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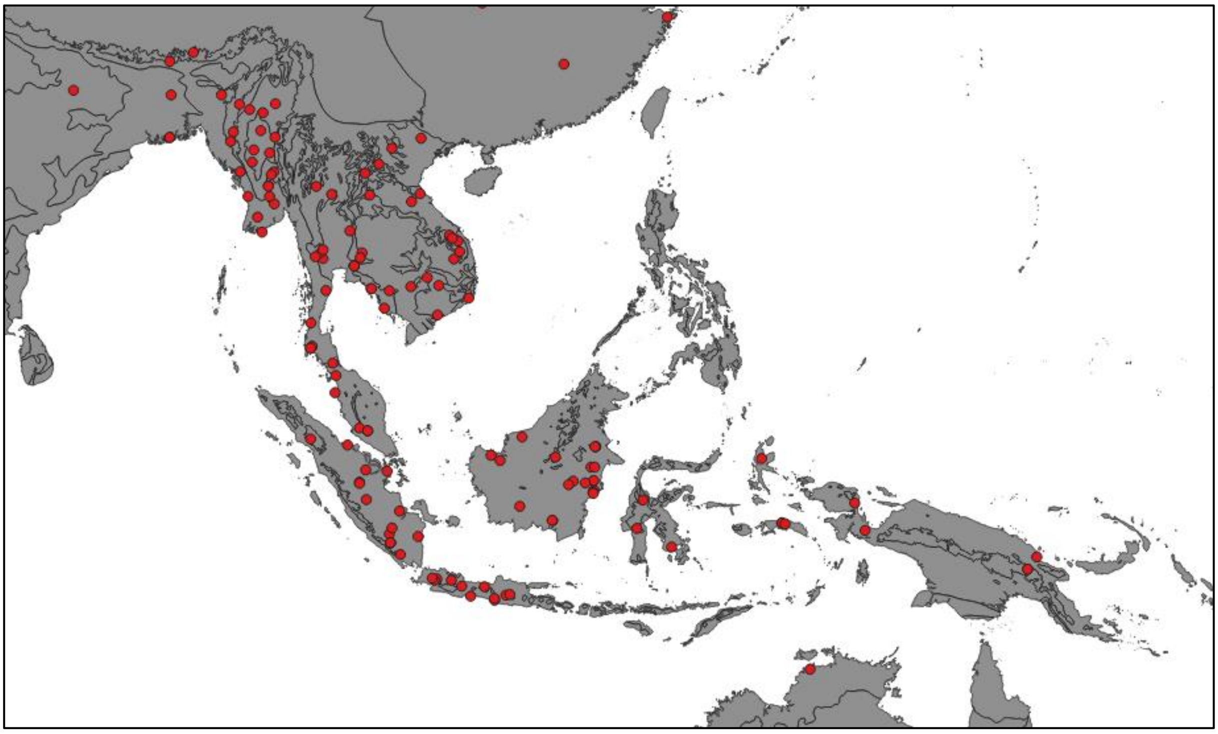

INVENTORY OF VOLUME AND BIOMASS TREE ALLOMETRIC MODELS FOR SOUTHEAST ASIA: 2018 UPDATE

UN-REDD Programme

August 2018
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The UN-REDD Programme, implemented by FAO, UNDP and UN Environment, has two components: (i) assisting developing countries prepare and implement national REDD strategies and mechanisms; (ii) supporting the development of normative solutions and standardized approaches based on sound science for a REDD instrument linked with the UNFCCC. The programme helps empower countries to manage their REDD processes and will facilitate access to financial and technical assistance tailored to the specific needs of the countries.

The application of UNDP, UN Environment and FAO rights-based and participatory approaches will also help ensure the rights of indigenous and forest-dwelling people are protected and the active involvement of local communities and relevant stakeholders and institutions in the design and implementation of REDD plans.

The programme is implemented through the UN Joint Programmes modalities, enabling rapid initiation of programme implementation and channelling of funds for REDD efforts, building on the in-country presence of UN agencies as a crucial support structure for countries. The UN-REDD Programme encourage coordinated and collaborative UN support to countries, thus maximizing efficiencies and effectiveness of the organizations' collective input, consistent with the "One UN" approach advocated by UN members.

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Disclaimer

The conclusions given in this information product are considered appropriate at the time of its preparation. They may be modified in the light of further knowledge gained at subsequent stages of the project.

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Executive Summary

Forested ecosystems perform an important function in the global carbon cycle. However, land use changes are disrupting the ability of forest to act as a carbon sink. A detailed understanding of forest quantification is needed to ensure efficient and accurate measurement, reporting and verification (MRV) of carbon stocks. Monitoring and MRV systems are necessary for participating in REDD+, therefore allometric models are needed to estimate biomass stocks and carbon storage. Tree allometric models are developed to relate an easily measured tree parameter to its biomass or volume, and have a wide range of forest-related applications. Developing new allometric models is costly and time-consuming, therefore allometric equations are often scarce and hard to obtain.

This report provides an update of the GlobAllomeTree database of tree allometric equations with a focus on Southeast Asia. In total, 993 new allometric models from 80 scientific articles have been included in the database. Data was sourced for 7 Southeast Asian countries, whilst Indonesia provided over one third of the total number of models. The models covered 88 taxonomic families, whilst 326 genera and 558 species were represented. The most common species recorded were *Tectona grandis* and *Acacia mangium*. The majority of the models were developed from measurements taken on trees in forest systems in the tropical rainforest ecozone.

Despite the large number of equations that were found, gaps still remain in the literature and further research is recommended where appropriate. Indonesia, Myanmar and Thailand were over-represented in this compilation, yet no data came from vast sections of each country. More research is recommended in the remaining Southeast Asian countries and further compilations are required to maintain the integrity of the allometric models found in GlobAllomeTree.

Introduction

Forest ecosystems perform an important role as a global terrestrial carbon sink as they have the ability to sequester significant amounts of carbon dioxide from the atmosphere through photosynthesis. Land use changes are causing a release of carbon from forest ecosystems, creating a dual role for forests as both a carbon sink and a carbon source. As much as 20% of global greenhouse gas emissions are attributed to changes in forest cover such as deforestation and forest degradation (Guadalupe *et al.*, 2018). Despite the importance of forests in the global carbon cycle, our understanding of forest carbon quantification must be improved. Therefore, there is a need for efficient and accurate systems for Monitoring, Reporting and Verification (MRV) of carbon stocks.

Reducing emissions from deforestation and forest degradation (REDD) may lead to a significant increase in sequestered forest carbon. In turn, it is an important component of climate change mitigation. Under the REDD+ mechanism, participating countries must have monitoring and MRV systems in place to capture their carbon inventory (UNFCCC, 2011). Methods for estimating biomass stocks and carbon storage are critical in the commercialization of carbon sinks and the effectiveness of REDD+.

The development of appropriate models to estimate tree biomass is an important aspect of forest management. Tree biomass, volume and carbon stocks can be estimated using several methods (Valentini *et al.*, 2000; Zheng *et al.*, 2004; Luyssaert *et al.*, 2007; Vashum and Jayakumar, 2012), however the use of allometric models is considered the most common method (Crow and Schlaegel, 1988; Chave *et al.*, 2014; Sandeep *et al.*, 2016). Tree allometric models can be used in a variety of functions, from supporting the commercial exploitation of timber to carbon estimation.

Allometric models relate easily measured tree parameters such as diameter at breast height or tree height with the tree's biomass or volume. Models are developed using the latest regression techniques with respect to factors that affect tree growth such as the tree species, age, location, climate and other abiotic factors. Despite their apparent simplicity, tree allometric models must be developed with care as inappropriate use of allometric models can introduce bias and error into carbon estimation (Picard, Saint-André and Henry, 2012; Birigazzi *et al.*, 2013; Sandeep *et al.*, 2014).

There is a large body of scientific work dealing specifically with tree allometric models, however many of these models are not readily accessible. There are numerous reasons for this, including the difficulty of retrieving scientific articles, private company reports, and post-graduate theses as well as comprehension of technical reports. Developing allometric models requires the felling of a sample of trees and is expensive, time-consuming and destructive (Sandeep *et al.*, 2014; Yuen, Fung and Ziegler, 2016). It is beneficial that research is readily available and not unnecessarily duplicated.

In order to provide free and easy access to allometric models, The Food and Agricultural Organization of the United Nations (FAO) launched the GlobAllomeTree platform (Henry *et al.*, 2013). The platform offers allometric models for several species of tree, shrub, lianas and mangroves mined from scientific literature. The models may further be classified by country, tree component, ecological zone or ecosystem allowing users to define their search. Models can be validated using Fantallometrik (Trotta *et al.*, 2013), a flexible software designed to compare models and calculate tree volume, biomass and carbon stocks.

Tropical forests are highly productive systems, capable of sequestering large amounts of carbon. They are said to constitute 60% of global forest cover (Dixon *et al.*, 1994; Sandeep *et al.*, 2016) and up to 60% of global photosynthesis (Malhi and Grace, 2000). Amongst the world's forest, tropical forests have the largest potential for climate change mitigation (Lasco, 2002). Therefore, there is great potential within the world's tropical forests to attract financial resources for afforestation and reforestation activities. Southeast Asia comprises a large amount of the world's tropical forest and therefore has an important role to play. However, there is a lack of data in Southeast Asia that makes carbon estimation difficult (Pan *et al.*, 2011).

Aim of the Report

The objective of this report is to provide an update of the GlobAllomeTree database with relevant tree allometric models for seven Southeast Asian countries - Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Thailand and Viet Nam. Models are obtained from both peer-reviewed scientific literature and national technical reports and validated using methods previously described by Birigazzi *et al*., (2015) through the Fantallometrik tool.

This report is part of the MRV series of allometric equation database reports of the UN-REDD Programme, together with those for Cambodia (Sarin *et al.*, 2012), Viet Nam (Inoguchi *et al.*, 2013), the United Republic of Tanzania (Vyamana and Sola, 2013), The Pacific (Poultouchidou, Monnier and Birigazzi, 2013), North America (Birigazzi *et al.*, 2013), and Bangladesh (Akhter, Hossain and Birigazzi, 2013), South Asia (Sandeep *et al.*, 2014) and China (Cheng, Gamarra and Birigazzi, 2014),.

Data Collection

In order to obtain tree allometric models, we undertook a review of the relevant literature on volume and biomass stocks for Southeast Asia. Documents were provided by in-country contacts with useful allometric models not yet found in the database. The literature was largely sourced from peer reviewed journal articles found through online libraries (Google Scholar, Scopus etc.), forestry journals, unpublished postgraduate research and reports from forestry departments. Two regional reviews (Anitha *et al.*, 2015; Yuen, Fung and Ziegler, 2016) were found to be particularly useful in locating further models. As the last review was completed in 2013, searches largely focused on the period of 2014 to present.

The literature review produced 80 documents containing 993 new allometric models for Southeast Asian trees, shrubs, bamboos, mangroves and lianas. Data was extracted from the articles and entered into the GlobAllomeTree Excel spreadsheet as per the instructions provided in the tutorial (Baldasso *et al.*, 2012). As several models accounted for multiple species or multiple locations, 4266 lines of data were needed to represent the models. The spreadsheet provides space to input sufficient information to make it easier for users to locate relevant models. The original sources were checked for input error using Fantallometrik (Trotta *et al.*, 2013) before the models were entered into our database. The database has 73 columns that can be used to enter the required data for each model. It can be broken down into the following sections:

- Plant ecology; population and ecosystem
- Geographic location where the model was developed including the Global Ecological Zone
- Model parameters including the variables (see Appendix 1 for a full list)
- Vegetative components (see Figure 1)
- Taxonomy, including family, genus and species
- Bibliography
- Model accuracy and precision statistics

The location coordinates for each study are normally provided in the paper, however when they were not provided we obtained coordinates through a Google Earth search. When more than one location was used in the data collection and they were adjacent, the mid-point between the sites was used. When models were designed for species in multiple locations, entries into the database were duplicated for each unique location. Locations were categorized according to Global Ecological Zone under the following five ecological classification systems: FAO (FAO, 2001), Udvardy (Udvardy, 1975), WWF (WWF, 2000), Bailey (Bailey, 1989) and Holdridge (Holdridge, 1947).

Terminology for the vegetative components of the models found during the literature review was not consistent. In order to standardize this aspect of the database, vegetative components were segmented into eleven compartments as per Henry et al., (2011) (Figure 1). Models were then classified by taxa up to the family level. In order to achieve consistency with nomenclature and avoid any confusion over common names, species were verified using the Taxonomic Name Resolution Service (Boyle *et al.*, 2013).

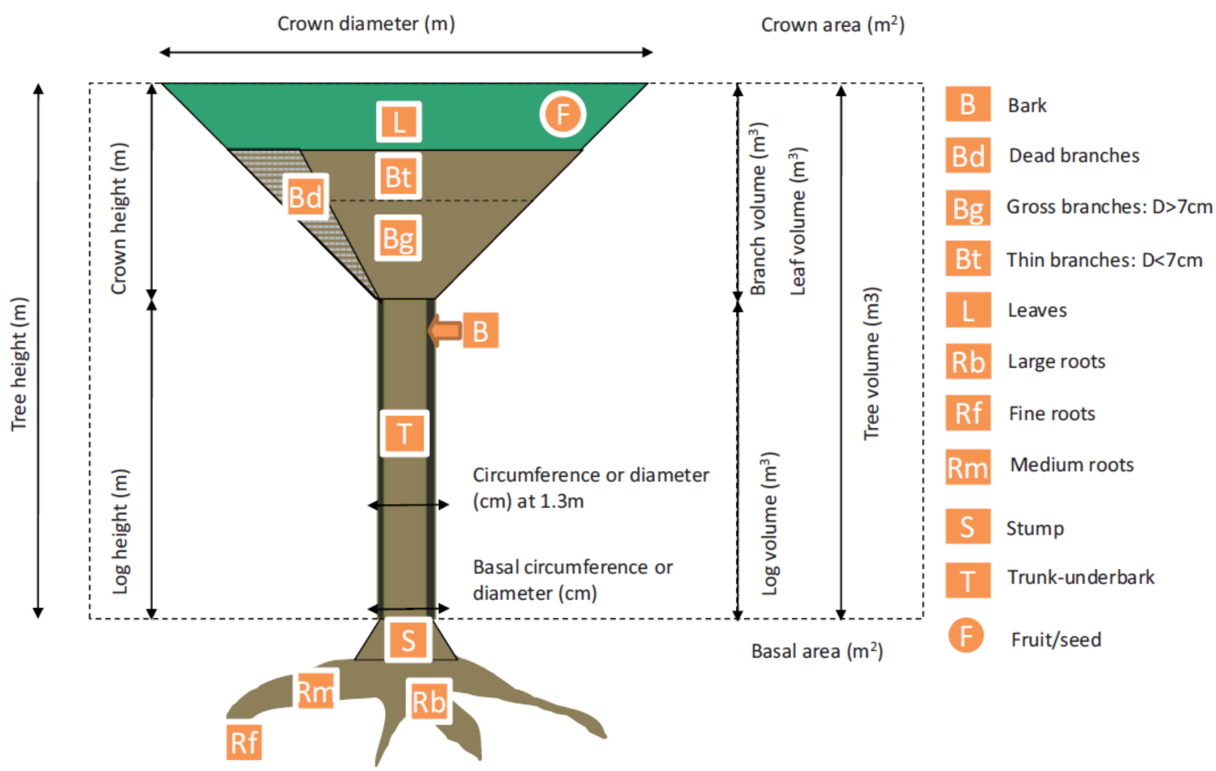

Figure 1.Tree component classification used in the data organization (Henry et al., 2011)

Data Description

In total, 993 new allometric models have been included in the database (Table 1). The models represent 558 defined taxa as well as 26 models with unspecified species or genus. Despite there being just under 1000 unique models, 4266 lines of data were entered. This is because a number of models were created using multiple species and/or multiple locations and therefore required additional entries.

In terms of relative country importance, Indonesia, Myanmar and Thailand were responsible for over 80% of the total models (Figure 2). It should be noted that 2 articles (Chan *et al.*, 2013; Leech *et al.*, 1990) represented a large majority (~95%) of the total data entered for Myanmar.

Table 1. Summary of the literature review and model collection by country

	Total Articles Collected	Lines of Data Entered	Number of Unique Models
Cambodia	4	50	50
Indonesia	40	643	353
Lao PDR	4	13	12
Malaysia	4	252	52
Myanmar	10	3004	244
Thailand	13	222	222
Viet Nam	5	85	60
Total	80*	4266	993

*Data from pantropical models is excluded from this table. Two articles had study sites located in different countries, which are duplicated in the country statistics.

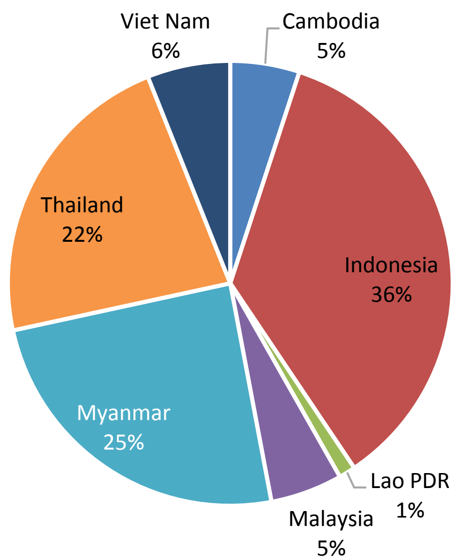

Figure 2. Distribution of allometric models by country

Location and Ecological Data

The geographical spread of the models provides coverage for most of the Southeast Asian landmass (Figure 3). The data was taken from 120 different locations, however areas such as Western New Guinea and northeast Myanmar were less represented. The Philippines, Brunei, East Timor and Singapore were not represented at all due to a lack of available data in our search.

Only five FAO Ecological Zones (FAO, 2001) were represented by the 120 locations (Figure 4-5); tropical dry forest, tropical moist deciduous forest, tropical mountain system, tropical rainforest and tropical dry shrubland. As can be seen in Figure 5, the major FAO Ecological Zone was tropical rainforest, with tropical shrubland and tropical mountain systems accounting for under 4% of the total locations.

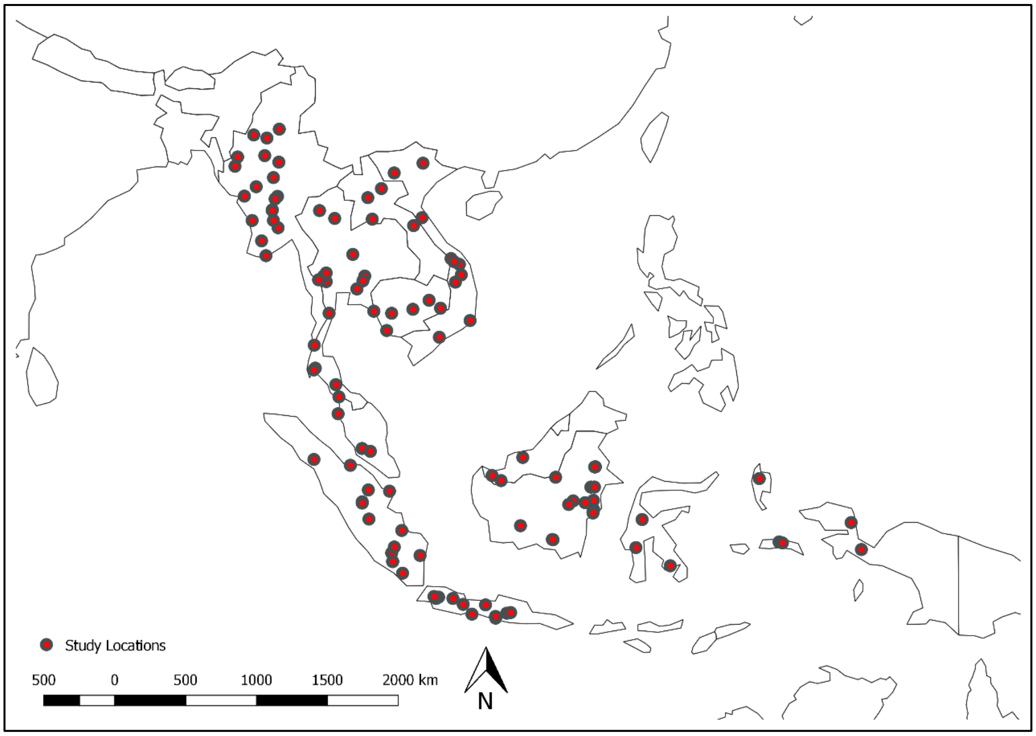

Figure 3. Geographic distribution of the study sites across Southeast Asia by country.

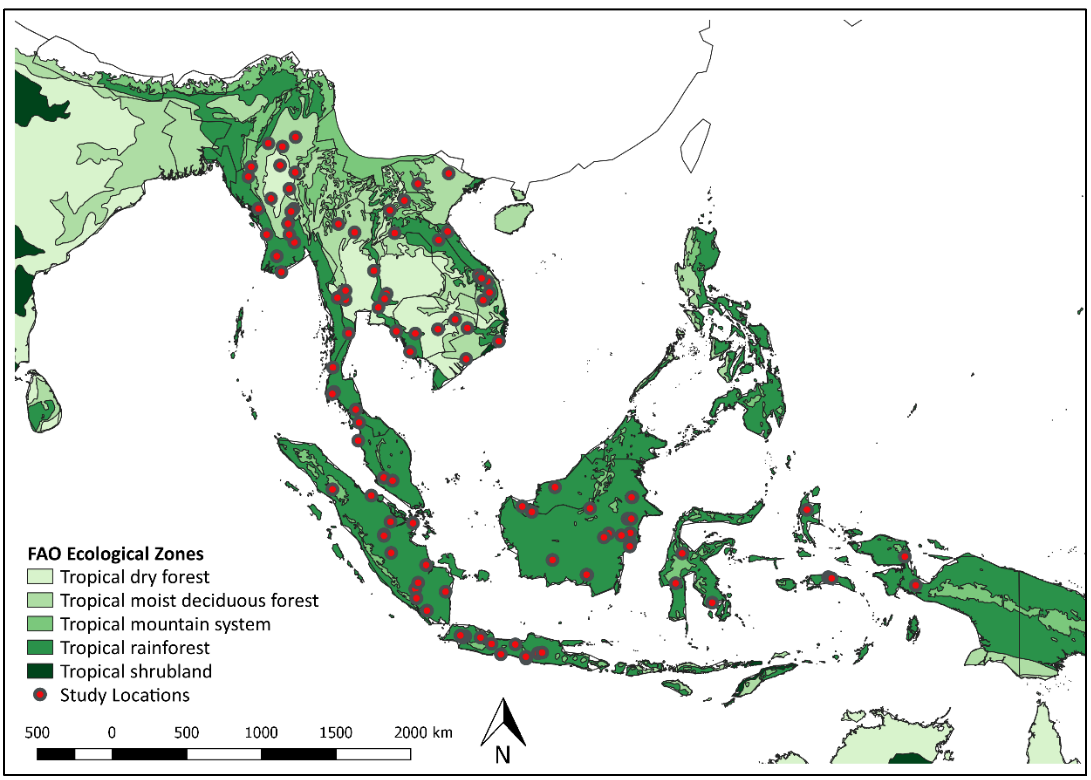

Figure 4. Geographical distribution of study sites based on FAO Ecological Zone Classification

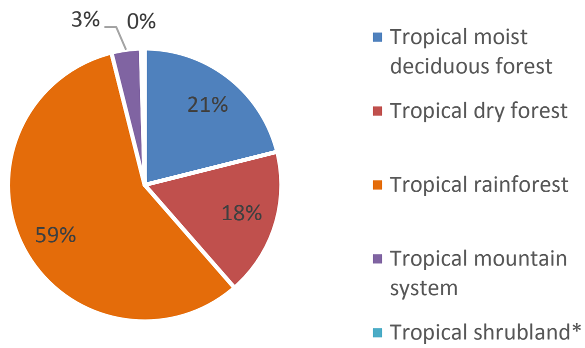

Figure 5. Proportion of models by FAO Ecological Zone, *Tropical shrubland represents 0.4% of the total models

Population Data

The main source of the data for the models is trees from forests as opposed to plantations or agroforestry (Figure 6) In total, 84% of the models are for trees with the remainder coming from mangroves (8%), followed by bamboo (6%) shrubs and lianas (Figure 7). In terms of ecosystem type, 65% of the models are for forests. The term forests can be quite broad, but in this case refers to non-managed or virgin forested land. It also includes mangrove forests that are not managed. The remainder of the models are from plantations (35%). This term refers to managed forests, plantations in the traditional sense, as well as mangrove plantations and agroforestry.

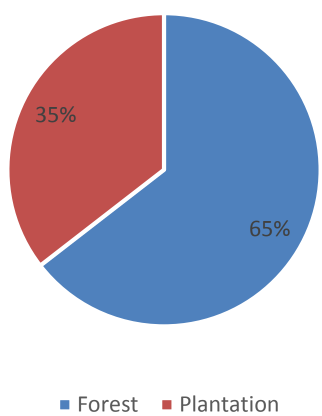

Figure 6. Model percentage by ecosystem type. Figures for forest include mangrove forests, whilst plantation includes mangrove plantations and agroforestry

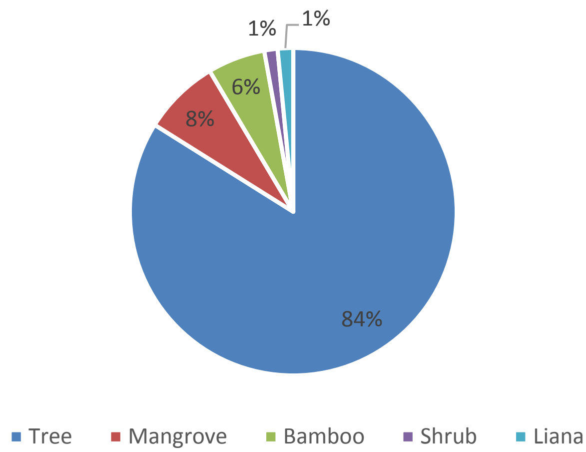

Figure 7. Model percentage by population type

Input variables and vegetation components

Models with one independent variable

Just under half of the total allometric models (44.4%) that were collected contained only one independent variable (Table 2). The following independent variables were observed:

- Diameter at breast height, 1.3m from the base of the tree (DBH, cm)
- Height (H, m)
- Diameter measured at the base of the tree (D0, cm)
- Age
- Diameter at 30cm height (D30, cm)
- Diameter at middle of stem height (Dm, cm)
- Basal area: stem cross-sectional area at DBH (BA, cm^2)
- Diameter at branch base (DBr, cm)
- Weight (W, g)
- Diameter at 50cm height (D50, cm)
- Basal diameter (DB, cm)
- Diameter of proximal root (Dprox, cm)
- Root diameter at cut points (Dr, cm)
- Length of the longest leaf (LL, cm)

Over 80% of the models with only a single independent variable used diameter at breast height (DBH) (Figure 8). The next most common independent variable used was height, which accounted for just over 10% of the models.

Table 2. Percentage of allometric models by number of input variables

	Percentage	Variable Names
One variable	44.4	DBH, H, D0, AGE, D30, Dm, BA, DBr, W, D50, DB, Dprox, Dr, LL
Two variables	40.6	DBH+H, DBH+WD, BA+WD, D20+H, D30+H, D30+WD, DBr+H,
Three variables	14.8	DBH+H+WD, D30+H+WD
Four variables	0.2	DBH+H+WD+CA

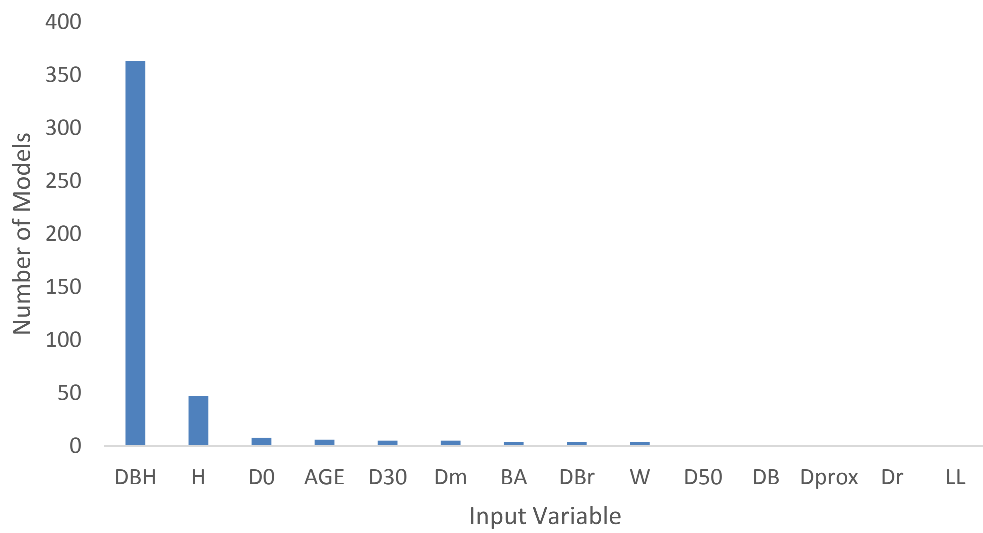

Figure 8. Number of models according to different independent variable

Models with more than one independent variable

The amount of allometric models that had two input variables was slightly lower (40.6%) than in those that had only one. A vast majority of those (88%) being a combination of DBH and height. The next most common combination was DBH and wood density (g cm^{-3}) which accounted for 7% of the models. In addition to the variables described above, the following variables were observed in models with two independent variables:

- Diameter at 20cm height (D20, cm)
- Wood density (WD, g cm^{-2})

15% of the models contained three input variables, whilst only two models had four input variables. In all of these models, wood density was the third variable. A full description of the input variables and combinations can be found in Table 2 and Appendix 1.

Tree Vegetative Component

The majority of the allometric models accounted for aboveground biomass, with only 7% of the total number of models predicting belowground biomass (Figure 9). The majority of models (~54%) predict total aboveground biomass or the biomass of the stem or trunk, whilst the remainder of the models predict smaller components such as leaves, branches, bark or fruit. There were a number of miscellaneous models that did not fit into any of these categories. These models mainly predict bamboo or liana components and have been included in the other category (Figure 9).

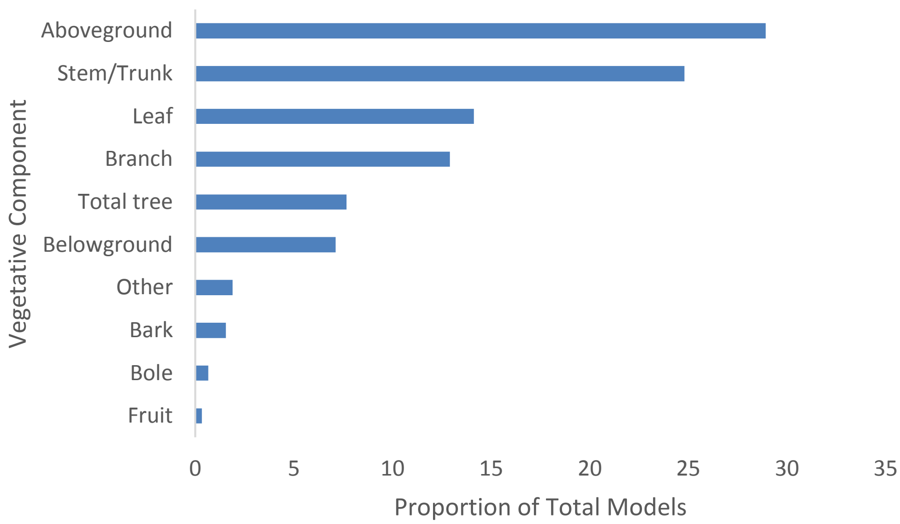

Figure 9. Proportion of allometric models available for each tree component

Model Output

Amongst the allometric models entered into the database, the majority have an output of biomass in kilograms. 89% of the unique models entered are for biomass, whilst 11% are for volume. Out of the models for volume, over 70% were from a single article (Leech *et al.*, 1990) and only 25 unique volume models were found elsewhere.

Description of Species and Taxonomy

The data collected represents 558 unique taxa defined either to the species level, or to the genus level (51 models). Furthermore, the 558 taxa were composed of 326 unique genera and 88 families. The most common family was Fabaceae, which accounted for 17% of all models (**Error! Reference source not found.**). In terms of species, the most common species included in the database were *Tectona grandis* (teak) and *Acacia mangium*, both accounting for 81 unique models. The next most common species were *Pinus merkusii* (62 models), *Dipterocarpus tuberculatus* (44 models), *Millettia pendula* (38 models) and *Xylia xylocarpa* (35 models). The full list is available in Appendix 2.

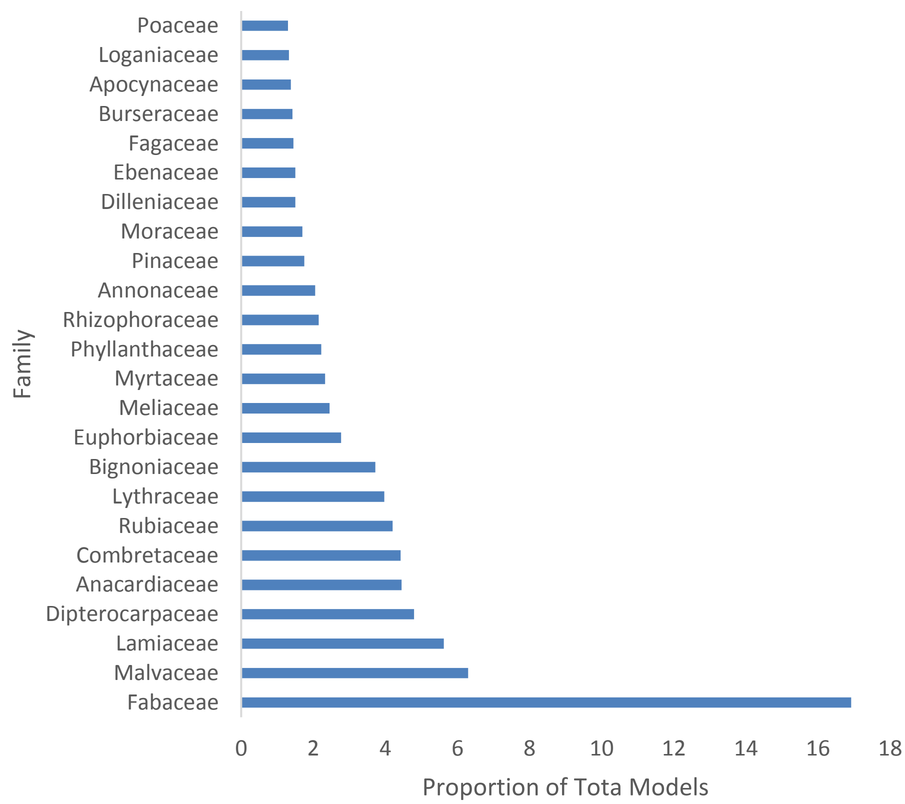

Figure 10. Proportion of allometric models by family

Allometric Models by Year

The focus of this report was to fill in the gaps in the database by adding models obtained from new research conducted after 2013. However, several articles and models from earlier than 2013 were found as a result of the literature review (Figure 11). In total, 33% of the models found during this compilation cover the period from 2014 to present. A further 16% of the recent compilation cover the years of 2012 and 2013. The remaining 51% of the models are from prior to 2012. Models were also obtained from as far back as 1968 and 1969, however none from the

1970s. A large number of models (11%) were found from 2005, which relate to research conducted in Thailand and Indonesia.

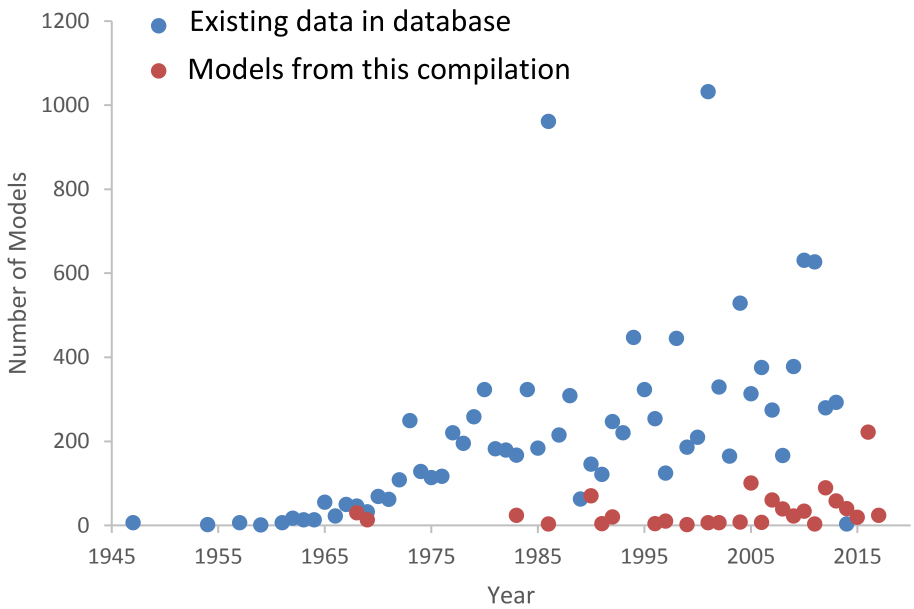

Figure 11. Number of allometric models entered per year

Descriptive Statistics and Sample Size

The extensive literature review completed in this compilation spanned a broad range of research methods. As can be seen in Figure 12, there was a large range in the sample sizes used to develop models. Data was unavailable on the sample size for 56 models. In total, 56% of all models usedsample sizes that had not been reported or else were below 30, whilst 44% of the models had a sample size above 30. The vast majority (86%) of models had a sample size between 0 and 150. The largest sample size for a volume model was by Leech *et al.*, (1990) who used 1681 individuals at the Shwebo and Lower Chindwin site. The biomass model with the largest sample size was Manuri *et al.*, (2017), who used 1201 individuals to develop a model for tropical lowland forest in Indonesia.

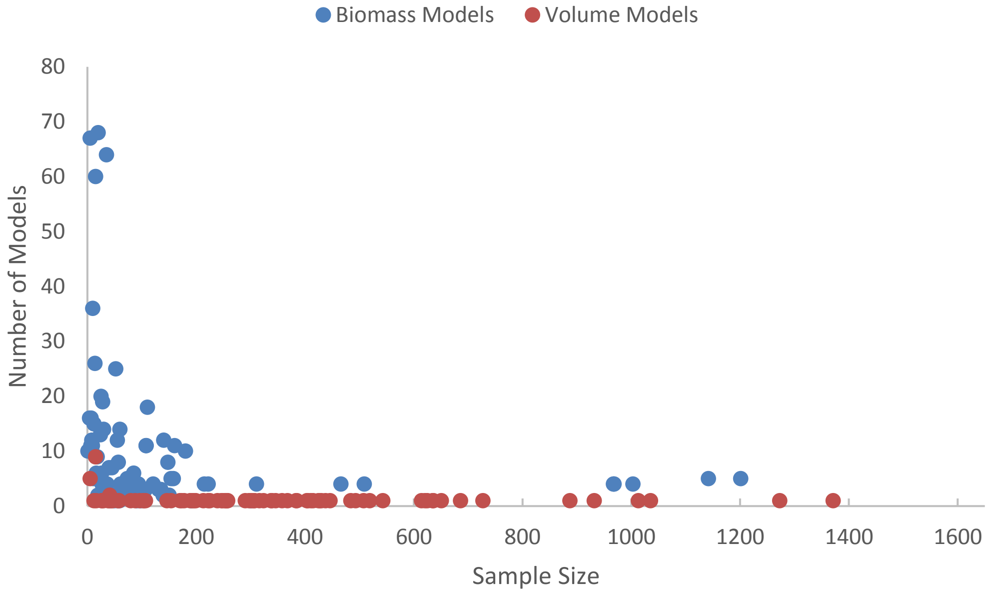

Figure 12. Number of models per sample size by biomas and volume

R^2 values ranged from 0.01 to 1, with 45% of the models reporting a R^2 greater than 0.9. In total 35% of the models did not report R^2, or reported other statistics. R^2 values of 0.99 and 0.98 were the most frequent, accounting for 5% of the total models and can be seen as outliers encircled in red in (Figure 13).

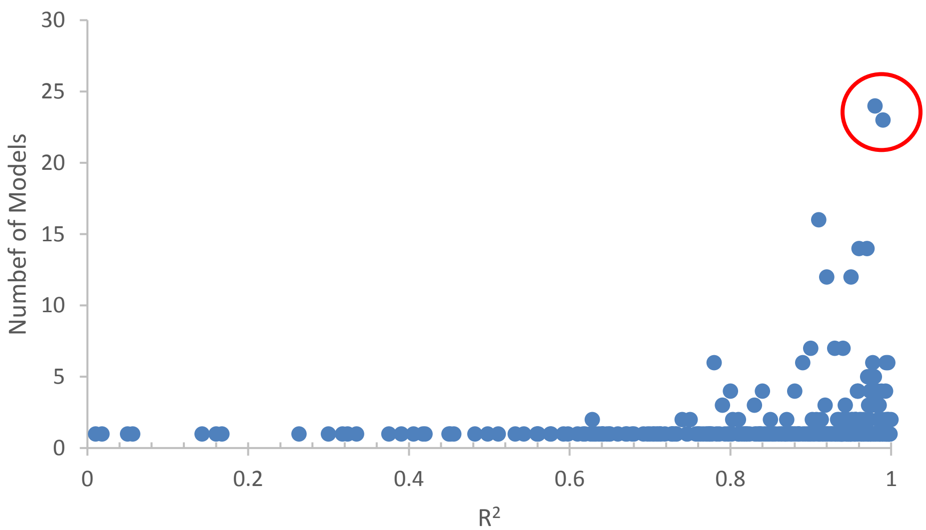

Figure 13. Frequency of R^2 for the models included in the compilation

Conclusions & Recommendations

80 articles were collected for this compilation, resulting in the entry of 993 allometric models into the GlobAllomeTree database for Southeast Asia. The models have been validated for syntax and operator error using the Fantallometrik tool. However, Southeast Asia represents a large and diverse region, comprising several countries and vegetation types. It is important that the variation is captured in the database. The majority of the region is dominated by tropical rainforest, however there are significant sections of other tropical ecological zones such a tropical dry forest or tropical mountain systems. Therefore, it is possible that some gaps remain in the literature that need to be addressed in the future. This can either be addressed through further literature review or through primary research to develop additional allometric models. It is costly, time-consuming and destructive to develop new models, therefore care should be taken before commencing new research.

From the analysis of this compilation, the geographical limitations of the database are clear. Some countries and regions appear to be underrepresented in the literature. More research may be required in Lao People's Democratic Republic, Malaysia and Cambodia to capture the structure of the local vegetation in more detail. Furthermore, Western New Guinea and northeast Myanmar were not represented in this compilation, suggesting little research has been done in these areas since 2013. The same can be said of The Philippines, Brunei, East Timor and Singapore, which were not represented in this compilation at all. Further research and a more targeted literature review is recommended in these areas.

Other shortcomings of the compilation may be the relative lack of models for non-tree populations. Shrubs, bamboo and mangroves have the potential to be important carbon stores in tropical forests, however shrubs represented only 1% of the models. The importance of root biomass (or belowground biomass) to carbon stock estimations was also underrepresented in this compilation. Aboveground, stem, leaf, branch and total tree biomass models were all more common than underground components. Therefore, a greater emphasis on models for belowground biomass components are recommended.

When analyzing the database by year, there appears to be a relative lack of data beyond 2013. It is unclear as to whether this trend is related to shortcomings of the literature review methodology or if there has been a decline in new research in the field of allometric modelling. For future reviews, targeted research to deepen the sample size for this time period would be useful to improve the database. There is also a lack of consistency in the reporting of the models that were found. Many models (56%) reported a sample size below 30, which can affect the accuracy of the models. To counter this concern, statistics can be used to provide context for the model. However, 35% of the models were not accompanied with an R^2 value.

There are concerns about the quality of a number of models, and therefore users should exercise caution when choosing models for biomass estimations. Careful consideration should be given to model statistics, particularly the sample size used for model development and the R^2 reported.

A more thorough database of allometric models for Southeast Asia will improve the assessment and monitoring of stored carbon. It would be valuable to fill in some of the gaps mentioned above to create a more comprehensive and thorough database for the region. This will permit improved forest management in the long run and assist participating countries with their REDD+ requirements.

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Appendix 1. List of acronyms used in the database

Acronym	Description	Unit	Population
Age	Age of the trees	yr	STAND
As	stem area	cm^2	TREE
Ac	canopy area	m^2	TREE
BA	Basal area: Stem cross-sectional area at DBH (1m30 height)	cm^2	TREE
BA0	Stem cross-sectional area at the soil	cm^2	TREE
BA0.2	Basal area at 20 cm above the soil	cm^2	TREE
BA5	Basal area at 5cm above the soil	cm^2	TREE
BBD	Branch Basal Diameter	cm	TREE
BD	Branch Diameter	cm	TREE
BT5	Bark Thickness at 5cm	mm	TREE
BT10	Bark Thickness at 10cm	mm	TREE
BT20	Bark Thickness at 20cm	mm	TREE
C	Circumference at 1.3m	cm	TREE
C5	Circumference at 5cm height	cm	TREE
C10	Circumference at 10 cm height	cm	TREE
C180	Circumference at 180 cm height	cm	TREE
C20	Circumference at 20 cm height	cm	TREE
C30	Circumference at 30 cm height	cm	TREE
C50	Circumference at 50 cm height	cm	TREE
Ca	Canopy area	m^2	TREE
CA	Crown area	cm^2	TREE
Cb	Basal circumference	cm	TREE
Cb5	Circumference at 5 cm from soil	cm	TREE
CD	Crown diameter	cm	TREE
CD1	Crown diameter maximum	cm	TREE
CD2	Crown diameter, perpendicular to maximum	cm	TREE
CH	Crown height	cm	TREE
CoC	Conical crown variable = CD^2H	cm^3	TREE
Cm	Crown mass	kg	TREE
Cs	average of Hc and CD	m	TREE
CPr	Parabolic crown variable	m^3	TREE
CR	Crown radius	cm	TREE
Ct	trunk circumference	cm	TREE
CV	Canopy volume	cm^3	TREE
CW	Corm weight	g	TREE
CWi	Crown width at 90deg to CWiM	cm	TREE
CWiM	Maximum crown width	cm	TREE
D	Diameter of the longest stem	cm	TREE
D0	Diameter at ground base	cm	TREE
D5	Diameter at 5cm height	cm	TREE
D10	Diameter at 10cm height	cm	TREE
D10ls	Diameter of 10cm height of longest stem	cm	TREE
D20	Diameter at 20cm height	cm	TREE
D30	Diameter at 30cm height	cm	TREE
D50	Diameter at 50cm height	cm	herbaceous

DB	Basal diameter	cm	TREE
DBH	Diameter at breast height	cm	TREE
DBH_M	Average of DBH	cm	STAND
DBr	Diameter at branch base	cm	TREE
DC	Collar diameter	cm	TREE
DCls	Collar diameter of longest stem	cm	TREE
Dew	East-west diameter of canopy projection	cm	TREE
Dm	Diameter measured at the middle of stem height	cm	TREE
DCr	Diameter of crown	cm	TREE
DM	Dry months	months	TREE/STAND
Dns	North-south diameter of canopy projection	cm	TREE
Dprox	Diameter of proximal root	cm	TREE
Dr	Root diameter at cut points	cm	TREE
DSH	Diameter at stump height	cm	TREE
DSUM10	Sum of the diameters at 10 cm from the soil	cm	STAND
Gch	Girth at collar height	cm	TREE
Gmh	Girth at measuring height	cm	TREE
H	Height	cm	TREE
Hc	Crown depth	m	TREE
Hd	Stand dominant height	cm	TREE
Hep	edible pseudostem height	cm	herbaceous
Hme	Merchantable height	cm	TREE
Ht	Height of the trunk	cm	TREE
Hp	pseudostem height	cm	herbaceous
Hrel	Relative height, where maximum biomass concentration occurs	cm	TREE
LiDAR H100	Average height of the 100 tallest trees in the hectare containing the plot measured from the LiDAR data	m	TREE
LL	Length of the longest leaf	cm	TREE
mcd	mean crown diameter	cm	TREE
MRBD	Main cable root basal diameter	cm	TREE
N	Number of trees per ha	$Tree*ha^{-1}$	STAND
NR	Number of ramifications emerging from root collar	#	TREE
R	Tree ring	nr	TREE
RBT	Relative Bark Thickness	mm	TREE
RW	Root weight	g	TREE
Sh	mean stand height	m	TREE
StH	Stem per hectare	#	TREE
StM	Stem Mass (per hectare)	t	TREE
SRBD	Side cable root basal diameter	cm	TREE
TSDM	Total Shoot Dry Mass	kg	TREE
Yr	Year	yr	TREE/STAND
Vs	Stem volume	dm^3	TREE
W	Weight	g	TREE
WD	Wood density	$g*cm^{-3}$	TREE
V	Volume	cm^3	TREE
V.P.	Stem volume including bark	cm^3	TREE

Appendix 2. Full list of species entered into the database

Species	Number of Equations
Acacia arabica	2
Acacia auriculiformis	4
Acacia catechu	10
Acacia crassicarpa	3
Acacia ferruginea	20
Acacia leucophloea	2
Acacia macrocephala	3
Acacia mangium	81
Acrocarpus fraxinifolius	6
Adenanthera pavonina	5
Adina cordifolia	8
Aegiceras corniculatum	5
Aegle marmelos	4
Agelaea macrophylla	14
Aglaia sapindina	2
Ailanthus triphysa	21
Alangium chinense	1
Albizia chinensis	10
Albizia lebbek	8
Albizia lucida	9
Albizia odoratissima	9
Albizia procera	7
Allantospermum spp.	5
Alnus nepalensis	1
Alseodaphne keenanii	5
Alseodaphne spp.	5
Alstonia scholaris	8
Alstonia spectabilis	5
Amherstia nobilis	1
Amoora rohituka	9
Amoora wallichii	3
Amorphophallus bulbifer	1
Anisoptera costata	3
Anisoptera oblonga	2
Anneslea fragrans	7
Anogeissus acuminata	31
Anogeissus phillyreifolia	1
Anthocephalus cadamba	9
Antiaris toxicaria	2
Antidesma ghaesembilla	1
Antidesma velutinum	22
Aporosa roxburghii	6
Aporosa villosa	8
Aquilaria agallocha	1
Archidendron spp.	5
Artabotrys oblongus	14
Artocarpus calophyllus	8
Artocarpus heterophyllus	2
Artocarpus lakoocha	7
Avicennia alba	5
Avicennia marina	5
Avicennia officinalis	9
Azadirachta excelsa	1
Azadirachta indica	7
Baccaurea sapida	6
Baccaurea spp.	5
Balanites triflora	5
Bamboos Bamboos	1
Bambusa blumeana	1
Bambusa polymorpha	7
Bambusa spp.	1
Bambusa tulda	6
Barringtonia acutangula	5
Bauhinia acuminata	3
Bauhinia malabarica	29
Bauhinia purpurea	1
Bauhinia racemosa	4
Bauhinia variegata	2
Berrya spp.	10
Betula alnoides	2
Bischofia javanica	1
Bombax insigne	20
Borassodendron borneense	2
Boschia mansonii	1
Boscia variabilis	3
Bouea burmanica	1
Bouea spp.	5
Bridelia retusa	9
Bruguiera cylindrica	7
Bruguiera gymnorrhiza	5
Bruguiera hainesii	1

Bruguiera parviflora	15
Bruguiera sexangula	10
Buchanania arborescens	3
Buchanania lancifolia	1
Buchanania lanzan	10
Butea monosperma	4
Callicarpa macrophylla	1
Callicarpa tomentosa	2
Calophyllum inophyllum	2
Calophyllum kunstleri	2
Calophyllum spp.	5
Campnosperma coriaceum	5
Cananga odorata	4
Canarium spp.	10
Canthium dicoccum	3
Carallia brachiata	7
Careya arborea	10
Casearia glabra	2
Cassia fistula	27
Cassia renigera	1
Cassia siamea	2
Cassia timorensis	1
Castanopsis spp.	9
Cedrela microcarpa	4
Cedrela multijuga	4
Cedrela serrata	1
Cedrela toona	6
Cephalostachyum pergracile	3
Cephalostachyum spp.	1
Ceriops decandra	5
Ceriops tagal	4
Ceriops zippeliana	8
Chromolaena odorata	1
Chukrasia tabularis	17
Chukrasia velutina	1
Cinnamomum inunctum	4
Cleidion spiciflorum	1
Cnestis palala	14
Coccoceras plicatum	1
Coffea arabica	1
Coffea spp.	1

Coptosapelta parviflora	14
Cordia dichotoma	9
Cordia fragrantissima	3
Cordia grandis	8
Crateva religiosa	4
Cratoxylum cochinchinense	3
Cratoxylum neriifolium	31
Cratoxylum prunifolium	5
Croton oblongifolius	9
Croton roxburghii	20
Crypteronia pubescens	2
Cyathostemma hookeri	14
Dacrydium spp.	3
Dacryodes spp.	5
Dalbergia cochinchinensis	7
Dalbergia cultrata	29
Dalbergia fusca	27
Dalbergia kurzii	9
Dalbergia obtusifolia	1
Dalbergia oliveri	7
Dalbergia ovata	28
Dalbergia paniculata	7
Dalbergia rostrata	14
Dalbergia sissoo	1
Dalbergia spp.	20
Dalbergia stipulacea	2
Decaspermum bracteatum	2
Dehaasia kurzii	1
Dendrocalamus strictus	4
Derris indica	20
Derris robusta	5
Dialium indum	4
Dialium spp.	5
Dichrostachys cinerea	2
Dillenia aurea	1
Dillenia indica	5
Dillenia parkinsonii	1
Dillenia parviflora	7
Dillenia parvifolia	1
Dillenia pentagyna	31
Diospyros burmanica	10

Diospyros ehretioides	30
Diospyros montana	9
Diospyros pendula	1
Diospyros peregrina	4
Diospyros spp.	6
Dipterocarpus obtusifolius	2
Dipterocarpus retusus	1
Dipterocarpus spp.	10
Dipterocarpus tuberculatus	44
Docynia indica	3
Dodonaea viscosa	2
Dolichandrone serrulata	7
Dolichandrone spathacea	2
Dorophyllum spp.	5
Dracontomelon mangiferum	4
Drimycarpus racemosus	3
Drypetes spp.	5
Duabanga grandiflora	10
Durio zibethinus	2
Dysoxylum binectariferum	2
Dysoxylum grande	2
Ehretia acuminata	1
Elaeis guineensis	11
Elaeocarpus floribundus	7
Elaeocarpus lanceifolius	6
Elaeocarpus sphaericus	2
Emblica officinalis	28
Engelhardia spicata	3
Eriobotrya bengalensis	6
Eriolaena candollei	27
Erythrina lithosperma	1
Erythrina stricta	3
Erythrina suberosa	30
Eucalyptus camaldulensis	16
Eucalyptus grandis	4
Eucalyptus spp.	20
Eugenia spp.	16
Eurya japonica	2
Excoecaria agallocha	1
Fagraea fragrans	1
Ficus brunneoaurata	2

Ficus cunia	21
Ficus glomerata	7
Ficus hispida	4
Ficus roxburghii	1
Ficus spp.	9
Firmiana colorata	28
Flacourtia cataphracta	7
Garcinia celebica	5
Garcinia cowa	3
Garcinia paniculata	1
Garcinia speciosa	3
Garcinia spp.	5
Garcinia xanthochymus	3
Gardenia coronaria	5
Gardenia erythroclada	22
Gardenia obtusifolia	2
Garuga pinnata	31
Gaultheria fragrantissima	1
Gelonium multiflorum	1
Geunsia pentandra	2
Gigantochloa nigrociliata	2
Gigantochloa scortechinii	1
Gliricidia sepium	1
Glochidion perakense	2
Glochidion spp.	1
Gluta tavoyana	1
Gmelina arborea	22
Gnetum latifolium	14
Gonocaryum litorale	2
Gonystylus bancanus	5
Grewia aspera	4
Grewia glabra	1
Grewia humilis	3
Grewia scabrophylla	4
Grewia tiliifolia	29
Gyrocarpus jacquinii	1
Haplophragma adenophyllum	10
Helicia erratica	3
Helicia terminalis	1
Heretiera spp.	5
Heritiera fomes	3

Heterophragma adenophyllum	20
Heterophragma sulfureum	8
Heynea trijuga	3
Hibiscus macrophyllus	2
Hibiscus tiliaceus	2
Holarrhena antidysenterica	7
Holoptelea integrifolia	8
Homalanthus populneus	1
Homalium foetidum	2
Homalium tomentosum	30
Hopea bancana	1
Hopea ferrea	4
Hopea helferi	1
Hopea mengarawan	1
Hopea minutiflora	1
Hopea odorata	8
Horsfieldia glabra	5
Hydnocarpus alpina	1
Hydnocarpus ilicifolia	4
Hydnocarpus spp.	9
Hymenaea courbaril	1
Hymenodictyon excelsum	8
Hymenodictyon orixense	20
Ilex macrophylla	5
Jatropha curcas	5
Juglans regia	8
Kandelia rheedii	2
Kayea nervosa	6
Khaya anthotheca	1
Khaya grandifoliola	1
Khaya senegalensis	1
Knema spp.	5
Koompassia spp.	5
Kydia calycina	6
Lagerstroemia calyculata	2
Lagerstroemia floribunda	2
Lagerstroemia hypoleuca	1
Lagerstroemia macrocarpa	23
Lagerstroemia parviflora	4
Lagerstroemia speciosa	10
Lagerstroemia spp.	2

Lagerstroemia tomentosa	29
Lagerstroemia venusta	26
Lagerstroemia villosa	31
Lannea coromandelica	20
Lannea grandis	11
Leucaena glauca	1
Libocedrus macrolepis	1
Limonia acidissima	3
Lindera assamica	1
Linociera terniflora	3
Lithocarpus spp.	5
Litsea glutinosa	8
Litsea monopetala	1
Lophopetalum filiforme	2
Lophopetalum fimbriatum	2
Lophopetalum spp.	5
Lophopetalum wallichii	3
Lumnitzera racemosa	22
Macaranga denticulata	9
Macaranga gigantea	1
Macaranga hypoleuca	1
Macaranga javanica	2
Macaranga triloba	3
Machilus odoratissimus	2
Machilus villosa	3
Madhuca butyracea	1
Madhuca spp.	5
Maesa indica	1
Mallotus floribundus	1
Mallotus paniculatus	1
Mallotus penangensis	2
Mallotus philippinensis	27
Mangifera caloneura	9
Mangifera indica	10
Mangifera spp.	5
Mangifera sylvatica	2
Manglietia hookeri	1
Manglietia insignis	4
Manilkara littoralis	3
Mansonia gagei	1
Maranthes corymbosa	1

Markhamia stipulata	22
Melaleuca cajuputi	6
Melaleuca spp.	3
Melanorrhoea glabra	1
Melanorrhoea usitata	10
Melastoma malabathricum	1
Melastoma sanguineum	1
Melia birmanica	3
Meliosma pinnata	2
Memecylon edule	1
Memecylon ovatum	4
Mesua ferrea	5
Mezzettia spp.	5
Michelia champaca	8
Michelia doltsopa	2
Michelia lacei	1
Microcos paniculata	4
Miliusa roxburghiana	9
Miliusa velutina	29
Millettia atropurpurea	2
Millettia brandisiana	29
Millettia pendula	38
Millettia pubinervis	3
Millettia pulchra	1
Millettia tetraptera	1
Mischocarpus fuscescens	1
Mischocarpus pentapetalus	5
Mitragyna parvifolia	6
Mitragyna rotundifolia	30
Mitragyna speciosa	1
Mitrephora maingayi	4
Morinda tinctoria	4
Morus laevigata	1
Multi-species Multi-species	2
Murraya koenigii	3
Nauclea orientalis	9
Neonauclea excelsa	8
Neonauclea sessilifolia	2
Oroxylum indicum	26
Ostodes paniculata	3
Osyris wightiana	1

Pahudia martabanica	2
Pajanelia rheedii	5
Palaquium obovatum	5
Palaquium polyanthum	2
Palaquium sukoei	2
Paraserianthes falcataria	3
Parashorea stellata	4
Parastemon urophyllus	5
Parishia spp.	5
Parkia insignis	6
Parkinsonia spp.	2
Peltophorum inerme	1
Pentace burmanica	4
Pentacme siamensis	13
Peronema canescens	3
Phoebe lanceolata	2
Phoebe paniculata	1
Pinus insularis	5
Pinus kesiya	3
Pinus merkusii	62
Piper aduncum	2
Piper attenuatum	20
Pithecellobium bigeminum	3
Pithecellobium dulce	2
Pithecellobium jiringa	2
Pittosporum napaulensis	4
Podocarpus neriifolius	3
Podocarpus wallichianus	1
Polyalthia simiarum	1
Pometia pinnata	5
Pongamia pinnata	3
Premna integrifolia	3
Premna latifolia	29
Premna pyramidata	8
Protium serratum	11
Prunus cerasoides	2
Pterocarpus indicus	3
Pterocarpus macrocarpus	23
Pterocymbium tinctorium	4
Pterospermum acerifolium	4
Pterospermum lanceifolium	6

Pterospermum semisagittatum	31
Pterospermum tinctorium	1
Pterygota alata	3
Putranjiva roxburghii	1
Quercus brandisiana	2
Quercus dealbata	3
Quercus helferiana	5
Quercus kingiana	2
Quercus lindleyana	4
Quercus mespilifolia	3
Quercus polystachya	3
Quercus semiserrata	5
Quercus serrata	3
Quercus spicata	5
Quercus spp.	1
Quercus truncata	4
Randia uliginosa	1
Rauvolfia serpentina	1
Rhizophora apiculata	10
Rhizophora candelaria	1
Rhizophora mucronata	11
Rhododendron spp.	1
Rhus paniculata	21
Rinorea bengalensis	8
Rourea rugosa	14
Sageraea listeri	2
Salacia spp.	14
Salix tetrasperma	2
Salmalia anceps	7
Salmalia insignis	11
Salmalia malabarica	10
Samadera indica	1
Sandoricum koetjape	3
Santalum album	1
Sapindus spp.	5
Sapium baccatum	4
Sapium insigne	9
Saraca indica	4
Sarcosperma arboreum	3
Scaphium spp.	5
Schima noronhae	2

Schima wallichii	10
Schizostachyum grande	1
Schizostachyum zollingeri	1
Schleichera oleosa	29
Schrebera swietenioides	6
Semecarpus anacardium	6
Semecarpus pandurata	3
Shorea argentea	3
Shorea assamica	5
Shorea balangeran	1
Shorea buchananii	2
Shorea cinerea	6
Shorea farinosa	1
Shorea floribunda	1
Shorea guiso	1
Shorea laevis	1
Shorea leprosula	1
Shorea oblongifolia	9
Shorea obtusa	30
Shorea roxburghii	3
Shorea selanica	1
Shorea spp.	5
Shorea teysmanniana	5
Shorea uliginosa	5
Sideroxylon burmanicum	20
Sideroxylon tomentosum	7
Sonneratia alba	5
Sonneratia apetala	6
Sonneratia caseolaris	7
Sonneratia griffithii	1
Spatholobus ferrugineus	14
Spondias pinnata	31
Stemonurus spp.	5
Sterculia foetida	2
Sterculia spp.	11
Stereospermum colais	20
Stereospermum fimbriatum	9
Stereospermum neuranthum	6
Stereospermum personatum	10
Stereospermum suaveolens	4
Streblus asper	4

Strychnos curtisii	14
Strychnos ignatii	14
Strychnos nux-blanda	24
Strychnos potatorum	1
Swintonia floribunda	11
Symplocos cochinchinensis	3
Syzygium polyanthum	1
Syzygium spp.	10
Tamarindus indica	3
Taxus baccata	2
Tectona grandis	81
Tectona hamiltoniana	6
Terminalia alata	9
Terminalia belerica	11
Terminalia bellirica	20
Terminalia bialata	1
Terminalia chebula	31
Terminalia coriacea	7
Terminalia crenulata	7
Terminalia oliveri	7
Terminalia pyrifolia	8
Terminalia tomentosa	22
Ternstroemia japonica	1
Tetracera macrophylla	14
Tetrameles nudiflora	8
Theobroma cacao	1
Thyrsostachys siamensis	24
Timonius lasianthoides	3
Trema amboinensis	2
Trema cannabina	1
Trema orientalis	1
Trewia nudiflora	5
Trichospermum kurzii	2
Tristania burmanica	8

Tristania spp.	3
Turpinia pomifera	1
Ulmus lanceifolia	1
Vatica pauciflora	1
Vatica spp.	8
Vernonia arborea	3
Vitex canescens	10
Vitex glabrata	8
Vitex limonifolia	7
Vitex peduncularis	5
Vitex pinnata	3
Vitex pubescens	33
Vitex quinata	1
Vitex trifolia	1
Walsura robusta	5
Walsura trichostemon	4
Wendlandia glabrata	8
Wendlandia grandis	1
Wendlandia paniculata	2
Willughbeia angustifolia	14
Willughbeia spp.	14
Wrightia tomentosa	6
Xanthophyllum flavescens	2
Xanthophyllum spp.	5
Xerospermum noronhianum	2
Xylia dolabriformis	8
Xylia xylocarpa	35
Xylocarpus granatum	7
Xylocarpus moluccensis	7
Zanthoxylum budrunga	6
Ziziphus incurva	1
Ziziphus mauritiana	1
Ziziphus rugosa	2
558	3966*

*This number is lower than the overall number of unique equations due to a number of equations not referring to a specific species.