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Extracting above-ground biomass in areas corresponding to FAO’s definition of “Forest” using open geospatial data: Results for ASEAN

Brian A. Johnson [1], Chisa Umemiya [1], Takeo Tadono [2], Mariko Harada [2], Osamu Ochiai [2], Ko Hamamoto [2]

[1] Institute for Global Environmental Strategies, 2108-11, Kamiyamaguchi, Hayama, Kanagawa, 240-0115, Japan
[2] Earth Observation Research Center, Japan Aerospace Exploration Agency, 2-1-1 Sengen, Tsukuba, Ibaraki, 305-8505, Japan

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Abstract

In this study, we extracted above-ground biomass (AGB) information for forests in different ecological zones of ASEAN (Association of Southeast Asian Nations) by integrating freely-available global AGB, forest, and ecological zone map products. Our objective was to assess the suitability of the data and proposed approach for national reporting of forest carbon stocks. We compared the satellite-derived AGB values of forests in ASEAN countries with the corresponding AGB values provided by the Intergovernmental Panel for Climate Change (IPCC) in their Guidelines for National Greenhouse Gas Inventories (which are derived from ground-based measurements of forest AGB). For this, we used a map integration approach that ensures that AGB data is extracted from areas corresponding to the Food and Agricultural Association (FAO) of the UN’s definitions of “forest” and “ecological zones”, as recommended by the relevant IPCC Guidelines. We found that the average satellite-derived AGB values extracted for each ecological zone were generally lower than the values for natural forests (but higher than the values for plantation forests) provided in the IPCC Guidelines. Further investigation showed that this was partly due to the presence of many erroneously low AGB values for forests in the extracted results, caused by errors in the data masks applied to the original global AGB map, including masks of cropland, urban areas, bare soil, and water bodies. Our findings suggest that further processing is necessary before using satellite-derived data for national reporting of forest carbon stocks in ASEAN countries, and we give a few possible options for this.

1. Introduction

1.1 Introduction

Countries are requested to regularly monitor their forest carbon stocks to support the implementation of various international environmental agreements, including the UN Sustainable Development Goals (United Nations Statistics Division, 2023), the UNFCCC Paris Agreement (United Nations, 2015), and the Kunming-Montreal Global Biodiversity Framework (CBD, 2022). This monitoring is typically done using a combination of remote sensing data (to estimate the total area of one or more types of forest) and ground-based measurements of forest carbon (to estimate the average carbon stocks of these one or more types of forest) (UNFCCC, 2009). Ground-based measurements of forest carbon stocks, however, are often sparse in developing countries, leading to high uncertainty when the data is used to estimate a country’s total forest carbon in above-ground biomass or other carbon pools.

Recently, satellite-derived above-ground biomass (AGB) maps with global coverage and up to 100 m spatial resolution have become available, e.g., the European Space Agency’s Biomass Climate Change Initiative (Biomass_cci) map product for the years 2010, 2017, 2018, 2019 and 2020 (Santoro, M and Cartus, O, 2023). These satellite-derived AGB maps can complement countries’ (sparse) ground-based measurements of forest AGB to allow for more accurate reporting of national forest carbon stocks. Use of satellite-derived AGB maps for national reporting requires further pre-processing, however. For one, the global maps may include the AGB values of other vegetation that is not considered as “forest” according to the definition being used by a country or UN organization (e.g., the Food and Agricultural Association of the UN (FAO, 2010)). Additionally, the global AGB maps may be inaccurate in some geographic areas due to, e.g., the presence of pixels containing a mixture of forest and non-forest land, or rough topography, among other factors (Bastos et al., 2022; Málaga et al., 2022).

In this study, we developed a simple processing workflow to extract the AGB values of areas corresponding to FAO’s definition of “forest” (FAO, 2010), within different “ecological zones” (FAO, 2012). We selected the ten member countries of the Association of Southeast Asian Nations (ASEAN) as the study site. As an initial rough assessment of the suitability of the satellite-derived data for national reporting in ASEAN countries, we cross-compared the results of the map outputs with the AGB values published in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Intergovernmental Panel on Climate Change, 2006). Countries often use these 2006 IPCC values for their national reporting to the UNFCCC and other international organizations when nationally-specific values are unavailable/insufficient (See Section 2.1. for further information). The main contribution of this study is its presentation of a workflow for processing satellite-derived global AGB maps in a way that is consistent with the FAO’s definitions of “forest” and “ecological zones” (as recommended by the IPCC Guidelines).

2. Methods and Materials

2.1 Study Area and Data

The ten ASEAN member countries include Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam. The ASEAN region contains relatively high forest cover, but is also experiencing significant forest losses (Feng et al., 2021). Further, there is a need for more AGB data in many ASEAN

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countries to support their forest carbon monitoring and reporting efforts.

Several freely-available global map products were used for our analysis (Table 1). The first was the Biomass_cci map, a satellite-derived AGB map for the year 2020 (Santoro, M and Cartus, O, 2023) (Figure 1 (a)). The Biomass_cci map was generated using a combination of various types of synthetic aperture radar (Sentinel-1, Envisat ASAR, PALSAR-2) and spaceborne LIDAR data (ICESAT and GEDI data) (Santoro, M and Cartus, O, 2023). As this map contains AGB values for various types of vegetation, it requires further processing to obtain the values of forests alone. Thus, a map of forest areas was also required.

The 2006 IPCC Guidelines state that the terminology used by countries for estimating biomass stocks and changes need to be consistent with the terminologies/definitions used by the FAO (Intergovernmental Panel on Climate Change, 2006). Thus, in this study we decided to follow the FAO's definition of "forest", i.e., *"Land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. Notably, it does not include land that is predominantly under agricultural or urban land use*" (FAO, 2010). Of existing global and regional forest maps, the PALSAR-2 Forest/Non-Forest (PALSAR-FNF) (JAXA, 2022) map was previously found to have the most similar definition of "forest" to that of the FAO definition (Johnson et al., 2023). For this reason, we selected the year 2020 PALSAR-FNF map (version 2) to identify forest areas in this study.

The third dataset used in this study was the Global Ecological Zones map produced by the FAO (FAO, 2012) (Figure 2). This dataset was selected to help extract the AGB values of forests in different ecological zones within the ASEAN region. Finally, we used country boundaries from the global administrative areas map dataset (https://gadm.org/; last accessed March 12, 2024) to divide ASEAN into continental and insular regions, because the 2006 IPCC Guidelines (which we compare our results with) provide different AGB values for continental and insular regions of Asia (Intergovernmental Panel on Climate Change, 2006).

Map product	Description	Spatial resolution
Biomass_cci	Global map of vegetation AGB (Mg/ha)	100m
PALSAR-2 Forest/Non-Forest map, version 2	Global map of areas corresponding to FAO's definition of "forest".	25m
Global Ecological Zones map	Map of ecological zones	n/a (delineated using various global maps)

Table 1. Satellite-derived global maps used in this study.

The fourth source of data used in our study was a set of AGB values of natural and plantation forests in different ecological zones of Asia (including "tropical rainforest", "tropical moist forest", "tropical mountain systems", and "tropical dry forest"), derived from ground-based measurements collected from these zones/regions and compiled in Table 4.7 of the IPCC Guidelines for National Greenhouse Gas Inventories (Intergovernmental Panel on Climate Change, 2006). The provided AGB values are average values (or in some cases, the approximate range of AGB values) for forests in a particular ecological zone, and thus do not contain coordinate information. According to IPCC Guidelines, these values can be considered as default ("Tier 1") AGB values that countries can use for their national reporting to the UNFCCC and other international organizations when country-specific values are not available or insufficient (Intergovernmental Panel on Climate Change, 2006).

2.2 Methodology

Our proposed workflow involved overlaying and integrating the datasets presented in Section 2.1. As the first step, we generated an ASEAN regional mosaic of AGB from the Biomass_cci dataset, and reprojected this map to the "Asia South Albers Equal Area Conic" projection to permit more accurate area calculations. This process was then repeated for the PALSAR-FNF map. Next, we resampled the PALSAR-FNF map to 100 m resolution to match the Biomass_cci dataset using a sum filter, and extracted all resampled pixels containing homogenous forest cover. This was done to reduce the extraction of AGB values of pixels containing a mixture of forest and non-forest lands in the next step. Then, we overlaid the Biomass_cci map and the map of homogenous forest areas, and extracted the AGB values of all homogenous forest areas in the ten ASEAN countries (Figure 1 (b)).

In addition to the national-level analysis of AGB, we also conducted a regional analysis, which involved extracting the AGB values of forests in different ecological zones and geographic regions (continental and insular) of ASEAN. For this, we first reprojected the Global Ecological Zones map to the "Asia South Albers Equal Area Conic" projection, and then overlaid the AGB map of homogenous forest areas with the reprojected Global Ecological Zones map (Figure 2) to extract AGB by ecological zone. Finally, we subdivided ASEAN into continental (Cambodia, Laos, Myanmar, Thailand, and Vietnam) and insular (Brunei, Indonesia, Malaysia, the Philippines, and Singapore) countries using the global administrative areas map, and overlaid the subdivided map with the "AGB by ecological zone" map. This was done to allow for a better comparison with AGB values provided in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, which are subdivided into continental and insular Asia (Intergovernmental Panel on Climate Change, 2006).
The final result of this regional-level analysis was a set of maps of forest AGB in four different ecological zones (tropical rainforest, tropical moist forest, tropical mountain systems, and tropical dry forest) and two geographic regions (continental and insular) of ASEAN. Figure 3 shows the processing workflow.

Lastly, we performed a cross-comparison of the results of this regional analysis and the AGB values of forests provided in the IPCC Guidelines. First, we computed the average AGB values of the forests located in each ecological zone and geographic region using our generated maps. Then, we calculated the difference between these values and the default AGB values of forests in the same zone/geographic region as reported in the IPCC Guidelines. In most cases, the IPCC Guidelines provided the average AGB value of forests in a particular ecological zone/geographic region, but for forests in the "Tropical mountain system" ecological zone, only a potential range of AGB values is provided due to limited ground-based measurements (see Table 2).

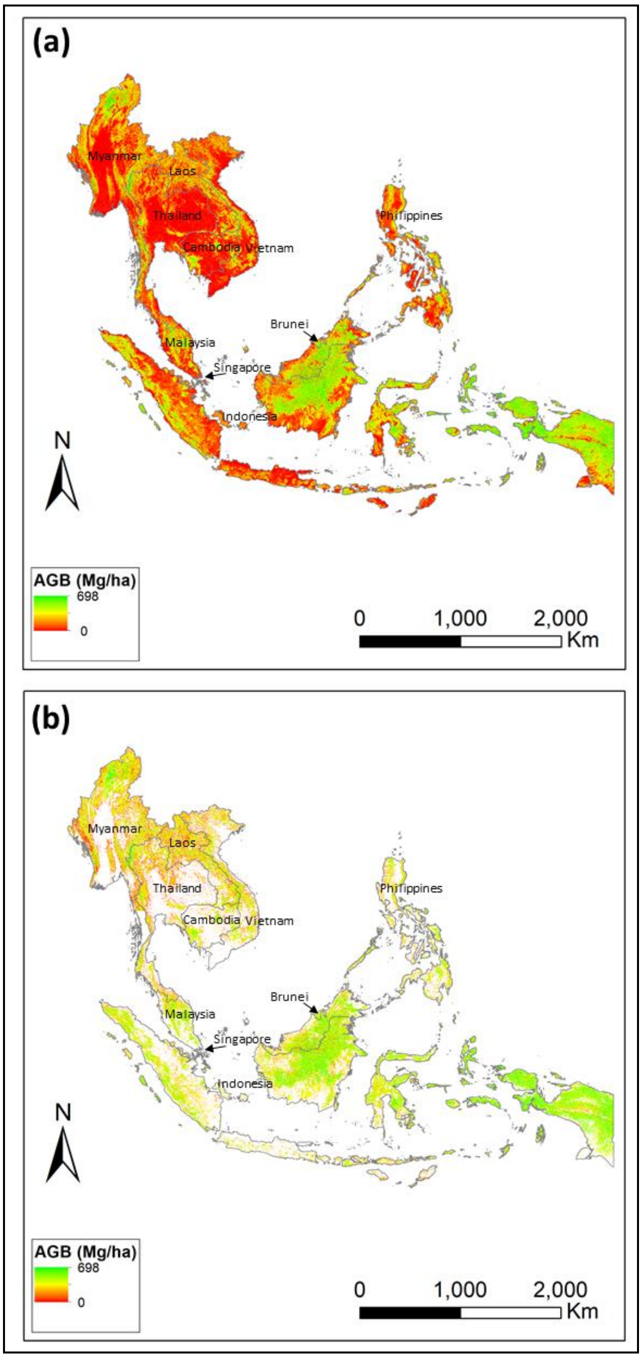

Figure 1. Original Biomass_cci map of ASEAN countries in the year 2020 (a), and the result after extracting AGB values only in areas corresponding to FAO’s definition of “forest” (b).

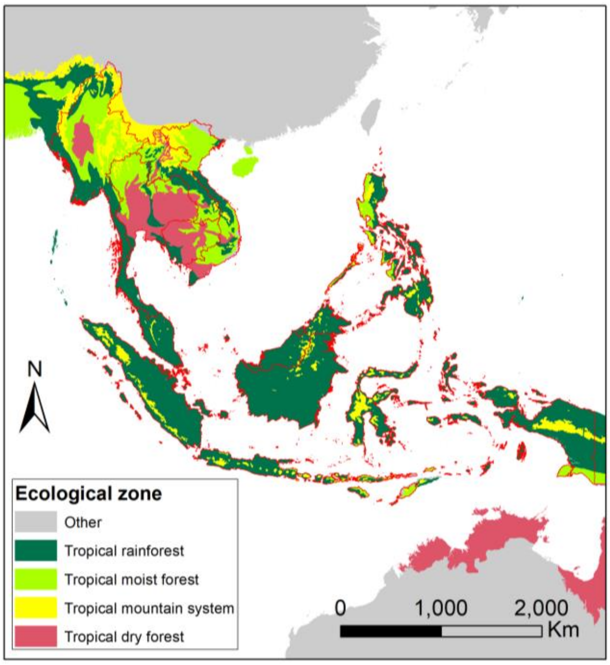

Figure 2. Global Ecological Zone map showing the four different forest ecological zones in ASEAN.

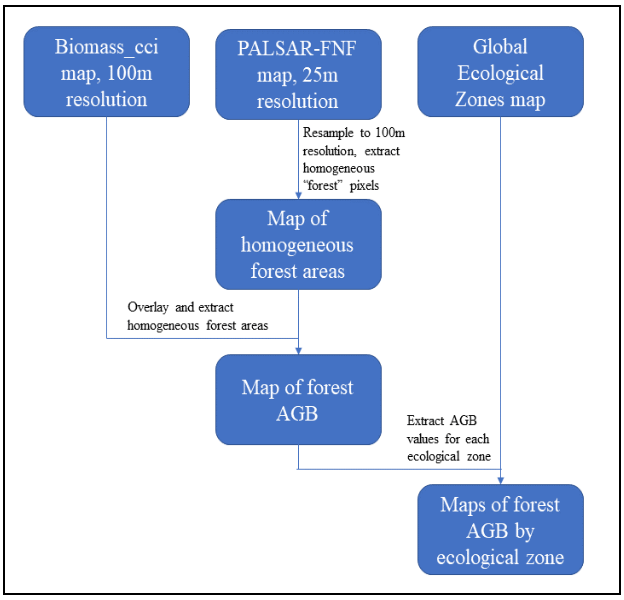

Figure 3. Processing workflow to extract forest AGB by ecological zone.

3. Results and Discussion

3.1 Regional Analysis and Comparison with IPCC Values

Table 2 shows the average AGB values extracted in our study, and the AGB values provided in the 2006 IPCC Guidelines (Intergovernmental Panel on Climate Change, 2006). Generally, the AGB values extracted from the satellite datasets were lower than the corresponding values of natural forests provided in the IPCC Guidelines. The satellite-derived values for the tropical rainforests, tropical moist forest, and tropical dry forest ecological zones (both for continental and insular countries) were all significantly lower than the IPCC values. For the tropical mountain system ecological zone, our results were near the middle of the range of values provided by the IPCC Guidelines (as already mentioned, they do not give an average AGB value for this ecological zone, only a typical range of values). On the other hand, our extracted AGB values were generally higher than the IPCC values for plantation forests. The fact that our extracted AGB values were between the IPCC Guidelines' values for natural forests and plantation forests is not too surprising considering that we used FAO's definition of "forest" to define the forest extent in our study; this "forest" definition includes both natural forests and many types of plantation forests (only excluding plantations that are primarily used for non-wood products, e.g., oil palm) (FAO, 2010). Our results for the tropical rainforest and tropical mountain system ecological zones were consistent with the values in the IPCC Guidelines in that the AGB values of insular countries were higher than those of continental countries; for both ecological zones, insular forests had over 50% higher AGB than continental forests. For tropical the moist forest ecological zone, however, our results differed from the values in the IPCC Guidelines in that continental countries had higher average AGB values than insular countries (the difference was only around 10% though).

Ecological zone	Our results (ASEAN)	IPCC value for natural forest (Asia)	IPCC value for plantation forest (Asia broadleaf)	IPCC value for plantation forest (Asia other)
Tropical rainforest (cont.)	155	280	220	130
Tropical rainforest (insular)	232	350		
Tropical moist forest (cont.)	151	180	180	100
Tropical moist forest (insular)	137	290		
Tropical mountain system (cont.)	153	50-220	40-150	25-80
Tropical mountain system (insular)	232	50-360		
Tropical dry forest (cont.)	n/a	130	90	60
Tropical dry forest (insular)	121	160		

Table 2. Extracted AGB values (Mg/ha) from the satellite datasets based on our results, and the corresponding values provided in Table 4.7 of the 2006 IPCC Guidelines (Intergovernmental Panel on Climate Change, 2006).

To better understand other potential reasons why the satellite-derived AGB values were lower than the values for natural forests provided in the IPCC Guidelines, we made scatterplots to visualize the pixel-level AGB values of forest areas in each ecological zone. From these scatterplots, we noticed the presence of many pixels with unrealistically low AGB values for forests (natural or plantation forests) in each ecological zone, and for forests in the ASEAN region as a whole. For example, the scatterplot of AGB values extracted for all forest areas in the ASEAN region in Figure 4 indicates that in the 1-20 Mg/ha range of AGB values, there were more pixels with lower AGB values than higher values, which is the opposite of what would be expected (all types of forests typically have much higher AGB values than ~20 Mg/ha). For values > 20 Mg/ha, a more typical pattern was seen in Figure 4, as AGB increased until reaching 181 Mg/ha (close to the average value) and subsequently decreased.

Checking the methodology used to generate the Biomass_cci dataset, we found that a data mask had been used to mask (i.e., exclude) areas that had been mapped as "cropland", "urban areas", "bare soil", "permanent snow/ice", or "water" in various ancillary datasets (European Space Agency, 2023). As with all remote sensing-derived map products, these datasets used as masks contain some degree of classification error and geolocation error. The AGB values extracted using our approach are erroneously low for areas classified as "forest" in the PALSAR-FNF map that partially overlap with one of these data masks (due to these classification and/or geolocation errors). In fact, many pixels classified as "forest" in the PALSAR-FNF map contained AGB values of 0 in the Biomass_cci map due to this data masking issue (note: we had excluded AGB values equal to 0 from our average AGB calculations in Table 2 because they were obviously erroneous). Another source of error is commission errors in the PALSAR-FNF map, as AGB values extracted for areas misclassified as "forest" will be erroneously low.

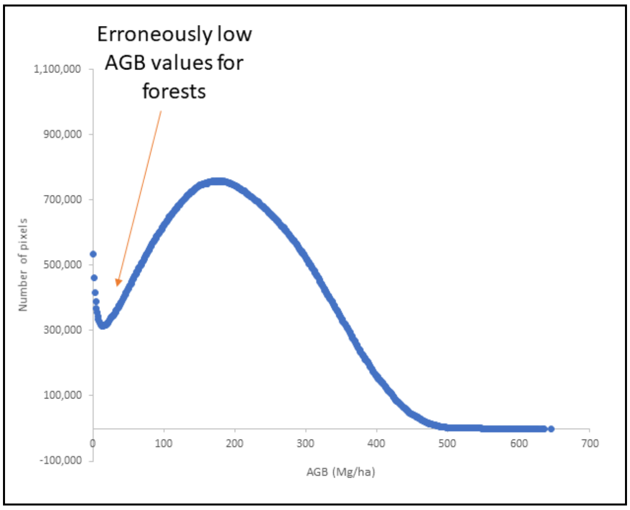

Figure 4. Scatterplot showing the AGB values of areas corresponding to FAÓ's definition of "forest" extracted from the satellite datasets. A decreasing trend in AGB is seen for AGB values < 20 Mg/ha, and these are likely to be erroneous values.

3.2 AGB Values of Forests in Each ASEAN Country

Table 3 shows the average AGB values of areas corresponding to FAO’s definition of “forest” in each ASEAN country. Insular ASEAN countries had higher average AGB values than continental countries, with Brunei, Indonesia, and Malaysia having the highest average AGB values (all > 200 Mg/ha) and Thailand, Laos, Vietnam, and Myanmar having the lowest values (~150 Mg/ha). The average AGB extracted for forests in the ASEAN as a whole was 197 Mg/ha. As mentioned in Section 3.1., the average AGB values reported here are likely underestimated, particularly for natural forests found in these countries.

Because of the presence of erroneously low AGB values found in our results, in addition the average AGB values of forests in each country, we also calculated the median (Table 3) and interquartile range of the AGB values for comparison, as these metrics are more resistant to the effects of erroneous outliers. Results of these calculations are shown as boxplots in Figure 5. Average AGB values exceeded median values for six out of ten countries, indicating that despite the erroneous low AGB values for some pixels, the data was generally not negatively skewed. This was due to the presence of some pixels with extremely high AGB values (see the upper bounds of the boxplots in Figure 5).

Country	Average AGB (Mg/ha) of forests	Median AGB (Mg/ha) of forests
Brunei	253	257.5
Cambodia	180	182.5
Indonesia	238	240.5
Laos	149	141.5
Malaysia	219	216.5
Myanmar	152	141.5
Philippines	168	161.5
Singapore	172	175.5
Thailand	137	125.5
Vietnam	149	144.5
ASEAN regional	197	191.5

Table 3. Average and median AGB values of areas corresponding to FAO’s definition of “forest” in each ASEAN country.

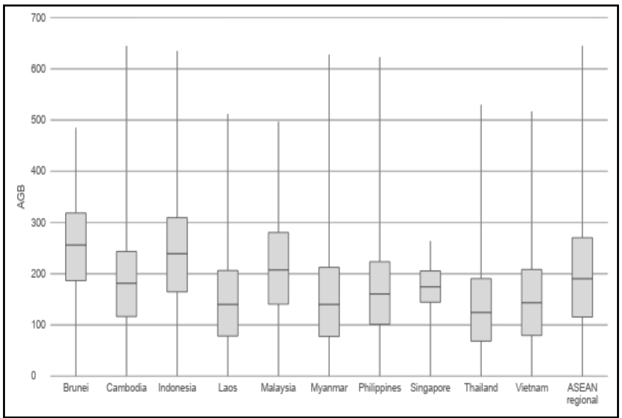

Figure 5. Boxplots showing median and interquartile range of AGB values for areas corresponding to FAO’s definition of “forest”.

Countries generally report their national above-ground forest carbon stocks by first converting the average AGB values (Mg/ha) of forests in each ecological zone and geographic region to corresponding values in tC/ha (according to the appropriate carbon fraction value), and then by multiplying this value by the total forest area (# of ha.) in the zone/region. Thus, countries wishing to use the open datasets described in this study for their national (or subnational) monitoring and reporting of forest carbon stocks should consider the limitations of the datasets, and develop workarounds to improve the accuracy of the extracted AGB values. A simple workaround could be to exclude any pixels having extracted AGB values below a certain threshold that is reasonable for forests, which could be determined based on local knowledge, ground-based measurements of forest AGB from the country, and/or by interpreting scatterplots of satellite-derived AGB values (as we did in this study). Using median or a trimmed mean value (e.g., excluding the minimum/maximum 5% of satellite-derived AGB values in each ecological zone) could also be appropriate for minimizing the inclusion of erroneous AGB values from national/subnational forest carbon estimates, although this would also have the effect of excluding high AGB forests from national forest carbon calculations, which would probably not be desirable. Finally, countries should ideally conduct an accuracy assessment (and possibly a bias correction) of the satellite-derived measurements using national or regional ground-based measurements of AGB (Málaga et al., 2022).

3.3. Limitations of this Study

In this study, we did not consider the effects of topography on the accuracy of the satellite-derived AGB products, although it could also be an important issue (e.g., if the AGB values are over- or under-estimated in forests located on rough terrain). Due to lack of georeferenced ground-based AGB data, we also did not conduct a formal quantitative accuracy assessment of the AGB measurements extracted using our approach (and instead relied on a cross-comparison with IPCC default values). The accuracy of the AGB values extracted using our approach may differ from the accuracy values reported in the Biomass_cci product documentation (European Space Agency, 2023), because our approach involves integrating this map with other global map products (which have their own sources of error). Thus, in future work we hope to compare our results with additional georeferenced ground-based measurements of forest AGB in different ecological zones of ASEAN. Finally, because the AGB values in the 2006 IPCC Guidelines do not distinguish between old-growth forests and other types of forest that typically contain less biomass (e.g., young secondary forests), they have been found to overestimate the AGB of younger secondary forests (Rozendaal et al., 2022). The IPCC has recently published refined default AGB values of forests in different age groups (including old-growth forests, secondary forests > 20 years old, and secondary forests ≤ 20 years old) (IPCC, 2019). Thus, if up-to-date global/regional/national maps of forest age can also be obtained, our methodology can be replicated to compare the satellite-derived AGB values with these refined IPCC default values in future work.

4. Conclusions

Here, we presented a map integration approach which allows for AGB values to be extracted for areas corresponding to FAO’s definition of “forest”. The approach was intended to be usable by countries for their national forest carbon inventory and reporting, so it is relatively simple and uses freely-available global geospatial datasets. It can also be used for sub-national monitoring, e.g., as part of local assessments of the effectiveness of nature-based solutions for climate change mitigation and adaptation (Johnson et al., 2022).

As an initial validation of the approach, we compared the extracted AGB values with IPCC default values of AGB in forest within different ecological zones and geographic regions of ASEAN. We found that the average AGB values extracted from the satellite data for each zone/region were generally lower than IPCC default values of natural forests, but higher than the default values of plantation forests. This was partly because FAO’s definition of “forest” incudes both natural and plantation forests, and partly because of the presence of pixels with erroneously low AGB values due to thematic errors in the different geospatial datasets used (caused by classification errors in each of the maps). Because of this issue, countries wishing to use the proposed approach (and these global map products in general) should carefully check the initial results and make efforts exclude erroneous AGB values, or their forest carbon stocks may be underestimated. We hope to further evaluate and improve the accuracy of the proposed approach in future work.

Acknowledgements

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