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Heartwood in *Santalum austrocaledonicum*

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Introduction
The value, commercial or traditional, of *Santalum austrocaledonicum* derives directly from the essential oils contained in its wood. Moreover, distillation tests made in New Caledonia have clearly shown that oils are only found in heartwood (1 to 5% of the heartwood weight), with the sapwood containing only traces (less than 0.1% of oil).

It is therefore of paramount importance to be able to assess heartwood quantities and understand heartwood formation on standing trees in order to obtain reliable figures of existing potential resources.

In a previous paper, Cherrier (1993) showed that sapwood width (and indirectly heartwood) is related to growing conditions: the better the conditions, the better the growth and the wider the sapwood. On the other hand, Quemin (1988) showed that heartwood was easily differentiated from sapwood and that differences in heartwood colour were likely to be linked with differences in host plants although the link was rather difficult to quantify. From anatomical and growth ring studies he derived a method to assess the age of a tree with a reasonable precision (± 15%).

However, both Quemin and Cherrier were not able to develop prediction models to forecast heartwood yield from standing trees. Their best model (equation 1) was only able to explain 70% of the heartwood weight variations by using 3 parameters: $C_{0.20}$ (girth over bark 20 cm above ground level), S (sapwood width) and H (height of the tree).

$$W = 6.3\,C_{0.20} + 19.9\,H - 47S - 297 \qquad (1)$$

Using the same data it has been possible to develop other predictive models both simpler and more powerful. These have been used in the recent sandalwood inventory carried out on the Isle of Pines.

Materials and Methods
A sample of 154 trees among those cut during the last commercial harvest of sandalwood on the Isle of Pines was used by Quemin (1988), to assess several characteristics related to heartwood formation, sapwood width, and to build predictive models, *etc*. We have utilised the same set of data but focusing only on heartwood yield prediction and considering only the following parameters:

+ W: heartwood weight (154 trees) including roots (with a separate measure of stem and root weight for 50 trees).

+ $C_{0.20}$: girth over bark measured 20cm above ground level (154 trees).

+ S: sapwood width (108 trees) was assessed on wood discs by measuring the girth (circumference), underbark (C_u) and of the heartwood (C_h) with a curvometer.

$$S = \frac{(C_u - C_h)}{2\pi}$$

+ Age: estimated for 51 trees by analysing growth rings on a part of the disc following a method developed by Quemin (1988).

Results

Characteristics of the Sample

Descriptive statistics for the parameters utilised are summarised (Table 1).

TABLE 1. Sample statistics

Statistic	W (kg)	$C_{0.20}$ (cm)	S (cm)	Age (years)
Mean	208	80.4	2.9	48
St. deviation	174	20.0	1.0	14
Minimum	21	40.0	1.4	27
Maximum	1096	141.0	6.7	83

For the 50 trees with separate measures of root and stem weight, heartwood from the roots represented an average of 30% of the total heartwood (range: 18 to 45%). It seems, therefore, logical to dig out the roots for commercial harvest, currently the normal practice in New Caledonia.

Heartwood weight increases with girth (Table 2, Figure 1) and variation within classes is large, even for small dimensions. If we compare these data with those of Rai (1990) and Fox *et al.* (1994) it seems that *Santalum austrocaledonicum* produces much more heartwood than *Santalum album*. Given that *S. austrocaledonicum* shows equivalent growth rates and oil content, it is clearly a most promising species for plantation development.

TABLE 2. Heartwood weight by girth classes

$C_{0.20}$ (cm)	W (kg)	σ	Sample	Cv (%)
< 60	72	39	18	54
$60 < 70$	123	61	34	50
$70 < 80$	167	62	43	37
$80 < 90$	197	117	24	60
$90 < 110$	287	127	19	45
> 110	577	228	16	39

Contrary to heartwood weight, sapwood width does not seem to increase (or decrease) with the size of the tree (Table 3, Figure 2). As suggested by Quemin (1988) and Cherrier (1993), it is likely that sapwood width is related both to growing conditions and age.

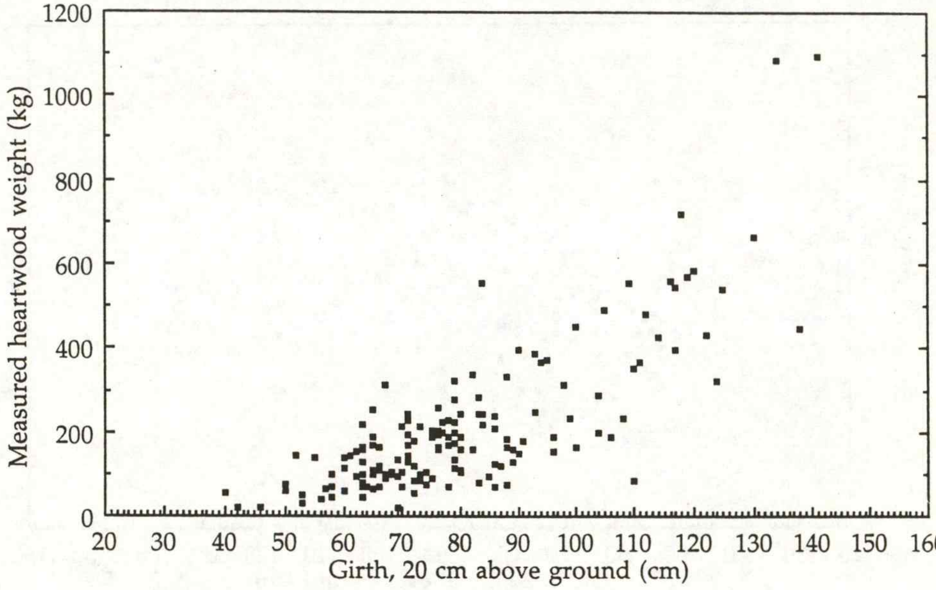

FIGURE 1. Relation between heartwood weight and girth over bark 20 cm above ground level.

Large and relatively young trees growing on good sites will have more sapwood than older or younger trees growing on adverse sites. On the other hand, they will also produce more heartwood.

TABLE 3. Sapwood width by girth classes

$C_{0.20}$ (cm)	S (cm)	σ	Sample	Cv (%)
< 60	2.6	0.8	14	30
60 < 70	2.7	0.5	20	19
70 < 80	2.6	0.9	29	35
80 < 90	3.6	1.2	17	33
90 < 110	2.8	0.7	17	25
> 110	3.7	1.7	11	46

From Figures 3 and 4 it is easy to note that except for very old trees, heartwood yield and sapwood width are not clearly related with age. Trees of a given age can produce very different quantities of heartwood according to their growing conditions. It is quite hazardous to try and give an age to a tree and forecast its heartwood content if there is no documented information concerning its life history. Heartwood yield forecasts based only on tree size seem to be more reliable.

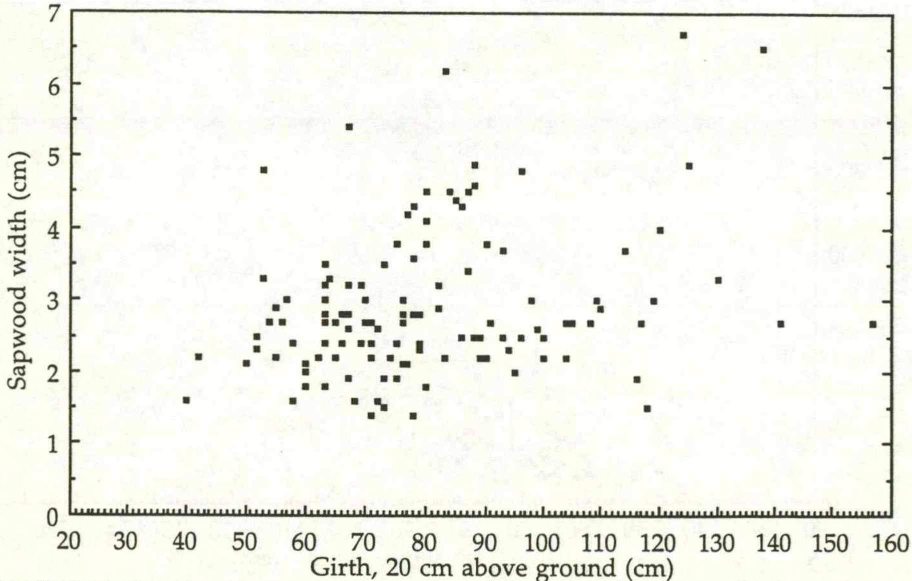

FIGURE 2. Relation between sapwood width and girth over bark 20 cm above ground level.

Heartwood Yield Estimates

Our purpose was to develop models superior to those previously elaborated by Cherrier (1993) and Quemin (1988).

The criteria required were that these new models should be more precise, more powerful and more robust than the former ones. When examining correlations between heartwood weight and some possible variables to be used in model building, we found:

	$C_{0.20}$	$C^2_{0.20}$	$C^3_{0.20}$	S
W	0.78	0.81	0.83	0.17

The best correlations are therefore with C^2 and C^3, whereas with the sapwood width, although significant, the value is low. However as it seemed important to take this parameter into account, we decided to create a new variable as follows:

$$C_h = C_{0.20} - 2\pi S$$

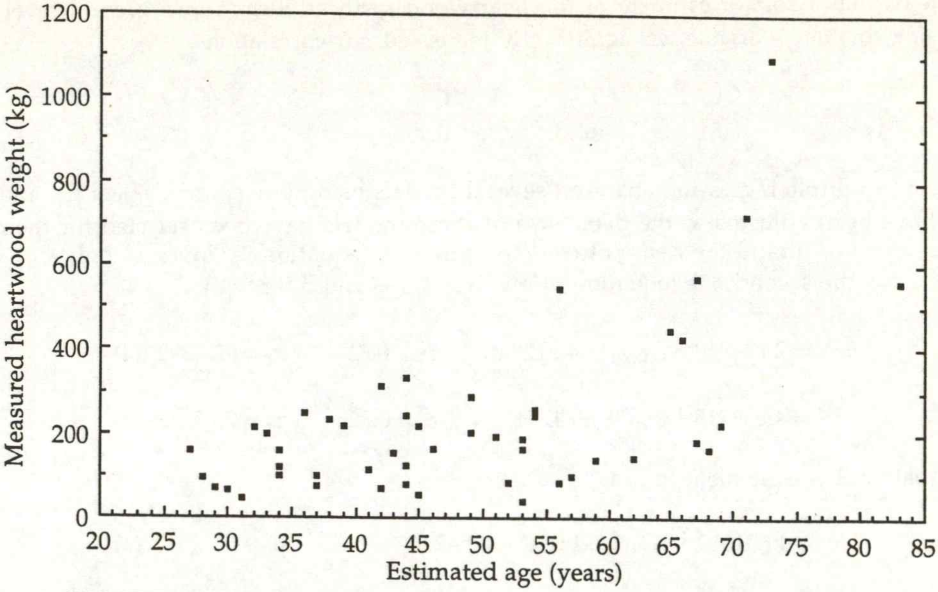

FIGURE 3. Relation between heartwood weight and age.

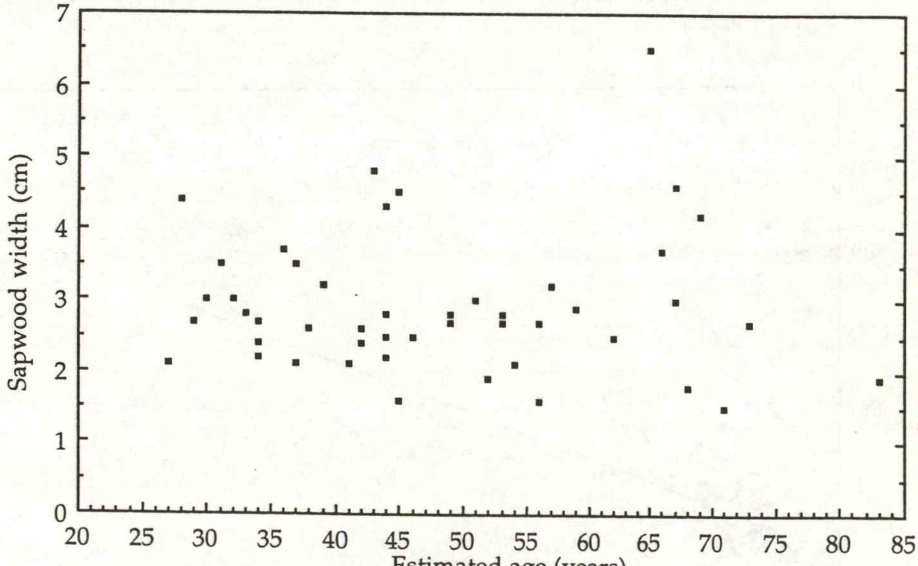

FIGURE 4. Relation between sapwood width and age.

C_h is then a sort of estimate of the heartwood girth at 20cm above ground level. Using this new variable we significantly increased our correlations:

	C_h	C^2_h	C^3_h
W	0.84	0.88	0.90

Using multiple regression analyses, several models using powers of $C_{0.20}$ or C_h and S have been adjusted to the data. Two of these models have been selected for their goodness-of-fit and their ease of use. The first one (equation 2) involves only $C_{0.20}$ whereas the second one (equation 3) involves $C_{0.20}$ and S through C_h.

$$W = 2.724910^{-4}\, C_{0.20}^3 + 42.1294 \qquad r^2 = 0.71 \qquad \sigma_r = 92.4392 \quad (2)$$

$$W = 4.831210^{-4}\, C_h^3 + 60.4774 \qquad r^2 = 0.82 \qquad \sigma_r = 73.9256 \quad (3)$$

Equation 3 is equivalent to :

$$W = 4.831210^{-4}\, (C_{0.20} - 2\,\pi S)^3 + 60.4774 \qquad (4)$$

For all the models, units are: W in kg; $C_{0.20}$, C_h and S in cm. Model (3) can also be summarized by a two-entry table, showing the joint effect of girth and sapwood width on heartwood yield (Table 4). The two models and corresponding data are illustrated as Figures 5 and 6.

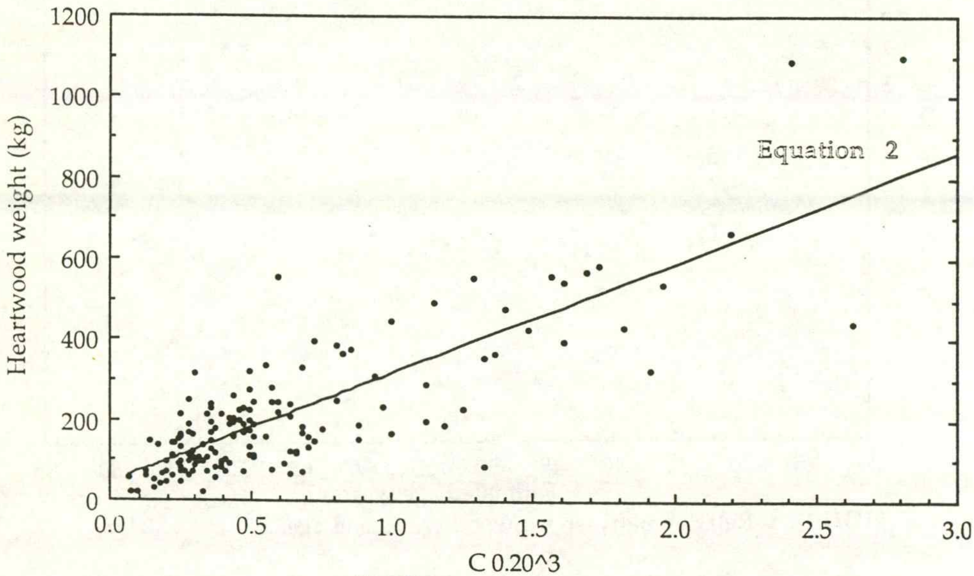

FIGURE 5. Model 2.

TABLE 4. Effect of girth and sapwood width on heartwood yield (units as before). Entries represent predicted weights of heartwood (kg) per tree for Model (3).

Sapwood	Girth at 20 cm above ground (C0.20)										
	40	50	60	70	80	90	100	110	120	130	140
1	79	101	135	185	254	344	458	599	771	975	1216
2	70	86	112	152	209	285	383	507	660	843	1060
3	65	75	94	125	171	234	319	426	560	724	920
4	62	68	81	104	140	192	263	356	473	618	793
5	61	64	72	88	116	158	216	295	396	523	679

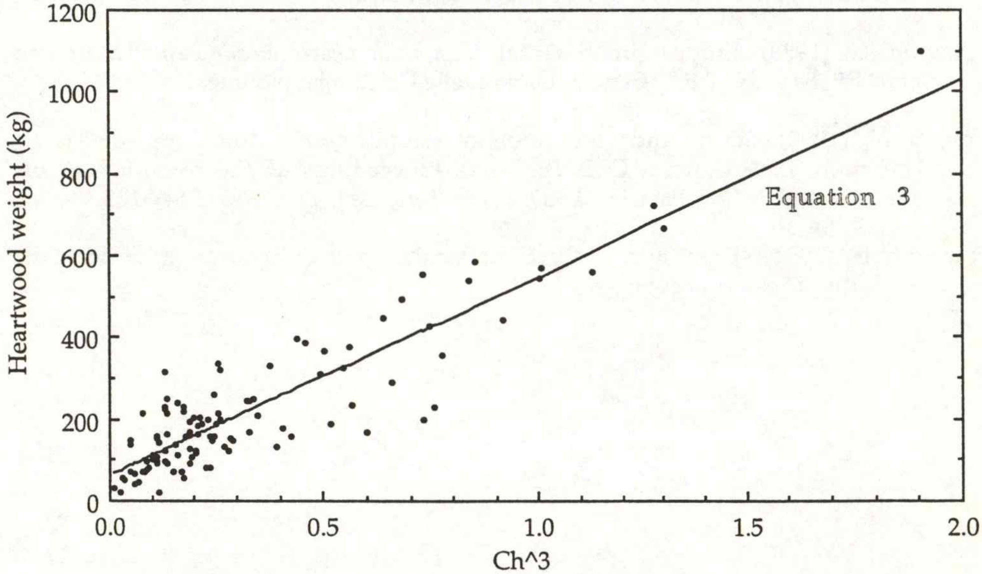

FIGURE 6. Model 3.

Conclusions

It is now possible to forecast heartwood yield on standing trees by means of relatively simple measures (girth and sapwood width) with a reasonable precision. Although this work was carried out on S. *austrocaledonicum*, it is probable that other *Santalum* species will follow the same pattern. Such relationships, involving the third power of the girth to forecast a weight or a volume have been found suitable in developing a volume table for firewood in West Africa (Nasi 1987).

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