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Wood decay associated with logging wounds in *Parashorea malaanonan*

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Abstract. Wood decay associated with wounding in 40 trees of *Parashorea malaanonan* growing in Ulu Segama Forest Reserve, Sabah, Malaysia, was estimated 7 years after logging in compartments where reduced-impact (RIL) or conventional (CL) logging methods were used. Trees of ≥30 cm diameter were felled and dissected to determine the volume of log occupied by decay. Scrapes were the most common types of wounds sampled, followed by basal wounds, broken tops or branches and butt log wounds. All wounded trees examined had decay, whereas only 25% of trees >30 cm diameter at breast height of this species in the reserve typically had stem decay. Median defect to gross volume of tree was ~5%, and was similar for trees in RIL and CL areas. However, defect volume per wound was greater in trees from CL areas relative to RIL areas, in particular, mid-bole wounds had greater defect volume in trees in CL areas as opposed to trees in RIL areas. The mean rate of decay was estimated at 68 cm^3 of timber per year for each cm^2 of wound area. Defect volume was positively correlated with wound size but was unrelated to tree size. *P. malaanonan* is vulnerable to wood decay following wounding; therefore, in eastern Sabah forests, where this species comprises a large proportion of the commercial volume, efforts to reduce incidental damage to residual stems during harvesting operations are an important component in protecting the growing stock.

Additional keywords: dipterocarp forest, selective logging, wound type.

Introduction

The type of harvesting practices used in a particular forest influence the level of site damage and incidence and severity of wounding to residual trees (Johns *et al*. 1996; Pinard and Putz 1996). Logging wounds provide an entry point for microbial infection and decay development into trees; the role of such wounds as foci for subsequent wood decay in residual trees is well known (Aho *et al*. 1983; Whitney 1991; Hennon and DeMars 1997; Vasiliauskas 2001). Therefore, preharvest planning and control for reducing damage during log extraction play critical roles in the maintenance of healthy growing stocks in managed forests.

In natural forests in the tropics, harvesting is usually selective and tree selection is controlled through the use of minimum felling diameters. Although the majority of forest areas under timber production are not being managed in a sustainable way (Poore *et al*. 1989), procedures aimed at promoting sustainable use of the forests have been established in the conventional system of logging, for example the Malayan Uniform System and Selective Management System, and also, lately, reduced-impact logging (RIL) (Nicholson 1965; Chai and Udarbe 1977; Appanah and Weinland 1990; Pinard *et al*. 1995).

As practised in the dipterocarp forests of Sabah, Malaysia, conventional logging (CL) and RIL contrast in terms of damage caused to the forest. Although both are selective cutting operations, CL typically results in 40–70% damage to residual trees (Nicholson 1958; Tay 1993; Pinard and Putz 1996). In contrast, RIL can reduce damage by half compared with CL (Pinard *et al*. 1995; Pinard and Putz 1996; Sist *et al*. 1998). These differences are evident as greater felling gap sizes (Johns *et al*. 1996), drier conditions in the understorey (Holdsworth and Uhl 1997), and higher quantities of dead wood on the forest floor (Johns *et al*. 1996; Pinard and Cropper 2000) in conventionally logged sites compared with RIL sites, at least for a period after logging. These differences in the physical and biotic environment may have implications for the development of wood decay in wounded trees. For example, the more open environment with more coarse woody debris in CL areas could harbour a greater fungal population and facilitate the spread of fungal spores. However, the more humid conditions in RIL forests, could promote faster decay development than in CL forests. These differing conditions in the environment and substrate might influence the course of microbial succession after logging and subsequently influence the development of decay in wounded trees.

When decay is associated with logging wounds, wound characteristics such as wound size and position, may also influence decay development. The general pattern appears to be

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that greater wound size results in a greater extent of decay (Parker and Johnson 1960; Aho *et al*. 1983; Whitney 1991). In terms of wound position, Wardlaw (1996) observed ~90% of decayed wound in *Eucalyptus* stands originated from a ground position that was typically due to skidding operations. In dipterocarp forest, the extent of decay related to damage to the aerial parts of the tree has received little attention in the literature, although the occurrence of such damage has long been recognised (Nicholson 1958; Fox 1968).

Tree damage is an unavoidable consequence of selective logging, and in old growth forests in Sabah where harvest intensities are relatively high, it can affect a large proportion of the residual trees. However, the development of decay in such stands remains poorly understood, particularly relative to type of wounding and the logging system (i.e. CL and RIL) used. Such an understanding could increase management efficiency by improving predictions of volume losses due to decay and mortality, and may also help to promote the adoption of RIL practices.

This study was conducted with the following objectives: (i) to quantify the extent of decay associated with wounding in *Parashorea malaanonan* trees in dipterocarp forests in Sabah, 7 years after logging; (ii) to compare the extent of wood decay in wounded trees in areas logged using CL and RIL systems; and (iii) to examine the relationship between the volume of defect with factors such as tree size, wound area and wound location.

Materials and methods

Study site and tree selection

Fieldwork was conducted in Ulu Segama Forest Reserve (5°0′N, 117°30′E and ~150–750 m a.s.l.) in south-eastern Sabah, between January and March 2000. The experimental area consisted of eight ~50-ha sub-blocks of mixed dipterocarp forest previously dominated by *P. malaanonan* in association with *Rubroshorea* species (Fox 1970). Mean basal area 3 years after logging was 22.2 m^3/ha in RIL sites and 15.5 m^3/ha in CL sites (M. Pinard, unpubl. data). Prior to logging, the forest canopy height averaged ~45 m with emergents to 70 m. Canopy heights after logging are unavailable. However, in 2005, 12 years after logging ~50% and 15% of the RIL and CL areas contained tall, closed canopy forest (P. Lincoln, unpubl. data).

The soils are of the Labang formation (Fox 1970), primarily derived from uplifted alluvial, tertiary sediments (Leong 1974), and the topography consists of short, steep ridges with most of the area having slopes exceeding 20° (Pinard and Putz 1996). Mean daily temperatures are 26.7°C with an annual rainfall of ~2750 mm/year (Danum Valley Field Centre records 1986–1993).

In 1993, the area was logged using ground based log extraction (bulldozer) with mean logging intensities ranging from 38 to 190 m^3/ha (Pinard and Putz 1996) as part of a carbon offset project with some areas logged using CL methods, and some logged according to RIL methods. The area was chosen for this study because it offered an opportunity for sampling relatively large trees that had experienced wounding during logging using the two different impact systems. The site history was also well documented.

Relatively large [diameter at breast height (DBH) class ≥30 cm] trees were selected for the work, partly because they represent the potential crop trees for the upcoming cutting cycle. Additionally, it was easier to consistently detect wounds attributable to the logging in 1993 in this size class of trees. Preliminary work suggested that smaller stems with wounds that could be confidently attributed to the 1993 logging event were much more difficult to find, perhaps because the damaged stems had died or because their recovery was more complete.

Forty trees of *P. malaanonan* (Blanco) Merr., 20 each from CL and RIL areas, were sampled in a stratified random manner where the strata were old skid trails within different sub-block or logging unit divisions; five trees were sampled in a given sub-block. Sampling was conducted along old skid trails because it was easier to encounter potential sample trees and because the likelihood of any visible stem damage dating to 1993 was higher than if sampling was conducted at random.

Sample trees had one or more visible wounds (broken top, broken branch, trunk scrape, butt-log wound or basal wounds) attributable to logging operations carried out in 1993. The characteristics (appearance, shape, position or size) of wounds caused by logging are readily distinguishable from those due to the stripping or wounding of bark by animals such as Sun bear (*Helarctos malayanus*) or deer (*Cervus unicolor* or *Cervus timorensis*). Generally, only one tree was selected in a given skid trail path (selected randomly from the pool of candidate trees). However, where appropriate trees were hard to find, more than one tree was selected from a given skid trail but a minimum distance of 100 m between trees was maintained to ensure replicates were independent. Sometimes trees for sampling were often difficult to find because the damaged trees were almost dead, or because the location (e.g. in a riparian zone or near a healthy crop tree) meant that the tree could not be felled without causing unacceptable damage to the forest owner.

Additional sampling of *Parashorea* trees for stem decay was conducted opportunistically during logging operations in Ulu Kuamut forest concession to determine background incidence for large *Parashorea* trees. Logging crews were followed in the forest camp and when *Parashorea* trees were felled, the logs were examined for incidence of decay. A total of 13 trees was inspected using this method.

Data collection

Stem volumes were calculated using the method developed by Forestal International Limited (1973). Assessment of decay associated with wounds followed published methods (White and Kile 1994; Hennon and DeMars 1997) as outlined below. For decay developing through basal wounds, only the above ground portion of the defect was measured. Measurements for each sample tree included DBH, total height and merchantable height (at 12 cm diameter). After felling the tree, each wound was examined and data including height from the ground to the base of wound, width and length of wound, girth and stem diameter at centre of wound were recorded. Width and length values were original dimensions of the wound as determined by dissection and removal of callus growth on the wound surface from the scars. Wound size was calculated as the product of the width and length of wound. Wounds were classified into five categories, as described in Table 1.

Table 1. Types of logging wounds found on *Parashorea malaanonan* trees in Ulu Segama Forest Reserve, Sabah, Malaysia

Wound type	Description[A]
Broken top	Top of tree or trunk snapped with removal of substantial portion of crown and tissues exposed to infection into trunk
Broken branches	Wound at or near base of branches; branch either snapped or split exposing tissue to infection into bole
Trunk scrape	Wound or scar, usually vertical, on trunk above skidder height (>3 m) up to upper bole; various widths/lengths exposing sapwood
Butt log wounds	Wounds to butt-log (buttress level up to ~3 m)
Basal wounds	Cankers/open wounds at stem base (ground level/buttress); large size; frequently with cavity (advanced heart rot)

[A] Adopted from Whitney (1991).

Boles were cut into 20–30-cm length discs, commencing at the midpoint of the external wound's length and continuing above and below the wound (or ground line) until discs were reached with no evidence of stain or decay. Each disc was dissected along a vertical plane and the boundaries of discolouration and decay were marked on the exposed surface with a permanent marker pen. Discolouration and incipient decay were determined by the Pick test (Wilcox 1983). The type of rot (brown or white), and the vertical and radial extent of the discoloured and decayed areas were recorded. The total volume of defect was calculated per wound. Additional sampling of wood chips to isolate and identify the causal agents of decay was conducted but is reported elsewhere (Sudin 2005).

Data analysis

Treatment comparisons were made using *t*-tests (for tree dimensions), Mann–Whitney U tests (for defect/decay volumes) and Chi-square tests (for frequency of wounds). Pearson and Spearman rank correlation analyses were used to determine associations between variables (volumes of defect against wound positions, wound area and tree DBH). Each wound was treated as a replicate in relation to decay developed. For comparisons among wound types in relation to defective volume of wounded trees, wounds were grouped into upper (broken top + broken branch), middle (trunk scrape) and lower (butt-log wound + basal wound); defect volumes were log-transformed and then compared between logging treatments using 1-way ANOVA.

Results

Characteristics of sampled trees

DBH of trees sampled from the CL areas were similar to those from RIL areas (Table 2). Their merchantable height was greater in CL examples compared with RIL samples. However, the merchantable volumes were not significantly different.

Fifty-nine wounds attributable to logging were encountered in the 40 sampled trees comprising 30 wounds in CL areas and 29 in RIL areas. Wood decay and discolouration were evident in all wounds examined.

The surface area of the wounds ranged from 0.005 to 1.155 m^2 (median = 0.068 m^2), with an interquartile range of 0.027 to 0.165 m^2. Although some wounds had callused, most lesions were large enough not to have occluded within the 7 years after logging. Inspections of discs cut from the wounded areas revealed that in many cases, wood had been removed at the time of damage, especially with basal wounds. Wound areas in CL areas (range = 0.007–0.884 m^2; median = 0.057 m^2) did not differ significantly ($Z = 0.713$; $P = 0.476$) from those in RIL areas (range = 0.005–1.155 m^2; median = 0.072 m^2).

Trees with single wounds were sampled more frequently than trees with multiple wounds in both areas, with single wounds representing 14 of 20 in the CL areas and 13 of 20 in the RIL areas.

Trunk scrapes were the most common wound type sampled (40%), followed by basal wounds (34%). Broken tops represented 14% of sampled wounds, whereas broken branches and butt-log wounds represented 7 and 5%, respectively.

Although the proportions of trunk scrapes and butt-log wounds varied between the two logging treatments (Fig. 1), frequency by wound types was generally comparable in the two logging areas ($\chi^2 = 3.264$; d.f. = 4; $P > 0.05$), although basal wounds were more frequent in RIL areas, and there were more trunk scrapes in CL areas.

Pattern of discolouration and decay development

Discolouration was typically pale brown, or yellow-brown, surrounding the decay and darker in heartwood, and was present in all *P. malaanonan* trees sampled. Sometimes, in freshly cut trees, the discoloured wood was indistinguishable from healthy wood or from natural colourations in the stems, such as nodes

Table 2. Characteristics of *Parashorea malaanonan* trees sampled from conventional logging and reduced-impact logging areas

Values presented are mean ± s.e., $n = 20$ trees per treatment. Results from statistical comparisons using *t*-tests are provided

Logging treatment	Diameter at breast height (cm)	Merchantable height[A] (m)	Merchantable volume[A] (m^3)
Conventional	53.3 ± 13.7	29.3 ± 7.7	4.7 ± 2.9
Reduced-impact	48.2 ± 12.7	23.7 ± 6.5	3.2 ± 2.6
Statistical test results	$t = 1.197$, d.f. = 38 $P = 0.239$	$t = 2.475$, d.f. = 38 $P = 0.018$	$t = 1.771$, d.f. = 38 $P = 0.085$

[A] Up to 12-cm bole diameter.

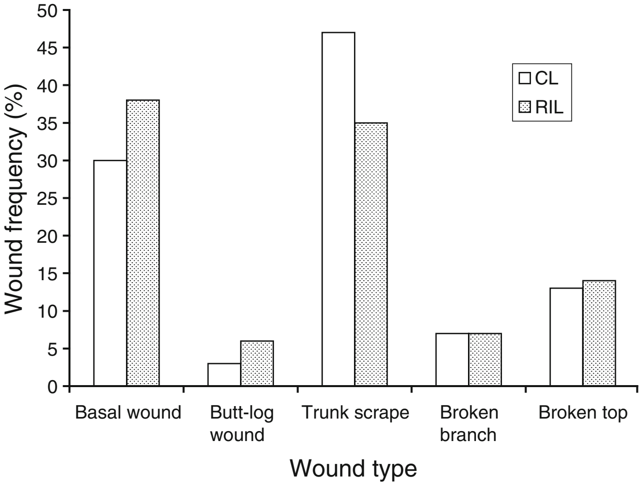

Fig. 1. Relative frequency of wounds by wound type in *Parashorea malaanonan* trees sampled in conventional logging (CL) and reduced-impact logging (RIL) areas. Twenty trees sampled in each logging treatment ($n = 40$).

or regions of compression wood. In areas with true decay, heartwood tissues were fibrous and dark brown. In some trees, clear zones with brown staining were observed, contrasting with the natural bright character of *P. malaanonan* timber.

Development of decay commonly extended beyond the infected wound surface and lesions. In most inspected wounds, decay was at an advanced stage, with softened woody tissues and dark staining, and reaction zones were apparent in scattered positions along the stems. In some trees, reaction zones were disrupted with cracks, increasing defect volumes.

Advanced decay typically extended towards the central heartwood of the tree, but the sapwood was also colonised. White rots, with timber bleached in colour, sometimes including pocket, mottled or stringy decay, were the more frequent type of decay columns.

Volume of discolouration and decay

The volume of discolouration and decay (defect volume) per wound was greater in CL trees than in RIL trees (Table 3). A corresponding effect was also observed in the defect volume per tree. However, the proportion of stem defect in wounded trees from CL areas (14.2%, s.e. = 3.6) was not significantly different from that in RIL areas (9.9%, s.e. = 2.6).

There was a positive correlation between DBH and volume of defect for trees growing in CL areas ($r = 0.603$, $n = 20$, $P = 0.000$), but not in the RIL areas (Fig. 2). However, wound area (m^2) was positively correlated with volume of defect in samples in RIL ($r_{s\,RIL} = 0.454$, $n = 30$, $P = 0.013$), but not for trees in the CL areas. Height of wound above ground was not correlated with defect volumes in either logging treatment.

Defect volumes developing from wounds to the upper bole or stem base were comparable in the two treatments ($n = 11$, $F = 0.099$, $P = 0.761$; and $n = 23$, $F = 0.844$, $P = 0.638$, respectively). However, mid-bole wounds produced greater defect volumes ($n = 22$, $F = 7.553$, $P = 0.012$) in CL areas compared with RIL areas (Fig. 3). Pooling the volume of defects in all samples, the rate of decay was estimated at 68 cm^3 per year for each cm^2 of wound area.

Discussion

Decay and discolouration were found in all wounds examined on *P. malaanonan* trees in the logged forest. Median stem volume losses were low, but the variability was great with individual trees showing as much as 44% stem volume losses at 7 years after wounding. Previous work (Pinard and Putz 1996) demonstrated that the overall incidence of fatal damage was much lower in RIL sites compared with CL sites, but the implications for wood decay arising from damage to individual trees receiving non-fatal wounds appeared important in both RIL and CL areas. Sampling trees along skidding trails in both CL and RIL areas explains the relative abundance of trunk scrapes and basal wounds on the sampled trees.

Sampling trees lacking external signs of wounding in both CL and RIL areas suggested that 75% of trees had no decay (M. Sudin, unpubl. data). Therefore, for the majority of trees sampled here, the decay observed probably arose as a consequence of wounds created during logging. However, about a fifth of the damaged trees sampled in this study may have already had some stem rot before logging (data not presented). Stem forking and some ground level entry points probably associated with root damage or infestation by insects could have served as an initial point for infection. Such modes of entry were associated with heart rot development in *Acacia mangium* in Sabah (Sudin *et al.* 1993). Wounding of trees already with stem decay may have influenced the rate of decay development. According to Boddy (2001), propagules of decomposer fungi in standing trees may be latently present within functional sapwood. Under conditions favourable to fungal growth (temperature, gaseous and drying regimes), which

Table 3. Median volume (m^3) of discolouration and decay (= total defect) associated with stem wounds in *Parashorea malaanonan*

Logging treatment	Volume of total defect per wound (m^3)			Volume of total defect per tree (m^3)		
	Volume (m^3)[A]	Volume range (m^3)	*n*	Volume (m^3)[A]	Volume range (m^3)	*n*
Conventional	0.281	0.002–3.06	30	0.360	0.002–3.493	20
Reduced-impact	0.082	0.01–1.16	29	0.160	0.031–1.246	20
Statistical test results	Z = 2.396, $P = 0.017$			Z = 1.505, $P = 0.022$		

[A] Volumes are median values, followed by extremes.

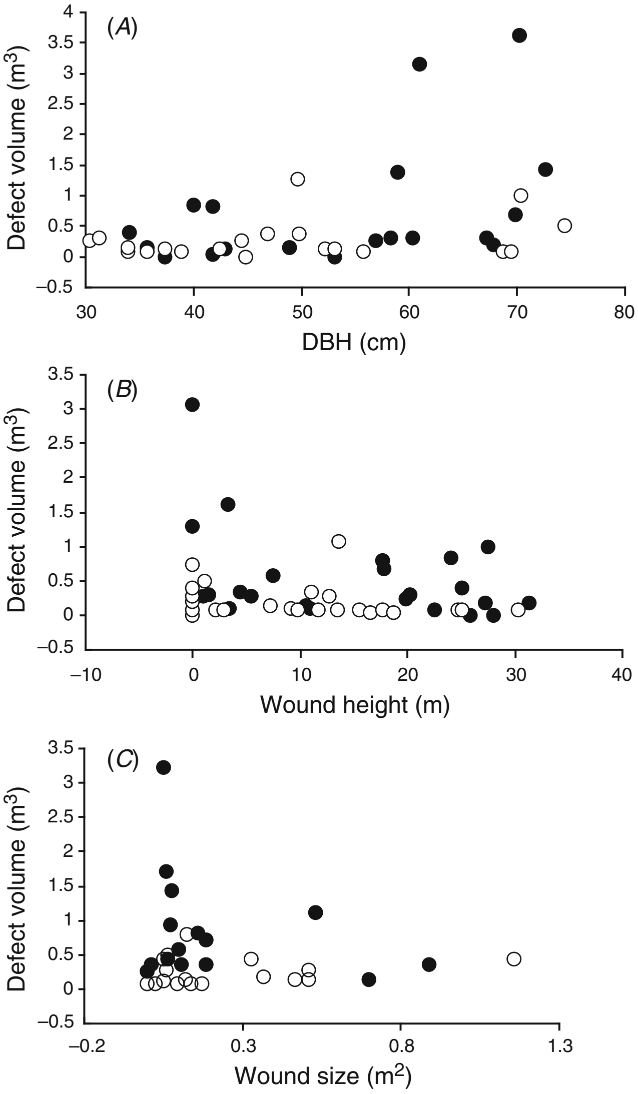

Fig. 2. Relationship between volume of defect (decay and discolouration) and (*A*) diameter at breast height (DBH), (*B*) height of wound above ground, and (*C*) size of wound in *Parashorea malaanonan* trees sampled in conventional logging (CL) (●) and reduced-impact logging (RIL) (○) areas.

can be promoted by wounding, these endophytic species may initiate and develop decay. With wounding, other primary colonisers arrive from outside and establish rapidly, and these fungi can cause substantial decay.

Fungal isolates were obtained from decayed wood of the sampled trees. They were characterised and identification was attempted. Five of the isolates were characterised as Hymenomycetes and showed positive results in ligninolytic and celluloytic tests (Sudin 2005).

Decay development from wounds recorded in the present study was comparable with similar studies in other forests. For example, staining and/or decay were reported in almost all logging wounds resulting on *Picea glauca* (Parker and Johnson 1960), *Quercus* sp. (Shigo 1972), *Abies* sp. (Aho *et al*. 1983), *Pinus strobus* (Whitney 1991), *Eucalyptus* sp. (White and Kile 1994) and *Larix occidentalis* (Allen and White 1997). In comparison with other Dipterocarpaceae in Sabah, *Parashorea* spp. are vulnerable to degradation (Burgess 1966). Sawmill operators also observed more vulnerability to wood borers in *Parashorea* (*P. malaanonan* and *P. tomentella*) logs than other dipterocarp species (Lim, Sinora Sdn Bhd; Chua, Superwood Sdn Bhd; James, Pacific Hardwood Sdn Bhd; pers. comm.).

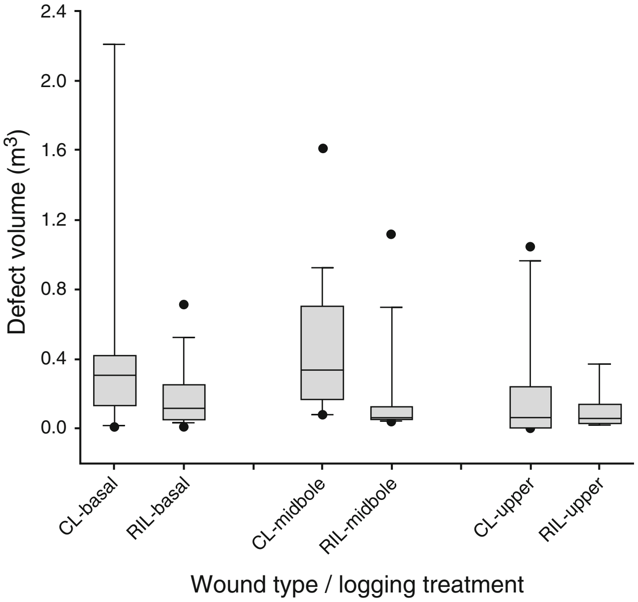

Fig. 3. Volume of defect in three wound types in *Parashorea malaanonan* trees sampled in conventional logging (CL) and reduced-impact logging (RIL) areas. Box edges indicate 25th and 75th percentile of data, respectively, with median line between. Error bars indicate the 10th and 90th percentiles. Individual points are outliers.

The observations made on residual trees 7 years after logging should be considered in the context that they represent only a subset of the population of the trees damaged during logging. Damaged trees have higher mortality rates than undamaged trees (Pinard and Putz 1996; Pinard and Cropper 2000). If stem decay increases the vulnerability of a tree to breakage, the decay recorded in remaining trees 7 years after logging is a conservative estimate of decay arising from the logging *per se*.

As the intensity of damage to trees of 40–60 cm DBH was similar immediately after logging in CL and RIL areas (Yap *et al*. 1993; Pinard and Putz 1996), the proportional loss of damaged trees to mortality could be similar for the two areas. However, mortality of damaged trees after logging was higher in the CL areas (5%) than the RIL (3%) areas over the first 4 years after logging (M. Pinard, unpubl. data), perhaps because of a higher incidence of tree fall in the open conditions that characterised much of the CL area. If stem decay results in some trees dying after logging, this difference in mortality rates between the sites may have influenced the comparisons made here, though it is difficult to predict how the results would have been affected. For example, higher mortality rates in CL trees might have differentially eliminated weaker trees, possibly those with relatively more stem decay, and the estimate of decay for trees in the CL area would be biased downwards.

Results from this study suggest that defect volume per wound and per tree were greater in CL areas than in RIL areas. These differences might partly be connected to the post-logging environments in the two areas. Although, following logging, the closed forest conditions in RIL areas would provide a more humid, stable microclimate conducive to the onset of microbial succession and decay development. More open conditions in CL areas might allow greater air movement, facilitating the spread of inoculum from existing woody debris to wounds. However, in the long term, humidity could be a contributing factor to decay development.

Higher humidity exists in RIL areas, since much of the canopy remains intact, reflecting lower temperatures compared with more open sites, as observed in Deramakot in central Sabah (Elz and Brühl 2001). These parameters might have positive or negative influences on host vigour, influencing susceptibility to decay. The abundant woody debris in CL areas may provide a habitat for small vertebrates, especially bark beetles and wood borers that enter the wood, potentially spreading inoculum or opening fresh wounds for infections.

Tree growth rate and vigour may have been a further factor influencing development of decay. Trees growing in more open stand conditions may have higher relative growth rates than those in more dense areas. Fast growing trees may invest less in defence against microorganisms than slow growing trees (Scheffer and Cowling 1966; Herms and Mattson 1992).

Categorising wounds into broken top, broken branch, trunk scrape, butt-log wounds and basal wounds, as used for the 59 wounds observed in this study, is consistent with methods used elsewhere (Nicholson 1958; Whitney 1991). Nicholson (1958), in analysing logging damage to a commercial forest in eastern Sabah, reported fallen or broken stems as the most common type (45%) of damage to trees; this incidence is comparable to the present study. A similar pattern was reported by Yap *et al*. (1993) in Sabah.

In addition to basal damage, mid-bole and top trunk damage was also observed on trees sampled along the skid trails in both the CL and RIL areas. Whether this upper damage was caused by falling trees or linked to the presence of vines is uncertain. Both factors can cause damage to the upper part of a tree during logging in dipterocarp forests (Nicholson 1958; Fox 1968; Pinard and Putz 1996).

A positive correlation was found between volume of defect and tree dimensions of trees sampled in CL areas, with 60% of the variation correlated with DBH. The figure implies that in most trees in CL, bigger boles are associated with greater decay. This positive correlation is difficult to explain as various factors could be involved in decay development and might contribute to decay volume-trunk size relationships. These factors include host vigour, size of vessels, different species of fungi with different growth rates, and also differences between different genets of the fungi.

On residual spruce, Parker and Johnson (1960) observed higher decay rates in the more vigorous, faster-growing trees than the less vigorous individuals. Hansen and Goheen (2000) found corresponding results on Douglas fir against a *Phellinus* sp. In the present study, various fungi were isolated, reinforcing the difficulties in directly applying the positive decay–trunk size relationship to a single factor. However, at the macroscopic level, severe wounding inflicted on trees plus the drier conditions in the CL areas may lead to stress, affecting vigour, and thereby increasing susceptibility to infection and decay, regardless of size.

Another factor could be the effect from the severe mechanical damage, such as that in CL trees, on the microclimate for decay set within the wood. Extensive bark death/loss in trees from severe mechanical damage expose the wood cylinder extant at the time of damage to air and drying conditions, where damaged tissues eventually become sealed off from adjacent xylem by the formation of tyloses and/or gums, resins and suberised layers. The formation of a dry zone progresses to a greater extent and increases aeration in the vascular elements (Boddy 1992). This situation (water column tension) is influenced by, among other factors, the physiology of the tree, soil water status, and atmospheric humidity. Again, CL areas have more gaps, more openings and are probably drier than RIL areas, as described by Elz and Brühl (2001) in Deramakot, Sabah. Such conditions subject the trees to further stress, leading to a greater vulnerability to infection. In contrast, it could be argued that trees in RIL areas were placed under less stress, i.e. less extensive abrasions (due to vigilant logging in the area), caused fewer wounds and bark death. Alternatively, RIL trees may be more able to defend against infection, reducing the likelihood of a correlation between decay and trunk size.

Although there was variability in defect volumes arising from wounds to trees sampled in CL areas relative to those in RIL areas, when expressed as a coefficient of variation (CV), there was more variation in defect volume in RIL wounds compared with CL wounds ($CV_{CL} = 1.38$, and $CV_{RIL} = 1.58$). This may have contributed to the lack of association between defect volume and tree size in RIL samples. Without temporal data obtained through repeated sampling over time, it is impossible to establish with certainty what the difference reflects. However, it is possible that the rate of decay development is generally slower in RIL trees than in CL trees, such that over time an association between defect volume and tree size may develop in the RIL trees.

The possible relationship between wound position and defect volumes has mixed support in the literature. Aho *et al*. (1983) observed more decay arising from wounds in contact with the ground than from those occurring higher in the tree, but no relationship was found for *Pinus contorta* (Allen and White 1997) or *P. malaanonan* (in the present study). In spruce, Parker and Johnson (1960) observed that the influence of wound position applied only to small wound areas. It may be that in the present study the combinations of large wound surface areas and defect volumes obscured any relationship with wound position.

The significant association between wound area and volume of defect in *P. malaanonan* trees in both logging treatments corroborates previous observations for various species, including spruce (Parker and Johnson 1960), western hemlock (Hunt and Krueger 1962), firs (Aho *et al*. 1983), western larch (Allen and White 1997) and *A. mangium* (Sudin *et al*. 1993).

Decay of the white rot type was prevalent in the *P. malaanonan* samples examined. Stain and decay advanced radially towards the pith, tangentially in surrounding heartwood, and vertically above and below the wound. Discolouration and reaction zones may have formed a barrier to the decay, consistent with the CODIT (compartmentalisation of decay in trees) concept (Shain 1971; Shigo and Marx 1977). Depending on the portion of the tree where the wound was inflicted, the extent of discolouration varied; in basal wounds, the relative proportion of defect due to discolouration was generally higher than for other wounds, adding more volume of total defect to decay. Therefore, the extent of discolouration arising from basal wounds was relatively greater for the total stem length. As observed here, wounds in *P. malaanonan* appear to be highly susceptible to decay. Assuming a linear progression of decay, the average rate of defect development in the samples studied was estimated to be 68 cm^3 wood for every 1 cm^2 of wound area per year. If decay increased at such a high rate, net timber recovery from affected trees would be very low over a 25–30-year cutting cycle.

Determining how decay development varies with logging method adds considerable useful information to the development of better management protocols. The analysis presented here may be important in accounting for site differences in productivity, community dynamics, and carbon biogeochemistry among ecosystems. One approach to combating decay in residual trees is by minimising wounding during silvicultural interventions. Although the additional costs of planning, controlling and monitoring operations are not trivial (Holmes *et al.* 2000; Tay 2000), timber losses due to microbial decomposition can be minimised, thus maintaining the best trees for the next cutting cycle. For species very vulnerable to decay (such as *P. tomentella*), trees wounded during harvesting operations may be extensively decayed by the end of a 30–40-year cutting cycle. Therefore, allowing salvage logging of wounded trees would be an option for optimising timber utilisation. However, where wounded trees are below the minimum felling diameter limit, a change in the regulation to allow their felling would represent a large shift in policy.

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