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Danaë M A Rozendaal, Daniela Requena Suarez, Veronique De Sy, Valerio Avitabile, Sarah Carter, C Y Adou Yao, Esteban Alvarez-Davila, Roel J W Brienen, João M B Carreiras, Alejandro Araujo-Murakami, Luzmiela Arroyo, Benjamin Barca, Timothy R Baker, Luca Birigazzi, Frans Bongers, Anne Branthomme, Roel J W Brienen, João M B Carreiras, Roberto Cazzolla Gatti, Susan C Cook-Patton, Mathieu Decuyper, Ben DeVries, Andres B Espejo, Ted R Feldpausch, Julian Fox, Javier G P Gamarra, Bronson W Griscom, Nancy Harris, Bruno Hérault, Earidice N Honorio Coronado, Inge Jonckheere, Eric Konan, Sara M Levitt, Simon I Lewis, Jeremy A Lindell, Justin Kassi N'Djia, Anny Estelle N’Guessan, Beatrix Marimon, Edward T A Mitchard, Abel Monteagudo, Alexandra Morel, Anssi Pekkarinen, Oliver L Phillips, Lourens Poorter, Lan Qie, Ervan Rutishauser, Casey M Ryan, Maurizio Santoro, Dor Santos Silayo, Plinio Sist, J W Ferry Slik, Bonaventure Sonké, Martin J P Sullivan, Gaia Vaglio Laurin, Emilio Vilanova, Maria H M Wang, Elaiikim Zhabahu and Martin Herold.

Laboratory of Geo-Information Science and Remote Sensing, Wageningen University, PO Box 47, 6700 AA Wageningen, The Netherlands.
Forest Ecology and Forest Management group, Wageningen University, PO Box 47, 6700 AA Wageningen, The Netherlands.
Plant Production Systems Group, Wageningen University, PO Box 430, 6700 AK Wageningen, The Netherlands.
Centre for Crop Systems Analysis, Wageningen University, PO Box 430, 6700 AK Wageningen, The Netherlands.
European Commission, Joint Research Centre (JRC), Ispra, Italy.
Conservation International, 2011 Crystal City Dr, Arlington, VA 22202, United States of America.
Department of Biological, Geological, and Environmental Sciences, University of Bologna, Bologna, 40126, Italy.
Department of Geography, Environment and Geomatics, University of Guelph, Guelph, ON, Canada.
Forest Ecology and Forest Management Group, Wageningen University, PO Box 47, 6700 AA Wageningen, The Netherlands.
World Agroforestry (ICRAF), P.O. Box 30677-00100 GPO, Nairobi, Kenya.
Escuela ECAPMA, UNAD, Calle 14 Sur No. 14-23, Bogotá, Colombia.
Forestry Division, Food and Agriculture Organization of the United Nations, Viale delle Terme di Caracalla, 00153 Rome, Italy.
European Commission, Joint Research Centre (JRC), Ispra, Italy.
The Nature Conservancy, Arlington, VA, United States of America.
The Nature Conservancy, Arlington, VA, United States of America.
Université de Montpellier, Fets et Sciences, Montpellier, France.
Université de Montpellier, Fets et Sociétés, Montpellier, France.
Institut National Polytechnique Félix Houphouët-Boigny, Yamoussoukro, Ivory Coast.
Instituto de Investigaciones de la Amazonia Peruana, Iquitos, Peru.
Permanent Executive Secretariat of REDD++, Abidjan, Côte d’Ivoire.
Department of Geography, University College London, Gower Street, London WC1E 6BT, United Kingdom.
RSPB Centre for Conservation Science, The Lodge, Sandy, Beds, United Kingdom.
A Rocha International, Cambridge, United Kingdom.
UFR Biosciences, Laboratoire de Botanique, Université Félix Houphouët-Boigny, Abidjan, Ivory Coast.
Universidade do Estado de Mato Grosso, Av Prof Dr Renato Figueiro Varella, s/n, Bairro Olaria, CEP 78690-000 Nova Xavantina, MT, Brazil.
* Author to whom any correspondence should be addressed.
Abstract

For monitoring and reporting forest carbon stocks and fluxes, many countries in the tropics and subtropics rely on default values of forest aboveground biomass (AGB) from the Intergovernmental Panel on Climate Change (IPCC) guidelines for National Greenhouse Gas (GHG) Inventories. Default IPCC forest AGB values originated from 2006, and are relatively crude estimates of average values per continent and ecological zone. The 2006 default values were based on limited plot data available at the time, methods for their derivation were not fully clear, and no distinction between successional stages was made. As part of the 2019 Refinement to the 2006 IPCC Guidelines for GHG Inventories, we updated the default AGB values for tropical and subtropical forests based on AGB data from >25,000 plots in natural forests and a global AGB map where no plot data were available. We calculated refined AGB default values per continent, ecological zone, and successional stage, and provided a measure of uncertainty. AGB in tropical and subtropical forests varies by an order of magnitude across continents, ecological zones, and successional stage. Our refined default values generally reflect the climatic gradients in the tropics, with more AGB in wetter areas. AGB is generally higher in old-growth than in secondary forests, and higher in older secondary (regrowth >20 years old and degraded/logged forests) than in young secondary forests (⩽20 years old). While refined default values for tropical old-growth forest are largely similar to the previous 2006 default values, the new default values are 4.0–7.7-fold lower for young secondary forests. Thus, the refined values will strongly alter estimated carbon stocks and fluxes, and emphasize the critical importance of old-growth forest conservation. We provide a reproducible approach to facilitate future refinements and encourage targeted efforts to establish permanent plots in areas with data gaps.

1. Introduction

Tropical forests contain two-thirds of the total global terrestrial biomass (Pan et al. 2013), but these forests and their carbon stocks are rapidly disappearing due to land use conversion (FAO). Accurate and current data on forest biomass are required for environmental policies and to inform management practices (Herold et al. 2019). In the Paris Climate Agreement, countries have agreed to promote climate change mitigation, for example by avoiding emissions from deforestation and forest degradation. Countries in the tropics and subtropics can benefit from reducing emissions from deforestation and forest degradation and forest enhancements (REDD+) programs by maintaining and increasing their forest carbon stocks, but are required to monitor forest carbon stocks and fluxes, following Intergovernmental Panel on Climate Change (IPCC) good practice guidance for National Greenhouse Gas (GHG) accounting (IPCC 2006, 2019).

Various methods for reporting on forest carbon stocks and fluxes can be applied, depending on the technical and financial capacity of a country. Reporting can be done (a) at the tier 1 level, based on IPCC default values of forest aboveground biomass (AGB) and net AGB change per continent and ecological zone in combination with maps of land cover (for
distinguishing secondary and old-growth forest); (b) at the tier 2 level when national-level data are available for estimating values for standing biomass and biomass change and land use; or (c) at the tier 3 level, which requires a higher level of detail such as biomass estimates based on a national forest inventory (NFI), repeated measurements from plots to estimate biomass change, and/or the use of process-based models (IPCC 2006, 2019). The availability of recent NFI data, or publicly available forest plot data in general, is limited in the tropics (Romijn et al. 2015, Liang and Gamarra 2020), thus IPCC default values are, in absence of more detailed data, widely used for carbon pool reporting, technical assessments (e.g. UNFCCC reviews), global assessments (e.g. FAO forest resources assessment) and by researchers (e.g. Achard et al. 2014). In 2015, 84 out of 99 tropical countries were still reporting forest carbon pools at the tier 1 level (Romijn et al. 2015).

IPCC AGB default values have been specified for natural forests per continent and global ecological zone (IPCC 2006). By distinguishing continents, biogeographical variation in forest structure and species composition is considered. For example, AGB of tropical forests is higher in parts of Africa and Asia than in most of South America (Sullivan et al. 2017). Similarly, because rainfall has a strong, positive effect on AGB (Becknell et al. 2012, Slik et al. 2013), IPCC AGB defaults were reported for different climatic zones. Despite their wide use, the 2006 IPCC default AGB values have shortcomings. AGB is also strongly influenced by other factors, such as disturbance, which is not captured by a single default value per continent and ecological zone. For secondary forests that regrow after complete forest clearance, for example on abandoned agricultural land, AGB increases with forest age (Rozendaal et al. 2017, Anderson-Teixeira et al. 2021), and is typically lower than in old-growth forests (Poorter et al. 2016). Similarly, forests that are not completely cleared, but degraded, for example through selective logging, have a lower AGB compared to old-growth forests (Berenguer et al. 2014, Rutishauser et al. 2015, Longo et al. 2016).

Because of limited data availability at the time, the 2006 AGB default values were based on only a few data sources. Moreover, it is not clear how they were defined or estimated (Langner et al. 2014), and not all data sources were traceable (see IPCC 2003, 2006). Moreover, no consistent measure of uncertainty was included, since default values consisted of either a single value with a range, a single value only, or a range only. As such, accurately accounting for uncertainty in carbon stock estimates was not possible. Since 2006, a large amount of high-quality AGB data from tropical forests have become available. Recently, research networks have published AGB values from plots in old-growth forests (Lewis et al. 2013, Brienen et al. 2015, Qie et al. 2017, Sullivan et al. 2017) and logged forests (Rutishauser et al. 2015) across the tropics, and for secondary forests in Latin America (Poorter et al. 2016). In addition, databases of forest AGB values have been made available (Anderson-Teixeira et al. 2018, Cook-Patton et al. 2020), and countries in the tropics are establishing their own NFIs. Average forest-biome specific AGB values have been published (Pan et al. 2013), as well as recovery rates for secondary forests across the tropics (Anderson-Teixeira et al. 2016, Cook-Patton et al. 2020), but these values were not taken up by the IPCC yet.

In this study, we refined the IPCC 2006 default AGB values for natural forests in both the tropics and the subtropics, as part of the 2019 Refinement to the 2006 IPCC guidelines for National GHG Inventories (IPCC 2019). We provide a rigorous, reproducible refinement by (a) incorporating suitable AGB data from forest plots that became available between 2006 and 2019; (b) providing separate estimates for successional stages; and (c) including a measure of uncertainty. We primarily relied on AGB data from forest plots, despite the increasing availability of pan-tropical and global remote-sensing-based datasets of forest AGB, because uncertainty of local AGB estimates (i.e. at the pixel-level) remains high (Herold et al. 2019). We used a new remote-sensing dataset of AGB (Santoro et al. 2021) to estimate default values for areas where plot data were not available. We facilitate future refinement by documenting the approach for deriving the 2019 AGB default values, and by identifying areas with limited data on forest AGB where data collection should be prioritized.

## 2. Methods

### 2.1. AGB data from forest plots

We compiled AGB data from plots in natural forests in the tropics and subtropics from (a) data from published studies, including studies from research networks and global databases; and (b) NFIs. We included plots from traceable sources only, thus with a literature reference and known geographical location (coordinates). Large-scale research networks that monitor the structure and dynamics of tropical old-growth (Malhi et al. 2002, Lewis et al. 2013, Anderson-Teixeira et al. 2015, ForestPlots.net et al. 2021) and degraded/logged forests (e.g. Rutishauser et al. 2015), or that measure forest recovery on abandoned agricultural land (e.g. Poorter et al. 2016), generally collect detailed information on the disturbance history and/or stand age of the plots. For plots that are established as part of NFIs, in a consistent way across a wide range of environmental conditions, such information is generally lacking. We particularly targeted plot data from NFIs in Africa and Asia, because for North and South America (hereafter the Americas) more plot data from published studies were available.
Census years of the included plots varied widely, but most measurements (96% of all plots) were done after the year 2000. Although the census year varied, by including recent data and by distinguishing successional stages, our AGB estimates represent average current AGB levels in tropical and subtropical forests. If a plot was repeatedly measured, only the most recent census was used. The minimum size of included trees was at least 10 cm diameter at breast height (dbh), or above deformity in the case of buttresses, with trees identified to the finest taxonomic resolution possible. For regrowing forests, the minimum dbh was generally 5 cm (Poorter et al 2016, Anderson-Teixeira et al 2018), because smaller trees comprise a substantial part of AGB (Hughes et al 1999). This means that we may have slightly underestimated AGB in old-growth forests. Nevertheless, trees between 5 and 10 cm dbh contribute little to AGB in old-growth forests, with a 1.178 times higher AGB for tropical dry forests when including trees between 5 and 10 cm dbh, but only a 1.033 and 1.020 times higher AGB for tropical moist and wet forests, respectively (Poorter et al 2015). We included aboveground live tree biomass, thus trees smaller than the minimum dbh, shrubs, lianas, herbs, necromass and belowground biomass were not included. For one dataset, dead trees were included as well, but this dataset comprised less than 1% of the total number of plots that was included from NFIs.

Most studies estimated tree biomass based on dbh, wood density, and in some cases tree height, based on general allometric equations for tropical trees (Chave et al 2005, 2014, Feldpausch et al 2012). If aboveground carbon was reported instead of AGB, the aboveground carbon value was divided by the IPCC conversion factor of 0.47 for conversion to AGB. If another conversion factor was used in the original source, we used the original conversion factor.

2.2. Successional stages

We calculated default AGB values per continent (Africa, the Americas, Asia), per global ecological zone (FAO 2012), and successional stage. Global ecological zones were defined as broad, climatic forest types, with an exception for mountain systems (here referred to as montane forests) that were classified based on altitude only (FAO 2012; appendix A (available online at stacks.iop.org/ERL/17/014047/mmedia)). Five global ecological zones were included for the tropics (rainforests, moist forests, dry forests, shrublands, montane forests), and four for the subtropics (humid forests, dry forests, steppe, montane forests). Three successional stages were distinguished: (a) old-growth forests, which we defined as forests with no record of human disturbance in the past 100 years (Anderson-Teixeira et al 2016, Poorter et al 2016), thus secondary forests >100 years old were regarded as old-growth forests; (b) older secondary forests >20 and ≤100 years old, including forests regrowing on abandoned agricultural land, and degraded (including logged) forests; and (c) young secondary forests ≤20 years old. Plots with information on disturbance history were assigned to a successional stage based on stand age for secondary forests, or disturbance history for degraded/logged forests. If plots lacked information on disturbance history, we determined the successional stage based on remote-sensing products (Tyukavina et al 2016, Potapov et al 2017, appendix B).

2.3. Calculation of default values based on forest plot data

Default values were calculated per continent, ecological zone, and successional stage if plot data were available. The methodology depended on the successional stage, and the number of available plots (figure 1). For old-growth forests, default values were calculated as the weighted mean across all plots, weighted by the square root of plot size, to account for the large variation in plot size (Brienen et al 2015, Rutishauser et al 2015, Requena Suarez et al 2019). Only old-growth plots with information on disturbance history were included, to guarantee that they were not subject to anthropogenic disturbance. Default values for old-growth forest were calculated if at least ten plots with information on plot size were available per continent and ecological zone (figure 1(a)).

For secondary forests in the Americas, the size of most individual plots was unknown. Therefore, default values for secondary forests were expressed as average AGB per 0.5° grid cell, instead of a plot-size weighted mean. As such, we accounted for spatial clustering of plots, and avoided overrepresentation of locations with many plots. We used 0.5° grid cells, because one 0.5° grid cell generally included one research site with chronosequence plots for secondary forests (Poorter et al 2016). Per continent, ecological zone, and successional stage, we first calculated average AGB per grid cell, and then averaged these to obtain the default value. If plot data with information on disturbance history were available for at least five grid cells for both young and older secondary forests, separate default values for both young and older secondary forests were calculated (figure 1(b)). If AGB data were available for secondary forest plots for at least five grid cells, with or without information on disturbance history, we calculated default values for all secondary forests together (figure 1(b)).

For continents and ecological zones for which not sufficient plot data were available to distinguish successional stages, we calculated a single default value per continent and ecological zone to represent all successional stages, if plot data (with or
without information on disturbance history) were available for at least five grid cells (figure 1(c)). For combinations of continent and ecological zone for which no plot data were available, we calculated AGB default values based on an AGB map (figure 1(c), appendix B). We made three exceptions to our general methodology. First, for tropical dry forests in Africa, we did not distinguish successional stages, although plot data were available per successional stage. These disturbance-adapted ecosystems are subject to chronic and acute disturbances (natural and anthropogenic; McNicol et al 2018), thus successional stages cannot be meaningfully distinguished. Second, for tropical dry forests in Asia, we also included a default value for all successional stages together although plot data were available for three grid cells only, because we preferred to use plot data (36 plots) over an estimate from a remote sensing-derived biomass map. Third, for old-growth subtropical forests in Asia, we included a grid cell mean instead of a plot-size weighted mean (table 1), because plot sizes were unknown.

In total, we included 2318 plots for the Americas, 22 279 plots for Africa, and 1291 plots for Asia (figure 2). A total of 3880 plots with information on disturbance history was included, with an average plot size of 2.9 ha (range: 0.001–42 ha). Plots were typically one hectare or larger for old-growth forests (Sullivan et al 2017) and logged forests (Rutishauser et al 2015), and on average 0.1 ha for regrowing forests (Poorter et al 2016). Plot-level AGB was included, but for some datasets AGB estimates were based on multiple plots at the same location (Slik et al 2015, Anderson-Teixeira et al 2018). In total, 22 008 plots without information on disturbance history were included. These, generally small, plots were mostly from NFIs, and had an average plot size of 0.1 ha (range: 0.01–1.85 ha). Overall, most plots were from tropical forests (25 681 plots in total), while only 207 plots were included in subtropical forests (figure 2).
Table 1. Refined 2019 IPCC AGB default values per continent, ecological zone and successional stage. The mean, SD, and the median are indicated; the mean and SD are included in the refined IPCC defaults (IPCC 2019). Method refers to the method of calculating the refined default values. Median AGB values were not included for old-growth data for continents and ecological zones when default values were based on a plot-size weighted mean. America includes both North and South America. The IPCC refers to montane forests as ‘mountain systems’; old-growth forests are included as ‘primary’ forests (IPCC 2019). YSF: young secondary forest (<20 years old); OSF: older secondary forest (>20 years old); SF: all secondary forests; OGF: old-growth forest; All: all successional stages. Weighted indicates AGB default values calculated as a plot-size weighted average, grid cell indicates that the default values were calculated based on 0.5° grid cell means, and AGB map indicates that the default value was derived from a global AGB map (Santoro et al 2021). References are included in appendix D.

| Ecological zone | Continent | Successional stage | Mean AGB (Mg ha\(^{-1}\)) | SD (Mg ha\(^{-1}\)) | Median AGB (Mg ha\(^{-1}\)) | Method | # plots | # grid cells | Ref |
|-----------------|-----------|--------------------|---------------------------|---------------------|----------------------------|--------|---------|-------------|-----|
| Tropical rainforest | Africa | OSF | 404.2 | 120.4 | — | Weighted | 451 | 9 | [1–12] |
| | | YSF | 212.9 | 143.1 | 141.6 | Grid cell | 97 | 9 | [5–7, 11, 13–16] |
| | America | OGF | 307.1 | 104.9 | — | Weighted | 487 | 9 | [3, 4, 9, 10, 18–21] |
| | | OSF | 206.4 | 80.4 | 208.3 | Grid cell | 328 | 26 | [9, 10, 22–28] |
| | | YSF | 75.7 | 34.5 | 67.1 | Grid cell | 513 | 23 | [9, 10, 14, 22, 23, 28–32] |
| | Asia | OGF | 413.1 | 128.5 | — | Weighted | 192 | 9 | [3, 4, 9, 10, 33–35] |
| | | OSF | 131.6 | 20.7 | 131.6 | Grid cell | 94 | 5 | [9, 10, 36, 37] |
| | | YSF | 45.6 | 20.6 | 50.6 | Grid cell | 88 | 7 | [9, 10, 37–39] |
| | | SF | 72.8 | 36.4 | 64.2 | Grid cell | 7530 | 52 | [9, 10, 16, 40–47] |
| Tropical moist forest | America | OGF | 187.3 | 94.0 | — | Weighted | 106 | 9 | [3, 4, 9, 10, 18–21] |
| | | OSF | 131.0 | 54.2 | 112.4 | Grid cell | 185 | 17 | [9, 10, 22–26] |
| | | YSF | 55.7 | 28.7 | 44.7 | Grid cell | 353 | 17 | [9, 10, 22, 23, 25, 26] |
| | Asia | All | 67.7 | 93.4 | 31.9 | Grid cell | 322 | 36 | [9, 10, 35, 48–50] |
| Tropical dry forest | America | SF | 127.5 | 72.6 | — | Weighted | 12 | 9 | [1–2, 4–3, 44, 1–51] |
| | | OSF | 118.9 | 81.3 | 121.1 | Grid cell | 72 | 6 | [9, 10, 22, 23, 54] |
| | Asia | All | 69.6 | 47.5 | 59.7 | Grid cell | 9410 | 47 | [9, 10, 22, 23, 54, 55] |
| Tropical shrubland | America | SF | 32.2 | 24.5 | 32.1 | Grid cell | 44 | 5 | [9, 10, 22, 23, 54, 55] |
| | Asia | All | 184.6 | 144.5 | 161.6 | Grid cell | 36 | 3 | [9, 10, 35, 48, 56] |
| Tropical montane forest | America | OGF | 195.0 | 95.6 | — | Weighted | 83 | 9 | [3, 4, 9, 10, 18–21] |
| | | OSF | 184.4 | 111.0 | 177.7 | Grid cell | 21 | 8 | [9, 10, 22, 23, 26, 69] |
| | | YSF | 75.9 | 51.1 | 74.9 | Grid cell | 114 | 8 | [9, 10, 22, 23, 26, 69, 70] |
| | Asia | OGF | 433.5 | 147.5 | — | Weighted | 23 | 9 | [5, 4, 9, 10, 34, 35] |
| | | SF | 66.4 | 61.0 | 48.5 | Grid cell | 329 | 19 | [9, 10, 50, 71–73] |
| Subtropical humid | America | All | 84.5 | 42.9 | 91.5 | AGB map | — | 3986 | [59] |
| | | OSF | 323.0 | 157.7 | 281.3 | Grid cell | 29 | 11 | [9, 10] |
| | | SF | 258.4 | 128.1 | 243.7 | Grid cell | 31 | 14 | [9, 10] |
| Subtropical dry forests | America | All | 65.2 | 27.1 | 60.2 | AGB map | — | 650 | [59] |
| | | SF | 115.9 | 46.2 | 110.8 | AGB map | — | 330 | [59] |
| Subtropical steppe | America | All | 70.9 | 26.2 | 75.6 | AGB map | — | 223 | [59] |
| | | SF | 50.5 | 23.9 | 47.0 | AGB map | — | 147 | [59] |
| Subtropical montane | America | All | 41.6 | 24.7 | 39.9 | AGB map | — | 2797 | [59] |
| | | SF | 35.1 | 22.2 | 26.8 | AGB map | — | 681 | [59] |
| | | OSF | 47.4 | 40.1 | 64.6 | AGB map | — | 1835 | [59] |
| forest | Asia | OGF | 250.2 | 59.4 | 247.5 | Grid cell | 115 | 17 | [9, 10] |
| | | SF | 155.2 | 41.7 | 166.5 | Grid cell | 32 | 14 | [9, 10] |

\(^{a}\) A default value of 155.3 Mg ha\(^{-1}\) based on Pan et al (2013) can be considered instead. The IPCC AGB to aboveground carbon conversion factor of 0.47 was used to derive total biomass. Belowground biomass is included in this estimate.

\(^{b}\) A default value of 112.8 Mg ha\(^{-1}\) based on Pan et al (2013) can be considered instead. Note that the IPCC AGB to aboveground carbon conversion factor of 0.47 was used to derive total biomass. Belowground biomass is included in this estimate.

\(^{c}\) A default value of 195.0 Mg ha\(^{-1}\) based on the default value for old-growth montane forest in the Americas can be considered instead.
Figure 2. Overview of locations of plots with information on disturbance history and plots without information on disturbance history (mostly data from NFI), as well as the FAO global ecological zones (FAO 2012) for which the refined default biomass values were estimated based on a global biomass map.
3. Results

AGB in tropical forests varied by an order of magnitude across continents, ecological zones, and successional stages based on the included plots (figure 3). For old-growth tropical forests in the Americas, our new, refined IPCC 2019 AGB default values decreased from rainforests (307.1 Mg ha\(^{-1}\)), to moist forests (187.3 Mg ha\(^{-1}\)), to dry forests (127.5 Mg ha\(^{-1}\)), and the default value for montane forests (195.0 Mg ha\(^{-1}\)) was close to the value for moist forests. Similarly, for the African tropics, the AGB default value for old-growth tropical rainforest was higher than for tropical moist forest. For tropical shrublands on all continents, refined default values were the lowest (38.3–71.5 Mg ha\(^{-1}\); table 1), although successional stages were not distinguished. For subtropical forests in Africa and the Americas across all successional stages, refined default values were highest for dry forests, unexpectedly, followed by humid forests and
Figure 4. Comparison between the refined 2019 (with SD) and previous (2006) default biomass values (AGB\textsubscript{DEF}) for the three continents, per ecological zone and successional stage. For Asia, 2006 AGB\textsubscript{DEF} is indicated for both continental and insular Asia. Tropical and subtropical montane forests were excluded because in 2006 only a range was included, not an estimate of average biomass. For AGB\textsubscript{DEF} 2006, no distinction between successional stages was made. YSF: young secondary forest (\(\leq 20\) years old); OSF: older secondary forest (>20 years old); SF: all secondary forests; OGF: old-growth forest; All: all successional stages.

Across all successional stages in tropical Asia, refined default values were unrealistically low for moist forest and high for dry forest. Similarly, for old-growth tropical montane forest in Asia, the default value was higher than the one for tropical rainforest on the same continent. These unrealistic values may either be a result of a low number of included plots, or where a single default value across successional stages was included, plots may have largely represented one successional stage. In these cases, we recommend using alternative values (table 1), either the value for another continent, or a general estimate across all successional stages based on Pan et al (2013).

Across continents, our refined default values for tropical old-growth rainforests, moist forests, dry forests, and for shrublands of all successional stages together were generally close to the previous values, with a range from 45% lower to 48% higher than the 2006 IPCC default values (figure 4). In contrast, for tropical secondary forests, refined default values were consistently lower than the 2006 values, with for young secondary forests, 4.0–7.7-fold lower values (figure 4). For subtropical forests, refined default values were generally slightly lower than the 2006 default values, except for default values for subtropical humid forests in Asia that were higher than the 2006 default values for continental Asia (figure 4). Across all continents and ecological zones for tropical and subtropical forests, standard deviations (SDs) of the refined default values were on average 55% (range: 16%–138%) of the refined default value (figure 4, table 1). Thus, uncertainty in the refined default values was large, indicating large variation in AGB within ecological zones.

4. Discussion

4.1. Refined IPCC AGB default values

We found large variation in AGB across continents, ecological zones, and successional stages. Our refined default values generally reflect the large-scale climatic gradients in the tropics. Forest biomass generally increases from drier to wetter forests because of a longer growing season and higher water availability (Poorter et al 2017, Sullivan et al 2020), which was also reflected in the refined default values for tropical old-growth forests, as they increased from dry, to moist, to rainforests (table 1). In addition, tropical forest biomass decreases with elevation (Leuschner et al 2007, Girardin et al 2010). Our refined default estimates were partly consistent with this pattern, as the default value for tropical montane forests was lower than the one for tropical rainforests in the Americas (table 1).
Where possible, we provided refined AGB default values per successional stage, differentiating between young and older secondary and old-growth forests. For all continents and ecological zones for which we distinguished between secondary and old-growth forests, AGB was lower in secondary forests than in old-growth forests, and increased from young to older secondary forests as forests regrow and vegetation biomass builds up, in agreement with ecological first principles and previous analyses for tropical forests (Martin et al. 2013, Anderson-Teixeira et al. 2016, Poorter et al. 2016, N’Guessan et al. 2019).

Our refined default AGB values were generally consistent with the IPCC 2006 default values for old-growth tropical rainforests and tropical moist forests, but were lower than previous values for secondary forests and for all successional stages combined, with the strongest deviations for young secondary forests (figure 4). These results suggest that IPCC 2006 default values for at least tropical rainforests and moist forests were largely defined based on data from old-growth forests (Langner et al. 2014), and stress the importance of differentiation by successional stage. By specifying separate default values for young secondary, older secondary, and old-growth forests, the reality of 21st century tropical forests is better reflected. In Latin America, for example, secondary forests account for 41% of the forest area (Chazdon et al. 2016), and are expected to expand in area.

Our refined default values provide a more realistic estimate of forest carbon stocks when only IPCC default AGB and AGB change values in combination with information on land cover can be applied for carbon accounting (tier 1 level). Using IPCC 2006 values almost certainly led to overestimated carbon stocks for many countries, because they reflected values for old-growth forests. Moreover, IPCC default values of net rates of AGB change have also been refined recently, with overall rates 30% lower than the 2006 default values (Requena Suarez et al. 2019). Taken together, refined estimates for both AGB and net AGB change will improve national estimates of forest carbon stocks and fluxes.

To be able to apply the refined default values, countries need to distinguish successional stages per ecological zone. For countries that do not have information on the extent of young, older, and old-growth forests per ecological zone, for example from a NFI, we recommend to largely follow the approach of Harris et al. (2021) for delimiting these successional stages based on remote-sensing products (appendix C).

4.2. Recommendations for future refinement
In our effort, we included the available, high-quality data to provide refined default values, but data gaps remain (figure 5). With the refined default values, we provided the SD of the default values as a measure of uncertainty, which indicates AGB variation among plots, but does not include the uncertainty of the plot-level AGB estimates. We included both plots from research networks and NFIs. While NFI plots are usually established following a probability sampling design (e.g. Tomppo et al. 2014), the design of a research plot network depends on the specific objectives of the research project, and may not cover spatial variation in environmental conditions, or plots may, for example, be established in locations that are easily accessible. We preferably included data from research networks for which detailed information on disturbance history was included, but for some default values solely based on NFI plots, the disturbance history was estimated based on remote-sensing products. In addition, the variation in allometric equations used for the biomass estimates may have introduced additional uncertainty, as biomass estimates vary with the allometric equation used (Chave et al. 2004).

We recommend future refinement by incorporating AGB data for ecological zones and successional stages that are currently undersampled, or for which data from plots with information on disturbance history were not available. The availability of AGB data from forest plots strongly varied across continents and ecological zones, with data gaps for secondary forests in Africa and Asia, and for subtropical forests in general (figure 2, table 1). Overall, availability of plot data with information on disturbance history was low for the drier areas in Africa, parts of Asia, and subtropical forests on all continents (figure 5). This may be because most dry forests in Africa are commonly used (McNicol et al. 2018), which complicates determining their disturbance history. Nevertheless, targeting collection of data from plots, along with detailed information on their disturbance history in these areas should be a priority, although on a per-area basis tropical moist and wet forests in Africa and the Americas remain also relatively undersampled (figure 5). Establishing permanent forest plots is essential, for accurate estimation of both AGB and AGB change over time, for all successional stages. For future refinement, we also recommend distinguishing successional stages in more detail, as the three included stages represent broad categories. Particularly, older secondary forests could be divided into degraded/logged forests and regenerating forests after complete removal of vegetation (e.g. shifting cultivation), because they are subject to distinct levels of disturbance with differential impacts on carbon stocks (Berenguer et al. 2014).

Our refined default values are well-suited for tier 1 level reporting, along with the refined IPCC default values for net biomass change (Requena Suarez et al. 2019), but for tier 2 and 3 level reporting other approaches would be needed for more accurate national estimation of carbon stocks. Within ecological zones, there was large variation in AGB (as indicated by the large SD), probably because of large variation in environmental conditions within each
Figure 5. Number of plots per 100,000 km² of natural forests per ecological zone. Natural forest areas per ecological zone were based on Schulze et al. (2019). We recommend targeted data collection in areas with low sampling intensity, particularly to increase the number of plots with information on disturbance history. (a) Plots with information on disturbance history; (b) plots without information on disturbance history.
ecological zone. We recommend accounting for variation in environmental conditions within ecological zones to increase precision in AGB estimates, as several climatic and edaphic factors influence tropical forest AGB. In old-growth tropical forests, AGB varies with climate and soil fertility (e.g. Quesada et al 2012, Poorter et al 2017, Sullivan et al 2020). For regrowing forests, AGB could be modeled as a function of stand age and climate, as these drive much of the variation in AGB in regrowing forests (Poorter et al 2016, Cook-Patton et al 2020), and soil fertility. In regrowing forests, including dry, moist, and wet tropical forests, in Latin America, such an approach has been applied on a continental scale (Chazdon et al 2016), but for Africa and Asia such information is lacking. Moreover, effects of forest cover in the landscape matrix (Bonner et al 2013) and previous land-use intensity (Jakovac et al 2021) on AGB in regrowing forests should also be considered. Similar approaches could be explored for degraded/logged forests, although quantifying forest disturbance levels for large areas remains challenging.

AGB maps based on remotely-sensed data are increasingly becoming available for the tropics, but pixel-level uncertainty is still very high, particularly for high-biomass tropical forests (Herold et al 2019), which limits their use in GHG inventories. Integrating NFI data with remote-sensing products may be an alternative approach for monitoring impacts of land-use change on AGB over large areas (Requena Suarez et al 2021), as NFIs have large geographical coverage, and should be further explored in the future (Bustamante et al 2016, Herold et al 2019).

5. Conclusion

We provided a rigorous refinement of the 2006 IPCC AGB default values for tropical and subtropical forests by integrating plot data from multiple sources to derive the refined 2019 AGB default values. Instead of a single default value per continent and ecological zone, we included separate values for young and older secondary forests, and for old-growth forests. For ecological zones for which no plot data were available, we used a global AGB map to estimate default values; for the tropics, this was done for a negligible part of the three continents. We now also consistently account for uncertainty by including the SD for all refined default values. While we provide a rigorous update to the previous default values, data gaps remain. High-quality data from well-distributed permanent forest plots is essential to fill these data gaps. We provide a reproducible approach to derive AGB default values to facilitate future refinement efforts. These refined AGB default values will aid in more accurate monitoring of forest carbon stocks and dynamics in tropical and subtropical forests.

Data availability statement

The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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ORCID iDs

Danaé M A Rozendaal  https://orcid.org/0000-0002-3007-3222
Daniela Requena Suarez  https://orcid.org/0000-0002-3081-6882
Veronique De Sy  https://orcid.org/0000-0003-3647-7866
Sarah Carter  https://orcid.org/0000-0002-1833-3239
References

Achard F et al 2014 Determination of tropical deforestation rates and related carbon losses from 1990 to 2010 Glob. Change Biol. 20 2540–54

Anderson-Teixeira K J et al 2015 CTFS-ForestGEO: a worldwide network monitoring forests in an era of global change Glob. Change Biol. 21 528–49

Anderson-Teixeira K J, Herrmann V, Morgan R B, Bond-Lamberty B, Cook-Patton S C, Ferson A E, Muller-Landau H C and Wang M M H 2021 Carbon cycling in mature and regrowth forests globally Environ. Res. Lett. 16 053009

Anderson-Teixeira K J, Wang M M H, McGarvey J C, Herrmann V, Tepley A J, Bond-Lamberty B P and LeBauer D S 2018 ForC: a global database of forest carbon stocks and fluxes Ecology 99 1507

Anderson-Teixeira K J, Wang M M H, McGarvey J C and LeBauer D S 2016 Carbon dynamics of mature and regrowth tropical forests derived from a pantropical database (TropForC-db) Glob. Change Biol. 22 1690–709

Becknell J M, Kuchar L K and Powers J S 2012 Aboveground biomass in mature and secondary seasonally dry tropical forests: a literature review and global synthesis For. Ecol. Manage. 276 88–95

Berenguer E, Ferreira J, Gardner T A, Aragao L, de Camargo P B, Cerri C E, Durigan M, de Oliveira R C, Vieira I C G and Barbier J 2014 A large-scale field assessment of carbon stocks in human-modified tropical forests Glob. Change Biol. 20 3713–26

Bonner M T L, Schmidt S and Shoo L P 2013 A meta-analytical global comparison of aboveground biomass accumulation between tropical secondary forests and monoculture plantations For. Ecol. Manage. 291 73–86

Brünen R J W et al 2015 Long-term decline of the Amazon carbon sink Nature 519 344–8

Bustamante M M C et al 2016 Toward an integrated monitoring framework to assess the effects of tropical forest degradation and recovery on carbon stocks and biodiversity Glob. Change Biol. 22 92–109

Chave J et al 2005 Tree allometry and improved estimation of carbon stocks and balance in tropical forests Oecologia 145 87–99

Chave J et al 2014 Improved allometric models to estimate the aboveground biomass of tropical trees Glob. Change Biol. 20 3177–99

Chave J, Condit R, Aguilar S, Hernandez A, Lao S and Perez R 2004 Error propagation and scaling for tropical forest biomass estimates Phil. Trans. R. Soc. B 359 409–20

Chazdon R L et al 2016 Carbon sequestration potential of second-growth forest regeneration in the Latin American tropics Sci. Adv. 2 e1501639

Cook-Patton S C et al 2020 Mapping carbon accumulation potential from global natural forest regrowth Nature 585 545–50

FAO 2020 Global Forest Resources Assessment 2020 Main Report (Rome: Food and Agriculture Organization of the United Nations)

FAO 2012 GEONETWORK: Global Ecological Zones (Rome: Food and Agriculture Organization of the United Nations)

Feldpausch T R et al 2012 Tree height integrated into pantropical forest biomass estimates Biogesosciences 9 3381–403

ForestPlots.net et al 2021 Taking the pulse of Earth’s tropical forests using networks of highly distributed plots Biol. Conserv. 260 108849

Girardin C A J et al 2010 Net primary productivity allocation and cycling of carbon along a tropical forest elevational transect in the Peruvian Andes Glob. Change Biol. 16 3176–92

Harris N L et al 2021 Global maps of twenty-first century forest carbon fluxes Nat. Clim. Change 11 234–40

Herald M et al 2019 The role and need for space-based forest biomass-related measurements in environmental management and policy Surv. Geophys. 40 757–78

Hughes R F, Kauffman J B and Jaramillo V J 1999 Biomass, carbon, and nutrient dynamics of secondary forests in a humid tropical region of Mexico Ecology 80 1892–907

IPCC 2006 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Agriculture, Forestry and Other Land Use vol 4, ed H S Eggleston et al (Japan: IGES) p 83

IPCC 2019 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Agriculture, Forestry and Other Land Use (Japan: IGES) vol 4, ed D Blain et al p 68

IPCC 2003 Good practice guidance for land use, land-use change and forestry (IPCC-LULUCF) National Greenhouse Gas Inventories Programme ed J Penman et al (Japan: IGES)

Jakovac C C, Junqueira A B, Crouzellez R, Pena-Claraos M, Mesquita R C G and Bongers F 2021 The role of land-use history in driving succession pathways and its implications for the restoration of tropical forests Biol. Rev. 96 1114–34

Langner A, Achard F and Grassi G 2014 Can recent pan-tropical biomass maps be used to derive alternative tier 1 values for reporting REDD plus activities under UNFCCC? Environ. Res. Lett. 9 124008

Leuschner C, Moser G, Bertsch C, Roderstein M and Hertel D 2007 Large altitudinal increase in tree root/shoot ratio in tropical mountain forests of Ecuador Basic Appl. Ecol. 8 219–30

Lewis S I et al 2013 Above-ground biomass and structure of 260 African tropical forests Phil. Trans. R. Soc. B 368 20120295

Liang J J and Jamarij V J 2016 Biomass resilience of neotropical secondary forests: a literature review Ecol. Model. 357 92–102

Morton D C 2016 Aboveground biomass variability across tropical forests derived from a pantropical database TropForC-db (RAINFOR) J. Veg. Sci. 27 855–68

Piponiot C, Zo-Bi I C and Hérault B 2019 Drivers of extensive growth in African woodlands J. Veg. Sci. 30 341–53

Potapov P et al 2017 The last frontiers of wilderness: tracking loss of intact forest landscapes from 2000 to 2013 Sci. Adv. 3 3

3
Qie L et al 2017 Long-term carbon sink in Borneo’s forests halted by drought and vulnerable to edge effects Nat. Commun. 8
Quesada C A et al 2012 Basin-wide variations in Amazon forest structure and function are mediated by both soils and climate Biogeosciences 9 2203–46
Requena Suarez D et al 2019 Estimating aboveground net biomass change for tropical and subtropical forests: refinement of IPCC default rates using forest plot data Glob. Change Biol. 25 3609–24
Requena Suarez D et al 2021 Variation in aboveground biomass in forests and woodlands in Tanzania along gradients in environmental conditions and human use Environ. Res. Lett. 16 044014
Romijn E, Lantican C B, Herold M, Lindquist E, Ochieng R, Wijaya A, Murdiyarso D and Verchot L 2015 Assessing change in national forest monitoring capacities of 99 tropical countries For. Ecol. Manage. 352 109–23
Rozendaal D M A et al 2017 Demographic drivers of aboveground biomass dynamics during secondary succession in neotropical dry and wet forests Ecosystems 20 340–53
Rutishauser E et al 2015 Rapid tree carbon stock recovery in managed Amazonian forests Cur. Biol. 25 R787–R8
Santoro M et al 2021 The global forest above-ground biomass pool for 2010 estimated from high-resolution satellite observations Earth Syst. Sci. Data 13 3927–50
Schulze K, Malek Z and Verburg P H 2019 Towards better mapping of forest management patterns: a global allocation approach For. Ecol. Manage. 432 776–85
Slik J W F et al 2013 Large trees drive forest aboveground biomass variation in moist lowland forests across the tropics Global Ecol. Biogeogr. 22 1261–71
Slik J W F et al 2015 An estimate of the number of tropical tree species Proc. Natl Acad. Sci. USA 112 7472–7
Sullivan M J P et al 2017 Diversity and carbon storage across the tropical forest biome Sci. Rep. 7
Sullivan M J P et al 2020 Long-term thermal sensitivity of Earth’s tropical forests Science 368 869–74
Tomppo E, Malimbwi R, Katila M, Makisara K, Henttonen H M, Charnuya N, Zahabi E and Otieno J 2014 A sampling design for a large area forest inventory: case Tanzania Can. J. For. Res. 44 931–48
Tyukavina A, Hansen M C, Potapov P V, Krylov A M and Goetz S J 2016 Pan-tropical hinterland forest: mapping minimally disturbed forests Global Ecol. Biogeogr. 25 151–63