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Kiln drying behavior utilizing drying rate of lumber from six fast-growth plantation species in Costa Rica

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ABSTRACT

The objective was to study the effect of the drying time and moisture content variations on the drying rate during kiln drying. The moisture content is a good predictor of the variation in drying rate; to determine the drying rate, the model $DR = a * t + b$ (where DR is the drying rate, t is the drying time, and a and b are constants) was used. *Cordia alliodora*, *Dipterix panamensis*, *Hieronyma alchorneoides*, and *Vochysia ferruginea* show a unique tendency, whereas *Enterololium cyclocarpum* and *Samanea saman* showed two tendencies. Drying rate in relation to time showed that it is possible to define the various stages during drying and the inflexion points in time where a change in the drying rate occurs. Two types of tendencies are shown in the drying rate vs. time relation in *C. alliodora*, *E. cyclocarpum*, and *S. saman*, whereas three tendencies appear in *D. panamensis*, *H. alchorneoides*, *V. ferruginea*. *C. alliodora*, *E. cyclocarpum*, and *S. saman* presented only one inflexion in the drying rate, which can be maintained at an average of 24.5, 11.64, and 7.83%/day, respectively, for those species. On the other hand, *D. panamensis*, *H. alchorneoides*, and *V. ferruginea* showed two inflexions.

KEYWORDS

Dry bulb temperature; inflexion; target moisture content; wet bulb temperature

Introduction

Kiln drying is the most widely employed drying method for systematically removing water from the lumber and for reaching a target moisture content within a reasonable drying time. The majority of kiln dryers work with a specific range of temperature and relative humidity, which depend on the lumber species to be dried and on the quality and final use of the product.^[1] Lumber drying is one of the most important stages in the manufacturing processes, because it contributes to dimensional stability, workability, and compatibility of the lumber with finishes and adhesives. Drying also increases the lumber's mechanical properties and resistance to biological degradation and improves its thermal, acoustic, and electrical isolation properties.^[2,3]

Adequately performing the drying process provides a final product with the appropriate characteristics. It is important to maintain good control of all of the stages of the process with the purpose of preventing the occurrence or increase in defects,^[2,4] which not only lead to a reduction in the economic value of the lumber but also to a decrease in its properties.^[2] In addition, maintaining control of the various stages of the drying process provides better control of the drying time, which is necessary to achieve a higher economic profit.^[5]

Drying rate (the loss of moisture within a time lapse) is a variable that can positively influence the quality and duration of the drying. This parameter is affected by characteristics inherent to the lumber,^[6,7] the characteristics of the drying chamber,^[8] and the environmental conditions in the chamber (temperature, relative humidity, and wind speed) present during drying.^[6]

Several research works have been conducted on the effect of various factors on the drying rate. For example, Klitzke and Batista^[7] used the drying rate as a predictor of the drying quality of three eucalyptus species by analyzing its defects. The effect of water vaporization on the drying rate of wood has also been studied.^[9,10] However, few studies^[11] have researched the drying rate variations in relation to the drying time or the effect of a moisture content decrease on the drying rate. One of the few studies that reported these effects was conducted by Shahverdi et al.,^[11] in which the authors studied the effect of the wet bulb depressions on the drying rate of *Populus alba* lumber.

There are many studies available on the behavior during kiln drying of different tropical timber species from natural forests,^[3,12,13] but few involved research on the drying rate. The studies on the drying of lumber that comes from fast-growth forest plantations of native tropical-climate species are even more limited.^[14] For example, Moya et al.^[14] evaluated, among other

Table 1. Dosimetric parameters and age of the plantations sampled.

Species	Age (years)	Density (trees/ha)	Total height (m)	Diameter at breast height (cm)	Heartwood (%)
<i>Cordia alliodora</i>	14	439	14.6	14.0	23.4
<i>Dipteryx panamensis</i>	13	458	20.4	15.6	24.8
<i>Enterolobium cyclocarpum</i>	20	122	14.8	35.4	33.1
<i>Hieronyma alchorneoides</i>	12	332	24.8	22.8	10.3
<i>Samanea saman</i>	20	148	16.3	32.9	52.5
<i>Vochysia ferruginea</i>	8	309	16.9	25.3	25.0

parameters, the average drying rate of 10 species from fast-growth plantations in Costa Rica, including native and exotic species. This study found that the drying rate varied from 4.8 to 30.5%/day. Additionally, it was found that half of the tropical plantation species show initial moisture contents (MC_i) above 110% and that the average drying rate is positively correlated to the specific gravity of the lumber. However, these studies do not establish the effect of the moisture content variation or the drying time on the drying rate.

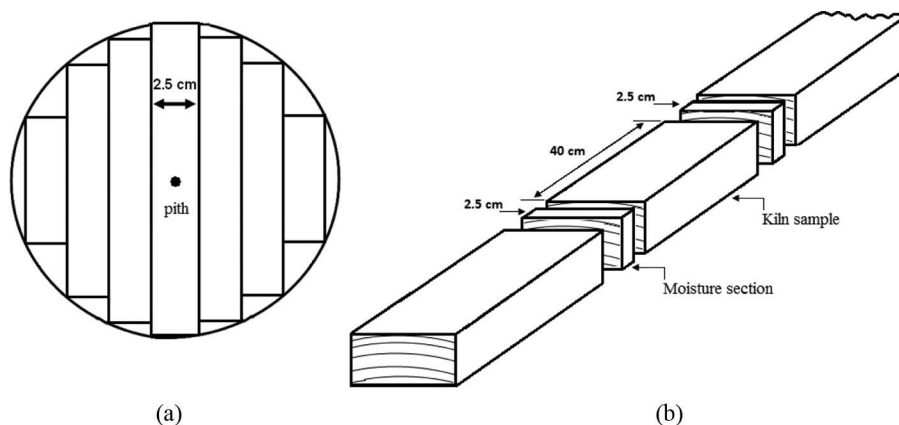
On the other hand, species from fast-growth forest plantations in Costa Rica have been studied extensively.^[15,16] At present, it is possible to find information regarding the physical, chemical, mechanical, and fuel wood properties^[17,18]; about the behavior during drying^[14,19]; as well as preservation and durability and workability of some of the native and exotic species.^[20] However, no information regarding the drying processes of native species like *C. alliodora*, *D. panamensis*, *E. cyclocarpum*, *H. alchorneoides*, *S. saman*, and *V. ferruginea*—which have been used in Costa Rica in various reforestation projects^[15,20–22]—is available, which causes a serious restriction to their use and exploitation.

Knowledge of the effects of drying time and moisture content variations on the drying rate of lumber during the kiln drying process of various fast-growth forest species in tropical climates will help improve control over the various stages of the drying process, and this will be reflected in the quality and cost-effectiveness of the drying process of the lumber. Therefore, the purpose of the present study is to determine the drying rate behavior of lumber, in addition to establishing variation models, the drying time inflexions, and the decrease in moisture content of the lumber, based on the drying rate of six species native to Costa Rica (*C. alliodora*, *D. panamensis*, *E. cyclocarpum*, *H. alchorneoides*, *S. saman*, and *V. ferruginea*), which are little known in the tropical area.

Materials and methods

Plantation description and tree sampling

Six different pure plantations located in several parts of Costa Rica were studied: *C. alliodora*, *D. panamensis*, *E. cyclocarpum*, *H. alchorneoides*, *S. saman*, and *V. ferruginea*. The initial planting density was 1,100 trees/ha (3×3 m spacing). At the time of sampling, the age varied from 9 to 20 years old and the density was at 122–575 trees/ha (Table 1). A total of nine trees per species were randomly selected for felling, including suppressed, intermediate, and dominant trees, in accordance with the methodology developed by Moya and Muñoz.^[17] Selected trees with straight trunks, normal branching, and no disease or pest symptoms were felled. Stem logs 2.5 m long were cut from the basal part to the commercial height (a stem diameter of 13.0 cm over the bark is considered as the minimum diameter for these species in Costa Rica).

**Figure 1.** (a) Sawing pattern used on each log and (b) sample obtained for determination of moisture content in the board.

Sawing pattern

The logs were sawn using a pattern commonly used by the Costa Rican furniture industry to produce 25-mm-thick boards. This sawing pattern is detailed in Moya and Muñoz^[23] and it produces boards with different grain patterns (flat sawn, quarter sawn, rift sawn, and double-rift sawn). All boards were edged (Fig. 1a).

Drying and moisture content control

Drying was conducted using an electrically heated 2-m³-capacity NARDI kiln dryer (Pilot model, Nardi Company, Italy). The drying schedules applied came from different sources (Table 2) and all species were dried separately. These schedules are commonly employed on wood from natural forests. All schedules included heating, drying, equalization, conditioning, and cooling. During the heating stage, optimal temperature conditions were achieved in a 4-h period and then maintained over a 2-h period, after which the drying stage began. The drying stage was made up of 8–10 steps until the target final moisture content (MC_f) was attained: 12% moisture content (MC) for *C. alliodora*, *E. cyclocarpum*, *H. alchorneoides*, and *V. ferruginea* and 10% MC for *D. panamensis* and *S. saman*. The equalization stage lasted 2 h from the moment all of the wood samples reached the target MC_f. A 2-h conditioning stage was programmed for the relief of the stresses that occur during the drying. Finally, the cooling stage was programmed at 25°C over a 6-h period. The equilibrium moisture content (EMC) is controlled inside the chamber by a commercial cellulose sensor with an error of 1%. It is important to clarify that different species were not compared because different drying schedules were used for the various species, making it impossible to compare drying rates among those species, because drying rates are obviously dependent of the schedule used.

For MC control, six representative samples were selected. Kiln samples 400 mm long were obtained from boards in the middle of the lumber packages and these were representative of the load.^[24] The samples were placed at different heights in the package inside the drying chamber. Before beginning drying, the MC_i was determined. It was measured from the 2.5 cm transversal section obtained from each board (Fig. 1b). MC was determined using ASTM standard D-4442-92 and it was calculated in relation to green weight.^[25] The MC value obtained was then attributed to the six representative samples. Kiln samples were weighed daily and their drying rate was established. Then the change in the schedule (step) was applied based on the MC of the six representative samples.

Table 2. Kiln schedules used for kiln drying of six plantation species native to Costa Rica.

Drying schedule	<i>Cordia alliodora</i>			<i>Dipteryx panamensis</i>			<i>Enterolobium cyclocarpum</i>			<i>Hieronyma alchorneoides</i>			<i>Samanea saman</i>			<i>Vochysia ferruginea</i>			
	T6-D2 ^c			Tropix 7 ^d			T3-E1 (modified) ^e			9 ^a C ^b			T3-E1 (modified) ^e			T2-D4 (modified) ^c			
Drying rate proposal (%/day)	15% before 30% MC and 4% after 30% MC			4%			9%			9% before 30% MC and 4% after 30% MC			9%			8% before 30% MC and 6% after 30% MC			
	DBT/WBT (°C)	E-MC (%)	MC (%)	DBT/WBT (°C)	EMC (%)	MC (%)	DBT/WBT (°C)	EMC (%)	MC (%)	DBT/WBT (°C)	EMC (%)	MC (%)	DBT/WBT (°C)	EMC (%)	MC (%)	DBT/WBT (°C)	EMC (%)	MC (%)	
Heating	49.0/47.0	19.0	—	37/—	—	—	40.0/0	—	—	40.0/—	—	—	40.0/—	—	60	35.0/—	—	—	
Drying	1	49.0/46.5	17.6	Green	40.0/37.0	15.8	Green	43.5/—	19.1	40	40.0/37.0	14.8	Green	43.5/—	60	37.5/34.0	14.3	50	
	2	49.0/46.0	16.3	40	44.0/38.0	11.5	40	43.5/41.5	17.6	40	40.0/35.0	12.5	40	43.5/41.0	19.1	60	37.5/32.0	11.9	40
	3	49.0/41.0	9.9	30	46.0/38.0	9.7	30	43.5/40.0	15.2	40	45.0/37.0	9.7	30	43.5/40.0	15.2	40	37.5/32.0	9.9	30
	4	60.0/32.0	2.9	20	48.0/38.0	8.4	20	43.5/37.5	12.0	35	50.0/40.0	7.9	25	43.5/37.5	12.0	35	43.5/32.0	7.6	25
	5	82.0/54.3	3.5	10	50.0/38.0	7.4	15	43.5/32.0	7.6	20	55.0/42.0	6.2	20	43.5/32.0	7.6	30	49.0/32.0	5.5	20
	6	—	—	—	—	—	—	49.0/32.0	5.5	20	55.0/37.0	5.0	15	49.0/32.0	5.5	25	54.5/32.0	4	15
Equalization Conditioning	7	—	—	—	—	—	54.5/32.0	4.0	10	—	—	—	54.5/32.0	4.0	20	—	—	—	
	8	—	—	—	—	—	60.0/32.0	2.0	15	—	—	—	60.0/32.0	2.0	15	—	—	—	
	9	82.0/69.0	10	50.0/42.0	10	10	71.0/43.5	3.4	10	55.0/47.0	10.0	10.0	50.0/42.0	10.0	10.0	65.5/51.5	12	12	
	82.0/64.0	13.5	50.0/46.0	14	14	50.0/46.0	14.0	14.0	55.0/51.0	15.0	15.0	50.0/46.0	14	14	65.5/61.5	14	14		

^aBoone et al.^[35]
^bJunta del Acuerdo de Cartagena.^[36]
^cSydney et al.^[37]
^dCentre de Coopération Internationale en Recherche Agronomique Pour le Développement.^[38]

Data analysis

The average, coefficient of variation, and maximum and minimum values were all determined for MC_i and MC_f . The average drying rate was calculated with the values from MC_i , MC_f , and drying time (Eq. (1)) and the experimental error is 3%.

$$\text{Average drying rate (\%/days)} = \frac{(\text{initial MC(\%)} - \text{final MC(\%)})}{\text{drying time (days)}}. \quad (1)$$

Next, the variation in MC with time was determined. For this purpose, data from the six control samples were employed. The variation in MC with time was modeled by means of an exponential or polynomial model (Eqs. (2) and (3)). The model showing the highest coefficient of determination (R^2) was selected. For *C. alliodora*, *D. panamensis*, *H. alchorneoides*, and *V. ferruginea* the selected model was exponential (Eq. (2)) and for *E. cyclocarpum* and *S. saman* the selected model was polynomial (Eq. (3)).

$$MC = a * e^{-b*t} \quad (2)$$

$$MC = at^2 + bt + c, \quad (3)$$

where MC is the moisture content (%); t is the drying time (hours); and a , b , and c are coefficients of the model. Because the drying process was done separately, each model of Eqs. (2) and (3) was calculated for each species.

Finally, the drying rate was determined for each drying measurement day, with the purpose of establishing the behavior with time of this parameter. For this, Eq. (1) was used again, but the initial and final MC values correspond to the MC obtained for each day during the whole drying process. This drying rate value was then correlated to the MC measured during the various days and a linear regression model was adjusted between these two variables. The data for *E. cyclocarpum* and *S. saman* presented two tendencies; therefore, the data were separated and the regression model was adjusted for each group of data. The drying rate and drying time were also correlated. As observed in this analysis, two to three tendencies or stages appeared

during the drying time and therefore a linear regression model was again adjusted for each stage. Once the models were adjusted, the inflexion points or the change in tendency between the variation in drying rate and time for each species were determined. Likewise, by means of Eq. (1), the average drying rate observed in the various drying stages established by the inflexion points was determined; the difference was that the initial and final MC values correspond to the MC shown by the wood at the beginning and the end of the stages found.

Results

Moisture contents and drying time

For *C. alliodora*, *E. cyclocarpum*, *H. alchorneoides*, and *V. ferruginea* the MC_i was over 100% (water content is greater than the oven-dried weight of wood), whereas for *D. panamensis* and *S. saman* it was less than 100% (Table 3). Almost all of the species showed a coefficient of variation (CV) greater than 20% in the MC_i values, with the exception of *E. cyclocarpum* (9.6%) and *S. saman* (13.6%). Concerning the MC_f , it was found that, among the species with a target MC of 10%, the value was 11.9% for *D. panamensis* and 10.9% for *S. saman*. For the rest of the species with a target MC of 12%, the MC_f varied from 9.7 to 12.4% (Table 3). As before, the CV of the MC_f was high and showed a variation greater than 20% for *D. panamensis*, *E. cyclocarpum*, *S. saman*, and *V. ferruginea*, whereas for *C. alliodora* and *H. alchorneoides* it was less than 20%.

Regarding the drying time, *E. cyclocarpum* was the species with the longest drying time (447 h), whereas *C. alliodora* was the species with the shortest drying time (168 h). The remaining species (*D. panamensis*, *H. alchorneoides*, *S. saman*, and *V. ferruginea*) showed drying times greater than 200 h but less than 400 h (Table 3). Concerning the average drying rate, *C. alliodora* was the species with the highest drying rate and *D. panamensis* was the species with the lowest drying rate (Table 3). *V. ferruginea* showed a high drying rate as well, greater than 12%/h, whereas the rest of the species (*E. cyclocarpum*, *H. alchorneoides*, and *S. saman*) showed values below 10%/h.

Table 3. Drying parameters of 25-mm-thick boards from six plantation species native to Costa Rica.^a

Species	Specific gravity	Initial moisture content (%)	Final moisture content (%)	Drying time (h)	Drying rate (%/day)
<i>Cordia alliodora</i>	0.39	165.8 (32.1) [107.9–250.8]	11.5 (9.7) [9.6–12.7]	168	21.6
<i>Dipteryx panamensis</i>	0.62	53.1 (21.9) [41.1–74.7]	11.9 (26.7) [7.1–16.1]	264	3.8
<i>Enterolobium cyclocarpum</i>	0.35	167.4 (9.6) [147.8–185.5]	9.7 (34.3) [5.7–14.2]	447	8.4
<i>Hieronyma alchorneoides</i>	0.50	111.6 (23.6) [82.3–152.7]	9.5 (7.7) [8.6–10.4]	254	9.6
<i>Samanea saman</i>	0.49	96.5 (13.6) [80.8–119.7]	10.9 (22.6) [6.3–12.7]	238	8.6
<i>Vochysia ferruginea</i>	0.37	183.5 (24.4) [118.9–238.3]	12.4 (26.9) [8.9–17.4]	319	12.9

^aValues in parentheses represent coefficients of variation, and values in brackets represent the minimum and maximum values.

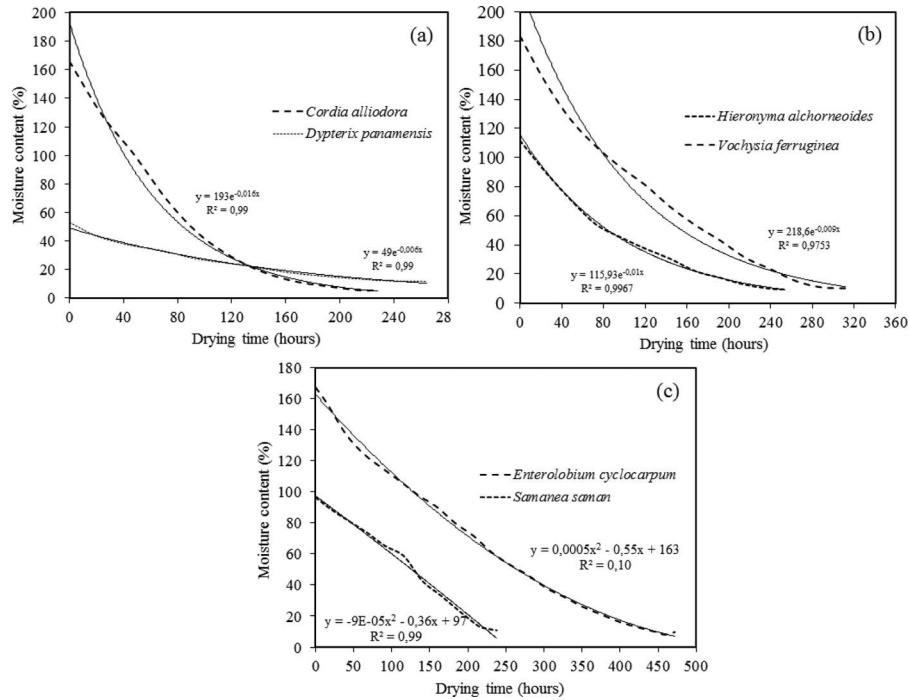


Figure 2. Variation in moisture content during drying: (a), (b) exponential model and (c) polynomial model.

Figure 2 presents the variation with time of the MC for the lumber. The MC was mathematically modeled based on the drying time by means of an exponential equation ($MC = a * e^{-b*t}$, where t is the drying time and a and b are constants that were calculated for each species) for *C. alliodora*, *D. panamensis*, *H. alchorneoides*, and *V. ferruginea* (Figs. 2a, 2b, 2d, and 2f), whereas for *E. cyclocarpum* and *S. saman* (Figs. 2c and 2e) the mathematical model employed was a quadratic polynomial ($MC = a * t^2 + b * t + c$, where t is the drying time and a , b , and c are constants). Almost all of the species (*C. alliodora*, *E. cyclocarpum*, *H. alchorneoides*, and *S. saman*) showed an R^2 greater than 90%, whereas *D. panamensis* and *V. ferruginea* showed an R^2 of 85 and 88% respectively.

Drying rate vs. moisture content

Figure 3 shows the relation between the drying rate and MC. For *C. alliodora*, *D. panamensis*, *H. alchorneoides*, and *V. ferruginea* the relation was linear (drying rate $= a * t + c$, where t is the drying time and a is a constant), showing a decrease in the drying rate as the MC decreases. In *H. alchorneoides* and *V. ferruginea* the R^2 is greater than 70% (Figs. 3d and 3f), whereas a greater dispersion is observed in *C. alliodora* and *D. panamensis*, where R^2 is 62 and 59%, respectively (Figs. 3a and 3b). *E. cyclocarpum* and *S. saman* also showed a linear relation between the drying rate and MC; however, two types of tendencies were observed. For

E. cyclocarpum, with MC less than 80% ($R^2 = 63\%$), the value of the constant drying rate in relation to the MC (RCMC, %/day-MC) is lower than that obtained when the MC exceeds 80%, with an R^2 of 69% (Fig. 3c). In *S. saman*, when the MC is lower than 40%, the value of RCMC (%/day-MC) is greater ($R^2 = 65\%$) than that observed for MCs above 40% ($R^2 = 32\%$; Fig. 3e).

An important aspect to highlight in *C. alliodora*, *E. cyclocarpum*, *H. alchorneoides*, and *V. ferruginea* is that the tendency that appeared in the drying rate when the MCs are greater than 20% does not appear when the MC is lower than 20%, which corresponds to drying rates under 5%/day. In addition, low dispersion of the drying rate values is observed when the MC decreases below 20% (Figs. 3a, 3c, 3d, and 3f).

Drying rate vs. drying time

A decrease in drying rate with drying time was observed (Fig. 4). However, two different stages were determined in *C. alliodora*, *E. cyclocarpum*, and *S. saman* (Figs. 4a, 4c, and 4e), whereas three stages were determined for *D. panamensis*, *H. alchorneoides*, and *V. ferruginea* (Figs. 4b, 4d, and 4f). In *C. alliodora* and *E. cyclocarpum*, for up to 144 and 159 h, respectively (Figs. 4a and 4c), the constant drying rate in relation to the drying time (RCDT) (%/day-h) is greater than the RCDT value observed for subsequent drying times. Nevertheless, for this first stage (from the beginning until 144 and 159 h for *C. alliodora* and *E. cyclocarpum*, respectively) the

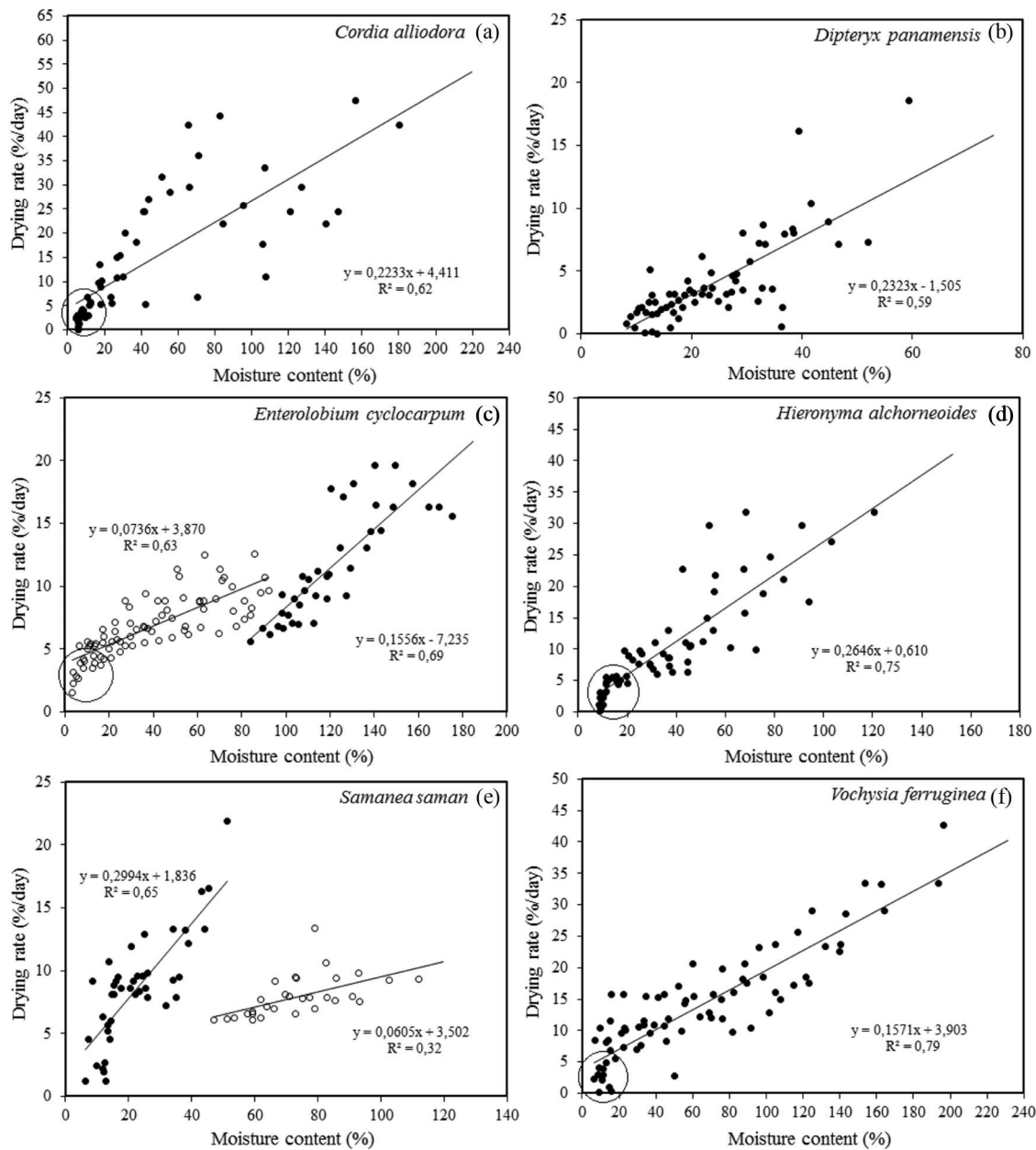


Figure 3. Variation in drying rate with moisture content for six plantation species native to Costa Rica.

R^2 is lower than that obtained for the stage subsequent to the aforementioned times (Figs. 4a and 4c). Contrariwise, in *S. saman*, for drying times less than 116 h, the RCDT value (%/day-h) was less than that obtained for drying times greater than 116 h, whereas the behavior of the R^2 was the same as with the two previous species (Fig. 4e).

With respect to the species in which three stages appeared (*D. panamensis*, *H. alchorneoides*, and *V. ferruginea*), the following were observed: (1) a first stage takes place from the beginning of drying until 68, 73, and 96 h for *D. panamensis*, *H. alchorneoides*, and *V. ferruginea*, respectively, in which higher RCDT

are obtained, with R^2 of 45, 7, and 56%, respectively; (2) in the stage between the previous times and 163, 168, and 216 h, respectively, more stable or constant RCDT was observed, with R^2 of 19, 9, and 4%, respectively; (3) with drying times greater than 163, 168, and 216 h, respectively, a behavior similar to that of the first stage is observed, where the drying rate decreases as the drying time increases. However, the decrease in RCDT for the third stage is lower (Figs. 4b, 4d, and 4f).

The results presented previously make it possible to establish points of inflexion in the variation in drying rate in relation to time. In *C. alliodora*, *E. cyclocarpum*,

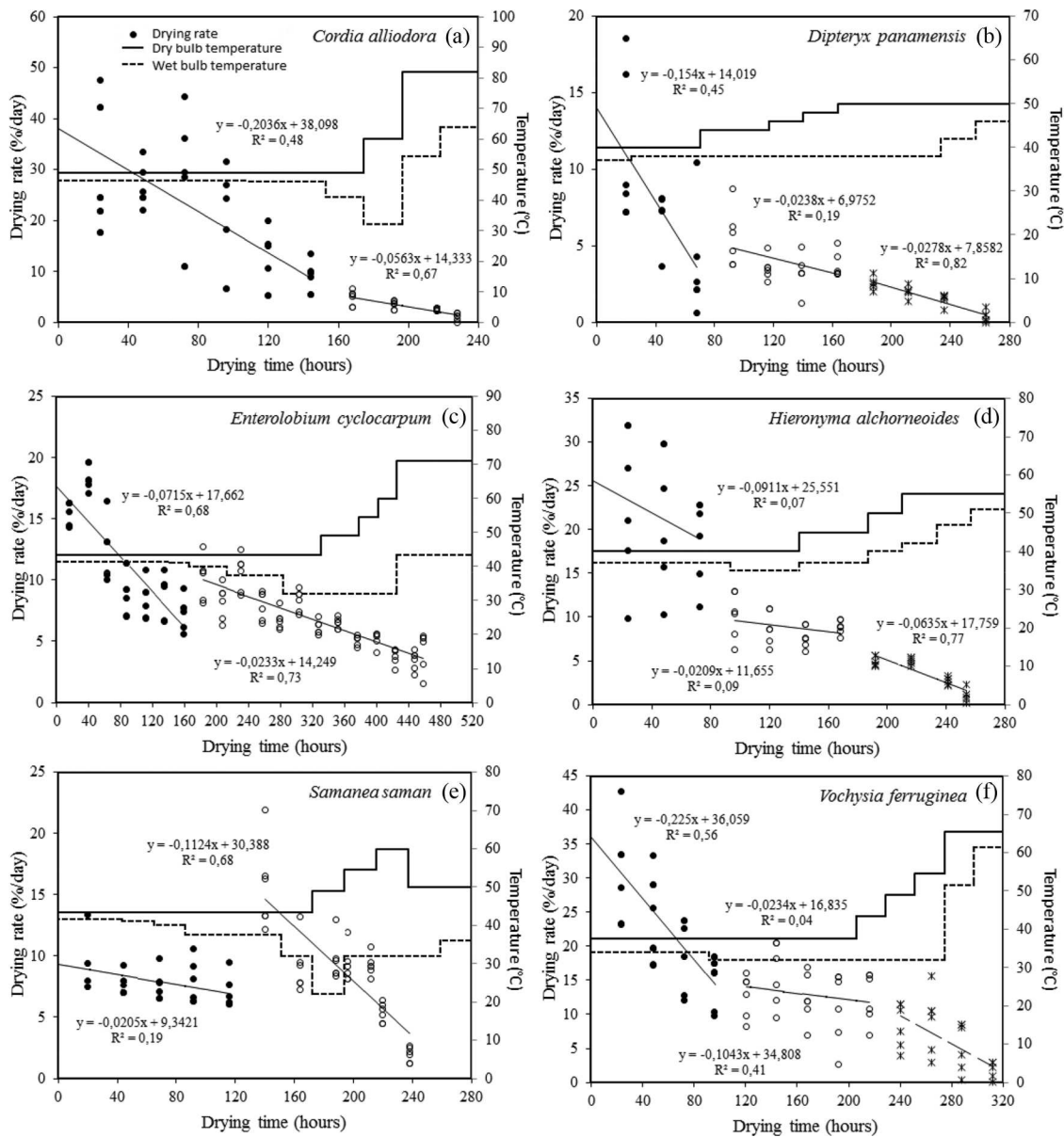


Figure 4. Variation in drying rate in relation to drying time for six plantation species native to Costa Rica.

and *S. saman*, for which two stages during drying were defined, the point of inflexion occurs at 144, 159, and 116h, respectively. For *D. panamensis*, *H. alchorneoides*, and *V. ferruginea*, for which three stages of drying are defined, the first inflexion occurs

at 68, 73, and 96h after drying began, whereas the second point of inflexion takes place at 163, 168, and 216h, respectively. The MC for each species at the points of inflexion and the drying rate for each stage of drying are shown in Table 4.

Table 4. Drying time, moisture content, and drying rate at the inflexion point of the gradient of variation in drying rate in relation to drying time for six plantation species native to Costa Rica.

Species	Point 1		Point 2		Drying rate (%/day)		
	Time (h)	Moisture content (%)	Time (h)	Moisture content (%)	Stage 1	Stage 2	Stage 3
<i>Cordia alliodora</i>	144	18.0			24.5	3.6	
<i>Dipteryx panamensis</i>	68	33.5	163	17.8	7.0	4.1	1.4
<i>Enterolobium cyclocarpum</i>	159	90.3			11.6	6.6	
<i>Hieronyma alchorneoides</i>	73	54.1	168	22.0	18.9	8.1	3.5
<i>Samanea saman</i>	116	58.6			7.8	9.4	
<i>Vochysia ferruginea</i>	96	93.6	216	31.1	22.5	12.5	5.2

Analysis of results

Moisture contents and drying times

The MC_i obtained in this study varied from 53.1 to 183.5%, similar to values obtained for other species from forest plantations in Costa Rica.^[14,17,26,27] However, in those specific studies, the studied plants showed coefficients of variation lower than 18%, in contrast to the coefficients of variation obtained in this study, most of which were greater than 20% (Table 3).

The high value found for the coefficient of variation of the studied species can be explained by the fact that the lumber samples were extracted from different parts of the tree. It has been noted that the variations in MC_i are determined by characteristics inherent to each species (such as the specific gravity and the sapwood–heartwood relation) and to the specific tree section (such as the distance from the board to the pith and the height of the tree).^[23,26–28]

The target MC for the species was 10% (*D. panamensis* and *S. saman*) and 12% (*C. alliodora*, *E. cyclocarpum*, *H. alchorneoides*, and *V. ferruginea*); however, considerable variations were observed (Table 3), despite the equalization and conditioning stages that were applied at the end of drying. These variations in MC_f of the species and in the target MC can be attributed to inadequate equalization and conditioning stages with time. On the other hand, these differences can also be attributed to differences between the moisture measured with electrical humidity gauges and the moisture estimated by employing the humidity control samples. In this study, the control of drying was done by employing humidity control samples. For the equalization and conditioning stages, however, because the time available was limited, it was necessary to use the electrical humidity gauges of the dryer. These electrical humidity gauges used in kiln dryers can be affected by factors in addition to the MC—extractives, for example^[29]—that appear in high values in tropical species.^[30] Furthermore, electrical humidity gauges are not precise for moisture contents over the fiber saturation point and, below this point, they require temperature adjustments, which renders them inappropriate for full control of the drying.^[31] A practical effect of the high variation in MC_f is that lumber with this high MC_f variation could be acceptable for use in construction but certainly not for value-added products.

Concerning the drying time, it was possible to observe differences among the species (Table 3). Langrish^[32] noted that species with high specific gravity and high percentages of heartwood require longer drying times compared to species with low specific gravity and low percentages of heartwood; nevertheless, the results from the present study differ

from those. It was not possible to establish a relation with drying time between the specific gravity and the heartwood percentage, with the exception of *E. cyclocarpum*, which is the species with the second to highest heartwood percentage and the one with the longest drying time, although it possesses the lowest specific gravity (Table 3). This means that the heartwood of *E. cyclocarpum* does influence the drying time.

The average drying rate variation found (from 3.84 to 21.6%/day, Table 3) for the six species had lower values than those obtained for the 10 forest plantation species in Costa Rica.^[14] The variation obtained in this parameter for the studied species as well as other species is attributed to the characteristics inherent to the wood,^[6,7] the characteristics of the drying chamber,^[8] and the conditions (temperature, relative humidity, and wind speed) used during drying.^[6] It is important to clarify that although the drying rates were compared between species, this situation could vary because the drying rates are obviously different for each drying schedule used.

Drying rate vs. moisture content

The coefficients of correlation (R^2) over 50% in the linear models between the drying rate and the MC for the six species (Fig. 3) indicate that the MC of the lumber can be used as a predictor of the variation in drying rate of these species. These low coefficients can be explained by the large variation in moisture content of kiln samples. For five of the species, with the exception of *E. cyclocarpum*, the coefficient of variation varied from 13.6 to 32.1% (Table 3), thus showing high moisture variation, and therefore differences in drying rate were found, decreasing the R^2 of the mathematical model. However, the tendencies found for *C. alliodora*, *D. panamensis*, *H. alchorneoides*, and *V. ferruginea* differed from those found for *E. cyclocarpum* and *S. saman* (Fig. 3). In the first four species, the drying rate decreased steadily as the MC decreased; that is, the RCMC was the same during the whole distribution of the MC.

Regarding *E. cyclocarpum* and *S. saman*, two linear tendencies are observed; that is, two RCMC appear (Figs. 3c and 3e). These two tendencies can be explained by the high percentage of heartwood present in these species (33.14 and 52.51%, respectively, when measured as a log) but, once the lumber is sawn, this percentage increases due to the removal of the ribs, which contain a high amount of sapwood, resulting in boards with high percentages of heartwood, as can be seen in Figs. 5c and 5e. This differs from the four previous



Figure 5. Heartwood presence (arrows) in dried lumber from six plantation species native to Costa Rica.

species, which show little to no heartwood in the sawn lumber (Figs. 5a, 5b, 5d, and 5f). Unlike heartwood, sapwood is permeable to liquids due to its lack of extractives in the intercellular spaces, thus allowing better and faster fluid movement than in the heartwood.^[33] The latter is less permeable because several chemical substances (extractives) tend to deposit in its cells, making fluid conduction through heartwood very slow.^[6,32,34] Consequently, the drying rate in *E. cyclocarpum* and *S. saman* could be affected by the transition between the sapwood and the heartwood, because water movement in heartwood is slower, causing changes in the drying rate tendency of these species (Figs. 3c and 3e).

Drying rate vs. drying time

Regarding the drying rate vs. drying time relation, two tendencies were observed for *C. alliodora*, *E. cyclocarpum*, and *S. saman* and three for *D. panamensis*, *H. alchorneoides*, and *V. ferruginea* (Fig. 4). This can be explained again by the limited water movement in the lumber, which is influenced by MC_b , the anatomical characteristics, and the heartwood–sapwood proportion of each species.^[33] In *E. cyclocarpum* and *S. saman* it is possible that the points of inflexion at 93.63 and 54.11% MC (Figs. 4c and 4e, Table 3), respectively, are a result of the differentiation between sapwood and heartwood (Fig. 5). For *C. alliodora*, the point of inflexion appears at an MC lower than 18%, which could be related to the water movement, because this species showed a lower heartwood percentage (Fig. 4a, Table 4).

In *D. panamensis*, *H. alchorneoides*, and *V. ferruginea*, in which three stages were defined in the drying rate in relation to time (Figs. 4b, 4d, and 4f), the first point of inflexion occurs at an MC greater than 50% (33.50, 54.11, and 93.63%, respectively), which could be related to the variations in water movement in the sapwood lumber. The second point of inflexion occurs at MC lower than 30% (17.81, 22.03, and 31.14%, respectively), which again indicates the influence of bound water movement on the drying rate (Figs. 4b, 4d, and 4f).

Modeling of the variation in drying rate based on time (Fig. 4) allows determination of the various stages that appear during drying as well as the points of inflexion in time for the drying rate. These points of inflexion result from changes in the dry bulb and wet bulb temperatures (DBT and WBT, respectively), which cause various bulb depressions during drying of lumber (Fig. 4). The first inflexion, in the majority of cases, corresponds to the first change in DBT and WBT or the first step of drying. The times of the first inflexion (indicated in Table 4 for the six species) correspond to a decrease in WBT for all of the species (Fig. 4), with the exception of *C. alliodora*, in which an increase in DBT occurs instead (Fig. 4).

For the species that showed one inflexion only, *C. alliodora*, *E. cyclocarpum*, and *S. saman*, this seems to indicate that the drying rate can be maintained at an average of 24.5, 11.64, and 7.83%/day, respectively, until the MC reaches the value indicated in the first step of the programs shown in Table 2, which means 45, 40,

and 60%, respectively. After this MC has been reached, the changes in DBT and WBT conditions will begin to produce a constant decrease in the drying rate with time (Figs. 4a, 4c, and 4e). To control the drying process, however, the average for that decrease could be employed: 3.6%/day for *C. alliodora*, 6.58%/day for *E. cyclocarpum*, and 9.40%/day for *S. saman*.

For *D. panamensis*, *H. alchorneoides*, and *V. ferruginea*, which showed two inflexions during drying, the drying rate can be maintained at the average indicated in Table 4 until the MC indicated in the first stage of the drying program (Table 2) is achieved, specifically, 40% for the first two species and 50% for *V. ferruginea*. In contrast to the previous species, these three species present a time period at which the drying rate is slightly constant before the drying rate starts to decrease again with time (Figs. 4b, 4d, and 4f). The average drying rates recommended for these species are those indicated in stage 2 of Table 4. This intermediate phase in the drying rate is not related to any strong change in DBT or WBT conditions when drying (Figs. 4b, 4d, and 4f); therefore, the change is probably more influenced by the movement of released water inside the lumber, because this period occurs before the fiber saturation point. Finally, in the third stage, the drying rate again decreases with time and it is advisable to maintain the drying rate at 1.44%/day in *D. panamensis*, 3.51%/day in *H. alchorneoides*, and 5.24%/day in *V. ferruginea* (Table 4).

An important aspect to highlight in relation to the various drying rates proposed for each species (Table 2) is that these are very different from the real rates found for the various species (Table 4). One factor that contributes to this is the high MC_i characteristic of tropical species (greater than 100%) such as *C. alliodora*, *E. cyclocarpum*, *H. alchorneoides*, and *V. ferruginea*, which make it impossible to maintain those rates during the whole drying process. This suggests the need to perform more studies involving the relation between the drying rate and drying time for tropical plantation species with high MC_i .

Conclusions

The MC_i for the six species varied from 53.1 to 183.5%. The MC_f varied 2% in relation to the average target defined for the species. The majority of species showed a coefficient of variation greater than 20% in the MC_i and MC_f values.

The MC of the lumber is a good predictor of the variation of the drying rate and it can be modeled by the relation drying rate = $a * t + b$ (where t is the drying time and a and b are constants), with R^2 greater than 50%. *C. alliodora*, *D. panamensis*, *H. alchorneoides*,

and *V. ferruginea* showed a unique tendency, whereas *E. cyclocarpum* and *S. saman* showed two tendencies, in which the point of change was at 80 and 40% MC, respectively. Moreover, it was observed that for MC lower than 20% (*C. alliodora*, *E. cyclocarpum*, *H. alchorneoides*, and *V. ferruginea*) the previously described model is hardly applicable.

Modeling of the variation in drying rate in relation to time made it possible to establish different stages that appear in the drying of each species, as well as establish the points of inflexion in time where a change in the drying rate occurs. Two types of tendencies are shown in the drying rate vs. time relation in *C. alliodora*, *E. cyclocarpum*, and *S. saman*, whereas three tendencies appeared in *D. panamensis*, *H. alchorneoides*, and *V. ferruginea*. *C. alliodora*, *E. cyclocarpum*, and *S. saman* showed only one inflexion in the drying rate, whereas *D. panamensis*, *H. alchorneoides*, and *V. ferruginea* showed two inflexions.

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