VESSEL TRAITS ACROSS A LAND USE GRADIENT IN THE TROPICAL RAINFORESTS OF SABAH, MALAYSIA

PALASIAH JOTAN

THESIS SUBMITTED IN FULFILLMENT FOR THE DEGREE OF MASTER OF SCIENCE

FACULTY OF SCIENCE AND NATURAL RESOURCES
UNIVERSITI MALAYSIA SABAH
2019

UMS
UNIVERSITI MALAYSIA SABAH

UNIVERSITI MALAYSIA SABAH

BORANG PENGESAHAN STATUS TESIS

JUDUL: **VESSEL TRAITS ACROSS A LAND USE GRADIENT IN THE TROPICAL RAINFORESTS OF SABAH, MALAYSIA**

IJAZAH: **SARJANA SAINS (PERHUTANAN)**

Saya **PALASIAH JOTAN**, Sesi **2017-2019**, mengaku membenarkan tesis Sarjana ini disimpan di Perpustakaan Universiti Malaysia Sabah dengan syarat-syarat kegunaan seperti berikut:-

1. Tesis ini adalah hak milik Universiti Malaysia Sabah.
2. Perpustakaan Universiti Malaysia Sabah dibenarkan membuat salinan untuk tujuan pengajian sahaja.
3. Perpustakaan dibenarkan membuat Salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. Sila tandakan (/):

☐	SULIT	(Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA 1972)
☐	TERHAD	(Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan).
☑	TIDAK TERHAD	

Disahkan Oleh,

NORAZLYNNE MOHD. JOHAN @ JACKLYNE
PUSTAKAWAN
UNIVERSITI MALAYSIA SABAH

(Tandatangan Pustakawan)

PALASIAH JOTAN
MS1521024T

Tarikh: 17 September 2019

(Prof. Madya. Dr Colin R. Maycock)
Penyelia Utama

(Prof. Madya. Dr Berhaman Ahmad)
Penyelia bersama

DECLARATION

I hereby declare that the material in this thesis is my own except for quotations, excerpts, equations, summaries and references, which have been duly acknowledged.

22 February 2019

....
PALASIAH JOTAN
MS1521024T

CERTIFICATION

NAME : **PALASIAH JOTAN**

MATRIC NO. : **MS1521024T**

TITLE : **VESSEL TRAITS ACROSS A LAND USE GRADIENT IN THE TROPICAL RAINFORESTS OF SABAH, MALAYSIA**

DEGREE : **MASTER OF SCIENCE (FORESTRY)**

VIVA DATE : **21 JUNE 2019**

CERTIFIED BY;

1. MAIN SUPERVISOR Signature

Assoc. Prof. Dr. Colin R. Maycock

2. CO-SUPERVISOR

Assoc. Prof. Dr. Berhaman Ahmad

ACKNOWLEDGEMENT

First and foremost, I would like to thank God Almighty for giving me the strength, knowledge and ability especially during all challenging moments in completing this research study. I would like to express my deepest gratitude to my supervisor Assoc. Prof. Dr Colin R. Maycock and co-supervisors Dr. Sabine Both, Prof. David F.R.P Burslem and Assoc. Prof. Dr Berhaman Ahmad for providing me support, invaluable guidance and suggestions in my journey towards this degree. This thesis would not have been possible without their guidance. A very special thanks goes to the UK Natural Environment Research Council (NERC) for providing the funding for this research study. I have a great pleasure in acknowledging my gratitude to Dr Kasia Ziemińska for laboratory support at the Environmental Change Institute, University of Oxford, United Kingdom, Dr Hedda J. Weitz and Jaime Buckingham for laboratory support at the School of Biological Sciences, University of Aberdeen, United Kingdom and Mr. Azli Sulid for providing laboratory support at Universiti Malaysia Sabah. I would like to express my great appreciation to Dr Laura Kruitbos and Unding Jami for logistical assistance. I thank the Sabah Biodiversity Council, Yayasan Sabah, the Maliau Basin and Danum Valley Management Committees the South East Asia Rainforest Research Partnership (SEARRP), and the Sime Darby Foundation by supporting the Stability of Altered Forest Ecosystems (SAFE) Project. I am grateful to the biggest source of my strength, my family who have provided me through emotional and moral support and to my fiancé for assistance and endless encouragement. Many thanks go to my friends who have supported me along the way and for all those I did not mention explicitly.

Palasiah Jotan

22 February 2019

ABSTRACT

Ecological plant strategies are reflected in anatomical constraints and trade-offs, influencing the distribution of species in different environmental conditions. In trees, wood anatomical traits serve multiple ecological functions such as structural stability, nutrient storage and water conductance. Vessel traits may determine the response of trees to disturbance such as selective logging which affected vast areas of forests in Borneo and which has been shown to change abiotic conditions. Trade-offs in vessel traits reflect different strategies used by trees to deal with water transport under various environmental conditions. Vessel traits can be essential for the fitness of trees especially when exposed to extreme (hot and dry) conditions in open gaps of selectively logged forest. This study investigates the differences in community level of vessel traits expression between old-growth (OG) and selectively logged forest (SL) in Sabah, Malaysian Borneo and explores the ecological trait variation of trees in these two different forest types. A total of 356 mature trees were sampled, capturing 192 species. From cross sections of branches, vessel area (A) and vessel diameter (VD) were measured and vessel lumen fraction (F), vessel density (N), hydraulically weighted diameter (D_h), vessel area to number ratio (S) also called as a vessel composition metric, and potential hydraulic conductivity (K_p) were calculated. Across all species S varied 61-fold and N showed 15-fold variation. There were significant differences in A (χ^2=3.60; p=0.044), VD (χ^2=4.05; p=0.039) and K_p (χ^2=4.37; p=0.035) between OG and SL: vessel area and diameter were significantly larger in trees present in SL compared to OG forest. In SL, larger A and VD values also contributed to the hydraulic conductivity (K_p) being higher than that of OG forest. These differences in K_p can be explained by the presence of pioneer species in SL that represent fast growing trees which would need efficient water transport to support their fast growth rates. Therefore, logging in tropical forests drives differential expression of wood anatomical traits in response to the modified environments created by the disturbance. Vessel traits of common OG species adapted to ensure high hydraulic resistance when soil moisture is limiting while common species of SL developed an efficient water transport system but their vessels lacked hydraulic safety under stressful environmental conditions. The present study provided an important insight into vascular strategies of trees in Bornean rainforest and highlighted potential limitations on forest resilience during future climatic extremes.

ABSTRAK

SIFAT-SIFAT PEMBULUH KAYU DI SEPANJANG GRADIEN GUNA TANAH DI HUTAN HUJAN TROPIKA SABAH, MALAYSIA

Strategi ekologi tumbuhan dicerminkan dalam kekangan anatomi dan perubahan, mempengaruhi pengagihan spesies dalam keadaan persekitaran yang berbeza. Dalam pokok, ciri-ciri anatomi kayu mempunyai pelbagai fungsi ekologi seperti kestabilan struktur, penyimpanan nutrien dan kealiran air. Ciri-ciri pembuluh boleh menentukan tindak balas pokok kepada gangguan seperti pembalakan terpilih yang mempengaruhi kawasan hutan yang luas di Borneo dan yang telah ditunjukkan mengubah keadaan abiotik. Kelainan dalam ciri-ciri pembuluh menggambarkan strategi yang berbeza yang digunakan oleh pokok untuk menangani pengangkutan air di bawah pelbagai keadaan persekitaran. Ciri-ciri pembuluh boleh menjadi penting untuk daya tahan pokok terutamanya apabila terdedah kepada keadaan ekstrim (panas dan kering) dalam jurang terbuka hutan yang dibalak. Kajian ini menentukan perbezaan ciri-ciri pembuluh dalam komuniti antara hutan dara (HD) dan hutan yang dibalak secara terpilih (HDST) di Sabah, Malaysia dan menentukan variasi sifat ekologi pokok di kedua-dua jenis hutan yang berlainan. Sebanyak 356 pokok matang telah disampel, mewakili 192 spesies. Dari bahagian keratan rentas, saiz pembuluh (A) dan diameter pembuluh (VD) diukur dan pecahan lumen pembuluh (F), ketumpatan pembuluh (N), diameter hidraulik (D_h), kawasan pembuluh kepada nisbah nombor (S) sebagai metrik komposisi pembuluh, dan potensi kekonduksian hidraulik (K_p) dikira. Dalam semua spesies, S bervariasi 61 kali ganda dan N menunjukkan variasi 15 kali ganda. Terdapat perbezaan yang ketara dalam A (χ^2=3.60; p=0.044), VD (χ^2=4.05; p=0.039) dan K_p (χ2=4.37; p=0.035) antara HD dan HDST: saiz pembuluh dan diameter pembuluh jauh lebih besar pada pokok yang terdapat di HDST berbanding di HD. Dalam HDST, nilai A dan VD yang lebih besar juga menyumbang kepada potensi kekonduksian hidraulik (K_p) yang lebih tinggi daripada HD. Perbezaan dalam K_p ini dapat dijelaskan oleh kehadiran spesies perintis dalam HDST yang mewakili pokok yang berkembang pesat yang memerlukan pengangkutan air yang efisien untuk menyokong kadar pertumbuhan yang cepat. Oleh itu, pembalakan di hutan tropika memacu pembezaan berlainan sifat-sifat anatomi kayu sebagai tindak balas kepada persekitaran yang diubahsuai yang dicipta oleh gangguan tersebut. Ciri-ciri pembuluh spesies lazim HD beradaptasi untuk memastikan rintangan hidraulik yang tinggi apabila kelembapan tanah terhad sementara spesies lazim HDST memacu sistem pengangkutan air yang cekap tetapi pembuluh mereka kekurangan hidraulik di bawah keadaan persekitaran yang tertekan. Kajian ini memberikan satu gambaran penting mengenai strategi pokok vaskular di hutan hujan tropika dan menyerlahkan potensi batasan ketahanan hutan pada iklim ekstrim masa depan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF ABBREVIATIONS

A	- Vessel area
ANCOVA	- Analysis of covariance
ANOVA	- Analysis of variance
D_h	- Hydraulically weighted vessel diameter
DBH	- Diameter at breast height
F	- Vessel lumen fraction
FAA	- Formalin acetic acid alcohol
GEM	- Global Ecosystem Monitoring
GIMP	- GNU Image Manipulation program
IAWA	- International Association of Wood Anatomists
K_p	- Theoretical/potential hydraulic conductivity
N	- Vessel number per area (vessel density)
OG	- Old-growth
S	- Vessel area to number ratio (vessel composition)
SAFE	- Stability of Altered Forest Ecosystems (SAFE) Project
SEARRP	- South East Asia Rainforest Research Partnership (SEARRP)
SL	- Selectively logged forest
VD	- Vessel diameter

LIST OF SYMBOLS

%	- Percentage
°C	- Degree celcius
°	- Degree
α	- Alpha
Σ	- Sum
=	- Equal to
<	- Less than
×	- Times
'	- Minute
E	- East
g	- Gram
ha	- Hectare
µm	- Micrometer
ml	- Millilitre
mm	- Millimetre
m	- Metre
MPa	- Megapascal Pressure Unit
N	- North
s	- Second

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Plant functional traits are all measurable features (morphological, physiological and phenological) for individual plants that influence their survival, growth, reproduction and fitness (Pérez-Harguindeguy *et al.,* 2013; Violle *et al.,* 2007; Ackerly, 2003). Traits play a key role in linking taxonomic diversity to ecosystem function (Townsend *et al.*, 2008). Plant traits allow the investigation of the functions of different tissues and thus into functional trade-offs that influence species distributions in different environmental conditions (Kraft *et al.,* 2008). Ecologists have used functional traits to understand ecological plant strategies and adaptation to environmental stress, e.g., anatomical characteristics are known to affect the functional performance of wood xylem in various environmental conditions such as drought events (Carlquist & Schneider, 2001).

Knowledge of plant stem anatomy is essential to understanding water transport in trees (Campbell *et al.,* 2016). Specifically, xylem anatomical traits serve multiple ecological functions such as structural stability, nutrient storage but also water conductance (Fan *et al.,* 2012; Baas *et al.,* 2004). For example, xylem vessel size is an important plant hydraulic trait which ensures that water supply is sufficient from the roots to the leaves to maximize growth performance and survival (Schreiber *et al.,* 2015). Large vessels transport water more efficiently than the smaller ones (Zanne *et al.,* 2010) but are also prone to hydraulic failure which is major cause of water stress in plants due to cavitation, i.e. air-filled conduits (Meinzer *et al.*, 2001). In addition to vessel size, other vessel characteristics such as vessel density, fraction and grouping have also direct bearing on water conductance efficiency through plant stems (Scholz *et al.,* 2013; Zanne *et al.,* 2010; Loepfe *et al.,* 2007; Tyree & Zimmerman, 2002). Hence, stem vessel size distribution, density and fractions all affect the hydraulic conductivity of xylem (Tyree & Ewers, 1991) and different combinations of vessel sizes and densities can reflect the strategies adopted by different plant species to deal with water deficit and to optimize water conductivity (Apgaua *et al.,* 2015; Zanne *et al.,* 2010) because variation in vessel traits will lead to a different hydraulic conductance (Hubbard *et al.,* 1999).

Different plant species are more successful in different landscapes or habitats because of the differences in their quantitative traits (Westoby & Wright, 2006). Better understanding of variation in vessel characteristics between tree species as well as in different environmental conditions is important for integrating and evaluating environmental influences on ecosystems (Zanne *et al.,* 2010) because xylem structure has important implications for whole plant function (Carlquist & Schneider, 2001; Tyree & Ewers, 1991; Carlquist & Hoekman, 1985). Better knowledge of both wood structure and function will improve our understanding of plant water use strategies especially in rainforest ecosystems (Apgaua *et al.,* 2015). Tropical forests are under increasing logging pressure (Asner *et al.,* 2009), and as a consequence, logged tropical forests are now more widespread than old-growth forests across most of the tropical regions (Edwards *et al.,* 2014). In anthropogenically modified forests, trees are exposed to altered conditions such as open areas with increased light but possibly also prolonged drought, under which different xylem traits may play a key role in plant growth and survival. Therefore, the study of wood anatomical traits and their variation among species is necessary to fully understand tree ecological strategies in both human disturbed and untouched tropical forest ecosystems.

Southeast Asian tropical rainforests are among the oldest, existing tropical ecosystems on Earth (Whitmore, 1984) and are globally known as biodiversity hotspots (Myers *et al.,* 2000) mostly dominated by tree species of the Dipterocarpaceae family (Brearley *et al.*, 2016; Rana *et al.*, 2009). However, in the last decades, logging and conversion into agricultural land have been major drivers to forest degradation in Southeast Asia (Wilcove *et al.,* 2013; Sodhi *et al.,* 2004). Among SE Asia, Malaysian Borneo is a centre of both oil palm and selective logging industries (Bryan *et al.,* 2013), which results not only in loss of biodiversity and alteration of ecosystem functions, but also in effects on residual vegetation, soils and waterways (Bryan *et al.,* 2010; Asner *et al.,* 2005) and changing tree species composition (Cleary, 2017; Berry *et al.,* 2008). In selectively logged forests, changes in tree species composition may lead to changes in functional traits of tree community, however, although there is some information on the impact of selective logging on functional diversity (Osazuwa-peters *et al.,* 2015; Carreño-Rocabado *et al.,* 2012; Díaz *et al.,* 1999), studies on wood anatomical traits in logged forests are practically missing, even though vessel traits can be crucial for tree resilience in human-disturbed forests.

This study is part of the Biodiversity and Land-use Impacts on Tropical Ecosystem Function (BALI, http://bali.hmtf.info) project under the Human Modified Tropical Forest Programme (HMTF, http://hmtf.info/). The present study investigates wood anatomical traits; more specifically it focuses on vessel traits in old-growth and selectively logged forest, explores the variability of vessel traits and the relationships between different vessel characteristics, and aims to reveal differences in vessel traits expressed by species present in the two forest types. Differences in vessel traits between the two forest types (old-growth and selectively logged forest) are expected to arise due to the presence of pioneer species (fast growing species with low wood density) in selectively logged forest, therefore the hypothesis of this study is the vessel traits of species dominant in selectively logged forest would reflect their need to capture and transport resources to support their fast growth rates, while species of old-growth forest (such as dipterocarps) would display more conservative traits. To compare vessel traits between selectively logged and old-growth forest, cross sections of branches of tree species from both forest types were analysed for mean vessel size, vessel diameter, vessel number per unit area, hydraulically weighted diameter, vessel lumen fraction, and vessel area to number ratio. Moreover, potential hydraulic conductivity was calculated using vessel lumen fraction and vessel area to number ratio, to reveal differences in the efficiency of water transport between the two forest types.

1.2 Significance of the study

Tree species with similar wood density may differ significantly in their xylem anatomy (Ziemińska *et al.,* 2013) and consequently also in their hydraulic conductivity. Studying wood density alone is not sufficient to fully understand water transport in trees, and alternative anatomical traits such as vessel characteristics should be explored. The present study provides important insights into vascular strategies of trees in the rainforests of Borneo. Because xylem vessels play a key role in ensuring enough water supply in trees, understanding how these traits vary across environments could potentially be important for selecting the most suitable trees to plant in restoration and reforestation. For example, planting tree species with a low hydraulic safety (i.e., with large vessels prone to embolism) should be avoided at sites where a water deficit may be expected, such as ridges exposed to potential desiccation. Moreover, knowledge of the vascular strategies of both old-growth and selectively logged forest species is crucial for preservation and management of these forests under future climate change. In Borneo the mean temperature and precipitation are predicted to rise and decline, respectively (Scriven *et al.,* 2015; IPCC, 2013), but the frequency and magnitude of El Niño Southern Oscillation (ENSO) droughts are also expected to increase (Herbert & Dixon, 2003; Walsh & Newbery, 1999). Recently sharp increases in tree mortality after drought were reported from both Bornean primary and secondary forests (Qie *et al.,* 2017). Hence an understanding of how trees cope with weather extremes is crucial for both preservation of old-growth forests and management and restoration of logged forests in Borneo.

1.3 Research objectives

a. To investigate community level differences in wood anatomical trait expression between old-growth forest and selectively logged forests.

b. To investigate ecological trait variation among trees in old-growth forest and selectively logged forest, and explore plant strategies with regards to wood anatomical properties.

1.4 Research questions

The thesis explores the following questions:

a. What is the variation in vessel traits among species of Bornean lowland rainforest?

b. What are the relationships between studied vessel characteristics, and do these relationships differ between old-growth and selectively logged forest?

c. Are there significant differences in vessel traits between species of old growth forests and selectively logged forests at the community level and if so, can these differences be linked to differences in plant strategies?

d. Do vessel traits in common species of selectively logged forest possess high hydraulic efficiency while vessel traits in common species of old-growth forest possess high hydraulic safety?

CHAPTER 2

LITERATURE REVIEW

2.1 Plant functional traits

Plant functional traits are all the morphological, physiological and phenological features measurable for an individual plant, from the cellular to the organismal level, which can affect its fitness (Pérez-Harguindeguy *et al.,* 2013; Violle *et al.,* 2007). Plant functional traits are widely used in ecological and evolutionary research for achieving a general predictive understanding of communities and ecosystems, and have become an active area of research on species distributional patterns at local, regional, and global scales (Cornwell & Ackerly, 2009; Ackerly & Cornwell, 2007; Violle *et al.,* 2007; Wright *et al.,* 2007). Ecologists use plant functional trait analyses as proxies for plant ecological strategies (Zanne *et al.,* 2010; Westoby, 1998). Trait based approaches are also increasing in the fields of agronomy and forestry (Garnier & Navas, 2012), nature conservation (Mace *et al.,* 2010) and archeobotany (Jones *et al.,* 2010).

Functional traits determine the response of organisms to stress or their effects on ecosystem processes (de Bello *et al.,* 2010). They may demonstrate adaptations to variation in the physical and biotic environments and display trade-offs among different functions within an organism. For example, drought-tolerant tree species often have narrow and small leaves with low specific leaf area (SLA) (Fonseca *et al.,* 2000) and high wood density (Poorter & Markesteijn, 2008). Variation in morphological and physiological traits within and among plant species underpins a continuum of plant strategies in response to important ecological processes at a range of scales (Pérez-Harguindeguy *et al.,* 2013; Reich *et al.,* 2003).

The relationship between plant characteristics and environmental conditions has long been recognized in the development of plant ecology (Cowles, 1899). Different types of plants are successful under different environmental conditions (Tardieu, 2013). The ecological and physiological processes that determine these relationships are still active areas of research even after more than a century, especially the examination of traits that contribute to ecosystem processes and species interactions (Sandel *et al.*, 2010; McGill *et al.*, 2006; Hooper *et al.*, 2005; Suding *et al.*, 2005). Hence, an approach that scales up traits from species level to community level gives further insights into how plant communities respond to environmental change and thus affect ecosystem processes (Mayfield *et al.*, 2010; Suding & Goldstein, 2008).

The functional traits of trees are essential for understanding the ecology of trees and forests (Swenson & Enquist, 2007; Westoby & Wright, 2006). Differences in quantitative traits that provide some adaptive advantage may contribute to variation in competitive ability of trees under specific circumstances (Westoby & Wright, 2006; Ackerly, 2003), for instance, higher leaf nitrogen concentrations may enhance carbon assimilation and tree growth in high irradiance (Poorter & Bongers, 2006) while higher wood density is usually associated with greater drought tolerance (Ackerly & Cornwell, 2007).

2.2 Functional traits in wood anatomy

A functioning water conducting system is essential to maximize tree growth rate and survival, therefore functional traits have been attributed to wood from the earliest day of botanical science and detailed studies on wood structure and function, mainly on tree hydraulics, are one of the most exciting fields in plant biology, evolution and forest ecology (Hacke & Sperry, 2015). According to Baas *et al.* (2016), understanding how functional traits of wood arise during wood formation in response to environmental changes is key to interpreting past wood reactions and predicting future growth responses. Each individual plant through its structure of cells, tissues and organs provides information regarding its past life and environment (Wimmer, 2002). Investigating traits that are specifically related to water conductivity in trees provides understanding on how drought events affect metabolic processes such as photosynthesis, transpiration and growth (Apgaua *et al.,* 2015).

Wood is involved directly in tree hydraulics, and the biophysical and functional anatomical traits of wood such as tissue density and xylem vessel size can be used to determine strategies used by different tree species to assure conductivity, safety of the pathway from embolism and capacitance (Beeckman, 2016; Apgaua *et al.,* 2015). Wood density has been traditionally regarded as a key plant trait affecting mechanical and physiological performance and has been linked with hydraulic strategies (Chave *et al.,* 2009), although it is now known that species with similar wood density might have different and diverse anatomies (Ziemińska *et al.,* 2013). Low wood density has been associated with fast growth (Chave *et al.,* 2006; Wright *et al.,* 2003) while in contrast high wood density is linked with high stress tolerance (Hacke & Sperry, 2015) and survival because of its association with higher hydraulic safety, stronger biomechanical support and resistance to pests and pathogens (Jacobsen *et al.,* 2007; Gelder *et al.,* 2006). Variation in wood density can be achieved anatomically by altering morphology (e.g., cell wall thickness and lumen area) or changing relative proportion of tissues (e.g., area in vessel fraction, fibre wall and lumen, and parenchyma) (Martínez-Cabrera *et al.,* 2009).

Hydraulic conductivity is an absolute measure of the ability of xylem to transport water and is highly variable across species (Melcher *et al.,* 2012). Vessel diameter, length and frequency are anatomical features that assist plants to deal with excessive water stress in a dry environment (Scholz *et al.,* 2013; Markesteijn *et al.,* 2011). Wide vessels are much more efficient water conductors than narrow ones, therefore, wood consisting of wider vessels has low density with high hydrauslic conductivity, whereas wood composed of narrow vessels within a fibre matrix will be dense with low hydraulic conductivity (Preston *et al.,* 2006). Consequently, xylem vessel diameter represents an important plant hydraulic trait to ensure that water supply is sufficient from the roots to the leaves to maximize growth performance and survival (Schreiber *et al.,* 2015). Increased vessel diameter increases efficiency of water conduction dramatically, however it decreases safety because larger vessels are more prone to cavitation by air seeding whereas smaller vessels are less vulnerable to embolism (Hacke *et al.,* 2006; Choat *et al.,* 2003). Xylem cavitation and embolism are known to be a major cause of water stress in plants (Tyree & Sperry, 1989). Cavitation represents a break in the water column and occurs due to a pressure difference between the external environment and inside the vessel (Tyree & Zimmerman, 2002). During cavitation water spontaneously transitions from liquid to a gas that gets trapped within the xylem conduits under excessive tension causing embolism (Baltzer *et al.*, 2009; Choat *et al.,* 2007). An embolism results from cavitated conduits becoming air-filled, which affects water conductivity efficiency to the canopy (Meinzer *et al.,* 2001) leading to branch sacrifice and even plant death (Anderegg *et al.,* 2012; Brodribb *et al.,* 2010).

2.3 Wood tissues

Angiosperm wood is a complex tissue composed of various cell types (Figure 2.1) (Evert, 2006). The key anatomical components of wood are defined by distinct tissues and cell types such as fibres, parenchyma and vessels (Figure 2.2), and these cell types can be directly related to specific ecological functions (Osazuwa-peters *et al.,* 2015). Fibres are usually the most abundant tissues in wood that function mainly in mechanical strength which is determined by the thickness of their cell walls and they also provide mechanical support for the photosynthetic leaf surfaces in a tree's canopy (Wiedenhoeft, 2010). Parenchyma derived by secondary cambium, which are physiologically living cells, is the second most abundant wood tissue and mainly function as nutrient storage and transport, pathogen defence and water storage but die during heartwood formation (Taylor *et al.,* 2002). There are two types of parenchyma: axial parenchyma which consists of axially elongate cells and runs along the long stem axis, and ray parenchyma which runs perpendicular to the long stem axis. Vessels represent the third most abundant wood tissue type and are composed of a series of individual cells, the vessel elements that are stacked one on top of the other whose main function is conduction of water and other substances in xylem from the soil to photosynthetic surfaces (Liew *et al.*, 2015; Zheng & Martínez-Cabrera, 2013; Tyree & Zimmerman, 2002).

REFERENCES

Abrantes, J., Campelo, F., García-González, I. & Nabais, C. 2013. Environmental control of vessel traits in *Quercus ilex* under Mediterranean climate, relating xylem anatomy to function. *Trees - Structure and Function.* 27(3), 655–662.

Ackerly, D.D. 2003. Community assembly, niche conservatism, and adaptive evolution in changing environments. International Journal of Plant Sciences. 164(3), 165–184.

Ackerly, D.D. & Cornwell, W.K. 2007. A trait-based approach to community assembly: Partitioning of species trait values into within- and among-community components. Ecology Letters. 10, 135–145.

Anderegg, W.R.L., Berry, J.A., Smith, D.D., Sperry, J.S., Anderegg, L.D.L. & Field, C.B. 2012. The roles of hydraulic and carbon stress in a widespread climate-induced forest die-off. Proceedings of the National Academy of Sciences. 109(1), 233–237.

Apgaua, D.M.G., Ishida, F.Y., Tng, D.Y.P., Laidlaw, M.J., Santos, R.M., Rumman, R., Eamus, D., Holtum, J.A.M. & Laurance, S.G.W. 2015. Functional traits and water transport strategies in lowland tropical rainforest trees. PLoS ONE. 10(6), 1–19.

Arbainsyah, de Iongh, H.H., Kustiawan, W. & de Snoo, G.R. 2014. Structure, composition and diversity of plant communities in FSC-certified, selectively logged forests of different ages compared to primary rain forest. Biodiversity and Conservation. 23(10), 2445–2472.

Asner, G.P., Brodrick, P.G., Philipson, C., Vaughn, N.R., Martin, R.E., Knapp, D.E., Heckler, J., Evans, L.J., Jucker, T., Goossens, B., Stark, D.J., Reynolds, G., Ong, R., Renneboog, N., Kugan, F. & Coomes, D.A. 2018. Mapped aboveground carbon stocks to advance forest conservation and recovery in Malaysian Borneo. Biological Conservation. 217(June 2017), 289–310.

Asner, G.P., Knapp, D.E., Broadbent, E.N., Oliveira, P.J.C., Keller, M. & Silva, J.N. 2005. Selective logging in the Brazilian Amazon. Science. 310(5747), 480–482.

Asner, G.P., Rudel, T.K., Aide, T.M., Defries, R. & Emerson, R. 2009. A contemporary assessment of change in humid tropical forests. Conservation Biology. 23(6), 1386–1395.

Baas, P., Beeckman, H., Čufar, K. & De Micco, V. 2016. Functional traits in wood anatomy. IAWA Journal. 37(2), 124–126.

Baas, P., Ewers, F.W., Davis, S.D. & Wheeler, E.A. 2004. The evolution of xylem physiology. The Evolution of Plant Physiology, pp. 273–295. Elsevier Academic Press, London, UK.

Baltzer, J.L., Grégoire, D.M., Bunyavejchewin, S., Noor, N.S.M. & Davies, S.J. 2009. Coordination of foliar and wood anatomical traits contributes to tropical tree distributions and productivity along the Malay-Thai peninsula. American Journal of Botany. 96(12), 2214–2223.

Bamber, R.K. 1987. Sapwood and heartwood. Forestry Commission of New South Wales.

Baraloto, C., Hérault, B., Paine, C.E.T., Massot, H., Blanc, L., Bonal, D., Molino, J.-F., Nicolini, E.A. & Sabatier, D. 2012. Contrasting taxonomic and functional responses of a tropical tree community to selective logging. Journal of Applied Ecology. 49(4), 861–870.

Barotto, A.J., Monteoliva, S., Gyenge, J., Martínez-Meier, A., Tesón, N. & Fernández, M.E. 2017. Wood density and anatomy of three Eucalyptus species: implications for hydraulic conductivity. Forest Systems. 26(1), 1–11.

Beeckman, H. 2016. Wood anatomy and trait-based ecology. IAWA Journal. 37(2), 127–151.

de Bello, F., Lavorel, S., Díaz, S., Harrington, R., Cornelissen, J.H.C., Bardgett, R.D., Berg, M.P., Cipriotti, P., Feld, C.K., Hering, D., da Silva, P.M., Potts, S.G., Sandin, L., Sousa, J.P., Storkey, J., Wardle, D.A. & Harrison, P.A. 2010. Towards an assessment of multiple ecosystem processes and services via functional traits. Biodiversity and Conservation. 19(10), 2873–2893.

Berry, N.J., Phillips, O.L., Lewis, S.L., Hill, J.K., Edwards, D.P., Tawatao, N.B., Ahmad, N., Magintan, D., Khen, C. V., Maryati, M., Ong, R.C. & Hamer, K.C. 2010. The high value of logged tropical forests: Lessons from northern Borneo. Biodiversity and Conservation. 19(4), 985–997.

Berry, N.J., Phillips, O.L., Ong, R.C. & Hamer, K.C. 2008. Impacts of selective logging on tree diversity across a rainforest landscape: The importance of spatial scale. Landscape Ecology. 23(8), 915–929.

Bischoff, W., Newbery, D.M., Lingenfelder, M., Schnaeckel, R., Petol, G.H., Madani, L. & Ridsdale, C.E. 2005. Secondary succession and dipterocarp recruitment in Bornean rain forest after logging. Forest Ecology and Management. 218(1–3), 174–192.

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

Both, S., Elias, D.M.O., Kritzler, U.H., Ostle, N.J. & Johnson, D. 2017. Land use not litter quality is a stronger driver of decomposition in hyperdiverse tropical forest. Ecology and Evolution. 7(22), 9307–9318.

Both, S., Riutta, T., Paine, C.E.T., Elias, D.M.O., Chino, R., Jain, A., Johnson, D., Kritzler, U.H., Kuntz, M., Majalap-Lee, N., Mielke, N., Pillco, M.X.M., Ostle, N.J., Teh, Y.A., Malhi, Y. & Burslem, D.F.R.P. 2018. Logging and soil nutrients independently explain plant trait expression in tropical forests. New Phytologist. 221(4), 1853–1865.

Brearley, F.Q., Banin, L.F. & Saner, P. 2016. The ecology of the Asian dipterocarps. Plant Ecology and Diversity. 9(5–6), 429–436.

Brodribb, T.J., Bowman, D.J.M.S., Nichols, S., Delzon, S. & Burlett, R. 2010. Xylem function and growth rate interact to determine recovery rates after exposure to extreme water deficit. New Phytologist. 188(2), 533–542.

Bryan, J., Shearman, P., Ash, J. & Kirkpatrick, J. 2010. Impact of logging on aboveground biomass stocks in lowland rain forest, Papua New Guinea. Ecological Applications. 20(8), 2096–2103.

Bryan, J.E., Shearman, P.L., Asner, G.P., Knapp, D.E., Aoro, G. & Lokes, B. 2013. Extreme differences in forest degradation in Borneo: Comparing practices in Sarawak, Sabah, and Brunei. PLoS ONE. 8(7), 1–7.

Campbell, G., Mielke, M.S., Rabelo, G.R. & Da Cunha, M. 2018. Key anatomical attributes for occurrence of Psychotria schlechtendaliana (Müll.Arg.) Müll.Arg. (Rubiaceae) in different successional stages of a tropical moist forest. Flora: Morphology, Distribution, Functional Ecology of Plants. 246–247(October 2017), 33–41.

Campbell, G., Rabelo, G.R., Cunha, M. D. 2016. Ecological significance of wood anatomy of Alseis pickelii Pilg. & Schmale (Rubiaceae) in a Tropical Dry Forest. Acta Botanica Brasilica. 30(1), 124–130.

Carlquist, S. 2001. Wood anatomy of the endemic woody Asteraceae of St Helena I: Phyletic and ecological aspects. Botanical Journal of the Linnean Society. 137(2), 197–210.

Carlquist, S. & Hoekman, D.A. 1985. Ecological wood anatomy of the woody Southern Californian flora. IAWA Journal. 6(4), 319–347.

Carlquist, S. & Schneider, E.L. 2001. Vessels in ferns: Structural, ecological, and evolutionary significance. American Journal of Botany. 88(1), 1–13.

Carreño-Rocabado, G., Peña-Claros, M., Bongers, F., Alarcón, A., Licona, J.C. & Poorter, L. 2012. Effects of disturbance intensity on species and functional diversity in a tropical forest. Journal of Ecology. 100(6), 1453–1463.

Chave, J., Coomes, D., Jansen, S., Lewis, S.L., Swenson, N.G. & Zanne, A.E. 2009. Towards a worldwide wood economics spectrum. Ecology Letters. 12(4), 351–366.

Chave, J., Muller-landau, H.C., Baker, T.R., Easdale, T.A. & Webb, C.O. 2006. Regional and phylogenetic variation of wood density across 2456 neotropical tree species. Ecological Society of America. 16(6), 2356–2367.

Chidumayo, E.N. & Gumbo, D.J. 2013. The environmental impacts of charcoal production in tropical ecosystems of the world: A synthesis. Energy for Sustainable Development. 17, 86–94.

Choat, B., Ball, M., Luly, J. & Holtum, J. 2003. Pit membrane porosity and water stress-induced cavitation in four co-existing dry rainforest tree species. Plant Physiology. 131(1), 41–48.

Choat, B., Sack, L. & Holbrook, N.M. 2007. Diversity of hydraulic traits in nine Cordia species growing in tropical forests with contrasting precipitation. New Phytologist. 175(4), 686–698.

Cleary, D.F.R. 2017. Impact of logging on tree, liana and herb assemblages in a Bornean forest. Journal of Sustainable Forestry. 36(8), 806–817.

Committee, I. 1989. IAWA List of microscopic features for softwood identification. IAWA Bulletin, pp. 219–332. Netherlands, Leiden.

Cornwell, W.K. & Ackerly, D.D. 2009. Community assembly and shifts in plant trait distributions across an environmental gradient in coastal California. Ecological Monographs. 79(1), 109–126.

Cowles, H.C. 1899. The ecological relations of the vegetation on the Sand Dunes of Lake Michigan. Botanical Gazette. 27(2), 95–117.

Davies, S.J. 2001. Tree mortality and growth in 11 sympatric Macaranga species in Borneo. Ecology. 82(4), 920–932.

Díaz, S., Cabido, M., Zak, M., Martínez Carretero, E. & Araníbar, J. 1999. Plant functional traits, ecosystem structure and land-use history along a climatic gradient in central-western Argentina. Journal of Vegetation Science. 10(5), 651–660.

Edwards, D.P., Ansell, F.A., Ahmad, A.H., Nilus, R. & Hamer, K.C. 2009. The value of rehabilitating logged rainforest for birds. Conservation Biology. 23(6), 1628–1633.

Edwards, D.P., Larsen, T.H., Docherty, T.D.S., Ansell, F.A., Hsu, W.W., Derhe, M.A., Hamer, K.C. & Wilcove, D.S. 2011. Degraded lands worth protecting: the biological importance of Southeast Asia's repeatedly logged forests. Proceedings of the Royal Society B: Biological Sciences. 278(1702), 82–90.

Edwards, D.P., Tobias, J.A., Sheil, D., Meijaard, E. & Laurance, W.F. 2014. Maintaining ecosystem function and services in logged tropical forests. Trends in Ecology and Evolution. 2014(9), 1–10.

Evert, R.F. 2006. Esau' s Plant Anatomy: Meristems, Cells, and Tissues of The Plant Body: Their Structure, Function and Development (3rd edition). Hoboken, New Jersey: John Wiley & Sons, Inc.

Ewers, R.M., Boyle, M.J.W., Gleave, R.A., Plowman, N.S., Benedick, S., Bernard, H., Bishop, T.R., Bakhtiar, E.Y., Chey, V.K., Chung, A.Y.C., Davies, R.G., Edwards, D.P., Eggleton, P., Fayle, T.M., Hardwick, S.R., Homathevi, R., Kitching, R.L., Khoo, M.S., Luke, S.H., March, J.J., Nilus, R., Pfeifer, M., Rao, S. V., Sharp, A.C., Snaddon, J.L., Stork, N.E., Struebig, M.J., Wearn, O.R., Yusah, K.M. & Turner, E.C. 2015. Logging cuts the functional importance of invertebrates in tropical rainforest. Nature Communications. 6(6836), 1–7.

Fan, Z.X., Zhang, S.B., Hao, G.Y., Ferry Slik, J.W. & Cao, K.F. 2012. Hydraulic conductivity traits predict growth rates and adult stature of 40 Asian tropical tree species better than wood density. Journal of Ecology. 100(3), 732–741.

Fiala, B., Meyer, U., Hashim, R. & Maschwitz, U. 2011. Pollination systems in pioneer trees of the genus Macaranga (Euphorbiaceae) in Malaysian rainforests. Biological Journal of the Linnean Society. 103(4), 935–953.

Fonseca, C.R., Overton, J.M., Collins, B. & Westoby, M. 2000. Shifts in trait combinations along rainfall and phosphorus gradients. Journal of Ecology. 88(6), 964–977.

Fortunel, C., Ruelle, J., Beauchêne, J., Fine, P.V.A. & Baraloto, C. 2014. Wood specific gravity and anatomy of branches and roots in 113 Amazonian rainforest tree species across environmental gradients. New Phytologist. 202(1), 79–94.

Garnier, E. & Navas, M.L. 2012. A trait-based approach to comparative functional plant ecology: Concepts, methods and applications for agroecology. A review. Agronomy for Sustainable Development. 32(2), 365–399.

Gaveau, D.L.A., Sheil, D., Husnayaen, Salim, M.A., Arjasakusuma, S., Ancrenaz, M., Pacheco, P. & Meijaard, E. 2016. Rapid conversions and avoided deforestation: Examining four decades of industrial plantation expansion in Borneo. Scientific Reports. 6, 1–13.

Gelder, H.A. Van, Poorter, L. & Sterck, F.J. 2006. Wood mechanics, allometry, and life-history variation in a tropical rain forest tree community. The New phytologist. 171(2), 367–378.

Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J.A., Laurance, W.F., Lovejoy, T.E. & Sodhi, N.S. 2011. Primary forests are irreplaceable for sustaining tropical biodiversity. Nature. 478(7369), 378–381.

Gleason, S.M., Westoby, M., Jansen, S., Choat, B., Hacke, U.G., Pratt, R.B., Bhaskar, R., Brodribb, T.J., Bucci, S.J., Cao, K.F., Fan, Z.X., Feild, T.S., Jacobsen, A.L., Johnson, D.M., Domec, J.C., Mitchell, P.J., Morris, H., Nardini, A., Pittermann, J., Schreiber, S.G., Sperry, J.S., Wright, I.J., Zanne, A.E., Cochard, H., Delzon, S., Domec, J.C., Fan, Z.X., Feild, T.S., Jacobsen, A.L., Johnson, D.M., Lens, F., Maherali, H., Martínez-Vilalta, J., Mayr, S., Mcculloh, K.A., Mencuccini, M., Mitchell, P.J., Morris, H., Nardini, A., Pittermann, J., Plavcová, L., Schreiber, S.G., Sperry, J.S., Wright, I.J. & Zanne, A.E. 2016. Weak trade-off between xylem safety and xylem-specific hydraulic efficiency across the world's woody plant species. New Phytologist. 209(1), 123–136.

Hacke, U.G. & Sperry, J.S. 2015. Functional and ecological xylem anatomy. Perspectives in Plant Ecology, Evolution and Systematics. 4(2), 97–115.

Hacke, U.G., Sperry, J.S., Wheeler, J.K. & Castro, L. 2006. Scaling of angiosperm xylem structure with safety and efficiency. Tree Physiology. 26(6), 689–701.

Hamer, K.C., Hill, J.K., Benedick, S., Mustaffa, N., Sherratt, T.N., Maryati, M. & Chey, V.K. 2003. Ecology of butterflies in natural and selectively logged forests of northern Borneo: the importance of habitat heterogeneity. Journal of Applied Ecology. 40(1), 150–162.

Hansen, M.C., Stehman, S.V., Potapov, P.V., Loveland, T.R., Townshend, J.R.G., DeFries, R.S., Pittman, K.W., Arunarwati, B., Stolle, F., Steininger, M.K., Carroll, M. & DiMiceli, C. 2008. Humid tropical forest clearing from 2000 to 2005 quantified by using multitemporal and multiresolution remotely sensed data. Proc. Natl. Acad. Sci. U.S.A. 105(27), 9439–9444.

Hardwick, S.R., Toumi, R., Pfeifer, M., Turner, E.C., Nilus, R. & Ewers, R.M. 2015. The relationship between leaf area index and microclimate in tropical forest and oil palm plantation: Forest disturbance drives changes in microclimate. Agricultural and Forest Meteorology. 201, 187–195.

Herbert, J.M. & Dixon, R.W. 2003. Is the ENSO phenomenon changing as a result of global warming? Physical Geography. 23(3), 196–211.

Hietz, P., Rosner, S., Hietz-Seifert, U. & Wright, S.J. 2017. Wood traits related to size and life history of trees in a Panamanian rainforest. New Phytologist. 213(1), 170–180.

Hiromi, T., Ichie, T., Kenzo, T. & Ninomiya, I. 2012. Interspecific variation in leaf water use associated with drought tolerance in four emergent dipterocarp species of a tropical rain forest in Borneo. Journal of Forest Research. 17(4), 369–377.

Hooper, D.U., Chapin III, F.S. & Ewel, J.J. 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. Ecological Monographs. 75(1), 3–35.

Hubbard, R.M., Bond, B.J. & Ryan, M.G. 1999. Evidence that hydraulic conductance limits photosynthesis in old Pinus ponderosa trees. Tree Physiology. 19(3), 165–172.

Inoue, Y., Kenzo, T., Tanaka-Oda, A., Yoneyama, A. & Ichie, T. 2015. Leaf water use in heterobaric and homobaric leafed canopy tree species in a Malaysian tropical rain forest. Photosynthetica. 53(2), 177–186.

IPCC. 2013. Climate change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., & Midgley P.M. (eds.), 1535 pp. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Iskandar, H., Snook, L.K., Toma, T., MacDicken, K.G. & Kanninen, M. 2006. A comparison of damage due to logging under different forms of resource access in East Kalimantan, Indonesia. Forest Ecology and Management. 237(1–3), 83–93.

Jacobsen, A.L., Agenbag, L., Esler, K.J., Pratt, R.B., Ewers, F.W. & Davis, S.D. 2007. Xylem density, biomechanics and anatomical traits correlate with water stress in 17 evergreen shrub species of the Mediterranean-type climate region of South Africa. Journal of Ecology. 95(1), 171–183.

Johansen, D.A. 1940. Plant Microtechnique. (1st edition). United States of America: McGraw-Hill Book Company, Inc.

Johns, A.D. 1985. Selective logging and wildlife conservation in tropical rain-forest: Problems and recommendations. Biological Conservation. 31(4), 355–375.

Jones, G., Charles, M., Bogaard, A. & Hodgson, J. 2010. Crops and weeds: the role of weed functional ecology in the identification of crop husbandry methods. Journal of Archaeological Science. 37(1), 70–77.

Kamiya, K., Harada, K., Tachida, H. & Ashton, P.S. 2005. Phylogeny of PgiC gene in Shorea and its closely related genera (Dipterocarpaceae), the dominant trees in southeast Asian tropical rain forests. American Journal of Botany. 92(5), 775–788.

Kraft, N.B., Valencia, R. & Ackerly, D.D. 2008. Functional traits and niche-based tree community assembly in an Amazonian forest. Science. 322(5901), 580–582.

Laurance, W.F., Sayer, J. & Cassman, K.G. 2014. Agricultural expansion and its impacts on tropical nature. Trends in Ecology and Evolution. 29(2), 107–116.

Lavorel, S., Díaz, S., Cornelissen, J.H.C., Garnier, E., Harrison, S.P., Mcintyre, S., Pausas, J.G., Pérez-Harguindeguy, N., Roumet, C. & Urcelay, C. 2007. Plant functional types: are we getting any closer to the Holy Grail? Terrestrial ecosystems in a changing world. The IGBP Series, Springer-Verlag: Berlin Heidelberg. pp. 149–160.

Liew, K.C., Bakansing, S.M. & Sulid, A. 2015. Wood Species of Sabah: An Illustrated Guide. Penerbit Universiti Malaysia Sabah: Kota Kinabalu, Sabah.

Loepfe, L., Martinez-Vilalta, J., Piñol, J. & Mencuccini, M. 2007. The relevance of xylem network structure for plant hydraulic efficiency and safety. Journal of Theoretical Biology. 247(4), 788–803.

Mace, G.M., Cramer, W., Díaz, S., Faith, D.P., Larigauderie, A., Le Prestre, P., Palmer, M., Perrings, C., Scholes, R.J., Walpole, M., Walther, B.A., Watson, J.E.M. & Mooney, H.A. 2010. Biodiversity targets after 2010. Current Opinion in Environmental Sustainability. 2, 3–8.

Magrach, A., Senior, R.A., Rogers, A., Nurdin, D., Benedick, S., Laurance, W.F., Santamaria, L. & Edwards, D.P. 2016. Selective logging in tropical forests decreases the robustness of liana–tree interaction networks to the loss of host tree species. Proceedings of the Royal Society of London B: Biological Sciences. 283, 1–8.

Malhi, Y., Adu-bredu, S., Asare, R.A., Lewis, S.L. & Mayaux, P. 2013. African rainforests: past, present and future. Phil. Trans. R. Soc. Lond. B. 368, 1–10.

Markesteijn, L., Poorter, L., Bongers, F., Paz, H. & Sack, L. 2011. Hydraulics and life history of tropical dry forest tree species: Coordination of species' drought and shade tolerance. New Phytologist. 191(2), 480–495.

Marsh, C.W., Greer, A.G. 1992. Forest land-use in Sabah, Malaysia: an introduction to Danum Valley. Phil. Trans. R. Soc. Lond. B. 335(1275), 331–9.

Marthews, T.R., Metcalfe, D., Malhi, Y., Phillips, O.L., Huasco, W.H., Riutta, T., Ruiz-Jaen, M.C., Girardin, C., Urruttia, R., Butt, N., Cain, R., Olivera Menor, I. 2012. Measuring Tropical Forest Carbon Allocation and Cycling: A RAINFOR-GEM Field Manual for Intensive Census Plots (v2.2). Manual, Global Ecosystems Monitoring network, http://gem.tropicalforests.ox.ac.uk/.

Martínez-Cabrera, H.I., Jones, C.S., Espino, S. & Jochen Schenk, H. 2009. Wood anatomy and wood density in shrubs: Responses to varying aridity along transcontinental transects. American Journal of Botany. 96(8), 1388–1398.

Mayfield, M.M., Bonser, S.P., Morgan, J.W., Aubin, I. & Vesk, P.A. 2010. What does species richness tell us about functional trait diversity? Predictions and evidence for responses of species and functional trait diversity to land-use change. Global Ecology and Biogeography. 19(July), 423–431.

Mayfield, M.M., Dwyer, J.M., Chalmandrier, L., Wells, J.A., Bonser, S.P., Catterall, C.P., DeClerck, F., Ding, Y., Fraterrigo, J.M., Metcalfe, D.J., Queiroz, C., Vesk, P.A. & Morgan, J.W. 2013. Differences in forest plant functional trait distributions across land-use and productivity gradient. American Journal of Botany. 100(7), 1356–1368.

McCulloh, K.A., Sperry, J.S. & Adler, F.R. 2004. Murray's law and the hydraulic vs mechanical functioning of wood. Functional Ecology. 18(6), 931–938.

McGill, B.J., Enquist, B.J., Weiher, E. & Westoby, M. 2006. Rebuilding community ecology from functional traits. Trends in Ecology and Evolution. 21(4), 178–185.

Meinzer, F.C., Clearwater, M.J. & Goldstein, G. 2001. Water transport in trees: current perspectives, new insights and some controversies. Environmental and Experimental Botany. 45(3), 239–262.

Melcher, P.J., Holbrook, N.M., Burns, M.J., Zwieniecki, M.A., Cobb, A.R., Brodribb, T.J., Choat, B. & Sack, L. 2012. Measurements of stem xylem hydraulic conductivity in the laboratory and field. Methods in Ecology and Evolution. 3(4), 685–694.

Morris, H. & Jansen, S. 2016. Secondary xylem parenchyma - From classical terminology to functional traits. IAWA Journal. 37(1), 1–15.

Morris, R.J. 2010. Anthropogenic impacts on tropical forest biodiversity: a network structure and ecosystem functioning perspective. Philosophical Transactions of the Royal Society B: Biological Sciences. 365(1558), 3709–3718.

Mouillot, D., Graham, N.A.J., Villéger, S., Mason, N.W.H. & Bellwood, D.R. 2013. A functional approach reveals community responses to disturbances. Trends in Ecology and Evolution. 28(3), 167–177.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B. & Kent, J. 2000. Biodiversity hotspots for conservation priorities. Nature. 403(6772), 853–858.

Olson, M.E. & Rosell, J.A. 2013. Vessel diameter-stem diameter scaling across woody angiosperms and the ecological causes of xylem vessel diameter variation. New Phytologist. 197(4), 1204–1213.

Osazuwa-Peters, O.L., Jiménez, I., Oberle, B., Chapman, C.A. & Zanne, A.E. 2015. Selective logging: Do rates of forest turnover in stems, species composition and functional traits decrease with time since disturbance? - A 45 years perspective. Forest Ecology and Management. 357, 10–21.

Osunkoya, O.O., Sheng, T.K., Mahmud, N.A. & Damit, N. 2007. Variation in wood density, wood water content, stem growth and mortality among twenty-seven tree species in a tropical rainforest on Borneo Island. Austral Ecology. 32, 191–201.

Paine, C.E.T., Baraloto, C. & Díaz, S. 2015. Optimal strategies for sampling functional traits in species-rich forests. Functional Ecology. 29(10), 1325–1331.

Pérez-Harguindeguy, N., Díaz, S., Lavorel, S., Poorter, H., Jaureguiberry, P., Bret-Harte, M.S., Cornwell, W.K., Craine, J.M., Gurvich, D.E., Urcelay, C., Veneklaas, E.J., Reich, P.B., Poorter, L., Wright, I.J., Ray, P., Enrico, L., Pausas, J.G., Vos, A.C. de, Buchmann, N., Funes, G., Quétier, F., Hodgson, J.G., Thompson, K., Morgan, H.D., Steege, H. ter, Heijden, M.G.A. van der, Sack, L., Blonder, B., Poschlod, P., Vaieretti, M. V., Conti, G., Staver, A.C., Aquino, S. & Cornelissen, J.H.C. 2013. New Handbook for standardized measurements of plant functional traits worldwide. Australian Journal of Botany. 23(34), 167–234.

Pfeifer, M., Kor, L., Nilus, R., Turner, E., Cusack, J., Lysenko, I., Khoo, M., Chey, V.K., Chung, A.C. & Ewers, R.M. 2016. Mapping the structure of Borneo's tropical forests across a degradation gradient. Remote Sensing of Environment. 176, 84–97.

Phillips, P.D., Yasman, I., Brash, T.E. & Van Gardingen, P.R. 2002. Grouping tree species for analysis of forest data in Kalimantan (Indonesian Borneo). Forest Ecology and Management. 157(1–3), 205–216.

Picard, N., Gourlet-Fleury, S. & Forni, É. 2012. Estimating damage from selective logging and implications for tropical forest management. Canadian Journal of Forest Research. 42(3), 605–613.

Pinard, M.A. & Cropper, W.P. 2000. Simulated effects of logging on carbon storage in dipterocarp forest. Journal of Applied Ecology. 37(2), 267–284.

Poorter, L. & Bongers, F. 2006. Leaf traits are good predictors of plant performance across 53 rain forest species. Ecology. 87(7), 1733–1743.

Poorter, L. & Markesteijn, L. 2008. Seedling traits determine drought tolerance of tropical tree species. Biotropica. 40(3), 321–331.

Poorter, L., McDonald, I., Alarco, A., Fichtler, E., Licona, J.C., Peña-Claros, M., Sterk, F., Villegas, Z., Sass-Klaassen, U., Alarcón, A., Fichtler, E., Licona, J.C., Peña-Claros, M., Sterck, F., Villegas, Z. & Sass-Klaassen, U. 2010. The importance of wood traits and hydraulic conductance for the performance and life history strategies of 42 rainforest tree species. New Phytologist. 185(2), 481–492.

Pratt, R.B., Jacobsen, A.L., Ewers, F.W. & Davis, S.D. 2007. Relationships among xylem transport, biomechanics and storage in stems and roots of nine Rhamnaceae species of the California chaparral. New Phytologist. 174(4), 787–798.

Preston, K.A., Cornwell, W.K. & DeNoyer, J.L. 2006. Wood density and vessel traits as distinct correlates of ecological strategy in 51 California coast range angiosperms. New Phytologist. 170(4), 807–818.

Preston, K.A., Cornwell, W.K., Denoyer, J.L., Preston, K.A., Cornwell, W.K. & Denoyer, J.L. 2006. Wood density and vessel traits as distinct correlates of ecological strategy in 51 California Coast Range angiosperms. New Phytologist. 170(4), 807–818.

Putz, F.E., Zuidema, P.A., Synnott, T., Peña-Claros, M., Pinard, M.A., Sheil, D., Vanclay, J.K., Sist, P., Gourlet-Fleury, S., Griscom, B., Palmer, J. & Zagt, R. 2012. Sustaining conservation values in selectively logged tropical forests: The attained and the attainable. Conservation Letters. 5(4), 296–303.

Schmitz, N., Verheyden, A., Beeckman, H., Kairo, J.G. & Koedam, N. 2006. Influence of a salinity gradient on the vessel characters of the mangrove species Rhizophora mucronata. Annals of Botany. 98(6), 1321–1330.

Scholz, A., Klepsch, M., Karimi, Z. & Jansen, S. 2013. How to quantify conduits in wood? Frontiers in plant science. 4(56), 1–11.

Schreiber, S.G., Hacke, U.G. & Hamann, A. 2015. Variation of xylem vessel diameters across a climate gradient: Insight from a reciprocal transplant experiment with a widespread boreal tree. Functional Ecology. 29(11), 1392–1401.

Schume, H., Grabner, M. & Eckmüllner, O. 2004. The influence of an altered groundwater regime on vessel properties of hybrid poplar. Trees - Structure and Function. 18(2), 184–194.

Scriven, S.A., Hodgson, J.A., McClean, C.J. & Hill, J.K. 2015. Protected areas in Borneo may fail to conserve tropical forest biodiversity under climate change. Biological Conservation. 184, 414–423.

Sellin, A., Rohejärv, A. & Rahi, M. 2008. Distribution of vessel size, vessel density and xylem conducting efficiency within a crown of silver birch (Betula pendula). Trees - Structure and Function. 22(2), 205–216.

Sherwin, H.W., Pammenter, N.W., February, E., Vander Willigen, C. & Farrant, J.M. 1998. Xylem hydraulic characteristics, water relations and wood anatomy of the resurrection plant Myrothamnus flabellifolius Welw. Annals of Botany. 81(4), 567–575.

Sist, P. 2000. Reduced-impact logging in the tropics: objectives, principles and impacts. Internal Forestry Review. 2(1), 3–10.

Sist, P., Fimbel, R., Sheil, D., Nasi, R. & Chevallier, M.H. 2003. Towards sustainable management of mixed dipterocarp forests of Southeast Asia: Moving beyond minimum diameter cutting limits. Environmental Conservation. 30(4), 364–374.

Sodhi, N.S., Koh, L.P., Brook, B.W. & Ng, P.K.L. 2004. Southeast Asian biodiversity: An impending disaster. Trends in Ecology and Evolution. 19(12), 654–660.

Sperry, J.S., Hacke, U.G. & Pittermann, J. 2006. Size and function in conifer tracheids and angiosperm vessels. American Journal of Botany. 93(10), 1490–1500.

Sperry, J.S., Meinzer, F.C. & McCulloh, K.A. 2008. Safety and efficiency conflicts in hydraulic architecture: Scaling from tissues to trees. Plant, Cell and Environment. 31(5), 632–645.

Sperry, J.S., Nichols, K.L., Sullivan, J.E.M. & Eastlack, S.E. 1994. Xylem embolism in ring-porous, diffuse-porous, and coniferous trees of Northern Utah and interior Alaska. Ecology. 75(6), 1736–1752.

Still, M.J. 1993. Population dynamics and spatial patterns of dipterocarp seedlings in a tropical rain forest. United Kingdom: University of Stirling.

Suding, K.N., Collins, S.L., Gough, L., Clark, C., Cleland, E.E., Gross, K.L., Milchunas, D.G. & Pennings, S. 2005. Functional- and abundance-based mechanisms explain diversity loss due to N fertilization. Proceedings of the National Academy of Sciences. 102(12), 4387–4392.

Suding, K.N. & Goldstein, L.J. 2008. Testing the Holy Grail framework: Using functional traits to predict ecosystem change. New Phytologist. 180(3), 559–562.

Swenson, N.G. & Enquist, B.J. 2007. Ecological and evolutionary determinants of a key plant functional trait: Wood density and its community-wide variation across latitude and elevation. American Journal of Botany. 94(3), 451–459.

Tardieu, F. 2013. Plant response to environmental conditions: Assessing potential production, water demand, and negative effects of water deficit. Frontiers in Physiology. 4(7), 1–11.

Tateishi, M., Kumagai, T., Utsumi, Y., Umebayashi, T., Shiiba, Y., Inoue, K., Kaji, K., Cho, K. & Otsuki, K. 2008. Spatial variations in xylem sap flux density in evergreen oak trees with radial-porous wood: Comparisons with anatomical observations. Trees - Structure and Function. 22(1), 23–30.

Taylor, A., Gartner, B. & Morrell, J. 2002. Heartwood formation and natural durability—A review. Wood and Fiber Science. 34(4), 587–611.

Townsend, A.R., Asner, G.P. & Cleveland, C.C. 2008. The biogeochemical heterogeneity of tropical forests. Trends in Ecology and Evolution. 23(8), 424–431.

Tyree, M.T. & Ewers, F.W. 1991. The hydraulic architecture of trees and other woody plants. New Phytologist. 119(3), 345–360.

Tyree, M.T. & Sperry, J.S. 1989. Vulnerability of xylem to cavitation and embolism. Annual Review of Plant Physiology and Plant Molecular Biology. 40(1), 19–38.

Tyree, T.M. & Zimmerman, H.M. 2002. Xylem structure and the ascent of sap. Berlin: Springer.

Van Gardingen, P.R., McLeish, M.J., Phillips, P.D., Fadilah, D., Tyrie, G. & Yasman, I. 2003. Financial and ecological analysis of management options for logged-over Dipterocarp forests in Indonesian Borneo. Forest Ecology and Management 183(1–3): 1–29.

Van Nieuwstadt, M.G.L. & Sheil, D. 2005. Drought, fire and tree survival in a Borneo rain forest, East Kalimantan, Indonesia. Journal of Ecology 93(1): 191–201.

Verburg, R. & van Eijk-Bos, C. 2003. Effects of selective logging on tree diversity, composition and plant functional type patterns in a Bornean rain forest. Journal of Vegetation Science. 14(1999), 99–110.

Villela, D.M., Nascimento, M.T., de Aragao, L.E.O.C. & de Gama, D.M. 2006. Effect of selective logging on forest structure and nutrient cycling in a seasonally dry Brazilian Atlantic forest. Journal of Biogeography. 33, 506–516.

Violle, C., Navas, M., Vile, D., Kazakou, E. & Fortunel, C. 2007. Let the concept of trait be functional! Oikos. 116, 882–892.

Walsh, R.P.D. & Newbery, D.M. 1999. The ecoclimatology of Danum, Sabah, in the context of the world's rainforest regions, with particular reference to dry periods and their impact. Philosophical Transactions of the Royal Society B: Biological Sciences. 354(1391), 1869–1883.

Weber Ronald P. (ed.): Old-Growth Forests and Coniferous Forests: Ecology, Habitat and Conservation pages, ISBN 978-1-63482-369-2, 2015 Nova Publishers, Inc.

Westoby, M. 1998. A leaf-height-seed (LHS) plant ecology strategy scheme. Plant and Soil. 199(2), 213–227.

Westoby, M., Falster, D.S., Moles, A.T., Vesk, P.A. & Wright, I.J. 2002. Plant ecological strategies: some leading dimensions of variation between species. Annual Review of Ecology and Systematics. 33(1), 125–159.

Westoby, M. & Wright, I.J. 2006. Land-plant ecology on the basis of functional traits. Trends in Ecology and Evolution. 21(5), 261–268.

Whitmore, T.C. 1984. Tropical rain forests of the Far East. (2nd edition). Oxford Clarendon: Press.

Whitmore, T.C. 1998. Potential impact of climatic change on tropical rain forest seedlings and forest regeneration. Climatic Change. 39, 429–438.

Wiedenhoeft, A.C. 2010. Chapter 3: Structure and function of wood. Wood Handbook - Wood as an engineering material. United States: University of Wisconsin. Pp 1–18.

Wilcove, D.S., Giam, X., Edwards, D.P., Fisher, B. & Koh, L.P. 2013. Navjot's nightmare revisited: Logging, agriculture, and biodiversity in Southeast Asia. Trends in Ecology and Evolution. 28(9), 531–540.

Wimmer, R. 2002. Wood anatomical features in tree-rings as indicators of environmental change. Dendrochronologia 20(1–2), 21–36.

Wright, I.J., Ackerly, D.D., Bongers, F., Harms, K.E., Ibarra-Manriquez, G., Martinez-Ramos, M., Mazer, S.J., Muller-Landau, H.C., Paz, H., Pitman, N.C.A., Poorter, L., Silman, M.R., Vriesendorp, C.F., Webb, C.O., Westoby, M. & Wright, S.J. 2007. Relationships among ecologically important dimensions of plant trait variation in seven neotropical forests. Annals of Botany. 99(5), 1003–1015.

Wright, S.J., Muller-landau, H.C., Condit, R. & Hubbell, S.P. 2003. Gap-dependent recruitment, realized vital rates, and size distributions of tropical trees. Ecology. 84(12), 3174–3185.

Zakaria, R., Nik Rosely, N.F., Mansor, M. & Zakaria, M.Y. 2008. The distribution of Macaranga, Genus (Family Euphorbiaceae) in Penang Island, Peninsular Malaysia. Journal of Bioscience. 19(2), 91–99.

Zanne, A.E., Westoby, M., Falster, D.S., Ackerly, D.D., Loarie, S.R., Arnold, S.E.J. & Coomes, D.A. 2010. Angiosperm wood structure: Global patterns in vessel anatomy and their relation to wood density and potential conductivity. American Journal of Botany. 97(2), 207–215.

Zheng, J. & Martínez-Cabrera, H.I. 2013. Wood anatomical correlates with theoretical conductivity and wood density across China: Evolutionary evidence of the functional differentiation of axial and radial parenchyma. Annals of Botany. 112(5), 927–935.

Ziemińska, K., Butler, D.W., Gleason, S.M., Wright, I.J. & Westoby, M. 2013. Fibre wall and lumen fractions drive wood density variation across 24 Australian angiosperms. AoB Plants 5, plt046.