Non-destructive techniques for wood quality assessment of plantation-grown teak

The present article describes criteria and methods for assessing specific qualities of plantation-grown teakwood. A new original non-destructive technique for *in situ* assessment of wood samples was developed. Criteria used to measure quality are density, grain, shrinkage, colour and natural durability–which determine the type of use and economic value of teakwood.

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Teak (*Tectona grandis* Linn. f.) is a multi-purpose wood with a wide range of end uses, from general carpentry and joinery to furniture and cabinet making, and from veneers to boat construction. It has an appealing golden colour with typical figures as well as its very interesting technological properties: medium specific gravity, high strength without heaviness, dimensional stability and non-corrosion. Besides, this wood is easy to process, has good seasoning behavior and offers very good resistance to weather, termites and decay.

To fulfill the growing demand and stall the depletion of natural stands (Myanmar, India, Thailand and Laos), teak is increasingly supplied to the international market from plantations established in various countries such as Malaysia, Indonesia, India, Trinidad, Costa Rica, Brazil, Côte d'Ivoire, Togo and Benin by smallholders and foreign investors (Holland, Australia, Germany, etc.)*. Furthermore, the development of commercial teak plantations worldwide is encouraged by its high market price**.

In this context, it is necessary to determine whether the highly appreciated technological quality of teak from natural forests could also be expected in plantation-grown teak. As the trend is towards much shorter rotations (15 to 25 years) than originally adopted (50 to 80 years), this question is even more crucial for economic and financial reasons.

Before providing answers to these important questions, it seems important to accurately define wood quality, and how it can be assessed. The methodological options proposed here are specifically focused on teak, taking into account its financial value, its specificity in terms of colour and high oleoresin and chemical extractive content. But basically the same methodology could be applied to other plantation tree species, after some key adjustments (e.g. in spectrophotocolorimetry or NIR technology calibration).

DEFINITION OF WOOD QUALITY

GENERAL APPROACH

It seems that currently, and especially for teak, wood quality defined by buyers and end users is often based solely on the visual aspect: i.e. colour, grain, texture and defects. In fact, from a general point of view applicable to any timber species, wood quality is commonly defined by a combination of five main factors, as presented in Table I.

In defect-free wood, modulus of elasticity, strength and hardness are generally closely correlated with specific gravity. Therefore specific gravity will be used for assessing mechanical properties.

KEY TECHNOLOGICAL TRAITS

From this analysis, which could be applied to all timber species, a more adapted approach can be implemented using the specific technological characteristics of teak.

It has been shown that some key technological characteristics of teak wood could be identified as related to end uses (DURAND, 1985). They are listed in Table II, in order of increasing importance.

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* Total surface area of teak plantations worldwide : less than 1million ha in 1930 ; more than 2 million ha in 1980 and 2.8 million in 1997.

** From 1 000 to 2 000 US$ /m^3 from natural stands and from 250 to more than 600 US$/m^3 for plantation grown teak (source ITTO Market Information Service).

TABLE I

THE MAIN WOOD QUALITY FACTORS RELATED TO TECHNOLOGICAL CHARACTERISTICS

Wood quality factors	Wood properties	Remarks
1. Mechanical factors	1a. Modulus of elasticity	1a, 1b, 1c and 1d are correlated to specific gravity
	1b. Modulus of rupture	
	1c. Maximum crushing strength	
	1d. Hardness (for flooring purposes)	
	1e. Growth stresses	(For younger tree development stages)
2. Physical factors	2a. Shrinkage	In three different directions of wood structure.
	2b. Tangential/radial shrinkage	An anisotropic ratio indicating dimensional stability.
	2c. Sorption properties such as fibre saturation point	Link to dimensional stability (cf. Box 1: The major physical aspects of wood: anatomy and ultra-structure)
3. Biological factors	3a. Decay resistance	Representing natural durability. (cf. Box 2: the role of extractives on natural durability)
	3b. Termite resistance	
	3c. Weather resistance	
4. Aesthetic factors	4a. Colour and veining	Can be qualified under the same generic term: the "figure"
	4b. Grain	
	4c. Texture	
5. Structural factors	5a. Heartwood/sapwood ratio	Important mostly in sawing as directly related to timber yield (i.e. sawn timber grade and recovery)
	5b. Bole shape (straightness, taper, buttressing, fluting)	
	5c. Knot size and frequency	
	5d. Grain angle	

cliché : M. Vernay

Grumes de teck.
Teak logs.

Some of these wood technological characteristics are critical for the considered end uses.

These relevant properties are as follows:

- Sapwood percentage.
- Specific gravity.
- Shrinkage.
- Figure in which colour seems to be the most important.
- Natural durability.

Timber yield clearly has to be taken into account for processing, but it is more a matter of geometrical assessment (DURAND, 1983).

VARIABILITY IN WOOD QUALITY FACTORS

SOME MAJOR RESULTS

Various reports on teakwood quality (SALLENAVE, 1958; DURAND, 1984; DURAND, 1985; SANWO, 1986; ZOBEL, 1989; TEWARI, 1992; BHAT, 1995; TINT *et al.*, 1995; SANGKUL, 1995; BHAT, 1999), indicate that:

· These five types of factors (mechanical, physical, biological, aesthetical and structural factors;) are affected by silvicultural treatments (spacing density, fertilizing, thinning, pruning), site conditions (climate, soil) and by genotype × environment (G × E) interactions.

· Plantation-grown teak is not necessarily inferior to natural forest teak, in terms of strength properties, shrinkage and structural factors.

In the literature, very few studies report on natural durability variations in teakwood. (BHAT, 1995; BHAT, 1999; TEWARI, 1992; ZOBEL, 1989).

THE NEED FOR FURTHER INVESTIGATIONS

As an illustration of the need for further investigations on teakwood quality and variability, Box 3 presents some data on teakwood properties derived from CIRAD-Forêt's database.

Plantation trees are expected to be more homogeneous than those from natural forests, at least when the genotype is kept homogeneous through the use of selected seed and especially clonal plantations: planted stands are usually even-aged or the age of the trees is known and determined at the time of felling; growing conditions are under close control through silvicultural practices (soil preparation, fer-

TABLE II

THE MAIN WOOD TECHNOLOGICAL CHARACTERISTICS RELATED TO THESE END USES, IN ORDER OF INCREASING IMPORTANCE

End uses	Wood technological characteristics
Joinery	– Natural durability – Shrinkage and movement in use or dimensional stability ("nervosity") – Strength – Sapwood percentage
Flooring and parquets	– Figure: colour, grain and texture – Shrinkage and movement in use or dimensional stability ("nervosity") – Natural durability – Hardness – Sapwood percentage
Furniture	– Figure: colour, grain, texture and knots – Shrinkage and movement in use or dimensional stability ("nervosity") – Strength – Sapwood percentage
Sliced veneer	– Figure: colour, grain and texture

Box 1. Major physical aspects of wood: anatomy and ultrastructure

The physical, mechanical and chemical behaviour of wood cannot be fully understood without reference to its physical organisation (anatomy and ultrastructure), including that of its chemical components. Each of the major component groups, i.e. cellulose, hemicelluloses, lignin, and extractives, makes unique contributions to the characteristic properties and behaviour of wood.

How each component affects wood quality also depends on each of the other components. We will see later why this remark is of key importance in the assessment of teakwood quality.

Moreover, it should be emphasized that most of these factors characterise the behaviour of a given timber structure. This behaviour is related to the intensity of these factors, e.g. in the case of growth stresses or shrinkage. However, heterogeneity within this timber structure may be even more important than intensity for evaluating the behaviour of this given structure.

In terms of end user requirements, this means that maximum homogeneity is required. It concerns both intra-tree variations (mainly the impact of juvenile wood and reaction wood) and inter-tree variations that could be linked to silviculture and genotype × environment effects.

Box 2. The role of extractives on dimensional stability and natural durability of teakwood

The natural resistance of teak to termites and decay is related to various anthraquinone derivatives, the most important being tectoquinone.

Good dimensional stability is highly probable due to the buckling effect of ethanol and hot water soluble extractives, although the chemical properties of the cell walls, such as low pentosan and high lignin content may also contribute.

Good abrasion resistance and hydrophobicity of freshly cut surfaces is caused by latex in cell lumena and cell walls, mainly in heartwood.

Total extractive content, as determined by classical extraction procedures, provides sufficient evidence on the decay and termite resistance and dimensional stability of the wood. The extractive content is lowest in sapwood and highest at the periphery of heartwood. The pith generally has a lower total extractive content and low natural durability.

Total extract content is influenced by both genetic and environmental factors.

tilizing, thinning, pruning, etc.). In fact, wood quality is not very homogenous in primary processing products as commonly observed through marked variations in the properties of various wood pieces coming from different parts of the same tree (cf. Box 4: within-tree variability in a plantation-grown tree).

In addition to this highly common variability (juvenile wood, reaction wood) in plantation timbers, certain tree populations have their own specific problems: branching behavior and abundant knots, induced by poor silvicultural practices and bad pruning, thus causing undesirable discoloration (Figure 1).

Box 3. Analysis of wood quality of plantation-grown teak and inter-tree variability

Physical and mechanical data on teak mainly from African plantations and from some natural stands are listed in Table III. From these data, it can be noted that:

a) globally, teakwood from African plantations is not necessarily inferior to natural grown teak, it is quite comparable;

b) there is high variability within each characteristic presented among plantation-grown teak;

c) this variability is not clearly linked to a geographical effect.

Obviously these remarks cannot be generalised to all plantations worldwide. For example, there are substantial differences between the figure of wood coming from different origins or provenances (DURAND, 1985). This difference in the visual aspect of teakwood from different origins is illustrated in Figure 1, and there are obvious colour variations in these wood samples coming from various plantations. The reasons for such variations are not well known, it seems however that, besides genetic and silvicultural effects, climate would have a significant effect on some characteristics.

It should be stressed that fast growing conditions generally seem to play a minor role in affecting end user requirements. Table III illustrates this latter point.

However, some important differences between the different origins of trees can be observed. Moreover, some difficulties should be foreseen, in the case of fast growing conditions, especially for natural durability, because of the lower heartwood proportion and lower extractive contents, as well as for sawing recovery owing to growth stresses and smaller log diameter with a higher proportion of knots (DURAND, 1981; DURAND, 1985). (Cf. Box 5: the case of three teak trees from a plantation in northern Côte d'Ivoire).

Although teak grows faster and reaches its largest dimensions under a fairly moist, warm tropical climate, it should be noted that under such fast growth conditions wood quality may be inferior (DURAND, 1984).

The wide variety of growth conditions and genetic × environmental interactions are all interrelated. This makes comparison between results from localised studies and using different protocols very difficult, and almost impossible to extrapolate for drawing up a specific high input management strategy. Only a few general trends and basic lessons can be drawn from previous studies, but they are insufficient to define realistic guidelines.

For all of these reasons, there is obviously an urgent need for further investigations, especially dealing with the effects of planting material origin, site conditions, and silvicultural management on the wood quality of plantation teak.

The findings of such investigations could be essential for the future development of teak plantations worldwide, not only industrial but also community-based or rural plantations, in terms of tree breeding and genetic improvement strategies, plantation management and financial investment.

THE PROPOSED CIRAD-FORET METHODOLOGY

RATIONALE

To assess wood quality from a representative sample that varies as a function of the size of plantation areas to be studied to analyse the effects of site conditions or silvicultural treatments, it is wise to consider a sampling protocol that is time saving, easy to manage and cost-effective and producing samples on which all required measurements can be made. For teak, the financial value and genetic potential of standing trees in plantations make usual sampling methods on felled trees unsuitable. A non-destructive method is therefore preferable.

Based on this principle, wood quality assessment will consist of measuring samples collected on standing trees, specific traits correlated with some technological factors affecting wood quality and determining the end use potential.

OPERATING PROCEDURES

☐ Core extraction from standing trees

Wood quality analysis using cores has an increasingly important role in tree selection and breeding, and can lead to an increase in plantation productivity. A hand borer designed in Scandinavia is generally used to take increment cores. This is satisfactory for taking small numbers of cores from softwoods, but not from medium density hardwoods. Moreover, this kind of borer extracts small diameter cores and induces some traumatism on the cores due to the fact that the borer forcefully penetrates without machining the core (i.e. producing chips) thus altering the wood structure. This would produce some artifacts for shrinkage measurements on such traditional increment cores.

To overcome these drawbacks, the use of a hand-held motor-driven drill is preferable. For example, the

Box 4. Within-tree variability in a plantation-grown tree

A first source of within-tree variability is the gradual passage from juvenile wood to mature wood, varying from pith to bark and from the top to the bottom part, as a result of the aging of the cambial meristem. Juvenile wood exists in all tree species. It concerns roughly the first fifteen rings, but in the case of fast growing trees harvested at the young stage, the proportion of this wood within the tree is obviously high. In the case of wood with marked heterogeneous rings, like porous hardwoods such as teak, radial developments associated with juvenility are altered by the growth rate, which significantly influences the ring structure and thus the average properties of the wood.

A further source of variation is the formation of reaction wood in angular parts of the tree. Reaction wood here is evidence of tropism whereby the tree tends to turn in a given direction. This is because reaction wood has higher growth stresses when it is being formed–it is under much greater tension than "normal" wood in hardwoods like teak. Apparently, man-made stands, especially under fast-growing conditions, tend to promote imbalances and, therefore, the formation of reaction wood. The technological characteristics of juvenile wood and tension wood are notably different in comparison with "normal" mature wood.

Box 5. Example of three teak trees from a plantation in northern Côte d'Ivoire

As an example, Figure 2 shows variations in important properties within 3 teak trees, about 30-years-old, from a plantation located in northern Côte d'Ivoire. No significant variations associated with height were observed.

Some slight variations (increase) in density, modulus of elasticity and shrinkage can be observed on these graphs from pith to bark.

Nevertheless, this trend cannot be generalised: there is an interesting "tree effect" from a selection point of view. As an example, tree n°3 has a higher density and modulus of elasticity than the other trees, in addition no significant variations were observed, and this relative intra-tree homogeneity could give this tree a good chance to be a candidate plus tree or putative mother tree for cloning.

There was also a very slight (decrease) or insignificant variation in some wood properties (in this case, density and transversal shrinkage) with ring width.

In other respects, as the first two graphs suggest, there is a significant correlation between density and total radial shrinkage.

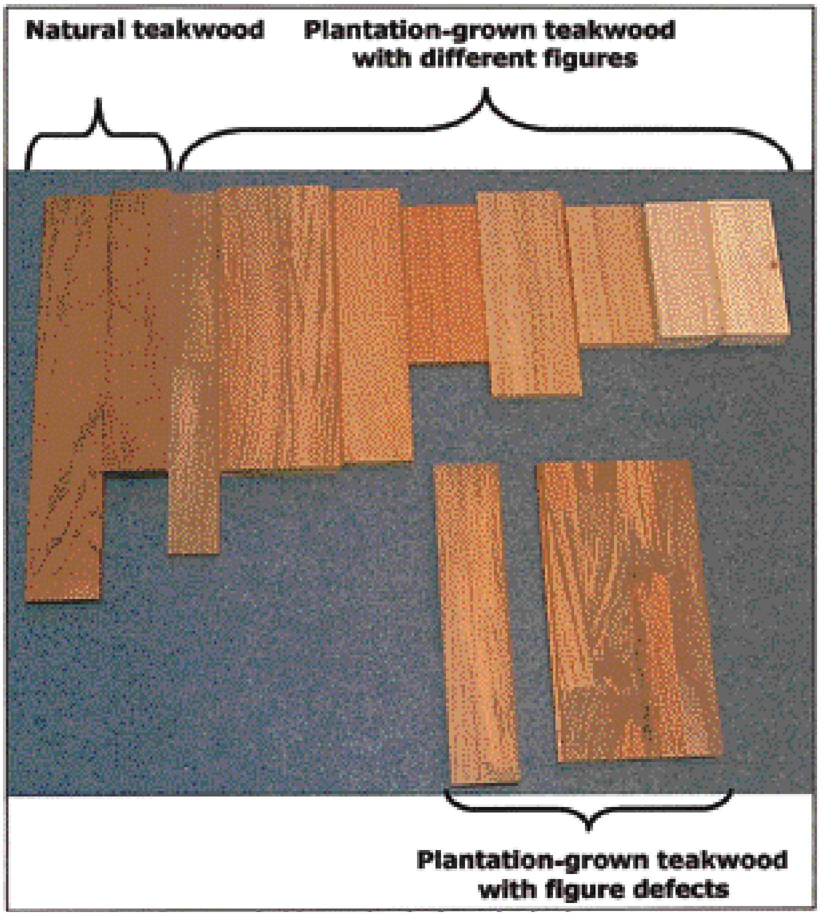

Figure 1. Different figure types of teak heartwood coming from various locations.
Aspects du bois de cœur pour des tecks de diverses provenances.

Trecor™ wood corer jointly developed by CSIRO and an Australian company could be a very helpful device. This tool extracts cores much faster than hand borers (about 2 min per core) and the cores are of much better quality. They have a 12 mm diameter, whereas the extraction leaves a 22 mm hole in the tree. Depending on the wood corer used, core length is either 30 or 40 cm. The holes left in the trees are easily plugged, as their diameter is the same as that of standard broom handles. Operators can limit stem defect development by inserting a plug of wood and spraying the area with a tar compound or a chemical insecticide fungicide.

The drilled increment core techniques are non-lethal but destructive since the tree remains alive but is wounded by the drilling. From a sample that represents a radius or diameter at a given height, it is possible to measure all the relevant properties mentioned above at different distances from the pith.

☐ Specific measurements carried out on the cores

Specific traits correlated with wood technological characteristics of importance for end uses to be measured on samples taken from standing trees are shown in Table IV.

Density

Depending on the precision required and the type of analysis, different techniques can be used:

· The water displacement method is a simple classical technique that is efficient and time saving when the basic density is measured. It is possible to measure density within large rings.

· X-ray tomography is obviously more complex and requires expensive equipment but gives interesting data on micro-density for the analysis of within-ring structure and/or growth traits. With continuous measurement along a radius, it is possible to qualify grain and texture.

Shrinkage

Shrinkage in the three axial directions can be measured. Longitudinal shrinkage along the grain could be considered as less useful than shrinkage in the two other directions and is surely more difficult to assess (scale of sizes about 0.1%). It could still be very helpful for detecting tension wood.

When small shrinkage values are measured in teak, it is necessary to develop an adapted metrological system, particularly when small dimension samples are used (about 10 mm). With this aim, CIRAD-Forêt has developed a new tool based on infrared triangulation that gives good precision on rough surfaces such as wood. It allows shrinkage measurement without contact in all directions for all sorts of samples.

Colour

Appearance and colour constitute the essential attractive features of the product. For humans, visual perception is determined by an interaction between light, an object, the eye, and the brain. But the human colour assessment process is subjective.

TABLE III

EXTRACT FROM THE CIRAD-FORET DATABASE ON WOOD PROPERTIES OF TEAK HEARTWOOD

Number	Country	S. P.	Vol. sh.	Tang. sh	Rad. sh	Crush.	Bend.	MOE	Dyn.	Split.	Extract	Lignin	Silica	R. D.	R. T.
09 306	*Indonesia-Java*	*0.69*	*5.7*	*3.7*	*2.4*	*58.6*	*102.9*	*9 221*	*16*	*17.1*	*17.7*	*29.7*	*0.43*	*1*	*1*
09 307	*Thailand*	*0.62*	*6.4*	*3.4*	*2.1*	*49.9*	*81.0*	*7 848*	*9*	*19.9*	*12.9*	*32.8*	*0.6*	*2*	*1*
25 972	*Myanmar*	*0.70*	*8.1*	*5.5*	*2.9*	*51.5*	*110.5*	*12 066*	*16*	*18.5*				*1*	*1*
16 476	Côte d'Ivoire	0.64	8.3	4.8	2.4	50.9	110.4	13 832	21	16.4					
16 477	Côte d'Ivoire	0.65	7.4	5.8	2.8	63.8	116.1	11 968	22	18.6					
16 478	Côte d'Ivoire	0.65	8.0	4.6	2.2	49.1	126.1	17 462	24	18.0					
16 479	Côte d'Ivoire	0.70	7.7	4.3	2.3	54.1	109.1	13 342	28	18.1					
09 943	Côte d'Ivoire	0.63	6.3	3.4	2.6	44.4	94.5	8 535	14	20.0	7.1	31.7	0.085	4	2
07 601	Benin	0.78	8.0	5.9	3.3	69.7	132.4	11 870	35	24.4	12.6	31.4	0.35	3	1
07 602	Benin	0.67	7.6	4.9	2.5	58.3	125.0	11 183	26	25.7	7.1	30.3	0.311		
21 334	Benin	0.64	7.8	4.5	2.2	64.1	126.8	10 595	43	21.7				2	1
21 335	Benin	0.70	8.4	4.6	2.6	56.5	120.7	9 320	47	21.5				2	2
21 336	Benin	0.59	8.4	4.4	2.8	45.6	97.2	8 44	33	22.0				3	2
21 337	Benin	0.64	8.3	5.2	2.2	60.7	113.6	10 399	35	21.7				2	1
21 338	Benin	0.69	8.5	5.2	2.9	66.6	123.8	11 674	30	23.6				2	1
21 339	Benin	0.63	8.0	4.8	2.6	59.9	122.4	11 282	31	18.5				2	2
29 149	Benin	0.58	6.6	5.0	2.8	58.5	108.7	10 301	15	13.5					
29 150	Benin	0.62	6.5	4.2	2.4	49.8	98.5	10 104	27	17.3					
29 153	Benin	0.59	7.1	5.1	2.4	52.2	98.4	9 516	16	16.1				2	4
29 154	Benin	0.69	7.5	4.9	2.2	59.9	118.1	12 361	19	17.7					
09 887	Congo	0.80	6.3	4.1	2.7	57.3	108.9	10 202	11	25.1	15.2	30.2	0.43	2	1
11 771	Congo	0.68	7.1	4.9	2.9	57.5	115.5	10 595	22	19.8	7.3	32.7	0.055	5	2
24 925	Burkina Faso	0.64	6.8	4.9	2.7	51.1	104.6	10 202	17	16.4				1	2
24 926	Burkina Faso	0.65	8.3	5.4	3.0	58.0	123.9	12 263	21	17.2				1	2
24 927	Burkina Faso	0.64	8.4	5.7	3.0	50.3	117.6	9 614	51	18.1				2	2
24 928	Burkina Faso	0.66	9.3	6.5	3.1	58.6	122.5	13 244	30	16.9				2	3
07 511	Togo	0.65	6.5	4.4	2.3	57.4	103.2	11 085	21	16.5	10.8	30.6	0.216	2	1
10 091	Togo	0.75	8.3	5.7	3.6	59.8	132.1	12 263	39	20.0	13.2	29.6	0.617	2	2
10 092	Togo	0.62	6.6	4.0	2.3	49.9	97.0	9 123	13	16.5	17.2	29.2	1.4	2	2
10 093	Togo	0.62	8.7	4.8	2.6	53.9	123.4	11 968	16	16.1	12.1	27.3	1.088	2	2
10 094	Togo	0.73	6.7	4.7	2.4	55.3			21	26.1	18.1	29	1.048	2	1
10 095	Togo	0.82	7.8	5.2	2.5	60.7	112.4	10 987	12	30.4	15.4	30.2	0.429	1	1
10 096	Togo	0.63	5.7	3.2	2.3	48.3	92.7	12 949	9	22.1	9.6	29.8	0.617	1	1
10 097	Togo	0.62	8.7	5.7	3.5	49.4	101.5	9 123	14	16.7	7.7	31.9	0.655	2	2
10 098	Togo	0.66	6.5	4.4	3.1	57.5	117.6	14 519	13	24.0	15.1	29.8	0.85	2	1
10 099	Togo	0.57	7.4	4.9	3.3	47.0	91.1	7 652	13	20.8	8.6	31.9	0.6	2	2
11 389	Togo	0.60	5.2	3.3	1.8	49.0	94.1	8 731	11	19.4	7.2	33.1	0.115	4	1
13 828	Togo	0.64	6.8	3.8	2.6	52.9	107.2	9 025	11	26.5				2	2
13 829	Togo	0.72	7.4	4.2	2.6	65.9	135.9	16 579	22	26.9				2	3

Each reference number is attributed to a tree which provided at least ten samples per property.
Trees from natural forests are in italics. The protocols were always the same for each characteristic.

N°: Reference number of the CIRAD-Forêt database on wood properties.
S. P.: Specific gravity.
Vol. sh.: Total volumetric shrinkage (%).
Tang. sh.: Tangential shrinkage (%).
Rad. sh.: Radial shrinkage (%).
Crush.: Crusing strength (MPa).
Bend.: Bending strength (MPa).
MOE: Modulus of elasticity (MPa).

Dyn.: Fracture energy in dynamic bending (Joule).
Split.: Spliting strength (N/mm). Property determined on clear samples at 12% moisture content.
Extract: Extract content (%).
Lignin: Klas on lignin content (%).
Silica: Silica content (%).
R. D.: Resistance to decay.
R. T.: Resistance to termites.

Quotation: 1 very resistant
2 resistant
3 moderately resistant
4 not very resistant
5 non-resistant

All properties were determined according to French standards (Normes AFNOR).

TABLE IV

METHODS USED FOR WOOD QUALITY ASSESSMENT

Wood technological characteristics	Methods to be used
Density (grain and texture)	Water displacement method, X-ray tomography
Shrinkage	Non-contact infrared system (for irregular samples)
Colour	Spectrophotocolorimetry
Natural durability	Laboratory decay and termite resistance tests

For this reason, colorimetry is an objective tool to measure colours, and especially the CIELAB colour system, which standardizes digital values of colorimetric functions of the human eye, has been sucessfully used to evaluate wood colour (NISHINO *et al.*, 1998) (cf. Box 6: the basics of colorimetry and spectrophotocolorimetry).

For colorimetric measurements, spectrocolorimeters are simple and rapid to use. They give stable and repeatable measurements with accuracy. They are increasingly cost-effective with a wider range of uses.

From the core, it is possible to measure colour at different positions between the pith and bark and on different planes in order to obtain a colour distribution.

Natural durability

Natural durability assessment is a tedious, complicated and time-consuming procedure. It requires a specialised laboratory with termite breeding and fungi culture strains in order to submit the wood to agent attack. Standard tests require large dimension specimens (several centimetres long) and often many replications. They always last more than several months to obtain reliable results. Nevertheless, it is possible to use specific screening tests on small specimens such as cores extracted from the tree, but specific research on appropriate protocols would be needed.

Box 6. The basics of colorimetry and spectrophotocolorimetry

The scientific basis of colour measurement is based on the existence of three different groups of signals coming from the eye of a human observer.

The spectral responses of these three types of receptors in the eye, as a function of wave-length, are now well known. In order to identify the response to colour stimuli in terms of numerical values, the quantitative values of colorimetric functions of the eye have been standardized and incorporated into the definition of the "standard observer" of the CIELAB colour system. The standard observer, like a standard illuminant, is a table of numerical values which represents a "normal and average human observer", but the responses are not specific to a particular observer.

Since the wood surface is never expressed with a single colour, it is difficult to describe its appearance using physical values. Besides, in various figures including grain and heartwood, the colour may vary significantly.

Colorimetry is an appropriate method for obtaining quantitative and objective information. The CIELAB colour system has been successfully used to evaluate wood colour (NISHINO *et al.*, 1998).

In our opinion, it would be preferable to establish exploitable correlations between standard tests and some simple chemical measurements such as total extractive content, as mentioned above, in order to overcome the disadvantages of classical methods while keeping a good assessment of natural durability.

TOWARDS A NEW TECHNOLOGY FOR ASSESSMENT AND CONTROL

Apart from wood density, measurement of the three other wood properties used to be expensive and time consuming. As emphasised in the first part of this paper, each of the major component groups of wood, i.e. cellulose, hemicelluloses, lignin, and extractives, make unique contributions to the characteristic properties and behaviour of wood.

Near-infrared (NIR) analysis is a very promising method for rapid measurement and quality control such as in agricultural and food industries. NIR analysis is a fast, environment-friendly analytical method that has gained widespread acceptance in recent years. Its accuracy is equal to the wet-chemical methods it replaces, but NIR gives faster results in just one minute. NIR testing is completely non-destructive and re-

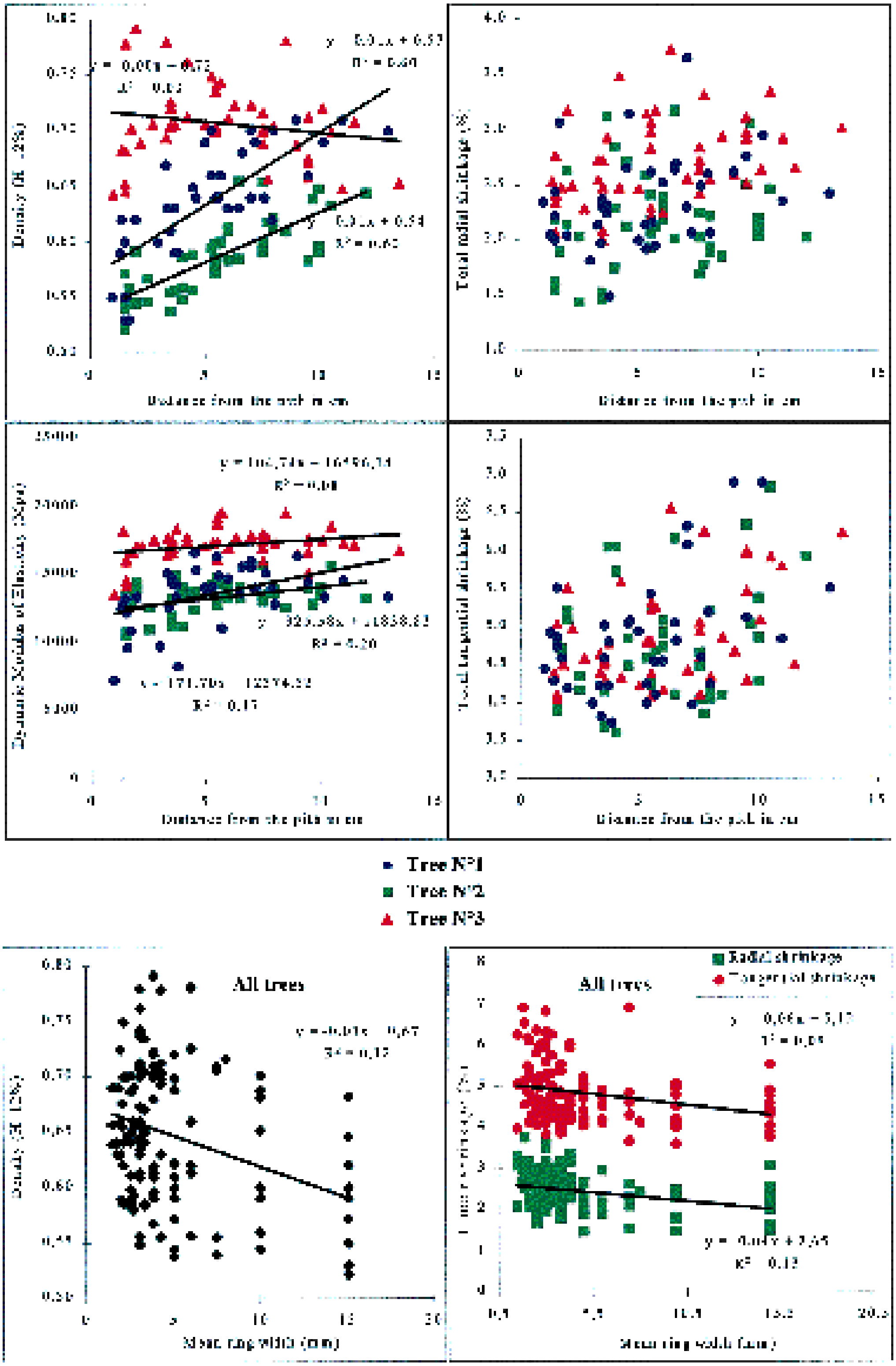

Figure 2. Variations of important properties within 3 teak trees of about 30 years old coming from a plantation located in northern Côte d'Ivoire. All heights mixed. Data extract from the CIRAD-Forêt data base on wood properties. Within each tree about 45 samples are measured.

Variations des principales propriétés de trois tecks agés de trente ans environ, dans une plantation située au nord de la Côte d'Ivoire. Toutes les hauteurs sont confondues. Extrait de la banque de données du CIRAD-Forêt sur les propriétés du bois. Pour chaque arbre, 45 échantillons environ sont mesurés.

quires no specific sample preparation, solvents or reagents.

NIR spectroscopy has a wide range of analytical applications: several industries use NIR spectroscopy, e.g. agriculture, food, paper, petrochemical, polymer and textile industries.

For wood products, NIR diffused reflectance spectroscopy is a rapid method for predicting pulp yield. It is based on vibrational spectroscopy which analyses changes in molecular vibrations that are closely associated with changes in molecular structure. (Cf. Box 7: The basics of NIR technology).

A major advantage that NIR spectroscopy has over other indicators is that the spectra contain simultaneous information about all the chemical constituents of wood. It is thus no longer necessary to decide *a priori* which factor is most important in determining a specific characteristic for a particular wood.

Moreover, the span of current scanning spectrophotometers includes all visible wave-lengths and others the possibility of obtaining colour measurements.

This NIR technology can assess technological characteristics of importance for end uses and therefore the wood quality of teakwood with a guarantee of reliability, accuracy and cost effectiveness. This promising approach should be one of the priority R&D activities of CIRAD-Forêt in the near future.

Box 7. The basics of NIR technology

How does it work? Bands in the infrared spectra of wood arise from vibrations of chemical bonds in the components. The band intensities depend on the change of dipole moment of bonds during vibration and thus the polarities of the bands. Consequently, band changes reflect intimate changes in the chemistry of the woods.

The near infrared spectrum contains information about major building blocks of the biological world. The functional groups that respond to NIR radiation are CH, OH and NH, which represent the backbone of all biological compounds. Spectra that occur in the NIR region consist of overtone and combination bands of the fundamental stretching vibrations of functional groups observed in the middle infrared region.

Although available scanning spectrophotometers span the 400-2 500 nm range, the most useful region of the NIR spectrum is 1 200-2 500 nm. For wavelengths below 1 200 nm, the weak absorption bands make reflectance measurements difficult and for those above 2 500 nm the bands become too strong and the samples have shorter path lengths.

In wood, the degree of overlap and band complexity makes NIR spectra almost impossible to interpret without the help of a computer. The ability to handle the absorbance data from many wavelengths, coupled with multivariate statistical methods, has enabled spectra interpetation.

Usually the constituent or property of interest is measured by conventional or even standard methods and is related to the band absorbances by a statistical model, involving some form of regression. This implies calibration of the system before its utilisation.

CONCLUSION

CIRAD-Forêt, from its wide-ranging tropical experience on plantation-grown timber technology, especially on teak, is in a position to propose a non-destructive method for in-situ assessment (on standing trees), of teakwood quality.

This method is based: (i) on specific wood sampling techniques, and (ii) on measurements (X-ray tomography, non-contact infra-red system, spectrophotocolorimetry) restricted to a limited number of relevant traits that are significantly correlated to the technological quality required by end users and silviculturists.

Several aspects still require some fine-tuning and improvement in the development of these non-destructive measurements: natural durability screening, or more interestingly, the establishment of exploitable correlations between standard tests and some simple chemical measurements like total extractive content.

Concurrently, a development-oriented research programme should be initiated on NIR spectroscopy technology, and especially regression analysis and calibration pertaining to some key characteristics, and more specifically chemical extractives and colour that can be correlated to technological traits of teakwood.

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RÉSUMÉ

MÉTHODES NON DESTRUCTIVES D'ÉVALUATION *IN SITU* DE LA QUALITÉ DU BOIS DE TECK DE PLANTATION

Etant donné ses propriétés technologiques exceptionnelles, le teck (*Tectona grandis* Linn. f.) est l'un des bois tropicaux les plus prisés. Du fait d'une importante demande et de la disparition des aires naturelles du teck, le bois commercialisé provient essentiellement de plantations exploitées selon des rotations toujours plus courtes. Après avoir défini la notion de qualité du bois et ses critères d'évaluation, l'article décrit la méthodologie et les techniques originales non destructives mises au point par le CIRAD-Forêt pour évaluer la qualité des tecks sur pied. Cette méthodologie novatrice, centrée sur le teck, consistera à mesurer sur des échantillons prélevés sur les arbres, les caractères spécifiques corrélés à quelques facteurs technologiques qui affectent la qualité du bois et déterminent les possibilités d'utilisation. En principe, elle pourrait être appliquée à d'autres essences de plantation après les adaptations indispensables comme, par exemple, le calibrage de la spectrocolorimétrie ou de la spectrométrie de réflexion dans le proche infrarouge ou NIRS (*near infrared spectroscopy*), une autre nouvelle technologie très prometteuse, qui est à l'étude au CIRAD-Forêt.

Mots-clés : *Tectona grandis,* bois de plantation, qualité, propriétés technologiques.

ABSTRACT

NON-DESTRUCTIVE TECHNIQUES FOR WOOD QUALITY ASSESSMENT OF PLANTATION-GROWN TEAK

Teak (*Tectona grandis* Linn. f.), because of its outstanding technological properties, is one of the most preferred tropical timbers in the world. For this reason, and due to the depletion of natural stands, teak is increasingly produced on plantations with much shorter rotations. It would therefore be of interest to determine whether the wood quality is similar when it comes from natural forests and plantations. After defining how wood quality can be assessed, results from the literature and from CIRAD-Forêt indicate significant between- and within-tree variations in plantation-grown teakwood. This need for assessing wood quality of plantation-grown teak led CIRAD-Forêt to develop its own methodology and non-destructive assessment techniques on standing trees, which are presented hereafter. The methodological options proposed here are specifically focused on teak, taking into account its financial value, its specificity in terms of colour and high oleoresin and chemical extractive content. But basically, the same methodology could be applied to other plantation tree species, after some key adjustments (e.g. in spectrocolorimetry or NIR spectroscopy calibration, as described hereafter).

A new promising but more sophisticated technique, currently explored by CIRAD-Forêt and also explained in this paper, is fully warrauted by the high market price of teak wood as well as the high investments required for teak plantation establishment and maintenance.

Key words: *Tectona grandis,* plantation wood, quality, technological properties.

RESUMEN

MÉTODOS NO DESTRUCTIVOS PARA LA EVALUACIÓN *IN SITU* DE LA CALIDAD DE LA MADERA DE TECA DE PLANTACIÓN

La teca (*Tectona grandis* Linn. f.) es una de las maderas preciosas más apreciadas por sus excepcionales propiedades tecnológicas. A causa de la importante demanda y de la desaparición de las zonas naturales de teca, la madera comercializada proviene esencialmente de plantaciones que se explotan con rotaciones cada vez más breves. Tras definir la noción de calidad de la madera y los criterios de evaluación, el artículo describe la metodología y las técnicas originales no destructivas elaboradas por el CIRAD-Forêt para evaluar la calidad de las tecas en pié. Esta tecnología innovadora, centrada en la teca, medirá en muestras de árboles, las características específicas correlacionadas con algunos factores tecnológicos que afectan a la calidad de la madera y determinan las posibilidades de uso. En principio, esta técnica se podría aplicar a otras especies de plantación después de realizar algunas adaptaciones indispensables como, por ejemplo, el calibrado de la espectrocolorimetría o de la espectrometría de reflexión en el infrarrojo cercano (NIRS), otra prometedora técnica que estudia el CIRAD-Forêt.

Palabras clave: *Tectona grandis,* madera de plantación, calidad, propiedades tecnológicas.

SYNOPSIS

MÉTHODES NON DESTRUCTIVES D'ÉVALUATION *IN SITU* DE LA QUALITÉ DU BOIS DE TECK DE PLANTATION

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Le teck (*Tectona grandis* Linn. f.) est utilisé dans des domaines très divers : menuiserie, ébénisterie, décoration et construction navale. Cela s'explique par sa couleur dorée attrayante avec son veinage caractéristique et ses propriétés technologiques très intéressantes : bois durable, mi-lourd, avec de bonnes résistances mécaniques et un faible retrait, facile à sécher et à usiner.

L'aire naturelle (Myanmar, Inde, Laos, Thaïlande) n'ayant cessé de se réduire et pour répondre à la forte demande, le teck a été planté dans de nombreux pays tropicaux : Malaisie, Indonésie, Inde, île de la Trinité, Costa Rica, Brésil, Côte d'Ivoire, Bénin, Togo. Les plantations commerciales sont d'ailleurs encouragées en raison des cours sur le marché international : de 250 à 600 US$/m^3 pour le teck de plantation à comparer à celui de forêt naturelle, entre 1 000 et 2 000 US$/m^3. (D'après ITTO Market Information Service, 1999).

Il convient de savoir si la qualité technologique tant appréciée des tecks de forêt naturelle est comparable pour ceux provenant de plantation. De plus pour des raisons économiques et financières, la tendance étant de réduire les rotations des plantations (15-25 ans au lieu de 50-80 ans traditionnellement), cette question devient encore plus importante.

Cet article précise les critères de qualité spécifiques du teck (notamment la couleur, les oléorésines) en fonction des utilisations possibles et propose une méthode d'évaluation de la qualité. Celle-ci pourrait être utilisée pour d'autres essences moyennant quelques adapations, en particulier des ajustements et des calibrages des techniques de spectrophotocolorimétrie et de spectrophotométrie proche infrarouge.

DÉFINITION DE LA QUALITÉ DU BOIS

Pour le teck, l'usage est d'évaluer la qualité du bois principalement sur des critères visuels (couleur, grain, défauts de forme du fût, présence de nœuds). D'une manière plus scientifique, la qualité se définit par un ensemble de cinq facteurs : mécaniques (élasticité, résistance, dureté, contraintes de croissance), physiques (densité, retrait, anisotropie, point de saturation des fibres), biologiques (durabilité naturelle), esthétique (couleur, fil, grain, texture) et structurels (pourcentage aubier/duramen, forme du fût, nœuds, direction du fil).

Généralement, les propriétés mécaniques sont bien corrélées avec la densité, qui pourra donc servir d'indicateur des caractéristiques mécaniques pour un bois sans défaut.

Certains de ces critères technologiques ont une influence déterminante sur l'aptitude du teck à une utilisation donnée : pourcentage d'aubier, densité, retraits, couleur, durabilité naturelle. La forme du fût détermine le rendement au sciage, important sur le plan économique.

VARIABILITÉ DE LA QUALITÉ

Les travaux sur la qualité du bois ont montré que : (a) les cinq facteurs déjà cités sont affectés par la sylviculture, les conditions du site et les interactions génétique x environnement ; (b) le teck de plantation n'est pas nécessairement inférieur à celui de forêt naturelle. La variabilité inter et intra-arbres est illustrée par une étude sur des tecks de plantations en Côte d'Ivoire.

MÉTHODE PROPOSÉE PAR LE CIRAD-FORÊT

En raison de la valeur et du potentiel génétique des tecks sur pied, une méthode non destructive a été mise au point qui remplace les procédés classiques de prélèvement d'éprouvettes sur des arbres abattus. Pour évaluer la qualité du bois sur un échantillonnage représentatif adapté à la taille des plantations et pour analyser l'effet des sites ou des traitements sylvicoles, un protocole de prélèvement d'échantillons a été mis au point. Ce protocole est suffisamment rapide, facile à mettre en œuvre, peu couteux et il fournit des échantillons assez volumineux pour permettre toutes les mesures nécessaires.

Pour prélever des échantillons, la tarrière du type TRECOR, mise au point par le CSIRO et une société australienne, est constituée d'un outil tranchant, entraîné par un moteur thermique puissant. Elle usine une carotte de 12 mm, qui laisse un trou de 22 mm de diamètre rebouché avec un tourillon traité avec un fongicide et un insecticide. Le prélèvement s'effectue rapidement (environ 2 min par carotte) et sans effort.

Les critères de la qualité du bois, corrélés aux propriétés technologiques qui déterminent le type d'emploi, sont mesurés sur ces éprouvettes selon les méthodes suivantes :

· La densité et le grain par la méthode du déplacement d'eau ou par la tomographie aux rayons X ;

· Le retrait au moyen d'un système à infrarouge ;

· La couleur par spectrocolorimétrie ;

· La durabilité naturelle par des essais de résistance aux champignons de pourriture et aux termites.

En réalité, à l'exception de la densité, ces mesures sont relativement coûteuses et fastidieuses.

Une nouvelle technologie d'évaluation de la qualité du bois, la spectroscopie en réflectance dans le proche infrarouge ou NIRS (*near infrared spectroscopy*), est explorée par le CIRAD-Forêt.

La NIRS est fondée sur la mesure de l'absorption moléculaire qui dépend de la structure moléculaire. Elle devrait pouvoir fournir des informations sur les éléments constitutifs du bois (cellulose, hémicellulose, lignines, oléorésines) qui conditionnent les propriétés technologiques et la couleur. Un travail d'analyses multivariables et de calibrage, en particulier sur les extraits chimiques et la couleur, devrait être entrepris pour appréhender simultanément les caractéristiques de la qualité de bois. On pourra alors évaluer, de façon rapide et fiable, la qualité globale par un nombre très limité de mesures.