EFFECTS OF MANAGEMENT REGIMES ON GROWTH ATTRIBUTES AND CARBON DENSITY IN TROPICAL FORESTS

By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Understanding the effect of management regimes on the long-term growth attributes and carbon density in tropical forests is essential in ensuring a sustained timber yield and safeguarding their role as carbon sinks to combat climate change. Previous studies have shown that logged-over tropical forests were not regenerating according to the Selective Management System's assumption. These findings were based on short-term data growth, a single study site and censuses carried out after extreme drought events. Thirty long-term permanent sample plots with a total size of 30 ha were analysed to understand the effect of Selective Management System regimes and the actual growth rate of logged-over forests. The perturbation of extreme drought events was also evaluated to understand the effect of climate change. These permanent sample plots were managed under three regimes: unlogged, moderately logged (all Dipterocarp $\geq$ 65 cm and Non-dipterocarps $\geq$60 cm dbh logged) and intensely logged (all Dipterocarps $\geq$ 50 cm and Non-dipterocarps $\geq$45 cm dbh logged). The plots were allowed to regenerate naturally without any silvicultural treatments carried out post-logging. The growth attributes used for this study were mortality, recruitment, stem density, basal area, timber volume and aboveground carbon density. The results showed no significant differences between moderately (772.85 stems ha^{-1}; 52.38 m^3 ha^{-1}; 87.38 tonnes C ha^{-1}) and intensely logged forests (665.22 stems ha^{-1}; 25.61 m^3 ha^{-1}; 58.36 tonnes C ha^{-1}) in forest stem density, timber volume and aboveground carbon density one year post-logging. Both logged forests showed a significant difference from unlogged forests (1,192.15 stems ha^{-1}; 219.93 m^3 ha^{-1}; 228.35 tonnes C ha^{-1}). Only basal area was significantly different between unlogged, moderately logged and intensely logged at 36.71 m^2 ha^{-1}, 16.64 m^2 ha^{-1} and 11.96 m^2 ha^{-1}, respectively. Annual mortality and recruitment rate were also significantly different between unlogged forests (1.8% yr^{-1}; 0.5% yr^{-1}) compared to the moderately logged (4.0% yr^{-1}; 2.1% yr^{-1}) and intensely logged (3.9% yr^{-1}; 2.1% yr^{-1}) forest. Thirty years post-logging, the intensely logged regime had a higher growth rate, especially for forest stem density (-9.54 stems ha^{-1} yr^{-1}), basal area (0.22 m^{2} ha^{-1} yr^{-1}), timber volume (1.85 m^{3} ha^{-1} yr^{-1}) and aboveground carbon density (1.65 tonnes C ha^{-1} yr^{-1}) compared to moderately logged (-12.91 stems ha^{-1} yr^{-1}; 0.12 m^{2} ha^{-1} yr^{-1};1.47 m^{3} ha^{-1} yr^{-1}; 1.16 tonnes C ha^{-1} yr^{-1}) and unlogged (-15.09 stems ha^{-1}; 0.02 m^{2} ha^{-1} yr^{-1}; 1.18 m^{3} ha^{-1} yr^{-1}; 0.57 tonnes C ha^{-1} yr^{-1}) forests. The actual recovery growth of timber volume (1.47 - 1.85 m^{3} ha^{-1} yr^{-1}) and aboveground carbon density (1.16 – 1.65 tonnes C ha^{-1} yr^{-1}) for logged forests were below the national average and required more than 30 years to recover to the pre-logging status. The extreme drought threshold of -1.70 midterm Standardized Precipitation Evapotranspiration Index impacted tropical forest growth and frequently occurred from 1990-2019. The extreme drought increased the mortality rate (4.0% yr^{-1}) and decreased the recruitment (1.8 % yr$^{-1)}$, forests stem density (-17.95 stems ha^{-1} yr^{-1}), basal area (0.17 m^{2} ha^{-1} yr^{-1}) and aboveground carbon density (1.6 tonnes C ha^{-1} yr^{-1}) in logged forests. The unlogged forests were affected by extreme drought by increased mortality (3.5% yr^{-1}), recruitment (8.9% yr^{-1}), stem density (60.09 stems ha^{-1} yr^{-1}) and basal area (0.62 m^{2} ha^{-1} yr^{-1}) but decreased timber volume (-1.3 m^{3} ha^{-1} yr^{-1}). Enhancing current practices such as longer cutting cycles, dipterocarps and non-dipterocarps tree species volume control, enrichment planting and climbers cutting, in addition to practising Reduced Impact Logging, will reduce the impact of logging and improve the growth and recovery rate of logged-over forests.

Keywords: Aboveground carbon density, Growth attributes, Management regimes, Sustainable Forest Management, Tropical Forest

SDG: GOAL 15: Life on Land

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KESAN REJIM PENGURUSAN TERHADAP ATRIBUT TUMBESARAN DAN KEPADATAN KARBON DI HUTAN TROPIKA

Oleh

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Memahami kesan rejim pengurusan terhadap atribut pertumbuhan jangka panjang dan kepadatan karbon hutan tropika adalah penting dalam memastikan pengeluaran kayu balak yang berkekalan, di samping memelihara peranan hutan sebagai penyerap karbon dalam menangani perubahan iklim. Kajian terdahulu menunjukkan bahawa prestasi pertumbuhan hutan tropika telah dibalak tidak seperti kadar pertumbuhan Sistem Pengurusan Memilih. Penemuan-penemuan ini adalah berdasarkan pertumbuhan jangka pendek, satu lokaliti kajian serta beberapa siri bancian yang dijalankan selepas kejadian kemarau yang melampau. Tiga puluh plot sampel kekal jangka panjang dengan saiz berjumlah 30 ha telah dianalisis untuk melihat kesan rejim Sistem Pengurusan Memilih dan kadar tumbesaran sebenar hutan yang dibalak. Kesan kemarau melampau terhadap kadar tumbesaran hutan tropika juga dinilai untuk memahami impak perubahan iklim. Plot sampel kekal ini diuruskan bawah tiga rejim pengurusan iaitu tidak dibalak, pembalakan sederhana (semua Dipterocarpa $\geq$ 65cm dan bukan Dipterokarpa $\geq$60cm dbh dibalak) dan pembalakan intensif (semua Dipterokarpa $\geq$ 50 cm dan bukan Dipterokarpa $\geq$45 cm dbh dibalak). Plot yang dibalak dibiarkan tumbuh semula secara semula jadi tanpa sebarang rawatan silvikultur. Atribut tumbesaran yang digunakan dalam kajian ini adalah kadar kematian, penokokan, kepadatan dirian hutan, keluasan pangkal, isipadu kayu dan kepadatan karbon atas tanah. Hasil kajian menunjukkan bahawa tiada perbezaan antara rejim sederhana (772.85 pokok ha^{-1}; 665.22 pokok/ha; 52.38 m^3 ha^{-1}; 87.38 tan C ha^{-1}) dan rejim intensif (665.22 pokok ha^{-1}; 25.61 m^3 ha^{-1}; 58.36 tan C ha^{-1}) terhadap kepadatan dirian hutan, isipadu kayu, dan kepadatan karbon atas tanah. Kedua-dua hutan dibalak mempunyai perbezaan signifikan dengan hutan tidak dibalak (1,192.15 pokok ha^{-1}; 219.93 m^3 ha^{-1}; 228.35 tan C ha^{-1}). Hanya keluasan pangkal mempunyai perbezaan signifikan di antara hutan tidak dibalak (36.71 m^2 ha^{-1}), rejim sederhana (16.64 m^2 ha^{-1}) dan rejim intensif (11.96 m^2 ha^{-1}). Kadar kematian dan penokokan untuk hutan tidak dibalak (1.8% tahun^{-1}; 0.5% /tahun) berbanding rejim sederhana (4.0% tahun^{-1}; 2.1% /tahun) dan rejim intensif (3.9% tahun^{-1}; 2.1% tahun^{-1}). Rejim intensif mempunyai kadar tumbesaran yang lebih tinggi terutamanya untuk kepadatan dirian hutan (-9.54 pokok ha^{-1} tahun^{-1}), keluasan pangkal (0.22 m^{2} ha^{-1} tahun^{-1}), isipadu kayu (1.85 m^{3} ha^{-1} tahun^{-1}) dan kepadatan karbon atas tanah (1.65 tan C ha^{-1} tahun^{-1}) berbanding rejim sederhana (-12.91 pokok ha^{-1} tahun^{-1}; 0.12 m^{2} ha^{-1} tahun^{-1}; 1.47 m^{3} ha^{-1} tahun^{-1}; 1.16 tan C ha^{-1} tahun^{-1}) dan hutan tidak dibalak (-15.09 pokok ha^{-1} tahun^{-1}; 0.02 m^{2} ha^{-1} tahun^{-1}; 1.18 m^{3} ha^{-1} tahun^{-1}; 0.57 tan C ha^{-1} tahun^{-1}). Prestasi pertumbuhan isipadu kayu (1.47 - 1.85 m^{3} ha^{-1} tahun^{-1}) dan kepadatan karbon atas (1.16 – 1.65 tan C ha^{-1} tahun^{-1}) hutan dibalak adalah bawah purata nasional dan memerlukan lebih daripada 30 tahun untuk pulih kepada status pra-pembalakan. Nilai ambang kemarau melampau -1.70 berdasarkan *Standardized Precipitation-Evapotranspiration Index* mempunyai kesan atas pertumbuhan hutan tropika dan berlaku dengan kerap sejak tahun 1990 - 2019. Kemarau melampau meningkatkan kadar kematian (4.0% tahun-^{1}) dan mengurangkan penokokan (1.8% tahun^{-1}), kepadatan pokok (-17.95 pokok ha^{-1} tahun^{-1}), keluasan pangkal (0.17 m^{2} ha^{-1} tahun^{-1}) dan kepadatan karbon atas tanah (1.60 tan C ha^{-1} tahun^{-1}) dalam hutan dibalak. Hutan tidak dibalak terjejas oleh kemarau yang melampau dengan peningkatan kematian (3.5% tahun-^{1}), penokokan (8.8% tahun-^{1}), kepadatan pokok (60.09 pokok ha^{-1} tahun^{-1}) dan keluasan pangkal (0.62 m^{2} ha^{-1} tahun^{-1}), tetapi mengalami penurunan isipadu kayu (-1.3 m^{3} ha^{-1} tahun^{-1}). Penambahbaikan kepada amalan semasa seperti pusingan tebangan yang lebih panjang, penetapan had isipadu dibalak spesies pokok dipterokarpa – bukan-dipterokarpa, tanaman mengaya, pemotongan akar pepanjat, dan amalan Pembalakan Berimpak Rendah akan mengurangkan kesan pembalakan dan meningkatkan kadar tumbesaran dan pemulihan hutan yang dibalak.

Kata Kunci: Kepadatan karbon diatas tanah, Atribut tumbesaran, Rejim pengurusan, Pengurusan hutan secara berkekalan, Hutan tropika

SDG: MATLAMAT 15: Kehidupan di Darat

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ACD	Aboveground Carbon Density
c	carbon
CI	confidence Interval
cm	centimetre
CO_2	carbon dioxide
dbh	diameter at breast height
ha	hectare
ha^{-1}	per hectare
m	meter
m^2	meter square
m^3	cubic meter
SMS	Selective Management System
SPEI	Standardized Precipitation Evapotranspiration Index
yr^{-1}	per year

CHAPTER 1

INTRODUCTION

1.1 General Background

Tropical forests serve as an important biome in regulating climate globally by exchanging atmospheric water and carbon, including supplying renewable raw materials (Lewis et al., 2015). Forests that are managed for sustained timber, fibre or energy yield while maintaining or increasing forest carbon stock are the most significant mitigation benefit in addressing climate change (Nabuurs et al., 2007; Pathak et al., 2022). It is estimated that tropical forests contain 141–159 billion tonnes C and sequester 0.47–1.3 billion tonnes C $yr^{-1,}$ equivalent to 8–13% of anthropogenic CO_2 emitted globally (Mackey et al., 2020). Any changes in mortality or growth of trees will have an impact on global CO_2 sequestration (Hubau et al., 2020).

Sustainable management of tropical forests is essential to ensure the sustained yield of timber and, at the same time, sequester atmospheric carbon to combat climate change. Implementing sustainable forest management strategies that will contribute to these benefits will require an understanding of the logging effect on forest growth attributes such as mortality, recruitment, stem density, basal area, volume and aboveground carbon density (Ding et al., 2019). Removing large commercial trees is the primary driver of forest degradation during logging. It is well-known that many smaller trees are damaged during logging and may die before becoming available for future harvests (Osone et al., 2016). Selective logging, widely practised in Southeast Asia, greatly impacts stand structure, species composition and regeneration dynamics of tropical forests (Hayward et al., 2021; Okuda et al., 2003; Okuda et al., 2019; Yamada et al., 2013). However, these logged-over forests still possess significant elements of their original biodiversity and will recover over time, especially with silvicultural treatments such as enrichment planting using indigenous tree species (Berry et al., 2010; Edwards et al., 2011; Philipson et al., 2020). Currently, 1.15 billion ha or 28.3% of the world's forest areas are designated primarily as production forests (FAO, 2020a).

Tropical forests in Peninsular Malaysia are categorised into State Land Forest, Wildlife Reserved and Permanent Reserved Forest. The Permanent Reserved Forest is managed under the principle of sustainable forest management, while the other two categories are meant for development and wildlife conservation, respectively. The Permanent Reserved Forest constitutes about 4.94 million ha, and only 2.92 million ha is classified as production forests under sustained yield (FDPM, 2023b). The remaining 2.02 million ha are managed as protection forests without any logging activities.

The production forests are managed under the Selective Management System (SMS) formulated in 1978. The system is a 30-year logging cycle based on growth performance as follows: (i) mean diameter growth of 0.77 cm yr^{-1}; (ii) mean gross volume growth of 2.75 m^3 ha^{-1} yr^{-1}; (iii) annual mortality rate of 0.90%; and (iv) annual ingrowth of 0.60% (FDPM, 2003).

These growth performance assumptions are based on tree inventory data obtained for trees greater than 30 cm diameter on 200 plots of 0.4 ha established in 1974 and re-censused for three years distributed across primary forests and in logged hill forests subjected to silvicultural treatments (FAO, 1978). Based on these assumptions, the system prescribes cutting limits of 45 cm dbh for non-dipterocarps and 50 cm dbh for dipterocarps species; and availability of 32 sound residual trees of 30–45 cm dbh per hectare post-logging. The system expects these residual trees to grow to become the next crop trees after 30 years and the logged-over forests are adequately stocked for a net volume of between 40–45 m^3 ha^{-1} (Thang 1987).

Logging may influence the value of future harvests by differentially affecting species in different groups. In Peninsular Malaysia, advances in wood processing and market development allow the commercial exploitation of all tree species that reach the minimum sizes to be harvested (Thang, 1987). However, timber derived from the Dipterocarpaceae family (the dipterocarps) attracts a higher price due to market acceptance and properties that make it suitable for various uses (Saw & Sam, 1999). As a result, the production of timber derived from dipterocarps amounted to 1.82 million m^3 or 46.6% of the total in Peninsular Malaysia in 2019 (FDPM, 2020). In order to sustain this yield, the SMS prescribes that the percentage of dipterocarps among residual trees should not be less than that in the pre-logging stand (Yong, 1996).

Permanent Reserved Forests are also important in Malaysia's commitment to achieving Nationally Determined Contribution under the United Nations Framework Convention on Climate Change. Sustainable forest management generates the most considerable sustained mitigation to combat climate change. In Malaysia, sustainably managed forests such as Permanent Reserved Forests removed 225.97 million tonnes of C yr^{-1} (MNRE, 2018) compared to the total emission of 317,627 mil tonnes C yr^{-1} for all sectors (MESTECC, 2018).

Climate change increases air temperature and changes precipitation regimes, including the timing, amount and inter-annual variability of rainfall, which significantly impact global forestry (Keenan, 2015) The concern about these impacts is not only on the ecosystems but also the ecological services such as timber supply, carbon storage, or biodiversity conservation (Bouchard et al., 2019). As for forest management, the potential effects are forest health, regeneration success, growth and productivity, distribution and composition of species, forest structure, and age-class distribution (Halofsky et al., 2018). Tree growth was observed to be increasing in some forests under longer growing seasons and warmer temperatures. However, shifts in vegetation distribution, including increased tree mortality due to drought or heat, were also recorded (Bouchard et al., 2019; Brecka et al., 2018; Keenan, 2015).

1.2 Problem Statement

Limited studies were conducted to investigate the growth attributes of logged-over forests in Peninsular Malaysia. Yong (1996) and Ismail (2007) studies reported that the volume growth was lower and the mortality rate higher than what was assumed by SMS, which concluded that the 30 years logging cycle for SMS was insufficient for a sustainable yield. However, their studies were based on short-term plots (an average of 9.4 years, with the shortest at two years and the longest at 15 years) and involved only one location (Yong, 1996). The timing of the last census carried out after an extreme drought event in late 1997 to early 1998 halted the growth of trees and increased mortality rate also affected the result. Further research on the actual growth performance using long-term plots similar to the SMS cutting cycles of 25-30 years and incorporating a comparison of logged and unlogged plots is required.

Yong (1996) and Ismail (2007) focused more on the recovery, and there were limited discussions on how management regimes impacted the tropical forests, especially immediately after logging operations. Management regimes affect the amount of basal area, volume and aboveground carbon stock removed, which eventually influences the recovery period (Putz et al., 2022). Tropical forests under management regime with lower logging intensity had a faster recovery rate of basal area, volume or aboveground carbon stock due to the higher number of stands retained post-logging (Okuda et al., 2021; Rutishauser et al., 2015) Understanding the impact of different management regimes to tropical forests one year post-logging and the actual recovery rate will assist forest managers in predicting the recovery period and practical cutting cycles for logged-over tropical forests.

The SMS management regime also prescribes the availability of 32 sound residual trees of 30–45 cm dbh per hectare post-logging. These residual trees will grow to become the next crop trees after 30 years. However, limited information is available on the number of residual trees that will fulfil the prediction of growing into the 45–50 cm diameter class. Dipterocarps are dominant trees in tropical forests and have a higher growth compared to other tree species (Brearley, 2012). The impact of management regime removing mature dipterocarps, leaving only small and intermediate-sized trees, remains poorly understood (Ashton & Kettle, 2012).

A lower growth rate may also result in a lower rate of carbon sequester as half of wood biomass is considered carbon stock. Sustainably managed Permanent Reserved Forests are important to Malaysia as these forests contribute to achieving Nationally Determined Contribution under the United Nations Framework Convention on Climate Change (MEWA, 2020). A lower carbon sequestration rate will affect Malaysia in achieving its Nationally Determined

Contribution. It is imperative to understand the actual long-term recovery rate for aboveground carbon stock in logged-over forests to assist forest managers in enhancing management practices to combat climate change.

Southeast Asia has been experiencing an increased temperature rate of 0.14 °C to 0.20 °C per decade, including a rising number of hot days and warm nights and a decline in cooler weather (Hijioka et al., 2014; Sentian et al., 2022). For the past four decades, Peninsular Malaysia has been experiencing an increased mean temperature of 0.13 °C to 0.24 °C which corresponded with increasing trend of drought occurrences (Fung et al., 2020; MEWA, 2020). This changing climate condition may affect the growth attributes of forests and carbon sequestration.

There were studies carried out on the impact of changing climate conditions on the tropical forest in Peninsular Malaysia. However, these studies were limited to forest basal area growth responding to temperature (Feeley et al., 2007); small trees responding to solar radiation (Dong et al., 2012); CO_2 effect on seedling growth (Tomimatsu et al., 2014); precipitation, temperature, relative humidity and vapour pressure deficit effect on cell layer growth (Wang & Hamzah, 2018); flowering condition for the dipterocarps (Chen et al., 2018; Yeoh et al., 2017); and forest structure and function sensitivity to air temperature, soil temperature, precipitation, total cloud cover, specific humidity and wind velocity (Sato, 2009). No study has been conducted to understand how extreme drought affects the growth attributes and aboveground carbon density in logged and unlogged tropical forests especially in Peninsular Malaysia. This lack of information leads to forest managers not incorporating drought adaptation into the current forest management practices even though with an increasing trends of extreme drought events in Peninsular Malaysia.

A forest is in the event of drought when the potential evapotranspiration is higher than the monthly precipitation (Aragão et al., 2007; Malhi et al., 2009). As occurrence of drought can be more than in a month period, it is importance to have a drought index that can assess drought duration and intensity. The Standard Precipitation Evapotranspiration Index (SPEI) is able to assess drought duration and intensity by using precipitation and temperature compared to other indices such as Standard Precipitation Index or Palmer Drought Severity Index (Fung et al., 2020).

Based on the discussion above, this study will answer the following questions: (i) are there any differences in the effect of management regimes on tropical forests one year post-logging? (ii) what is the actual growth rate for logged-over forests? and (iii) how does an extreme drought event affect tropical forests growth attributes? These insights will provide new information and understanding of the effect of the management regimes and the actual recovery rate of logged tropical forests, including the response of tropical forests to extreme drought events.

1.3 Objectives of Research

This research aims to determine the effect of management regimes and extreme drought on the growth attributes and aboveground carbon density of tropical forests in Peninsular Malaysia by analysing the growth attributes of long-term permanent sample plots. The specific objectives are:

i. To analyse the effect of management regimes one on mortality, recruitment, stem density, basal area, timber volume and aboveground carbon density; and

iii. To analyse tropical forest extreme drought perturbation based on the Standardised Precipitation Evapotranspiration Index (SPEI).

The results from this study will provide new information on effect logging intensity on mortality, recruitment, stem density, basal area, timber volume and aboveground carbon density in logged forests one year post-logging. The growth rate derived from long-term growth plots will better assist forest managers in deciding the next and future cutting cycles that will optimise the production of timbers from logged forests. The information on tropical forests' perturbation to extreme drought events will provide new understanding to forest managers in formulating adaptation practices for forest management.

1.4 Research Hypothesis

This study will test the hypothesis that (i) different management regimes do not have a significant effect on logged forests one year post-logging; (ii) different management regimes do not significantly affect the growth rate of logged forests managed under the Selective Management System; and (ii) extreme drought events do not affect tropical forests growth.

1.5 Limitation of Study

The limitation of this study is that there is no pre-logging inventory record found for each study sites. Records on the exact timber volume and number of trees extracted from the study sites were also not found as these reports are usually kept by the contractors and the State Forestry Department. These manual reports were usually dispose-off by the respective State Forestry Department, five years after logging operation ceased to operate.

REFERENCES

Adams, H. D., Zeppel, M. J. B., Anderegg, W. R. L., Hartmann, H., Landhäusser, S. M., Tissue, D. T., Huxman, T. E., Hudson, P. J., Franz, T. E., Allen, C. D., Anderegg, L. D. L., Barron-Gafford, G. A., Beerling, D. J., Breshears, D. D., Brodribb, T. J., Bugmann, H., Cobb, R. C., Collins, A. D., Dickman, L. T., … McDowell, N. G. (2017). A multi-species synthesis of physiological mechanisms in drought-induced tree mortality. *Nature Ecology and Evolution*, *1*(9), 1285–1291. https://doi.org/10.1038/s41559-017-0248-x

Aleixo, I., Norris, D., Hemerik, L., Barbosa, A., Prata, E., Costa, F., & Poorter, L. (2019). Amazonian rainforest tree mortality driven by climate and functional traits. *Nature Climate Change*, *9*(5), 384–388. https://doi.org/10.1038/s41558-019-0458-0

Aragão, L. E. O. C., Malhi, Y., Roman-Cuesta, R. M., Saatchi, S., Anderson, L. O., & Shimabukuro, Y. E. (2007). Spatial patterns and fire response of recent Amazonian droughts. *Geophysical Research Letters*, *34*(7), 1–5. https://doi.org/10.1029/2006GL028946

Ashton, P. (1988). Dipterocarp biology as a window to the understanding of tropical forest structure. *Ann. Rev. Ecol. Syst*, *19*, 347–370. www.annualreviews.org

Ashton, P., & Kettle, C. J. (2012). Dipterocarp biology as a window to the understanding of tropical forest structure: Where are we looking now? *Biotropica*, *44*(5), 575–576. https://doi.org/10.1111/j.1744-7429.2012.00913.x

Banin, L., Lewis, S. L., Lopez-Gonzalez, G., Baker, T. R., Quesada, C. A., Chao, K. J., Burslem, D. F. R. P., Nilus, R., Abu Salim, K., Keeling, H. C., Tan, S., Davies, S. J., Monteagudo Mendoza, A., Vásquez, R., Lloyd, J., Neill, D. A., Pitman, N., & Phillips, O. L. (2014). Tropical forest wood production: A cross-continental comparison. *Journal of Ecology*, *102*(4), 1025–1037. https://doi.org/10.1111/1365-2745.12263

Bansal, M., Morley, R. J., Nagaraju, S. K., Dutta, S., Kumar Mishra, A., Selveraj, J., Kumar, S., Niyolia, D., Medigeshi Harish, S., Babiker Abdelrahim, O., eldin Hasan, S., Rangana Ramesh, B., Dayanandan, S., Morley, H. P., Ashton, P. S., & Prasad, V. (2022). Southeast Asian Dipterocarp origin and diversification driven by Africa-India floristic interchange. *Science*, *375*, 455–460. https://www.science.org

Bates, D., Mächler, M., Bolker, B. M., & Walker, S. C. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Beguería, S., Vicente-Serrano, S. M., Reig, F., & Latorre, B. (2014). Standardized precipitation evapotranspiration index (SPEI) revisited: Parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *International Journal of Climatology*, *34*(10), 3001–3023. https://doi.org/10.1002/joc.3887

Bennett, A. C., Mcdowell, N. G., Allen, C. D., & Anderson-Teixeira, K. J. (2015). Larger trees suffer most during drought in forests worldwide. *Nature Plants*, *1*, 1–5. https://doi.org/10.1038/nplants.2015.139

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. https://doi.org/10.1007/s10531-010-9779-z

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. https://doi.org/10.1016/j.foreco.2005.07.009

Bouchard, M., Aquilué, N., Périé, C., & Lambert, M. (2019). Tree species persistence under warming conditions : A key driver of forest response to climate change. *Forest Ecology and Management*, *442*, 96–104. https://doi.org/10.1016/j.foreco.2019.03.040

Brearley, F. Q. (2012). Ectomycorrhizal associations of the Dipterocarpaceae. *Biotropica*, *44*(5), 637–648.

https://doi.org/10.1111/j.1744-7429.2012.00862.x

Brearley, F. Q., Banin, L. F., & Saner, Philippe. (2016). The ecology of the Asian dipterocarps. *Plant Ecology and Diversity*, *9*(5–6), 429–436. https://doi.org/10.1080/17550874.2017.1285363

Brecka, A. F. J., Shahi, Chander., & Chen, H. Y. H. (2018). Climate change impacts on boreal forest timber supply. *Forest Policy and Economics*, *92*, 11–21. https://doi.org/10.1016/j.forpol.2018.03.010

Brienen, R. J. W., Phillips, O. L., Feldpausch, T. R., Gloor, E., Baker, T. R., Lloyd, J., Lopez-Gonzalez, G., Monteagudo-Mendoza, A., Malhi, Y., Lewis, S. L., Vásquez Martinez, R., Alexiades, M., Álvarez Dávila, E., Alvarez-Loayza, P., Andrade, A., Aragaõ, L. E. O. C., Araujo-Murakami, A., Arets, E. J. M. M., Arroyo, L., … Zagt, R. J. (2015a). Long-term decline of the Amazon carbon sink. *Nature*, *519*(7543), 344–348. https://doi.org/10.1038/nature14283

Burges, F. P. (1968). An ecological study of the hill forests of the Malay Peninsula. *The Malayan Forester*, *31*(4), 314–325.

Cazzolla Gatti, R., Castaldi, S., Lindsell, J. A., Coomes, D. A., Marchetti, M., Maesano, M., Di Paola, A., Paparella, F., & Valentini, R. (2014). The impact of selective logging and clearcutting on forest structure, tree diversity and above-ground biomass of African tropical forests. *Ecological Research*, *30*(1), 119–132. https://doi.org/10.1007/s11284-014-1217-3

Chave, J., Andalo, C., Brown, S., Cairns, M. A., Chambers, J. Q., Eamus, D., Folster, H., F., Fromard., Higuci, N., Kira, T., Lescure, J. P., Nelson, D. W., Ogawa, H., Puig, H., Riera, B., & Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Ecosystem Ecology*, *145*, 87–99. https://doi.org/10.1007/s00442-005-0100-x

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B. C., Duque, A., Eid, T., Fearnside, P. M., Goodman, R. C., Henry, M., Martínez-Yrízar, A., Mugasha, W. A., Muller-Landau, H. C., Mencuccini, M., Nelson, B. W., Ngomanda, A., Nogueira, E. M., Ortiz-Malavassi, E., … Vieilledent, G. (2014). Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, *20*(10), 3177–3190. https://doi.org/10.1111/gcb.12629

Chen, Y. Y., Satake, A., Sun, I. F., Kosugi, Y., Tani, M., Numata, S., Hubbell, S. P., Fletcher, C., Nur Supardi, M. N., & Wright, S. J. (2018). Species-specific flowering cues among general flowering Shorea species at the Pasoh Research Forest, Malaysia. *Journal of Ecology*, *106*(2), 586–598. https://doi.org/10.1111/1365-2745.12836

Clark, D. A. (2004). Sources or sinks? The responses of tropical forests to current and future climate and atmospheric composition. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *359*(1443), 477–491. https://doi.org/10.1098/rstb.2003.1426

Clark, D. A. (2007). Detecting tropical forests ’ responses to global climatic and atmospheric change : Current challenges and a way forward. *Biotropica*, *39*(1), 4–19.

Condit, R., Hubbell, S. P., & Foster, R. B. (1995). Mortality rates of 205 Neotropical tree and shrub species and the impact of a severe drought. *Ecological Monographs*, *65*(4), 419–439.

Dahalan, M. P. (2021). *Konsep dan Amalan Sistem Pengurusan Memilih (Selective Management System) di Semenajung Malaysia. Sesi Konsultasi Bersama Pihak Berkepentingan Bagi Semakan Semula Konsep dan AmalanSistem Pengurusan Memilih.*

Dayanandan, S., Ashton, P. S., Williams, S. M., & Primack, R. B. (1999). Phylogeny of the tropical tree family Dipterocarpaceae based on nucleotide sequences of the chloroplast rbcL gene. *American Journal of Botany*, *86*(8), 1182–1190. https://doi.org/10.2307/2656982 de Avila, A. L., Schwartz, G., Ruschel, A. R., Lopes, J. do C., Silva, J. N. M., Carvalho, J. O. P. de, Dormann, C. F., Mazzei, L., Soares, M. H. M., & Bauhus, J. (2017). Recruitment, growth and recovery of commercial tree species over 30 years following logging and thinning in a tropical rain forest. *Forest Ecology and Management*, *385*, 225–235. https://doi.org/10.1016/j.foreco.2016.11.039

de Luis, M., Novak, K., Čufar, K., & Raventós, J. (2009). Size mediated climate-growth relationships in Pinus halepensis and Pinus pinea. *Trees - Structure and Function*, *23*(5), 1065–1073. https://doi.org/10.1007/s00468-009-0349-5

Deb, J. C., Phinn, S., Butt, N., & McAlpine, C. A. (2018). Climate change impacts on tropical forests: Identifying risks for tropical Asia. *Journal of Tropical Forest Science*, *30*(2), 182–194.

https://doi.org/10.26525/jtfs2018.30.2.182194

Ding, Y., Zang, R., Lu, X., & Huang, J. (2019). Functional features of tropical montane rain forests along a logging intensity gradient. *Ecological Indicators*, *97*, 311–318. https://doi.org/10.1016/j.ecolind.2018.10.030

Dionisio, L. F. S., Schwartz, G., Lopes, J. do C., & Oliveira, F. de A. (2018). Growth, mortality, and recruitment of tree species in an Amazonian rainforest over 13 years of reduced impact logging. *Forest Ecology and Management*, *430*(August), 150–156.

https://doi.org/10.1016/j.foreco.2018.08.024

Dong, S. X., Davies, S. J., Ashton, P. S., Bunyavejchewin, S., Nur Supardi, M. N., Kassim, A. R., Tan, S., & Moorcroft, P. R. (2012). Variability in solar radiation and temperature explains observed patterns and trends in tree growth rates across four tropical forests. *Proceedings of the Royal Society B: Biological Sciences*, *279*(1744), 3923–3931. https://doi.org/10.1098/rspb.2012.1124

Edwards, D. P., Larsen, T. H., Docherty, T. D. S., Ansell, F. A., Hsu, W. W., Derhé, 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. https://doi.org/10.1098/rspb.2010.1062

Ellis, P. W., Gopalakrishna, T., Goodman, R. C., Putz, F. E., Roopsind, A., Umunay, P. M., Zalman, J., Ellis, E. A., Mo, K., Gregoire, T. G., & Griscom, B. W. (2019). Reduced-impact logging for climate change mitigation (RIL-C) can halve selective logging emissions from tropical forests. *Forest Ecology and Management*, *438*, 255–266. https://doi.org/10.1016/j.foreco.2019.02.004

Esquivel-Muelbert, A., Baker, T. R., Dexter, K. G., Lewis, S. L., Brienen, R. J. W., Feldpausch, T. R., Lloyd, J., Monteagudo-Mendoza, A., Arroyo, L., Álvarez-Dávila, E., Higuchi, N., Marimon, B. S., Marimon-Junior, B. H., Silveira, M., Vilanova, E., Gloor, E., Malhi, Y., Chave, J., Barlow, J., … Phillips, O. L. (2019). Compositional response of Amazon forests to climate change. *Global Change Biology*, *25*(1), 39–56. https://doi.org/10.1111/gcb.14413

FAO. (1973). *A National Forest Inventory of West Malaysia 1970 - 1972*. FAO.

FAO. (1978). *Forestry development, Peninsular Malaysia. Project results, conclusions and recommendations.*

FAO.(2020a). *Forest Resources Assessment 2020 : Main report.* https://doi.org/https://doi.org/10.4060/ca9825en

FAO. (2020b). *Global Forest Resource Assessment 2020: Malaysia report.*

FDPM.(2003). *Forestry Manual: Vol. III*. Forestry Department Peninsular Malaysia.

FDPM.(2019). *Forestry Statistic Peninsular Malaysia*. Forestry Department Peninsular Malaysia.

FDPM.(2023a). *Forest Management Certification*. . https://www.forestry.gov.my/en/2016-06-07-02-31-39/forest-management-certification

FDPM.(2023b). *Forestry Statistic*. https://www.forestry.gov.my/en/2016-06-07-02-53-46/2016-06-07-03-12-29

Feeley, K. J., Joseph Wright, S., Nur Supardi, M. N., Kassim, A. R., & Davies, S. J. (2007). Decelerating growth in tropical forest trees. *Ecology Letters*, *10*(6), 461–469. https://doi.org/10.1111/j.1461-0248.2007.01033.x

Feldpausch, T. R., Lloyd, J., Lewis, S. L., Brienen, R. J. W., Gloor, M., Monteagudo Mendoza, A., Lopez-Gonzalez, G., Banin, L., Abu Salim, K., Affum-Baffoe, K., Alexiades, M., Almeida, S., Amaral, I., Andrade, A., Aragão, L. E. O. C., Araujo Murakami, A., Arets, E. J. M., Arroyo, L., Aymard C., G. A., … Phillips, O. L. (2012). Tree height integrated into pantropical forest biomass estimates. *Biogeosciences*, *9*(8), 3381–3403. https://doi.org/10.5194/bg-9-3381-2012

Fontes, C. G., Chambers, J. Q., & Higuchi, N. (2018). Revealing the causes and temporal distribution of tree mortality in Central Amazonia. *Forest Ecology and Management*, *424*(May), 177–183. https://doi.org/10.1016/j.foreco.2018.05.002

Fung, K. F., Huang, Y. F., & Koo, C. H. (2020). Assessing drought conditions through temporal pattern, spatial characteristic and operational accuracy indicated by SPI and SPEI: case analysis for Peninsular Malaysia. *Natural Hazards*, *103*(2), 2071–2101. https://doi.org/10.1007/s11069-020-04072-y

Gaui, T. D., Costa, F. R. C., Coelho de Souza, F., Amaral, M. R. M., de Carvalho, D. C., Reis, F. Q., & Higuchi, N. (2019). Long-term effect of selective logging on floristic composition: A 25 year experiment in the Brazilian Amazon. *Forest Ecology and Management*, *440*, 258–266. https://doi.org/10.1016/j.foreco.2019.02.033

Gora, E. M., & Esquivel-Muelbert, A. (2021). Implications of size-dependent tree mortality for tropical forest carbon dynamics. In *Nature Plants* (Vol. 7, Issue 4, pp. 384–391). Nature Research. https://doi.org/10.1038/s41477-021-00879-0

Granzow-de, Í., Lloret, F., Ruiz, J. E., & Vandermeer, J. H. (2012). Tree mortality following ENSO-associated fires and drought in lowland rain forests of Eastern Nicaragua. *Forest Ecology and Management*, *265*, 248–257. https://doi.org/10.1016/j.foreco.2011.10.034

Halofsky, J. E., Andrews-key, S. A., Edwards, J. E., Johnston, M. H., Nelson, H. W., Peterson, D. L., Schmitt, K. M., Swanston, C. W., & Williamson, T. B. (2018). Forest Ecology and Management Adapting forest management to climate change : The state of science and applications in Canada and the United States. *Forest Ecology and Management*, *October 2017*, 0–1. https://doi.org/10.1016/j.foreco.2018.02.037

Harris, I., Osborn, T. J. , Jones, P., & Lister, D. (2020). Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data*, *7*(109), 1–18. https://doi.org/10.1038/s41597-020-0453-3

Hayward, R. M., Banin, L. F., Burslem, D. F. R. P., Chapman, D. S., Philipson, C. D., Cutler, M. E. J., Reynolds, G., Nilus, R., & Dent, D. H. (2021). Three decades of post-logging tree community recovery in naturally regenerating and actively restored dipterocarp forest in Borneo. *Forest Ecology and Management*, *488*, 1–11. https://doi.org/10.1016/j.foreco.2021.119036

Hector, A. (2015). *New statistics with R : An introduction for biologists*. Oxford University Press.

Hijioka, Y. , E. Lin, J.J. Pereira, R.T. Corlett, X. Cui, G.E. Insarov, R.D. Lasco, E. Lindgren, & A. Surjan. (2014). *Asia. In Climate Change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (V. R. , Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, & L.L. White, Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Hubau, W., Lewis, S. L., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A., Daniels, A. K., Ewango, C. E. N., Fauset, S., Mukinzi, J. M., Sheil, D., Sonké, B., Sullivan, M. J. P., Sunderland, T. C. H., Taedoumg, H., Thomas, S. C., White, L. J. T., Abernethy, K. A., Adu-Bredu, S., … Zemagho, L. (2020). Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature*, *579*(7797), 80–87. https://doi.org/10.1038/s41586-020-2035-0

Ismail, H. (2007). *Optimization of cutting cycle and growing stock for sustainable harvest in timber production forests in Peninsular Malaysia.* [Unpublished Doctoral dissertation]. Universiti Putra Malaysia.

Ismail, H., Nurhajar, Z. S., Wan Shukri, W. A., Samsudin, M., & Harfendy, O. (2010). Second growth forests: Are they growing and have they recovered? *The Malaysian Forester*, *73*(2), 171–185.

ITTO. (2015). *Voluntary guidelines for the sustainable management of natural forest. ITTO Policy and Development Series 20.* www.itto.int

JPSM. (2007). *Laporan Inventori Hutan Nasional Ke Empat Semenanjung Malaysia*.

JPSM. (2012a). *Panduan analisa data tumbesaran (Growth) dan tumbesaran dan pengeluaran (Growth & Yield)*. Jabatan Perhutanan Semenanjung Malaysia.

JPSM. (2012b). *Spesies Dipterokarpa Terancam di Semenanjung Malaysia* (L.S.L Chua, M.Shuhaida, & B.Aslina, Eds.). JPSM.

JPSM. (2013). *Nota Panduan kajian “Tumbesaran” dan “Tumbesaran dan Pengeluaran.”* JPSM.

JPSM. (2014). *Pekeliling Ketua Pengarah Perhutanan Semenanjung Malaysia Bilangan 3 Tahun 2014: Peraturan Memotong Akar/Pepanjat (CL) dan Memotong Bertam*.

Kato, R., Yoshiya, T., & Ogawa, H. (1978). Plant Biomass and growth increment studies in Pasoh Forest. *Malayan Nature Journal*, *30*(2), 211–224.

Katovai, E., Katovai, D. D., Campbell, M., Laurance, S. G., Edwards, W., & Laurance, W. F. (2021). Structural Recovery of Logged Forests in the Solomon Islands : Implications for Conservation and Management. *Tropical Conservation Science*, *14*, 1–13.

https://doi.org/10.1177/19400829211028125

Keenan, R. J. (2015). Climate change impacts and adaptation in forest management : A review. *Annals of Forest Science*, *72*, 145–167. https://doi.org/10.1007/s13595-014-0446-5

Kenzo, T., Furutani, R., Hattori, D., Kendawang, J. J., Tanaka, S., Sakurai, K., & Ninomiya, I. (2009). Allometric equations for accurate estimation of above-ground biomass in logged-over tropical rainforests in Sarawak, Malaysia. *Journal of Forest Research*, *14*(6), 365–372. https://doi.org/10.1007/s10310-009-0149-1

Lewis, R. A., & Davis, S. R. (2015). Forest certification, institutional capacity, and learning : An analysis of the impacts of the Malaysian Timber Certification Scheme. *Forest Policy and Economics*, *52*, 18–26. https://doi.org/10.1016/j.forpol.2014.12.011

Lewis, S. L., Edwards, D. P., & Galbraith, D. (2015). Increasing human dominance of tropical forests. *Science*, *349*, 827–831.

Lewis, S. L., Phillips, O. L., Sheil, D., Vinceti, B., Baker, T. R., Brown, S., Graham, A. W., Higuchi, N., Hilbert, D. W., Laurance, W. F., Lejoly, J., Malhi, Y., Monteagudo, A., Vargas, P. N., Sonké, B., Nur Supardi, M. N., Terborgh, J. W., & Martínez, R. V. (2004). Tropical forest tree mortality, recruitment and turnover rates: Calculation, interpretation and comparison when census intervals vary. *Journal of Ecology*, *92*(6), 929–944. https://doi.org/10.1111/j.0022-0477.2004.00923.x

Lewis, S. L., Sonké, B., Sunderland, T., Begne, S. K., Lopez-Gonzalez, G., van der Heijden, G. M. F., Phillips, O. L., Affum-Baffoe, K., Baker, T. R., Banin, L., Bastin, J. F., Beeckman, H., Boeckx, P., Bogaert, J., De Cannière, C., Chezeaux, E., Clark, C. J., Collins, M., Djagbletey, G., … Zemagho, L. (2013). Above-ground biomass and structure of 260 African tropical forests. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *368*, 1–14. https://doi.org/10.1098/ rstb.2012.0295

M. Mohd Nasir, A.M. Richard, Nor Akhirrudin, M., Endot, S., & A. Latiff. (2017). New Discovery of Shorea kuantanensis (Dipterocarpaceae) in Peninsular Malaysia. *The Malaysian Forester*, *80*(2), 125–128.

Mackey, B., Kormos, C. F., Keith, H., Moomaw, W. R., Houghton, R. A., Mittermeier, R. A., Hole, D., & Hugh, S. (2020). Understanding the importance of primary tropical forest protection as a mitigation strategy. *Mitigation and Adaptation Strategies for Global Change*, *25*(5), 763–787. https://doi.org/10.1007/s11027-019-09891-4

Malhi, Y., Aragão, L. E. O. C., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., Sitch, S., McSweeney, C., & Meir, P. (2009). Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(49), 20610–20615. https://doi.org/10.1073/pnas.0804619106

Manokaran, N., & Kochummen, K. M. (1987). Recruitment, growth and mortality of tree species in a lowland dipterocarp forest in Peninsular Malaysia.

Journal of Tropical Ecology, *3*(4), 315–330. https://doi.org/10.1017/S0266467400002303

Margrove, J. A., Burslem, D. F. R. P., Ghazoul, J., Khoo, E., Kettle, C. J., & Maycock, C. R. (2015). Impacts of an extreme precipitation event on dipterocarp mortality and habitat filtering in a Bornean tropical rain forest. *Biotropica*, *47*(1), 66–76. https://doi.org/10.1111/btp.12189

Martin, A. R., & Thomas, S. C. (2011). A reassessment of carbon content in tropical trees. *PLoS ONE*, *6*(8), 1–9. https://doi.org/10.1371/journal. pone.0023533

McDowell, N., Allen, C. D., Anderson-Teixeira, K., Brando, P., Brienen, R., Chambers, J., Christoffersen, B., Davies, S., Doughty, C., Duque, A., Espirito-Santo, F., Fisher, R., Fontes, C. G., Galbraith, D., Goodsman, D., Grossiord, C., Hartmann, H., Holm, J., Johnson, D. J., … Xu, X. (2018). Drivers and mechanisms of tree mortality in moist tropical forests. *New Phytologist*, *219*(3), 851–869. https://doi.org/10.1111/ nph.15027

MESTECC. (2018). Malaysia Third National Communication and Second Biennial Update Report to the UNFCCC. In *Ministry of Energy, Science, Technology, Environment and Climate Change*.

MEWA. (2020). *Malaysia Third Biennial Update Report to UNFCCC*.

MNRE. (2014). *Malaysia's Submission on Reference Levels for REDD+ Results Based Payments under UNFCCC*.

MNRE. (2018). *Malaysia's submission on reference levels for REDD+ results based payments under UNFCCC*.

Mohd., R., Hadi, Y., Mohamed, S., Mukhtar, A., & Abdul Ghani, A. N. (1988). Sustained Yield As An Objective of Malaysian Forest Management. *The Malaysian Forester*, *51*(1), 6–22.

MTCC. (2023). *Certified forest.* Malaysia Timber Certification Council.

Myster, R. W. (2016). The Physical Structure of Forests in the Amazon Basin: a Review. *Botanical Review*, *82*(4), 407–427. https://doi.org/10.1007/s12229-016-9174-x

Nabuurs, G. J. , O. Masera, K. Andrasko, P. Benitez-Ponce, R. Boer, M. Dutschke, E. Elsiddig, J. Ford-Robertson, P. Frumhoff, T. Karjalainen, O. Krankina, W.A. Kurz, M. Matsumoto, W. Oyhantcabal, N.H. Ravindranath, M.J. Sanz Sanchez, & X. Zhang. (2007). *Summary for Policy Makers. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)]. Cambridge Press, Cambrige*.

Nepstad, D. C., Moutinha, P., Dias-Filho, M. B., Dabidson, E., Cardinot, G., Markewitz, D., Figueiredo, R., Vianna, N., Chambers, J., Ray, D., Guerreiros, J. B., Lefebvre, P., Sternberg, M., Barros, L., Ishida, F. Y., Tohvler, I., Belk, E., Kalif, K., & Schwalbe, K. (2002). The effects of partial throughfall exclusion on canopy processes, aboveground production, and biogeochemistry of an Amazon forest. *Journal of Geophysical Research*, *107*(D20), 1–18. https://doi.org/10.1029/2001jd000360

Nepstad, D. C., Veríssimo, A., Alencar, A., Nobre, C., Lima, E., Lefebvre, P., Schlesinger, P., Potter, C., Moutinho, P., Mendoza, E., Cochrane, M., & Brooks, V. (1999). Large-scale impoverishment of amazonian forests by logging and fire. *Nature*, *398*(6727), 505–508. https://doi.org/10.1038/19066

Okuda, T. , Suzuki, M. , Adachi, N. , Seng Quah, E. , Hussein, A. , & Manokaran, N. ,. (2003). Effect of selective logging on canopy and stand structure and tree species composition in a lowland dipterocarp forest in Peninsular Malaysia. *Forest Ecology and Management* , *175*, 297–320.

Okuda, T., Shima, K., Yamada, T., Hosaka, T., Niiyama, K., Kosugi, Y., Yoneda, T., Hashim, M., Quah, E. S., & Saw, L. G. (2021). Spatiotemporal changes in biomass after selective logging in a lowland tropical rainforest in Peninsular Malaysia. *Tropics*, *30*(2), 11–23. https://doi.org/10.3759/TROPICS.MS20-03

Okuda, T., Yamada, T., Hosaka, T., Miyasaku, N., Hashim, M., Lau, A. M. S., & Saw, L. G. (2019). Canopy height recovery after selective logging in a lowland tropical rain forest. *Forest Ecology and Management*, *442*(April), 117–123. https://doi.org/10.1016/j.foreco.2019.03.045

Osone, Y., Toma, T., Warsudi, Sutedjo, & Sato, T. (2016). High stocks of coarse woody debris in a tropical rainforest, East Kalimantan: Coupled impact of forest fires and selective logging. *Forest Ecology and Management*, *374*, 93–101. https://doi.org/10.1016/j.foreco.2016.04.027

Ovenden, T. S., Perks, M. P., Clarke, T. K., Mencuccini, M., & Jump, A. S. (2021). Threshold response to extreme drought shifts inter-tree growth dominance in Pinus sylvestris. *Frontiers in Forests and Global Change*, *4*, 1–12. https://doi.org/10.3389/ffgc.2021.737342

Pathak, M., Slade, R., Shuckla, P. R., Skea, J., Pichs-Madruga, R., & Urge-Vorsatz, d. (2022). *Mitigation of Climate Change Climate Change 2022 Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. www.ipcc.ch

Pearson, T. R. H., Brown, S., Murray, L., & Sidman, G. (2017). Greenhouse gas emissions from tropical forest degradation: An underestimated source. *Carbon Balance and Management*, *12*(1). https://doi.org/10.1186/s13021-017-0072-2

Philipson, C. D., Cutler, M. E. J., Brodrick, P. G., Asner, G. P., Boyd, D. S., Moura Costa, P., Fiddes, J., Foody, G. M., Van Der Heijden, G. M. F., Ledo, A., Lincoln, P. R., Margrove, J. A., Martin, R. E., Milne, S., Pinard, M. A., Reynolds, G., Snoep, M., Tangki, H., Wai, S., … Burslem, D. F. R. P. (2020). Active restoration accelerates the carbon recovery of human-modified tropical forests. *Science*, *369*, 838–841. https://www.science.org

Powers, J. S., Vargas G., G., Brodribb, T. J., Schwartz, N. B., Pérez-Aviles, D., Smith-Martin, C. M., Becknell, J. M., Aureli, F., Blanco, R., Calderón-Morales, E., Calvo-Alvarado, J. C., Calvo-Obando, A. J., Chavarría, M. M., Carvajal-Vanegas, D., Jiménez-Rodríguez, C. D., Murillo Chacon, E., Schaffner, C. M., Werden, L. K., Xu, X., & Medvigy, D. (2020). A catastrophic tropical drought kills hydraulically vulnerable tree species. *Global Change Biology*, *26*(5), 3122–3133. https://doi.org/10.1111/gcb.15037

Primack, R., & Corlett, R. (2005). *Tropical Rainforests: An Ecological and Biogeographical Comparison*. Blackwell Publishing.

Putz, F. E., Coley, P. D., Lu, K., Montalvo, A., & Aiello, A. (1983). Uprooting and snapping of trees: structural determinants and ecological sequences. *Canadian Journal of Forest Research*, *13*(5), 1011–1020.

Putz, F. E., Romero, C., Sist, P., Schwartz, G., Thompson, I., Roopsind, A., Ruslandi, R., Medjibe, V., & Ellis, P. (2022). Sustained Timber Yield Claims, Considerations, and Tradeoffs for Selectively Logged Forests. *PNAS Nexus*. https://doi.org/10.1093/pnasnexus/pgac102

Qie, L., Lewis, S. L., Sullivan, M. J. P., Lopez-Gonzalez, G., Pickavance, G. C., Sunderland, T., Ashton, P., Hubau, W., Abu Salim, K., Aiba, S. I., Banin, L. F., Berry, N., Brearley, F. Q., Burslem, D. F. R. P., Dančák, M., Davies, S. J., Fredriksson, G., Hamer, K. C., Hédl, R., … Phillips, O. L. (2017). Long-term carbon sink in Borneo's forests halted by drought and vulnerable to edge effects. *Nature Communications*, *8*(1966), 1–11. https://doi.org/10.1038/s41467-017-01997-0

Rozak, A. H., Rutishauser, E., Raulund-Rasmussen, K., & Sist, P. (2018). The imprint of logging on tropical forest carbon stocks: A Bornean case-study. *Forest Ecology and Management*, *417*, 154–166. https://doi.org/10.1016/j.foreco.2018.03.007

Rozendaal, D. M. A., Phillips, O. L., Lewis, S. L., Affum-baffoe, K., Alvarez-Davila, Andrade, A., Aragao, L. E. O. C., Araujo-Murakami, A., Baker, T. R., Brienen, R. J., Camargo, J. L. C., Comiskey, J. A., Kamden, M. N. D., Fauset, S., Feldpausch, T. R., Killeen, T. J., Laurance, W. F., Laurance, S. G. W., Lovejoy, T., … Vanderwell, M. C. (2020). Competition influences tree growth, but not mortality, across environmental gradients in Amazonia and tropical Africa. *Ecology*, *101*(7), 1–11.

https://doi.org/10.1002/ecy.3052

Ruslandi, Cropper, W. P., & Putz, F. E. (2017). Tree diameter increments following silvicultural treatments in a dipterocarp forest in Kalimantan, Indonesia: A mixed-effects modelling approach. *Forest Ecology and Management*, *396*, 195–206. https://doi.org/10.1016/j.foreco.2017.04.025

Rutishauser, E., Hérault, B., Baraloto, C., Blanc, L., Descroix, L., Sotta, E. D., Ferreira, J., Kanashiro, M., Mazzei, L., D'Oliveira, M. V. N., De Oliveira, L. C., Peña-Claros, M., Putz, F. E., Ruschel, A. R., Rodney, K., Roopsind, A., Shenkin, A., Da Silva, K. E., De Souza, C. R., … Sist, P. (2015). Rapid tree carbon stock recovery in managed Amazonian forests. *Current Biology*, *25*(18), R787–R788. https://doi.org/10.1016/j.cub.2015.07.034

Sato, H. (2009). Simulation of the vegetation structure and function in a Malaysian tropical rain forest using the individual-based dynamic vegetation model SEIB-DGVM. *Forest Ecology and Management*, *257*(11), 2277–2286. https://doi.org/10.1016/j.foreco.2009.03.002

Saw, L. G., & Sam, Y. Y. (1999). Conservation of Dipterocarpaceae in Peninsular Malaysia. *Journal of Tropical Forest Science*, *12*(3), 593–615.

Seng, H. W., Ratnam, W., Noor, S. M., & Clyde, M. M. (2004). The effects of the timing and method of logging on forest structure in Peninsular Malaysia. *Forest Ecology and Management*, *203*(1–3), 209–228. https://doi.org/10.1016/j.foreco.2004.07.050

Sentian, J., Payus, C. M., Herman, F., & Kong, V. W. Y. (2022). Climate change scenarios over Southeast Asia. *APN Science Bulletin*, *12*(1), 102–122. https://doi.org/10.30852/sb.2022.1927

Sevanto, S., Mcdowell, N. G., Dickman, L. T., Pangle, R., & Pockman, W. T. (2014). How do trees die? A test of the hydraulic failure and carbon starvation hypotheses. *Plant, Cell and Environment*, *37*(1), 153–161. https://doi.org/10.1111/pce.12141

Sheil, D., Burslem, D. F. R. P., & Alder, D. (1995). The interpretation and misinterpretation of mortality rate measures. *The Journal of Ecology*, *83*(2), 331–333. https://doi.org/10.2307/2261571

Sheil, D., Jennings, S., & Savill, P. (2000). Long-term permanent plot observations of vegetation dynamics in Budongo , a Ugandan rainforest. *Journal of Tropical Ecology*, *16*, 765–800. https://doi.org/10.1017/S0266467400001723

Shek, D. T. L., & Ma, C. M. S. (2011). Longitudinal data analyses using linear mixed models in SPSS: Concepts, procedures and illustrations. *TheScientificWorldJournal*, *11*, 42–76. https://doi.org/10.1100/tsw.2011.2

Shenkin, A., Bolker, B., Peña-Claros, M., Licona, J. C., & Putz, F. E. (2015). Fates of trees damaged by logging in Amazonian Bolivia. *Forest Ecology and Management*, *357*, 50–59. https://doi.org/10.1016/j.foreco.2015.08.009

Sist, P., Mazzei, L., Blanc, L., & Rutishauser, E. (2014). Large trees as key elements of carbon storage and dynamics after selective logging in the Eastern Amazon. *Forest Ecology and Management*, *318*, 103–109. https://doi.org/10.1016/j.foreco.2014.01.005

Sullivan, M. J. P., Lewis, S. L., Affum-Baffoe, K., Castilho, C., Costa, F., Sanchez, A. C., Ewango, C. E. N., Hubau, W., Marimon, B., Monteagudo-Mendoza, A., Qie, L., Sonké, B., Martinez, R. V., Baker, T. R., Brienen, R. J. W., Feldpausch, T. R., Galbraith, D., Gloor, M., Malhi, Y., … Phillips, O. L. (2020). Long-term thermal sensitivity of earth's tropical forests. *Science*, *368*(6493), 869–874. https://doi.org/10.1126/science.aaw7578

Swaine, M. D., Lieberman, D., & Putz, F. E. (1987). The dynamics of tree populations in tropical forest: A review. *Journal of Tropical Ecology*, *3*(4), 359–366. https://doi.org/10.1017/S0266467400002339

Symington, C. F. (2004). Ecological distribution of the Dipterocarps in the Malay Peninsula. In P. S. , Ashton & Appanah (Eds.), *Forester's Manual of Dipterocarpaceae* (Vol. 16, pp. 14–32). Forest Research Institute Malaysia & Malaysian Nature Society.

Talbot, J., Lewis, S. L., Lopez-Gonzalez, G., Brienen, R. J. W., Monteagudo, A., Baker, T. R., Feldpausch, T. R., Malhi, Y., Vanderwel, M., Araujo Murakami, A., Arroyo, L. P., Chao, K. J., Erwin, T., van der Heijden, G., Keeling, H., Killeen, T., Neill, D., Núñez Vargas, P., Parada Gutierrez, G. A., … Phillips, O. L. (2014). Methods to estimate aboveground wood productivity from long-term forest inventory plots. *Forest Ecology and Management*, *320*, 30–38. https://doi.org/10.1016/j.foreco.2014.02.021

Thang, H. C. (1987). Forest management systems for tropical high forest, with special reference to Peninsular Malaysia. *Forest Ecology and Management*, *21*(1–2), 3–20. https://doi.org/10.1016/0378-1127(87)90069-7

Tomimatsu, H., Iio, A., Adachi, M., Saw, L. G., Fletcher, C., & Tang, Y. (2014). High CO2 concentration increases relative leaf carbon gain under dynamic light in Dipterocarpus sublamellatus seedlings in a tropical rain forest, Malaysia. *Tree Physiology*, *34*(9), 944–954. https://doi.org/10.1093/treephys/tpu066

Trugman, A. T., Detto, M., Bartlett, M. K., Medvigy, D., Anderegg, W. R. L., Schwalm, C., Schaffer, B., & Pacala, S. W. (2018). Tree carbon allocation explains forest drought-kill and recovery patterns. *Ecology Letters*, *21*(10), 1552–1560. https://doi.org/10.1111/ele.13136

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, *23*(7), 1696–1718. https://doi.org/10.1175/2009JCLI2909.1

Walker, A. P., De Kauwe, M. G., Bastos, A., Belmecheri, S., Georgiou, K., Keeling, R. F., McMahon, S. M., Medlyn, B. E., Moore, D. J. P., Norby, R. J., Zaehle, S., Anderson-Teixeira, K. J., Battipaglia, G., Brienen, R. J. W., Cabugao, K. G., Cailleret, M., Campbell, E., Canadell, J. G., Ciais, P., … Zuidema, P. A. (2021). Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO2. *New Phytologist*, *229*(5), 2413–2445. https://doi.org/10.1111/nph.16866

Wang, K. H., & Hamzah, M. Z. (2018). Different cambial activities in response to climatic factors of three Malaysian rainforest Shorea species with different stem diameters. *Trees* , *32*, 1519–1530. https://doi.org/10.1007/s00468-018-1730-z

Whittaker, R. H. (1975). *Communities and ecosytems* (II).

Yamada, T., Hosaka, T., Okuda, T., & Kassim, A. R. (2013). Effects of 50 years of selective logging on demography of trees in a Malaysian lowland forest. *Forest Ecology and Management*, *310*, 531–538. https://doi.org/10.1016/j.foreco.2013.08.057

Yeoh, S. H., Satake, A., Numata, S., Ichie, T., Lee, S. L., Basherudin, N., Muhammad, N., Kondo, T., Otani, T., Hashim, M., & Tani, N. (2017). Unravelling proximate cues of mass flowering in the tropical forests of South-East Asia from gene expression analyses. *Molecular Ecology*, *26*, 5074–5085. https://doi.org/10.1111/mec.14257

Yong, T. K. (1996). *Growth and development of a selectively cut hill dipterocarp forest in Peninsular Malaysia* [Unpublished Master dissertation]. University of British Columbia.

Zhang, Q., Shao, M., Jia, X., & Wei, X. (2017). Relationship of climatic and forest factors to drought- and heat-induced tree mortality. *PLoS ONE*, *12*(1). https://doi.org/10.1371/journal.pone.0169770

Zhao, D., Bullock, B. P., Montes, C. R., & Wang, M. (2020). Rethinking maximum stand basal area and maximum SDI from the aspect of stand dynamics. *Forest Ecology and Management*, *475*, 1–10. https://doi.org/10.1016/j.foreco.2020.118462

Zuur, A. F., Ieno, E. N., & Smith, G. M. (2007). *Analysing Ecological data*. Springer. https://doi.org/https://doi.org/10.1007/978-0-387-45972-1