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The Carbon Content of Trees

George Matthews

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Summary

Calculations of the quantities of carbon stored by trees requires a knowledge, not only of their growth rates, but also of the proportions of carbon contributing to their chemical make-up. This Technical Paper presents the results of a search of the literature for reported values for carbon contents and results of estimations of carbon contents from reported analyses for cellulose and other constituents by solvent extraction, and data from destructive distillation experiments.

It is concluded that the commonly assumed value of 50 % for the carbon content of dry wood is satisfactory for most purposes, but appropriate allowances should be made for any water present.

The Carbon Content of Trees

Introduction

The carbon content of trees has become of increasing interest in recent years because of their possible influence on the 'greenhouse effect' by removal of carbon dioxide from and release of oxygen into the atmosphere by photosynthesis.

Estimates of carbon storage in trees and wood are often reported without any reference to methods of calculation or the bases on which the calculations have been made. It seems to be tacitly assumed that trees contain approximately 50% carbon, but the basis for this assumption is rarely given.

For a number of reasons determination of an accurate value of carbon content applicable to a single species let alone a genus or family of trees is impossible. The carbon in a tree is bound in the organic compounds making up the body of the tree, mainly cellulose, hemicelluloses and lignins, and the proportions of these vary with species, position in the tree, the nature of the cells, the geographic location, age, and probably other factors, as reflected in the ranges of values reported in the literature:

	%
Cellulose	35–85
Hemicellulose	5–46
Lignin	13–35
Extractable compounds	1–26
Protein	0.2–2.1
Ash (inorganic)	0.6–2.3

Since the carbon contents of these substances are considerably different, this variation in composition would be expected to result in appreciable variations in carbon contents of trees.

This Technical Paper reports the results of a search of the literature for direct analyses for carbon, and for other analytical data that might be used to estimate carbon contents, and reviews the values so obtained.

Methods of assessment

Three main methods of assessment of carbon contents of trees are available:

1. direct analysis for carbon;

2. estimation from analyses for constituent compounds whose carbon contents are known;

3. estimation from destructive distillation data.

With all these methods, when using previously published data, there is commonly some doubt arising from uncertainty about the state of the specimens used. Although specimens are usually nominally 'dried' before analysis, it is difficult to achieve and maintain absolute dryness, and water content is not always reported.

Direct analysis for carbon

Accurate chemical analysis for carbon has been possible for many years, and some values reported here date back to 1883, but there is no reason to doubt the reliability of earlier reports merely because of their age. However, the extent to which variations in values reflect true variations in actual carbon content is uncertain, due to uncertainty about the state of samples and their locations within the tree. More refined and convenient spectrographic methods have been available for some years (Horton *et al.*, 1971) but these do not appear to have been used to perform analyses of wood or other tree specimens. There seems to be little point in embarking upon a large-scale programme of analyses at this stage.

A search of the literature revealed 64 reported values for carbon contents obtained by direct or 'ultimate' analyses. These are summarised in Table 1. The full results are detailed in the Appendix, Table 11.

Table 1 Carbon contents of woods obtained by direct analysis

	Carbon content (%) Mean	Range	Number of values
Ash	49.29	49.18–49.4	2
Aspen	49.85	49.39–50.3	2
Beech	49.14	48.5–50.9	8
Birch	48.76	46–50.6	7
Chestnut	50.28		1
Elm	50.2		1
Hickory	51.6		1
Hornbeam	48.99		1
Lime	49.4		1
Maple	50.0	49.8–50.2	2
Oak	48.95	46–50.6	9
Poplar	49.8	49.7–49.9	2
Sourwood	52.2		1
Tupelo	47.9		1
Willow	50.56	49.92–51.2	2
Fir	50.59	50–51.4	3
Larch	49.78	49.57–50.1	4
Pine	49.91	45.8–50.9	7
Spruce	49.34	47–50.31	8
'Wood'	50		1

As will be seen the species are not well defined, and these analyses cover no more than 23 taxa. Even for nominally the same species the quoted carbon content can apparently vary by as much as 10% (birch, oak and pine).

Table 2 Carbon contents of wood calculated from extractive analysis data

	Carbon content (%) Mean	Range	Number of values
Alder	50.2	49.8–51.4	3
Ash	49.8	48.1–51.3	4
Aspen	48.4	46.4–49.9	6
Balsa	48.6	47.1–49.8	3
Basswood	49.3	48.3–50.6	3
Beech	49.3	47.8–50.3	7
Birch	49.4	46.4–54.2	16
Blue gum	49.3		1
Catalpa	49.0		1
Cherry, fire	47.7		1
Elm	49.1	48.6–49.3	3
Hickory	48.1	46.1–49.2	3
Maple	49.5	48.0–51.5	8
Mesquite	50.1	49.7–50.5	2
Oak	49.4	46.3–51.4	7
Poplar	50.0	49.6–50.3	2
River red gum	50.7		1
Sweetgum	43.2		1
Tupelo	50.4	50.1–50.7	2
Wattle	48.8		1
Willow	50.9		1
Yemene	49.8		1
Eucalyptus	48.7	47.6–49.7	2
Cedar	51.1	49.6–52.1	10
Cypress	51.2		1
Fir	50.2	47.2–51.8	12
Hemlock	49.8	47.6–51.0	7
Juniper	51.1		1
Larch	50.5	50.3–50.9	3
Pine	49.9	47.5–52.5	27
Redwood	49.9	48.2–51.6	2
Spruce	49.8	47.2–52.7	14
Tamarack	49.8	49.5–50.0	4
Angelique	50.6	50.4–50.7	2
Greenheart	51.2	51.1–51.2	2
Kakeralli	50.9	50.5–51.3	2
Mahogany	48.1	47.7–48.4	2
Tanary	51.3	51.0–51.5	2
Teak	49.4	49.1–49.7	2
Abiurana	50.1		1
Breu branco	50.3		1
Cordia alliodora	50.7	50.6–50.7	2
Hymenaea coubaril	48.5	48.5	2
Imbauba	49.5		1
Licaria cayennensis	50.5	50.0–50.9	2
Manilkara bidentata	50.2	49.6–50.6	4
Ocotea rubra	50.7	50.7	2
Pau mulato	50.7		1
Pseudosamanea guachapele	49.4	49.3–49.5	2
Tabebuia guayacan	50.7	50.6–50.8	2

Analyses for constituent compounds

Determinations of the constituent compounds of trees have usually been with the objective of assessing their value as sources of raw materials, especially cellulose for the paper industry. The determinations have been carried out by 'extractive' analysis, that is by extraction of samples with selective solvents and under various conditions, which hopefully separate the constituents, thus permitting calculations of their concentrations.

Unfortunately solvent extractions rarely produce pure, separate components, and, because determination of actual carbon contents has not been an objective of these analyses, some interpretation of reported results is usually necessary, and some assumptions have to be made about the proportions and nature of some constituents, particularly as the analyses for the different components commonly sum to well over 100%. Even when the total is close to 100%, as in so-called 'summative' analysis, there is some suggestion (Browning, 1963) that this is due to fortuitous balancing of experimental errors. The situation is further complicated by the fact that different authors report their findings differently. For example, some authors report values for 'solubles', 'resin', wax, fat, protein, uronic anhydride and pectin, while others report none or a selection of these.

However, the contributions from the major constituents, cellulose, hemi-cellulose and lignin, should be calculable with reasonable accuracy, and errors in estimating contributions from other constituents should not produce gross errors in estimates of total carbon contents. In the calculations here, this has been assumed to be the case, and the concentrations of the various constituents including ash but excluding water have been adjusted to total 100% to yield carbon contents based on dry wood.

The chemical compositions of cellulose and lignin are well established, and carbon contents of 44.4% and 66.7%, respectively, can be safely assumed. Hemi-celluloses are copolymers of various carbohydrates with uronic acid and acetyl substituent groups, indicating carbon contents between 44.4% and 45.5%, depending on specific composition. A value of 45% has been assumed for present purposes.

The minor extractives, usually described as 'solubles', include a variety of more or less complex organic substances with individual carbon contents ranging from 40% to nearly 94% and a value of 40% has been used in these calculations. Hexosans were included with cellulose because their carbon contents are the same. Likewise, pentosans were included with hemi-celluloses. It has been assumed that 'solubles in hot water' and 'solubles in strong solvent', quoted by some authors, together give a good estimate of total 'solubles'. Minor errors in these figures should not result in gross errors in the calculated carbon contents.

The carbon contents calculated from extractive analyses are summarised in Table 2. The full results are presented in the Appendix, Table 12.

Where the summed totals of the constituents have differed appreciably from 100%, the results have been adjusted proportionally to give that total. Where separate analyses have been published for sapwood and heartwood, or springwood and summerwood, means have been calculated and quoted in the tables. Where values for one or more of 'solubles', resin, wax, fat, protein, uronic anhydride and pectin, have been quoted by authors, these have been grouped together under 'other organic'.

Estimation from destructive distillation data

The main interest in destructive distillation of wood has been for the production of charcoal, wood vinegar and other products, and analyses have usually been orientated to that end.

Calculation of carbon contents from these data is complicated by the fact that the carbon content of the charcoal, which can be significantly lower than 100%, is rarely quoted, and the same is true of the nature of the residual impurities in the charcoal. Moreover, the nature of the expelled gases is usually not reported in detail, and these, and the other decomposition products, can vary considerably in composition.

However, it has been suggested (Thorpe, 1913) that the distillation can be represented by the chemical equation:

$$\underset{\text{Wood}}{2C_{42}H_{54}O_{28}} \longrightarrow \underset{\text{Charcoal}}{3C_{16}H_{10}O_2} + 28H_20 + 5CO_2 + 3CO + \underset{\text{Products in tar, etc.}}{C_{28}H_{32}O_9}$$

This suggests directly a wood carbon content of 49.9% and, incidentally, indicates a carbon content for charcoal of 82.1%.

The charcoal figure is in good agreement with the values given by Klason *et al.* (1910) from practical destructive distillation data but the wood values are less uniformly in agreement. The relevant figures are reproduced in Table 3.

Table 3 Klason *et al.*'s figures for carbon contents of charcoal and woods

	Carbon content (%)	
	Charcoal	**Wood**
Beech	82.1	45.7
Birch	82.2	43.8
Pine	82.5	50.6
Spruce	82.5	48.0

Klason *et al.* (1908) appear to be the only authors who give full analytical data for their destructive distillation experiments, apart from some doubt about the fractions described as 'sodium salts of carboxylic acids' and 'tars'. Assuming that the former have a carbon content of 29.3% and the latter a carbon content of 85% permits direct calculation of carbon contents of the woods, as reported in the second column of Table 13 in the Appendix.

Other authors (Klason *et al.*, 1907/8, 1913; Martin, 1913; Farmer, 1967) have usually reported results in terms of yields of charcoal, tar, wood vinegar, wood vinegar containing acetic anhydride and gas. The carbon contents of these are not given. That of charcoal can be as low as 81.15% and as high as 90.36% (Thorpe, 1913), depending on the particular wood and on the distillation conditions. Wood tar contains an enormous number of substances, for example paraffins and other hydrocarbons, high boiling phenols and their esters, such as guaiacol, kreosol, pyrogallic esters, fatty acids and esters, and pitch. A carbon content of 85% has been estimated from this information and has been assumed in the calculations. Wood vinegar contains approximately 10% acetic acid, 1-2% methanol, 0.1% acetone and small amounts of other organic compounds. A carbon content of 13% has been estimated and used in the calculations. Likewise 'wood vinegar containing acetic anhydride' has been estimated to contain approximately 15.9% carbon.

The composition of the gas can apparently vary significantly according to pyrolysis conditions. Carbon dioxide and carbon monoxide are usually supposed to be the main constituents, but appreciable proportions of hydrogen and nitrogen have also been reported. Taking a typical analysis, a carbon content of 54% by weight has been estimated. Sometimes the volume of gas expelled per given weight of wood has been reported, so that, in addition to making assumptions about the composition of the gas, Avogadro's hypothesis has to be invoked to obtain estimates of carbon content by weight.

The carbon contents given in the tables have been calculated on the basis of these assumptions. Two values for carbon content of charcoal have been used to show its effect on the values obtained for overall carbon content of the woods. It seems likely that the lower value is the nearer to the true value.

A summary of the estimated values of wood carbon contents is given in Table 4. Full results are presented in the Appendix, Table 13.

Table 4 Carbon contents of woods calculated from destructive distillation data

	Carbon content of wood (%)	
	82.1% C in charcoal	90.4% C in charcoal
Beech	40.4–46.5	42.4–49.4
Birch	39.6–44.3	41.6–46.9
Oak	41.4–44.6	43.5–47.5
'Hardwood'	49.7	52.6
Fir	43.9	46.1
Pine	43.2–51.2	46.2–54.2
Spruce	47.9	50.9

Apart from Klason's value for pine, and Farmer's (1967) for 'hardwood', these figures are well below those quoted in the literature for direct analysis or obtained by calculation from extractive analyses data as reported herein. Particularly in view of the three values that are of the same order, it is suggested that the uncertainties inherent in estimating from previously published destructive distillation data make this approach unreliable and, for this reason, the values in Table 13 should be discounted.

Sudborough *et al.* reported destructive distillation data on 49 varieties of Indian trees but did not give details of all the products. For this reason, and because of the tenuous nature of assumptions that generally have to be made when using such data for present purposes, as mentioned above, these have not been used for estimations in the present work.

Variation of carbon content throughout a tree structure

A small number of reported analyses of trees differentiate between heartwood and sapwood, and carbon contents due to Lange and Violette are quoted (in Bunbury, 1923) for various parts of trees. Ritter and Fleck (1923, 1926) give some extractive analysis figures for springwood and summerwood.

The reported variations of carbon content between different parts of trees are surprisingly small relative to the range of variations in overall carbon contents.

Daube (1883) presented carbon contents for sapwood and heartwood for a few trees as shown in Table 5.

Table 5 Carbon contents of sapwoods and hardwoods

	Age (years)	Carbon contents (%) Sapwood	Heartwood
Beech	180	48.92	49.06
Oak	125	49.15	50.25
Larch	103	49.57	49.86
Pine	104	50.18	54.38
Spruce	75	50.03	49.55

The analytical data of Ritter and Fleck for heartwood and sapwood, and springwood and summerwood, do not permit accurate direct calculations of carbon contents, and, as discussed previously, assumptions have to be made if they are to be used for present purposes.

Making these assumptions, the differences between the calculated carbon contents for heartwood and sapwood were in most cases less than 1%, only 3 out of the 14 cases giving higher values. There was a very slight but inconclusive indication that sapwood might tend to have a slightly higher concentration of carbon than heartwood.

A similar comment may be made about the apparent differences between springwood and summerwood, though the carbon content of the latter was usually lower and never higher than that of the former.

Lange differentiated between trunk, branch and twig, as given in Table 6. Table 7 gives Violette's values for carbon contents for various parts of a 31-year-old pear tree.

Anderson and Pigman (1947) reported results of extractive analyses of outer bark, inner bark, cambial zone, young sapwood, sapwood and heartwood of black spruce, but these are not sufficiently complete to justify estimation of carbon contents. However, their figures do suggest only relatively small differences between heartwood and sapwood, while 'young sapwood' contained less lignin and pentosans than these. Inner bark and cambial zone had very much lower lignin concentrations, but outer bark had a higher lignin content than any of the other regions.

Table 6 Carbon content variation within trees (Lange)

	Carbon content (%)						
	Aspen	Beech	Birch	Oak	Willow	Fir	Pine
Trunk	50.31	50.89	50.61	50.64	51.75	51.39	
Main branch						52.04	52.15
Twig	51.02	50.08	51.93	50.89	54.03		

Table 7 Carbon content variation within trees (Violette)

	Carbon content (%) Wood	Bark
Leaves	45.0	
Branch, top section	48.4	52.5
Branch, middle section	49.9	48.9
Branch, lower section	48.0	46.9
Trunk	48.9	46.3
Root, top part	49.3	49.1
Root, middle part	47.4	50.4
Root, lower part	45.1	

This latter observation accords with the findings of Poller and Knappe (1988), who reported the following carbon contents for different parts of 'Scotch Fir'.

	%
Stemwood	49.3
Branchwood	50.0
Trunkwood	50.5
Bark	52.9
Inner bark	49.3
Needles	52.9

They carried out extractive analyses on the various parts. Using the method of estimation described herein, the carbon contents so calculated do not agree very well with those quoted by the authors. However these results do confirm the variations and their order of magnitude between different parts of a tree, though general conclusions about the way these variations occur cannot be made on the basis of the data available.

Jayme and Schorning (1938, 1940) found the cellulose content of beech to vary with age and location in the tree, as summarised in Table 8.

Table 8 Variation of cellulose content with age

Age (years)	% 'Resistant pure cellulose' Place on tree above ground 0.1–0.5m	5–12m	average
30	33.71	35.06	34.39
43	35.44	35.74	35.59
86	34.76	35.90	34.83
86	34.65	36.70	35.68
86	35.53	36.19	35.86
108	36.90	36.75	36.83
114	35.88	35.51	35.65
114	35.81	35.11	35.46
Average overall			35.51

Without information on content of lignin and other constituents these figures cannot be used to estimate total carbon contents. However, although the variations reported here were presumably real, they are small compared with the range of values found in the literature generally (i.e. 35% to 66%).

To what extent variations similar to those reported in this section are to be expected in other species is open to question.

Discussion

On the whole, in view of the assumptions that have been necessary, the results obtained from extractive analyses data are remarkably consistent and in good agreement with results of 'ultimate analyses' where comparisons are possible. Perhaps this provides more confidence in the extractive analysis results in those cases where 'ultimate analyses' are not available.

Klason *et al.* (1910) are alone in giving full analysis of destructive distillation products, and also calculating carbon contents of the woods. With few exceptions carbon contents calculated from published destructive distillation data are appreciably lower than those obtained from the other two sources.

Farmer (1967) states that the charcoal has 17.5% volatiles. If this comprised mainly hydrocarbons the true carbon content of charcoal could be as high as 95.6% but using this value rather than the lower values quoted elsewhere in the literature increases the carbon contents calculated for woods by one or two units only, bringing them closer but generally not up to the values obtained by the other methods.

It has been suggested that the main factor that determines carbon content is the lignin/cellulose ratio. The mean ratios of lignin to cellulose and lignin to cellulose plus hemicellulose for the broad classes of tree, taken from extractive analysis data, are listed in Table 9.

These figures suggest that conifers and tropical species tend to have higher lignin to cellulose ratios than broadleaf species, but mask the considerable spread of values found within each group.

Table 9 Lignin/cellulose ratios

	Lignin/α-cellulose	Lignin/total [a] cellulose
Broadleaf	0.48	0.31
Conifer	0.56	0.46
Tropical	0.62	0.48

[a] α – cellulose + hemicellulose.

Bunbury (1923) presented figures apparently showing some increase in both cellulose and lignin contents of the trunk of alderwood over a period of 7 to 70 years, but they are not sufficiently detailed to justify any conclusions as to any possible changes in overall carbon contents with age.

It is clear that the carbon content of a tree or a wood product is very dependent on water content, and this has to be borne in mind when assessing carbon storage capacity.

Conclusions

The distributions of carbon contents obtained by the various methods are illustrated by the histograms of Figures 1 and 2 in which the numbers of examples found for the 1% step around each whole number percentage are plotted. Values having a decimal of 0.5% are placed in the higher of the possible bands.

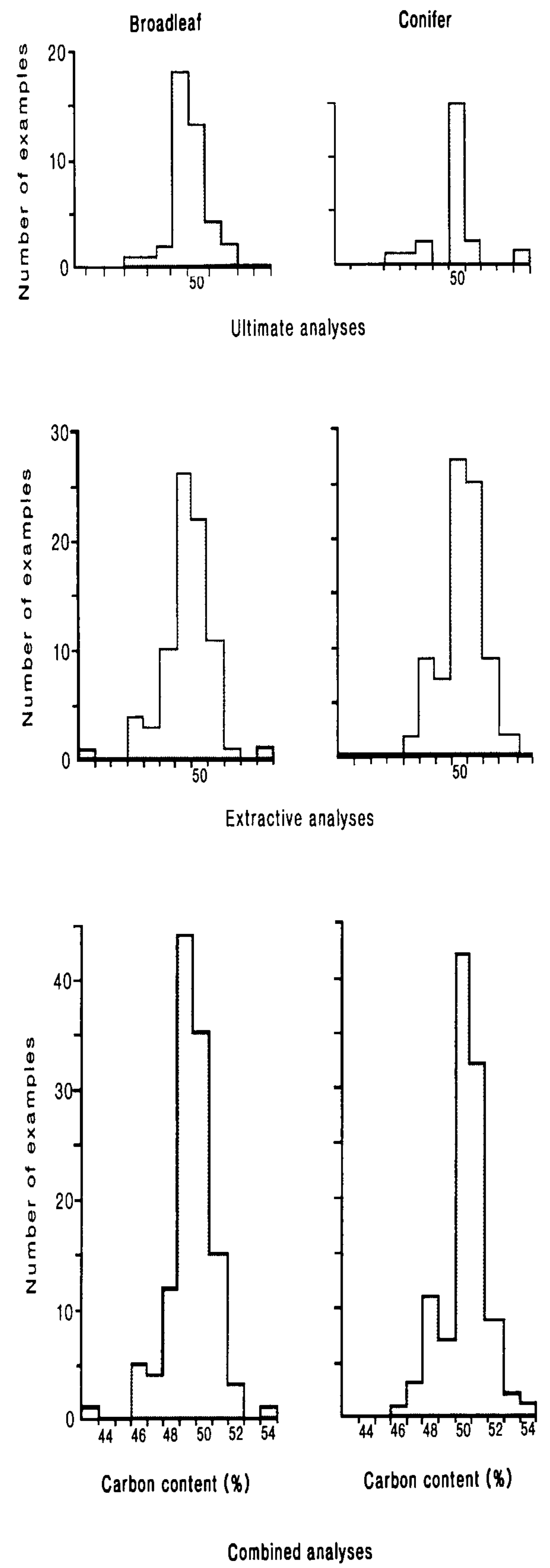

Figure 1 Carbon contents of broadleaves and conifers

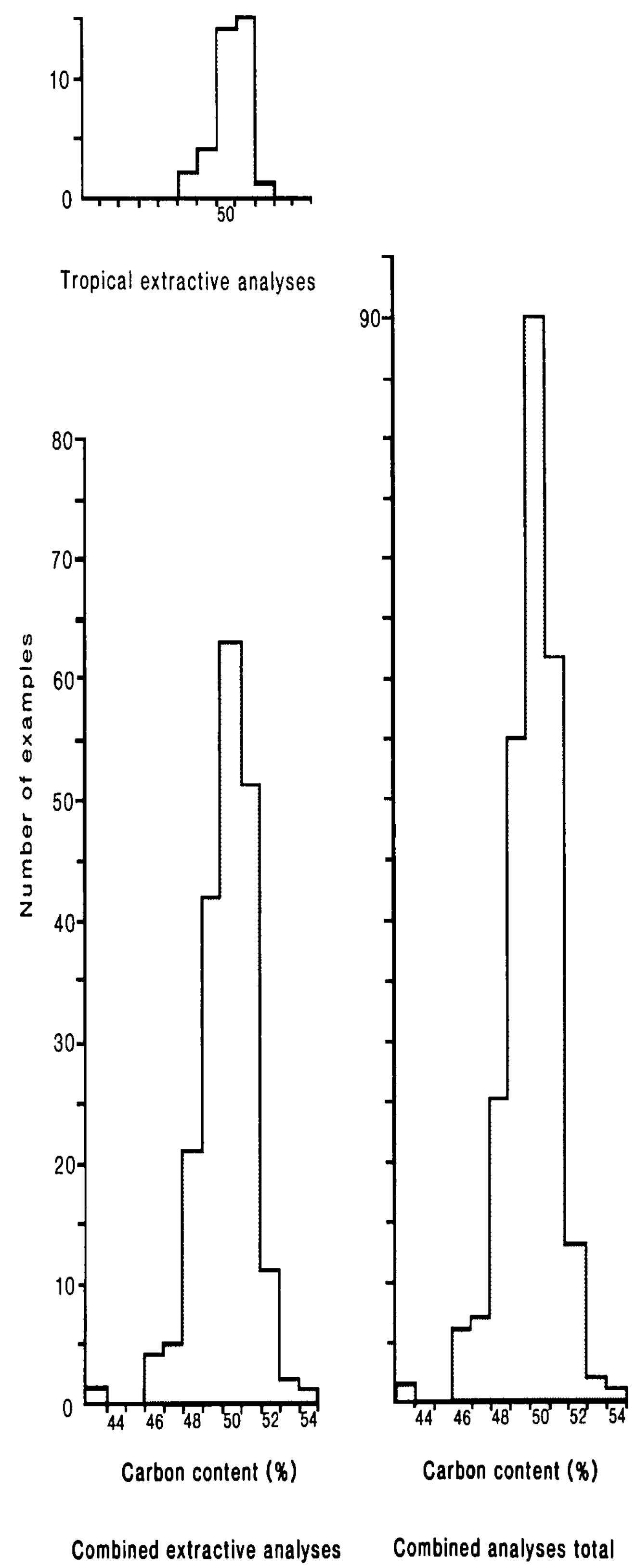

Figure 2 Carbon contents of tropical trees and combined values of all varieties

Table 10 gives the mean values for the three broad types of wood.

Apart from a suggestion that the carbon contents of broadleaf trees are generally slightly lower than those of conifers and tropical trees, the variation in mean values is surprisingly small in view of the methods of calculation employed, and further conclusions about relationships between specific species cannot generally be supported by these results, or the detailed results in the Appendix.

Variations due to age of trees, positions from which samples have been taken, location of trees, time of year and experimental errors, together tend to mask any real variations that may exist between species.

It is apparent, however, that the values of carbon contents tend to cluster around 49% to 51%, there being some indication that the former value is appropriate for broadleaf trees, and 50% appropriate for conifers and tropical species.

In view of the uncertainty attached to the analyses and to the estimations of tree growth, a value of 50%, or a factor of 0.5 times dry tree weight, seems reasonable to adopt for projection and other calculations. It must be remembered that the water content of timber depends on its previous treatment and storage conditions, and may be sufficiently high to reduce appreciably the overall carbon content. For example, a 20% water content would reduce the carbon content to around 40%.

It may be noted that these represent photosynthesised carbon dioxide amounting to 1.83 times the dry weight of a tree.

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Table 10 Comparison of results from the three different methods

	Carbon contents (%)			
	Ultimate analysis	Extractive analysis	Destructive distillation 82.1% C in charcoal	Destructive distillation 90.4% C in charcoal
Broadleaf	49.4	49.3	41.7	44.0
Conifer	49.8	50.1	45.9	47.4
Tropical		50.1		

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APPENDIX

The full results of carbon content analyses are presented in the three tables that follow.

Table 11 Carbon contents by direct analysis

	% Carbon	Reference
Ash	49.18	Gottlieb (1883)
	49.4	Bunbury (1923)
Aspen	49.39	Chevandier (1884)
	50.3	Bunbury (1923)
Beech	48.5	Bunbury (1923)
	48.7	Klason *et al.* (1910)
	48.9	U.S. Dept. A.F.S. (1952)
	49.01	Gottlieb (1883)
	49.28	Chevandier (1884)
	50.9	Bunbury (1923)
Beech, sapwood	48.92	Daube (1883)
Beech, heartwood	49.06	Daube (1883)
Birch	46	Matthews (1989)
	48.6	Bunbury (1923)
	48.7	Klason *et al.* (1910)
	48.88	Gottlieb (1883)
	49.8	Klason (1913)
	50.22	Chevandier (1884)
	50.6	Bunbury (1923)
Chestnut	50.28	Sherman and Amend (1911)
Elm	50.2	Brasch and Wise (1956)
Hickory	51.6	Reichle *et al.* (1973)
Hornbeam	48.99	Gottlieb (1883)
Lime	49.4	Bunbury (1923)
Maple	49.8	Bunbury (1923)
Maple, red	50.2	Reichle *et al.* (1973)
Oak	46	Matthews (1989)
	46.8	Reichle *et al.* (1973)
	49.2	U.S. Dept. A.F.S. (1952)
	49.4	Bunbury (1923)
	49.62	Chevandier (1884)
	50.16	Gottlieb (1883)
	50.6	Bunbury (1923)
Oak, sapwood	49.15	Daube (1883)
Oak, heartwood	50.28	Daube (1883)
Poplar	49.7	Bunbury (1923)
Poplar, tulip	49.9	Reichle *et al.* (1973)
Sourwood (sorrel)	52.2	Reichle *et al.* (1973)
Tupelo, black	47.9	Reichle *et al.* (1973)
Willow	49.92	Chevandier (1884)
	51.2	Bunbury (1923)

Table 11 cont'd

	% Carbon	Reference
Fir	50.36	Gottlieb (1883)
	51.4	Bunbury (1923)
Fir, silver	50.0	Bunbury (1923)
Larch	49.6	U.S. Dept. A.F.S. (1952)
	50.1	Bunbury (1923)
Larch, sapwood	49.57	Daube (1883)
Larch, heartwood	49.86	Daube (1883)
Pine	50.2	U.S. Dept. A.F.S. (1952)
	50.9	Klason *et al.* (1910)
Pine, sapwood	50.18	Daube (1883)
Pine, heartwood	54.38	Daube (1883)
Pine, Corsican	48	Matthews (1989)
Pine, Scots	49.9	Bunbury (1923)
Pine, shortleaf	45.8	Reichle *et al.* (1973)
Spruce	49.6	Bunbury (1923)
	50.0	U.S. Dept. A.F.S. (1952)
	50.2	Klason *et al.* (1910)
	50.31	Gottlieb (1883)
Spruce, sapwood	50.03	Daube (1883)
Spruce, heartwood	49.55	Daube (1883)
Spruce, Sitka (N.Yorks)	47	Matthews (1989)
Spruce, Sitka (N.Lakes)	48	Matthews (1989)
'Wood'	50	Thorpe (1913)

Table 12 Carbon contents calculated from extractive analysis data (%)

	Reference(s)	Ash	Cellulose	Hemicellulose	Lignin	Other organic substances	Estimated carbon
Alder	Konig and Becker (1919)	0.49	47.3	22.9	23-26	4.72	51.4
Alder, gray	Sjostrom (1981)	1.4	38.3	30.9	24.8	4.6	49.4
Alder, red	Ritter and Fleck (1923, 1926)		34.9	45.7		c.21	49.8
Ash	Konig and Becker (1919)	0.83	45.9	23.7	26	3.54	51.3
Ash, black	Clermont and Schwartz (1952)	0.7	47.4	21.2	18.6	4.7	48.1
Ash, white	Ritter and Fleck (1923, 1926)		35.4	39.2	23.6	19.7	49.4
	Ritter and Fleck (1923, 1926)	0.45	44.6	29.5	27.9	21.1	50.4
Aspen	Schwalbe and Becker (1919)	0.32	47.8	38.8	18.2	10.51	49.9
Aspen, big-tooth	Freeman and Petersen (1941)	0.3	63.6	15.6	16.6	7.0	48.4
Aspen (poplar)	Clermont and Schwartz (1951)	0.38	52.5	14.6	18.1	26.17	46.4
Aspen, trembling	Tinnell (1957, 1958)	0.2	60.4	16.4	16.3	3.3	47.1
Aspen, quaking	Wise and Jahn (1952)		48.8	18.8	19.3	21.6	49.0
	Wise and Jahn (1952)		50.1	18.7	19.2	20.0	49.1
Balsa	Ritter and Fleck (1922)	2.12	54.2		26.5		47.1
	Sjostrom (1981)	1.2	47.7	27.6	21.5	2.0	48.8
	Mahood and Cable (1922) Ritter and Fleck (1922) Schorger (1917)	2.12	44.2	28.5	26.5		49.8
Basswood	Clermont and Schwartz (1952)	0.6	45.0	22.9	17.2	7.6	48.3
	Wise and Jahn (1952)	0.7	48.2	16.6	20.0	24.0	49.0
	Mahood and Cable (1922) Ritter and Fleck (1922) Schorger (1917)	0.86	50.1	34.8		25.7	50.6
Beech	Tinnell (1957, 1958)	0.4	50.8	18.0	22.1	4.8	47.8
	Clermont and Schwartz (1952)	0.4	43.6	23.6	22.2	2.7	49.1
	Wise and Jahn (1952)	0.5	51.2	20.2	21.0	16.5	49.3
	Freeman and Petersen (1941)	0.44	60.4	25.0	21.4	2.6	49.4
	Sjostrom (1981)	1.3	39.4	33.3	24.8	1.2	49.6
	Konig and Becker (1919)	0.96	49.8	24.3	22.7	2.28	49.8
	Schwalbe and Becker (1919)	1.17	54.5	38.5	22.5	7.35	50.3

Table 12 continued

	Reference(s)	Ash	Cellulose	Hemicellulose	Lignin	Other organic substances	Estimated carbon
Birch	Schwalbe and Becker (1919)	0.39	46.1	45.9	19.6	7.15	50.5
	Konig and Becker (1919)	0.46	45.0	24.0	26.4	4.17	51.4
	Konig and Becker (1919)	0.68	46.5	25.9	28.3	3.76	54.2
Birch, paper	Sjostrom (1981)	2.1	39.4	34.5	21.4	2.6	48.4
	Wise and Jahn (1952)	0.4	46.9	21.8	19.2		49.0
	Freeman and Peterson (1941)	0.23	53.3	16.0	18.6	7.1	49.1
	Wise and Jahn (1952)		44.7	23.3	19.3	16.9	49.3
Birch, silver	Sjostrom (1981)	1.4	41.0	32.4	22.0	3.2	48.8
Birch, white	Clermont and Schwartz (1951)	0.29	51.0	19.2	18.5	27.26	46.4
	Tinnell (1957, 1958)	0.2	46.8	25.1	18.9	4.6	47.4
Birch, yellow	Clermont and Schwartz (1952)	0.3	42.6	26.6	18.8	4.1	48.3
	Tinnell (1957, 1958)	0.3	51.2	20.7	21.3	4.2	48.3
	Freeman and Petersen (1941)	0.31	58.4	17.0	19.4	2.7	49.0
	Ritter and Fleck (1923, 1926)	0.33	47.1	33.2	24.7	19.3	49.6
	Wise and Jahn (1952)	0.8	51.0	22.6	22.7	18.0	49.6
	Mahood and Cable (1922)						
	Ritter and Fleck (1922)	0.52	46.6	42.0		20.5	51.3
	Schorger (1917)						
Catalpa	Ritter and Fleck (1923, 1926)		30.4	45.4	18-24	24-35	49.0
Cherry, fire	Freeman and Petersen (1941)	0.29	59.1	14.6	13.5	5.3	47.7
Elm, American	Wise and Jahn (1952)	0.4	55.2	16.2	20.5	16.3	49.4
Elm, white	Tinnell (1957, 1958)	0.8	43.8	20.8	23.9	4.5	48.6
	Clermont and Schwartz (1952)	1.1	47.2	18.5	23.4	3.3	49.3
Hickory	Ritter and Fleck (1922)	0.69	56.2		23.4		46.1
	Mahood and Cable (1922)						
	Ritter and Fleck (1922)	0.69	44.7	31.1	23.4	19.7	49.1
	Schorger (1917)						
Hickory, pignut	Ritter and Fleck (1923, 1926)	0.43	49.0	27.9	22.4	17.5	49.2

Table 12 continued

	Reference(s)	Ash	Cellulose	Hemicellulose	Lignin	Other organic substances	Estimated carbon
Maple, red	Tinnell (1957, 1958)	0.2	50.7	17.8	24.0	3.5	48.9
	Wise and Jahn (1952)	0.7	44.5	17.1	22.8	20.4	49.8
Maple, sugar	Tinnell (1957, 1958)	0.3	54.1	15.6	22.7	4.4	48.0
	Clermont and Schwartz (1952)	0.4	46.8	22.2	21.1	3.7	49.1
	Freeman and Petersen (1941)	0.58	60.3	15.2	21.1	2.9	49.2
	Sjostrom (1981)	0.8	40.7	30.8	25.2	2.5	49.8
	Mahood and Cable (1922)						
	Ritter and Fleck (1922)	0.44	48.3	36.6		17.9	51.5
	Schorger (1917)						
Mesquite	Ritter and Fleck (1922)	0.54	45.5		30.5		49.7
	Mahood and Cable (1922)						
	Ritter and Fleck (1922)	0.54	38.1	22.0	30.5	30.8	50.5
	Schorger (1917)						
Oak, chestnut	Wise and Jahn (1952)	0.4	46.8	19.2	24.3	25.8	50.0
Oak, southern red	Tinnell (1957, 1958)	0.8	43.8	19.6	23.9	4.5	46.3
	Brasch and Wise (1956)	0.2	43.7	20.0	25.2	7.8	49.6
	Wise and Ratcliff (1947)	0.2	45.7	23.3	25.2	3.3	49.7
	Wise and Pickard (1955)						
Oak, tambark	Ritter and Fleck (1922)	0.83	58.0	24.9			48.8
	Ritter and Fleck (1923, 1926)	0.83	44.8	32.8	24.9	30.8	50.0
Oak, white	Ritter and Fleck (1923, 1926)	0.50	38.3	34.6	32.5	24.0	51.4
Poplar	Konig and Becker (1919)	1.03	51.3	22.3	21.7	3.76	50.3
Poplar, yellow	Ritter and Fleck (1923, 1926)	0.35	49.1	29.8	23.8	17.6	49.6
Blue gum	Sjostrom (1981)	0.3	51.3	25.2	21.9	1.3	49.3
River red gum	Sjostrom (1981)	1.7	45.0	19.2	31.3	2.8	50.7
Sweetgum	Tinnell (1957, 1958)	0.2	43.3	17.8	23.7		43.2
Tupelo, black	Brasch and Wise (1956)	0.7	45.6	17.1	25.8	8.4	50.1
	Wise and Ratcliff (1947)	0.7	46.5	23.4	25.8	3.7	50.7
	Wise and Picard (1955)						

Table 12 continued

	Reference(s)	Ash	Cellulose	Hemicellulose	Lignin	Other organic substances	Estimated carbon
Wattle, black	Sjostrom (1981)	0.9	42.9	33.6	20.8	1.8	48.8
Willow	Konig and Becker (1919)	0.83	48.0	23.3	24.0	3.21	50.9
Yemane	Sjostrom (1981)	0.9	47.3	21.1	26.1	4.6	49.8
Eucalyptus	Ritter and Fleck (1922)	0.24	57.6		25.1		47.6
	Mahood and Cable (1922)						
	Ritter and Fleck (1922)	0.24	47.9	32.2	25.1	19.1	49.7
	Schorger (1917)						
Cedar, eastern white	Tinnell (1957, 1958)	0.2	55.0	8.8	30.7	4.2	49.6
Cedar, incense	Ritter and Fleck (1923, 1926)	0.39	41.7	17.1	34.2	18.3	51.5
	Ritter and Fleck (1922)	0.34	41.6		37.7		51.7
	Mahood and Cable (1922)						
	Ritter and Fleck (1922)	0.34	39.2	14.4	37.7	22.0	52.1
	Schorger (1917)						
Cedar, western red	Brasch and Wise (1956)						
	Wise and Ratcliff (1947)	0.3	52.6	8.1	32.5	4.2	51.0
	Wise and Pickard (1955)	0.3	52.7	14.6	32.5	0.5	52.1
Cedar, white	Ritter and Fleck (1923, 1926)	0.37	51.4	15.2	32.3	15.1	51.3
Cedar, yellow	Ritter and Fleck (1922)	0.43	53.9		31.3		49.7
	Ritter and Fleck (1923, 1926)	0.23	54.5	13.0	28.9	13.4	50.7
	Mahood and Cable (1922)						
	Ritter and Fleck (1922)	0.43	53.3	11.8	31.3	16.0	51.1
	Schorger (1917)						
Cypress, bald		0.91	50.4	11.6	33.8	17.5	51.2
Fir	Konig and Becker (1919)	0.76	55.6	11.6	28.0	3.48	51.8
Fir, balsam	Clermont and Schwartz (1951)	0.4	66.1	7.0	27.7	19.0	47.7
	Tinnell (1957, 1958)	0.2	60.2	5.3	29.4		49.7
	Sjostrom (1981)	0.9	38.8	28.5	29.1	2.7	50.6

Table 12 continued

	Reference(s)	Ash	Cellulose	Hemicellulose	Lignin	Other organic substances	Estimated carbon
Fir, Douglas	Brasch and Wise (1956) Wise and Ratcliff (1947) Wise and Pickard (1955)	0.3	53.7	6.2	28.4	3.4	47.2
	Tinnell (1957, 1958)	0.4	59.0	5.5	31.5	2.8	50.3
	Sjostrom (1981)	0.0	38.8	26.3	29.3	5.3	50.8
	Mahood and Cable (1922) Ritter and Fleck (1922) Schorger (1917)	0.38	62.6	9.3		17.1	50.9
	Wise and Jahn (1952)	0.2	50.4	6.8	27.2	19.5	51.0
	Ritter and Fleck (1923, 1926)		50.2	18.3	30.9	14.8	51.2
	Brasch and Wise (1956) Wise and Ratcliff (1947) Wise and Pickard (1955)	0.3	57.2	14.1	28.4	0.6	51.2
Fir, Noble	Wise and Jahn (1952)	0.4	42.8	9.0	29.3	12.3	50.3
Hemlock, eastern	Clermont and Schwartz (1951)	0.28	53.0	12.5	29.6	17.9	47.6
	Tinnell (1957, 1958)	0.2	57.7	4.6	32.5	3.3	50.5
	Sjostrom (1981)	0.5	37.7	27.9	30.5	3.4	51.1
Hemlock, mountain	Wise and Jahn (1952)	0.5	42.6	7.0	27.0	16.8	49.6
Hemlock, western	Brasch and Wise (1956) Wise and Ratcliff (1947) Wise and Pickard (1955)	0.5	48.6	7.3	30.4	6.2	48.2
	Wise and Jahn (1952)	0.3	52.5	9.2	27.8	10.8	50.7
	Brasch and Wise (1956) Wise and Ratcliff (1947) Wise and Pickard (1955)	0.5	51.6	15.5	30.4	1.2	51.0
Juniper, common	Sjostrom (1981)	1.4	33.0	30.3	32.1	3.2	51.1
Larch, Siberian	Sjostrom (1981)	0.4	41.4	29.6	26.8	1.8	50.4
Larch, western	Mahood and Cable (1922) Ritter and Fleck (1922) Schorger (1917)	0.23	55.4	16.0		23.0	50.3
	Wise and Jahn (1952)	0.4	50.0	7.8	26.8	14.8	50.9

Table 12 continued

	Reference(s)	Ash	Cellulose	Hemicellulose	Lignin	Other organic substances	Estimated carbon
Pine	Schwalbe and Becker (1919)	0.39	56.5	17.3	26.4	4.25	52.3
	Konig and Becker (1919)	0.53	54.7	10.8	29.5	4.44	52.5
Pine, jack	Clermont and Schwartz (1951)	0.19	47.5	16.2	27.4	24.3	47.8
	Tinnell (1957, 1958)	0.2	57.6	8.5	28.6	3.9	49.3
	Wise and Jahn (1952)	0.3	45.2	9.7	26.7	14.9	49.6
Pine, Loblolly	Tinnell (1957, 1958)	0.3	58.5	8.5	27.7		49.0
	Brasch and Wise (1956)						
	Wise and Ratcliff (1947)	0.3	51.3	10.1	29.5	4.9	49.5
	Wise and Pickard (1955)						
	Ritter and Fleck (1923, 1926)		46.3	22.0	26.5	15.4	50.0
	Brasch and Wise (1956)						
	Wise and Ratcliff (1947)	0.3	55.0	15.3	29.5	1.1	51.8
	Wise and Pickard (1955)						
Pine, longleaf	Mahood and Cable (1922)						
	Ritter and Fleck (1922)	0.37	57.6	12.0		28.7	50.0
	Schorger (1917)						
Pine, lodgepole	Wise and Jahn (1952)	0.2	43.8	9.2	25.0	16.1	50.9
Pine, Monterey	Brasch and Wise (1956)	0.2	57.0	9.3	26.5	4.8	49.6
	Wise and Ratcliff (1947)	0.2	54.8	16.4	26.5	1.4	50.3
	Wise and Pickard (1955)						
	Sjostrom (1981)	0.9	37.4	33.2	27.2	1.8	50.5
Pine, red	Clermont and Schwartz (1952)	0.2	47.8	15.1	23.4		49.5
	Wise and Jahn (1952)		46.8	10.0	26.2	16.9	50.8
Pine, Scots	Sjostrom (1981)	0.3	40.0	28.5	27.7	3.5	50.5
Pine, slash	Wise and Jahn (1952)	0.2	46.1	8.6	28.0	12.5	51.1
Pine, western white	Ritter and Fleck (1922)	0.2	59.7		26.4		47.5
	Mahood and Cable (1922)						
	Ritter and Fleck (1922)	0.2	59.7	10.2	26.4	19.0	50.0
	Schorger (1917)						
	Ritter and Fleck (1923, 1926)		51.7	17.1	25.8	21.8	50.0
	Wise and Jahn (1952)	0.3	42.3	7.9	25.4	23.9	50.9
Pine, white	Clermont and Schwartz (1951)	0.18	48.1	14.1	25.6	28.3	48.1
	Tinnell (1957, 1958)	0.2	57.6	7.5	29.3	4.0	49.4
	Ritter and Fleck (1923, 1926)	0.33	50.2	12.6	26.3	22.7	49.7

Table 12 continued

	Reference(s)	Ash	Cellulose	Hemicellulose	Lignin	Other organic substances	Estimated carbon
Pine, western yellow	Ritter and Fleck (1922)	0.46	57.4		26.7		48.5
	Mahood and Cable (1922)						
	Ritter and Fleck (1922)	0.46	55.1	11.3	26.7		49.9
	Schorger (1917)						
Redwood	Ritter and Fleck (1922)	0.21	48.5		34.2		48.2
	Mahood and Cable (1922)						
	Ritter and Fleck (1922)	0.21	47.6	11.4	34.2	21.1	51.6
	Schorger (1917)						
Spruce	Schwalbe and Becker (1919)	0.39	60.8	17.4	28.3	6.86	51.1
	Klason (1908)		53.0	14.0	29.0	4.0	52.7
Spruce, black	Clermont and Schwartz (1951)	0.21	51.1	15.2	27.3	17.0	47.2
	Tinnell (1957, 1958)	0.4	61.9	8.0	28.0	4.1	49.0
	Brasch and Wise (1956)	0.4	53.6	10.5	28.0	5.2	49.8
	Wise and Ratcliff (1947)	0.4	51.5	17.4	28.0	1.1	50.2
	Wise and Pickard (1955)						
Spruce, Engelmann	Wise and Jahn (1952)	0.2	44.3	9.2	26.3	15.0	50.9
Spruce, Norway	Sjostrom (1981)	0.9	41.7	28.3	27.4	1.7	50.3
Spruce, Swedish	Jayme and Finck (1944)		55.2	6.7	28.2	4.8	48.3
	Stockman and Hagglund (1948)		57.7	8.1	28.9	1.4	49.2
Spruce, white	Clermont and Schwartz (1951)	0.22	50.2	16.4	27.0	19.1	47.6
	Tinnell (1957, 1958)	0.3	59.3	8.4	27.1	3.6	49.0
	Sjostrom (1981)	0.3	39.5	30.6	27.5	2.1	50.6
	Mahood and Cable (1922)						
	Ritter and Fleck (1922)	0.31	59.4	16.3		12.9	51.9
	Schorger (1917)						
Tamarack	Wise and Jahn (1952)	0.3	44.4	8.3	26.2	14.4	49.5
	Tinnell (1957, 1958)	0.2	61.5	5.3	28.6	2.9	49.7
	Wise and Jahn (1952)		45.6	8.2	26.5	12.7	49.8
	Clermont and Schwartz (1952)	0.3	49.5	13.3	24.8	11.0	50.0

Table 12 continued

	Reference(s)	Ash	Cellulose	Hemicellulose	Lignin	Other organic substances	Estimated carbon
Angelique	Tinnell (1957, 1958)	0.6 0.6	42.9 45.2	12.0 14.7	31.6 31.6	9.6 5.4	50.4 50.7
Greenheart	Tinnell (1957, 1958)	0.2 0.2	43.3 44.7	10.0 13.2	31.2 31.2	13.4 9.5	51.1 51.2
Kakeralli	Tinnell (1957, 1958)	0.6 0.6	49.0 46.6	13.4 13.2	29.1 29.1	5.8 9.9	50.5 51.3
Mahogany	Tinnell (1957, 1958)	0.6 0.6	38.6 40.2	10.9 16.0	24.1 24.1	20.8 16.3	47.7 48.4
Tanary	Tinnell (1957, 1958)	0.8 0.8	47.3 47.3	14.3 12.5	31.0 31.0	5.3 9.1	51.0 51.5
Teak	Tinnell (1957, 1957)	1.4 1.4	37.0 35.3	12.2 11.7	30.5 30.5	15.1 18.9	49.1 49.7
Abiurana	Lauer (1958)	1.0	47.6	16.8	24.8	3.9	50.1
Breu branco	Lauer (1958)	0.6	48.7	17.2	27.4	6.9	50.3
Cordia alliodora	Wise *et al.* (1951)	0.98 0.98	42.7 45.4	14.2 16.9	29.7 29.7	12.5 6.6	50.6 50.7
Hymenaea coubaril	Wise *et al.* (1951)	0.85 0.85	42.8 40.4	20.1 16.1	20.3 20.3	13.8 18.8	48.5 48.5
Imbauba	Lauer (1958)	0.6	49.2	17.4	24.8	9.4	49.5
Licaria cayennensis	Wise *et al.* (1951)	0.03 0.03	46.3 43.7	11.0 11.3	29.5 29.5	10.4 13.9	50.0 50.9

Table 12 continued

	Reference(s)	Ash	Cellulose	Hemicellulose	Lignin	Other organic substances	Estimated carbon
Manilkara bidentata (from Puerto Rico)	Wise *et al.* (1951)	0.7	47.5	15.1	24.4	9.2	49.6
		0.7	44.4	15.6	24.4	13.5	50.6
Manilkara bidentata (from Surinam)	Wise *et al.* (1951)	0.37	46.3	16.3	26.1	7.5	50.3
		0.37	43.9	14.8	26.1	11.8	50.3
Ocotea rubra	Wise *et al.* (1951)	0.19	47.8	12.5	29.4	10.1	50.7
		0.19	45.7	11.7	29.4	13.9	50.7
Pau mulato	Lauer (1958)	0.8	48.3	13.9	28.3	5.4	50.7
Pseudosamanea guachapele	Wise *et al.* (1951)	0.58	41.8	14.3	24.1	18.0	49.3
		0.58	45.4	13.4	24.1	13.2	49.5
Tabebuia guayacan	Wise *et al.* (1951)	0.33	44.2	13.2	29.1	13.4	50.6
		0.33	46.5	14.3	29.1	8.6	50.8

Table 13 Carbon contents of woods calculated from destructive distillation data (%)

		Carbon content of charcoal (%)		
	Klason	82.1	90.4	Reference
Beech	45.1			Klason *et al.* (1907, 1908)
		40.4	42.4	Martin (1913)
Beech (slow heat)		42.0	44.2	Martin (1913)
Beech (quick heat)		40.8	42.6	Martin (1913)
Beech (Meyer process)		44.6	47.2	Martin (1913)
Birch	42.5			Klason *et al.* (1907, 1908)
		39.6	41.7	Martin (1913)
Birch (slow heat)		43.0	45.4	Martin (1913)
Birch (quick heat)		39.8	41.6	Martin (1913)
Oak		41.4	43.5	Martin (1913)
Oak (slow heat)		44.6	47.5	Martin (1913)
Oak (quick heat)		42.4	44.1	Martin (1913)
'Hardwood'		49.7	52.6	Farmer (1967)
Fir		43.9	46.1	Martin (1913)
Pine	49.9			Klason *et al.* (1907, 1908)
Pine (slow heat)		43.7	46.2	Martin (1913)
Pine (quick heat)		43.2	45.3	Martin (1913)
Spruce	46.7			Klason *et al.* (1907, 1908)

Two values for carbon content of charcoal have been used to show its effect on the values obtained for overall carbon content of the woods. It seems likely that the lower value is the nearer to the true value. The Klason values, which are based on the authors' reported values for carbon contents of charcoals, are included for comparison.

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