SCHEDULE MODIFICATION OF DRYING RATE TO DECREASE THE DRYING TIME OF JUVENILE *TECTONA GRANDIS* L. WOOD

Alexander Berrocal
E-mail: aberrocal@itcr.ac.cr

*Róger Moya**†
Instituto Tecnológico de Costa Rica
Escuela de Ingeniería Forestal
Apartado 159-7050, Cartago, Costa Rica
E-mail: rmoya@itcr.ac.cr

Brian Bond†
Department of Sustainable Biomaterials
Virginia Tech, Blacksburg, VA
E-mail: bbond@vt.edu

María Rodriguez-Solis
Instituto Tecnológico de Costa Rica
Escuela de Ingeniería Forestal
Apartado 159-7050, Cartago, Costa Rica
E-mail: maria.rodriguez@itcr.ac.cr

Freddy Muñoz
Escuela de Ingeniería Forestal
Instituto Tecnológico de Costa Rica
Apartado 159-7050, Cartago, Costa Rica
E-mail: fmunoz@itcr.ac.cr

Diego Pérez
Life Forestry Costa Rica S.A.
San José Apartado 733-2250, Curridabat, Cartago
E-mail: diegoperez@racsa.co.cr

(Received June 2016)

Abstract. The authors investigated modifying schedules to increase the drying rate (DR) and reduce the total drying time for *Tectona grandis* L. wood from juvenile plantations. The initial MC ranged from 92% to 115%. A conventional teak schedule was used as the basis for developing two faster drying schedules and for comparison. The modifications resulted in a reduction in drying time from 125 to 105 h, a 16% energy savings with less than 1% MC variation in dried lumber; however, this change caused a slight decrease in wood quality. The relationship between the DR, the lumber's MC, and drying time was modeled. As expected, the dry-bulb temperature and wet-bulb depression had the greatest influence on DR; however, an inflection point was found in the relationship between DR and MC at a 40% MC for all three drying schedules. The inflection point indicates when diffusion becomes the primary driving force of moisture movement, thereby limiting the DR, and indicating when the kiln conditions should be accelerated to minimize the total drying time. DR_{hour} should remain more than 0.5%/h (high value for tropical species) for the first 72 h (3 da), until the lumber reaches 40% MC and then be lowered to 0.5%/h until drying is completed.

Keywords: kiln drying, energy consumption, dry-bulb temperature, wet-bulb temperature, wood drying.

---

* Corresponding author
† SWST member

Wood and Fiber Science, 49(4), 2017, pp. 1-13

INTRODUCTION

Tectona grandis is the most commonly used species in tropical climates for commercial reforestation and contains large amounts of juvenile wood. One of the problems with juvenile wood from fast-growth plantations is that it has relatively long drying times (Moya et al 2013, 2017; Berrocal et al 2017) compared with other tropical species. For example, Salas and Moya (2014) reported that the drying period for *T. grandis* is between 9 and 11 da, whereas other species such as *Bombacopsis quinata* and *Terminalia amazonia*, can be dried in as little as 4 da (Moya et al 2013).

Research on the drying of *T. grandis* has focused on the use of moderate-to-high temperature drying methods and drying quality. Hsueh and Jing-Sheng (1997) studied three different drying methods for *T. grandis* from plantation trees and found faster drying times and less energy consumption with high temperature drying compared with conventional drying; however, they failed to mention the actual drying times. Basri and Wahyudi (2013) compared the quality of lumber from young *T. grandis* trees (less than 10 yr in age) to lumber from trees more than 45 yr of age and found lower quality in lumber dried from young tress. They recommended the use of temperatures higher than 50°C. Pleschberger et al (2013) found that alternating the drying temperature along with the EMC in a kiln schedule has a small but significant decreasing effect on the specific fracture energy in the radial/longitudinal as well as in the tangential/longitudinal direction for high temperature and EMC drying of *T. grandis* plantation wood. They mentioned that the decrease in mechanical properties had no effect in end products.

One method to reduce the drying time when kiln drying lumber is to control the drying rate (DR) or rate of moisture loss achieved each day. Controlling the drying process using DR can be used to positively influence drying quality and reduce drying times (Oltean et al 2011; Murphy and Schindler 2011; Moya et al 2011). The optimal DR for a particular species and thickness is affected by the characteristics of wood (Denig et al 2000; Klitzke and Batista 2010; Tenorio et al 2016), the drying chamber (Espinoza et al 2007), and drying conditions (temperatures, RH, and wind velocity) (Denig et al 2000). The DR for each species and thickness varies and can be controlled to improve drying time or quality (Denig et al 2000).

There are several ways to control the drying process for hardwoods. Denig et al (2000) suggest that to fine tune the drying process, the response of the lumber should be monitored, such as by assessing wood quality, and then the drying schedule adjusted as needed. Another way is to measure the DR of the samples (moisture loss per day or 24 h), then compare the measured daily moisture loss to the published safe DR for that species, and adjust the schedule to achieve this safe DR. For many species and thicknesses, there is a published DR that will result in high-quality dried lumber and minimal drying time. Exceeding this rate greatly increases the risk of quality loss. Denig et al (2000) provides the DR for several major hardwood species and various thicknesses of lumber used in the United States. It is important to note that DR represents the daily MC loss and not the average MC loss of several days of drying; eg, an 8% loss today and 2% loss tomorrow does not have the same impact on wood quality as 5% each day.

The DR as discussed is used for hardwood species with longer drying times (more than 10 da) and for species from temperate areas (Denig et al 2000). Research on the DR for fast-grown tropical plantation species is less understood. Wood from these trees dries fairly rapidly (less than 10 da), has high initial MC (more than 100%) and DR per day can be as high as 40% in the initial stage (Tenorio et al 2016). Thus, the application of DR per day as recommended by Denig et al (2000) may not be optimal for achieving the fastest drying times with the best quality for tropical wood from fast-grown trees. Recently, Tenorio et al (2016) modeled the variation of DR, measured per hour, in relation to drying time and MC for six tropical wood species. They mention that drying time for these tropical species can be reduced by understanding the relationship between DR and drying time or the relationship between DR and MC. The authors believe that the DR computed more than a shorter period, such as between 8 and 10 h, and converted into MC loss per hour would be more practical for reducing the drying time of certain tropical species. Therefore, the DR used in this project would not be comparable to the DR as calculated using a 24-h period as used by Denig et al (2000).

Research on the drying of *T. grandis* wood from fast growing plantations is limited and little work has been conducted regarding the reduction of drying time when using moderately high temperatures (more than 80°C) when drying juvenile teak wood. The objective of this research was to investigate the modification of schedules to increase the DR, as defined as the moisture loss per hour, and reduce the total drying time for *T. grandis* L. wood from juvenile plantations. The electrical energy (kWh) used for drying and measuring drying defects (cup, bow, crook, twist, checks, and split) were used as the criteria to compare each schedule.

MATERIAL AND METHODS

Plantation and Sampling Characteristics

The lumber used for testing was produced from a second thinning of an 11-yr-old *T. grandis* plantation. The stand density was 475 trees ha^{-1}, with an average diameter at breast height of 23 cm and total height of 14 m at sampling time. The plantation was located in the northern region of Costa Rica, on the property of Life Forestry Costa Rica S.A. The area had a mean annual temperature of 27-32°C, and annual precipitation of 3500 mm. Seven to nine logs were cut from fresh thinned trees, until a minimum diameter of 13 cm was reached. The average diameter for logs was 17 cm. The proportion of heartwood was measured according to methods used by Tenorio et al (2016). Logs were then sawn using the sawing patterns shown in Fig 1a. and detailed in Moya (2007). A total of 1800 edged 25-mm-thick boards were randomly selected for the six different tests. Boards were stored in plastic bags and located in chamber at 8°C and 100% of RH to prevent moisture loss until used in the drying tests. The amount of time the samples were stored was dependent on the amount of time that was required to conduct the other drying tests. Samples were removed from the plastic bags only when another test was ready to start. The maximum time that samples were stored was 2 wk. No fungal activity was observed on any of the samples tested.

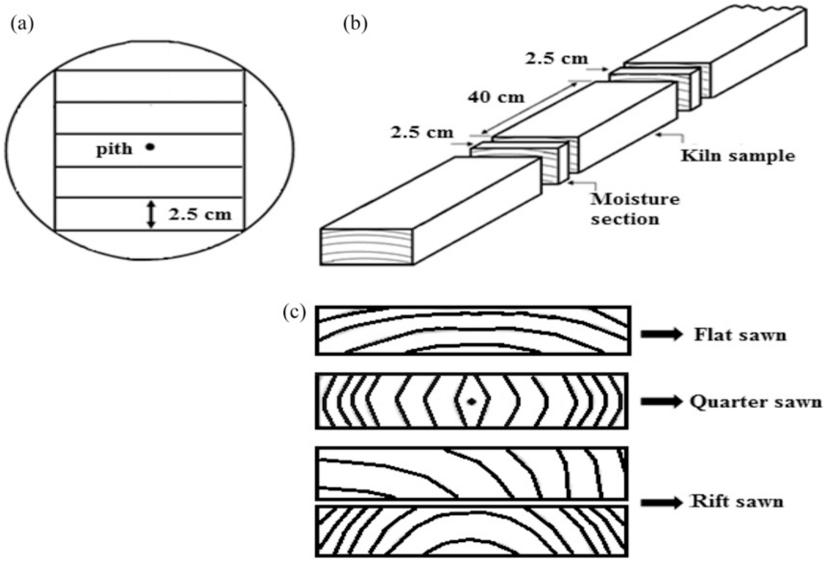

Figure 1. Sawing pattern used in each log (a), sample obtained for determining MC (b) and cutting types on the wooden boards (c).

Drying Schedules

Three schedules were tested: the first as a baseline for comparison; the second a modification of the first with steps to accelerate drying (accelerate DR); and the third having further changes to accelerate the DR. Modifications to the second and third schedule were based on the results of the previous schedule tested and will be discussed in detail below. The volume of material sawn allowed for each of the three schedules to be tested with two replications, but each batch was composed by 300 boards.

The first schedule, drying schedule 1, (DS-1) is the commonly used schedule for *T. grandis* in Costa Rica, which is a modified version of the "H" schedule recommended by Boone et al (1998) for *T. grandis* (Table 1). A DR of 0.40%/h for *T. grandis* wood from plantation trees is typical as indicated by Moya et al (2013), Salas and Moya (2014). Although this schedule provided good dried-lumber quality, the drying times were longer than for other species from fast-growth plantations (Moya et al (2013); Salas and Moya (2014)). The longer drying times for teak are likely a result of the schedule having been developed for wood from natural forests, which usually has a higher extractive content and a different anatomical structure. The authors believe that faster drying could be achieved for wood from fast-growth plantations due to its lower extractive content, higher juvenile wood content, and different anatomical structure (Moya et al 2014).

The second drying schedule (DS-2) was aimed at achieving a faster DR; therefore, several temperatures and equilibrium moisture contents were changed and three steps added to the DS-1 schedule. In the three additional steps, the EMC was also reduced (Table 1). The authors hypothesized that by increasing the differences in EMC between steps, a faster DR would be obtained. Also, a step was added between the first and second steps of DS-1, to reduce the EMC. The second additional step was then added between second and third steps to reduce temperature and EMC. The third additional step was added before the last step, where the EMC was again reduced (Table 1).

On completion of the drying tests using schedule DS-2, additional schedule modifications were made to further reduce the total drying time. The drying schedule 3 (DS-3) used the same number of steps as DS-2; however, a 5°C higher dry-bulb temperatures (DBTs) was used after the lumber dropped below the Fiber Saturation point (FSP) (Table 1). The temperature was raised instead of further lowering the EMC because of the greater influence of temperature on drying below FSP.

Table 1. Different drying schedules for wood of *Tectona grandis* tested on kiln drying.

	Drying schedule 1 (DS-1)*				Drying schedule 2 (DS-2)				Drying schedule 3 (DS-3)			
Step	Number	DBT/WBT (°C)	EMC %	MC (%)	Number	DBT/WBT (°C)	EMC (%)	MC (%)	Number	DBT/WBT (°C)	EMC (%)	MC (%)
Heating	1	55/–	—	>60	1	55/–	—	>60	1	55/–	—	>60
	2	58/54	14.0	>60	2	58/54	14.0	>60	2	58/54	14.0	>60
Drying	1	60/56	13.8	30	1	60/56	13.8	30	1	58/54	13.8	30
	2	60/52	10.0	25	1-a	60/54	12.5	30	1-a	60/54	12.5	30
	3	70/58	7.7	20	2	60/52	10.0	25	2	60/52	10.0	25
	4	70/55	6.4	15	2-a	65/55	8.5	25	2-a	65/55	8.5	25
	5	75/50	3.7	10	3	70/58	7.7	20	3	70/58	7.7	20
					3-a	75/58	6.4	20	3-a	75/60	6.4	20
					4	75/55	5.2	15	4	80/60	5.0	15
					5	75/50	3.7	10	5	80/55	3.7	10
Equalization		75/70	11.0	12		75/70	11.0	12		80/74	11.0	12
Conditioning		75/68	11.5	—		75/68	11.5	—		80/75	11.5	—
Cooling		35/28	11.5	—		35/–	—	—		35/–		—

DS, drying schedule; DBT, dry-bulb temperature; WBT, wet-bulb temperature.

* Schedule h (adjust) from Boone et al 1988.

All drying tests were conducted in a conventional kiln with a 2 m^3 capacity and using an electrical powered heat. Green lumber was stacked 10 boards wide and 30 pieces high, for a total of 300 pieces per charge. The stickers used were 2.5 × 2.5 cm. Each drying schedule was performed in duplicate; therefore, a total of six drying charges were conducted. The target MC for all charges was 12% based on the anticipated EMC in the main zone of Costa Rica, which is 10-14% (Tuk 2007). The order of drying tests were 1) two charges using the D-1 schedule, 2) followed by two charges using the D-2 schedule, and 3) finally two charges dried using the D-3 schedule.

MC and Kiln Control

The MC was determined before and after drying for all lumber using the ASTM-4442-07 standard (ASTM 2012). To determine the MC before drying, ("initial MC" [MC_i]) a cross section of 2.5 cm thick was extracted from each board (Fig 1b) and the MC_i was measured. For the final MC (MC_f) a cross section of 2.5 cm thick was extracted from each board after drying and MC was measured.

Six kiln samples were selected randomly and used to control each charge. Kiln samples of 40-cm length were cut from boards using the procedures outlined by Simpson (1991). The samples were placed at different heights in the charge and were weighed each 8-10 h. The average sample MC was then compared with the MC used for control in the schedule (Table 1). If the average sample MC was lower than MC listed for that step in the schedule, the chamber conditions were modified according to the schedule. Also, these data were used to determine the DR during drying and any relationship between DR with drying time and DR with MC variation.

The kiln temperature and RH were measured and controlled to meet the drying schedule using a computerized system.

Energy Input Used during Drying

The electricity input is defined as the total electrical energy used for drying and was determined using a PowerLogic Power model Meter Series 200 (Schneider Electric, Germany). Readings, in kilowatt hours, were taken at conclusion of the drying charge.

Drying Defect Evaluation

Warp (twist, crook, bow, and cup), cracks, and splits were measured both before and after drying as a way to compare the quality of lumber dried using each schedule. To measure warp, the methods proposed by Hallock and Malcom (1972), Milota (1996) were used. Crack and split measurements were taken using the methodology proposed by Shmulky and Dahlen (2007). The Chilean standard Nch993EO72 (Pérez et al 2007) was used to determine the index of quality (QI) for twist, crook, cup, and bow parameters according to Eq 1 (Pérez et al 2007). For splits and checks the classification system used by the American Softwood Lumber Standard PS20-05 (NIST 2005) was adopted, which establishes four different categories (Table 2). These two standards were adopted since there are currently no standards for tropical hardwoods and a method for comparison was needed.

$$\mathrm{QI} = \frac{(N\mathrm{a}\cdot 0 + N\mathrm{b}\cdot 0.5 + N\mathrm{c}\cdot 2.0 + 2.5\cdot N\mathrm{d})}{M} \tag{1}$$

where QI = quality index; *N*a = number of pieces without any presence of warp; *N*b =

Table 2. Drying defects and limits values for classification used the *Tectona grandis* dried lumber.

Drying defects	Limits of quality
Cup	Not present: 0 mm, slight: 1-3 mm, moderate: 3-5 mm severe: > to 5 mm
Bow	Not present: 0 mm, slight: 1-3 mm, moderate: 3-6 mm severe: > to 6 mm
Crook	Not present: 0 mm, slight: 1-2 mm, moderate: 2-3 mm severe: > to 3 mm
Twist	Not present: 0 mm, slight: 1-5 mm, moderate: 5-8 mm severe: > to 8 mm
Checks	Not present: 0 mm, slight: 1-10 mm, moderate: 10-25 mm, severe: > to 25 mm
Splits	Not present: 0 mm, slight: 1-25 mm, moderate: 25-42 mm, severe: > to 42 mm

Source: Kauman and Mittak (1966), Pérez et al (2007).

number of pieces with a slight presence of warp; *N*c = number of pieces with a moderate presence of warp; *N*d = number of pieces with a severe presence of warp; *M* = total number of pieces.

Finally, the dried-lumber quality index was classified using the methodology proposed by Kauman and Mittak (1966). An explanation of this methodology is presented in Moya et al (2013) and Salas and Moya (2014). The classification includes the following categories:

a. if QI is close to 0 indicate a lower presence of defects and is classified as excellent.
b. If QI varied from 0.1 to 0.5 is classified as very good
c. If QI varied from 0.51 to 1.0 is classified as good
d. If QI varied from 1.1 to 1.5 is classified as satisfactory
e. If QI varied from 1.51 to 2.0 is classified as regular
f. If QI varied from 2.1 to 3.0 is classified as defective
g. If QI varied from 3.1 to 5.0 is classified as poor
h. If QI is over 5.0 is classified as very poor

Data Analysis

The average values and coefficient of variation (CV) for MC_i and MC_f for each drying schedule (two charges per schedule) were determined. Then, an analysis of variance was carried out to establish differences in MC_i and MC_f between the different drying schedules (two charges per schedule).

The average values for MC_i and MC_f were then calculated for the six control samples and used to determine the average DR ($DR_{average}$) with Eq 2 and DR by time (DR_{hours}) for each charge. $DR_{average}$ means the average DR (moisture loss per day) determined by Eq 3. DR_{hours} is MC loss per hour (Eq 4), derived from the MC measured each 8-10 h (Eq 5).

$$\text{Average drying rate } (\%/\text{h}) = \left(\text{MC}_\text{i}\%\text{-MC}_\text{f}\%\right) \text{ total drying time(h)} \quad (2)$$

$$\text{Drying rate}_\text{hour} \ (\%/\text{h}) = \frac{\text{MC(\%)at time 1-MC(\%)at time 2}}{\text{Time between measurements(h)}} \quad (3)$$

$$MC = a \times e^{-b \times t} \quad (4)$$

$$DR = at^2 + bt + c \quad (5)$$

where MC_i = average initial MC for the six samples (%), MC_f = average final MC for the six samples (%) and t = drying time (hr), DR (% hr^{-1}); t = total drying time (h); a, b, and c: coefficients of model.

MC loss during drying and the relationship between MC and drying time was modeled using an exponential relationship (Eq 3), known as the Henderson and Pabis model (De Souza et al 1995). After modeling, the relationship between DR_{hour} regarding MC of wood and drying time (h) was established. In the relationship of DR_{hour} and MC two different linear tendencies were observed, DR before and after 40% MC. The authors tested Proc NLin statement with SAS software (SAS Institute, USA) to confirm this separation; however, no significant relationship between DR_{hour} and MC was found ($p > 0.05$). Two liner tendencies ($Y = mx + b$) were clearly visible in all three drying schedules, where each represented a different performance of DR_{hour} with decreasing of MC. The first trend was calculated from green condition until 40% in MC and the second one from this MC until end of drying. The MC where first tendency ends or changes and where second begins is called an inflection point. The existence of an inflection point required that a regression model be developed for each trend (below and above 40% MC). Once the data were adjusted to the models, inflection points or tendency changes were determined between DR_{hour}'s variation and the MC for each drying schedule. SAS software was used for the statistical analysis.

The relationship between DR_{hour} and drying time was modeled using a polygonal trend line of grade 2 for all schedules (DS-1, DS-2, and DS-3) (Eq 4). The best-fit models were chosen based on their determination coefficient (R^2).

Table 3. Initial and final MC, drying time, and average drying rate for the three evaluated drying schedules (DSs) for juvenile wood of *Tectona grandis*.

Drying schedule	Initial MC (%)	Final MC (%)	Heartwood (%)	Drying time (h)	Average drying rate (% hours^{-1})
DS-1	141 (20.1) A	12.58 (8.8) A	65.5	125	1.03
DS-2	92 (19.4) B	11.74 (8.0) B	82.7	140	0.57
DS-3	106 (18.7) C	12.74 (8.6) A	67.3	105	0.89

Letters indicate statistical significances at 99%. The values in parenthesis represent the coefficient of variation.

RESULTS

Drying Time, Average DR and Final MC

The total drying time was 125 h for DS-1, 140 h for DS-2, and 105 h for DS-3 (Table 3). Lumber dried using the DS-1 schedule had the highest $DR_{average}$ (1.03%/da), whereas lumber dried using the DS-2 schedule had the lowest DR (0.89%/da). The MC_i of lumber used in DS-1 and DS-3 was higher than 100%, whereas lumber used in DS-2 had a MC_i of 92%. The MCi was statistically different for the lumber used for testing all three schedules. The MC_f in dried lumber varied from 11.74% to 12.74%, with the statistically lowest value for lumber dried using the DS-2 schedule (Table 2). The CV for MC_f in dried lumber in the different drying schedules varied from 8.0% to 8.6%, but the CV in MC_i varied from 18.7% to 20.1% (Table 2).

MC decreasing with time was similar in all schedules. The relationship was modeled through an exponential equation ($MC = a \times e^{-b \times t}$, where t is drying time, a and b are constants) with R^2 superior to 88% (Fig 2).

DR vs MC

Two different trends were observed in drying schedules for the variation of DR_{hour} with MC (Fig 3). For DS-1 and DS-2, the schedules with the longest drying times, the relationship between DR_{hour} and MC was directly proportional, but a change was observed when wood reached 40% MC (Fig 3a and b). For both drying schedules and the two MC ranges (green to 40% and from 40% to MC_f target), there is a decreasing of DR_{hour} when MC decreased (Fig 3a and b). For dried lumber with the DS-3 schedule, the one with the shortest drying time, two trends were also observed with

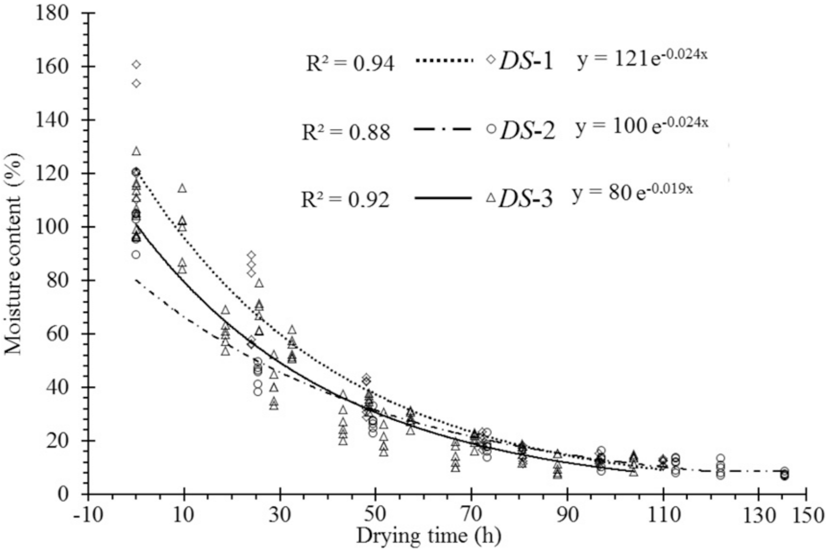

Figure 2. Variation of MC of juvenile wood of *Tectona grandis* for three drying schedules in Costa Rica.

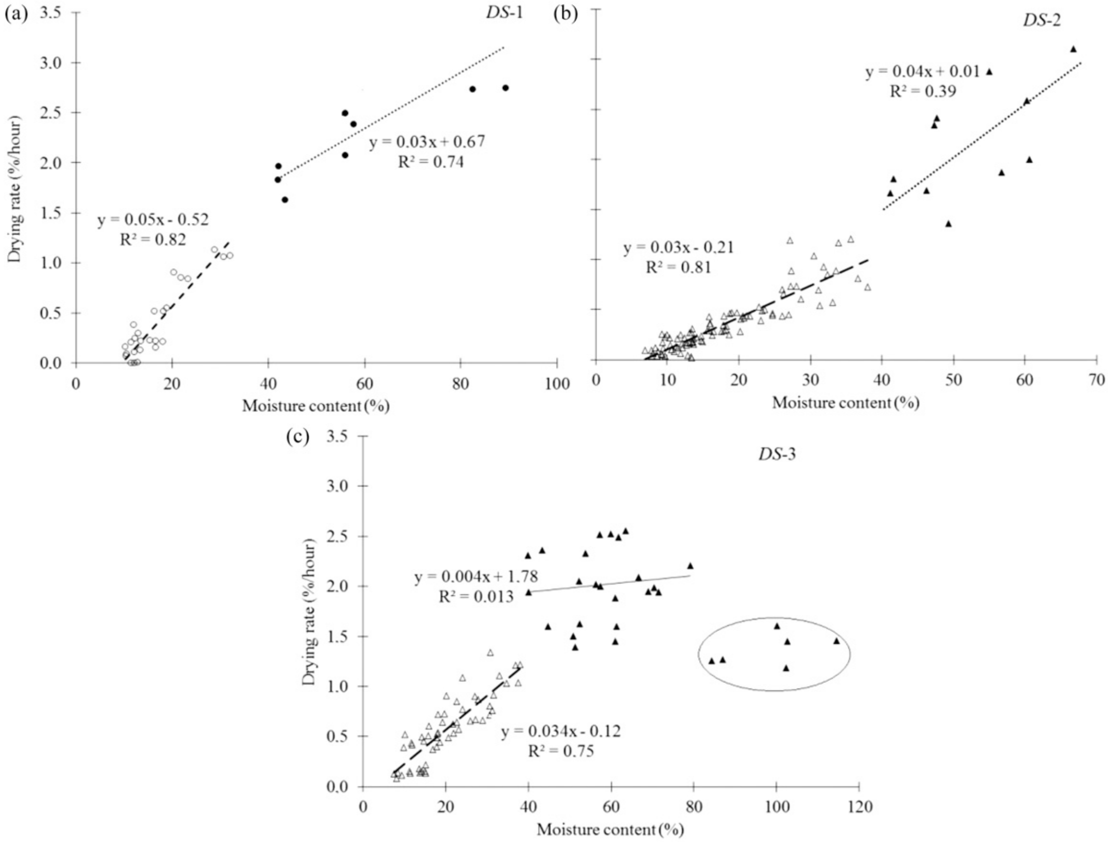

Figure 3. Variation of drying rate by MC in the three drying schedules applied to juvenile wood of *Tectona grandis.*

the same inflection point at 40% of MC (Fig 3c). However, no linear relationship between DR_{hour} and MC was observed from green to 40%, the only linear relationship being from 40% to MC_f target. Grubb's test for outliers was used to determine that six data points close to 100% MC (Fig 3c) were considered outliers and did not adequately model the relationship between DR_{hour} and MC in wood with MC higher than 40% (Fig 3c).

DR vs Drying Time

DR per hour (DR_{hour}) decreased with drying time for all drying schedules (Fig 4a). DR per hour (DR_{hour}) for DS-1 decreased from 2.7%/h to 0.7%/h within a period of 24-72 h, DR_{hour} of DS-2 decreased from 2.0%/h to 0.01%/h by the end of a 140-h period, and DR_{hour} of DS-3 decreased from 1.5%/h to 0.02%/h within a period of 24 to 96 h (Fig 4a). By the end of drying (105 h), DR_{hour} steadily declined from 0.02%/h to 0.01%/h (Fig 4a). Modeling the variation of DR_{hour} with time showed that the best fit model was a polynomial with grade 2 in dried lumber for all schedules and with R^2 superior to 82% (Fig 4b).

Energy Consumption

The energy consumption for the three schedules varied from 230 to 341 kW h, where the DS-3 consumed the least energy compared with the other schedules (Fig 5), achieving an energy savings of 32% in relation to DS-1 and 25% in relation to DS-2.

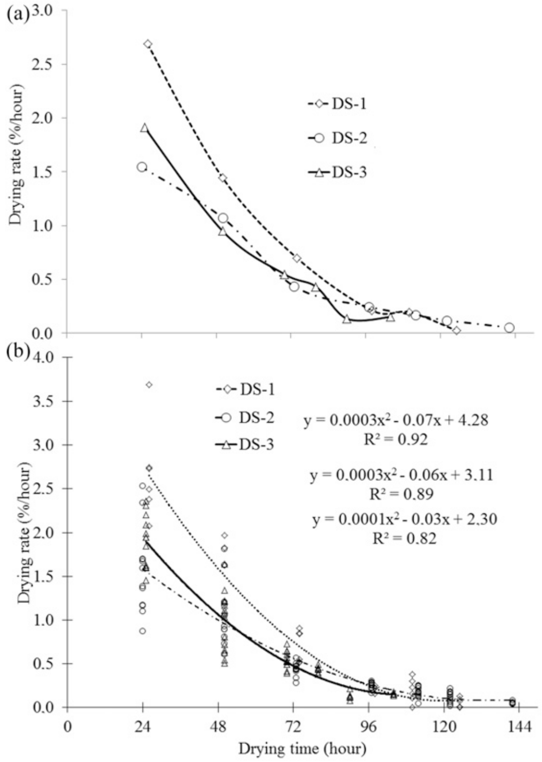

Figure 4. Variation (a) and best fit model (b) of drying rate vs drying time for the three drying schedules applied to juvenile wood of *Tectona grandis.*

Drying Defects

The dried-lumber quality measured using the QI showed that lumber dried using the DS-1 schedule had "excellent" quality for twist and cup but resulted in "defective" for bow. For other drying defects the dried lumber was cataloged as "satisfactory" or "very good" quality (Table 4). Dried-lumber quality for the DS-2 schedule was similar to DS-1, but was slightly lower in DS-3 for twist, cup, check and splits (Table 4).

DISCUSSION

All three schedules resulted in a total drying time between105 and 142 h, times that were 46-51% faster than that reported by Salas and Moya (2014) who used the schedule DS1 for teak from fast-growth plantations. The $DR_{average}$ in hours for all drying times (0.57-1.03% /h) was higher than values reported for other tropical plantation species processed by many sawmills in Costa Rica Tenorio et al (2016). For example, 0.2-1.27%/h reported in Moya et al (2013) for *Vochysia guatemalensis*, *Acacia mangium*, *Alnus acuminata*, *Bombacopsis quinata*, *Swietenia macrophylla*, *T. amazonia*, *Terminalia oblonga*, *Cupressus lusitanica*, and *Gmelina arborea* or 0.16-0.90%/h reported in Tenorio et al (2016) for *Cordia alliodora*, *Dipteryx panamensis*, *Enterolobium cyclocarpum*, *Hieronyma alchorneoides*, *Samanea saman*, and *Vochysia ferruginea*.

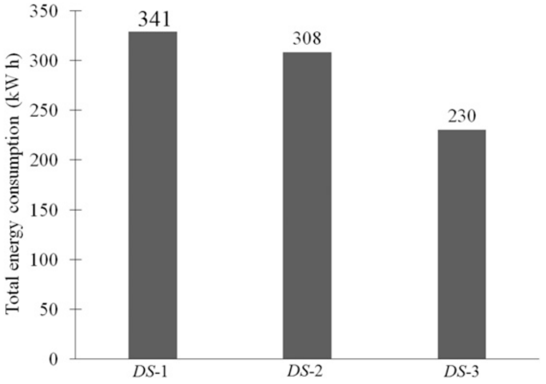

Figure 5. Total energy consumption (kWh) of the three evaluated kiln drying schedules of juvenile wood of *Tectona grandis*.

The difference in the DRs between three drying schedules can be attributed to the different temperatures and EMC values used between the steps used and differences in the amount of heartwood. The lumber from trees with a higher percentage of heartwood had a lower DR (Table 3). For example, lumber with the highest average DR was produced from trees with the lowest percentage of heartwood, and lumber produced from trees with the largest amount of heartwood, such as DS-2, the average DR decreased, even though the MC_i was 40% lower than the lumber tested in the other schedule (Table 3). This suggests that trees with a higher percentage of heartwood than what was used in this study, such as trees with higher age or trees growing in regions with lower rainfall, the DR will decrease and the drying time will likely increase. Teak trees with greater age (Moya et al

Table 4. Dried-lumber quality index for *Tectona grandis* with three drying schedule (DS).

Drying schedule	Twist	Crook	Bow	Cup	Check	Split
DS-1	Excellent	Satisfactory	Defective	Excellent	Excellent	Excellent
DS-2	Excellent	Regular	Regular	Excellent	Excellent	Excellent
DS-3	Very good	Regular	Regular	Very good	Very good	Very good

2014) and from regions with less rainfall have a higher percentage of heartwood (Moya and Calvo-Alvarado 2012). However, even with the increase in heartwood, using the DS-3 schedule should allow shorter drying compared with the recommended drying schedule (DS-1).

The $DR_{average}$ values attained in this research were higher than those found in other studies for teakwood with the same thickness such as Salas and Moya (2014), who reported an average 0.40%/h for *T. grandis* using schedule recommend for by Boone et al (1998) or DS-1. One possible reason for this significantly higher MC loss per hour could be the difference in wood age, where older trees, such as those used in Salas and Moya (2014) have a greater heartwood content and higher density than in juvenile trees (Moya et al 2014). Both of these factors would result in lower permeability and a smaller MC loss per hour.

The correlation coefficients (R^2) in the linear models for the relationship between DR_{hour} and MC (Fig 3) suggest that for all three schedules, the MC of lumber is a feasible indicator of DR_{hour} variation. This relationship is negative, meaning that after the wood reached 40% MC, the MC loss per hour decreased, suggesting that the ideal DR should be established according to MC of wood. The authors propose that the decrease in DR with the reduction of the MC at 40% is the irreducible MC for teak, the point below which diffusion takes over from permeability as dominating moisture migration processes (Walker 2006). This MC that this occurs is influenced by the different types of water in wood (Walker 1993; Tenorio et al 2016). During the initial stages of kiln-drying, free water leaves cell lumens and intercellular spaces by evaporation more easily and with less energy consumption (Skaar and Siau 1981; Denig et al 2000). However, when lumber reached 40%, then the major portion of water is located in the cell walls (bound water), moving through cell walls by diffusion and making the evaporation more difficult to occur (Walker 1993). The authors suggest that an understanding of the relationship between DR_{hour} and MC could be used to optimize drying in relation to drying time and wood quality; thus reaching better economy in drying.

An inflection point occurred at 40% MC for all three schedules (Fig 3), despite differences in MC_i, temperatures, and EMC used in each schedule. However, there were differences in the linear relationship representing the relation between MC and DR for the three different drying schedules. For the two schedules with longer drying times (DS-1 and DS-2) there is a significant lineal mathematical relationship (Fig 3a and b), but the schedule for fastest drying does not have a significant linear relationship (Fig 3c). Although, DS-3 and DS-2 use similar drying conditions (temperature and RH), the relationship between MC and DR when the MC was greater than 40% was different (Fig 3b-c). These differences can be attributed to a lower MC_i for the wood used to test DS-2 (Table 3), the lumber quickly reached 40% in MC (approximately 24 h after initiated drying).

Variations in DR_{hour} with MC and the presence of inflection points have also been found in other plantation grown tropical species (Tenorio et al 2016). The authors found that wood of *Enterolobium cyclocarpum* and *Samanea saman* have inflection points at 80% and 40%, similar to values found in the present study. The authors attributed the inflections to the relationship between DR_{hour} and MC to different water diffusion rates in sapwood and heartwood and a large change in drying conditions (temperature and EMC). However, the variations in the inflections points in teakwood cannot be attributed only to heartwood-sapwood presence. As discussed, the variation inflection points are affected by other intrinsic wood properties as initial MC or drying conditions in the chamber (temperature or humidity).

DR vs Drying Time

The results show that DR_{hour} should remain more than 0.5%/h (high value for tropical species) for the first 72 h (3 da), until the lumber reaches 40% MC and then be lowered to 0.5%/h until drying is completed (Fig 4a). The relationship between DR_{hour} and drying time is highly influenced by the variations of DBT and wet-bulb temperature (WBT) during the drying process (Tenorio et al 2016). For example, Tenorio et al (2016) found that there is a change in the relation DR_{hour} and MC and they showed that the MC where relationship change occurs was when depressions of DBT and WBT were high. During the drying stage, the wet-bulb depression (WBD) increased as MC decreased for the three drying schedules. In the slower drying schedules (DS-1 and DS-2), a WBD of four at 25°C in the eighth drying stage was applied with changes of approximately 2°C, and the DBT was increased 5°C after the fourth stage until a temperature of 75°C was reached. For the fastest drying schedule (DS-3), WBD increased 5°C for each drying stage but DR remained the same in all stages, even with a WBD change of 3°C per stage was added and a final DBT temperature of 80°C was used, resulting in faster drying.

These results are consistent with Tenorio et al (2016) where there were change in the tendency (inflection point) in the modeling of DR variations regarding MC were produced by a large WBD changes, which reduced drying time when applied at the beginning of drying (at 80% MC) as in schedules DS-2 and DS-3. This implied less energy consumption, especially in DS-2 (Fig 5) due to the shorter drying time.

Evaluation of Others Aspects

Important aspects related to the three different drying schedules is the uniformity of the MC_f (Table 3) and the quality of the dried lumber (Table 4). The MC_f was 12.68% for DS-1 and 11.74% for DS-2 and 12.74% for DS-3 (Table 3) indicating that all schedules are capable of reaching the proper target regardless of drying time. The dried-lumber quality was acceptable based on the QI ranging from superior to "very good" for DS-1 and DS-2 (specially for twist and cup defects), but the DS-3, with the shortest drying time produced slightly lower quality, with greater amounts of twist, cup, checks, and splits (Table 4). The increased defects for lumber from the DS-3 schedule likely resulted from the high temperature used, particularly at the end of the schedule and the faster DR (Pleschberger et al 2013). Although heartwood color can be an important aspect of quality for teak lumber, color measurements were not taken. Previous research on *T. grandis* plantation wood, has focused on the application of high temperature drying and dried-lumber quality (Hsueh and Jing-Sheng 1997; Basri and Wahyudi 2013; Pleschberger et al 2013). Wood color dried using DS-1 (Salas and Moya 2014) and the use of a steaming treatment to improve color has been studied by others (Berrocal et al 2016, 2017; Moya et al 2017).

CONCLUSIONS

The traditionally recommend drying schedule (Schedule h from Boone et al [1988]) for *T. grandis* was modified using higher temperatures, decreasing EMC and the addition of three new stages. Modifications resulted in the fastest drying schedule reducing the drying time in *T. grandis* wood by 16% with less energy consumption, more uniform MC_f and acceptable lumber quality. An inflection point in the relationship of DR-MC at 40% in MC was identified for fast plantation grown teak, regardless of the schedule used. The inflection point occurs due to differences in the diffusion rates for free water and bond water. The inflection MC indicates the point where the DR should be changed to accelerate drying and minimize drying time. DR_{hour} should remain over 0.5%/h for the first 72 h (3 da), until the lumber reaches 40% MC and then be lowered to 0.5%/h until drying is completed.

Identification of the two different DRs for *T. grandis* drying is an important finding and modifying schedules to accommodate the change can lead to a significant reduction in drying time.

ACKNOWLEDGMENTS

The authors wish to thank the *Vicerrectoría de Investigación y Extensión* at the *Instituto Tecnológico de Costa Rica* (ITCR), and we thank Life Forestry Costa Rica S.A. for providing a sample of their 11-year-old teak trees from their plantations for the present study.

REFERENCES

American Society for Testing and Materials (ASTM) (2012) Standard test methods for direct moisture content measurement of wood and wood-base materials. D-4442-07. American Society for Testing and Materials, West Conshohocken, PA.

Basri E, Wahyudi I (2013) Wood basic properties of Jati Plus Perhutani from different ages and their relationships to drying properties and qualities. Jurnal Penelitian Hasil Hutan 31(2):93-102.

Berrocal A, Moya R, Rodriguez-Solis M, Starbird R, Muñoz F (2016) Surface chemical and colour characterization of juvenile *Tectona grandis* wood subjected to steam-drying treatments: Effect of grain pattern and moisture content. Surf Rev Lett 23:1-14.

Berrocal A, Moya R, Rodriguez-Solis M, Muñoz F (2017) Drying of plantation-grown *Tectona grandis* wood with daily-controlled drying rate schedules: Effects on the final moisture content, drying time, wood colour and drying defects. J Trop For Sci 29(1):69-79.

Boone R, Sidney R, Charles J, Kozlik P, Bois J, Wengert E (1988) Dry kiln schedules for commercial woods: Temperate and tropical. Gen Tech Rep FPL-GTR-57 USDA For Serv, Forest Prod Lab, Madison, WI.

Denig J, Wengert EM, Simpson WT (2000) Drying hardwood lumber. Forest Products Laboratory-USDA, Madison, WI. 138 pp.

De Souza A, Simpson WT, Verril SP (1995) Laboratory test for grouping tropical species for kiln drying. Wood Sci Technol 29:353-362.

Espinoza O, Bond BH, Araman P (2007) A survey of Bolivian lumber drying operations. Forest Prod J 57(6): 88-92.

Hsueh A, Jing-Sheng N (1997) Study on the kiln drying of teak, India-charcoal trema, Formosan alder and schefflera tree 3-cm thick lumber. Bull National Pingtung Polytechnic Ins 6(1):41-48.

Hallock HY, Malcolm FB (1972) Sawing to reduce warp in plantation red pine studs. Research paper FLP-164. USDA Forest Service, Madison, WI.

Klitzke RJ, Batista DC (2010) Tests of drying rate and scoring of defects for the prediction of conventional kiln drying quality of eucalyptus wood. Scientia Forestalis 38 (85):97-105.

Kauman WG, Mittak G (1966) Drying test of Coigüe (*Nothofagus dombeyi*). Informe Técnico N° 25 INFOR, Chile. 25 pp [In Spanish with abstract in English].

Moya R (2007) Industrialization and marketing of wood from plantation in Costa Rica. Recursos Naturales y Ambiente 49:154-162 [In Spanish with abstract in English].

Moya R, Calvo-Alvarado J (2012) Variation of wood color parameters of *Tectona grandis* and its relationship with physical environmental factors. Ann Sci 69 (8):947-959.

Moya R, Bond B, Quesada-Pineda H (2014) A review of heartwood properties of *Tectona grandis* trees from fast-growth plantations. Wood Sci Technol 48(2):411-433.

Moya R, Urueña E, Salas C, Muñoz F, Espinosa O (2013) Kiln drying behavior of lumber from ten fast-growth plantation species in Costa Rica. Wood Mater Sci Eng 8:37-45.

Moya R, Aguilar D, Tenorio C, Bond B (2011) Variation of moisture content in kiln dried plantation grown lumber of *Vochysia guatemalensis*. Wood Fiber Sci 43:121-129.

Moya R, Berrocal A, Moya R, Rodriguez-Solis M, Muñoz F (2017). Effect of steam-drying treatment on moisture content, drying rate, color and drying defects in juvenile wood of *Tectona grandis* from fast-growth plantations. Drying Techn, DOI: 10.1080/07373937.2017.1280503.

Milota MR (1996) Method of measurement of bow and crook. For Prod J 41:65-68.

Murphy JT, Schindler S (2011) Globalizing development in Bolivia? Alternative networks and value-capture challenges in the wood products industry. J Econ Geogr 11: 61-85.

National Institute of Standards and Technology (NIST) 2005. Softwood lumber standard: Voluntary product standard PS 20-05. Department of Commerce, Washington, DC.

Oltean L, Teischinger A, Hansmann C (2011) Influence of low and moderate temperature kiln drying schedules on specific mechanical properties of Norway spruce wood. European J Wood Prod 69:451-457.

Pérez P, Ananias RA, Hernandez G (2007) Estudio experimental study of drying of canelo *Drimys winteri*. Maderas Cienc Tecnol 9:59-70 [In Spanish with abstract in English].

Pleschberger H, Hansman C, Müller U, Teischinger A (2013) Fracture energy approach for the identification of changes in the wood caused by the drying processes. Wood Sci Technol 47:1323-1334.

Salas C, Moya R (2014) Kiln-, solar-, and air-drying behavior of lumber of *Tectona grandis* and *Gmelina arborea* from fast-grown plantations: Moisture content, wood color, and drying defects. Drying Technol 32:301-310.

Shmulky R, Dahlen J (2007) Influence of sawing solution and pith location on warp in 2 by 4 lumber sawn from small-diameter loblolly pine stems. For Prod J 57:73-75.

Simpson W (1991) Properties of wood related to drying. Pages 11-150 *in* W Simpson, ed. Dry kiln operator's manual handbook AH-188. USDA For Serv, Forest Prod Lab, Madison, WI.

Skaar C, Siau JF (1981) Thermal diffusion of bound water in wood. Wood Sci Technol 15:102-112.

Tenorio C, Salas C, Moya R (2016) Kiln drying behavior utilizing drying rate of lumber from six fast-growth plantation species in Costa Rica. Drying Technol 34(4):443-453.

Tuk J (2007) Lumber, design and construction (1st ed.). Colegio Federado de Ingenieros y de Arquitectos de Costa Rica, San José. 235 pp [In Spanish].

Walker JCF (1993) Water in wood. Pages 68-94 *in* Primary wood processing, principles and practice. Springer Verlag, The Netherlands.

Walker JCF (2006) Drying of timber. Page 602 *in* Primary wood processing: Principles and practice (2nd ed.). Dordrecht, Springer, The Netherlands.