An Assessment of the Carbon Footprint of Tropical Hardwood Sawn Timber Production

Jegatheswaran Ratnasingam,[a] Geetha Ramasamy,[a,]* Weiching Toong,[a]
Abdul Latib Senin, [a] Mohd Ashadie Kusno,[a] and Neelakandan Muttiah [b]

The demand for sawn timber throughout the world is steady, as wood is one of the most important raw materials available to mankind. Yet, the production of sawn timber through sawmilling activities causes environmental issues and is perceived to have a potential effect on global warming. Studies on this aspect is very limited, especially for tropical hardwoods. The intention for this study was to evaluate the carbon footprint of manufacturing sawn timber from round wood using a gate-to-gate life cycle approach. The functional unit used was 1 m^3 of rough green sawn timber. Primary data on yield and energy consumption during the sawmilling process were collected on a monthly basis throughout 2013. Greenhouse gas emissions, which include CO_2, CH_4, and N_2O, were determined using emission factors. The carbon footprint was then calculated on the basis of the equivalency factor, described as CO_2-eq. The carbon footprint assessment shows a result of 499 kg CO_2-eq/m^3 and 696 kg CO_2-eq/m^3 for Light Red Meranti and Dark Red Meranti sawn timber, respectively. The results showed that there were no significant differences in the carbon footprint of Light Red Meranti and Dark Red Meranti sawn timber production.

Keywords: Carbon footprint; Life cycle; Sawmilling; Meranti; Energy consumption

*Contact information: a: Universiti Putra Malaysia, Faculty of Forestry, 43400 UPM, Serdang, Selangor, Malaysia; b: Centre for Energy Sustainability, Energy Consultants Pte. Ltd., No. 8-Block 2 Selegie Centre, Brass Road, 54360 Singapore; *Corresponding author: gita209@gmail.com*

LIST OF ACRONYMS

SFM	Sustainable forest management
ITTO	International Tropical Timber Organization
LCA	Life cycle assessment
CO_2-eq	Carbon dioxide equivalent
CO_2	Carbon dioxide
CH_4	Methane
N_2O	Nitrous oxide
IPCC	International Panel on Climate Change
CML	Centre of Environmental Science, Leiden University
HHV	Higher heating value

INTRODUCTION

Logs for sawn timber production in Malaysia are usually obtained from the natural forest, forest plantations, or imported logs. According to the National Timber Policy (2009) report, tropical hardwood logs obtained from the natural forest are more consistent in supply for the sawmill industry compared with logs from forest plantations and imported supplies. The forest in Peninsular Malaysia is not replanted, and the logged forest is usually allowed to self-regenerate. Since the late 1990s, enrichment planting in the logged-over forest in Peninsular Malaysia was halted (Ratnasingam and Ioras 2006). It was felt that the regeneration potential of the logged-over forest was sufficient to improve the stocking density until the next harvesting rotation. Inevitably, this also significantly reduced the cost of forest management. The natural forest in the country is managed according to a sustainable forest management (SFM) scheme, as advocated by the International Tropical Timber Organization (ITTO) for best practices in forest management (Blaser *et al*. 2011). Natural forest is described as forest stands in which tree species generate instinctively. The natural forest in Malaysia has been sustainably managed for more than three decades (Thang 1987) and is capable of producing high-quality saw logs in a sustainable manner. Common high-quality saw logs produced from the natural forest are usually tree species that belong to the family Dipterocarpaceae. Countless species from the genera *Anisoptera*, *Dipterocarpus*, *Dyobalanops*, *Hopea*, *Shorea*, and *Parashorea* yield high-quality sawn timber that has a high demand in the world market (Blaser *et al*. 2011).

The steady demand for tropical sawn timber, both in the local and international markets, has increased the supply pressure for saw logs from the natural forest. The large number of sawmills are increasingly facing saw log deficits. The sawmilling sector in Malaysia started in the early 1900s primarily for domestic consumption. The industry developed further into a large manufacturing sector after independence in 1957. It is no surprise that the sawmilling industry in Malaysia dominated the wood-based sector for a long time (Woon and Norini 2002). In line with SFM practices in the natural forest, the supply of saw logs from the natural forest has been maintained at 8 million m^3 per year to ensure sustainable production. This has brought about added pressure on existing sawmilling capacity, which has inevitably resulted in the closure of several sawmills in recent years (Fig. 1) (National Timber Policy 2009).

A sufficient supply of saw logs is essential for a competitive sawmilling industry. In the case of Malaysia, the natural forest area in Peninsular Malaysia is much smaller than that available in East Malaysia (Table 1).

Table 1. Forested Area in Malaysia

Year	Peninsular Malaysia	East Malaysia		Total	Production Forest in Peninsular Malaysia	Production Forest
		Sabah	Sarawak			
	million hectares					(%)
2000	5.94	4.42	8.20	18.56	2.76	46.46
2005	5.87	4.36	8.07	18.30	2.80	47.70
2010	5.86	4.30	7.83	17.99	2.83	48.29
2011	5.81	4.43	7.82	17.98	2.10	36.14
2012	5.79	4.43	7.81	18.03	2.10	36.27
2013	5.79	4.43	7.81	18.03	2.10	36.27
Sources: Statistics on Commodities 2011 (2012) and Statistics on Commodities 2013 (2014)						

As a result, the sawmilling capacity in Peninsular Malaysia has decreased over the years. The main factors for the decline of the sawmilling capacity in Peninsular Malaysia are as follows: (1) reduced supply of saw logs from the natural forest, and (2) excess capacity in sawmilling sector (Fig. 2) production.

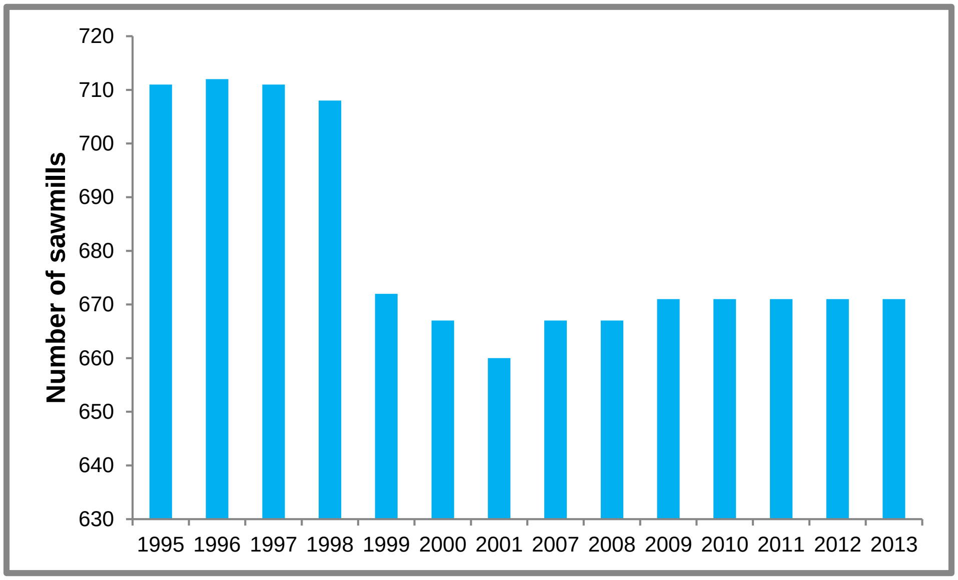

Fig. 1. Number of sawmills in Peninsular Malaysia (Source: Statistics on Commodities 2011 (2012) and Statistics on Commodities 2013 (2014))

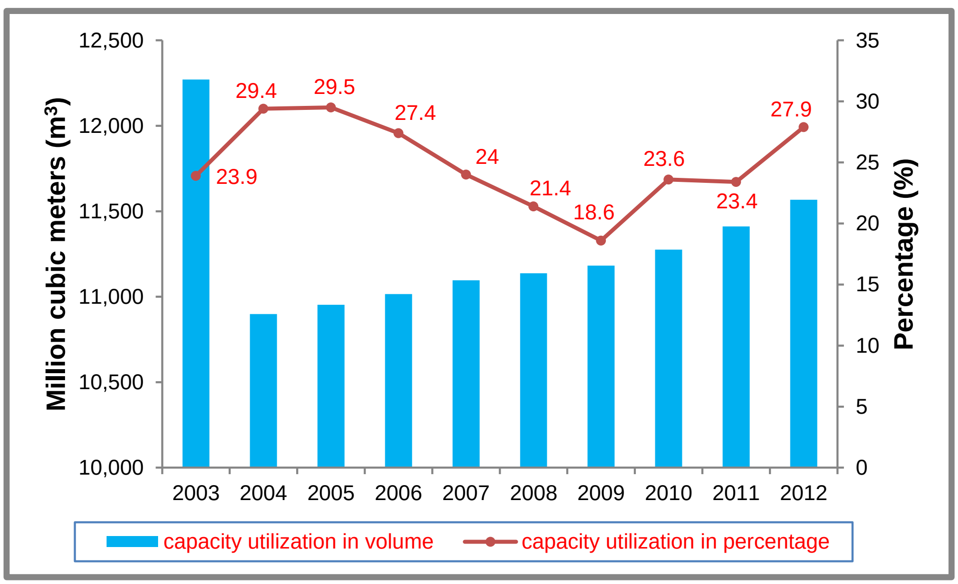

Fig. 2. Sawmilling capacity utilization in Peninsular Malaysia (Source: Malaysian Timber Industry Board 2014)

The current harvesting operation in Peninsular Malaysia is close to the 1,000 m elevation, where the natural forest is predominantly of the hill forest type. This forest type has several tree species belonging to the genus *Shorea* of the Dipterocarpaceae family, which produces sawn timber that has a high demand in the world market (National Timber Policy 2009). The most common *Shorea* species produced from this forest type are the

Dark Red Meranti (*Shorea* spp.) and Light Red Meranti (*Shorea* spp.), which have a well-established commercial acceptance in the market. It has been noted that the Meranti species still dominate the primary wood-based industry in terms of saw logs and sawn timber production in Peninsular Malaysia, as shown in Table 2 (Blaser *et al*. 2011).

Table 2. Common Saw Log Species Available in Peninsular Malaysia

Species	Scientific Name	Average annual harvest (m^3)
Light Red Meranti	*Shorea* spp.	838 000
Dark Red Meranti	*Shorea* spp.	657 000
Keruing	*Dipterocarpus* spp.	562 000
Kempas	*Koompassia malaccensis*	385 000
Balau	*Shorea* spp.	218 000
Source: Blaser *et al*. (2011)		

The global demand for further processing of sawn timber into wood products is inevitable because of its characteristics as an environmentally favourable material compared with materials such as steel, plastic, and concrete (Lippke *et al.* 2004; González-García *et al*. 2012; Bergman *et al.* 2014). Khairul Izzudin *et al.* (2014) noted that sawn timber is important in Malaysia as a raw material for the construction, furniture, and furniture components sectors. Although wood products have been recognized as an important potential climate change mitigation agent (Tellnes *et al*. 2012), the use of wood products in Malaysia is very much focused on its economic and availability factors, rather than its environmental benefits. In this context, studies on the environmental values of wood and wood products are limited in this country (Chen 2003).

Several studies have revealed that the sawmilling sector triggers environmental impacts (Kinjo *et al.* 2005; Eshun *et al.* 2010; Bergman and Bowe 2012). The consumption of resources, particularly wood material, energy, and water, during the production of sawn timber contributes to environmental burdens and impacts. The known environmental impacts that have been assessed from sawmilling activities include global warming, acidification, ozone depletion, human toxicity, photochemical ozone formation, and eutrophication potential (Kinjo *et al.* 2005; Puettmann *et al.* 2010; Tellnes *et al.* 2012). Among all the listed environmental impacts, Tellnes *et al.* (2012) suggested that global warming potentials seem to have the highest profile because of the release of CO_2 in large quantities. This observation is supported by other researchers who have carried out studies in different fields (Röös *et al.* 2010; Wu *et al.* 2012; Muñoz *et al.* 2013; Gemechu *et al.* 2013). Boguski (2010) described the carbon footprint as the calculation and conversion of the amount of greenhouse gases (GHGs) caused by a particular activity into carbon dioxide equivalents (CO_2-eq).

Therefore, a preliminary study of the carbon footprint as a result of sawn timber production in Peninsular Malaysia was undertaken using the life cycle assessment (LCA) approach. In this study, the GHG emissions from each activity within the sawn timber product system boundary were converted to CO_2-eq to determine the carbon footprint attributable to the sawn timber production process. The findings of this study will provide benchmark values for the carbon footprint of the sawmilling sector, which is considered the oldest wood processing industry in Malaysia.

EXPERIMENTAL

Because of resource consumption during the production of rough green sawn timber, the carbon footprint was evaluated in accordance with the LCA methodological framework. LCA is an analytical tool that evaluates the environmental profile on the basis of resource consumption (material, energy, and water) and releases into the environment (wood wastes, airborne emission, and waterborne emission). In Malaysia, the concept of LCA is still not widely used, especially in the wood-based industries (Khairul Izzuudin *et al.* 2014). Therefore, a study on the carbon footprint of the Malaysian sawmilling sector was much needed, and this study attempts to do so using the revised ISO 14040 standard for framework and guidance (2006) and the ISO 14044 standard for technical requirements and guidelines (2006).

Scope of the Study

This study analyzed the carbon footprint associated with sawn timber production from gate to gate, which considers the logs from their entry to the sawmill through the production of rough green sawn timber. Off-road transportation activity within the sawmill was included as part of this study. The study of the carbon footprint assessment was carried out in accordance with the study by Zhang *et al.* (2015), in which a flow chart was developed to identify the system's boundary and priorities, followed by data collection for analysis, the final calculation of the results, and the uncertainty analysis.

Description of the System in the Study

The assessment of the carbon footprint was carried out in the largest sawmill in Peninsular Malaysia. The investigation concentrated on saw logs of the *Shorea* species, in view of the fact that these species are the most predominant saw logs available for exploitation for sawn timber production in Peninsular Malaysia. In relation to this fact, the sawmill chosen for this study had a consistent supply of Light Red Meranti (*Shorea* spp.) and Dark Red Meranti (*Shorea* spp.) all year round. The carbon footprint for the Light Red Meranti and Dark Red Meranti sawn timber was identified during the sawing processes of the saw logs. The sawmilling process flow for rough green sawn timber production is divided into four main sub-processes. The saw logs were initially cut into flitches in the primary breakdown process. These flitches were then moved on the conveyor to the next cutting process. The flitches were re-sawn into sawn timber in the secondary breakdown process. The quality control process ensured that all defects found on the sawn timber were cross-cut and removed. This rough green sawn timber was then sorted and packaged for shipment. The off-road transportation included in the study was related to the movement of logs from the log yard to the sawmill and the movement of sawn timber for quality control activities.

System Boundary

The flow of the inputs, outputs, and environmental releases during sawn timber production was defined by the system boundaries. Two elements of the system boundaries, comprising the foreground (on-site) and background (cumulative) system boundaries, as shown in Fig. 3, were reflected to determine the carbon footprint of the sawn timber production process. The dotted line presents the foreground system boundary, showing releases to the environment from production processes. In the meantime, the background system boundary (shown as the solid line) included emissions from resource consumption.

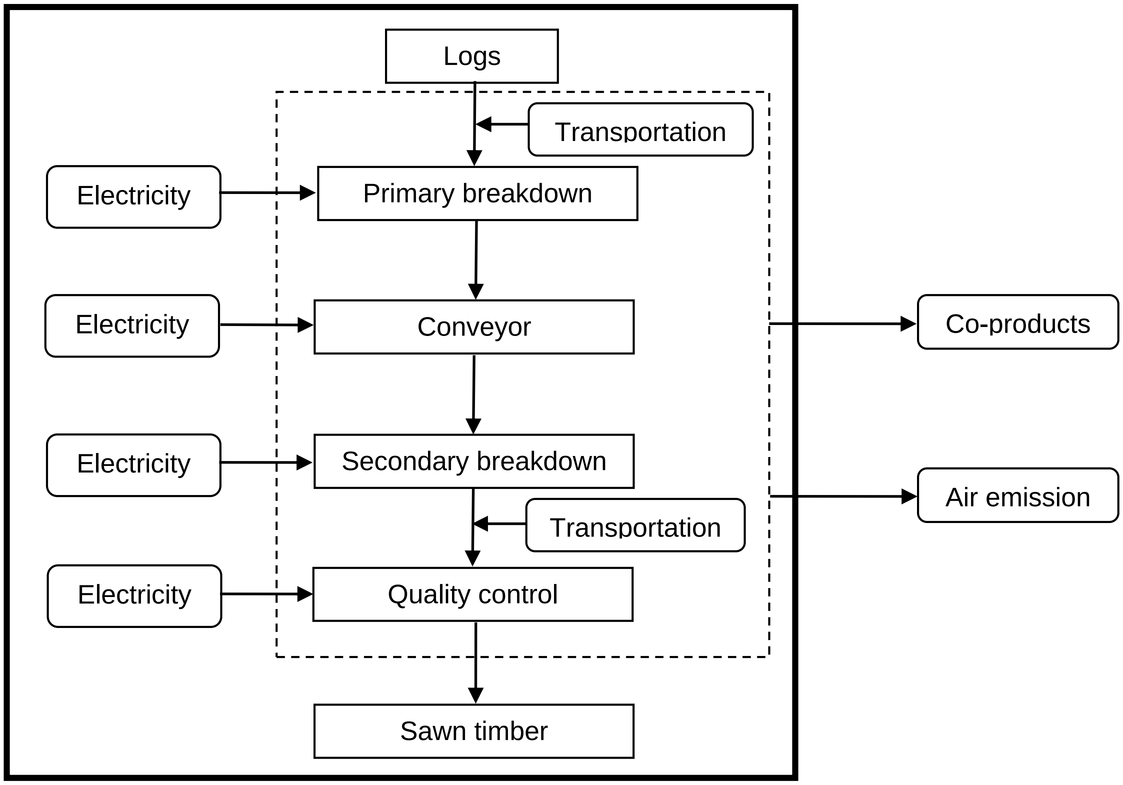

Fig. 3. Gate-to-gate system boundaries of sawn timber production

When setting the system boundaries, two main aspects were excluded from this study, which was not required in the ISO LCA protocol. These were the machinery used in the sawmill and the workforce. By excluding these components, machinery maintenance or replacement, as well as the heat and noise produced in the sawmill during the production of sawn timber, were neglected. On the other hand, the energy used by the workforce as well as the related transportation energy was also not taken into consideration.

Functional Unit

The functional unit has been described as the quantitative performance of an investigated product (Finnveden *et al.* 2009). Apart from the measurement of the studied products or processes, Gustavsson and Sathre (2011) pointed out that the functional unit performs as a reference unit. In this study, the investigated product was the rough green sawn timber of the *Shorea* species. Volume is normally used as the unit of measure for sawn timber (Milota *et al.* 2005; Bergman and Bowe 2012; Martínez-Alonso and Berdasco 2015). Therefore, the functional unit for the carbon footprint assessment in this study was standardized as per-unit volume basis for 1.0 m^3 of Light Red Meranti and Dark Red Meranti rough green sawn timber.

Data Collection

The data related to the input were collected on a monthly basis throughout the year 2013. The essentials that were taken in the carbon footprint evaluation of the sawmill were as follows:

(1) The first part of the data collection determined the flow of saw logs and the energy consumption in every stage of the sawn timber production process. The study quantified the saw logs in terms of the volume and the yield of sawn timber, as well as the production of wood waste. Meanwhile, the analysis of energy consumption was categorized into electrical energy and diesel fuel energy. Electrical energy was used to operate the sawmill machines for the conversion of saw logs into sawn timber, while diesel fuel energy was used for off-road transportation activities.

(2) Once the resource consumption was identified, the release of GHGs, which are composed of CO_2, CH_4, and N_2O, were calculated. The data used in this study consisted of activity data and emission factors. Activity data were related to the on-site measurement of the electrical energy and diesel fuel energy consumed during the sawmilling activity. In addition to this, the electricity used in the sawmill was generated off-site, from the combustion of fossil fuels in power stations. The electricity generated by the specific fossil fuel was in accordance to the data for 2013, as reported by Mahlia (2002). Coal, gas, petroleum and hydro power were specified as 20.46%, 45.95%, 1.49%, and 32.10%. The emission factor is the factor value associated with the emission of CO_2, CH_4, and N_2O. The value of the emission factor was based on the International Panel on Climate Change (IPCC) (2013). The emission of CO_2, CH_4, and N_2O was determined by multiplying the activity data by the emission factor.

(3) The carbon footprint was assessed using the Centre of Environmental Science, Leiden University (CML) guide (Guinée *et al.* 2001, updated 2015). The emission of these GHGs was translated into a carbon footprint with an equivalency factor of C_{O2}-eq. Each of the GHGs was converted into C_{O2}-eq by multiplying each of the components with the equivalency factor. The equivalency factors for CO_2, CH_4, and N_2O were 1, 25, and 298, respectively (Guinée *et al.* 2001, updated 2015).

RESULTS AND DISCUSSION

The results of the LCA study on the carbon footprint of Light Red Meranti and Dark Red Meranti sawn timber production are presented in this section. All the outputs produced are mean values on a 1-m^3 basis.

Product Yield

Rough green sawn timber is the main product of sawmilling activity. The average annual production of Light Red Meranti and Dark Red Meranti rough green sawn timber is shown in Fig. 4. 153.30 m^3 of incoming Light Red Meranti saw logs, resulted in 85.79 m^3 of rough green sawn timber. Overall, the average yield was 55.96% during the production of Light Red Meranti rough green sawn timber. On the other hand, an incoming Dark Red Meranti saw log volume of 133.16 m^3 resulted in 61.04 m^3 of rough green sawn timber, giving a yield of 45.84%.

Apart from sawn timber, the flow of saw logs in the production process also resulted in wood loss in the form of off-cuts, shavings, sawdust, and splinters. Off-cuts were sold by the studied sawmill for recovery purpose, while sawdust, splinters and shavings were sold for energy production in boilers. Hence, these wood losses were considered as co-products. Dark Red Meranti generated a slightly higher volume of co-products compared with Light Red Meranti. The differences in the proportions of co-products were 1.11, 1.08, 1.54, and 0.87 m^3 for off-cuts, shavings, sawdust, and splinters, respectively.

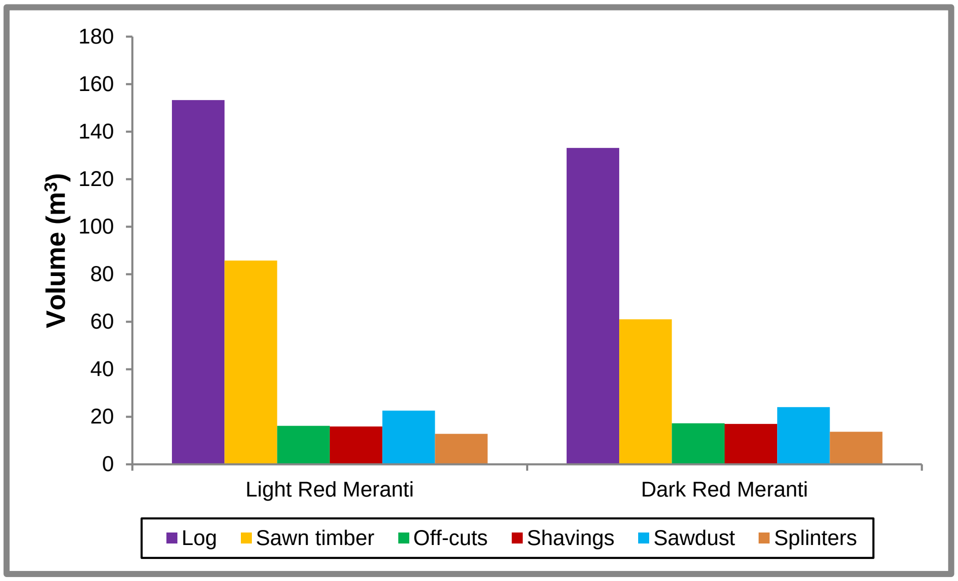

Fig. 4. The average yield of sawn timber and co-products

The conversion of logs into rough green sawn timber produced off-cuts, sawdust, splinters, and shavings. This process is known as a multi-output process (Jungmeier *et al.* 2002). As more than one product was produced in the sawmilling activity, allocation approach was taken into consideration in this study. Allocation is described as the partitioning of the environmental loads among the different products studied (Ekvall and Finnveden 2001).

Three different types of allocation approaches are used, namely consideration of all products as co-products, considering sawn timber as the main and only product, and the economic value approach (Jungmeier *et al.* 2002). The allocation approach chosen in this study was the approach which considered sawn timber as the main and only product. The sawn timber was regarded as being responsible for the environmental loads.

Energy Consumption

The sawmill studied used electricity and diesel fuel energy for converting saw logs into rough green sawn timber. Electrical energy was used to drive the motors in the primary breakdown bandmill, conveyor, secondary breakdown bandmill, and quality control unit processes during the conversion of Light Red Meranti and Dark Red Meranti saw logs into rough green sawn timber. Vigon *et al.* (1993) described the energy used to operate the sub-system processes as process energy. The study found that 30.70 and 49.10 MJ were required to produce 1 m^3 of Light Red Meranti and Dark Red Meranti rough green sawn timber, respectively (Fig. 5).

As shown in Fig. 5, the variation of electrical energy consumed by the two species were 6.19 MJ/m^3, 11.77 MJ/m^3, 0.44 MJ/m^3, and 0.006 MJ/m^3 for primary breakdown bandmill, secondary breakdown bandmill, quality control, and conveyor unit processes, respectively. It appeared that the secondary breakdown unit process consumed the highest electrical energy. The possible explanation for this can be attributed to the use of a large number of motors to operate the secondary breakdown bandmills. On the other hand, the electrical energy consumed by the conveyor could be neglected relative to the other operations. Gopalakrishnan *et al.* (2012) pointed out that conveyors normally do not use much electrical energy.

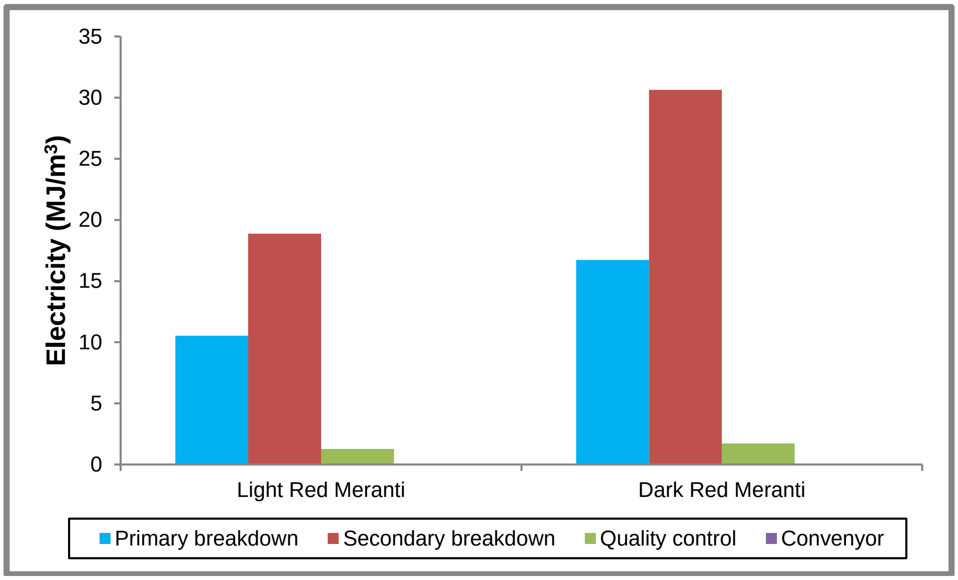

Fig. 5. Comparative energy consumption of the wood species

Diesel fuel energy was used in the sawmill for saw logs and rough green sawn timber transportation, as described by Vigon *et al.* (1993). To produce 1 m^3 of Light Red Meranti and Dark Red Meranti rough green sawn timber, 0.24 and 0.38 L of diesel fuel were used, respectively. The energy value of diesel fuel was determined using the higher heating value (HHV) approach described by Puettmann *et al.* (2010). In this context, the HHVs of diesel fuel used in this sawmill were determined to be 8.96 and 14.18 MJ/m^3 for Light Red Meranti and Dark Red Meranti, respectively.

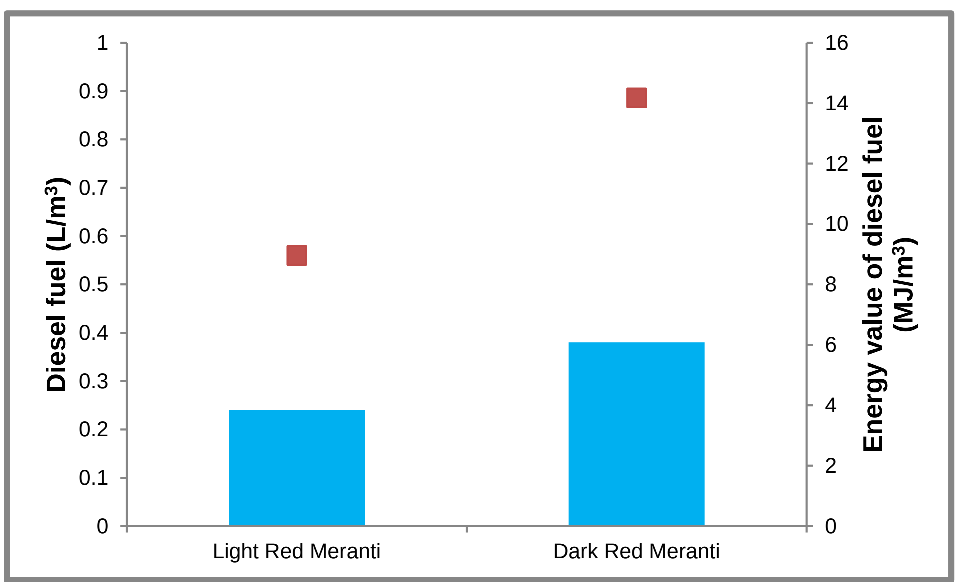

Fig. 6. Comparative diesel fuel energy consumption of the wood species

Greenhouse Gas (GHG) Emissions

Resources consumption during sawn timber production resulted in the emission of different types and quantities of certain gaseous elements to the environment. In the context of this study, the emission of GHGs gaseous, namely CO_2, CH_4, and N_2O were the only elements taken into account, as the study emphasized on the assessment of carbon footprint.

The loss of wood during the production process was accounted for as carbon loss. Nonetheless, the release of CO_2 from co-products was categorized as biogenic CO_2 (Berman *et al.* 2014). Biogenic CO_2 is well-known as being carbon-neutral because the CO_2 released to the environment during the burning or decomposition of wood is reabsorbed during the growth of the tree (Bergman and Bowe 2012). Meanwhile, the wood waste used for further processes is regarded as climate change mitigation measures (Ingerson 2011). Muñoz *et al*. (2013) pointed out that wood or biomass is normally assigned a global warming potential of 0, *i.e.*, wood does not theoretically contribute to the carbon footprint.

On the other hand, the combustion of fossil fuel for off-site electrical energy generation and transportation results in the emission of several components to the environment in different amounts, depending on the quantities and types of fossil fuel used (Ratnasingam *et al.* 2014). Saidur *et al.* (2007) described the emissions on the basis of the fuel contents fuels, which are composed of carbon, sulfur, nitrogen, and their compounds. The release of CO_2, CH_4, and N_2O attributed to energy consumption is inevitable.

Table 3 depicts the average amounts of gases released as a consequence of electricity and diesel fuel consumption during the sawn timber production process. Overall, the emission of CO_2 was higher than that of CH_4 and N_2O. In fact, the emissions of CH_4 and N_2O can be regarded as almost zero, in view of the fact that the release of CO_2 was 100%. This result was supported by the study of Bergman *et al.* (2014) who viewed that the release of CO_2 from the combustion of fossil fuels is the main point to the global warning issue.

Table 3. Comparative Emission of Greenhouse Gases (Emissions are allocated per m^3 of rough green sawn timber)

GHGs	Light Red Meranti (kg/m^3)		Dark Red Meranti (kg/m^3)	
	Electricity	Diesel Fuel	Electricity	Diesel Fuel
CO_2	1.44E+00	6.64E-01	2.30E+00	1.05E+00
CH_4	7.83E-05	8.96E-05	1.25E-04	1.42E-04
N_2O	1.11E-05	5.38 E-06	1.78E-05	8.51E-06

Carbon Footprint

Figure 6 depicts the release of CO_2-eq associated with electricity and diesel fuel consumption during the sawmilling of Light Red Meranti and Dark Red Meranti. It is clear that the carbon footprint for 1 m^3 of sawn timber from Dark Red Meranti was slightly higher than that of Light Red Meranti. The difference in the carbon footprint per 1 m^3 between the two species was calculated to be 1.26 kg CO_2-eq.

The normality of the carbon footprint results was assessed using the Shapiro-Wilks test. As shown in Table 4, no significant difference was found for the carbon footprint variables ($p = 0.319$). Because the p-value was larger than 0.05, the null hypothesis of normality cannot be rejected. Therefore, the carbon footprint variable in this study is shown to be normally distributed. The normal distribution of the carbon footprint variables is presented in Fig. 7.

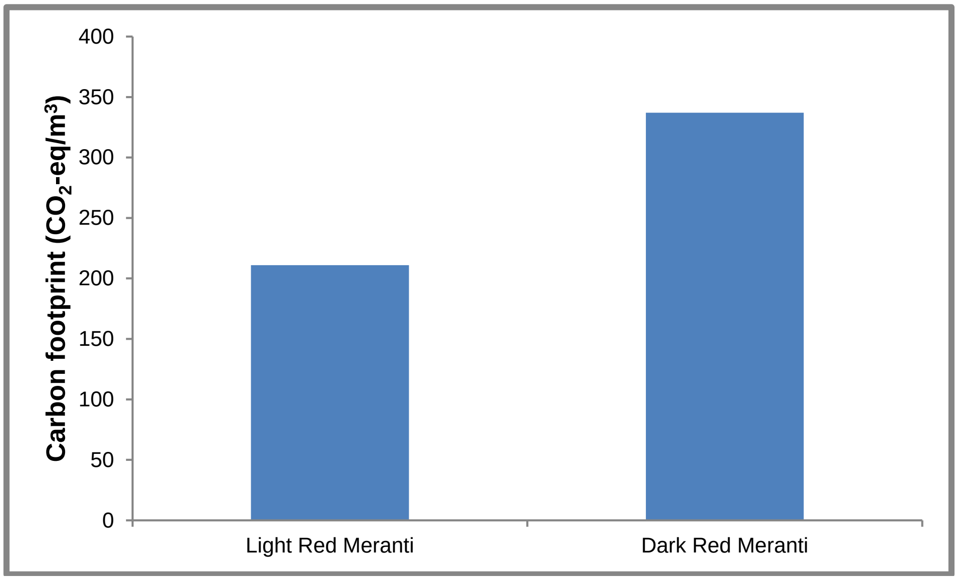

Fig. 6. Comparative carbon footprint of the wood species

Table 4. Test of Normality for the Variable of Carbon Footprint

		Statistic	df	Sig.
Mean	2.7403	0.937	16	0.319
Standard deviation	1.4571			

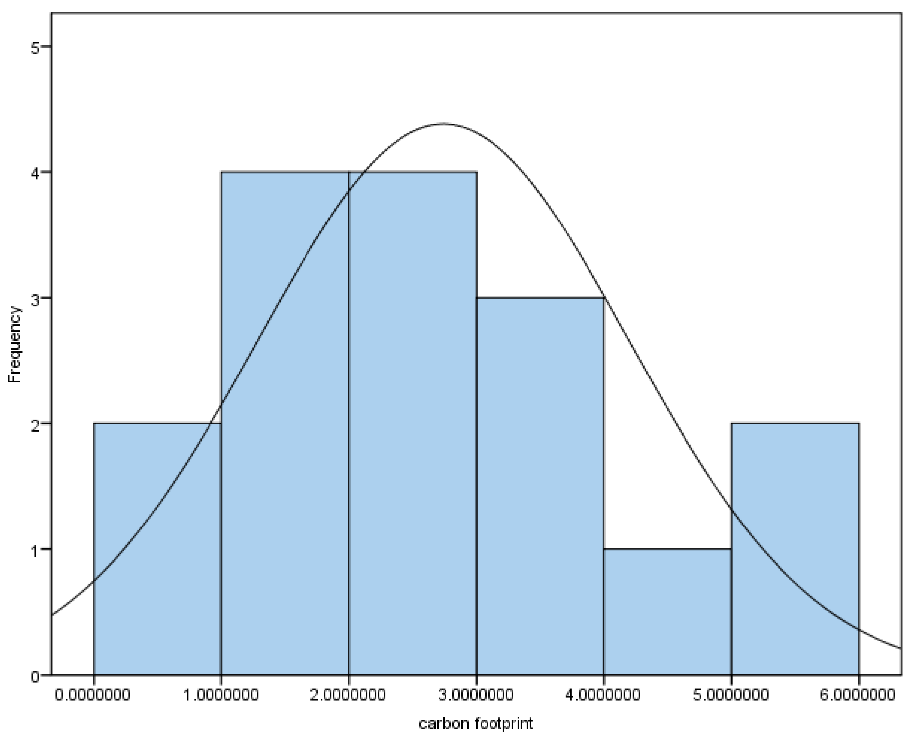

Fig. 7. Normal distribution of the carbon footprint variables

Nevertheless, the t-test (Table 5) showed that the carbon footprint when sawing Light Red Meranti was not significantly different compared with the sawing of Dark Red Meranti ($p > 0.05$).

Table 5. T-Test for Carbon Footprint for Wood Species Comparison

Carbon footprint			F	df	Sig.
Light Red Meranti	Mean	2.1126	2.871	14	0.084
	Standard Deviation	1.0401			
Dark Red Meranti	Mean	3.3679			
	Standard Deviation	1.6024			

Although there was no significant difference during the sawing of the two species, the apparent difference in the carbon footprint of the two species must be highlighted. The variability in energy consumption, particularly in the amount of electricity consumed, is attributable to the difference in the density of the two species. The ranges in density of Light Red Meranti and Dark Red Meranti are 385 to 755 kg/m^3 and 415 to 885 kg/m^3, respectively. Many previous studies have shown that the cutting power during the sawing and machining processes is affected positively by wood density (Klamecki 1979; Akbulut and Koc 2003; Darmawan *et al.* 2008; Ratnasingam *et al.* 2008, 2009; Ramasamy and Ratnasingam 2010). Generally, the requirement for cutting force of the saw increased proportionately with increasing density of the wood being sawn. Furthermore, the log dimensions, such as log length and log diameter, affect the amount of electrical energy consumed during the sawing process. The quality of the log and its moisture content also affect the power consumed during the sawing process.

Based on this study, the average annual carbon footprint for the production of Light Red Meranti and the Dark Red Meranti sawn timber in Peninsular Malaysia was calculated. The volume of sawn timber produced is based on the average annual harvest of the saw logs, as shown in Table 2. The calculated average annual carbon footprints for Light Red Meranti and Dark Red Meranti sawn timber were estimated to be 211 kg CO_2-eq and 337 kg CO_2-eq, respectively.

When compared with the sawn timber production of other wood species, it appears that tropical hardwood sawn timber production carries a comparatively higher release of CO_2-eq (Table 6). This could be explained by its lower yield and higher proportion of wood waste produced in the sawmilling sector in the tropical region. It is apparent that the release of GHGs to the environment was closely related to the inefficiencies in the sawmills during the sawn timber production (Ong 1986; Ho and Gan 2003).

The final product in this study was the rough green sawn timber, while in previous studies the final product was kiln dried sawn timber. Nevertheless, the value of CO_2-eq in this study is quite comparable for the kiln dried sawn timber of other wood species. According to Bergman *et al.* (2014), denser wood have higher moisture contents which require higher energy to dry the wood. As a consequence, the release of CO_2-eq will be proportionately higher. However, when compared to wood species which has almost similar or higher density than the Meranti wood species, the value of CO_2-eq did not differ much. This is quite contrary from the study by Martínez-Alonso and Berdasco (2015) who found very small release of GHGs for air dried Sweet Chestnut sawn timber (Table 6). It may therefore be taken into consideration that the inefficiencies in the sawmills play a significant role in determining the release of GHGs.

Table 6. Comparison of Carbon Footprint with Previous Studies

Species	Scientific Name	Density (kg/m^3)	Carbon Footprint (kg CO_2-eq/m^3)	References
Light Red Meranti	*Shorea* spp.	747	211	This study
Dark Red Meranti	*Shorea* spp.	768	337	This study
Douglas fir	*Pseudotsuga menziesii*	510	353	Milota *et al*. (2005)
Western Hemlock	*Tsuga heterophylla*	429	258	Milota *et al.* (2005)
Pine	*Pinus radiata*	550	398	McCallum (2009)
Ash	*Fraxinus* spp.	449	407	PE International AG (2012)
Beech	*Fagus* spp.	417	377	
Hickory	*Carya spp.*	705	463	
Hard Maple	*Acer saccharum*	833	394	
Soft Maple	*Acer spp.*	737	390	
Red Oak	*Quercus rubra*	705	496	
White Oak	*Quercus alba*	545	556	
Walnut	*Juglans* spp.	769	427	
Sweet chestnut (air dried sawn timber)	*Castanea sativa* Mill.	560	95.2	Martínez-Alonso and Berdasco (2015)
Sweet chestnut (kiln dried sawn timber)		560	383.7	

In addition, this study applied the gate-to-gate system boundary to assess the global warming potential, which is similar to the studies undertaken by Milota (2005) and McCallum (2009). However, the studies by PE International AG (2012) and Martínez-Alonso and Berdasco (2015) used the cradle-to-gate system boundary for the environmental performance assessment, which reported slightly higher or comparable GHGs emission values in relation to this study.

Nevertheless, the GHG emissions and impacts to the environment from tropical and non-tropical wood cannot be fully addressed within the scope of this study. A full cradle-to-grave analysis would be needed to understand the full environmental implications of using tropical wood. Furthermore, land use change which is extensive in the tropical region has been known to greatly influence the global warming potential results and conclusions of such studies.

CONCLUSIONS

1. This study presented the carbon footprint or global warming potential of Light Red Meranti and Dark Red Meranti sawn timber production of Peninsular Malaysia using the gate-to-gate concept. The carbon footprint for Light Red Meranti and Dark Red Meranti was kg CO_2-eq/m^3 and 696 kg CO_2-eq/m^3 of rough green sawn timber.
2. Generally, the carbon footprint of sawn timber varied with wood species. However, the analysis showed that there is no significant difference in the release of GHGs from the electricity usage during the cutting process of Light Red Meranti and Dark Red

Meranti. Therefore, the assumption that Dark Red Meranti resulted in a higher contribution to the carbon footprint in comparison to Light Red Meranti is inconclusive.

3. Tropical hardwood sawn timber production has a higher carbon footprint compared with the sawn timber production of non-tropical wood species. The noted difference can be attributed to the lower sawmilling yield and the larger proportion of waste produced by the sawmilling sector in the tropical region.

REFERENCES CITED

Akbulut, T., and Koc, E. (2003). "Effects of panel density, panel temperature, and cutter sharpness during edge machining on the roughness of the surface and profiled areas of medium density fiberboard," *Forest Products Journal* 54(12), 67-70.

Bergman, R. D., and Bowe, S. A. (2012). "Life-cycle inventory of manufacturing hardwood lumber in Southeastern US," *Wood and Fiber Science* 44(1), 71-84.

Bergman, R., Puettmann, M., Taylor, A., and Skog, K. E. (2014). "The carbon impacts of wood products," *Forest Products Journal* 64(7/8), 220-231. DOI: http://dx.doi.org/10.13073/FPJ-D-14-00047

Blaser, J., Sarre, A., Poore, D., and Johnson, S. (2011). *Status of Tropical Forest Management 2011*, ITTO Technical Series No. 38, International Tropical Timber Organization, Yokohama, Japan.

Boguski, T. K. (2010). "Life cycle carbon footprint of the National Geographic magazine," *The International Journal of Life Cycle Assessment* 15(7), 635-643. DOI: 10.1007/s11367-010-0210-5

Chen, S. S. (2003). *General Activity of Life Cycle Assessment in Malaysia*, Environmental and Energy Technology Centre, SIRIM Berhad, Malaysia.

Darmawan, W., Usuki, H., Quesada, J., and Marchal, R. (2008). "Clearance wear and normal force of TiN-coated P30 in cutting hardboards and wood-chip cementboards," *Holz als Roh- und Werkstoff* 66(2), 89-97. DOI: 10.1007/s00107-007-0213-5

Ekvall, T., and Finnveden, G. (2001). "Allocation in ISO 14041 - A critical review," *Journal of Cleaner Production* 9(3), 197-208. DOI: 10.1016/S0959-6526(00)00052-4

Eshun, J. F., Potting, J., and Leemans, R. (2010). "Inventory analysis of the timber industry in Ghana," *The International Journal of Life Cycle Assessment* 15(7), 715-725. DOI: 10.1007/s11367-010-0207-0

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennigton, D., and Suh, S. (2009). "Recent developments in life cycle assessment," *Journal of Environmental Management* 91(1), 1-21. DOI: 10.1016/j.jenvman.2009.06.018

Gemechu, E. D., Butnar, I., Goma-Camps, J., Pons, A., and Castells, F. (2013). "A comparison of the GHG emissions caused by manufacturing tissue paper from virgin pulp or recycled waste paper," *The International Journal of Life Cycle Assessment* 18(8), 1618-1628. DOI: 10.1007/s11367-013-0597-x

González-García, S., Lozano, R. G., Estévez, J. C., Pascual, R. C., Moreira, M. T., Gabarrell, X., i Pons, J. R., and Feijoo, G. (2012). "Environmental assessment and improvement alternatives of a ventilated wooden wall from LCA and DfE perspective," *The International Journal of Life Cycle Assessment* 17(4), 432-443. DOI: 10.1007/s11367-012-0384-0

Gopalakrishnan, B., Mardikar, Y., Gupta, D, Jalali, M., and Chaudhari, S. (2012). "Establishing baseline electrical energy consumption in wood processing sawmills for lean energy initiatives: A model based on energy analysis and diagnostics," *Energy Engineering* 109(5), 40-77. DOI: 10.1080/01998595.2012.10531822

Guinée, J. B., Gorrér, M., Heijungs, R., Huppes, G., Kleijin, R., de Koning, A., van Oers, L., Sleeswijk, A. W., Suh, S., and Udo de Haes, H. A. (2001, updated 2015). *Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards*, Kluwer Academic Publishers, Dordrecht.

Gustavsson, L., and Sathre, R. (2011). "Energy and CO_2 analysis of wood substitution in construction," *Climate Change* 105(1-2), 129-153. DOI: 10.1007/s10584-010-9876-8

Ho, K.S., and Gan, K.S. (2003). Saw doctoring practices in Peninsular Malaysia. *Timber Technology Bulletin* 27, 1-7.

Ingerson, A. (2011). "Carbon storage potential of harvested wood: summary and policy implications," *Mitigation and Adaptation Strategies for Global Change* 16(3), 307-323. DOI: 10.1007/s11027-010-9267-5

ISO 14040. (2006). "Environmental management – Life cycle assessment – Principles and framework, second edition," International Organization for Standardization, Geneva, Switzerland.

ISO 14044. (2006). "Environmental management – Life cycle assessment – Requirements and guidelines," International Organization for Standardization, Geneva, Switzerland.

Jungmeier, G., Werner, F., Jarnehammar, A., Hohenthal, C., and Richter, K. (2002). "Allocation in LCA of wood-based products experiences of cost action E9," *The International Journal of Life Cycle Assessment* 7(6), 369-375. DOI: 10.1007/BF02978686

Khairul Izzudin, M., Amir Hamzah, S., and Sabrina, H. A. (2014). "Life cycle assessment at a sawmill manufacturing company in Terengganu, Malaysia," in: *From Sources to Solution*, A. Z. Aris, T. H. Tengku Ismail, R. Harun, A. M. Abdullah, and M. Y. Ishak (eds.), Springer, Singapore. DOI: 10.1007/978-981-4560-70-2_87

Klamecki, B. E. (1979). "A review of wood cutting tool wear literature," *Holz als Roh- und Werkstoff* 37(7), 265-276. DOI: 10.1007/BF02607429

Kinjo, M., Ohuchi, T., Kii, H., and Murase, Y. (2005). "Studies of life cycle assessment of Sugi Lumber," *Journal of the Faculty of Agriculture* 50(2), 343-351.

Lippke, B., Wilson, J.B., Perez-Garcia, J., Bowyer, J., and Meil, J. (2004). "CORRIM: Life-cycle environmental performance of renewable building materials," *Forest Products Journal* 54(6), 8-19.

Mahlia, T. M. I. (2002). "Emissions from electricity generation in Malaysia," *Renewable Energy* 27(2), 293-300. DOI: 10.1016/S0960-1481(01)00177-X

McCallum, D. (2009). *Carbon Footprint*, Nelson Forests Ltd. http://www.douglasfir.co.nz/resources/CarbonFootprint_2011.10.14.pdf

Martínez-Alonso, C., and Berdasco, L. (2015). "Carbon footprint of sawn timber products of *Castanea sativa* Mill. in the north of Spain," *Journal of Cleaner Production* 102(1), 127-135. DOI: 10.1016/j.jclepro.2015.05.004

Milota, M. R., West, C. D., and Hartley, I. D. (2005). "Gate-to-gate life cycle inventory of softwood lumber production," *Wood and Fiber Science* 37(SI), 47-57.

Muñoz, I., Rigarlsford, G., Canals, L. M. I., and King, H. (2013). "Accounting for greenhouse gas emissions from the degradation of chemicals in the environment,"

The International Journal of Life Cycle Assessment 18(1), 252-262. DOI: 10.1007/s11367-012-0453-4
National Timber Policy. (2009). *NATIP National Timber Policy 2009–2020*, Ministry of Plantation Industries and Commodities, Malaysia.
Ong, M.S. (1986). The implications of the industrial master plan on the development of wood-based industry in Malaysia. *The Malaysian Forester* 49(3), 241-248.
PE International AG (2012). *Life Cycle Assessment of Rough-Sawn Kiln-Dried Hardwood Lumber*. Final report for American Hardwood Export Council (AHEC).
Puettmann, M. E., Wagner, F. G., and Johnson, L. (2010). “Life cycle inventory of softwood lumber from the Inland Northwest US,” *Wood and Fiber Science* 42(SI), 52-66.
Ramasamy, G., and Ratnasingam, J. (2010). “A review of cemented tungsten carbide tool wear during wood cutting processes,” *Journal of Applied Sciences* 10(22), 2799-2804. DOI: 0.3923/jas.2010.2799.2804
Ratnasingam, J., and Ioras, F. (2006). *Colonial British Forestry in Malaysia and the Years Thereafter*. Colorcom Grafik Sistem Sdn. Bhd., Malaysia.
Ratnasingam J., Tee, C. T., and Farrokhpayam, S. R. (2008). “Tool wear characteristics of oil palm empty fruit bunch particleboard,” *Journal of Applied Sciences* 8(8), 1594-1596. DOI: 10.3923/jas.2008.1594.1596
Ratnasingam J., Ma, T. P., Ramasamy, G., and Manikam, M. (2009). “Tool wear characteristics of cemented tungsten carbide tools in machining oil palm empty fruit bunch particleboard,” *Journal of Applied Sciences* 9(18), 3397-3401. DOI: 0.3923/jas.2009.3397.3401
Ratnasingam, J., Ramasamy, G., Lim, T.W., Abdul Latib, S., and Muttiah, N. (2015). “The prospects of rubberwood biomass energy production in Malaysia,” *BioResources* 10(2), 2526-2548. DOI: 10.15376/biores.10.2.2526-2548.
Röös, E., Sundberg, C., and Hansson, P. -A. (2010). “Uncertainties in the carbon footprint of food products: A case study on table potatoes,” *The International Journal of Life Cycle Assessment* 15(5), 478-488. DOI: 10.1007/s11367-010-0171-8
Saidur, R., Hasanuzzaman, M., Sattar, M. A., Masjuki, H. H., Irfan Anjum, M., and Mohiuddin, A. K. M. (2007). “An analysis of energy use, energy intensity and emissions at the industrial sector of Malaysia,” *International Journal of Mechanical and Materials Engineering* 2(1), 84-92.
Statistics on Commodities 2011. (2012). Ministry of Plantation Industries and Commodities. Putrajaya, Malaysia.
Statistics on Commodities 2013. (2014). Ministry of Plantation Industries and Commodities. Putrajaya, Malaysia.
Tellnes, L. G. F., Nyrus, A. Q., and Flaete, P. O. (2012). “Carbon footprint of products from Norwegian sawmilling industry,” in: *Proceedings of the Biennial Meetings of the Scandinavian Society of Forest Economics*, C. L. Todoroki and E. M. Rönnqvist (eds.), Hyytiälä, Finland.
Thang, H. C. (1987). “Can the existing wood resources in Malaysia meet future domestic requirements?,” *The Malaysian Forester* 50(2), 217-234.
Vigon, B. W., Tolle, D. A., Cornaby, B. W., Latham, H. C., Harrison, C. L., Boguski, T. L., Hunt, R. G., and Sellers, J. D. (1993). *Life Cycle Assessment: Inventory Guidelines and Principles*, Risk Reduction Engineering Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH.

Woon, W.-C., and Norini, H. (2002). *Trends in Malaysian Forest Policy*. Policy Trend Report. Forest Research Institute Malaysia (FRIM), Kepong, Malaysia.

Wu, H. J., Yuan, Z. W., Zhang, L., and Bi, J. (2012). "Life cycle energy consumption and CO_2 emission of an office building in China," *The International Journal of Life Cycle Assessment* 17(2), 105-118. DOI: 10.1007/s11367-011-0342-2

Zhang, S., He, B., Zhao, L., and Zhou, J. (2015). "Application of carbon footprint assessment methodology to the case of coated ivory board," *BioResources* 10(2), 2656-2666. DOI: 10.15376/biores.10.2.2656-2666

Article submitted: April 2, 2015; Peer review completed: June 10, 2015; Revised version received and accepted: June 23, 2015; Published: July 2, 2015.
DOI: 10.15376/biores.10.3.5174-5190