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Root rot in tree species other than *Acacia*

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Abstract

Surveys of root disease were conducted in forest plantations of *Azadirachta excelsa, Tectona grandis* and *Khaya ivorensis* throughout Peninsular Malaysia. Two major root diseases were found, namely white root disease and brown root disease caused by *Rigidoporus lignosus* and *Phellinus noxius*, respectively. A destructive root disease of *K. ivorensis* caused by an unidentified fungus was found in the state of Negeri Sembilan. These diseases were observed to be closely associated with poor land preparation and areas with a previous history of root disease. Based on experience gained from the management of root-rot disease in rubber plantations, good land management, the construction of isolation trenches and the application of fungicides are suggested as valuable tools in the control of root-rot disease in forest tree plantations.

Root disease causes significant mortality in many forest plantations and is a common explanation for failure in the early phase of plantation development (Wingfield 1999). In particular, root disease is a major threat to plantation monocultures that have been established on land converted from natural forest with poor land-clearing techniques (Lee 1993). Furthermore, the low species and genetic diversity and uniform age of plantations create conditions favourable for the development and spread of root-disease pathogens.

In India, Indonesia, Malaysia and Thailand, root rot has been identified as the most serious disease in plantations of tropical acacias (Old et al. 1997). Root rot is also the most destructive disease of rubber trees and can kill the tree irrespective of age or health status, causing economic losses to the latex industry in many countries (Nandris et al. 1987a; Liyanage 1997; Semangun 2000: Guyot and Flari 2002). The disease has also been reported to aggressively kill fruit trees (Singh 1973; Wood and Lass 1985; Ann et al. 2002).

In Malaysia, interest in forest plantations boomed in the 1990s, and several fast-growing species were introduced. Among these were sentang (*Azadirachta excelsa* (Jack) Jacobs), teak (*Tectona grandis* L.) and khaya (*Khaya ivorensis* A. Chev.). These species were planted with little knowledge of potential pest and disease threats. In 1997, the Forest Research Institute Malaysia (FRIM) began disease surveys throughout Peninsular Malaysia to determine the health status of the most common forest plantation species. Root-disease incidence was the main thrust of the surveys as root diseases have the potential to cause high levels of tree mortality.

Materials and methods

Disease surveys

Root-disease surveys were conducted randomly on 34 forest plantations throughout Peninsular Malaysia from 1997 (Mohd Farid et al. 2005). The surveys focused on plantations of sentang, teak and khaya. Complete and random censuses were conducted in

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small (<0.4 ha) and large-scale plantations (>0.4 ha), respectively. In large-scale plantations, plots of 20 × 20 trees were randomly established and surveyed. In both small and large-scale plantations, trees selected for sampling were inspected individually. Background information on the establishment of the plantations was documented, including planting techniques, land clearing, site history, source of planting materials and silvicultural treatments. Trees suffering from root disease were identified based on observation of both above- and below-ground symptoms. The root system of suspected diseased trees was excavated to examine for potential pathogens.

Pathogens were isolated from root samples in an attempt to identify the organisms causing the root-rot disease. Morphological studies were conducted both macroscopically and microscopically and fungal features were described according to Stalpers (1978). Pathogenicity tests were conducted on 6-month-old seedlings using the method described by Mohd Farid et al. (2001). These tests were conducted under natural field conditions using selected isolates of *Rigidoporus lignosus* (Batu Anam, Johor), *Rigidoporus vinctus* (Pelong, Terengganu) and *Phellinus noxius* (Lendu, Malacca and Tebuk Pulai, Selangor).

Results and discussion

Disease survey

The surveys revealed that disease incidence was variable depending on tree species, land-management practices and location. Root disease was found in only 10 of 34 plantations surveyed (Table 1). Two main diseases were found: white root and brown root disease. White root rot was more dominant on sentang, while brown root disease was present in both teak and sentang plantations. White root disease was recorded in monocultures of sentang at Sik, Kedah and in sentang inter-planted with rubber trees in Batu Anam, Segamat, Ca'ah and Labis in Johor. Disease infection on sentang was recorded from as early as 1 year after planting. Similar results were gained by Maziah et al. (2001) with root-rot disease identified as a major threat to sentang plantations in the early stages of establishment (1–3 years old) and to rubber trees 1–4 years old (Tan and Ismail 1991).

Brown root disease was observed in teak plantations in Sabak Bernam, Selangor and Kuala Kangsar in Perak as well as on sentang in Sik, Kedah and Lendu, Malacca. Maziah and Lee (1999) have previously reported that teak trees 2 years old and above were frequently infected by root disease in Malaysia, and Browne (1968) notes that brown root disease was destructive on teak of 2–12 years old in forest plantations in some countries. In this study, infection of teak trees was recorded from as early as 1 year after planting.

Root disease was found mostly in plantations with poor land preparation, where stumps and wood debris had been left on the ground to decay. The disease was also frequently observed in plantations with a previous history of root disease. Usually, untreated disease centres were also associated with disease incidence and it was considered likely that the pathogen in the new plantations originated from the diseased roots of previous crops. Root disease was low or absent in plantations that has received good land preparation by removing most of the stumps and wood debris (Table 1). Similar observations have been made by Van der Pas and Hood (1983) in *Pinus radiata* plantations in New Zealand.

Overall, the majority of the plantations surveyed were free from root disease. This appeared to be associated with good land preparation and no previous history of root disease. Stumps and wood debris were mechanically removed and burned in the majority of these plantations. However, while root disease was not evident, symptoms of poor tree health, such as stunted growth, small canopy size, small stems and leaves, multiple branching, and sparse and pale foliage, were common. The majority of teak and sentang growers considered poor tree health to have a significant impact on production, particularly during the early phase of plantation establishment (Mohd Farid et al. 2005). The condition is thought to be due to lateritic and/or compacted soil, which impedes the growth of trees. Below ground, cracking of the root surface and a lack of feeder roots were common external signs of affected trees. The main anchoring root, however, was consistently found to be alive and strong enough to support the tree.

Root disease

Macroscopic and microscopic identification of fruitbodies, infected roots and isolates, as well as pathogenicity tests, led to the identification of white root disease and brown root disease caused by *R. lignosus* and *P. noxius,* respectively. The fungi were the causal organisms as proven in the pathogenicity tests.

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Table 1. Host, location, pathogen and land management of forest plantations in Peninsular Malaysia

Host	Site and state	Pathogen	Land management			Age
			Planting technique	Previous history of root disease (Yes/No)	Land preparation	
Teak	Sabak Bernam, Selangor[a]	*Phellinus noxius*[d]	Monoculture	Yes	Poor	10
Teak	Sabak Bernam, Selangor[b]	*P. noxius*[d]	Monoculture	Yes	Poor	10
Teak	Perak River Estate, Kuala Kangsar, Perak	*P. noxius*[d]	Monoculture	Yes	Good	1
Teak	Kaki Bukit, Perlis[a]	Nil	Monoculture	No	Good	8
Teak	Kaki Bukit, Perlis[b]	Nil	Monoculture	No	Good	10
Teak	Kaki Bukit, Perlis[c]	Nil	Monoculture	No	Good	9
Teak	Timah Tasuh, Perlis	Nil	Monoculture	No	Good	8
Teak	Chuping, Perlis	Nil	Monoculture	No	Good	8
Teak	Kompt. 1A/ 99 & 1B/ 99. Bukit Bintang Forest Reserve, Perlis	Nil	Monoculture	No	Good	4
Teak	Bukit Bintang Forest Reserve, Perlis	Nil	Monoculture	No	Good	16
Teak	Kompt. 22 & 23. Bukit Perangin Forest Reserve, Changlon, Kedah	Nil	Monoculture	No	Good	18
Teak	Kompt. 1, 2, 3 & 5 Bukit Perangin Forest Reserve, Changlon, Kedah	Nil	Monoculture	No	Good	18
Teak	Bukit Enggang Forest Reserve, Changlon, Perlis	Nil	Monoculture	No	Good	21
Teak	Tampin, Negeri Sembilan.	Nil	Monoculture	No	Good	7
Sentang	Batu Anam, Segamat, Johor.	*Rigidoporus lignosus* [e]	Mix (sentang × rubber)	Yes	Poor	6
Sentang	Km5. Labis Muar, Johor	Nil	Mix (sentang × rubber)	No	Good	7
Sentang	Pelong, Terengganu	*R. vinctus*	Monoculture	Yes	Poor	3
Sentang	Lendu, Malacca	*P. noxius* [d]	Monoculture	No	Good	1
Sentang	Labis – Muar, Johor	Nil	Monoculture	No	Good	5
Sentang	Ca’ah- Muar, Johor	Nil	Monoculture	No	Good	5

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Table 1. (cont'd) Host, location, pathogen and land management of forest plantations in Peninsular Malaysia

Host	Site and state	Pathogen	Land management			Age
			Planting technique	Previous history of root disease (Yes/No)	Land preparation	
Sentang	KM 37.5, Labis- Yong Peng, Johor	Nil	Monoculture	No	Good	8
Sentang	Km 0.5, Segamat-Muar, Johor	Nil	Monoculture	No	Good	7
Sentang	Bukit Hari, FRIM	Nil	Monoculture	No	Good	5
Sentang	Sik, Kedah	*R. lignosus* [e] *P. noxius* [d]	Monoculture	Yes	Poor	7
Sentang	Kaki bukit, Perlis	Nil	Monoculture	No	Good	8
Sentang	Jementah, Johor	Nil	Monoculture	No	Good	8
Sentang	Ulu Tiram, Johor	Nil	Monoculture	No	Good	6
Sentang	Teluk Intan, Perak	Nil	Monoculture	No	Good	6
Sentang	Bt 9, Jeniang, Kedah	Nil	Monoculture	No	Poor	6
Sentang	Sg. Chinoh Estate, Trolak Perak.	Nil	Monoculture	No	Good	5
Sentang	Labis, Johor	*R. lignosus* [e]	Mix (sentang × rubber tree)	Yes	Poor	7
Sentang	Ca'ah, Johor	*R. lignosus* [e]	Mix (sentang × rubber tree)	Yes	Poor	5
Khaya ivorensis	Felda Titi, Negeri Sembilan	Unidentified	Monoculture	Yes	Poor	3
Khaya ivorensis	Felda Jengka, Pahang	Nil	Monoculture	No	Good	1

[a,b,c] Distinguish between plantations located in the same district
[d] Brown root disease
[e] White root disease

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These pathogens have wide host ranges and are responsible for most root and butt rot diseases in tropical rainforests (Lee 1997). Both *R. lignosus* and *P. noxius* are economically important pathogens as they are responsible for causing more losses than all other pests and diseases combined, especially in rubber plantations (Fox 1977a; Johnston 1989). *Rigidoporus lignosus* is economically important on rubber and timber, especially in Indonesia, Malaysia, Sri Lanka and the Ivory Coast (Liyanage 1997a; Semangun 2000). It is the most destructive disease of rubber (Fox 1977b; Nandris et al. 1987a; Guyot and Flori 2002) and the only disease that directly kills the tree irrespective of age and vigour (Tan and Ismail 1991). *Phellinus noxius* is also a destructive fungal pathogen. It has been recorded on rubber, cocoa, tea, fruit trees and forest trees (Pegler and Waterston 1968; Singh 1973; Wood and Lass 1985; Nandris et al. 1987a,b; Chang 1995; Ann et al. 2002).

In the field, the above-ground symptoms associated with each disease were similar; below-ground symptoms varied. Above ground, the symptoms were wilting, yellowing of leaves, loss of leaf lustre, bark shrinkage, large canopy gaps, defoliation and dieback. The presence of these symptoms usually indicated that the trees were beyond the point of recovery, as the fast progress of infection leads to rapid death (Ismail and Azaldin 1985). Spread of both diseases to adjacent healthy trees was primarily through root contact. This is the most common mode of disease-spread in plantation-grown rubber (Anon. 1974; Holliday 1980; Nandris et al. 1983, 1987a; Rajalakshmy and Jayarathnam 2000), teak (Tewari 1992), *Acacia mangium* (Lee 1997; Maziah 2002; Ito, unpublished data) and Douglas-fir (Wallis and Reynolds 1965). Frequently, the source was infected old stumps or wood debris remaining in the soil or standing diseased trees. In rubber plantations, the source of inoculum for root disease infection is mainly from infected rubber trees, stumps or forest trees (Rajalakshmy and Jayarathnam 2000). This is similar to root rot observed on *A. mangium* by Old et al. (2000).

White rhizomorphs on the root surface were the main indicator in identifying *R. lignosus* in the field. Their presence means that the whole root system has already been exposed to the disease (Wheeler 1974). The disease survey showed that white root disease occurred in both sentang monocultures and sentang inter-planted with rubber. In monocultures, disease incidence was relatively low and diseased trees were scattered or solitary. In mixed plantations, dead trees were more clustered.

Brown root disease was found in both teak and sentang plantations. On teak, the disease caused basal root rot (BRR) at Sabak Bernam, Selangor and root rot at Kuala Kangsar, Perak. Its diagnosis was based on rotting symptoms advancing up the root collar. At present, BRR has been found only on teak at or above 10 years of age where it is planted on marine clay soil known locally as Bernam series. Patches of dead trees were also an indicator of BRR. Below ground, BRR was identified by the presence of a rough sheet of brown mycelial crust on the root surface. Soil particles, mainly of sand, frequently adhered to the crust. In more advanced stages, a honeycomb structure of golden brown hyphae was formed in the rotted wood. These features have been observed and described in detail by various other investigators (Anon. 1974; Nandris et al. 1983, 1987b; Ann et al. 1999). Two plantations of sentang located in Sik, Kedah and Lendu, Malacca were infected by brown root disease that killed both solitary trees and patches of trees irrespective of their health status.

One incidence of root disease was observed in *K. ivorensis* at Felda Titi, Negeri Sembilan caused by an unidentified fungus. Both below-ground and above-ground observations revealed that the disease symptoms were similar to brown root disease caused by *P. noxius*, with some small variations. The surface of the infected tree root was often covered with a brown mycelial crust with adhering soil particles. The crust was usually whitish in colour when young, becoming brownish over time. Further study is needed to identify the unknown pathogen.

Control and management of root disease

At present, the incidence of root disease in forest plantations in Peninsular Malaysia is relatively low compared with that in rubber tree and oil-palm plantations. This destructive disease has the potential, however, to be a major threat to the timber plantation industry in the future. Experience gained in the containment and control of root disease in rubber plantations could provide useful strategies to prevent the spread of the disease in forest plantations.

In rubber plantations, root diseases are managed by cultural practices, especially through land clearing (Old et al. 2000). Therefore, during the conversion of

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land for the establishment of timber tree plantations, stumps and woody debris should be removed and destroyed. The aim of this activity is to reduce the source of potential inoculum in the soil. This approach could minimise the incidence of the disease in the plantations (Fox 1977b; Liyanage and Peries 1982). In rubber plantations, the construction of isolation trenches around trees identified as diseased is another recommended control strategy. This is the most common and popular method of root disease control to prevent disease spread to adjacent healthy trees through root contact (Maziah and Lee 1999). However, the method is costly and labour intensive, especially when large areas or many patches of disease occur in the plantation.

The most common practice of rubber growers to combat white root disease is the application of fungicides by means of soil drenching. Several fungicides, such as hexaconazole, tridemorph, propiconazole, tridemefon, cyproconazole and penconazole, have shown promise in the control of disease caused by *R. lignosus*. The efficacy of the fungicide treatment, however, reduces with increasing levels of infection (Ismail and Shamsuri 1998). Fungicides should therefore be applied only on newly infected trees or trees at mild infection levels.

Conclusion

Two major root diseases of forest plantation species, white root (*R. lignosus*) and brown root (*P. noxius*), were found during the surveys. Sentang was susceptible to white root disease, especially when interplanted with rubber trees. Brown root disease, in comparison, was found in both teak and sentang plantations. A root disease caused by an unidentified fungus was found on khaya at Felda Titi in Negeri Sembilan. This pathogen killed its host aggressively without showing early symptoms. Trees infected by this disease were almost indistinguishable from healthy trees, with symptoms discernible only during the advanced stages of infection.

The survey also revealed that infection started mainly from infected roots of trees, stumps or root remnants remaining in the soil, and that spread to adjacent trees was through root contact. Good land preparation by removing all woody debris and stumps in the soil before plantation establishment was therefore considered vital to reduce disease incidence.

Based on the experience of rubber-tree growers in the control of white root rot disease caused by *R. lignosus*, good land clearing during site preparation, the construction of isolation trenches and the application of fungicides are recommended as valuable tools to help manage root rot disease in forest tree plantations.

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The biological control of Ganoderma root rot by *Trichoderma*

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Abstract

This paper describes the ability of *Trichoderma* spp. to act as agents for biological of *Ganoderma*. Certain species of *Ganoderma* are potential root-rot pathogens and are capable of causing serious damage to many types of plantation-tree species in Indonesia. Biological control of plant pathogens aims to decrease dependence on chemical treatments which may cause environmental pollution and the development of resistant strains. Filamentous fungi such *Trichoderma* that are mycoparasites of plant pathogens have potential for the biocontrol of plant disease. Species of *Trichoderma* are one of the most widely tested agents. Although the mechanism of mycoparasitism is not fully understood, expression of extracellular cell-wall degrading enzymes is assumed to be involved in this process, including the action of chitinolytic and glucanolytic enzymes. As reported for other chitinolytic systems, the endochitinase (EC 3.2.1.14) is among the most effective for both antifungal and lytic activities in comparison with other types of chitinolytic enzymes. Recently, 32-kDa endochitinolytic enzymes have been purified from *Trichoderma reesei* and characterised. We have tested the antagonistic ability of *Trichoderma* isolates against some plant pathogenic fungi, such as *Ganoderma* spp., *Rigidoporus microporus*, *Rhizoctonia* spp., *Fusarium* sp., and *Sclerotium rolfsii*. Results show that *Trichoderma* spp. can suppress the development of fungal pathogens in vitro and in glasshouse experiments.

Intensive forestry is based on growing one or few tree species over large areas. These plantation ecosystems are ecologically unbalanced and favour epidemics of pathogens or pests that interfere with the production of a healthy, valuable tree crop. Prevention of such epidemics in forest plantations cannot be achieved through the use of chemical fungicides since it would not be cost-effective or environmentally sustainable. Consumers are increasingly concerned about the chemical pollution of the environment, and pathogens could become resistant to available chemicals if these are used indiscriminately. The options currently available to manage soil-borne disease are limited, and measures must be developed to avoid the start of an epidemic by preventing inoculum build-up.

In agriculture, and to some extent forestry, the chemical treatment of pests has been replaced or reduced through the use of biologically based fungicides. A broad definition of biological control is the reduction of the amount of inoculum or disease-producing activity of a pathogen accomplished by or through one or more organisms other than humans (Cook and Baker 1983). This definition includes the use of less-virulent variants of the pathogen, more resistant cultivars of the host, and microbial antagonists that interfere with the survival or disease-producing activities of the pathogen. This paper discusses the development of a biological control for Ganoderma rot root disease using antagonistic fungi of the genus *Trichoderma.*

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What are *Ganoderma*?

The Ganodermataceae are cosmopolitan basidiomycetes which cause root rot of many temperate and tropical hardwoods by decomposing lignin as well as cellulose and related polysaccharides (Hepting 1971; Blanchette 1984; Adaskaveg and Ogawa 1990; Adaskaveg et al. 1991, 1993). Successive replanting of monocultures such as *Acacia mangium* Willd. in Southeast Asia can be rapidly exploited by soil-borne fungi such as *Ganoderma*, and this particular problem will become more serious as more areas move into second or even third-rotation planting. Environmental considerations also mean that native forest areas can no longer be exploited, making further replanting of these plantation forests inevitable. It is thus essential to develop appropriate, integrated management systems for root rot diseases.

Ganoderma spp. have been found worldwide on a range of broad-leaved hosts (Phillips and Burdekin 1989). Butt rot and root rot symptoms of *Ganoderma* spp. have been recognised on planted *Acacia* in northern Australia (C. Mohammed, pers. comm.), in a provenance trial in Peninsular Malaysia, in northern Sumatra (Lee 1996) and elsewhere in Indonesia (Irianto et al. 2006). Root-rot disease caused by *Ganoderma* spp. has been reported as the most serious disease of *A. mangium* in West Bengal, India (Sharma and Florence 1996).

What are *Trichoderma*?

Trichoderma spp. are fungi that are often dominant components of the soil microflora in widely varying habitats. This may be attributable to their diverse metabolic capability and their aggressively competitive nature. Strains of *Trichoderma* are rarely associated with disease in living plants.

The high degree of ecological adaptability shown by strains within the genus, coupled with their amenability to cultivation on inexpensive substrates, make *Trichoderma* isolates attractive candidates for a variety of biological control applications (Hjeljord and Tronsmo 1998). As fast-growing saprophytes, *Trichoderma* can compete ecologically over the long term as well as at the time of application and are able to colonise potential infection courts, such as growing roots, wounds, or senescent tissue, as they become available. As living organisms, biological control agents can act as aggressive mycoparasites and adapt to changes in their habitat in a manner not possible by chemical fungicides. *Trichoderma* can be used to attack established pathogens as well as preventing the establishment of disease.

Antagonistic mechanisms of *Trichoderma*

In addition to colonising roots, *Trichoderma* spp. attack, parasitise and otherwise obtain nutrition from other fungi. Since *Trichoderma* spp. grow and proliferate when there are abundant healthy roots, they have evolved numerous mechanisms to enable them to attack other fungi and to enhance plant and root growth.

A list of recently described mechanisms follows:

- mycoparasitism — in which one fungus derives its nutrition from another without any benefit in return. The interaction can be where the parasite is biotrophic or necrotrophic as is the case for *Trichoderma*.
- antibiosis — an association between two organisms that is detrimental to the vital activities of one of them and, in fungi, is usually mediated by toxic metabolites produced by one organism
- competition for nutrients or space — the active requirement for resources in excess of those immediately available to two or more organisms. The production of toxic metabolites is known to be affected by the nutrient status of the growth medium (Ghisalberti and Sivasithamparan 1991; Howell and Stipanovic 1995).
- tolerance to stress through enhanced root and plant development
- solubilisation and sequestration of inorganic nutrients
- induced resistance
- inactivation of the pathogen’s enzymes.

Trichoderma strains produce a variety of volatile and non-volatile toxic metabolites. Of these, some are considered to be antibiotics as they can inhibit the growth of other microorganisms without physical contact between the fungi. The best known of the antifungal metabolites produced by isolates of this genus is the coconut-scented 6-n-pentyl-2H-pyran-2-one (PPT) (Claydon et al. 1987). In addition, many strains of *Trichoderma* are able to produce extracellular cell-wall-degrading enzymes which are also capable of killing at a distance. These, however, are traditionally included in the concept of mycopara-

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sitism, due to their integral role in direct physical interactions.

Trichoderma as biological control agents for agents of root-rot disease including *Ganoderma*

In order to test the potential antagonistic effects of *Trichoderma* spp. against various root-rot pathogens causing problems in Indonesia, we prepared cultures by placing agar plugs containing the mycelia of the two antagonists (*Trichoderma* and root-rot pathogen) on opposite sides of the agar plate. The plant pathogenic fungi tested against *Trichoderma* spp. isolates were *Ganoderma* spp. (Widyastuti and Sumardi 1998; Widyastuti et al. 1998a, 1999), *Rigidoporus microporus* (Widyastuti et al. 1998b), *Rhizoctonia* spp. (S.M. Widyastuti, Harjono, Sumardi and N.S. Lestari, unpublished data; S.M. Widyastuti, Sumardi, Harjono and E. Windyarini, unpublished data), *Fusarium* sp. (S.M. Widyastuti, Sumardi and Y. Mitikauji, unpublished data) and *Sclerotium rolfsii* (Widyastuti et al. 2003). Control plates were inoculated with only one of the antagonists but on both sides of each individual plate in order to simulate growth conditions as comparable as possible to those in the test plates. Replicates comprised of a minimum of three plates per combination of each pair of fungi. Interaction zones, i.e. the areas of contact and subsequent overlap of hyphae of *Trichoderma* spp. and pathogenic fungi, were observed at various magnifications in situ by light microscopy.

Among the 120 isolates of *Trichoderma* spp. tested against the pathogenic fungi we recorded examples of the basic types of antagonistic behaviour — antibiosis, mycoparasitism, and competition (Figure 1). The type of antagonism that appeared the most effective in inhibiting the root-rot pathogens tested was mycoparasitism (when the *Trichoderma* grew within the pathogen's colony (Figure 1a)). Antagonism by competition occurred when both the pathogen and *Trichoderma* grew but the growth of *Trichoderma* limits the full access of the pathogen to the substrate (Figure 1b). No one colony was able to dominate the substrate once hyphal contact was established (Figure 1b). Interactions typical of antibiosis were observed, i.e the *Trichoderma* isolate is producing toxic compounds and the colony of the root-rot pathogen is severely restricted and clearly contained by the *Trichoderma* (see Figure 1c in comparison to 1b).

In another experiment, three *Trichoderma* isolates, previously shown to have high antagonistic ability (*T. koningii* isolate T1, *T. reesei* isolate T13 and *T. harzianum* isolate T27; Figure 2) were tested against isolates of *Ganoderma* collected from different tree species. It was significant, however, that these *Trichoderma* isolates of known high antagonistic ability actually varied greatly in their level of antagonism towards the different *Ganoderma* isolates. Widyastuti et al. (1999) showed in paired cultures that a *Trichoderma* isolate which was highly effective against one isolate of a pathogen could have minimal effect on other isolates of this pathogen (Table 1). This might be related to the high pathogen–*Trichoderma* specificity of antagonistic mechanisms due to antibiosis (Howell and Stipanovic 1995) and cell-wall-degrading enzymes (Haran et al. 1996). This specificity theory is most probable since the *Ganoderma* isolates could have been different isolates of the same *Ganoderma* species or isolates of different *Ganoderma* species and their identity will be tested in future work.

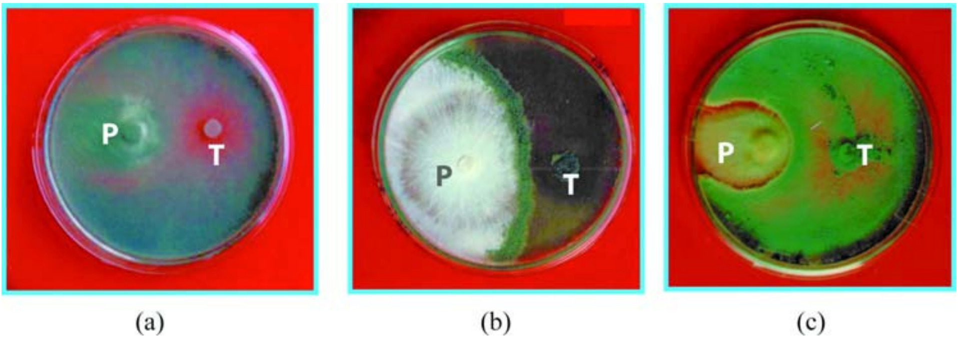

Figure 1. Three basic interaction mechanisms between *Trichoderma* and pathogenic fungal isolates: (a) mycoparasitism, (b) competition, (c) antibiosis. Key**:** **T** = *Trichoderma,* **P** = Pathogen.

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Microscopic observation of antagonistic interactions between *Ganoderma philippi* and *Trichoderma*

Hyphal interactions were observed under a light microscope with hyphae that had been stained in 10% (v/v) lactophenol blue for 5 minutes. Observations of the zone of the confrontation between *Trichoderma* and *Ganoderma philippi* isolates indicated a range in the types of hyphal interactions. The diameter and the intensity of staining of *Ganoderma* and *Trichoderma* fungal hyphae were different, so they were easily distinguished from each other (Figure 3a–c). All *Trichoderma* isolates were frequently observed to grow parallel to the pathogen. Hyphae of *T. reesei* and *T. harzianum* often coiled around the pathogen (Figure 3a,b), but no coiling was shown by *T. koningii* (Figure 3c). *Trichoderma reesei* and *T. harzianum* both produced appresoria at the tips of short branches (Figure 3d) or formed a hook-like structure (Figure 3e). No such structures were produced by *T. koningii*. The above responses observed (growing parallel to the pathogen, coiling, appresoria, hooks) are considered to be examples of mycoparasitic activity and are similar to those described by Elad et al. (1983), who observed the mycoparasitic activity of *T. harzianum* against *S. rolfsii* and *R. solani* using scanning electron and fluorescence microscopy.

Trichoderma reesei was the most effective mycoparasite in interactions with *Ganoderma* isolates, followed by *T. koningii* and *T. harzianum* (Widyastuti et al. 2003; Figures 2–3 in this paper). In interactions with pathogenic fungi other than *Ganoderma*, *T. koningii* has displayed a typical antibiosis inhibition pattern of confinement (e.g. Figure 1c), whereas in interactions with *Ganoderma* the *T. koningii* isolate T1 demonstrated limited mycoparasite properties (with hyphae growing parallel to the pathogen). This isolate T_1 can most probably exhibit both main types of fungal inhibition, mycoparasitism and antibiosis depending on the particular species of fungal pathogens with which it is interacting (Widyastuti et al. 2003).

Table 1. Growth inhibition of *Ganoderma* spp. from eight different tree species in co-culture with three *Trichoderma* spp. isolates

Isolate number	Tree species	Mean growth inhibition (%)		
		T. koningii (T_1)	*T. reesei* (T_{27})	*T. harzianum* (T_{13})
13	*Paraserianthes falcataria*	62.8	100.0	56.4
24	*Leucaena leucochepala*	99.5	100.0	89.4
2	*Acacia mangium*	94.3	96.5	79.8
9	*A. auriculiformis*	96.4	98.4	86.6
19	*Cassia siamea*	98.6	98.3	90.6
10	*Delonix regia*	97.0	98.2	83.0
4	*A. mangium*	98.8	98.2	84.6
17	*Dalbergia latifolia*	98.5	95.7	71.6

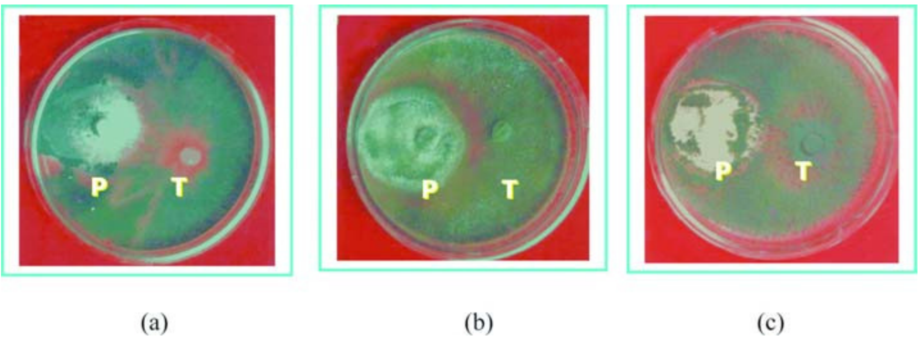

Figure 2. Antagonistic ability of three *Trichoderma* isolates varied towards pathogenic fungi (*Ganoderma* sp.) grown in paired cultures on agar: (a) *Ganoderma* sp. vs *T. Reesei*; (b) *Ganoderma* sp. vs *T. Koningii*; (c) *Ganoderma* sp. vs *T. harzianum*. Key: **P** = Pathogen, **T** = *Trichoderma*

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Extra-cellular enzyme production in *Trichoderma–Ganoderma philippi* interactions

Extracellular cell-wall-degrading enzymes such as chitinolytic and glucanolytic enzymes are believed to be involved in mycoparasitism. Recently, 32-kDa endochitinolytic enzyme was purified and characterised from *T. reesei* (Harjono et al. 2001; Harjono and Widyastuti 2001a) and tested for its ability to inhibit colony and hyphal growth of *G. philippii* isolate T_{13} (Harjono and Widyastuti 2001b).

The colony development of *G. philippii* is clearly inhibited at concentrations of 90–200 mg/mL (Figure 4a). A concentration of 80 µg/mL shows only an obscure inhibition zone. No inhibition zone is observed at concentrations of 40–70 µg/mL.

Microscopic observations revealed that morphological changes in *G. philippii* hyphae were induced by *T. reesei* 32-kDa endochitinase (Table 2). Branching and segmentation of hyphal tips occurred at 60 µg/mL of endochitinase application (Table 2 and Figure 4b,c). At this concentration, the enzyme also caused swollen hyphal tips (Figure 4d).

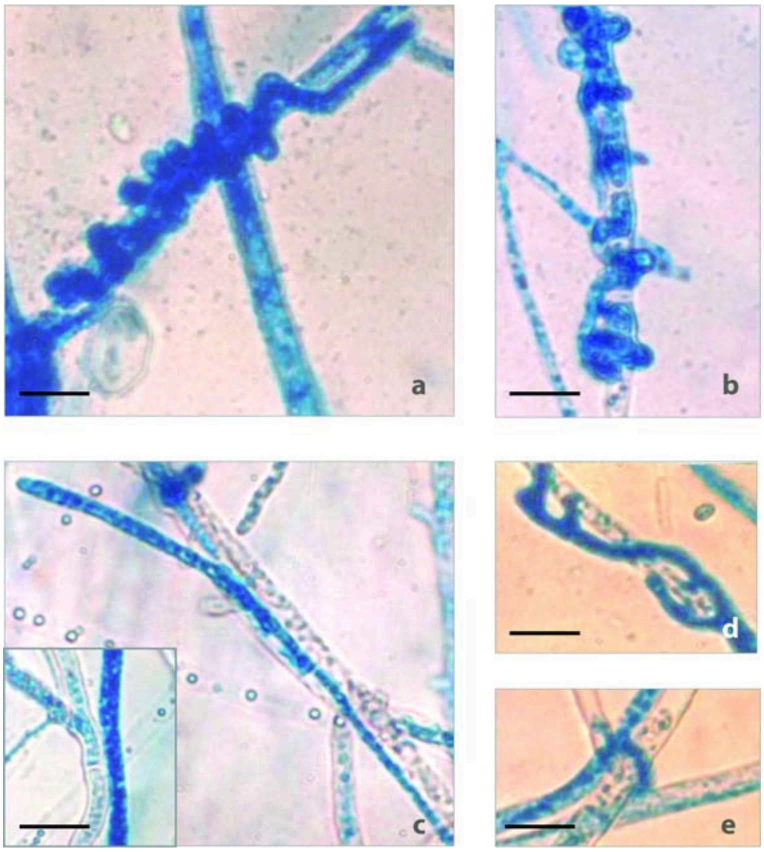

Figure 3. Light microscopy of *Trichoderma* hyphae interacting with that of *Ganoderma*: (a and b) Condensed coiling of *T. reesei* and *T. harzianum*, respectively, around a hypha of *Ganoderma* sp. (c) *T. koningii* could grow parallel to hypha of *Ganoderma* sp. but no coiling was observed. (d) Appresorium-like structures, formed by *T. reesei,* also found in *T. harzianum* but not in *T. koningii*. (e) Hook-like structure found in *T. reesei* and *T. harzianum* which serve as an attachment to the host mycelium. (Bar represents 10 µm).

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Hyphal necrotic lesions were observed at concentrations 80, 90, 100 and 200 µg/mL (Table 2). The latter 32-kDa endochitinase concentrations caused permanent hyphal necrosis of *G. philippii* (Figure 4e). Hyphal lysis by the enzyme was observed at a concentration of 90 µg/mL and the mean percentage increased dramatically at a concentration of 200 µg/mL (Table 2). At this high concentration, cell bursting and protoplast release was observed not only on hyphal tips (Figure 4g), but also on mature hyphae (Figure 4h). Enzyme application at low concentrations (80 µg/mL) failed to suppress the growth of hyphae (Figure 4f).

Efficacy of formulated *Trichoderma* as a biological control agent tested against *Sclerotium rolfsii*

Greenhouse experiments were used to evaluate the efficacy of isolates T_{13} (*T. reesei*), T_{27} (*T. harzianum*) and T_1 (*T. koningii*) as biological control agents in a formulation of alginate beads (Widyastuti et al. 2003, 2006a,b,c), against a common damping-off pathogen, *Sclerotium rolfsii*. The levels of biological control achieved for the damping-off by *S. rolfsii* on pine seedlings by applying *Trichoderma* spp. to soil are recorded in Table 3. The application of formulated *Trichoderma* into potting soil 4 days before the pathogen *S. rolfsii* was inoculated gave the best disease suppression, with the *Trichoderma* delaying the initiation of symptoms and reducing disease incidence. *Trichoderma reesei*, *T. harzianum* and *T. koningii* delayed the initiation of symptoms and decreased disease incidence by 73%, 67% and 47%, respectively, when applied 4 days before disease inoculation. Disease reduction by *Trichoderma* declined drastically when *Trichoderma* was applied 4 days after inoculation with *S. rolfsii*. Adaptation and establishment of *Trichoderma* before pathogen inoculation probably increases antagonistic capability. Our results agree with findings of Widyastuti et al. (2002) that formulated *Trichoderma* needs a period of adaptation in order to actively inhibit the growth of pathogenic fungi.

Table 3. Control by three isolates of *Trichoderma* formulated in alginate beads of damping-off caused by *Sclerotium rolfsii* in greenhouse-grown pine seedlings

Trichoderma isolates	Disease reduction according to *S. rolfsii* inoculation[a]		
	4 days before	At the same time	4 days after
T. koningii isolate T_1	46.7*b*	43.3*ab*	3.3*b*
T. reesei isolate T_{13}	73.3*a*	50.0*a*	23.3*a*
T. harzianum isolate T_{27}	66.7*a*	56.7*a*	6.7*b*

[a] Data in each column which are followed by a common letter are not statistically different (p=0.05). Percentage disease reduction was calculated by counting the number of dead or dying plants in 15-day-old pine seedlings.

Table 2. Microscopic observations of the morphological anomalies in *G. philippii* hyphae caused by 32-kDa *Trichoderma reesei* endochitinase[a]

Endochitinase concentration (µg/mL)	Appearance of abnormal hyphae[b]				
	Segmented	Branched	Swollen	Necrotic	Lysed
0	–	–	–	–	–
40	–	–	–	–	–
50	–	–	–	–	–
60	1.7	0.8	1.8	–	–
70	1.7	2.5	0.8	–	–
80	4.2	2.5	2.5	5.0	–
90	6.7	5.0	2.5	8.3	1.7
100	10.8	5.8	7.5	11.7	9.2
200	7.5	8.3	6.7	15.8	14.2

[a] Data obtained 12 hours after enzyme application.
[b] Percentage of 120 hyphae observed under microscope (mean of two replications).
– Indicates that at these concentrations the endochitinase did not induce a morphological response in *Ganoderma* hyphae.

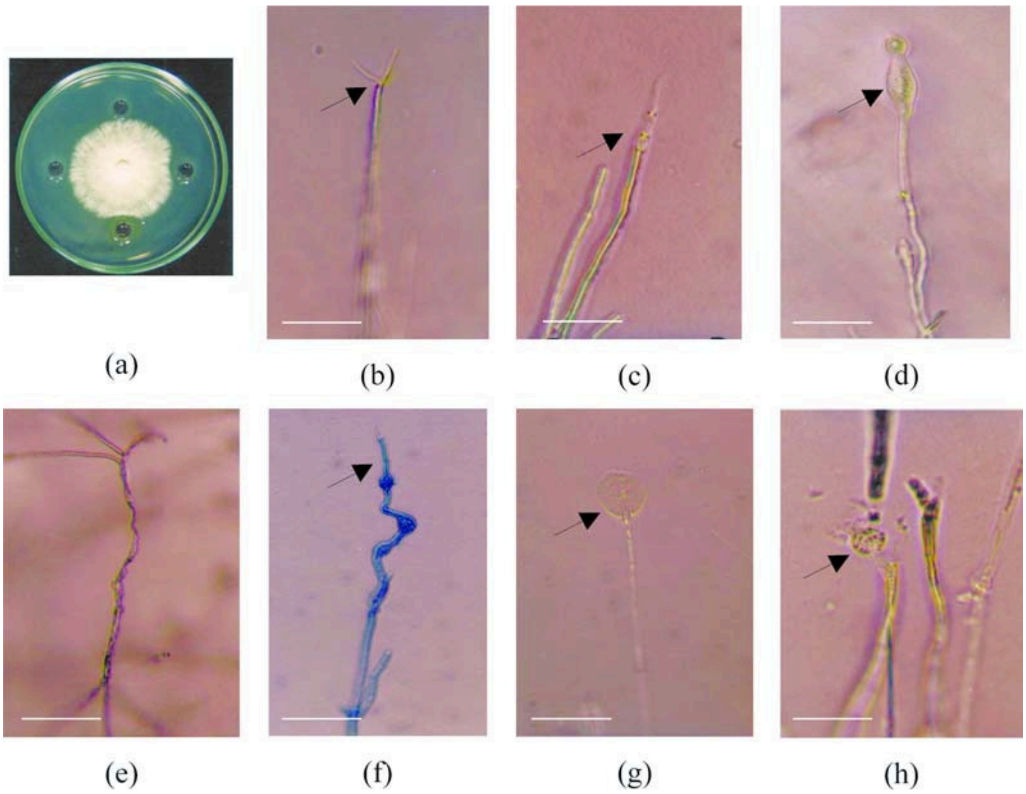

Figure 4. Effects of the 32 k-Da *T. reesei* endochitinase on hyphae of *G. philippii*: (a) Growth inhibition of *G. philippii* in response to various endochitinase concentrations (from top, in clockwise direction, 50, 100, 200, 0 μg/mL); (b, c, d) Branching, segmentation and swollen hyphal tip of *G. philippii* in the presence of endochitinase at 60 μg/mL and above; (e) *G. philippii* hyphae necrotic at hyphal tip grown in the presence of endochitinase higher than 70 μg/mL; (f) Hyphae of *G. philippii* after enzyme exposure of 80 μg/mL showing recovery after swelling and continued normal hyphal growth; (g) Cell bursting and protoplast release of hyphal tips in the presence of endochitinase at 90 to 200 μg/mL; (h) Cell bursting and protoplast release of mature hyphae. (Bars = 30 μm)

Conclusion

This paper provides an overview of various aspects of the antagonism of *Trichoderma* isolates that are relevant to their use as biological control agents. We are now able to screen *Trichoderma* isolates for traits relevant to antagonism, and select isolates according to their potential for biological control. Applied in appropriate biologically based formulations and delivery systems and at the right stage of the disease cycle, specific *Trichoderma* isolates selected for high levels of *Ganoderma*-suppressive activity warrant further investigation. Such *Trichoderma* isolates offer the potential for consistent and effective control of *Ganoderma* root rot without using chemical fungicides and the ensuing dangers of environmental pollution and the development of fungicide resistance.

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Minimising disease incidence in *Acacia* in the nursery

Budi Tjahjono[1]

Abstract

Disease management in the nursery requires detailed knowledge of the potential pathogens and their interactions with the seedlings and their environment. The behaviour of the pathogen must also be considered in the wider context of the nursery operation. The conditions that favour a range of foliar, stem and root diseases of *Acacia* seedlings in the nursery are described. Integral control strategies are discussed in general, and in detail for *Xanthomonas* sp., the common bacterial leaf blight of *Acacia crassicarpa*.

Reforestation of the industrial plantation forest (or HTI) in Indonesia should be undertaken by planting seedlings immediately after an area has been cut over. Implementing this recommendation, however, requires the timely supply of seedlings and often creates a demand for high rates of production from plantation nurseries. To attain this goal, uniform, vigorous, high-quality seedlings must be produced and disease incidence and losses kept to a minimum. Seedling losses in the nursery directly affect rates of plantation establishment, as well as increasing maintenance costs during the rotation.

Nursery management

It is important to identify the actual and potential disease problems in the nursery in order to implement an effective disease-management strategy. Detailed knowledge of the pathogen and its interaction with the seedling and environment is vital. Information on the origin of the pathogen, how it is spread, the severity of its impact, what environmental and host factors favour its development, and its response to fungicides, all contribute to the development of control strategies.

Disease management must be considered in the context of the wider nursery operation: container management, shading, irrigation, fertiliser application, pest control and sanitation. Most diseases in nurseries can be adequately managed by the application of good cultural practices. Poor practices, such as incorrect sowing depth, high seedling density and inappropriate levels of shade, can increase the incidence and severity of diseases.

Crowding of seedlings encourages the development of some diseases that are much reduced or disappear after the stock has been transplanted in the field. Whether the seedlings are grown under shade net, plastic protection or the open sky also affects the occurrence of nursery diseases. Excessive shade, resulting in low light intensity, tends to lower soil temperature and raise the water potential, favouring the development of damping-off disease. Conversely, seedbeds under high light intensity tend to have higher soil temperature and lower soil-water potential, conditions that favour the development of seedling blight and shoot blight.

The selection of growing medium is also important in nursery disease management. Seedbed soils and container mixes for acacia seedlings need to have good

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structure, be free-draining and slightly acid (pH5–5.5). Poor drainage causes waterlogging damage and can lead to the development of soil-borne diseases. An ideal medium for container production of acacia seedlings has an organic base to support the nursery production phase (about 10–12 weeks), with sufficient added fertiliser to reduce follow-up fertiliser application to a minimum. Organic-based media also provide a receptive base should inoculations of mycorrhizae or biological control agents be required. Acacia seedling growth is generally restricted in the nursery after 10 weeks through reduced irrigation and fertiliser. If seedlings are retained in the nursery for more than 12 weeks, there is potential for severe levels of diseases to develop.

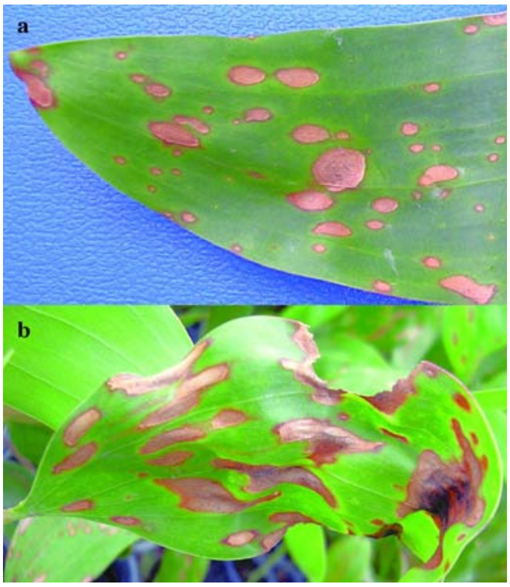

Figure 1. Common leaf diseases in *Acacia crassicarpa*: (a) *Pestalotiopsis* leaf spot; (b) *Phaeotrichoconis* leaf spot

Foliage diseases

For an infection to be established, fungi and bacteria that cause foliage diseases usually require conditions of high moisture and free water in and around stems and foliage for long periods. Foliage diseases are therefore most prevalent in locations where frequent rain or the continuous use of overhead irrigation allows these conditions to develop.

Common leaf diseases in *Acacia crassicarpa* A. Cunn. ex Benth. seedlings are *Pestalotiopsis* leaf spot (Figure 1a), *Phaeotrichoconis* leaf spot (Figure 1b) and bacterial leaf blight caused by *Xanthomonas* sp. Important leaf diseases on *Acacia mangium* Willd. seedlings are phyllode rust disease caused by *Atelocauda digitata* (Figure 2), anthracnose disease and tip necrosis caused by *Colletotrichum* sp.

Stem and root diseases

From germination through the first few weeks after emergence, the succulent radicle and hypocotyl tissues of *Acacia* seedlings are extremely susceptible to attack by damping-off fungi. *Pythium, Rhizoctonia* and *Fusarium* are fungi that commonly cause damping-off. The exact cause of many root diseases is often difficult to determine without laboratory analysis. Pre-emergence damping-off is caused by fungi that rot seedlings before they emerge. Post-emergence damping-off is caused by fungi that infect and kill stem tissues at ground level after seedling emergence, resulting in seedling collapse. Because damping-off is significantly influenced by environmental conditions, the severity of this disease fluctuates from year to year. In general, conditions that reduce seedling growth and vigour predispose nursery stock to increased infection from damping-off fungi. Nitrogen fertilisers applied before or during the first few weeks after seedling emergence may also increase infection. Other diseases of seedlings include canker and dieback pathogens. These attack the stems and branches of nursery seedlings, cause sunken lesions and malformations, and often lead to seedling death.

Integrated disease management

The basic approach to disease management in the nursery should be to avoid disease rather than have to apply controls after a disease outbreak. Common ways to minimise disease in nurseries that raise *Acacia* seedlings include:

- use of high-quality seeds from genetic material that has disease resistance
- cultural control through growing conditions, media and cultural practices
- proper irrigation and drainage
- good hygiene and quarantine
- the application of chemical or biological control, including selective pesticides that kill or inactivate the pathogen but cause relatively no harm to the seedlings.

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Figure 2. Phyllode rust caused by *Atelocauda digitata* on *Acacia mangium* seedlings

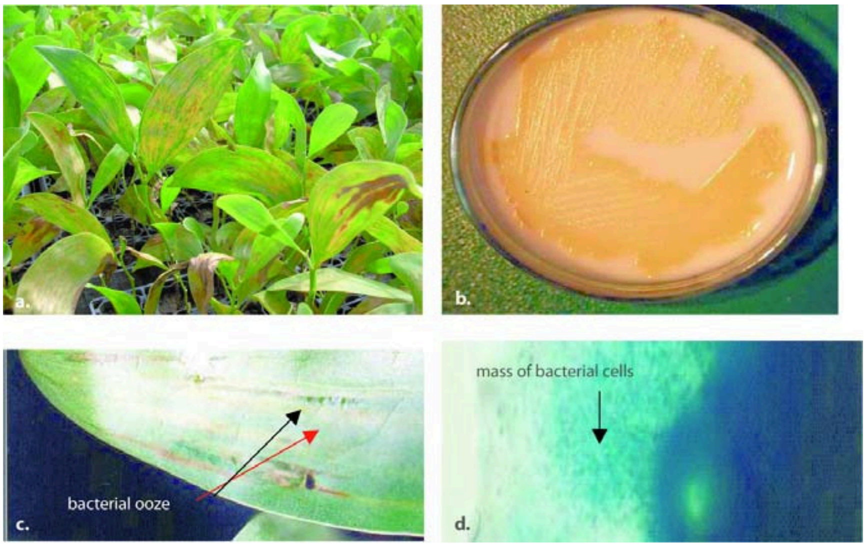

Figure 3. Common bacterial leaf blight in *A. crassicarpa* seedlings: (a) symptoms; (b) yellow colony of pathogenic bacteria *Xanthomonas* sp.; (c) leaf with bacterial ooze; (d) cross-section of infected leaf (400× magnification)

Several cultural practices can reduce or control nursery diseases. Good-quality growing media and full containers encourage the growth of vigorous seedlings that are better able to resist stress and disease. Good hygiene and housekeeping, based on the nursery area being kept well-drained, clean and orderly, reduce disease infection and loss of seedlings. Watering should be done only as needed and the irrigation systems should be regularly inspected for leaks or blockages. Foliage diseases in particular can be inhibited by reducing seedbed density in order to lower humidity and increase air circulation around the leaves. The removal and controlled burning of heavily infected and dead seedlings from seedbeds will

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reduce the source of inoculum, as well the likelihood of subsequent infection of other nursery seedlings.

Chemical or biological pesticides may be used to protect seedlings from infection or eradicate a pathogen already present in the nursery. Spraying with a fungicide, for instance, protects the seedlings by coating the foliage with a chemical barrier that is toxic to foliar pathogens. Such chemical control requires proper timing to coincide with periods of potential infection. Soil fumigation before planting can control root-disease pathogens, but seldom will it completely eradicate them.

The concept of integrated disease management in the nursery can be represented by the palm of the hand and its five fingers. Each finger represents one of the five components of disease control (see dot points above); the palm is the nursery manager. The palm is central to coordinating the five fingers. A single approach to disease management in the nursery seldom leads to disease control.

The integrated management of common bacterial leaf blight — a case study

Bacterial leaf blight of *A. crassicarpa* caused by *Xanthomonas* sp. is a common problem in the nursery (Figure 3). *Acacia mangium* and *Acacia auriculiformis* A. Cunn. ex Benth. appear immune to this disease. Conditions that predispose seedlings to the development of bacterial leaf blight include:

- stress due to excess or lack of water, lack or imbalance in nutrition, unsuitable growing media and/or excess nitrogen fertiliser application
- poor sanitation of media, water supplies and tube sterilisation
- intense rainfall or strong splash water from irrigation
- leaf scars/lesions as entry points for the bacteria.

The recommended steps for integrated control are:

- use suitable growing media with adequate porosity but high water retention
- water only when required and ensure fertiliser applied is balanced
- maintain good nursery hygiene with proper drainage
- remove and burn dead and severely diseased plants
- handle seedlings gently to reduce scars and lesions
- sterilise (using steam if possible) equipment, seedbed, containers
- apply bactericide: Agrept 20 WP and Kibox (copper oxychloride)
- plant non-host plant material, i.e. species other than *A. crassicarpa.*

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Developing a strategy for pruning and thinning *Acacia mangium* to increase wood value

Chris Beadle[1]

Abstract

Timber production from *Acacia mangium* plantations in Indonesia can potentially supply both domestic and export markets for furniture and other functional and appearance products. In plantations, there is potential for large and persistent branches to develop, and the threat of persistent dead branches and of heart rot. This has resulted in the need for pruning systems based on the removal of green branches from below, and thinning systems that ensure final-crop trees retain green branches until pruning is completed, as well as maintaining acceptable rates of growth of the retained trees. This paper outlines a pruning and thinning strategy for *A. mangium* that attempts to meet the criteria required for growing high-quality, clear-wood plantations. Form-pruning to encourage the development of good form ahead of lift-pruning is used in a system that results in about 300 stems/ha of trees pruned to 4.5 m in the final crop. It is concluded that heart rot is made worse by pruning when the plant material is susceptible and a sufficient source of fungi is present to invade pruning wounds.

Acacia mangium Willd. plantations represent a significant proportion of the wood supply to the pulp and paper industry in Indonesia (Rimbawanto 2002). The species is fast growing and of medium density. When free from defects, the wood looks similar to teak (Gales 2002). The timber is also used in the domestic market in Indonesia for furniture and other functional and appearance products, and exported for finger-jointing in a developing overseas market (Hardiyanto 2006). With relatively short rotations of no more than 20 years to produce saw logs (Srivastava 1993), *A. mangium* timber production could supply a substantial part of the solid-wood market in the medium term. Knots and heart rot are undesirable characteristics that reduce the strength, appearance and value of the timber. Variable numbers of trees are also multi-stemmed at the base, the proportion probably related to genotype and site conditions (Srivastava 1993). Single stems are required for plantation silviculture and are essential for solid-wood production. A pruning strategy therefore becomes necessary.

When managed for pulpwood, *A. mangium* plantations are established at around 1000 stems/ha. Such planting densities are too high for all the trees to be managed for solid wood. A lower stocking at planting is one option but experience from growing other species suggests that starting with higher stockings ensures that there are sufficient potential final-crop trees in the stand that meet criteria for pruning (Beadle et al. 1994). Higher stockings also impose some control on average branch size. Large branches are more difficult to prune and potentially more susceptible to decay entry. A thinning strategy therefore becomes an inevitable part of the silviculture of *A. mangium* plantations for solid-wood production.

Pruning

Acacia mangium has persistent branches. This has led to the development of lift-pruning regimes where

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branches are removed from the base of the tree upwards to convert the bottom log to clear or knot-free wood (Mead and Speechly 1991; Weinland and Zuhaidi 1991). The results of studies of a number of species indicate that the preferred practice is green pruning that removes live rather than dead branches. Dead branches are associated with a high percentage of discoloration and decay in unpruned *A. mangium* (Ito and Nanis 1994). Pruning live branches also prevents the development of loose knots and decreases the size of the knotty core.

The removal of live branches inevitably reduces the productive capacity of an individual tree because of the loss of green leaf area. This is of particular concern in systems where only a proportion of the planted trees are selected for pruning, potentially putting them at a competitive disadvantage against the unpruned trees. Prescriptions must therefore optimise clear-wood production in such a way that there is no significant effect on tree growth after pruning.

Large branches are generally associated with poor stem form and with a high risk of decay entry after pruning. In a study of fungal infection two years after pruning *A. mangium*, Weinland and Zuhaidi (unpublished data; see Srivastava (1993)) noted that wounds of diameter >20 mm were always infected whether the branches had been removed when green or dead. In *Eucalyptus nitens* (Maiden), the length of decay columns increased exponentially when the diameter of pruned branches was >20 mm. Branches at a narrow angle to the stem were also associated with a greater risk of decay (Mohammed et al. 2000). Thus, control of branch size is of vital importance in the silviculture of plantations managed for solid wood. Stocking and form-pruning provide two options for such control. Increasing the initial stocking density will reduce the incidence of large branches (Neilsen and Gerrand 1999) but more intense inter-tree competition will then reduce the average growth of individual trees. Form-pruning selectively removes branches throughout the crown and can be used to reduce average branch size before subsequent lift-pruning (Pinkard 2002).

The proportion of branches that can be removed at any one pruning before growth is affected is a function of species and site (Table 1). Slower-growing species, for example, are more affected by pruning than faster-growing species. In one experiment in Malaysia, *A. mangium* tolerated the removal of 40% of its crown length by lift-pruning before growth was significantly affected (Majid and Paudyal 1992). Growth is less affected by pruning on a high than a low quality site (Pinkard and Beadle 1998a), so pruning severity must be reduced on sites associated with slower rates of growth. In general, pruning affects height growth less than it does diameter growth. In a stand planted at 1100 stems per hectare in South Sumatra (C.L. Beadle, K. Barry, E. Hardiyanto, R. Irianto, Junarto, C. Mohammed and A. Rimbawanto, unpublished data), height and diameter growth following removal of 25% of crown length using lift-pruning was significantly greater 18 months after pruning than in an unpruned control (Table 2). However, the pruning treatment had been singled while the controls had not, and it is likely that competition between multiple stems slowed individual stem growth of the controls.

In the same stand in South Sumatra, a form-pruning treatment removed selected branches up to 3 m height that were either large or competing with the leader and until 25% leaf area had been removed from the tree. The effects on tree growth were not significantly different from those observed with lift-pruning (Table 2). However, form-pruning was associated with improved stem straightness expressed as reduced kink: more than 80% of the trees were assessed as having slight or no kinks in the first 3 m of the stem, the part that had been form-pruned (Table 3). Although current tree spacings at planting and existing planting stock are inevitably associated with the development of some large branches (>30 mm), pruning appeared to offer some level of control of their number in this experiment.

Table 1. The percentage of crown length removed above which growth is reduced in a range of tree species pruned in plantations

Species	%
Acacia mangium[a]	40
A. melanoxylon[b]	25
Eucalyptus grandis[c]	40
E. nitens[d]	50
Pinus patula[e]	25
P. radiata[f]	35
P. sylvestris[g]	40
Cryptomeria japonica[h]	30

[a]Majid and Paudyal (1992); [b]Medhurst et al. (2003); [c]Bredenkamp et al. (1980); [d]Pinkard and Beadle (1998); [e]Karani (1978); [f]Sutton and Crowe (1975); [g]Långström and Hellqvist (1991); [h]Fujimori and Waseda (1972)

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Table 2. Mean stem diameter, height increment and green crown lift of *Acacia mangium* 18 months after pruning at a plantation in South Sumatra. Means sharing the same letters are not significantly different at $p<0.05$. At age 18 months, when the trees were pruned (see text), their average height and diameter were 4.3 m and 4.1 cm, respectively, and there were no significant differences between treatments.

Pruning treatment	Diameter increment (cm)	Height increment (m)	Green crown lift (m)
Control	6.83 *a*	7.44 *a*	2.49 *a*
Form	8.28 *b*	8.35 *b*	3.07 *a*
Lift	8.06 *b*	8.20 *b*	2.74 *a*

Green pruning triggers physiological responses that increase biomass production to a level that is significantly greater than in a similar unpruned tree growing under the same environmental conditions. These physiological changes can be detected within a few days to weeks after pruning in eucalypts and acacias, and may be sustained for several months (Pinkard and Beadle 2000; Medhurst et al. 2006). These changes in physiological activity are observed as an increased rate of crown development (Pinkard and Beadle 1998b) expressed through higher rates of leaf expansion, greater leaf development in the upper crown, greater leaf area to branch basal area ratio and reduced leaf senescence. Significant increases in light-saturated rates of single-leaf net photosynthesis are also observed to occur throughout the crown, though decrease in magnitude with depth in the canopy (Pinkard et al. 1998; Medhurst et al. 2006).

Table 3. Percentage of assessed trees by kink class between 0–3 m height, 18 months after pruning at a plantation in South Sumatra. The class codes for kink were: (1) no kinks, (2) slight kinks, (3) stem deviation stays within the centre line, (4) stem deviates outside the centre line. The trees had been form-pruned to 3 m height at pruning (see text).

Pruning treatment	Percentage of trees by class code			
	1	2	3	4
Control	25.0	36.2	19.4	19.4
Form	55.6	27.8	8.3	8.3
Lift	25.0	36.1	13.9	25.0

The implication of these findings is that pruning severity should be linked to the capacity of these compensatory responses to result in no significant change in the growth of the pruned trees compared with the unpruned trees in the stand. As pruning is normally undertaken to a height of at least 4.5 m, two or more lifts are required to ensure that crown removal in any one lift does not exceed the level that triggers a significant reduction in growth rate. While the compensatory responses just referred to have been demonstrated to work adequately for first-lift pruning in *E. nitens* and *A. melanoxylon* growing in a temperate climate (Pinkard and Beadle 2000; Medhurst et al. 2006), the physiological responses to subsequent lifts have not been as thoroughly investigated. The much higher rates of growth observed in a tropical species mean that the elapsed time between each lift-pruning will be a few months only. In the experiment in South Sumatra referred to above, the base of the green crown was, on average, between 2.5 and 3.1 m above ground level 18 months after pruning (Table 2), and substantially beyond the height (≤1.5 m) to which branches had been pruned in the lift-pruning treatment.

Thinning

Thinning serves to maximise the diameter growth of trees by reducing intra-specific competition. In the present context this is achieved by the harvesting or removal of unpruned trees. In *A. mangium* plantations managed for solid wood, the numbers of pruned trees in the final crop and the thinning strategy adopted will depend on the target tree-size and rotation length. The commercial value of the thinned trees may also dictate the timing of the thinning operation. There are, however, some useful principles that have emerged from thinning trials with other species that can help develop a workable strategy for thinning *A. mangium*.

Thinning intensity affects stand growth. In a *E. nitens* stand established at 1143 stems/ha (3.5 m × 2.5 m spacings), cumulative basal area growth per hectare was unaffected by thinning to 300 stems/ha seven years after thinning, while the removal of greater than 66% of standing basal area at thinning

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(that resulted in a stand density of 100 stems/ha) was associated with a significant reduction in cumulative basal area growth per hectare (Medhurst et al. 2001). Individual tree growth was improved with thinning intensity and, in general, the dominants and co-dominants were the trees in the stand that produced a significant basal area response to thinning.

The growth response occurs because of changes in the distribution of light and canopy photosynthesis in the stand following thinning (Medhurst and Beadle 2005). Significantly higher fractions of incident light are found in the middle and lower crowns of the trees and significantly greater light-saturated rates of photosynthesis are observed in the leaves of the lower crown, compared with unthinned stands. In the results of a study by Medhurst and Beadle (2005), these changes were expressed through changes in the distribution of foliar nitrogen (N) content that result in positive relationships between N content and the fraction of incident light or light-saturated photosynthetic rate. The increases in N content are related to a significant decrease in specific leaf area (leaf area per unit leaf weight; Medhurst and Beadle (2005)). Changes in leaf area per tree are associated with an increase in crown length in thinned stands (Medhurst 2000).

These observations suggest that thinning at or soon after canopy closure will maximise the growth response: conversely, delaying thinning until after there has been appreciable crown lift will reduce the magnitude of the response. Thinning intensity should be commensurate with the maximisation of light interception, and therefore of growth, by individual trees. However, as thinning regimes aim to maximise stand production as well as optimise tree size, the ideal residual stand density after thinning will be that which will lead to maximum leaf area index (leaf area per unit ground area) towards the end of the rotation, or just ahead of the next thinning. This will depend, of course, also on the tree sizes that are being sought at harvest. Medhurst et al. (2001) found that, in general, the lower the quality of the site, the lower was the ability of the stand to respond to thinning. Thinning intensity therefore needs to increase with increasing site quality: smaller individual tree sizes are a given on lower-quality sites. As trees have a capacity to develop longer tree crowns on high-quality sites, delaying thinning will not, up to a point, preclude a growth response from thinning.

A pruning and thinning strategy

The pruning and thinning strategy presented here uses current establishment practices for *A. mangium*. The pruning strategy is in part based on current practice used for *A. mangium* in Indonesia and *Eucalyptus globulus* and *E. nitens* in Australia (Gerrand et al. 1997), with the addition of form-pruning. As form-pruning to date has been used only as a research tool, its benefits require further testing. The thinning strategy is linked to observations of current growth rates of *A. mangium* in Australian and Indonesia. The timing of each operation attempts to meet the criteria described above for optimising the quantity and quality of clear wood produced.

Acacia mangium plantations are established at 3 × 3 m spacings (1111 stems/ha). The pruning and thinning strategy is then based on the following requirements:

- Form and lift-pruning to 4.5 m tree height, and thinning to reduce the stocking from 1111 to 296 stems/ha.
- Four silvicultural interventions after planting, excluding the need for any fertiliser application and weed control.
- Every fifth row is an outrow removed at first thinning. These rows, equivalent to 222 stems/ha, are not used to select trees for pruning.
- The maximum number of trees available to select those for pruning is therefore 889 stems/ha (1111 – 222 = 889 stems/ha), equivalent to a selection ratio based on 296 stems/ha at final stocking of about 1:3.

Implementing the strategy is a four-step process (see Figure 1).

Step 1

Stage of growth: age 4–6 months

Operations

- Single trees

Step 2 (Figure 1a)

Stage of growth: Mean total height @ 4 m

Operations

- Form-prune two of every three trees of 889 trees, i.e. 593 stems/ha, to 2.5 m (removes large branches >15–20 mm diameter and high angle branches). The trees selected for form-pruning should be those that meet criteria for good form (Table 4).

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Step 3 (Figure 1b,c)

Stage of growth: Mean total height @ 8 m

Operations

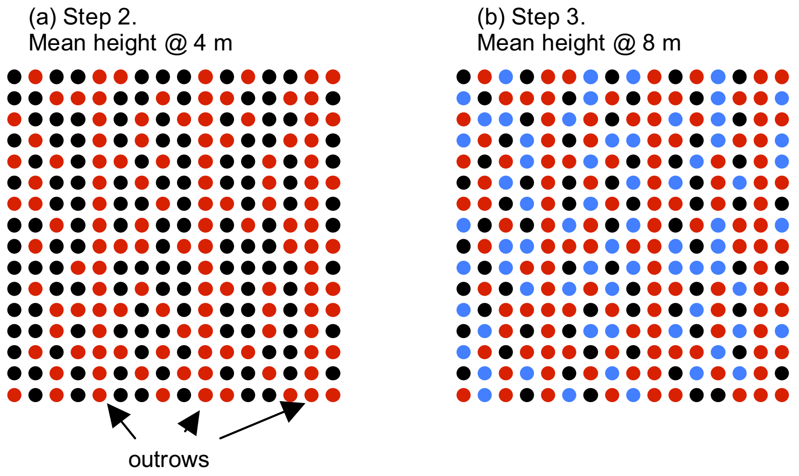
- Form-prune the best one of two trees pruned to 2.5 m (i.e. 296 of 593 stems/ha) to 4.5 m.
- Lift-prune these trees to 2.5 m.
- Thin all outrow trees (222 stems/ha) and the trees that were not pruned at Step 2 (296 stems/ha). This reduces the stocking from 1111 to 593 stems/ha).

Step 4 (Fig. 1d)

Stage of growth: Mean total height @ 12 m

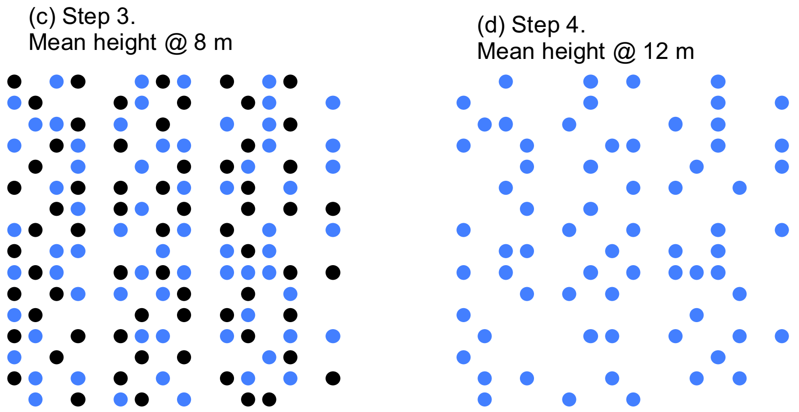
Operations

- Lift-prune to 4.5 m trees that were form-pruned to 4.5 m.
- Thin those trees that were form-pruned to 2.5 m only (295 stems/ha). This will create the final stocking of 296 stems/ha.



(a) Step 2.
Mean height @ 4 m

(b) Step 3.
Mean height @ 8 m



(c) Step 3.
Mean height @ 8 m

(d) Step 4.
Mean height @ 12 m

Figure 1. A representation of a pruning and thinning strategy for *Acacia mangium*. The trees are singled at age 4–6 months (see *Step 1* in text). (a) In *Step 2,* two (black) out of every three trees are form-pruned to 2.5 m. (b) In *Step 3,* the better (blue) of each two trees form-pruned in *Step 2* is now form-pruned to 4.5 m. The same trees are lift-pruned to 2.5 m. (c) Also in *Step 3,* the outrows (red) and the trees not pruned (also red) in *Step 2* are thinned (harvested). (d) In *Step 4,* the trees form-pruned to 4.5 m are now lift-pruned to 4.5 m. The trees form-pruned only to 2.5 m in *Step 2* are harvested. The final stocking rate is 296 stems/ha.

This strategy is based on form and lift-pruning to 4.5 m in height. Both are done in two sections (to 2.5 m and then to 4.5 m), first the form-pruning then, after the tree has grown another 4 m in height, the lift-pruning is undertaken in the section that was previously form-pruned. The removal of branches >15–20 mm diameter during form-pruning anticipates that these branches would have been >30 mm diameter at lift-pruning. Care should be taken not to remove more than 25–30% of the total leaf area during pruning at any of the above stages.

Table 4. Criteria that together define acceptable form for pruning an individual tree (adapted from Beadle et al. (1994)). These are used to ensure that the better trees are selected for pruning. If insufficient trees required for clear wood meet these criteria, it may be necessary to select some trees that do not meet all the criteria. Form-pruning is a mechanism for increasing the number of trees that will eventually meet the criteria.

1	Single-stemmed and free of secondary leaders[a]
2	Straight stem with minimal stem deformations from the vertical
3	Stems free from wounds and disease
4	No branches already >30 mm in diameter
5	Butt sweep limited to the bottom 0.3 m

[a] Secondary leaders that form above the final pruning height can be acceptable

Two thinning operations are also required, one when the average tree height is about 8 m, the second when tree height is about 12 m. The size of the thinned trees may be suitable for pulpwood but care should be taken not to damage retained trees during the thinning operations. This is assisted by the creation of an outrow at the first thinning to help access to the other rows for individual tree removal. In one sense the strategy is conservative in that it may not be necessary in *Step 2* to form-prune twice the number of trees that are going to be retained in the final crop: the additional form-pruning is a cost but it allows greater choice of the final-crop trees at *Step 3*. However, the timing of the thinning operation is to some extent speculative and assumes that each of the two operations will occur before canopy lift commences in the pruned trees. The required size of the final-crop trees will determine the time of harvest. Given the types of growth rates experienced in *A. mangium* plantations, rotation lengths of no longer than about 10–12 years are assumed or inter-tree competition will probably start to compromise individual tree-growth rates. Thinning regimes that reduce final-crop stocking to lower levels will then be required (Mead and Speechly 1991; Srivastava 1993) and will be essential anyway if tree sizes >30 cm diameter breast height over bark are required.

Heart rot

Cut surfaces from pruning and singling are potential infection courts for the entry of decay-causing fungi (Gales 2002; Lee 2002). Infection of heartwood by a range of white-rot fungi leads to heart rot, in which the decayed wood appears fibrous and stringy as well as a pale yellowish-white (Lee et al. 1988). Whereas heart rot can be tolerated in wood destined for pulp, it is not acceptable in solid-wood products.

Heart rot has been recorded in pruned plantations of *A. mangium* during a number of studies in Malaysia (Lee et al. 1988; Ito 2002). Unhealed pruning wounds have been recorded as contributing to up to 62.5% of heart rot infections (Lee et al. 1988). During a survey of heart rot in *A. mangium* plantations in Indonesia, Barry et al. (2004) found the highest incidence of heart rot was associated with a region where pruning occurred. In contrast, Zakaria et al. (1994) found no relationship between the incidence of heart rot and pruning of *A. mangium* in Malaysia. In a study in South Sumatra, no heart rot was detected 18 months after pruning (Beadle et al., unpublished data). In an *A. mangium* provenance trial, also conducted in South Sumatra, Suberanjeriji-plus (seed stock similar to that used by Beadle et al.) trees were found to have the second lowest incidence of heart-rot infection associated with drill wounds of a total of six provenances (Barry et al. 2006). Thus, while pruning has been linked to increased heart rot in some regions in Indonesia (Barry et al. 2004) and Malaysia (Lee et al. 1988) it appears to be of importance only when the plant material is susceptible and a sufficient source of heart rot fungi is present to invade the wounds.

Synthesis

While the fundamental requirements of green pruning and thinning in plantations managed for solid wood are well established, the development of pruning and thinning schedules for *Acacia mangium*

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remain in its infancy. Form-pruning appears to offer an approach for improving stem straightness. However, its coordination with subsequent lift-pruning requires further investigation. How to schedule the timing of thinning operations is a complex issue. The first requirement is that their timing should ensure that branches remain green but at the same time do not become large. The second requirement is that the timing of thinning should aim maximise tree growth rates, stand production and the value of the thinned as well as the final-crop trees. Just how to manage what can be difficult compromises should also be a focus for new research.

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Options for solid-wood products from *Acacia mangium* plantations

Eko B. Hardiyanto[1,2]

Abstract

Acacia mangium wood has proved to be not only suitable for producing high-quality pulp and paper, but also an excellent material for solid-wood products. There has been growing interest in utilising wood of *A. mangium* for solid wood, corresponding with the declining availability of logs from native forests. The currently available sawlogs of *A. mangium* are harvested from unpruned and unthinned plantations, and consequently are of low quality (many knots and poor stem form) with poor recovery of sawn timber. Proper silvicultural techniques that incorporate pruning and thinning are of crucial importance in growing plantations for solid wood. *Acacia mangium* can be grown for solid-wood products with a rotation of around 10 years that is expected to produce a total stem volume more than 200 m^3 per ha: about 30% of it will be for solid wood. Minimum tree diameter at breast height will be 30 cm. The current price of sawlogs of *A. mangium* (from unpruned and unthinned plantations) is considered low, but it is expected to increase with reducing availability of logs from natural forest, increased familiarity of its users with the wood, and better log quality from plantations managed specifically for solid-wood products.

Since the early 1990s, industrial forest plantations have been developed in Indonesia. As of 2004, a total of 2,500,966 ha of pulp plantation and 865,256 ha of sawlog plantation had been established (Dirjen BPK 2005). Acacia plantations have been established primarily to produce wood for the pulp and paper industries. *Acacia mangium* Willd. is the main plantation species planted on mineral soils, while *Acacia crassicarpa* A. Cunn. ex Benth. is the only species grown on peat land. The pulp properties of *A. mangium* wood are comparable to those of many *Eucalyptus* species. A number of studies on the utilisation of *A. mangium* show that its wood is not only excellent for pulp and paper, but also good for wood products such as plywood, furniture, flooring and light construction. Lately there has been growing interest in utilising wood of *A. mangium* for solid-wood products. This corresponds with the reduced availability of logs from native forests. The continuing pressure to protect native forest will further enhance the opportunity to develop sawlog plantations of *A. mangium*.

Solid-wood utilisation

Various studies have been conducted to examine the suitability of *A. mangium* for products other than pulp and paper. The density of *A. mangium* wood varies from 420 to 483 kg/m^3. It is considered to be stable, with shrinkage from fresh to air dry of around 6.4% tangentially and 2.7% radially (Abdul-Kader and Sahri 1993). Its fibre is relatively straight and only in certain cases is found to have interlocked grain (Yamamoto 1998).

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The timber of *A. mangium* dries well, fairly rapidly and without serious defects when a suitable kiln schedule is used (Abdul-Kader and Sahri 1993). However, the wood is prone to initial checking and can also collapse and shrink during drying, resulting in substantial losses (Yamamoto 1998), hence the need for a proper kiln schedule to obtain good-quality timber.

The wood of *A. mangium* is classified as light hardwood with low to moderate strength. It has good machining properties and is suitable for making furniture, cabinets, mouldings, and door and window components (Abdul-Kader and Sahri 1993). The wood is also suitable for light structural works, agricultural implements, boxes and crates (Abdul-Kader and Sahri 1993; Yamamoto 1998). A recent study on the mechanical properties of sawn timber indicated that the wood of *A. mangium* can be used for construction and meets the requirements of the Indonesian Standard for Wood Construction (Amalia 2003; Firmanti and Kawai 2005). The wood of *A. mangium* can also be easily processed into veneer and plywood. The peeling process is considered easy and the green veneers produced are tight, smooth and of acceptable quality (Abdul-Kader and Sahri 1993; Yamamoto 1998).

Heart-rot disease in *A. mangium* has been reported in a number of studies and can reduce the utilisation of solid wood since heart rots reduce timber volume and quality (Lee et al. 1988; Lee 2002; Ito 2002). A recent survey conducted at a number of sites in Indonesia revealed that the incidence of heart rot varied according to site, from low (6.7% East Kalimantan, 11.3% South Sumatra) to reasonably high (35.3% Jambi, 46.7% West Java). A combination of differing plantation management strategies—for example, pruning, age and local conditions—explained the differences in heart-rot incidence (Barry et al. 2004). Pruning was reported to be linked to increased incidence (Barry et al. 2004), but may be of importance only when the plant material is susceptible and a sufficient source of heart-rot fungi is present in the environment to invade the wounds caused by pruning. In addition, while wounds caused by singling are typically assumed to have a large impact on the incidence of heart rot, an influence of singling on heart-rot incidence in a provenance trial in the Riau province of Sumatra was not apparent (Barry et al. 2006). A pruning study in South Sumatra also detected no heart rot 18 months after singling and pruning (C. Beadle, K. Barry, E.B. Hardiyanto, R. Irianto, Junarto, C. Mohammed and A. Rimbawanto, unpublished data). In areas where the incidence of heart rot is low, the development of sawlog plantations is considered to be possible.

Knots are the major factor limiting the utilisation of solid wood harvested from unpruned stands of *A. mangium*. Consequently, unless silvicultural techniques are used to control branching and hence the occurrence of knots, the quality of wood from this species may limit its utilisation. The recovery rate of sawn timber board from sawlogs harvested from unpruned and unthinned *A. mangium* stands is low; about 38% at PT. Musi Hutan Persada (Supriyadi, pers. comm. 2005) and 35% in S. Kalimantan (Thorp 2005), for example. By applying specific silvicultural treatments, there is the potential to substantially increase the recovery rate of *A. mangium* sawlogs.

Another defect that may reduce the general quality of the end product and limit the usefulness of the *A. mangium* sawlogs is end-splitting, particularly of trees harvested from stands under 10 years old. End-splitting is a phenomenon manifested during felling and cross-cutting of logs; it is caused by high growth stress which normally occurs in fast-growing tree species, particularly hardwoods. Growth stress is generated within woody tissue as a result of the tendency of differentiating cells to contract during cell maturation in the longitudinal direction and expand in the transverse direction (Malan 1995). In *Eucalyptus grandis,* growth stress is reported to be highly heritable, and has no relationship with other characteristics such as diameter, tree height and wood density (Malan 1995). Observations of logs harvested from *A. mangium* trees of more than 10 years of age revealed that the proportion of logs showing end-splitting was small.

Silviculture of plantation for solid-wood products

Establishment

The method of plantation establishment of *A. mangium* developed for solid-wood products is similar to that for plantations grown for pulp. The site is generally prepared manually by blanket spraying existing unwanted vegetation with herbicide. Seedlings raised in the nursery are planted manually at an initial stocking rate of 1100/ha. Genetically improved seeds should be used for growing sawlog plantations. Trees should be fertilised using a basal fertiliser of phosphorus at planting time, usually in the planting hole. Nitrogen fertiliser may not be required in the

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second rotation as a lack of a positive response is likely due to high nitrogen content available in the soil as a result of the fixing of atmospheric nitrogen by the previous plantation (Hardiyanto et al. 2004). Reducing weed competition is of crucial importance in the early phase of plantation establishment so that trees can grow optimally and close their canopy in the first year. Weeds are normally controlled by hand-weeding at age 3–4 months followed by a second hand-weeding and herbicide application at about 6 months of age. Depending on the weed growth, the hand-weeding may be reapplied at age 12 months.

Singling and pruning

In the establishment of plantations for solid wood it is of paramount importance to have early silvicultural intervention that utilises pruning and thinning. The timing and method of pruning and thinning is crucial. As *A. mangium* has weak apical dominance and is inherently multi-stemmed, singling is necessary. Singling to cull and leave one of the best stems is carried out when trees are around 3–4 months old.

Unlike plantations grown for pulp, plantations to be utilised for solid-wood have to be pruned to produce high-quality logs. This is important, as *A. mangium* does not shed dead lower branches naturally and often the dead branches persist for a long time and are associated with deterioration in wood quality (Malan 1995; Waugh 1996). Green and dead knots caused by branching reduce sawn timber yields. Dead branches result in loose knots that fall out to leave holes in the sawn timber. Dead branches are also associated with a high percentage of discoloration and decay (Ito and Nanis 1994). The objective of pruning is therefore to maximise the amount of clear wood produced by a tree. If branches are properly pruned while green, then there is a high probability that new wood will grow over the pruned branch stubs and that knot-free clear wood will be grown on the stem. Green pruning, that is, removal of leaf area, has the potential to decrease tree growth rates, particularly stem diameter. A study on pruning of *A. mangium* revealed that removing the crown below 50% of tree height depressed growth significantly, especially stem diameter (Majid and Paudyal 1992). The first lift-prune, to 40% of the tree height, should therefore be carried out when trees are about 6 months old and about 2.5–3.0 m tall. This should avoid a significant reduction in stem diameter growth. The second pruning, to a height of 4 m, should be conducted at 1.5–2.0 years old, at the same time as the first thinning when trees are around 8–9 m tall. The last pruning should be carried out at 4–5 years of age to a pruning height of 6 m. The minimum length of sawlog is 4 m (Hardiyanto 2004).

As mentioned previously, *A. mangium* has poor apical dominance and tends to have large branches. In a study of fungal infection 2 years after pruning, Weinland and Zuhaidi (1992) noted that wounds of diameter >20 mm were always infected whether the branches had been removed when green or dead. Therefore, control of branch size using form-pruning is vital in the silviculture of plantations managed for solid wood. Unlike lift-pruning, form-pruning selectively removes branches throughout the crown and can be used to reduce average branch size before a subsequent lift-pruning (Pinkard 2002) or to correct potential deviation of stems from a pathway of vertical growth (Medhurst et al. 2003). A pruning trial conducted at an 18-month-old stand of *A. mangium* at PT. Musi Hutan Persada’s plantation found that form-pruning reduced the number of trees with large branches and increased the number of trees with better stem form (reduced the number of stem kinks) (C. Beadle et al., unpublished data). In the same trial, lift and form-pruning were found to have no association with heart rot (C. Beadle et al., unpublished data).

Thinning

Thinning involves the removal of part of the stand in order to concentrate future volume growth on fewer and better-quality stems. The advantage of thinning is that trees left behind have greater resources (water, light, space to grow) and therefore increase in size more rapidly. Thus, by selecting the best trees for retention and enabling those to grow faster, the rate of increase of stand value increases.

Thinning improves stand quality through the removal of deformed trees and a reduction in the time taken for trees to reach valuable sawlog size. Thinning is the most powerful tool to manipulate the development of the plantation and the quality of the final stand. Thinning increases timber revenue by increasing the volume of sawlog produced. This is because larger trees attract significantly higher prices, as they are less expensive to harvest (on a Rp/m^3 basis) and yield more-valuable end products.

Acacia mangium is very competitive for light, moisture and nutrients and it is important that it maintains active growth. Early thinning allows the best

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trees in the stand to take advantage of any improved growing conditions. To ensure this, the first thinning should be conducted when the majority of trees are around 8–9 m in height; this should occur at 1.5–2.0 years of age, with overall stocking reduced to 500–550 trees/ha. The remaining trees can then maintain good growth until about age 4–5 years when inter-tree competition resumes. The second thinning is then carried out to leave 200–250 trees/ha. The remaining trees are grown on until the final harvest at around age 10 years. The growth data reported from *A. mangium* stands previously thinned show that at about 10 years of age the average diameter at breast height is more than 30 cm and the average height was more than 26 m. About 30% of the total stem volume can be utilised for sawlog while the remaining wood can be used for pulp (Figure 1) (Hardiyanto and Supriyadi 2005).

Economic prospects

At present it is difficult to estimate the future demand for *A. mangium* timber, as its milling, kiln drying and related characteristics are still being assessed. However, demand for *A. mangium* timber has increased steadily in recent years as the industry gains more confidence in its availability and experience in how to use it, and wood supplies from natural forest continue to decline.

The increasing demand for wood from plantations, including that of *A. mangium,* will likely cause a rise in log prices and the investment in plantations for solid-wood utilisation will become economically viable. Current prices of harvested sawlog from unpruned and unthinned *A. mangium* stands are considered low due to low log quality (many knots and poor stem form). Logs harvested from managed sawlog plantations are expected to have better sawlog yield, wood quality and product value and command higher prices. Nevertheless, the economic aspects of growing plantations for solid wood (growing cost and value of logs) need to be assessed and compared with those of growing pulp plantations

Future research and development

As mentioned in the preceding section, the development of *A. mangium* plantations for solid wood is still in its infancy and therefore much research work has

Figure 1. A 10-year-old, thinned stand of *Acacia mangium* in Merbau, South Sumatra having average stem diameter, height and total stem volume of 36.6 cm, 26 m and 228.7 m^3/ha, respectively.

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yet to be done. The following areas need attention in the future research and development of *A. mangium* plantations for solid-wood products:

- genetic improvement — to improve growth, minimise the size and severity of the juvenile core, reduce shrinkage properties and reduce growth stress
- clonal propagation — to reduce variation between trees in a stand and increase the potential for processing more uniform logs
- silviculture — to manipulate tree spacing, thinning, and fertiliser application after thinning to reduce growth stress, tension wood and end-splitting
- harvesting and log grading — to develop techniques in felling, log-making and log handling to reduce end-splitting and improve log sorting.

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