platform | | | |
|---|---|---|---|---|---|
| | | | | Ground | |
| | | Aerial | Roadside | Line transect | 9-tree plot |
| B | 1.3 | 0/2 | 3/6 | 4/7 | 1/8 |
| D | 0.9 | 0/2 | 5/7 | 1/5 | 1/7 |
| C | 0.6 | 0/2 | 1/6 | 0/5 | 0/6 |
| A | 0.1 | 0/2 | 0/5 | 0/5 | 0/5 |
| E | 0.1 | 0/2 | 0/5 | 0/5 | 0/5 |

## Dead top (artificial)

At the time of the field exercises, the artificial dead tops were a dull olive colour fading to a straw-brown colour. The artificial dead tops were highly visible and readily detected from the air, even at low incidence-levels (Table 4). However, because of their low incidence, they were not detected by the roadside survey. Ground surveys, were little better than roadside surveys in detecting dead tops at the incidence deployed in the study. Both types of ground survey failed to detect symptoms at incidences below 1% (Table 4). In two stands (A and B), the blitz surveys detected the artificial dead tops at only 20 and 40% of the deployed incidence. In both of these stands dead tops also occurred naturally throughout the whole 2.5 ha plots at incidences of 12 and 0.6% respectively which caused confusion during inspections.

TABLE 4: Summary of the deployed incidence of dead tops (artificial) in five *E. globulus* plantations compared with the proportion of observers who detected the presence of dead tops from aerial, roadside and ground inspections.

| Plantation | Deployed incidence (% ) | Blitz[1] (% ) | Inspection platform | | | |
|---|---|---|---|---|---|---|
| | | | | | Ground | |
| | | | Aerial | Roadside | Line transect | 9-tree plot |
| B | 2 | 40 | 2/2 | 0/6 | 1/6 | 1/6 |
| C | 1 | 100 | 2/2 | 0/7 | 2/7 | 0/7 |
| A | 0.2 | 20 | 1/2 | 0/5 | 0/5 | 0/5 |
| D | 0.1 | 100 | 2/2 | 0/7 | 0/7 | 0/7 |
| E | 0 | - | 0/2 | 0/5 | 0/5 | 0/5 |

[1] Percentage (overall) of artificial dead top symptoms detected during blitz surveys.

## Defoliation

Defoliation was common in three of the five plantations (Table 5). Damage was light to moderate in these plantations and was mostly a top-down pattern of damage. Defoliation was not reliably detected from the air and the two occasions it was detected were in the plantations suffering the least amount of damage (Table 5). Roadside and both types of ground survey were all very efficient in detecting defoliation at the levels present in the five plantations (Table 5).

Table 5: Summary of the incidence of each of three severity levels of crown defoliation in five *E. globulus* plantations measured from blitz surveys compared with the proportion of observers who detected defoliation from aerial, roadside and ground inspections

| Plantation | Incidence from blitz survey (%) | | | Inspection platform | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | Ground | |
| | <25 | 25 - 50 | >50 | Aerial | Roadside | Line transect | 9-tree plot |
| E | 22.5 | 9.3 | 1.6 | 0/2 | 4/5 | 5/5 | 4/5 |
| D | 17.3 | 3.7 | 1.3 | 0/2 | 7/7 | 5/5 | 7/7 |
| A | 15.1 | 8.5 | 0.5 | 0/2 | 5/5 | 4/5 | 3/5 |
| C | 6.7 | 3.0 | 0.2 | 1/2 | 4/6 | 3/5 | 3/6 |
| E | 6.6 | 0.2 | 0.1 | 1/2 | 6/6 | 7/7 | 7/7 |

## Discolouration

Discolouration, typically a chlorosis of the leaves in the lower crown, was moderately common in three of the five plantations (Table 6). In most cases, however, trees were only mildly affected (<25% of crown). Aerial inspection detected symptoms of discolouration 50% of the time in these three of the five plantations. Two of those plantations had the highest incidence of trees with moderately severe levels of discolouration. The third related to the detection of foliar discolouration in some larger (and hence more visible) trees growing in windrows. Plot-based ground surveys were generally more efficient in detecting discolouration than the line transect survey.

TABLE 6: Summary of the incidence of each of three severity levels of crown discolouration in five *E. globulus* plantations measured from blitz surveys compared with the proportion of observers who detected discolouration from aerial, roadside and ground inspections.

| | Incidence from blitz survey (%) | | | Inspection platform | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | Ground | |
| Plantation | <25 | 25 - 50 | >50 | Aerial | Roadside | Line transect | 9-tree plot |
| B | 22.9 | 4.7 | 0.8 | 1/2 | 3/6 | 4/7 | 8/8 |
| E | 3.5 | 1.1 | 0.7 | 1/2 | 0/5 | 4/5 | 3/5 |
| D | 10.4 | 4.3 | 0.4 | 1/2 | 1/7 | 1/5 | 3/7 |
| C | 15.3 | 1.6 | 0.4 | 0/2 | 0/6 | 2/5 | 5/6 |
| A | 0.6 | 0 | 0.1 | 0/2 | 0/5 | 2/5 | 0/5 |

## Necrotic leaf lesions

Necrotic leaf lesions, principally caused by *Mycosphaerella* spp. (plus some occasional *Phaeopleospora eucalypti*), were prevalent in four of the plantations and was quite severe in two of those (Table 7). Aerial inspection was only able to detect necrotic leaf lesions in the two plantations that had a high incidence of severely affected trees and then with only 50% efficiency (Table 7). Roadside and both ground surveys were very efficient in detecting necrotic leaf lesions in the four plantations that had high levels of infection. The detection efficiency of two ground surveys was higher than the roadside inspection at the low levels of leaf infection in Plantation B (Table 7).

TABLE 7: Summary of the incidence of each of three severity levels of necrotic leaf lesions in five *E. globulus* plantations measured from blitz surveys compared with the proportion of observers who detected necrotic leaf lesions from aerial, roadside and ground inspections.

| Plantation | Incidence from blitz survey(%) | | | Inspection platform | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | Ground | |
| | <25 | 25 - 50 | >50 | Aerial | Roadside | Line transect | 9-tree plot |
| E | 22.5 | 16.2 | 23.2 | 1/2 | 5/5 | 5/5 | 5/5 |
| D | 30.8 | 28.7 | 20.9 | 1/2 | 7/7 | 4/5 | 7/7 |
| A | 26.2 | 23.5 | 11.4 | 0/2 | 5/5 | 5/5 | 4/5 |
| C | 18.7 | 3.3 | 1.4 | 0/2 | 6/6 | 5/5 | 4/6 |
| B | 3.7 | 0.4 | 0.1 | 0/2 | 2/6 | 5/7 | 4/8 |

## Cryptic damage on the stem/branches (artificial)

None of the inspection platforms examined were efficient in detecting any of the simulated cryptic damage affecting the stem and branches (kino, cankers and borers) at the deployed incidence. The blitz surveys only achieved 20–60% detection of the deployed artificial kino flow in two of the stands (B and C) (Table 8). Similar results in the blitz surveys were achieved with the other two artificial cryptic symptoms (borer and canker) (data not shown).

TABLE 8: Summary of the deployed incidence of kino (artificial) in five *E. globulus* plantations measured from blitz surveys compared with the proportion of observers who detected the presence of kino from aerial, roadside and ground inspections.

| Plantation | Deployed incidence (% ) | Blitz[1] (% ) | Inspection platform | | | |
|---|---|---|---|---|---|---|
| | | | | | Ground | |
| | | | Aerial | Roadside | Line transect | 9-tree plot |
| C | 2 | 60 | 0/2 | 0/7 | 1/7 | 0/7 |
| D | 1 | 100 | 0/2 | 0/7 | 0/7 | 0/7 |
| B | 0.2 | 20 | 0/2 | 0/6 | 1/6 | 0/6 |
| E | 0.1 | 100 | 0/2 | 0/5 | 0/5 | 0/5 |
| A | 0 | - | 0/2 | 0/5 | 0/5 | 0/5 |

[1] Percentage (overall) of artificial kino symptoms detected during blitz surveys.

## Cryptic damage on the stem/branches (natural)

Stem and branch galls were rare in all but one of the plantations (Table 9). Neither aerial nor roadside inspections were able to detect stem galls in any of the five plantations. Ground surveys were only able to reliably detect galls in the plantation with the highest incidence of stem and branch galls (Table 9).

TABLE 9: Summary of the incidence of stem and branch galls in five *E. globulus* plantations measured from blitz surveys compared with the proportion of observers who detected the presence of stem and branch galls from aerial, roadside and ground inspections.

| Plantation | Incidence from blitz survey (%) | Inspection platform | | | |
|---|---|---|---|---|---|
| | | | | Ground | |
| | | Aerial | Roadside | Line transect | 9-tree plot |
| E | 1.9 | 0/2 | 0/5 | 3/5 | 3/5 |
| D | 0.7 | 0/2 | 0/5 | 1/5 | 0/7 |
| A | 0.6 | 0/2 | 0/5 | 1/5 | 0/5 |
| B | 0.2 | 0/2 | 0/7 | 0/7 | 1/7 |
| C | 0.2 | 0/2 | 0/5 | 1/5 | 0/6 |

# DISCUSSION

Aerial inspection at low altitudes using a helicopter was very reliable at detecting recently dead tops down to very low incidences. We achieved higher efficiency of detection than the simulation reported by Appleton, et al., (2000) in which low-altitude inspection from a helicopter was used to detect individual *P. radiata* trees with tops painted either red or white. The fact that the simulation for dead tops that we used was more realistic than that used by Appleton et al. gives added confidence that the results we obtained were a good approximation of operational surveys in eucalypt plantations.

Dead tops were the only damage symptom reliably detected from the air. The inability to detect mortality, a similar symptom visually, was not surprising given that the mortality had occurred well before the survey and affected trees had been overtopped by adjacent healthy trees. This is a similar problem to that experienced when trying to detect the initial stages of a wood-wasp (*Sirex noctilio*) outbreak in pine plantations from the air where the mortality is initially concentrated in suppressed trees (Forestry Tasmania, unpublished health surveillance records). However, detection of recently dead or currently dying trees within the dominant or codominant strata should be similar to the results obtained for simulated dead tops. Our experience from operational surveillance of eucalypt plantations is that individual trees that have recently died are regularly detected using inspection from helicopters flying at low altitudes.

Surprisingly, the detection rate of the artificial dead tops during the intensive blitz surveys was lower than the aerial surveys. Detection of symptoms in the upper crown from the ground some times relies on looking into a bright background, particularly if conditions are overcast. Under such conditions the upper part of the crown appears as a dark silhouette with little expression of colour, the main visual cue used to discriminate recently dead tops from adjacent healthy tops. A naturally high incidence of dead tops, particularly in Stand A may have also contributed to the low detection rate of dead tops in the blitz surveys because assessors failed to differentiate artificial from natural dead tops in some of the instances where they detected dead tops.

The other three types of damage that produce visual symptoms in the crown (defoliation, discolouration and necrotic leaf lesions) were not reliably detected from the air at the levels measured. However, both defoliation (predominantly top-down defoliation by chrysomelid leaf beetles (*Paropsisterna* spp.) and the eucalypt weevil, *Gonipterus scutellatus*) and necrotic leaf lesions (predominantly *Mycosphaerella* spp.) were reliably detected from the road at all but the lowest measured incidence (<5% of trees affected). The threshold levels of damage for reliable detection of necrotic leaf lesions and defoliation, in particular, occur well below levels that are operationally significant and begin to produce measurable growth impacts. This commonly occurs when the average loss of leaf area attains or exceeds 25–50% (Lundquist & Purnell, 1987; Candy, Elliott & Bashford, 1993; Elliott, Bashford, & Greener, 1993; Carnegie & Ades, 2003).

Roadside surveys were unable to detect the most cryptic symptoms that affected only the stem. Moreover, these cryptic symptoms affecting the stem were rarely detected from the ground regardless of whether transect or plot-based surveys were used. The roadside survey and the two types of ground surveys did only sample a small proportion of the stand (0.33 and 1.45%, respectively, for the plot and transect surveys), contributing partly to the low detection efficiency. Increasing the sample rate would obviously increase detection rate but at considerable cost. Based on the average time spent doing the 40-tree transects, we calculate the cost per hectare would increase by about AU$1.80 for each percent increase in the number of trees sampled. However, even blitz surveys, which provided 100% sample of the trees, failed to achieve 100% detection efficiency for any of the artificial cryptic symptoms (overall average detection rate for cryptic symptoms was 55%). This result is not surprising given access to individual trees was often quite difficult due to dense woody weed growth in some of the plots. Stand E, which had the best access as it was an ex-pasture site, achieved a rate of detection approaching 90% for the three cryptic symptoms.

The finding that ground surveys were unable to reliably detect cryptic damage symptoms at low incidence dispels our belief that the plot-based ground surveys had such a detection capability. This belief arose from the detection of stem galls in a 3-year-old *Pinus radiata* plantation during routine health surveys in 1999 (Forestry Tasmania unpublished records;

Ridley, 1999). At that time, health surveys of plantations on State forest in Tasmania included a ground survey using a regular array of 9-tree plots, which sampled plantations at the rate of four plots every 10 hectares (Wardlaw, 2008), the same density as in the current study. The ground survey also provided an additional, but unquantified, detection capacity provided by walking between plots. It was during the walking between plots that the pine galls were initially detected. A post-detection blitz survey found that trees with galls occurred at an incidence of 0.1% throughout the affected plantation, the lowest incidence tested in the current study. In this study, stem and branch galls were only detected in 9-tree plots in two of the five plantations. Even then, there was only a 50% chance of detection at an incidence of 1.9%, nearly 20-times higher than in the *P. radiata* plantation in which the stem galls were detected. Even with the additional sampling provided by brief inspection of trees in travelling between plots, the results of this study strongly suggest the detection of stem galls at low incidence in the *P. radiata* plantation was a rare event that is unlikely to be repeated regularly in routine surveys. This contradicts the results of Bulman et al. (1999) who reported that simulated cryptic stem symptoms could be detected in New Zealand port environs surveys with moderate reliability. However, it is difficult to compare the results of their study with those reported here because they associated their most cryptic symptom (painted tags placed under bark) with the dead or dying trees or stumps. This could, in effect, greatly increase the incidence at which that cryptic symptom occurred because it was associated with a small number (assumed) of readily recognisable target trees. The parkland setting of the port environs in which the New Zealand study was conducted would also have provided easier conditions in which to locate and inspect the individual target trees compared with young eucalypt plantation trees growing amongst dense understorey vegetation.

The inclusion of ground surveys to augment aerial and roadside inspections of plantations cannot be recommended as a way of improving the capacity of the survey to detect cryptic symptoms at low incidence. This result reinforces the notion that routine surveillance of plantations should not be afforded the status of an early warning system to detect new incursions of exotic pests and pathogens of forestry significance. However, aerial and roadside inspections of plantations remain vital for health management by providing a relatively cost-effective means of detecting operationally significant damage. The main gap in the method is the inability to detect the early stages of stress-induced outbreaks of wood-boring insects (e.g. *S. noctilio* in pines) or stem canker epidemics such as *Endothia gyrosa* (e.g. Wardlaw, 1999) before significant permanent damage (mortality or stem degrade) occurs. The use of static traps, which are able to detect very low populations of wood-boring insects, may fill this gap in the current method of health surveillance in plantations, particularly at-risk plantations (eg un-thinned plantations at mid-rotation). This surveillance tactic warrants further investigation.

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