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Variability in and relation between tree growth, heartwood and oil content in sandalwood (*Santalum album* L.)

Sandal (*Santalum album* L.) is traditionally and commercially popular for its heartwood and oil extracted from the heartwood (hereafter just 'oil'). Apart from many customary uses, the scented wood is suited for creating exquisite handicrafts, whereas the oil has well-known applications in perfumery and pharmaceutical industries[1]. There is a renewed interest for cultivation of sandal on private land due to the spiralling prices (an auction in Tamil Nadu in 2009–10 fetched a staggering Rs 53.27 lakhs for a tonne of sandalwood; Tamil Nadu Forest Department (pers. commun.)) and favourable amendments made to the rules governing sandal cultivation by the governments of Karnataka and Tamil Nadu[2], which account for nearly 90% of sandalwood available in the country[3]. Prior to these amendments, the rules declared it a royal tree, which credited every tree, including those grown in private land to be government property[4]. With green felling banned on forest lands in India and a widespread cry for forest conservation, it is imminent that private plantations are going to be the future source of sandalwood in the country. In this changing scenario, tree breeders and plantation managers may have to gear up for maximizing productivity of sandal on private lands; the hitherto practice of extracting naturally growing trees had not called for productivity maximization so far. The primary information required for the purpose will be: (1) quantified variation across individuals with respect to heartwood and oil content, and (2) relation between the two and the most easily measurable growth character, tree diameter. These will be crucial for developing efficient management schedules and for selecting superior performers.

There may be several reasons for the current paucity of data on these important traits. Crucial being the necessity for quantifying variation before the trees start maturing; maturity is known to culminate in a near-constant proportion of heartwood to the total tree diameter[5]. Therefore, it is best to assess variation in the heartwood content at the juvenile–mature interface, which in tropical hardwoods is approximately 20 years[6,7]. (The interface is characterized by having large variation in growth as well as other important wood traits such as density, strength and fibre length when compared with mature wood[8].) This puts information on age as an overriding necessity for quantifying variation, which has been lacking because heartwood is traditionally extracted from trees that naturally occur; known-aged plantations are not substantial even on forest lands. Additionally, surrogate measurements of age are hampered because of indistinct growth rings[9] and unreliability of girth approximations. In this context, the aim of the present study was to quantify variation in heartwood and oil content of sandal, and to work out their relationship with tree diameter among individuals at their juvenile–mature interface.

Trees used in the study were part of the germplasm bank of sandal established during 1982–83 by the Institute of Wood Science and Technology (IWST), Bangalore, which was then known as Sandal Research Centre. This bank was established at Gottipura Field Research Station, Hoskote (13°6′N, 77°48′E), which is approximately 35 km from Bangalore (unfortunately the entire germplasm was lost to thieves in 2003–2004). This germplasm was best suited for measuring variation, as it was an assemblage of sandalwood accessions from the existing natural populations in four southern states of India – Karnataka, Tamil Nadu, Andhra Pradesh and Kerala. The assemblage was of those mature trees whose growth and heartwood content were considerably high at the time of selection. There was no information on their performance prior to maturity. Therefore, we still expected data from such an assemblage to reflect variation existing in sandal populations in arguably the centre of origin for the species. The study was conducted during 2002–2003 when the trees were 20 years old, which, we assume, is the approximate period when trees are at their juvenile–mature interface[6,7]. At the time of this study the germplasm consisted of 51 accessions, with each accession represented by nine individuals planted in 3×3 blocks. A spacing of 3×3 m was maintained between individuals. As sandal is known to be a root parasite, *Pongamia pinnata* was provided as a host. The area was well protected from grazing/fire, supported with irrigation during the first two years only, and weeded. There was no serious pest or disease incidence during any of the years. Further details of germplasm bank can be obtained from Srimathi[10].

Data on tree diameter, heartwood diameter and oil content were recorded from 37 accessions (high mortality prevented utilization of all 51 accessions). Three individuals per accession were randomly chosen, which brought the total number of trees from which data were recorded to 111. Girth of the tree was recorded at 2 ft above the ground and converted to diameter. Pressler's increment borer was used to draw two core samples from each tree at approximately 2 ft from the ground and at right angles to each other. As heartwood concentration is highest towards the base of the tree, we deviated from the standard practice of measuring girth and taking core samples at breast height. A core sample contains radial lengths of bark (bark thickness), sapwood (sapwood thickness) and a portion of the heartwood. It is therefore possible to estimate the diameter of the heartwood by subtracting twice the combined lengths of the bark and sapwood thickness from the tree diameter. Oil content (expressed as per cent by weight) was estimated by cold extraction method. Heartwood from a core sample was cut into fine pieces and soaked in known volume of hexane. The sample was kept aside for 18 h with periodic shaking. The optical density of the supernatant was measured at 219 nm (max) using UV spectrophotometer (Shimadzu-240). The procedure is detailed in Shankaranarayana *et al.*[11].

Data were pooled across all individuals for analyses. It was found that one of the individuals was an outlier (occurring in accession number K5), and was therefore excluded from analyses. Further, heartwood had not initiated in 15 individuals of five accessions. Hence the 15 individuals were also not considered wherever data involving heartwood and oil were analysed. Frequency distribution of the trees with respect to total diameter, heartwood diameter and oil percentage was individually plotted and tested

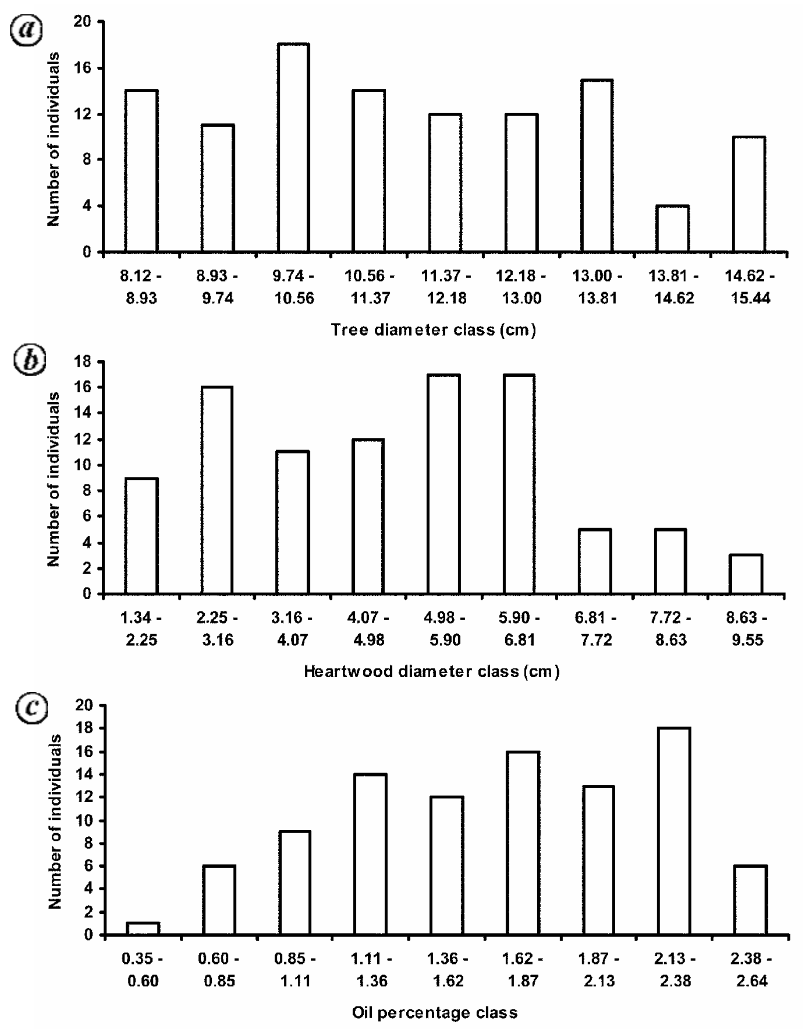

Figure 1. Frequency distribution of known-aged sandalwood trees along (***a***) tree diameter, (***b***) heartwood diameter and (***c***) oil percentage in the heartwood.

for deviation from normality using chi-square goodness-of-fit. Correlation between tree diameter and heartwood diameter, and tree diameter and oil percentage was carried out to study the relation between the variables. Similarly, proportion of heartwood to the total diameter was correlated with oil percentage.

Considerable variation has been recorded for tree diameter, heartwood diameter and oil percentage. Tree diameter varied from 8.12 to 15.44 cm (11.48 ± 1.97 cm), with maximum number of trees ($n = 18$) in the diameter class 9.74–10.56 cm. Heartwood diameter varied from 1.34 to 9.55 cm (4.83 ± 2.46 cm), with 36% of the trees falling in the diameter class 4.98–6.81 cm. Only 13.61% of the trees had heartwood diameter > 6.81 cm. Oil percentage varied from 0.39 to 2.64 (1.67 ± 0.51). Interestingly, 57% of the individuals had oil percentage ranging from 1.11 to 2.13. Frequency distribution of tree diameter, heartwood diameter and oil content indicated that the data were normally distributed (Figure 1; $\chi^2 = 6.19$, $P > 0.52$; $\chi^2 = 9.29$, $P > 0.24$, and $\chi^2 = 11.31$, $P > 0.12$ respectively).

Figure 2 shows a positive correlation between tree diameter and heartwood diameter ($r = 0.63$, $P < 0.01$). However, tree diameter and oil percentage were not correlated ($r = 0.095$, $P > 0.05$). Also, there was no relation between heartwood proportion and oil content ($r = 0.00$; $P > 0.05$).

Non-formation of heartwood till the time of sampling, as seen in ~14% of the individuals here, has been observed elsewhere too. Results from a study carried out in Australia on 14-yr-old sandal trees showed that heartwood had not formed in 25% of the individuals[12]. A number of events may be responsible for the transformation of sapwood to heartwood, like death of parenchyma, extractive formation, changes in enzyme activity and other ephemeral changes. However, factors triggering this conversion are not known, and therefore temporal variation in the heartwood formation cannot be reasonably explained. However, heartwood formation in sandal trees is speculated to generally start around 10–13 years of age[3].

Quantifying variation in heartwood diameter and oil concentration in sandalwood is of considerable importance for species improvement programmes. Information on available range of variation in the desired traits facilitates selection of superior genotypes and paves the way for sandalwood domestication in the long run[13]. Additionally, the data generated allow quantifying the relationship between the measured traits. Similar to the current findings, a strong positive relationship between tree diameter and heartwood diameter was observed in an uneven aged population of *Santalum austrocaledonicum* in the islands of Vanuatu[13]. Similar relationships have been reported in other tropical and temperate species. For instance, tropical species like *Acacia* sp.[14], *Acacia melanoxylon*[15], *Eucalyptus globulus*[16,17], *Pterocarpus angolensis*[18] and *Tectona grandis*[19], and temperate species such as *Juglans nigra*[20], *Larix decidua*[21], *Pinus canariensis*[22] and *Thuja plicata*[23] show positive relation between tree diameter and heartwood diameter.

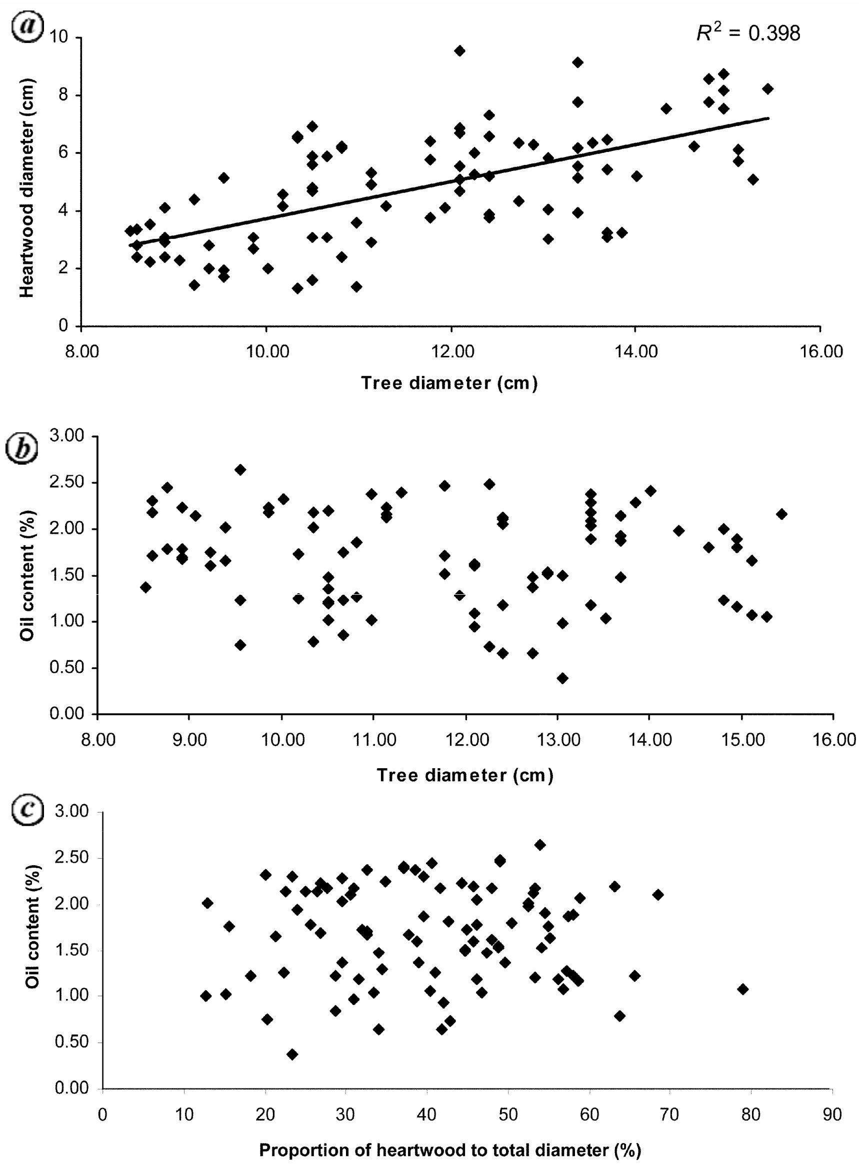

Figure 2. Relationship between (***a***) tree diameter and heartwood diameter, (***b***) tree diameter and oil content, and (***c***) proportion of heartwood to total diameter and oil percentage.

Heartwood formation follows the growth of pith and sapwood[24]. Once initiated, the heartwood is more or less continuously added[25]. Heartwood volumes are cumulative and increase with tree age in a near linear fashion[26]. In other words, higher the girth, larger would be the heartwood area and larger would be the heartwood volume. Therefore, tree girth/diameter can be used as an indicator for selecting genotypes under tree improvement programmes, where heartwood is the targeted trait. It was also found in this study that there was a weak significant positive correlation between tree diameter and heartwood proportion ($r = 0.30$, $P < 0.05$). It is important to note that this relationship would become stronger as the trees age (from maturity onwards), since the rate of sapwood increase slows down compared to that of the heartwood[27]. This differential growth rate continues till the extent of radial width of sapwood to the total tree diameter becomes a near constant. Therefore, selections made from among aged individuals may not be accurate. On the other hand, juvenile selections would also be unsuitable as heartwood formation may not have initiated. Consequently, selections made at the juvenile–mature interface would be better suited for identifying superior genotypes.

The absence of any relationship between heartwood proportion and oil content indicates that heartwood formation and oil accumulation may be two independent processes. Though oil formation occurs only in the heartwood, it is not necessary for oil accumulation to be linearly related to heartwood growth. However, as trees mature and rate of heartwood growth becomes a near constant, oil accumulation continues at a rate independent of the heartwood, leading to increase in oil content with tree age. It is a common feature to record higher concentration of heartwood extractives among older trees rather than in younger trees[28].

The results can be used to clarify an existing belief that oil content is higher in trees growing in dry/harsh conditions than those in fertile tracts. Size of the trees (height, canopy and diameter) growing in drier conditions will be usually lower than what is generally expected for a given age. Smaller diameter trees will certainly have smaller heartwood diameter. Given that oil formation is independent of heartwood growth, and assuming constant amount of oil being formed irrespective of tree/heartwood growth, trees of the same age but with smaller diameter may tend to have greater percentage of oil in the heartwood. As the mechanism involved in oil synthesis in this species remains elusive, further deductions are not possible.

This study has direct relevance for tree breeders and plantation managers. From the tree breeder's perspective, considering girth/diameter as the single important criterion would help in identifying superior genotypes having higher heartwood content. The considerable variation existing for the species with respect to the economically relevant traits could well be exploited. Ignoring the belief that harsher conditions lead to greater oil content, the present study suggests that plantation managers should look towards maximizing growth. It is important to recognize that a deeper understanding of the relationship between heartwood and oil is hampered by the lack of information on mechanism of natural synthesis of sandalwood oil.

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