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ORIGINAL ARTICLE

General, physical and mechanical properties, termites resistance and drying defects of lumber of *Tectona grandis* from plantations of different climatic and sites fertility condition

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Abstract The influence of climatic and site fertility conditions affect wood quality from fast growing trees. The change in tree diameter, thickness of sapwood, heartwood percentage and bark and pith tissue, physical and mechanical properties, resistance to termite attack and the presence of drying defects on lumber boards were evaluated. Four teak trees (*Tectona grandis* L.f.) from fast growing plantations in Costa Rica were selected for the study. Teak trees of 11 years old growing in two climatic conditions and two fertility types (high and low fertility) in Costa Rica were studied. The results showed that tree diameter, sapwood thickness, pith diameter and its percentage were higher in the climate with more rainfall and greater fertility. However, the percentage of heartwood and bark were higher at low fertility sites with less rainfall. It was also observed that only sites with low fertility produce modifications in specify gravity, fiber saturation point, initial moisture content, MOR in flexion in green and dry condition, MOE in bending and resistance to termite attack. Incidence and magnitude of defects increased with drying, and were mainly affected when wood comes from younger trees from high fertility sites and growing in tropical moist forest climate.

Keywords *Tectona grandis* · Physical properties · Mechanical properties · Morphology · Costa Rica

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Introduction

Tectona grandis is a deciduous tree widely planted in large areas in many tropical countries of Latin America, Asia, Africa and Oceania (Moya et al. 2014) covering about 4.35 million ha in 52 different countries (Kollert and Cherubini 2012).

Teak can be planted in tropical zones around the equator below 1000 m altitude, with annual rainfall in excess of 1500 mm, and fertile, deep and well drained soils (Tewari 1999). It is interesting to note that sites for teak plantations have different geographical and rainfall conditions compared to its natural habitat in Asia (Kollert and Cherubini 2012). For example, in Central America, teak has been grown on sites with different precipitation levels, temperatures, and fertility (De Camino et al. 2002). But nowadays, a high demand for new planting sites has led to the establishment of forest plantations on marginal agricultural lands (steep slopes or acid infertile soils), requiring the management of soil fertility to maintain fast-growth plantations at acceptable levels (Moya et al. 2014). Teak plantations under this specific practice were able to produce logs from first and second thinning. Lumber produced from these trees is inferior in quality but acceptable for furniture production (Kollert and Cherubini 2012). Under these plantation management practices, logs to export with a minimum diameter of 12 cm can be produced in less than 6 years (Pérez and Kanninen 2005).

In Costa Rica, teak has been planted in several sites and regions with varied climatic and topographical conditions (Moya and Pérez 2008; Moya et al. 2014). However, two regions are worth mention in this country: (i) the coastal region of the Pacific Ocean with a tropical dry climate characterized by the presence of a well-defined dry season; and (ii) the region consisting north and northwest zones of the country with moist to wet tropical climate having a very small dry period (Alvarado 2001).

Wood properties are affected by climate and soil type, altering its quality, which can have an impact in their properties, wood industrialization and product manufacture from trees of these forest plantations (Cutter et al. 2004). In teak wood, Bhat and Priya (2004) established that timber from low fertility sites produces timber with low mechanical resistance, attributed to a higher amount of parenchyma and low fibers content. Studies conducted by Moya and Pérez (2008), Moya et al. (2009), Moya and Calvo-Alvarado (2012) and Kokutse et al. (2010a, b) showed variations in wood properties due to changes in climatic conditions and soil fertility where trees were planted. Other studies have shown variations in wood properties due to site effect (Bhat et al. 2001, 2005; Kokutse et al. 2004; Pérez and Kanninen 2003; Thulasidas and Bhat 2007).

Although, a limitation of all these studies is that they were conducted with trees greater than 20 years old, which did not necessarily reflect wood performance when it comes from lower ages than 11 years old, which are characterized by having a high proportion of juvenile wood (Moya et al. 2014). In this context, the present study aims to evaluate the effect of two climatic conditions (moist tropical and wet tropical) and two sites (high and low fertility) of Costa Rica on the morphological properties of the log (heartwood, sapwood, pith and its eccentricity), physical properties (specific gravity, density and shrinkage), mechanical properties, resistance to termite attack and drying defects during kiln drying.

Materials and methods

Study site

The selected locations described two climatic conditions in Costa Rica. One is closer to the Caribbean Sea (N10°15′–N10°50′ and W83°15′–W83°60′) and the second near the Pacific Ocean (N09°00′–N9°50′ and W83°30′–W84°50′). The Caribbean location is classified as tropical wet forest (TWF), while Pacific location is classified as tropical moist forest (TMF) according to Holdridge (1982) and Bolaños et al. (1999). TWF records a mean annual precipitation of 4000 mm/year and a mean annual temperature of 25–30 °C (Fig. 1a). In the other hand, the TMF records 3630 mm/year and 27–32 °C of precipitation and temperature respectively. The aforementioned life zone shows a water deficit between January and April (Fig. 1b).

Sampled plantations

Two plantations of 11 years old were selected in each region. One was classified as high fertility site (HFS) and the other as low fertility site (LFS). All plantations were established at an initial density of 1110 trees per ha (spacing of 3 × 3 m). TMF plantations have a better growth in diameter, requiring greater thinning amount at 12 years old, reaching a final density of 200–220 trees per ha. Whereas TWF plantations had lower growth, therefore a less intensive management was practiced; hence, plantation density was higher in relation to TMF (Table 1).

Tree selection and sampling

For each plantation, 9 defect-free straight trees were selected and felled, with the plantation average diameter. A cross-sectional disc of 3.0 cm thick was taken at breast height (BH). Two stem sections (with 1.25 m in length) were obtained from each tree: one from tree base to DBH and second one from 2.5 m high to BH. Afterwards, logs of 2.5 m were taken from 2.5 m height to commercial tree height, where tree diameter was equal to 13 cm. The North–South direction was marked on each stem cross-section and logged for later identification at the laboratory.

General properties

Diameter, bark thickness, bark percentage (bark thickness/total diameter of the tree expressed as a percentage), heartwood percentage (heartwood diameter/total diameter expressed as a percentage), sapwood thickness, pith diameter and pith eccentricity were determined at BH. Next, total bark and heartwood cross-sectional area were calculated as a geometric circle. Bark thickness was determined by computing the difference between total area and area without bark.

Physical properties

Properties determined were: specific gravity (SG), radial shrinkage (RS), tangential shrinkage (TS) and total volumetric shrinkage (VS), ratio of tangential shrinkage/radial shrinkage (Ratio T/R), fiber saturation point (FSP), and green moisture content (MC). These properties were measured from cross-section extracted from BH level. A 3.0 cm wide block was cut along the center (including the pith) of each disk and divided into two sub samples for studying the physical properties. Green weight and volume from each subsample were determined according to the standard D-2395-07 (ASTM 2014a). Wood samples were oven-dried at 103 °C for 48 h. This oven-dry weight was used in order to determine VS, MC, and SG. Both, TS and RS were determined according to D-143-09 (ASTM 2014b).

Mechanical properties

Basal logs below BH level (1.3 m) were used for the mechanical properties determination. Logs were sawn

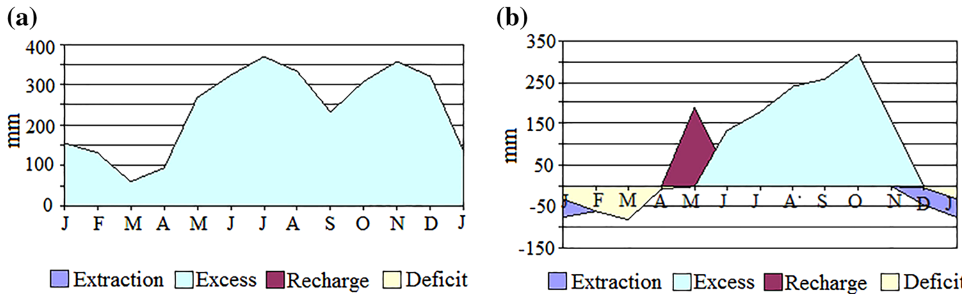

Fig. 1 Climate diagrams for the **a** tropical moist forest (TWF) and **b** tropical wet forest (TMF) regions. *Note* to describe climate for each study area, climate diagrams were prepared using meteorological data with at least 25 years of monthly average temperature records and precipitation from La Rita (N10°15′40″–W83°45′36″) station, for BHT and from Jicote (N09°55′33″–W84°03′33″) Jicote station

Table 1 Dasometric characteristics of four plantations of *Tectona grandis,* sampled in two climatic conditions and two fertility sites

Climatic condition	Site fertility	Density (trees ha^{-1})	Diameter breast height (cm)	Growth rate (mm/years)	Total height (m)	Basal area (m^2 ha^{-1})
Tropical moist forest (TMF)	High (HFS)	210	37.0	26.4	22.8	22.77
	Low (LFS)	210	25.9	18.5	20.8	11.32
Tropical wet forest (TWF)	High (HFS)	290	31.0	22.1	24.6	22.06
	Low (LFS)	390	19.4	13.9	19.0	11.63

according to D-143-09 standards (ASTM 2014b). The cut samples were separated in two parts, one part was used for testing in a dry condition and the other half were conditioned 21 °C and 65 % relative humidity (equilibrium moisture content of 12 %) and then tested. Four types of mechanical tests were conducted in this study: center-point flexure test and bending strength to grain (MCS), hardness test and shear strength. For flexure and MCS test, rupture modulus (MOR) and elasticity modulus (MOE) were determined.

Resistance to termite attack

Termite resistance was evaluated using dry wood termites (*Cryptotermes brevis* Walker). From the wood disc extracted from BH level, 4 samples pieces (size 3 × 2 × 1 cm) were obtained from sapwood and heartwood, respectively. Samples were oven-dried in an oven at 103 ± 2 °C temperature during 48 h. Then these samples were conditioned to 12 % moisture content. Each sample was placed in petri dishes and 40 termites (39 workers and one soldier) were added and then stored at 27 ± 1 °C temperature for a 90 days period (11.4 weeks). Every week, dead termites were counted from each petri dish. To measure mortality degree, the classification criteria of D 3345-08 standard (ASTM 2014c) was followed. When the 90 day trial ended, the oven-dried samples were reweighted. Having both weights (before and after the test), weight loss percentage was calculated, allowing the classification for wood resistance into four categories according to D-2017-05 standard (ASTM 2014d).

Drying defects

To evaluate drying defects, lumber extracted from sampled trees were used. Before sawing the log, the north–south diameter was marked. Logs were sawn into 2.5 cm-thick boards and these were cut parallel from north to south. Then the boards were edged. Green lumber was stacked in packages (1.0 m wide, 1.3 m high, and 3.3 m long). Cross-section pieces (stickers) of 2.5 x 2.5 cm were used to separate the samples. One pile was made for air-drying, where wood was left piled up in the open, conveniently protected from the sun and the rain. Air-drying was performed in Cartago, province of Costa Rica (9°50′59″N, 83°54′37″W). The site has an altitude of 1380 m with an annual temperature between 15 and 24 °C and an average precipitation of 1563.5 mm. Air-drying was carried out from February to May and the final moisture content of dried-lumber was 14 %. Each board was evaluated before (green condition) and after air-drying to determine the presence of defects such as warp (bow, cup, crook and twist), splitting and checking were also determined. The method suggested by Salas and Moya (2014) was used to evaluate drying defects. Boards were measured for maximum bent, and warp on a flat table. The following procedure was used for warp (bow, cup, crook, twist) measurement: (1) Each piece was positioned on a flat table to examine warp type extent. (2) When the warp was very small, the meaningful determination seemed insignificant; a judgment of "no warp" was assigned. (3) The measurement for warp presence was made through the insertion of a calibrated wedge. With the wedge inserted to a point of mild refusal, the measurement was made by reading the calibrated vertical face of the wedge. Drying defects values were reported as magnitude of the defect in relation to length of the board (mm m^{-1}) in green condition and after natural drying.

Statistical analysis

Normal distribution assumptions, variance homogeneity and extreme data absence of general, physical and mechanical properties, weight loss for termites decay and drying defects were verified using the SAS System PROC UNIVARIATE procedure Version 8.1 for Windows (SAS Institute Inc., Cary, NC). Afterwards, these wood properties and drying defects were compared to the difference between two climatic conditions and two site fertility by ANOVA, where wood properties, weight loss and drying defects were depend variables, climatic conditions and site fertility as independent variables. The mixed linear model was used in the variance analysis (Eq. 1), where climatic conditions (CC) and site fertility (SF) as fixed effects, and the interactions between climatic conditions and site fertility (Eq. 1). The GLM procedure from SAS was applied to estimate the variation sources significance. The difference between average of wood properties and drying defects were conducted by CONTRACT statement procedure from SAS. SAS 8.1 Windows program was used.

$$Y_{ij} = \mu + CC_i + SF_j + CC \times SF_{ij} + e_{ij} \quad (1)$$

where Y_{ij} is the single observation of wood properties or drying defects of the ij-observations, μ is the overall mean, CC is the ith-climatic conditions as fixed effect, SF is jth-site fertility as fixed effects and $CC \times SF_{ij}$ is the random interaction between the i climatic conditions, the j-site fertility and e_{ij} is the residual random effect.

Results and discussion

General properties

Figure 2 shows mean values of the morphological variables of the evaluated teak trees. Primarily, for site fertility effect (HFS and LFS) in the same climate type, it was observed that the Tropical Wet Forest climate (TWF) produced statistical difference between HFS and LFS trees, however in the tropical moist forest climate (TMF), a statistical difference was observed in DBH and heartwood (Fig. 2a, c). For the other properties, no difference was found between the two sites with different fertility levels.

Likewise, for the climate type effect in the same fertility type, it was found that trees from the TWF of HFS have DBH, thickness of sapwood and pith (diameter and percentage) statistically greater than the TMF trees (Fig. 2a, b, e, f). In contrast, proportion of heartwood and bark in the TMF trees was statistically significant and higher than the TWF in the HFS (Fig. 2c). Bark thickness had no difference for either climatic condition in this fertility type (Fig. 2c, d). Regarding LFS, it was revealed that DBH and pith eccentricity are statistically significant and higher in trees from TWF (Fig. 2a, f), but again heartwood percentage was statistically similar in TMF trees (Fig. 2). Whereas no statistical difference was found in sapwood thickness, bark thickness and pith diameter between trees from climatic conditions in LFS (Fig. 2b, d, e).

As expected, higher rainfall allows an increased on the diameter growth of trees (Pérez and Kanninen 2003; Moya and Pérez 2008), as observed in the present study. Trees growing on the site with TWF had logs larger in diameter (Fig. 2a); this because throughout the year, soil presents wet conditions for tree growth (Fig. 1a). Those conditions are not present in TMF (Fig. 1b). During months of May to January, moisture conditions in the soil are unfavorable. Large diameter logs obtained in most fertile site was probably due to suitable nutrient conditions for the species, including appropriate levels of carbon and nitrogen, low phosphorus levels (Gunaga et al. 2011).

Sapwood thickness, heartwood percentage, bark percentage and pith (diameter and percentage), did not follow the same trend to diameter growth in relation to climate type and the fertility of the site (Fig. 2b–f). Sapwood thickness in TWF is statistically significant and higher compared to TMF on the high fertility site, but different to the low fertility site (Fig. 2b). Whereas heartwood percentage is higher in TMF trees, no significant difference was observed in relation to the fertility in TWF sites (Fig. 2c). This condition might be explained referring to sapwood thickness, by the fact that in *T. grandis* this tree part tended to a uniform thickness in different heights and ages (Moya et al. 2014). High heartwood percentage found in trees growing in lower rainfall site TMF is consistent with Moya and Pérez (2008), Thulasidas and Bhat (2009), Pérez and Kanninen (2003) and Kokutse et al. (2010b).

Although some differences were observed in the proportion of bark, the difference was insignificant (Fig. 2d). Bark proportion in teak had a considerable variation with height and tree age, but low variation with tree diameter (Pérez and Kanninen 2003; Tewari and Mariswamy 2013), which could explain the lack of significant difference under the conditions studied. Indicating that bark is a slightly dependent factor on tree diameter.

Pith in *T. grandis* trees is an important feature since pith is very evident and is reflected directly into the board white sealing (Akachuku and Abolarin 1989). TWF trees have larger diameter and higher percentage of pith in lumber and pith would be included in a greater number of boards

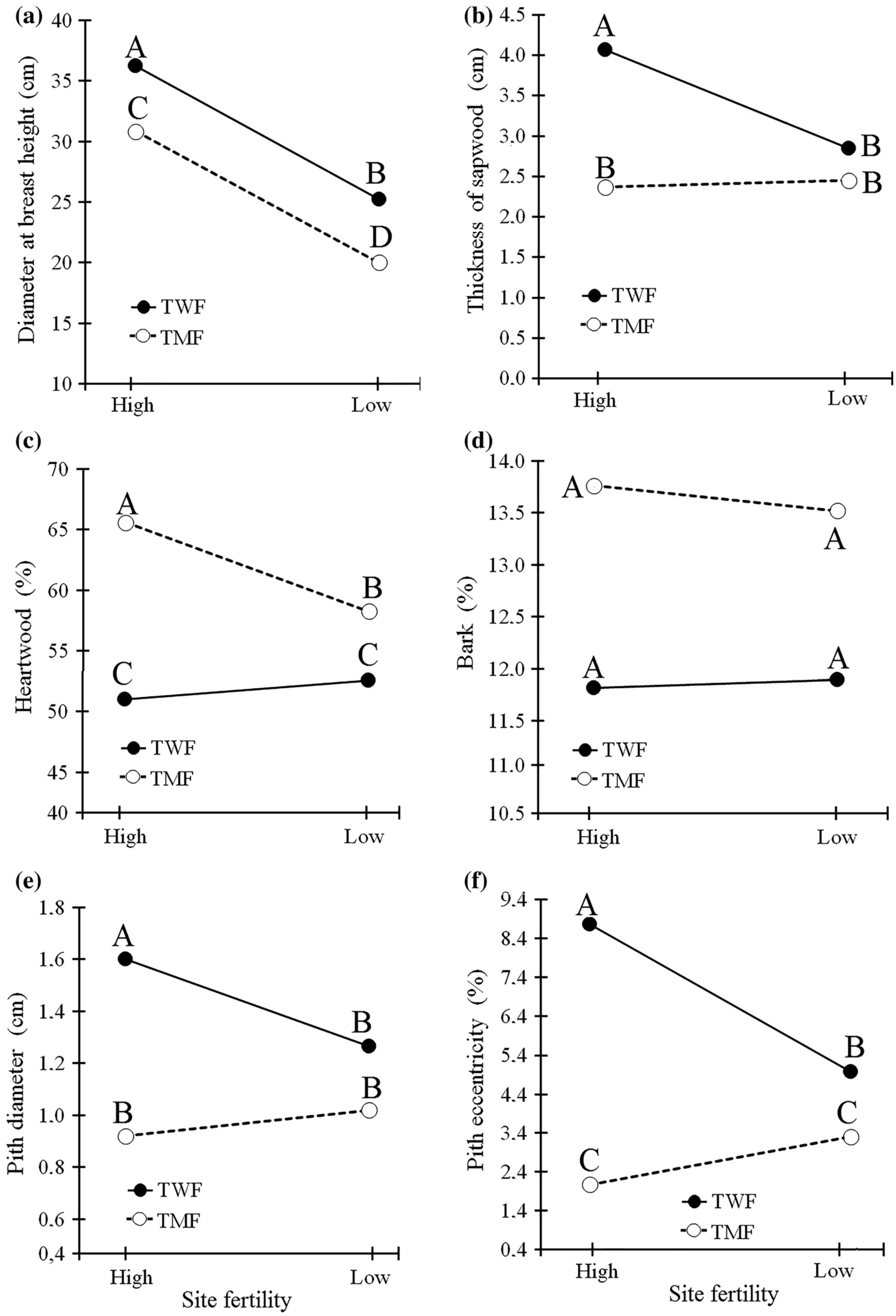

Fig. 2 Tree mean characteristics of *Tectona grandis* growing in two regions in two sites with different fertility in Costa Rica. Letters A, B, C next to this value indicates that the values are statistically different at a confidence level of 95 % for the same properties

(Moya et al. 2008). Also, it has been observed that trees with larger diameter as in this case, TWF trees produced larger pith diameter and therefore percentage of this tissue is higher (Fig. 2e–f). But when you consider site fertility factor, it only showed difference between the TWF sites. This dependence of pith to climate is similar to what is observed in other hardwood species, where it was found that pith variation is affected by site, tree height, topography and environmental conditions (Akachuku and Abolarin 1989; Moya et al. 2008). These results suggest that pith diameter has ontogenetic trend and can be controlled by factors such as biological, physiological or genetic factors during the formation of primary parenchyma tissue in the procambial zone (Moya et al. 2008).

Physical and mechanical properties

Physical properties of wood from different climatic conditions or different site fertilities were slightly affected (Table 2). It was observed that for trees from TWF climate in the LFS, SG and FSP were statistically different from the other site conditions or climate. MC was statistically lower in TWF trees, but without difference between the types of fertilities in the same climate type (Table 2).

Mechanical properties evaluated in green condition showed slight significant differences between both climates and fertility sites (Fig. 3). It was found that MOR in flexion was statistically significant and higher for TMF trees on the high fertility site (Fig. 3a), but trees in this type of climate produced wood of lower MOE in relation to TWF sites with different fertility (Fig. 3b). Whereas, wood from low fertility site in TMF produced wood with lower resistance to shear than TWF trees or wood from trees of the HFS in TMF (Fig. 3f). Finally, MOR and MOE for MCS and flexure test and teak hardness in green condition indicated that wood was not statistically affected by climate type or fertility site (Fig. 3c–e).

Lumber evaluation in dry condition, except for MOR of MCS in trees from high fertility site (Fig. 3c), showed no differences between climate type or fertility site. This occurred in the case of MOR and MOE in flexure test (Fig. 3a, b), MOE in MCS (Fig. 3d), hardness (Fig. 3e) and shear stress (Fig. 3f). At low fertility sites, the TMF trees had lower resistance in MOR and MOE in flexure test (Fig. 3a, b) and MOE in MCS (Fig. 3d). It was found that timber from low fertility sites produces weaker wood, due to a higher quantity of parenchyma and low fibers content (Bhat and Priya 2004). Whereas for the other mechanical properties tested, there were no differences between wood from different climates or fertility sites.

Values found for physical and mechanical properties of teak, evaluated in this study are similar to other work done with teak growing in conditions of rapid growth (Moya and Pérez 2008; Bhat and Indira 2005; Solórzano et al. 2012; Moya et al. 2013), except for fiber saturation point where no literature is reported.

Regarding variation between different climate types and fertility sites, it is important to note that low variation (Table 2; Fig. 3) was presented. Changes were only observed in the specific gravity, fiber saturation point, initial moisture content, MOR in flexion in green and dry condition, and MOE in MCS of the low fertility site from TWF. This behavior is not consistent with results obtained by Moya and Pérez (2008), Bhat and Priya (2004) and Bhat et al. (2001), who mainly studied specific weight, and in all cases, it varies with the fertility of sites or climatic conditions.

Poor differences were noticed between different fertility sites and climatic conditions can be explained with two aspects: (i) tree age and (ii) lack of a relation between tree diameter and wood properties. Trees used had an age near to the rotation of cutting (18 years). Moya et al. (2014) indicates that in teak trees growing in conditions of rapid growth, juvenile wood production ends at 6 years old, therefore, at 11 years old the amount of mature wood contained in the tree is very high. Thus, at 11 years old, differences in properties found in juvenile period are diluted by averaging the entire cross section of the tree stem in mature trees. The second aspect that may explain the lack of variation in properties is that it was found that the age of the tree has a greater influence on wood properties than the variation that can have the diameter of the tree (Moya and Pérez 2008; Solórzano et al. 2012).

Resistance to termite attack

Termite mortality showed, for all evaluated conditions (site fertility and region), a linear relationship with time, stabilizing at 90 % after twelve evaluation weeks (Fig. 4a, b). For heartwood of TMF–HFS showed differences in the mortality rate compared to wood from the TWF–HFS, being the last lower (80 %) after 12 weeks of trials. Meanwhile, timber

Table 2 Physical properties of *Tectona grandis* growing in two regions in two sites with different fertility in Costa Rica

Wood properties	High fertility site		Low fertility site	
	Tropical moist forest	Tropical wet forest	Tropical moist forest	Tropical wet forest
Specific gravity	0.54^{A}	0.55^{A}	0.54^{A}	0.50^{B}
Radial shrinkage	2.4^{A}	2.3^{A}	2.7^{A}	2.8^{A}
Tangential shrinkage (%)	6.0^{A}	5.6^{A}	5.9^{A}	6.6^{A}
Total volume shrinkage (%)	6.7^{B}	8.0^{A}	5.7^{B}	8.0^{A}
Ratio of tangential/radial shrinkage	2.5^{A}	2.4^{A}	2.2^{A}	2.2^{A}
Fiber saturation point (%)	26.2^{A}	26.3^{A}	25.1^{A}	29.5^{B}
Green moisture content (%)	107^{A}	95^{B}	104^{A}	90^{B}

The letters A or B, next to the value indicates that the values are statistically different at a confidence level of 95 % for same properties

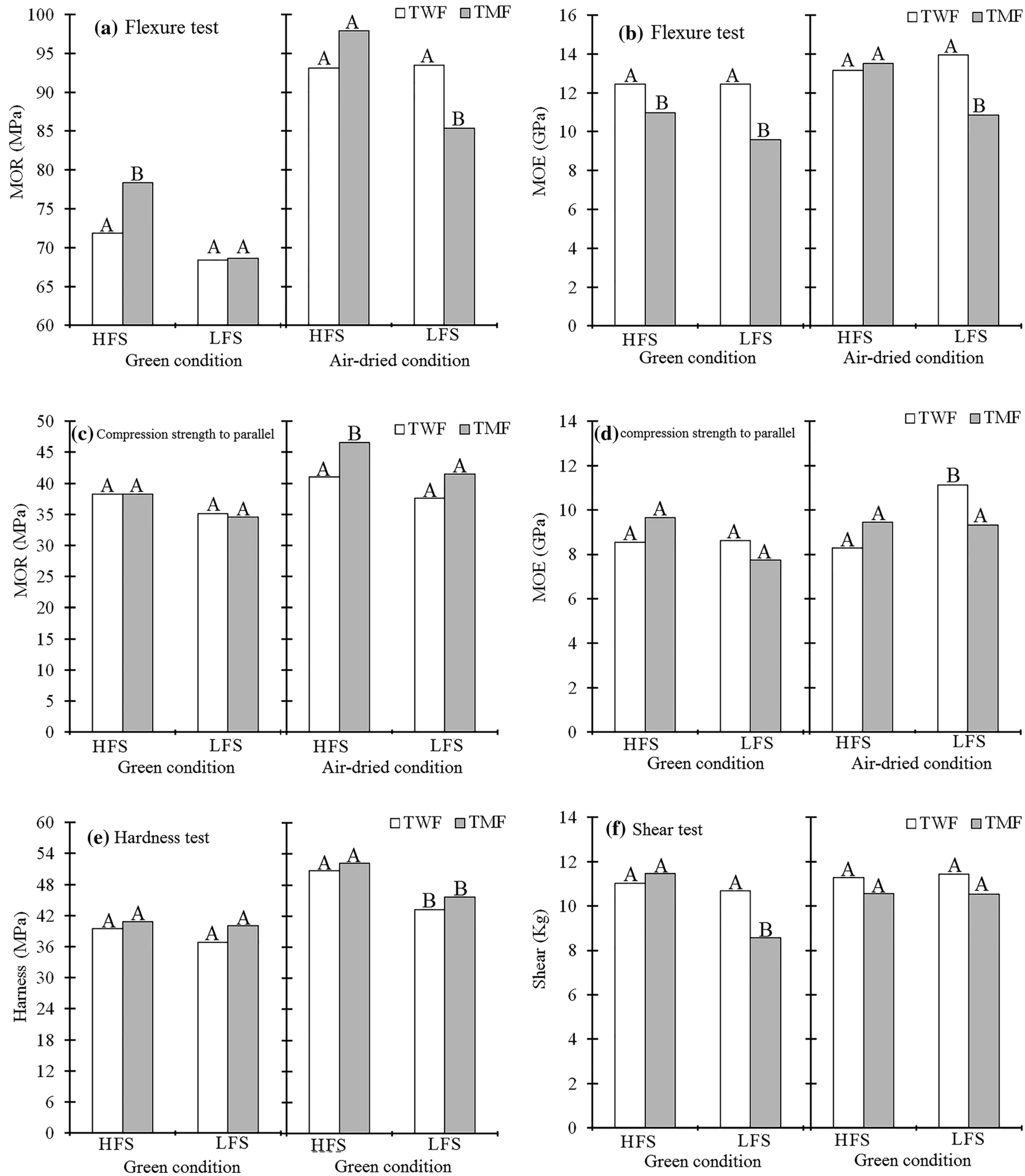

Fig. 3 Mechanical properties in green and dry condition of *Tectona grandis* trees growing in two regions in two sites with different fertility in Costa Rica. **a** MOR in flexion test, **b** MOE in flexure test, **c** MOR in bending strength to parallel, **d** MOE in bending strength to parallel, **e** hardness test and **f** shear test. The letters next to this value indicates that the values are statistically different at a confidence level of 95 % for same properties

from TMF–LFS and TWF–LFS showed no major differences in mortality rate, in both cases, a 90 % mortality at 12 weeks test was reached. Similar were the values to those obtained by timber from TMF–HFS (Fig. 4a). For sapwood the difference in the magnitude of the mortality rate between TMF–HFS and TWF–HFS was comparatively less than the magnitude observed in heartwood. Also timber from TMF–LFS showed no difference in termite mortality in relation to TWF–LFS, in all cases the magnitude of the mortality was 90 % at the end of the 12 weeks (Fig. 4b).

For termites from the *C. brevis* species analyzed in this study, the mean termite survival was greater than 65 % both in sapwood and heartwood, at 2 weeks test (Fig. 4a, b). Lukmandaru and Takahashi (2008) reported with *Reticulitermes speratus* Kolbe termites survival of 50 % in teak sapwood and 40 % in teak heartwood after 2 weeks of treatment. The mean survival rate value of termites under complete starvation condition is 16 % after the 2-week test period. Based on these results, the natural termites activity of teak wood is not thought to be acute.

In relation to weight loss in wood by termites, no significant difference was observed between sites of high and low fertility for TWF and TMF regions for heartwood (Fig. 4c), nor was observed significant difference between sapwood of the LFS sites in both regions. But in the HFS sapwood, weight loss was less significant in the TMF region compared to the TWF region (Fig. 4d).

Regarding weight loss, less than 1.4 %, the ASTM 2017 standard classifies teakwood both sapwood and heartwood is considered, as highly resistant to attack by dry wood termites. However, it is noteworthy that sapwood of HFS–TMF showed less weight loss, being a different behavior to the other conditions evaluated. This difference can be explained by the fact that wood samples of the same age group and radial part may belong to different classes of antitermitic resistance (Lukmandaru and Takahashi 2008). Likewise, high resistance to attack by termites in teak of 11 years, from plantations in two regions of Costa Rica and under two management schemes is an advantage, because results are similar to those reported by Da Costa et al. (1961) and Rudman et al. (1967) with wood from trees growing in natural forests (30–50-years old). This is an encouraging result considering the recent increase of juvenile wood utilization. On the other hand, termite susceptibility in sapwood must be taken into consideration, since sapwood percentage is relatively high in younger trees than 51 years old (Lukmandaru and Takahashi 2008).

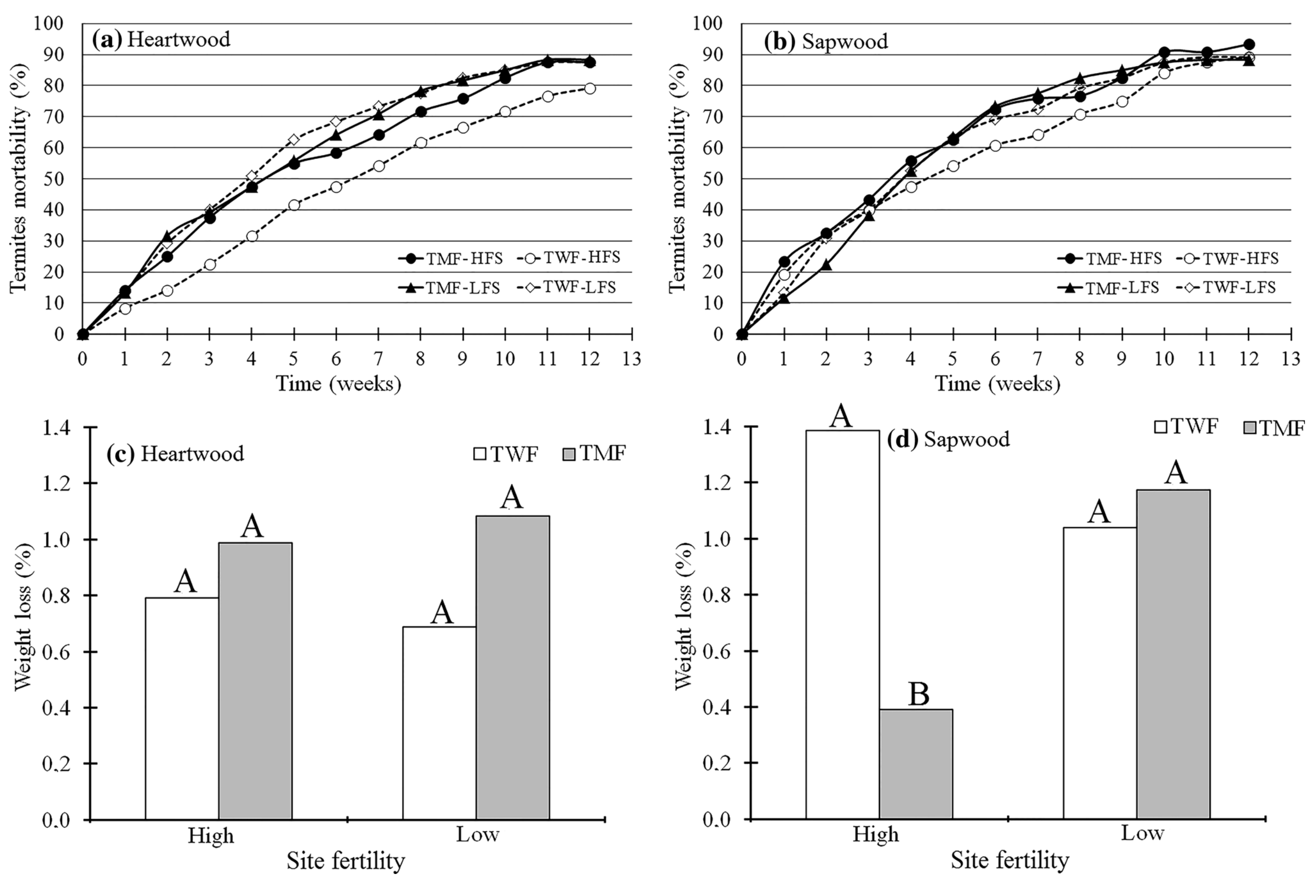

Fig. 4 Termites mortality (%) and weight loss (%) for heartwood and sapwood of teakwood from two regions of Costa Rica: **a** Termite mortality in heartwood, **b** termite mortality in sapwood, **c** weight loss in heartwood and weight loss in sapwood (**d**). The letters next to this value indicates that the values are statistically different at a confidence level of 95 % for same properties

Drying defects

The incidence percentage is presented in Fig. 5 and Table 3 (in relation to all boards evaluated) and the magnitude of the defects found in the boards respectively before and after drying for the climate type or site fertility. It is important to note that timber from younger trees with an age of 11 years, after the sawing process the lumber develops warp, cracks and split. However, some differences in the incidence of these defects were found depending on from where the trees originated: (i) Lumber before drying showed a higher incidence of crook, cup and twist on boards from trees at the TMF (Fig. 5a, c, d), (ii) bow defect was lower in trees at TMF site (Fig. 5b) and (iii) the occurrence of cracks and splits interacted with fertility site (Fig. 5e, f). Fertility site evaluation, for the same climatic condition, it was found that crook, bow, cup and check defects on boards before drying were less in high fertility site (Fig. 5a–c, f). According to Serrano and Cassens (1998) at the same age, those trees with larger diameters tend to produce less distorted green lumber as a result of growth stress release. Mostly because, the longitudinal growth stress generated at the surface is distributed over the years on a larger diameter area. Whereas, split defects were lower in the low fertility site (Fig. 5f). Bow and twist showed no significant difference by site fertility type (Fig. 5b, d). Defects magnitude on dried-lumber (Table 3) do not have the same behavior: crook was statistically higher in wood from TMF in high fertility site and the rest showed no difference. Bow and cup were statistically at greater magnitude in lumber from TMF trees. For twist, it presented no difference between climates evaluated. Therefore, the presence of check and split again depended both on fertility type of the site and climatic condition.

After the drying process, the incidence and magnitude of drying defects increased (Fig. 5; Table 3) except checking that was more or less stable (Fig. 5e). Lumber, after drying, showed a greater incidence of crook, cup and twist from trees

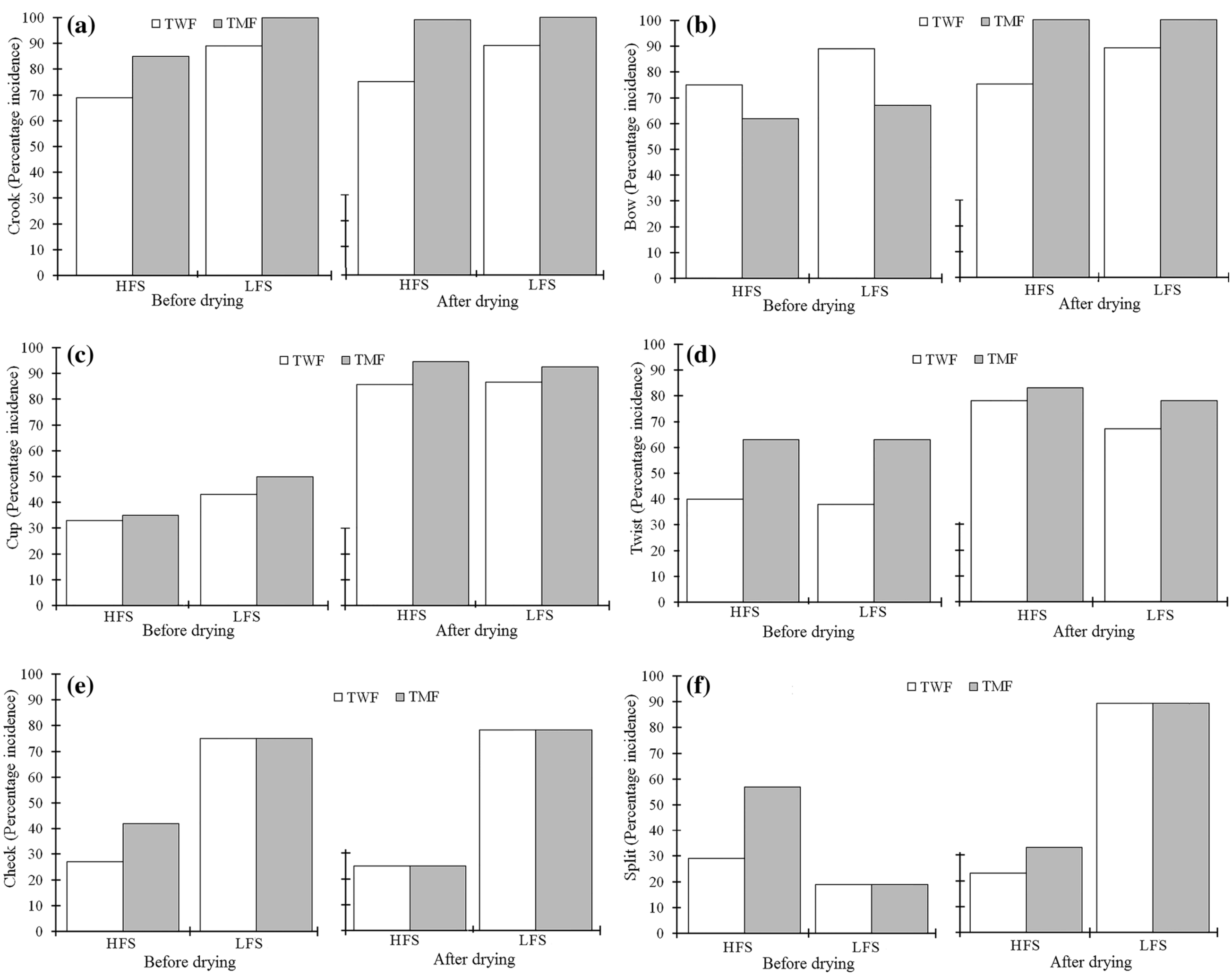

Fig. 5 Percentages of incidence for different drying defects in *Tectona grandis* growing in two regions in two sites with different fertility in Costa Rica

Table 3 Defects in timber before and after drying in *Tectona grandis* growing in two regions in two sites with different fertility in Costa Rica

Drying defects	Time	High fertility site		Low fertility site	
		Tropical moist forest	Tropical wet forest	Tropical moist forest	Tropical wet forest
Crook (mm m^{-1})	Before	3.36^{A}	1.27^{B}	1.40^{B}	1.00^{B}
	After	4.22^{A}	1.30^{B}	3.91^{A}	0.88^{B}
Bow (mm m^{-1})	Before	3.09^{A}	1.49^{B}	5.14^{C}	1.73^{B}
	After	3.80^{A}	1.85^{B}	6.08^{C}	1.95^{B}
Cup (mm)	Before	1.47^{A}	0.75^{B}	2.17^{A}	0.87^{B}
	After	1.34^{A}	087^{A}	1.68^{A}	0.97^{A}
Twist (mm m^{-1})	Before	0.71^{A}	0.80^{A}	0.81^{A}	0.50^{A}
	After	1.30^{A}	1.06^{A}	1.70^{B}	1.11^{A}
Check (mm)	Before	86.88^{A}	25.25^{D}	46.67^{C}	67.14^{B}
	After	80.71^{A}	25.58^{D}	48.33^{C}	69.00^{B}
Split (mm)	Before	107.68^{A}	85.67^{B}	54.00^{B}	94.75^{AB}
	After	98.07^{A}	85.67^{B}	94.25^{A}	98.38^{A}

The letters next to this value indicates that the values are statistically different at a confidence level of 95 % for same defects

of TMF (Fig. 5a–d) and the incidence of cracks and splits interacted with fertility site (Fig. 5e, f). Bow and twist showed no difference in type of site fertility (Fig. 5b, d). Defect magnitude in the wood after drying (Table 3) indicated that: crook, bow and twist were statistically significant and higher in wood from TMF. Cup showed no difference between climates and split and check defects again depended on the climate type and fertility site. In contrast no variations were found between HFS and LFS; however, difference observed in crook for any condition. For bow and twist, difference was found between HFS and LFS in the TMF climate but not for TMF. In the HFS, checks were significantly higher than values of LFS from TWF, but in the case of TWF, the opposite was observed. In the LFS wood, checks were greater than those from HFS. Finally, splits showed no significant difference between sites for TWF, in the TMF climate, timber from HFS produced a larger amount of split than LFS wood (Table 3).

Warp, split and check presence on green lumber of different provenance can be explained by juvenile wood and growth stresses present in the trees. High percentage of juvenile wood in trees under 11 years old, cause wood distortions during the sawing process.

Drying defects (warp, split and check), measured in incidence and magnitude, agree with values obtained by Moya et al. (2013) and Salas and Moya (2014). And the increment in defects after drying can be explained by the shrinkage within boards, especially in juvenile wood present in the air dried-lumber (Bhat et al. 2001). Variation between years produces different shrinkage within a board, producing an increment of defects in dried-lumber in relation to green-lumber.

High values found in the magnitude of drying defects of trees from high fertility site in the TMF (Table 3) can again be explained by further increase in diameter that occurs in these trees. As has been mentioned, the intensity growth stresses in teak trees increased with increasing diameter of the trees (Serrano and Cassens 1998). Therefore, the largest diameter of the trees in the HFS condition of TWF results with the greatest drying defects. And conversely, small diameter trees, such as those found at sites of low fertility, the magnitude and incidence of drying defects is less evident.

Conclusions

General properties (diameter, heartwood percentage, bark and pith, sapwood thickness and pith diameter), physical (specific gravity, radial, tangential and volume shrinkage, ratio of tangential shrinkage/radial shrinkage, fiber saturation point, and green moisture content) and mechanical (center-point flexure test, bending strength to parallel, hardness test and shear strength), termites attack resistance and drying defects (warp, check and split), are altered by climatic conditions and fertility site where teak trees grow. In all cases the change in properties was attributed to differences that occur in tree diameter.

Tree diameter and pith (diameter and percentage) were higher in trees growing in the TWF climate. However, percentage of heartwood and bark were higher in Tropical wet forest. These same tree variables are general and statistically affected in high fertility site. Regarding differences between types of climate and fertility sites, variations were observed in specific gravity, fiber saturation point, green moisture content, volumetric shrinkage MOR in flexion in green and dry condition, MOE in MSC and resistance to termite attack from low fertility site in the tropical wet forest.

According to these results it can be concluded that higher fertility sites of the two provenances tend to produce mechanically more resistant wood. The incidence and magnitude of drying defects increased with air drying, and those were highly variable. Therefore, further studies are required to determine clear tendencies about this behavior.

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