the hosts also showed high chlorophyll contents and carbon fixation rates than the unparasitized sandalwood plants. In the same sandalwood-host associations, sandalwood plants always showed more negative water potential values than the associated hosts, thus maintaining a water potential gradient favorable to sandalwood in order to abstract xylem derived solutes from the host roots *via* haustoria which establish the intimate connection between the two partners. Examination of both parasitized and unparasitized roots of sandalwood showed Vesicular Arbuscular Mycorrhizal (VAM) infections. However the VAM infections were less in partasitized roots than those of unparasitzed roots. Successful inoculation of VAM should provide the additional nutritional support required for these woody root hemiparasitic species. The identification of VAM fungi and their role in soil fertility of sandalwood plantations/ nurseries are yet to be ascertained (see Kathriarachchi and Tennakoon, 2000).

**Host Associations**

A detailed study to evaluate the performance of sandalwood plants with a range of pot hosts and the ecological, biological and physiological phenomena associated with these different host-parasitic associations was commenced in January 2000 at the Botany Department, University of Peradeniya, Sri Lanka. The findings of this long-term study should unravel complexities associated with *Santalum*-host associations in Sri Lanka, at least to some extent. In addition to the cultural importance, considerable environmental and economic benefits can be achieved by growing sandalwood in developing countries like Sri Lanka. To achieve these goals, collaborative research programs between sandalwood growing countries should be undertaken as agreed in the last International Symposium on "Sandalwood and its Products" held in Bangalore, India (Radomiljac *et al* 1998).

The findings of this long-term study should unravel complexities associated with *Santalum*-host associations in Sri Lanka, at least to some extent.

**Acknowledgements**

The assistance provided by Hashendra Kathriarachchi, Chandima Danapala and Sarath Kapukotuwa with growth experiments and PCR studies are gratefully acknowledged. Thanks are also due to Profs. Nimal and Savithri Gunatilleke for valuable comments and suggestions and Dr. Ranamalie Amarasinghe for comments on PCR studies.

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# Queensland Sandalwood (*Santalum lanceolatum*): Regeneration Following Harvesting

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*In 1994, a trial, funded by Queensland Department of Primary Industries Forestry, was established near Hughenden investigating regeneration of natural stands of Queensland sandalwood from two harvesting methods, vis, stump cutting vs stump pulling. Merchantable size trees in five, one hectare plots were harvested by the respective methods and vegetative regeneration was recorded over the successive five year period. Overall indications are that retaining sandalwood stumps is unlikely to result in a greater amount or more successful coppice regeneration following harvesting than stump pulling, and that it may well result in less successful cpppice regeneration.. Data from the trial suggests that the proportion of pulled stumps that produce coppice is higher than the coppice produced through the cut stump method, and these are more likely to survive. Concerns about the impact of stump pulling on soil properties and erosion are unwarranted as the number of sandalwood removed from any area is relatively few and the area of soil disturbed during the operation is very small.*

**Introduction**

*Santalum lanceolatum* R. Br. is the most widespread of all Australian *Santalum* species, with a range extending throughout Queensland, including Cape York Peninsula, and into New South Wales and parts of Victoria, South Australia and Western Australia. It grows as a tall shrub up to 7-8 m, with a deep and usually drooping crown. Trees of merchantable size (>12 cm diameter at 1.3 m height) generally occur in northern regions, above about 25° latitude.

*S.lanceolatum* generally grows within clumps of other species or other sandalwood saplings. Queensland sandalwood reaches its largest size (exceptional individuals can reach over 30 cm in diameter at 1.3 m) in the Mitchell Plains and delta country at the southern end of the Gulf of Carpentaria (rainfall 870 - 1250 mm). In these circumstances it occurs on the outer edge of black tea tree (*Melaleuca acacioides*) or gutta percha (*Excoecaria parvifolia*) scrub adjacent to gidgee (*Acacia cambagei*) areas and around drainage lines. It is rarely found in open woodlands or in association with eucalypts. In lower rainfall regions further south it occurs on and around basalt 'walls', along drainage lines, and on scrub edges, usually in association with acacias (Applegate et al. 1990).

Harvesting of sandalwood by European and Chinese immigrants in Queensland commenced in the Cape York Peninsula region in about 1865. Cutters and export facilities were concentrated around Cooktown, Coen, Weipa, and Somerset and, later, near Normanton. Harvesting developed in the Hughenden area in the 1920's (Duus 1987, Davis 1996).

In recent years, 200 – 400 tonnes of sandalwood has been harvested annually from State lands in Queensland. Queensland sandalwood is mostly exported to Taiwan where it is powdered and mixed with various resins and other aromatics to make incense sticks (Gordon 1992). Selling prices vary considerably depending on market conditions, but those received for Queensland wood are generally lower than for Western Australian (*S.spicatum*) or Indian or Indonesian (*S.album*) wood because of lower oil content and different optical properties of the oil distilled from the heartwood (Keenan 1996). Returns to the state on unprocessed material over the last two decades have ranged from $1.5 M in 1995, to $83 500 in 1999, depending on quantity harvested and fluctuating market prices (DPI-F Annual Report 1995; 1999).

Following reintroduction of harvesting on State lands in Queensland in the mid 1980's the harvest technique involved cutting the stem at ground level. Early in 1994 this changed to pulling the entire stem and root-ball from the ground. Cutting areas are assessed before harvesting and a cutting limit applies which states trees must be at least 12 cm DBH (1.3m) before harvest. In the past the high value and demand for sandalwood has led to over-harvesting of the resource worldwide (Kealley 1989). Kealley (1991) also noted that the sandalwood resource is declining throughout its range, outside of conservation reserves, owing to its lack of regeneration associated with the over-harvesting. Ensuring adequate regeneration has been an objective of the WA sandalwood research program for many years and one area of investigation has been harvest method and associated effects on regeneration. In Queensland, changing harvest method to stump pulling has increased the recovered mass of heartwood by around 30 percent (*pers comm.* Brian Chambers, Telgem Sandalwood Harvesting, Richmond). Applegate et al. (1990), however, claimed that this practice was partly to blame for the decimation of the sandalwood resource in some southern Indian states, since it prevents coppice regeneration from roots and stumps. In contrast, a major reason the WA sandalwood industry cites for stump pulling as their harvesting method is that it leads to high levels of initial root coppicing, and thus improved regeneration (Kealley 1991). Despite the value of the timber there has been little investigation of the ecology or silviculture of sandalwood in Queensland. This is the first study to determine the effects of cutting stems compared with pulling stumps on the regeneration of natural stands of sandalwood. This study is based on a sandalwood harvest at a site near Hughenden in March 1994.

**Objectives**

The study aimed to:

- quantify the effect of harvesting on the sandalwood population,
- compare the vegetative regeneration after stems had been harvested by different harvesting methods, and
- monitor the survival and growth of the coppice regeneration.

**Study Area**

The study was conducted on the 'Spring Valley' pastoral holding, approximately 50 km north west of Hughenden (20.84 S, 144.20 E). The climate of the region is semi-arid with long-term average annual precipitation of 485 mm, most of which falls in the wet between December and March. Mean daily temperature in the region varies from 9° C in the dry, winter months, to over 36° C in the summer months (Figure 2). In December and January it is not uncommon to experience daytime temperatures above 40°C for several weeks in succession in the Hughenden area (Applegate et al. 1990).

The study site is located on a basalt 'wall'. These large boulder fields are a prominent feature in the region and are derived from Holocene lava flows and rise up to 60 m above the surrounding plains (Clarke and Paine 1970). Soils within the basalt 'wall' are in general extremely shallow and occur mainly between the large areas of rock. Sandalwood occurs as scattered individuals among the boulders in association with gidgee (*Acacia cambagei*) and other dryland species.

A 5 ha (500 x 100 m) area was surveyed in a harvest area on the 'wall' and this was stratified into five separate one hectare plots for the purpose of assessment. The area was stratified on the basis of increasing percentage of exposed rock and decreasing soil pockets, ie, increasing site 'harshness'. Plot 1 had the least areas of exposed rock with plot 5 having the most rock and least amount of soil.

> In the past, the high value and demand for sandalwood has led to over-harvesting of the resource worldwide....

**Harvesting and Assessment**

Within each plot, trees were marked for cutting based on the accepted DPI-F harvesting regime (Keenan 1996) of removal of all stems greater than 12 cm DBH. Harvesting occurred in March 1994. A total of 41 stems greater than 12 cm DBH were removed from the five hectares in the harvest with approximately equal numbers pulled and cut. Eight stems per hectare were harvested.

Harvest methods involved either 'cutting' or 'pulling'. Cutting involved trees being cut with a chainsaw at ground level with minimal soil disturbance around the stump. Only above ground timber was removed. 'Pulling' involved removal of the root-ball from the ground using a winch and tractor. Large roots and above ground timber are harvested. Soil around the stump location is disturbed often leaving a slight depression in which broken off roots are exposed.

**Results**

Figure 1 details the survival of coppice material from cut and pulled harvest methods in all five hectare plots. It represents the amount of regeneration (numbers) per tree as a proportion of the number of trees harvested by that method, for the entire site (all plots).

These results (Figure 1) show that there was more coppicing early on from the cut stumps than from the pulled stumps immediately after harvesting . Over the length of the experiment the entire coppice from cut stumps died (Photo 1), and at the most recent measure the only surviving coppice was from pulled stumps (Photo 2).

## Discussion

### Regeneration by Coppice (Cut vs Pull)

When disturbed, sandalwood species will vegetatively regenerate from both the cut stump and the disturbed root zone. This coppice is often referred to as stump coppice or root coppice (root suckers) (Barrett 1989, Applegate *et al* 1990, Loneragan 1990). Early studies in coppicing *S.spicatum* in the Goldfields region of WA (Loneragan 1990) found that 4.5 percent of stems coppiced, but none of

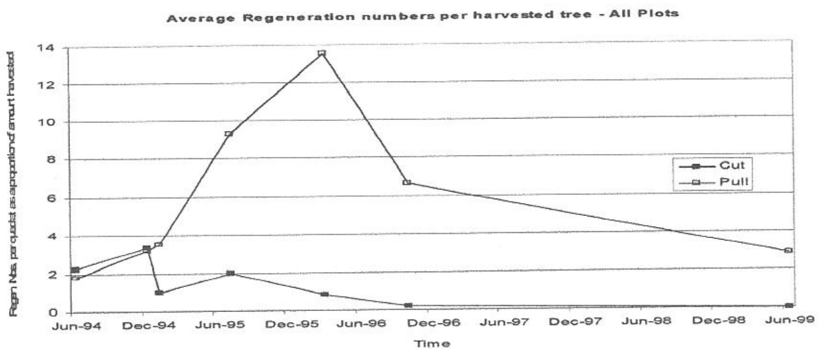


**Figure 1:** Average regeneration numbers for each of the harvest methods.

the coppice survived. More recently, it has been found that root and stem coppicing is often successful, with survival up to 80 percent after 2 years, in milder climates (Barrett 1989).

In this study the degree of soil disturbance following harvesting was relatively small. The basalt 'wall' geomorphology consists of a high percentage of surface boulder material that tends to effectively retain the clayey soils in the interstices of the boulders. Depressions resulting from stump pulling may concentrate small amounts of water or dew. However they are not capable of contributing to water borne soil erosion due to the low rainfall and the uneven surface characteristics of the 'wall' structure.

Also, because of the low number of stems per hectare removed, the area disturbed by harvest is very small, with about 0.08% of the area affected by stump pulling.

**Reasons for Mortality**

*Climate*

In early and later assessments root coppice appeared healthier than stump coppice. This was potentially due to more favourable microclimate conditions found in the depressions created by stump pulling. Much of the early coppice on stumps died off during the dry season. The study was undertaken following a drought where rainfall for the 3 year period 1992 – 1994 was the lowest during the 113 years of record at Charters Towers (220km ESE of the study area), although probably not as severe as five dry years from 1931 – 1935 (Clewett *et al* 1994). Good rainfall, approximately 60 mm, fell in December 1994 and January 1995, and may have caused the peak in coppice produced from both cut and pulled methods in mid-1995 (Figure 1). This suggests that the initiation of coppice development is heavily dependent on climatic conditions. Similar results have been reported following pulling of sandalwood (*S.spicatum*) in the Goldfields region of WA (Barrett 1989, Loneragan 1990, Kealley 1991), suggesting that soil moisture is critically important to the amount and survival of regeneration. Applegate *et al* (1990) concur with these climatic reasons, with field observations of Queensland sandalwood suggesting that successful regeneration of sandalwood is reliant on favourable soil moisture conditions over an extended period.

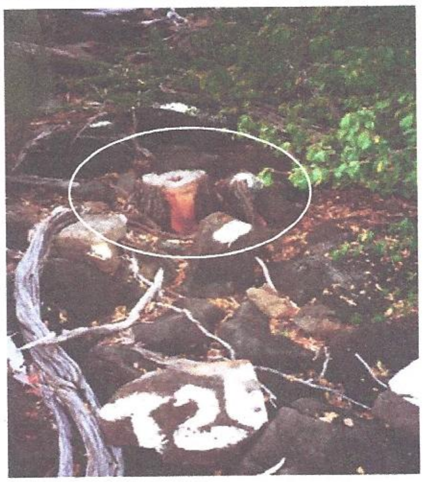

**Photo 1:** This tree was harvested by the cut method, where the stump is left remaining in the ground. This method initially resulted in slightly higher vegetative regeneration, or stump coppice. As the exposed stump starts to desiccate, the stump coppice is also killed. This photo was taken in Jun 99, over 5 years after harvesting. There is no surviving regeneration from this individual.

*Shade*

Sandalwood is a hemiparasitic tree. Hosts are known to provide shade as well as nutrition (Rao 1942, Loneragan 1990, Barrett and Fox 1994). Seedlings are very sensitive to over-exposure by sunlight. Early growth of sandalwood after regeneration is best in the shade of bushes and clumps of vegetation (Rao 1942, Barrett and Fox 1994). When growing *S.album* in planted trials Barrett and Fox (1994) found that some shade, even shade microcosms, is beneficial to sandalwood establishment and that survival in full sun was poor in comparison to any of the trialed shade regimes. The effect of harvesting method on shade was not fully tested in this study. However, observations indicate that when the stump is pulled and a small amount of soil is disturbed, small depressions are produced. These depressions may capture water or dew and shade, creating a more favourable microclimate for early growth. In comparison, remaining stumps in the cut method are ex-


**Photo 2:** A mass (>10) of very healthy root coppice from a pulled stump at the 'Spring Valley' regeneration trial. Leaves look very healthy, with no evidence of browsing. The site has plenty of shade provided by rocks, grass and over canopy. This photo was taken in Jan 95, 11 mths after the tree was harvested, and following a significant wet season.

posed to more sunlight and tend to desiccate quickly, perhaps generating less ideal growth conditions. Harvesting method produced no discernible differences of shade cover to the sandalwood harvest sites.

*Browsing, Grazing and Fire*

The fate of coppice depends not only on climatic conditions, but also on the degree of grazing by rabbits, wildlife and stock (Applegate et al. 1990, Kealley 1991). Similarly, results from the early Western Australian regeneration studies indicated significant mortality could be attributed to fire, browsing and grazing (Loneragan 1990). The basalt 'wall' areas around Hughenden are relatively free of grazing and fire. The structure of the 'wall' is difficult for stock to traverse and offers little fodder to be grazed, therefore graziers generally exclude their stock from these areas to avoid stock injury or loss. Fire is also infrequent due to lack of sufficient fuel to carry a fire. Browsing on smaller sandalwood by native animals, eg rock wallabies, is seasonal. Some browsing damage to coppice was observed and may have contributed to some coppice mortality. No differences were observed in the amount of browsing on coppice from either harvest method. Browsing, grazing and fire may not be major factors in survival and growth of regeneration of sandalwood on the basalt 'wall' areas.

**Regeneration by Seed**

The relative importance of coppicing in the regeneration of sandalwood in the study area in comparison to regeneration from seed is uncertain. Current evidence from all monitored sites suggests that about half of the harvested trees across a range of pastoral holdings surveyed had sandalwood trees within the 5-m radius of the quadrat. Similarly, the stand structure of the 'Spring Valley' site indicates that at 5 years after harvest there are high numbers of seedlings and saplings in smaller size classes that appear to have originated from seed. This observation is contrary to the suggestion that seedlings developed from seed do not reach maturity because of adverse climatic conditions, unreliable summer rains, grazing, browsing and fire (Applegate et al. 1990, Applegate and McKinnell 1993). WA studies with *S.spicatum* suggest that seed production is variable between trees and years and related to seasonal conditions, genetic variability, host and nutrition, and that in above average rainfall years seed production is heavy (Loneragan 1990, Kealley 1991). Even though the rainfall levels over the period of the trial were relatively low there appears to have been significant amounts of regeneration over the trial site. Concurrent studies of Queensland sandalwood phenology suggest that it flowers and sets seed prolifically under good climatic conditions. These studies also suggest that the size (age) of the tree may not be as important for viable seed set as the site and seasonal conditions. Therefore, cutting size limits (>12 cm DBH) are sufficient to ensure adequate seed production is maintained on these areas, as even small (2 m height) trees were observed producing seed. These early results concur with phenology findings for WA sandalwood (Barrett 1989, Loneragan 1990, Kealley 1991).

**Conclusion**

The objectives of this experiment are threefold: (i) to quantify the effect of harvesting on the sandalwood population, (ii) compare vegetative regeneration after stems had been harvested by different harvesting methods, and (iii) monitor the survival and growth of the coppice regeneration.

Evidence from this trial suggests that cut vs pull may not be a pertinent question with regard to regeneration following harvesting of sandalwood from basalt 'walls' and regeneration by seed may be more important. In regard to harvest method, more coppice initiated from the pull method than from the cutting method, and at age 5 is still surviving. Data from the trial suggests that the proportion of pulled stumps that produce coppice is higher than the coppice produced through the cut stump method, and these are more likely to survive. In addition, the pulled stump method provided an economic benefit with a 30 percent increase in recovered mass of sandalwood heartwood in comparison with the cut method. Harsh climatic conditions (drought, low and irregular rainfall, and summer temperatures above 40° C) and native animal browsing almost certainly contributed to the mortality of some of the coppice.

While this trial is not definitive, results are consistent with research from other areas including Western Australia where stump pulling has been the major harvest method for many years. To understand the ecology of this species fully, further research into regeneration on a range of sites, climates, soils, geology, shade levels and land uses is required. Further, the role of regeneration by seed, conceivably the most important regeneration on basalt 'wall' areas, needs to be investigated as well as seedling response and edaphic factors of other, differing ecosystems where commercial harvesting is occurring.

**Acknowledgments**

This project is ongoing with funding provided by Department of Primary Industries Forestry. We would like to thank all past and present DPI Forestry and Queensland Forestry Research Institute staff who have worked on this trial, especially Arthur Johnston and Rasid Karamujic. We appreciate the contribution of Geoff Kent and Allan Davis (DPI Forestry) and Marks Nester (QFRI) for their comments and reviews of the manuscript. We also acknowledge the leasee, Eugene Cox, for allowing us continued access to the research area.

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*The Sandalwood Research Newsletter is produced by the Department of Conservation and Land Management, Western Australia.*

*Editor: Tanya Vernes* *Typesetting and Publishing: Narelle Brook*