Can recent pan-tropical biomass maps be used to derive alternative Tier 1 values for reporting REDD+ activities under UNFCCC?

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Abstract

The IPCC Guidelines propose 3 Tier levels for greenhouse gas monitoring within the forest land category with a hierarchical order in terms of accuracy, data requirements and complexity. Due to missing data and/or capacities, many developing countries, potentially interested in the reducing emissions from deforestation and forest degradation scheme, have to rely on Tier 1 default values with highest uncertainties. A possible way to increase the credibility of uncertain estimates is to apply a conservative approach, for which standard statistical information is needed. However, such information is currently not available for the IPCC values. In our study we combine a recent global forest mask, an ecological zoning map and the pan-tropical AGB datasets of Saatchi and Baccini to derive mean forest AGB values per ecological zone and continent as well as their corresponding confidence intervals. Such analysis can be considered transparent as the datasets/methodologies are well documented. Our study leads to alternative Tier 1 values and allows the application of statistically-based conservative approaches. Our AGB estimates derived from Saatchi and Baccini datasets are 35% and 24% lower respectively than the IPCC values. When restricting the analysis to intact forest landscapes resulting AGB estimates derived from Saatchi and Baccini datasets get closer to the IPCC values with 13% and 1% differences respectively (underestimation). This suggests that the IPCC default values are mainly based on plots in mature forest stands. However, as tropical forests generally consist of a mixture of intact and degraded stands, the use of IPCC values may not properly reflect the reality. Finally, we propose to use the average composite of the Saatchi and Baccini datasets to produce improved alternative IPCC Tier 1 values. The values derived from such approach can easily be updated when newer and/or improved pan-tropical AGB maps will be available.

Keywords: IPCC, UNFCCC, REDD+, biomass, Tier 1, tropical forest

Introduction

Emissions from tropical deforestation and forest degradation are estimated to account for 7–14% (17% when including peat degradation) of the total anthropogenic CO2 emissions (Baccini et al 2012, Harris et al 2012). A reduction of deforestation and forest degradation activities in the tropics can therefore contribute significantly to greenhouse gas (GHG) emission reductions. The reducing emissions from deforestation and forest degradation (REDD+) scheme in combination with conservation, the sustainable management of forests and enhancement of forest carbon stocks) under the United Nations Framework Convention on Climate Change
(UNFCC). is expected to offer results-based payments to developing countries for reducing emissions from forested lands. In this context, countries may claim for incentives based on reports of their forest carbon stock and forest area changes and related GHG emission reductions (UNFCC 2014). A broad participation under REDD+, gradually covering all countries and all land uses, is essential to prevent international leakage due to displaced deforestation activities and associated emissions (Atmadja and Verchot 2012, Wunder 2008).

At the 17th Conference of the Parties (COP-17) of the UNFCC (UNFCC 2012) it was decided that developing countries will use the most recent IPCC guidance and guidelines, as adopted (i.e. IPCC 1996) or encouraged (i.e. IPCC 2003 Good Practice Guidance, GPG) by the COP, to estimate GHG emissions and removals. Moreover, we can assume that countries will wish to use the updated information from the IPCC 2006 guidelines as scientific input to their emissions and removals estimates (GOF-GOLD 2014). According to such Guidelines there are two basic inputs necessary for calculating national GHG inventories: activity data (describing area changes in forest cover) and emission factors (describing changes in carbon stock per area unit). For the former the IPCC distinguishes between six different land use classes (forest land, cropland, grassland, wetlands, settlements and other land), providing methodological guidance for each land use remaining the same and for each land-use change. Activity data are assessed using three different approaches, which have no hierarchical order in terms of accuracy. While Approach 1 only describes the total area as well as change for each land use class without providing any spatially explicit information, Approach 2 additionally tracks the conversions between the single land use classes. Approach 3 finally adds the spatial component of land use conversions (IPCC 2006, GOF-GOLD 2014). Regarding Emissions Factors the IPCC Guidelines list three hierarchical tiers that differ in their analytical complexity, data requirements and costs: Within the Tier 1 approach the IPCC Guidelines provide default carbon stock values per ecological zone (table 4.12 of IPCC 2006; URL www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_04_Ch4_Forest_Land.pdf#page=63 - accessed 11.2014). The Tier 2 approach uses country-specific data directly or indirectly based on repeated field sample plots. Tier 3 operates with spatially higher resolution data derived from country-specific remote sensing estimates and/or detailed (and repeated) field sample plots, possibly associated with modeling (IPCC 2006, GOF-GOLD 2014). While Tier 1 data have large uncertainty ranges, Tier 2 and Tier 3 data are expected to be more accurate and precise (Bucki et al. 2012). One main challenge of implementing REDD+ is the trade-off between the requirement for high quality forest monitoring systems and the associated costs. At the early stages of REDD+, most developing countries lack the financial and technical capital required to implement country-level forest monitoring (UNFCCC 2009). Therefore, a number of countries will have to rely on the IPCC Tier 1 default values instead of deriving higher tier data (Romijn et al 2012). However, through the phased approach of REDD+, countries will be able to improve this data over time through an iterative process under the UNFCCC.

The large uncertainties of the Tier 1 values essentially reflect the problem of representativeness of single default Emission Factors per ecological zone and continent as well as the lack of transparency how these values were derived. Gibbs et al. (2007) highlights the problem of assigning an average AGB value to a whole biome due to the large variation in forest biomass within each biome relating to further factors, such as slope, elevation, drainage class, soil type and land-use history. Furthermore, the Tier 1 default values of the IPCC 2006 guidelines are based on compilations of AGB and AGB growth tables per ecological zone and continent as documented in the same report. Except for a limited number of modifications almost all AGB values per ecological zone and continent of the IPCC 2006 Guidelines were already mentioned in the IPCC 2003 GPG, which only partly fit with the original values of Brown et al. (1993) and Brown and Gaston (1995) as summarized in IPCC 1996 revised 1996 guidelines. In addition, the values were rounded and the ecological zones of Montane Moist and Montane Dry forests of the 2003 GPG were combined into tropical mountain systems in the 2006 guidelines. It is the continuous updating and/or combining of databases, often in conjunction with ‘best guesses’ of experts that blur the original data sources, thus leading to a reduced transparency of the Tier 1 default values (Gibbs et al. 2007, UNFCCC 2009).

Besides the IPCC default values other studies also aimed at deriving representative biomass values per region or biome using different approaches. Gibbs et al. (2007) and Raman-kuty et al. (2007) provide comprehensive compilations of various studies showing biome-type and/or region-based tropical biomass estimates. While Brown and Lugo (1982) and Olson et al. (1983) obtained single biomass values for tropical and dry forests based on several literature sources, Brown (1997) and Houghton (1999) used forest inventories or compilations of harvest measurements from various studies to derive biomass estimates per single forest type and region respectively. Malhi et al. (2006) combined basal area with mean wood density values, both derived by interpolation of sample plot data, to derive AGB estimates in Amazonia. In contrast to most above studies Brown et al. (2001) as well as Gaston et al. (1998) and Gibbs and Brown (2007, 2008) account also for anthropogenic disturbances besides climatic, edaphic, geomorphological indices and land use/vegetation types. Based on the Global Land Cover 2000 map (GLC2000, Bartholomé and Belward 2003) Ruesch and Gibbs (2008) synthesized a global vegetation carbon stock map using AGB values from IPCC 2006 guidelines per ecological zone and continent (which are more detailed than the default Tier 1 values). These input values were modified by Ruesch and Gibbs (2008) according to different rule-sets and ‘best guesses’. While this approach considers specifically burnt forests or forest mosaics as disturbed vegetation types (assigned to half of the respective IPCC values), a separation between intact and degraded forest types or regrowth is not implemented.
The application of remote sensing allows deriving large-scale wall-to-wall carbon stock maps, thus helping to tackle the issue of interpolating small-scale forest inventory plots (Goetz et al. 2009). However, direct biomass measurements based solely on satellite remote sensing are not feasible and data has to be correlated with field-based measurements (Saatchi et al. 2007). Synergies between different remote sensing data sources can be necessary to overcome drawbacks of single observing systems (De Sy et al. 2012). A profound overview of remote sensing technologies for forest carbon stock monitoring is given in Goetz and Dubayah (2011). Initial approaches using coarse spatial resolution satellite imagery in combination with direct field plot measurements and space-borne lidar (light detection and ranging) data were applied for South America and Africa by Saatchi et al. (2007) and Baccini et al. (2008) respectively. More recently these approaches have been improved and applied to derive wall-to-wall pan-tropical biomass maps at 1 km (Saatchi et al. 2011) and 500 m (Baccini et al. 2012) resolution.

These two maps have been analyzed for their consistencies (Mitchard et al. 2013, 2014) and used to estimate tropical carbon losses (Baccini et al. 2012, Harris et al. 2012, Achard et al. 2014), but have so far not been evaluated regarding their potential to derive alternative Tier 1 default values of the IPCC guidelines. Until operational forest carbon stock monitoring becomes feasible to derive Tier 2 emission factors at national level, the use of alternative Tier 1 values based on existing pan-tropical maps could be regarded as viable solution for such non-Annex I countries, thus adding more transparency to the Tier 1 approach. Specific objective of our study is therefore the question to what extent the pan-tropical biomass maps of Saatchi et al. (2011) and Baccini et al. (2012) can be used to derive improved Tier 1 default values and provide pan-tropical, continental and country-level data tables for a large REDD+ end-user community.

Methods

Study area and data

The study area comprises almost all countries of the pan-tropical belt except for Mexico, China and Australia (Beuchle et al. 2011), which almost exclusively consist of non-Annex I countries.

AGB values of the two wall-to-wall pan-tropical biomass maps depict the situation around the years 2000 and 2007 for Saatchi et al. 2011, (referred to as Saatchi dataset) and Baccini et al. 2012, (referred to as Baccini dataset) respectively. Both studies use similar approaches with a combination of field inventory plots that partly overlap with Geoscience Laser Altimeter System (GLAS) data points from the space-born Ice, Cloud, and land Elevation Satellite (ICESat) to deduce the AGB values for all non-overlapping GLAS data points. While Baccini et al. (2012) specifically measured the AGB within GLAS shot locations, Saatchi et al. (2011) used previously existing field measurements that did not necessarily coincide with GLAS shot locations. In a next step various spatial coarse-resolution satellite data—several products from the moderate resolution imaging spectroradiometer (MODIS) sensor, shuttle topology graphy mission (SRTM) and quick scatterometer (QSCAT) data (the latter only for the Saatchi dataset)—were used to extrapolate spatially the AGB GLAS point values to a wall-to-wall coverage. The two approaches are scientifically quite similar (Mitchard et al. 2013).

Several ancillary datasets are utilized in our study: (i) the Globcover-2009 map (Bontemps et al 2011) is used to derive a forest mask. For that sake all closed to open forest cover classes excluding mosaics and other vegetation classes are combined to separate forest from non-forested areas; (ii) the intact forest landscapes dataset (IFL, Potapov et al 2008) is used to further distinguish large intact forests (>500 km²) showing no signs of significant human disturbances from non-IFL within the Globcover-2009 forest mask; (iii) the FAO ecological zones (FAO 2001), (iv) the spatial extent of the continental zones (as provided by Ruesch and Gibbs 2008) and (v) the global country boundaries 2012 (FAO 2012) are used in the spatial analysis.

Data analysis

While keeping its native resolution (500 m), the Baccini dataset is warped to fit the geographic WGS 84 projection of the Saatchi dataset. Besides, a combined product of the Saatchi and Baccini datasets is calculated using the pixel-based mean of all available pixel values. For that purpose the Saatchi dataset is spatially resampled to 500 m using nearest neighbor. Moreover, due to the different geographic extents of both datasets as well as gaps of no data values, missing average values are filled with the only existing AGB value from one of the two datasets.

By combining the available ancillary datasets different raster maps are created that serve as input data for our zonal statistics analysis. First the ecological zones dataset is intersected with the Globcover-2009 forest mask. The resulting map is further unified with the IFL and non-IFL masks. Additionally, the results are combined with the continental zones dataset. The maps are finally resampled to fit the native spatial resolutions of the Saatchi (1 km) and Baccini (500 m) datasets.

A zonal statistics analysis (using the spatial analyst module of ESRI ArcGIS 10.2) is undertaken in order to derive mean AGB values (tons of dry matter per hectare) per ecological zone from the Saatchi, Baccini and their combined dataset, with their corresponding 50% confidence intervals (CI) at pixel-level. The resulting AGB values are then compared to the IPCC Tier 1 default values as well as to the AGB values per ecological zone and continent from the IPCC 2006 guidelines. In the latter case average AGB values are calculated from the minimum—maximum range for the ecological zones where the IPCC guidelines report only AGB ranges (tropical and subtropical mountain systems). In addition, country-level values are also calculated.

In order to avoid a biased sampling and to maintain a conservative approach for maximum credibility of the AGB estimates the minimum sample size per geographic extent
(e.g. at pan-tropical and continental scale) is determined using the following formula (Cochran 1977) and affected ecological zones were flagged accordingly (Bartlett et al. 2001).

\[ n \geq \left( \frac{1.96^2 \sigma}{\text{MOE}} \right)^2, \]

where \( n \) is the minimum sampling size, the factor 1.96 is the corresponding \( z \)-value of the 95\% confidence level, \( \sigma \) is the standard deviation for each ecological zone as derived by analyzing the pan-tropical datasets and MOE stands for the acceptable Margin Of Error, which is set to \( \pm 1 \) ton of AGB. Besides the minimum sample area the fuzziness of the analyzed region also has a large effect on the representativeness of the respective AGB value due to geographic inaccuracies in the AGB datasets or ecological zones but its effect is difficult to assess. Generally speaking, areas with a large perimeter-to-area ratio are less likely to deliver representative AGB values. However, to remain conservative and avoid unnecessary sample-based artifacts the acceptable MOE is deliberately set to \( \pm 1 \) tons of AGB.

\section*{Results}

The Baccini dataset does not cover sub-tropical dry forests, sub-tropical steppe and temperate mountain forests. In comparison the spatial extent of the Saatchi map is larger and should allow deriving AGB values for all tropical ecological zones. However, small regions that have a higher risk of providing non-representative biomass values are identified (Cochran 1977) and flagged to exclude them from further analysis. Reliable estimates are therefore not available for sub-tropical steppe and temperate mountain systems (table 1 in supplementary information, available at stacks.iop.org/ERL/9/124008/mmedia; figure 1(a)) and even a combination of both datasets does not allow closing these gaps. Furthermore, when considering IFL versus non-IFL areas the number of ecological zones with reliable estimates is reduced due to smaller sample sizes (figures 1(b)–(c)). On the other hand, both datasets allow producing AGB estimates for tropical desert forests with 53 t ha\(^{-1}\) and 16 t ha\(^{-1}\) for Saatchi and Baccini respectively, while the IPCC Guidelines do not provide any value for this ecological zone.

The Saatchi and Baccini derived AGB estimates are much lower than IPCC Tier 1 values (table 1 in supplementary information and figures 1(a)–(c)). Overall AGB estimates are 79 t ha\(^{-1}\) and 56 t ha\(^{-1}\) lower than IPCC values (area weighted means) for Saatchi and Baccini respectively. However, when restricting the comparison to IFL areas, the AGB estimates come closer to IPCC Tier 1 values with 39 t ha\(^{-1}\) (Saatchi) and 6 t ha\(^{-1}\) (Baccini) global difference respectively (lower values). As for tropical and sub-tropical mountain systems the IPCC 2006 guidelines do not provide AGB mean values (only ranges) these classes are excluded from our analysis.

The mean AGB values per pan-tropical ecological zone show a good consistency between Saatchi and Baccini datasets with a correlation coefficient \( (R^2) \) of 0.87. When restricting the regression to intact forest areas (Potapov et al. 2008) \( R^2 \) is even higher: 0.97. For non-IFL \( R^2 \) is lower: 0.80.

The Baccini dataset provides higher biomass values than the Saatchi dataset for almost all ecological zones except tropical shrubland and tropical desert forest (figure 1(a)). The higher AGB values of the Baccini dataset are mainly obtained in Africa and America with in average +19 t ha\(^{-1}\) and +43 t ha\(^{-1}\) respectively. And while the AGB values seem to be more similar in Insular Asia (+11 t ha\(^{-1}\) for Baccini), the Saatchi dataset shows clearly higher biomass values in continental Asia with +35 t ha\(^{-1}\) above the Baccini values (continental-based alternative Tier 1 values are given in tables 2(a)–(c) (supplementary information), table 1 and displayed in figures 2(a)–(f) and 3(a)–(f); figure 4 visualizes the continental-based AGB values of the combined dataset over the forest mask of Globcover-2009).

The Saatchi dataset leads surprisingly to similar AGB values for different ecological zones in Africa: tropical moist deciduous forest (62 t ha\(^{-1}\)), tropical dry forest (56 t ha\(^{-1}\)), tropical shrubland (51 t ha\(^{-1}\)), tropical desert forest (53 t ha\(^{-1}\)), sub-tropical humid forest (61 t ha\(^{-1}\)), sub-tropical dry forest (57 t ha\(^{-1}\)) and sub-tropical mountain systems (53 t ha\(^{-1}\)). Baccini delivers a more credible range of decreasing biomass values from tropical moist deciduous forest (94 t ha\(^{-1}\)) over tropical dry forest (74 t ha\(^{-1}\)) and tropical shrubland (43 t ha\(^{-1}\)) to tropical desert forest (14 t ha\(^{-1}\)) (tables 2(a)–(b) in supplementary information; figure 2(d)).

Average AGB differences of 49 t ha\(^{-1}\), 73 t ha\(^{-1}\) and 51 t ha\(^{-1}\) are found when comparing the continental AGB values of corresponding ecological zones for IPPC, Saatchi and Baccini datasets respectively, reflecting differing plant communities of corresponding ecological zones between the different continents. Furthermore the African AGB estimates derived from the Saatchi and Baccini dataset by ecological zones are in average 85 t ha\(^{-1}\) and 66 t ha\(^{-1}\) beneath their corresponding ecological zones in the two other continents.

An obvious flaw is detected within the Saatchi dataset when comparing the AGB values of the ecological zone of tropical dry forests in America for intact and non-IFL strata. With 49 t ha\(^{-1}\) the non-IFL areas contain on average ten tons more biomass than the IFL areas (values marked with two asterisks in tables and figures). This lower value can be explained by the presence of randomly scattered single-pixel artifacts with a single AGB value of 450 t ha\(^{-1}\) within the non-IFL area of tropical dry forests. This specific artifact value is further found within the IFL subset of the same ecological zone and within tropical mountain systems, but to a negligible extent. Such artifacts are only detected in America. In comparison, the Baccini dataset provides higher AGB average values for tropical dry forests in America at 126 t ha\(^{-1}\) and 117 t ha\(^{-1}\) for IFL and non-IFL areas respectively (table 2b in supplementary information).

\section*{Discussion}

We assessed how the individual pan-tropical AGB maps of Saatchi et al. (2011), Baccini et al. (2012) or a combination of
both maps could be used to obtain alternative Tier 1 values. Besides some minor limitations due to their geographic extent and restrictions in minimum sample size, both datasets deliver alternative values for almost all ecological zones within the tropics. The methodology of AGB estimation of both these datasets is well described, thus leading to a higher transparency when compared to the hitherto default values of the IPCC 2006 guidelines. Furthermore, our analysis provides additional statistical information (50% CI at pixel-level), thus allowing the implementation of a statistically-based conservative discount factor (Grassi et al 2008). The 50% CI is used when the conservativeness concept is applied in the adjustment procedure during the review of GHG inventories under the Kyoto Protocol (UNFCCC 2006). Given this important precedent, and given that using the 95% CI may result in overly conservative estimates, we consider the 50% CI useful when discussing the conservativeness in the REDD+ context. Our approach can help in raising the credibility of possible REDD+ result-based payments, by reducing the likelihood of overestimating the magnitude of reduced emissions or increased removals (Grassi et al 2013).

A comparison of the Saatchi and Baccini datasets was undertaken by Mitchard et al (2013) globally and by Mitchard et al (2014) over the Amazon basin and concluded that no single map was generally superior to the other even though there are substantial differences. However, it has to be taken into account that the Saatchi dataset depicts the situation around 2000–2001, while Baccini shows the situation around 2007–2008. Besides the differences of the two maps which arise from the use of various data and applied biomass models, there were also actual land cover changes on the ground (e.g. deforestation and forest degradation, but also forest enhancements and the establishment of plantations) taking place during the 2000s.

Figure 1. Diagrams of pan-tropical AGB data (tons of dry matter per hectare) analyzed per ecological zone. While (a) shows the AGB values of the total forest area, the two following figures separate the AGB estimates between intact forest landscapes (b) and non-intact forest landscapes (c). Bars marked with one asterisk indicate insufficient large sample sizes.
The question whether the use of the pan-tropical datasets also leads to a higher accuracy as compared to the IPCC default values is not directly tackled in this study due to missing AGB reference values. A statistically valid sample of units distributed over the pan-tropical belt with a size of whole map pixels (25–100 ha) would be necessary to evaluate the accuracy of the Saatchi/Baccini datasets (Mitchard et al. 2013). The use of other (local) reference datasets that do not comply with above requirements is therefore prohibited. Sub-pixel sized observation units cannot represent correctly AGB values of full pixels because of the small-scale heterogeneity of tropical forests (Gibbs et al. 2007). Furthermore, a non-random or alternatively non-regular sampling design is not valid for deriving the average AGB value of a whole region, due to the variation in forest biomass that relates to different factors, such as slope, elevation, drainage class, soil

Table 1. Comparison of continental AGB data between IPCC (2006) default values and values derived from the combined datasets of Saatchi and Baccini. All AGB values are given in t ha⁻¹ (tons of dry matter per hectare). The ‘50%’ columns show the range of the measured biomass values that lie within 50% of the confidence interval (CI) at pixel level. Cells marked with one asterisk flag small sample sizes.

| Ecological zone                  | Continent          | IPCC               | Combined datasets     |
|----------------------------------|--------------------|--------------------|-----------------------|
|                                  |                    | Mean (50%)        | Intact forest Mean (50%) | Non-intact forest Mean (50%) |
|                                  |                    | AGB/Range Mean     |                       |                         |
|                                  |                    | 205 ±69            | 286 ±28               | 162 ±66                 |
|                                  |                    | 242 ±43            | 269 ±23               | 192 ±51                 |
|                                  |                    | 243 ±60            | 307 ±27               | 236 ±61                 |
|                                  |                    | 250 ±52            | 282 ±34               | 239 ±56                 |
|                                  |                    | 77 ±23             | 269 ±55               | 77 ±22                  |
|                                  |                    | 123 ±53            | 227 ±43               | 99 ±41                  |
|                                  |                    | 197 ±60            | 295 ±34               | 192 ±59                 |
|                                  |                    | 165 ±57            | 174* ±67*             | 164 ±56                 |
|                                  |                    | 64 ±23             | 164 ±37               | 63 ±22                  |
|                                  |                    | 79 ±24             | 82 ±17                | 79 ±25                  |
|                                  |                    | 150 ±54            | 279 ±33               | 143 ±51                 |
|                                  |                    | 160 ±50*           | 182* ±71*             | 142* ±46*               |
|                                  |                    | 46 ±23             | 154* ±47*             | 45 ±21                  |
|                                  |                    | 135 ±47            | –                     | 135 ±47                 |
|                                  |                    | 107 ±39            | –                     | 107 ±39                 |
|                                  |                    | 70 ±36*            | 168* ±36*             | 168* ±36*               |
|                                  |                    | 121 ±55            | 249 ±34               | 103 ±46                 |
|                                  |                    | 195 ±58            | 256 ±35               | 161 ±56                 |
|                                  |                    | 264 ±49            | 305 ±33               | 254 ±50                 |
|                                  |                    | 253 ±32            | 258 ±28               | 249 ±35                 |
|                                  |                    | 51 ±26             | –                     | 51 ±26                  |
|                                  |                    | 61 ±20             | –                     | 61 ±20                  |
|                                  |                    | 110 ±52            | 249* ±9*              | 109 ±52                 |
|                                  |                    | 169 ±33            | –                     | 169 ±33                 |
|                                  |                    | 90 ±26             | –                     | 90 ±26                  |
|                                  |                    | 57 ±26             | –                     | 57 ±26                  |
|                                  |                    | 140 ±39            | –                     | 140 ±39                 |
|                                  |                    | 110 ±52            | 249* ±9*              | 109 ±52                 |
|                                  |                    | 169 ±33            | –                     | 169 ±33                 |
|                                  |                    | 57 ±26             | –                     | 57 ±26                  |
|                                  |                    | 140 ±39            | –                     | 140 ±39                 |
|                                  |                    | 160 ±30*           | 135* ±30*             | 135* ±30*               |
|                                  |                    | 70 ±17             | –                     | 70 ±17                  |
|                                  |                    | 53 ±5               | –                     | 53 ±5                   |
|                                  |                    | 60 ±17             | –                     | 60 ±17                  |
|                                  |                    | 203 ±57            | 257 ±62               | 193 ±54                 |
|                                  |                    | 50 ±30*            | –                     | 50 ±30*                 |
|                                  |                    | 100 ±17*           | –                     | 100 ±17*                |
|                                  |                    | 130 ±20*           | –                     | 130 ±20*                |
Figure 2. Continental-level diagrams of AGB data (tons of dry matter per hectare) analyzed per ecological zone for America and Africa. In the first row the AGB values of the total forest area are displayed (a), (d). While the second row shows the AGB values for the intact forest landscapes (b), (e), the third row displays the AGB values for the non-intact forest landscapes (c), (f). Bars marked with one asterisk indicate insufficient large sample sizes and bars with two asterisks indicate flaws in the dataset.
type and land-use history (Gibbs et al 2007, Houghton et al 2001). This last point highlights the importance of an unbiased sampling design (combining sampling within mature and non-mature stands) for any future forest inventory with the aim of proper emission factor assessment.

The scope and nature of the sampling design is also a point of criticism regarding the accuracy of the IPCC default values themselves. Gibbs et al (2007) point out that bibliographic studies, on which the IPCC default values are based, generally focus on mature forest stands, which are not representative for whole ecological zones. This point is supported by our study as AGB values of all pan-tropical ecological zones (area weighted average) are about 35% (Saatchi) and 24% (Baccini) lower than the IPCC default values of the corresponding zones. Moreover, when analyzing IFL areas only, the AGB values of Saatchi and Baccini come closer to the IPCC default values with 13% and 1% underestimation respectively. As forests generally consist of a mixture of intact and non-intact stands, spatial averaging of areas showing disturbances or spatial heterogeneity in forest cover within the coarse resolution pixels of the Saatchi and Baccini maps results in lower AGB values. Thus, IPCC Tier 1 default values may lead to an overestimation of AGB and the use of the Saatchi/Baccini datasets seems to be more appropriate. Furthermore, deriving the difference between IFL and non-IFL biomass values could be used as a first approximation to obtain AGB losses due to forest degradation, thus allowing a country to derive more detailed emission estimates. Unfortunately, due to the limited extent of IFL areas several ecological zones do not have corresponding IFL values.

A comparison between both pan-tropical maps generally shows higher AGB values from Baccini than Saatchi except for ecological zones of low biomass, such as tropical desert forest and tropical shrubland. The large AGB value of the Saatchi database for tropical desert forest (53 t ha$^{-1}$) as compared to 16 t ha$^{-1}$ from Baccini indicates a bias towards high biomass values within low AGB ecological zones of that dataset – most probably related to a single region-specific allometric equation between Lorey’s height and AGB as this high value is only observed within the African continent.

Besides the global Tier 1 default values the IPCC 2006 guidelines also provide continental-based AGB estimates per ecological zones. Due to the existence of distinct ecosystems on different continents, an analysis at continental level is needed to derive more relevant AGB values in comparison to a pan-tropical analysis. Our study shows that tropical mountain systems in continental Asia have a 165 t ha$^{-1}$ higher AGB value as compared to Africa when derived from the Saatchi dataset (figures 2(d), 3(a)). A comparison of continental AGB values of all corresponding ecological zones within the same dataset shows average differences of 49 t ha$^{-1}$, 73 t ha$^{-1}$ and 51 t ha$^{-1}$ for IPCC, Saatchi and Baccini respectively, thus supporting the subdivision of the pan-tropical AGB values per ecological zone into continental-based values.

The reliability of the alternative Tier 1 estimates is influenced by the quality of the pan-tropical biomass maps involved, but also as a result of zonal statistical analysis arising from spatial inaccuracies of the ecological zone dataset due to its generalized scale of 1:1 million (FAO 2001). Specifically, the analysis of smaller subsets of ecological zones gives rise to higher risks of deriving non-representative AGB values because noise in the pan-tropical biomass datasets or spatial inaccuracies has larger effects in smaller areas. A country-level analysis is therefore recommended only for larger countries with sufficiently large-scale ecological zones (table 3).

The continent-level analysis of the biomass datasets also reveals scattered single-pixel artifacts in the Saatchi map for the tropical dry forest ecological zone of America. However, as these artifact pixels represent only 0.04% of the total number of pixels in that ecological zone, we consider that they have a negligible impact on our results at pan-tropical and continental level. In order to maintain a high level of transparency and reproducibility the input datasets are not modified or filtered, but the results that are affected by these artifacts are flagged in table 2(a) (supplementary information).

With no single pan-tropical AGB map recognized as being more accurate than the other combined with the problematic of potentially differing biomass patterns at a local scale (Mitchard et al 2013) we face the question how to deal with the AGB results from both maps. An interesting approach for data fusion of different biomass maps is shown by Ge et al (2014) for a study area in East Africa using a weighted averaging methodology but due to lack of higher accuracy reference maps, such approach is yet not feasible for processing pan-tropical datasets. Mitchard et al (2013) showed that even though there are large pixel-based differences in the estimates, average AGB values become more similar when being analyzed on country-level, revealing the ability of both datasets to estimate reliable regional-scale biomass levels. Finally, the average composite of both pan-tropical datasets is chosen as the most credible and reasonable approximation to derive alternative estimates (table 2(c) in supplementary information; table 1 -shortened version of table 2(c)- in paper) to the current IPCC Tier 1 values.

Conclusion

Based on the results of our work, we conclude that the pan-tropical biomass maps of Saatchi et al (2011) and Baccini et al (2012) can be used to derive alternatives to the IPCC Tier 1 default values, which are applicable in the context of REDD+. In particular, we suggest using the average composite of the Saatchi and Baccini datasets analyzed by continental ecological zone (table 2(c) in supplementary information and table 1). Wherever feasible, we recommend using country-based estimates (table 3 in supplementary information) in order to best reduce the uncertainty of the estimates. Overall, we believe that our approach has several potential advantages as compared to the use of the hitherto existing Tier 1 values, including: (i) it reflects better the natural mixture of intact and degraded stands within tropical forests; (ii) it represents better the ecological zones; (iii) the availability of statistical information allows for the application of conservative approaches to increase the credibility of
Figure 3. Continental-level diagrams of AGB data (tons of dry matter per hectare) analyzed per ecological zone for continental and insular Asia. In the first row the AGB values of the total forest area are displayed (a), (d). While the second row shows the AGB values for the intact forest landscapes (b), (e), the third row displays the AGB values for the non-intact forest landscapes (c), (f). Bars marked with one asterisk indicate insufficient large sample sizes and bars with two asterisks indicate flaws in the dataset.
possible REDD+ result-based payments; (iv) it may provide a first approximation of AGB losses due to forest degradation through the comparison of IFL and non-IFL biomass values; (v) it is transparent, as the datasets/methodologies are well documented. Furthermore, our approach is flexible: as it can be expected that more accurate versions of these maps will be available in the near future, our approach can easily be updated with any new dataset.

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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
Atmadja S and Verchot L 2012 A review of the state of research, policies and strategies in addressing leakage from reducing emissions from deforestation and forest degradation (REDD+) Mitig. Adapt. Strateg. Glob. Change 17 311–36
Baccini A et al 2012 Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps Nat. Clim. Change 2 182–8
Baccini A, Laporte N, Goetz S J, Sun M and Huang D 2008 A first map of tropical Africa’s above-ground biomass derived from satellite imagery Environ. Res. Lett. 3 045011
Bartholomé E and Belward A S 2005 GLC2000: a new approach to global land cover mapping from Earth observation data Int. J. Remote Sens. 26 1959–77
Bartlett J E, Kotrlik J W and Higgins C C 2001 Organizational research: determining appropriate sample size in survey research Inf. Technol., Learn. Perform. J. 19 1
Beuchle R, Eva H D, Stibig H-J, Bodart C, Brink A, Mayaux P, Johansson D, Achard F and Belward A 2011 A satellite data set for tropical forest area change assessment Int. J. Remote Sens. 32 7009–31
Bontemps S, Defourny P, Bogaert E V, Arino O, Kalogirou V and Perez J R 2011 GLOBCOVER 2009—Products Description and Validation Report URL (http://due.esrin.esa.int/globcover/ LandCover2009/GLOBCOVER2009_Validation_Report_2.2. pdf) (accessed 05.2014)
Brown S 1997 Estimating biomass and biomass change of tropical forests: a primer Forestry Paper 134 (Rome: FAO)
Brown S and Gaston G 1995 Use of forest inventories and geographic information systems to estimate biomass density of tropical forests: application to tropical Africa Environ. Monit. Assess. 38 157–68
Brown S, Iverson L R and Prasad A 2001 Geographical Distribution of Biomass Carbon in Tropical Southeast Asian forests: A
UNFCCC 2006 Good practice guidance and adjustments under Article 5, paragraph 2, of the Kyoto Protocol FCCC/KP/CMP/2005/8/Add.3 Decision 20/CMP.1 URL (http://unfccc.int/resource/docs/2005/cmp1/eng/08a03.pdf) (accessed 11.2014)

UNFCCC 2009 Cost of implementing methodologies and monitoring systems relating to estimates of emissions from deforestation and forest degradation, the assessment of carbon stocks and greenhouse gas emissions from changes in forest cover, and the enhancement of forest carbon stocks FCCC/TP/2009/1 URL (http://unfccc.int/resource/docs/2009/tp/01.pdf) (accessed 06.2014)

UNFCCC 2012 Conference of the Parties, Report of the Conference of the parties on its seventeenth session, held in Durban from 28 November–11 December 2011, Addendum, art two: action taken by the Conference of the Parties at its seventeenth session, contents, decisions adopted by the COP17, outcome of the work of the ad hoc working group on long-term cooperative action under the Convention FCCC/CP/2011/9/Add.1 decision 2/CP17 URL (http://unfccc.int/resource/docs/2011/cop17/eng/09a01.pdf) (accessed 07.2014)

UNFCCC 2014 Conference of the Parties, Report of the Conference of the parties on its nineteenth session, held in Warsaw from 11–23 November 2013, addendum, part two: action taken by the Conference of the Parties at its nineteenth session, contents, decisions adopted by the COP19, on modalities for measuring, reporting and verifying UN- FCCC/CP/2013/10/Add.1 decision 14/CP19 URL (http://unfccc.int/resource/docs/2013/cop19/eng/10a01.pdf) (accessed 07.2014)

Wunder S 2008 How do we deal with leakage? ed A Angelsen Moving Ahead With REDD Issues, Options and Implications (Bogor Indonesia: Center for International Forestry Research (CIFOR)) chapter 7