International Journal of Applied Earth Observation and Geoinformation 122 (2023) 103452

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

Better monitoring of forests according to FAO's definitions through map integration: Significance and limitations in the context of global environmental goals

Brian A. Johnson [a,*], Chisa Umemiya [a], Damasa B. Magcale-Macandog [b], Ronald C. Estoque [c], Masato Hayashi [d], Takeo Tadono [d]

[a] Institute for Global Environmental Strategies, Hayama, Kanagawa 240-0115, Japan
[b] Institute of Biological Sciences, University of the Philippines Los Baños, Laguna 4031, Philippines
[c] Center for Biodiversity and Climate Change, Forestry and Forest Products Research Institute, Tsukuba, Ibaraki 305-8687, Japan
[d] Earth Observation Research Center, Japan Aerospace Exploration Agency (JAXA), 2-1-1 Sengen, Tsukuba, Ibaraki 305-8505, Japan

ARTICLE INFO

Keywords:
Forest monitoring
Biodiversity conservation
Kunming-Montreal Global Biodiversity Framework
Data fusion
Ecosystem services

ABSTRACT

National monitoring of forests is essential for tracking progress towards various global environmental goals, including those of the Kunming-Montreal Global Biodiversity Framework and the Paris Agreement. Inconsistent national definitions of "forest", however, can complicate the tracking of global progress towards achieving these goals. The FAO's (Food and Agricultural Organization of the UN) definition of "Forest" is well-known and broad enough to be applicable globally, but it is difficult for countries to produce national forest maps according to this definition using only a single source of remote sensing data. Here, we developed an approach to integrate multiple existing land use/land cover (LULC) maps and generate an integrated map of forests and "Other land with tree cover" that is more consistent with FAO definitions. The proposed approach is based on merging thematic information from the global "PALSAR-2 Forest/Non-forest map", a global forest/non-forest map, with that of a national map containing more detailed LULC classes. By applying the map integration approach at the national level in the Philippines as a case study, we identified 5.937 ± 0.217 Mha of "Missing forest" that were not included in the country's national LULC map, mainly forest patches in areas that were predominantly "Brush/shrub", "Grassland", or "Marshland/swamp" lands. We also identified 4.294 ± 0.258 Mha of land corresponding to FAO's definition of "Other land with tree cover" that were previously unmapped; specifically, patches of tree cover on predominantly agricultural and urban lands. Based on these additional areas of "Forest" and "Other land with tree cover" identified, we further estimated an additional 145,480 GgCO$_2$/year of carbon sinks. Our approach is generalizable enough to potentially be applied in other countries for more standardized forest and ecosystem services monitoring.

1. Introduction

Forests provide a wide range of benefits, or "ecosystem services", including habitat for native species (Sodhi et al., 2010), carbon sequestration and storage (Ameray et al., 2021), food/wood/water provisioning (Naime et al., 2020), and mitigation of climate-related hazards like flooding and landslides (Debele et al., 2019; Johnson et al., 2022). Recognizing the importance of forests and their many benefits, several global initiatives have adopted forest conservation-related goals or targets, including the Convention on Biological Diversity's (CBD) "Kunming-Montreal Global Biodiversity Framework", the UN Framework Convention on Climate Change's (UNFCCC) "Paris Agreement" (UNFCCC, 2016), and the "UN Sustainable Development Goals" (SDGs) (United Nations, 2015) (Table 1).

To support these ongoing global initiatives, countries are requested to regularly monitor their forests and other natural ecosystems, and report the results to the international organizations responsible for tracking progress towards the relevant goals/targets. The definition of "Forest" used by countries, however, can vary significantly due to ecological factors or economic/political reasons (Romijn et al., 2013). In

* Corresponding author.
E-mail address: johnson@iges.or.jp (B.A. Johnson).

https://doi.org/10.1016/j.jag.2023.103452
Received 15 May 2023; Received in revised form 4 August 2023; Accepted 6 August 2023
Available online 12 August 2023
1569-8432/© 2023 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Table 1
Examples of goals/targets related to forest conservation under different global sustainability initiatives.

Global sustainability initiative	Goals/targets related to forest conservation	Indicators used for tracking progress towards these goals/targets (not a comprehensive list)
CBD Kunming-Montreal Global Biodiversity Framework	Goal A: "The integrity, connectivity and resilience of all ecosystems are maintained, enhanced, or restored, substantially increasing the area of natural ecosystems by 2050" (CBD, 2022a).	"Forest area as a proportion of total land area" (CBD, 2022b). "Extent of natural ecosystems" (CBD, 2022b).
	Goal B: "Biodiversity is sustainably used and managed and nature's contributions to people, including ecosystem functions and services, are valued, maintained and enhanced, with those currently in decline being restored, supporting the achievement of sustainable development for the benefit of present and future generations by 2050" (CBD, 2022a).	"Services provided by ecosystems" (CBD, 2022b).
UNFCCC Paris Agreement	"Parties should take action to conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gases …, including forests" (UNFCCC, 2016).	National GHG Inventories (Intergovernmental Panel on Climate Change, 2006).
UN Sustainable Development Goals	Goal 15: "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss" (United Nations, 2015).	"Forest area as a proportion of total land area" (United Nations, 2015).

some cases, "Forest" may be defined based on the land-use or zoning regulations of the land (regardless of whether trees are present or not) (Department of Environment and Natural Resources, 2022; Estoque et al., 2022). In other cases, "Forest" may be defined as any land containing trees exceeding a specified tree height and/or tree canopy cover threshold (Hansen et al., 2013). Finally, some definitions of "Forest" are based on both land-use and tree height/tree canopy cover criteria (FAO, 2010). As an example of varying national definitions of forest even among nearby countries, Indonesia has a minimum threshold of 30 percent canopy cover for areas defined as "Forest" (Republic of Indonesia, 2022), while the Philippines has a minimum threshold of 10 percent canopy cover (Quilloy, 2020). Importantly, estimates of national forest changes over time can vary significantly depending on the definition of "Forest" used (Romijn et al., 2013).

The adoption of nationally-specific definitions of "forest" may be sensible for biodiversity conservation and sustainable forest management efforts within a particular country's context, e.g., if the country's forests have very different ecological properties from those in other countries. The wide range of forest definitions used by different countries, however, makes it difficult to consistently track progress towards global goals/targets like the ones listed in Table 1. Thus, in addition to monitoring forests based on these various country-specific definitions, it would be beneficial if countries also report their forest statistics according to a more globally consistent definition when reporting on progress towards these global goals/targets.

The Food and Agricultural Organization (FAO) of the UN has been monitoring the world's forests since 1948 through its forest resources assessment (FRA) reports. FAO's FRA reports are produced every five years, and provide global forest statistics by compiling the information from countries' national forest resource assessments (i.e., "FRA country reports") (FAO, 2020). Thus, the FAO's definitions of "Forest" and other types of non-forest land, including "Other land with tree cover", "Other wooded land", and "Other land", are probably the most widely known (Table A1). The FAO defines "Forest" as "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). Areas with tree cover reaching these thresholds that are located on predominantly agricultural or urban land are instead defined as "Other land with tree cover" (Table A1). Aside from this general definition, FAO provides several additional notes to further clarify what constitutes "Forest", e.g., excluding fruit trees, oil palm, and agroforestry systems where crops are grown beneath the tree canopy (Table A1).

Countries are requested to adhere to FAO definitions when preparing their FRA country reports, as well as when reporting to various other international organizations. For example, the IPCC's "Guidelines for National GHG Inventories" states that when reporting national GHG emissions to the UNFCCC,"terminology used in the methods for estimating biomass stocks and changes need to be consistent with the terminologies and definitions used by the FAO" (Intergovernmental Panel on Climate Change, 2006). Tracking of global progress towards Goal 15 of the SDGs (Table 1) is also done using forest area statistics from FRA country reports. A benefit of the FAO definition of "Forest" (hereafter "FAO-Forest") for global forest monitoring is its broad nature; it includes nearly all types of tree species, and even includes areas that presently lack tree cover (if the tree cover is expected to regenerate in the future). This allows FAO-Forest to be applied in practically any site where forests are located. It is very challenging, however, for countries to actually to generate maps and forest area statistics that are strictly in accordance with FAO-Forest.

Because FAO-Forest is based on a combination of land use, minimum tree cover height, minimum canopy cover, and even tree usage criteria (i.e., excluding oil palm and other tree plantations established mainly for purposes other than wood harvesting), it is very difficult to produce accurate maps of these areas using common remote sensing image classification approaches. Optical satellite remote sensing data – the main source of data countries use to generate national forest maps – does not directly measure tree height. Lidar remote sensing instruments, on the other hand, are capable of directly measuring tree height (and volume) (Zhang et al., 2022), but Lidar data is still typically sparse at a national level. As a workaround, recent research has focused on combining spaceborne Lidar data and optical satellite data to generate global wall-to-wall tree height maps through regression modelling approaches (Potapov et al., 2021). L-band Synthetic Aperture Radar (SAR) satellite sensors can also measure vegetation structural information (as the radar signal is scattered by the tree trunk and branches), and is thus more sensitive to tree height and stem volume than optical imagery (Balzter et al., 2003; JAXA, 2022; Nesha et al., 2020). Notably, 25 m resolution L-band SAR data from the ALOS (Advanced Land Observation Satellite) satellite series is freely available for several years through JAXA's website (https://www.eorc.jaxa.jp/ALOS/en/dataset/fnf_e.htm; last accessed July 14, 2023) and Google Earth Engine (https://code.earthengine.google.com/; last accessed July 14, 2023), so it can potentially complement optical satellite data for forest monitoring according to FAO-Forest.

In addition to the challenge of monitoring tree height, it is also difficult to distinguish between tree species that correspond to FAO-Forest and tree species that do not (e.g., fruit trees or oil palm) in optical imagery due to their similar reflectance characteristics. Third, it is challenging to identify areas where tree cover is likely to reach, but does not currently reach, the FAO-Forest minimum thresholds, as these areas do not have easily distinguishable reflectance characteristics. Despite these challenges, it is often possible for skilled satellite image interpreters to identify areas that correspond to FAO-Forest based on other visual clues in the imagery like the length of tree shadows (to help estimate tree height) and the landscape context (e.g., the size and spatial pattern of the tree cover across the landscape). This process remains quite difficult, however, for automated classification approaches, unless ancillary data is available (e.g., detailed land-use or zoning maps).

Due to the above challenges, it would seem beneficial to combine multiple types of geospatial information to better identify areas corresponding to FAO-Forest and "Other land with tree cover". For example, combining a map of tree or forest cover with a map of land use could help prevent the mapping of "Forest" in areas of agricultural or urban land use. This type of map integration process could be particularly useful to combine map products that were produced using different types of remote sensing data (e.g., optical vs. SAR data) or different mapping methodologies (automated vs. manual mapping approaches), so-as to leverage the particular strengths of each individual map.

Several prior studies have utilized map integration approaches for monitoring of forest areas at a national level. As one example, Margono et al., (2014) combined a national map of primary forests (generated using an automated classification approach) with a global tree cover change map (also generated using an automated classification approach) to identify changes in tree cover within the primary forests of Indonesia. Johnson (2015) combined a national LULC map of Thailand (produced using a manual mapping approach) and a global tree cover change map wetlands (generated using an automated classification approach) to identify changes in tree cover within different types of forest ecosystems between 2000 and 2012. The Philippine government, in its Forest Reference Level submitted to the UNFCCC (Republic of the Philippines, 2022), combined a national LULC map (produced using a manual mapping approach) and a national tree cover change map (generated using an automated classification approach) to estimate the GHG emissions and removals associated with tree cover changes at the national level. Other studies using similar map integration methods exist, but to our knowledge, none of them have been applied for the purpose of generating integrated maps that are more consistent with FAO definitions.

1.1. Objective of this study

The main objective of this study was to develop a map integration approach for generating national-level maps more consistent with FAO-Forest, so-as to support countries in reporting their forest area statistics to the FAO and other relevant international organizations. Our approach combines the thematic information from the PALSAR-2 "Forest/Non-forest map" version 2 (JAXA, 2022) and a national LULC map to generate the integrated map. The approach leverages the strengths of PALSAR-2 data (e.g., its sensitivity to forest structure and ability to penetrate cloud cover), and the strength of national LULC maps (e.g., their ability to identify areas under predominantly urban or agricultural land use).

We tested the proposed approach through a case study of the Philippines, which focused on identifying additional areas corresponding to FAO-Forest that were missing in the national LULC map (hereafter, "Missing forest"). In this case study, we also used the approach to identify and map "Other land with tree cover" at the national level; specifically, tree patches on areas of predominantly urban or agricultural land use that otherwise corresponded to FAO-Forest. Finally, we estimated the additional CO_2 sinks of these areas of "Missing forest" and "Other land with tree cover" based on IPCC's Guidelines for National GHG Inventories.

2. Methods and materials

2.1. Study area

We selected the Philippines as the case study site because it is a country with high forest cover, which much of the country's rich biodiversity and many of its people rely on. The primary watersheds that supply water for irrigation, energy production, industries, and households are all forest lands, so it is important to protect these forests to ensure adequate water availability and water quality. Historically, the Philippine islands were primarily covered with forest, and the country has a relatively high proportion of endemic species because of its unique island biogeographical history. Different types of forests are found in each of the country's four climate regions. The first climate region has one wet and one dry season, with each lasting around six months (Republic of the Philippines, 2022). The second region has no dry season and a pronounced higher rainfall period from December – February. The third region has one wet and one dry season, with the dry season lasting only 1–3 months (Republic of the Philippines, 2022). The fourth region is wet year-round, with similar amounts of rainfall throughout the year (Republic of the Philippines, 2022). The two climate regions with wetter climates (i.e., the second and fourth climate regions) tend to have forests with higher above-ground biomass (due to the presence of larger trees and denser canopy cover) than the climate regions with pronounced dry seasons (Republic of the Philippines, 2022). Major forest types include tropical Dipterocarp forest, pine forest, mossy forest (in high mountainous areas), and mangrove forest (Quilloy, 2020).

Many of the natural tropical forests in the Philippines have been cut down for wood or converted to agricultural areas over the past century, resulting in a loss of habitat for endemic species. Remains of the biodiversity that was formerly present in broad lowland forests can be found in the forest fragments that still exist, typically in places not suited for farming or wood extraction (e.g., areas with steep slopes) (van Weerd et al., 2003). To prevent further loss and degradation of Philippine forests, a number of national policies have been enacted focusing on forest conservation, including the Republic Act 7586 (National Integrated Protected Areas System Act of 1992), and the Republic Act 9147 (An Act Providing for the Conservation and Protection of Wildlife Resources and their Habitats).

Although the importance of forests and the ecosystem services they provide is well recognized in the Philippines, the country has adopted varying definitions of "Forest" in its national reports prepared by different government organizations, leading to differing estimates of its national forest cover and the ecosystem services they provide. For example, in the most recent FRA country report submitted to FAO (Quilloy, 2020), "Forest" is defined using a 10% minimum canopy cover threshold and excludes perennial trees like coconut, oil palm, and banana. On the other hand, in the country's Forest Reference Level submitted to the UNFCCC, "forest" is mapped using a 30% minimum canopy cover threshold and does not exclude perennial trees (Republic of the Philippines, 2022). Further, a national law enacted in 1987 officially classified 15.8 Mha (52.7% of the total land area) of the Philippines as "forest land", and the remainder as "alienable and disposable land" (Department of Environment and Natural Resources, 2022). This legal "forest land" area has not been changed since 1987. Notably, the FRA country report and Forest Reference Level both reported forests in areas located outside of the legally classified "forest land" (i.e., on "alienable and disposable land"), as well as non-forest areas in areas legally classified as "forest land", so the legal land classification is apparently not used as a basis for ongoing national forest monitoring efforts. These differing forest definitions can potentially complicate biodiversity and climate change policies within the country, and also make it difficult to track the country's progress in the context of global forest conservation-related goals.

2.2. Data

2.2.1. Map 1: National LULC map of the Philippines

The map integration approach developed in this study utilizes national and global LULC maps. The national LULC map was produced by the Philippine National Mapping and Resources Information Authority (NAMRIA) for the year 2020 (Fig. 1). This "NAMRIA-2020" map was generated using a manual mapping approach (polygon digitization) based on visual interpretation and ground validation of 10 m resolution Sentinel-2 satellite images acquired circa 2020 (2016–2021). The minimum mapping unit of the map is not explicitly specified, but is at least 10 m × 10 m based on its reported use of Sentinel-2 imagery. The NAMRIA-2020 map, and the general information on how it was produced, were kindly provided by NAMRIA through an official request. The LULC classes in the NAMRIA-2020 map are the same as those in the 2015 map of the Philippines, also produced by NAMRIA, and the country's most recent FAO FRA country report provides a definition for each LULC class (Table 2) (Quilloy, 2020). We have considered this NAMRIA-2020 map as the most recent official LULC map of the Philippines, as the previous NAMRIA maps have been used for reporting forest statistics to FAO (Quilloy, 2020).

The NAMRIA-2020 map contains three LULC classes that at least partially correspond with FAO-Forest (Table 2). The "Closed forest" and "Open forest" LULC classes both have a minimum tree cover threshold of 10% or higher, exclude agricultural tree species, and can be assumed to have a minimum tree height threshold of 5 m (based on the maximum tree height threshold of 5 m, defined for the "Brush/Shrub" LULC class). The "Mangrove" LULC class, on the other hand, does not have a specified tree cover or tree height threshold, but instead is intended to include areas with specific tree species (mangrove species, and other tree species like *nipa* (a palm species) that grow in mangrove ecosystems). All three of these LULC classes were reported as the entirety of the country's "forest" areas in the most recent FRA country report (Quilloy, 2020). These three LULC classes differ from FAO-Forest, however, in that they do not include areas where tree height/canopy cover are currently below the FAO thresholds, but are expected to reach them in the future. Some areas where tree cover is currently below these thresholds may have been inadvertently mapped by NAMRIA as "forest", however, e.g., if the tree patches were very small in size, or if the image interpreter could not tell whether the tree cover exceeded the minimum thresholds or not based on the Sentinel-2 imagery. Notably, the areas considered as representing forest in this NAMRIA-2020 map are not limited to areas officially delineated as "forest land" by the national law enacted in 1987 (Department of Environment and Natural Resources, 2022), and can also be located in areas classified as "alienable and disposable land".

Aside from the three forest LULC classes, the "Brush/Shrub" LULC class from the NAMRIA-2020 map was reported as "Other wooded land" in the latest FRA country report, and generally corresponds with the FAO definition of "Other wooded land". It was noted, however, that many of the areas mapped as "Brush/Shrub" were areas where trees had

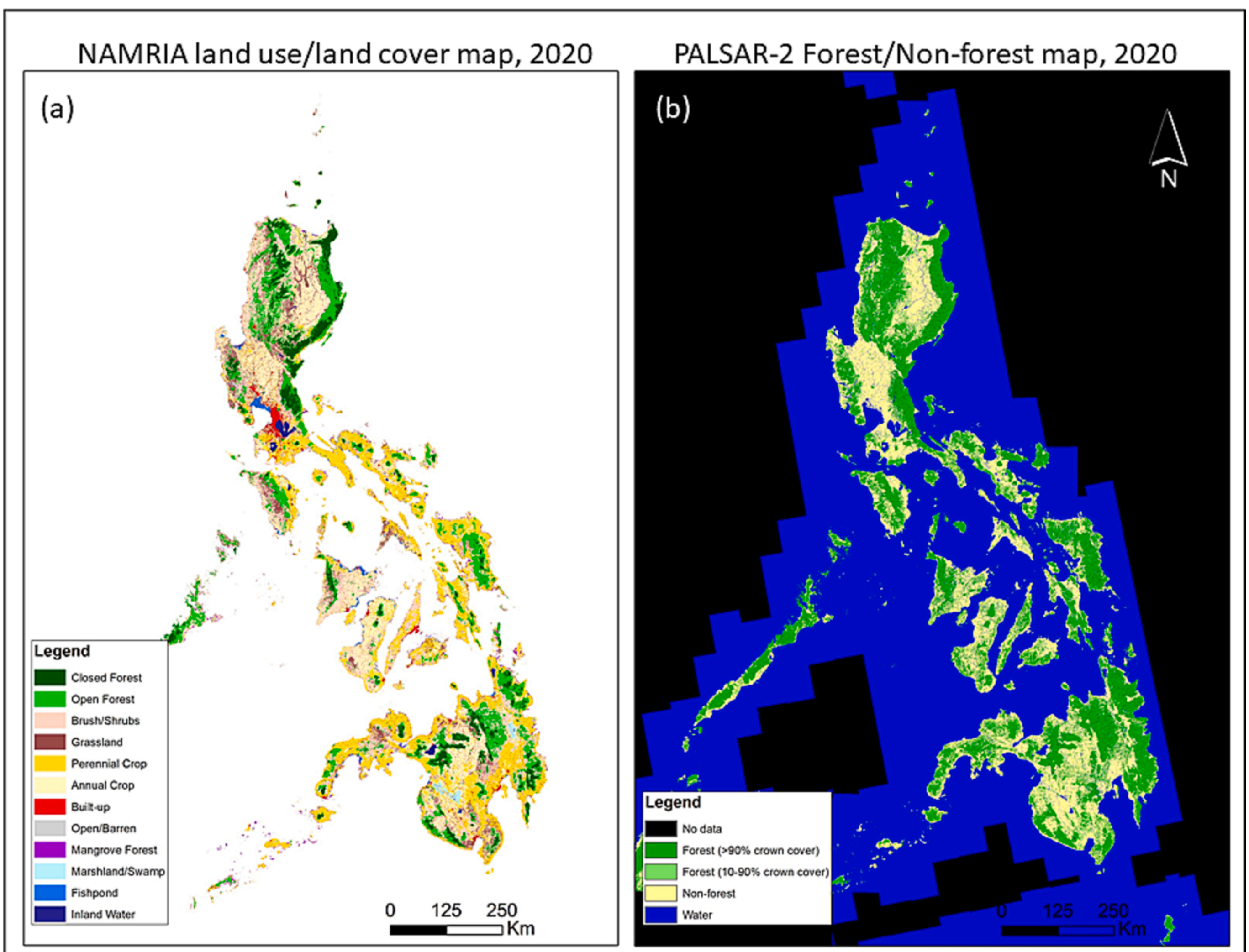

Fig. 1. NAMRIA-2020 map (a) and PALSAR-FNF map (b) showing forests and other LULC types in the Philippines.

Table 2
Definitions of land-use/land-cover classes in NAMRIA-2020 map, and their corresponding class according to FAO definitions, as reported in the Philippines most recent FRA country report (Quilloy, 2020).

NAMRIA-2020 LULC class	Definition	Corresponding FAO classification
Closed Forest	"Formation where trees in various storey and undergrowth cover a high proportion (>40 percent) of the ground and do not have a continuous dense grass layer. They are either managed or unmanaged forest, in advance state of succession and may have been logged over one or more times, having kept their characteristics of forest stands, possibly with modified structure and composition."	Forest
Open Forest	"Formations with discontinuous tree layer with coverage of at least 10% and less than 40%. They are either managed or unmanaged forests, in initial state of succession."	Forest
Mangrove	"The type of natural forest occurring on tidal mudflats along the sea coast extending along the streams where the water is brackish and composed mainly of bakauan, pototan, langarai, api-api, nipa and the like."	Forest
Brush/Shrub	"Refers to vegetation types where the dominant woody elements are shrubs i.e. woody perennial plants, generally of more than 0.5 m and less than 5 m in height on maturity and without a definite crown. The height limits for trees and shrubs should be interpreted with flexibility, particularly the minimum tree and maximum shrub height, which may vary between 5 and 7 m approximately."	Other wooded land
Perennial crop	"Land cultivated with long term crops that do not have to replanted for several years after each harvest. Harvesting components are not timber but fruits, latex and other products that do not significantly harm the growth of the planted trees or shrubs."	Other land
Annual crop	"Land cultivated with crops with a growing cycle of up to one year, which must be newly sown or planted for further production after harvesting."	
Built-up areas	"Composed of areas of intensive use with much of the land covered by structures. It includes cities, towns, villages, strip developments along highways, transportation, power, and communication, facilities, and areas occupied by mills, shopping centers, etc."	
Marshland	"A natural area usually dominated by grass-like plants such as cattails and sedges that are rooted in bottom sediments but emerge above the surface of the water. It contains emergence vegetation and usually develop in zones progressing from terrestrial habitat to open water."	
Grassland	"Areas predominantly vegetated with grasses suchata, Themada, Saccharum spp., among others."	
Barren land	"Land not covered by (semi) natural or artificial cover. Includes among others, sand dunes, river wash and rocky or stony areas"	
Inland water	"Area occupied by major rivers, lakes and reservoirs."	
Fish pond	Fish ponds	

been recently planted/degraded forests had been rehabilitated under the country's National Greening Programme (Quilloy, 2020). Thus, many of these areas classified as "Brush/Shrub" by NAMRIA may actually correspond to FAO-Forest because the tree cover either currently exceeds, or is expected to exceed, the FAO-Forest minimum tree height and canopy cover thresholds.

2.2.2. Map 2: High-resolution global LULC map (PALSAR-2 Forest/Non-Forest map)

To identify areas of "Missing forest" and "Other land with tree cover" (areas located on urban or agricultural areas that otherwise corresponded to FAO-Forest), we considered several publicly-available global LULC maps for the year circa 2020 having a similar spatial resolution (~10–30 m) and a "forest" LULC class or similar (e.g., "tree"). Our rationale for using global maps rather than other national or regional maps for this purpose was so that the map integration approach can potentially be applied in many other countries (because the data is available globally). We identified seven global LULC maps fitting these criteria from a literature search, and after reviewing the definitions of the different LULC classes in these maps (see Supplementary File S1 for a detailed discussion), we found that the PALSAR-2 Forest/Non-Forest map product had a definition of "forest" that most closely matched FAO-Forest (JAXA, 2022). Thus, it was determined to be the most suitable global LULC map for use in our study.

We used the most recent version of the PALSAR-2 Forest/Non-Forest (PALSAR-FNF) map (Version 2.0.0.) in this study, as its accuracy is reportedly higher than that of the Version 1 map (JAXA, 2022; Shimada et al., 2014). Version 2.0.0. data is currently available for the years 2017–2020. We used the year 2020 PALSAR-FNF map (Fig. 1) because it corresponded with the year of the NAMRIA-2020 map. For the Southeast Asia region, the User's accuracy of the "forest" class of the PALSAR-FNF 2020 map is reportedly 0.993, while the Producer's accuracy is 0.861 (JAXA, 2022). These PALSAR-FNF maps were generated by classifying ALOS-2 L-band SAR imagery using the random forest algorithm (Breiman, 2001), a popular machine-learning classification algorithm for remote sensing image analysis (Belgiu and Drăguţ, 2016). A separate classification model, with separate training data, was used for classifying the imagery on each continent to account for varying regional forest cover characteristics (JAXA, 2022). Several efforts were made to ensure that the areas mapped as "Forest" in this dataset were consistent with FAO-Forest. First, training samples for the "forest" class were visually checked using high resolution images to ensure that the amount of tree cover exceeded 10% and the forest area exceeded 0.5 ha., and tree shadows were inspected to help judge that tree height exceeded 5 m. Additionally, separate training data for "cropland" and "oil palm plantations" classes were collected and used for the random forest classification process to better separate agricultural areas from "Forest", and the "global human settlements layer" (Pesaresi et al., 2016) was utilized to prevent tree cover in settlement areas (urban areas) from being mapped as "Forest" (JAXA, 2022)). Although two different forest classes with different crown cover ranges exist in the PALSAR-FNF map (Fig. 1), we merged them into a single class for this study because both had greater than 10% canopy cover.

According to the PALSAR-FNF map documentation, the definition of "Forest" in this dataset exactly matches that of FAO-Forest. It is unclear, however, how areas where tree height/tree canopy cover is expected to reach (but does not currently reach) the FAO-Forest minimum thresholds were correctly mapped as "Forest" in the PALSAR-FNF map. The PALSAR-FNF maps were generated using satellite imagery from only a single year, or in some cases, images from two consecutive years (JAXA, 2022). Thus, areas where tree cover was missing or below the FAO-Forest thresholds within this one- or two-year period are unlikely to be mapped correctly as "Forest". Conversely, some areas under predominantly agricultural or urban land-use may also have been inadvertently mapped as "Forest" in the PALSAR-FNF map, e.g., large tree patches within areas of agricultural or urban land-use. For these two reasons, we have interpreted a slightly different definition of "forest" in the PALSAR-FNF map, namely "Land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover of more than 10 percent. It does not include land that is predominantly under agricultural or urban land use at the level of the mapping unit (25 m × 25 m)". This alternative definition acknowledges that the areas where tree cover is expected to recover to the FAO-Forest thresholds are not mapped as "Forest", while tree patches larger than 25 m × 25 m in size in agricultural or urban areas are potentially mapped as "Forest".

2.3. Integrating national and global LULC maps to generate a new map in line with FAO definitions

The next step of the map integration process is to combine the information from the national and global maps to identify areas of "Missing forest" and "Other land with tree cover" that were not included in the national LULC map. This is accomplished by crosswalking all combinations of LULC information in the two maps. Fig. 2 (a) shows the general procedure for this map integration, while a more specific procedure for the Philippine case study (considering the NAMRIA-2020 map) is shown in Fig. 2 (b). Because the PALSAR-FNF map cannot identify areas where tree cover is expected to (but does not presently exceed) the minimum thresholds for FAO-Forest, however, the map integration procedure does not attempt to reduce the area of "Forest" reported in the national LULC map. The FAO categories "Other wooded land", and "Other land" are also included in Fig. 2 for reference, but because the PALSAR-FNF map only allows for identifying areas of tree cover, we have focused our analysis on the "Forest" and "Other land with tree cover" FAO categories in this study.

The map integration process was conducted using Geographic Information Systems software (ArcMap 10.8.2.) and tools. First, we reprojected the NAMRIA-2020 and PALSAR-2 FNF maps to the same coordinate system (GCS1983) and projection (UTM51) to allow them to be overlaid. Next, we overlaid the two maps, and after confirming accurate spatial alignment between them, we conducted an "Intersect" operation to generate a new polygon map layer containing both the NAMRIA-2020 and PALSAR-FNF LULC class information at each location in the Philippines. From this intersected map, we then crosswalked

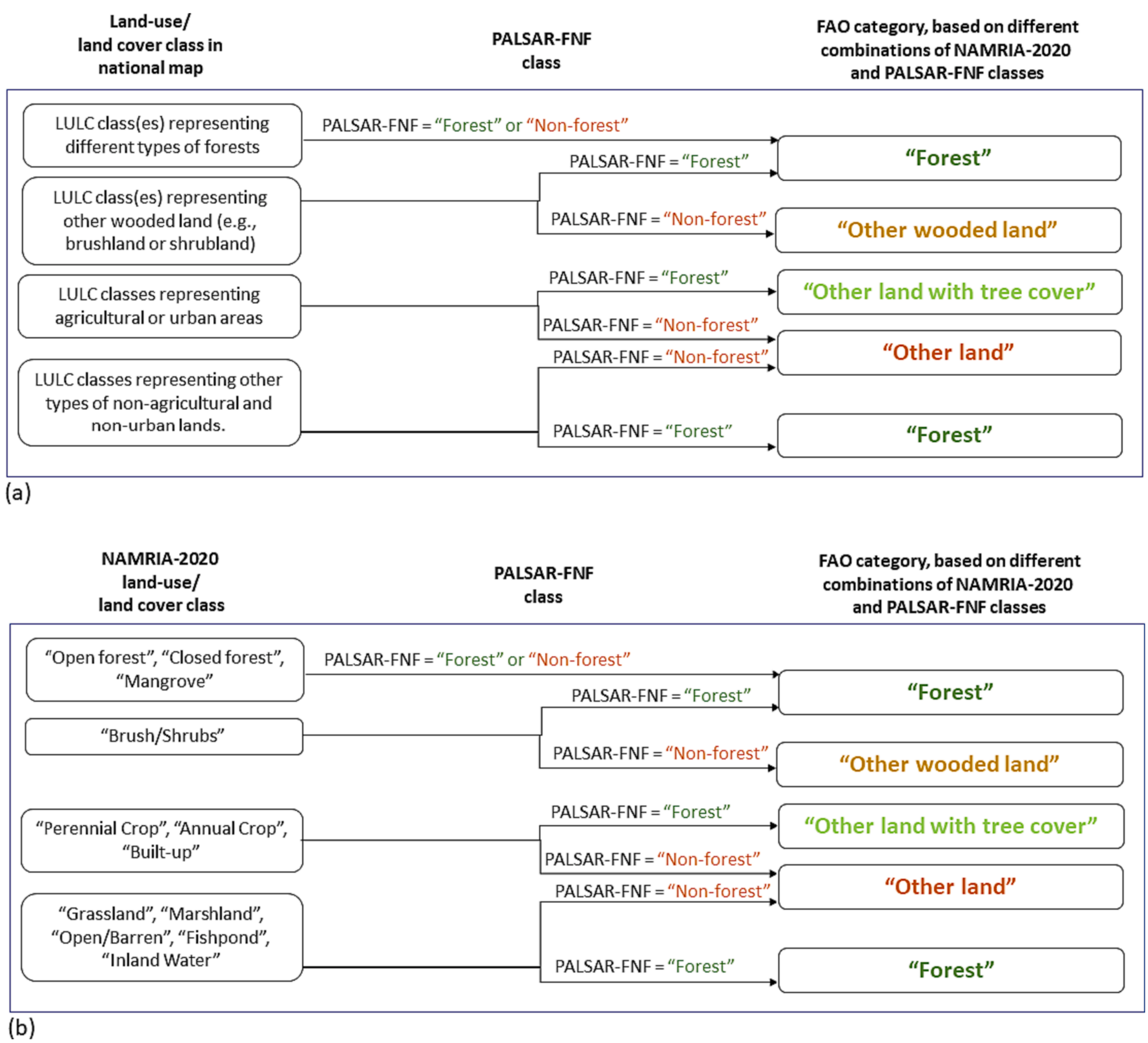

Fig. 2. Procedure for combining LULC information from the PALSAR-FNF map and a more detailed national LULC map to identify additional areas consistent with the FAO definitions of "Forest" and "Other land with tree cover". General procedure (a), and procedure adopted for the Philippines case based on the NAMRIA-2020 LULC map (b).

the different combinations of NAMRIA-2020 LULC classes and PALSAR-FNF classes to identify areas corresponding to each FAO category (Fig. 2 (b)). The final output of this process was an integrated map having a spatial resolution of 25 m.

Areas belonging to the NAMRIA-2020 LULC class "Open forest", "Closed forest", or "Mangrove" were all considered to be "Forest" in the integrated map regardless of the PALSAR-FNF class, because PALSAR-FNF only maps the current, and not the expected, tree height/canopy cover conditions (while the NAMRIA-LULC map may include some of these areas that are expected to reach the FAO-Forest minimum thresholds in the future). Areas having the NAMRIA-2020 LULC class "Brush/Shrubs" were considered to be "Forest" in the integrated map if they were also mapped as "Forest" in the PALSAR-FNF map, because the tree cover currently exceeds FAO-Forest thresholds and the predominant land use is not agricultural or urban. Otherwise, these "Brush/Shrub" areas were considered to be "Other wooded land" in the integrated map, because the tree cover does not currently exceed the FAO-Forest thresholds, and there is no information available suggesting that it is expected to the future. Areas having the NAMRIA-2020 LULC class of "Annual crop", "Perennial crop", or "Built-up" were considered to be "Other land with tree cover" in the integrated map if they were mapped as "Forest" in the PALSAR-FNF map, because these areas contain tree cover exceeding the FAO-Forest thresholds but their predominant land-use is agricultural or urban. Finally, all other areas in the NAMRIA-2020 map ("Grassland", "Marshland", "Open/Barren", "Fishpond", "Inland Water" areas) were considered to be "Forest" in the integrated map if they were mapped as "Forest" in the PALSAR-FNF map, because the tree cover currently exceeds FAO-Forest thresholds, and the predominant land use is not agricultural or urban. Otherwise, these areas were considered to be "Other land" in the integrated map, because the tree cover does not currently exceed the FAO-Forest thresholds, and there is no information available suggesting that it is expected to the future.

2.4. Accuracy assessment of the integrated map results

To understand the accuracy of the integrated map, we conducted a formal accuracy assessment. Two main factors affect the accuracy of this map. The first is the accuracy of the original NAMRIA-2020 map. The second is the performance of the proposed map integration process, which is affected by the accuracy of the original PALSAR-FNF dataset as well as the methodology used for the map integration. The first factor was beyond our control, but the second factor was directly related to our proposed methodology. Thus, we focused our accuracy assessment on the second factor. Specifically, we conducted an accuracy assessment for the mapped areas of "Missing forest" and "Other land cover" that were the main results of the map integration process. Standard accuracy metrics were calculated for these two classes, including Producer's accuracy (related to omission errors) and User's accuracy (related to commission errors) (Jensen, 2005). Further, because the mapped areas of these classes in the integrated map may not accurately reflect their actual area coverage due to potential biases in the mapping protocol, we calculated bias-corrected area estimates for the "Missing forest" and "Other land with tree cover" classes using good practices for land cover area estimation (Olofsson et al., 2014).

For the accuracy assessment, we created an initial reference dataset with 750 samples of 25 m × 25 m in size (corresponding to the pixel size of the PALSAR-FNF map), using a class-stratified random sampling approach (Olofsson et al., 2014). 500 samples were generated in areas classified as "Forest" in the original PALSAR-FNF map, and 250 samples were generated in areas classified as "Non-forest" in this map. These 750 samples were then overlaid onto the integrated map. Samples located in areas of "Missing forest" (n = 158) or "Other land with tree cover" (n = 126) in the integrated map were recorded as such. On the other hand, samples located in areas mapped as "Forest" in original the NAMRIA-2020 map (n = 224) were removed from the initial reference dataset because our map integration procedure had no impact on these areas (see Fig. 2). Finally, samples located in all other areas in the integrated map, i.e., areas classified as "Other land" or "Other wooded land", were recorded as belonging to the more general "Other land" class for accuracy assessment purposes (n = 242), because our map integration procedure did not attempt to differentiate between these two classes. To identify the actual, or reference, land cover information at the remaining 526 sample locations, we visually interpreted high-resolution images from 2020 (or the nearest cloud-free date available) using Google Earth Pro. Samples found to contain agricultural tree cover through this visual interpretation, e.g., fruit trees, oil palm, or trees with crops growing below the canopy, were considered to be "Other land" for accuracy assessment purposes because we sought to only identify areas of non-agricultural tree cover in the "Other land with tree cover" class.

2.5. Use of integrated map for national reporting

As mentioned previously, FAO's definitions provide a general standard for monitoring of forests and non-forest lands (including "Other land with tree cover") within the UN system, and following this standard can help to monitor global progress towards international environmental initiatives. "Forest area as a proportion of total land area" is an indicator for tracking progress towards two of these agreements: Goal A of the Kunming-Montreal Global Biodiversity Framework (CBD, 2022b), and Goal 15 of the UN Sustainable Development Goals (United Nations, 2017). Thus, the area of "Forest" calculated through our map integration procedure can be directly used for more standardized monitoring of this indicator.

In the context of the UNFCCC Paris Agreement, sinks and reservoirs of GHGs in forests are requested to be reported in countries' National GHG Inventories. To demonstrate how the proposed map integration process can support this, we also calculated CO_2 sinks in the areas of "Missing Forest" and "Other land with tree cover" identified in the integrated map of the Philippines, following the IPCC Guidelines for National GHG Inventories (Intergovernmental Panel on Climate Change, 2006). According to the IPCC Guidelines, CO_2 sinks can be estimated by multiplying forest area by CO_2 removal factors for different land use categories. Nationally-specific removal factors are preferred when available, while IPCC default values can be used when no nationally-specific data is available for a certain land use category. In our study, values for removal factors were based on the Philippines national GHG inventory manual (Environmental Management Bureau, 2011), which contained nationally-specific values for several land use categories.

Areas of "Missing forest" identified in the integrated map were assumed to be second-growth forests, which have an average annual CO_2 removal rate of 4.0 tC/ha/yr according to nationally-specific estimates (Environmental Management Bureau, 2011). Additional areas of "Other land with tree cover" identified in lands mapped as "Annual Crop" or "Perennial Crop" in NAMRIA-2020 were assumed to be agroforestry tree species grown on fallow land (improved fallow), which have an average annual CO_2 removal rate of 3.7 tC/ha/yr according to nationally-specific estimates (Environmental Management Bureau, 2011). Finally, areas of "Other land with tree cover" located in lands mapped as "Built-up" in NAMRIA-2020 were assumed to be urban tree cover of various types, which have an average annual CO_2 removal rate of 4.0 tC/ha/yr according to IPCC default values (no nationally-specific values were available (Intergovernmental Panel on Climate Change, 2006). Both above-ground and below-ground biomass were estimated. The main source of uncertainty in these estimations is related to the fact that each type of forest or tree cover has only a single CO_2 removal rate, which is typically an average value based on a limited number of field surveys. However, because there is a relatively small (~7.5%) difference in the estimated CO_2 removal rates of second-growth forest, agroforestry tree species, and urban trees, some misclassification of "Missing forest" as "Other land with tree cover", and vice-versa, should not have a significant impact on the estimated CO_2 sinks at the national level.

3. Results and discussion

3.1. Accuracy of "Missing forest" and "Other land with tree cover" areas in integrated map

The "Missing forest" areas identified in the integrated map had a User's accuracy of 0.905 and a Producer's accuracy of 0.827 based on the population error matrix containing reference sample counts (Table 3). The "Other land with tree cover" areas in this map had a User's accuracy of 0.822 and a Producer's accuracy of 0.881 (Table 3). These accuracy values are generally satisfactory for national mapping (greater than 80%). The accuracy values of the "Missing forest" class were somewhat lower than the values reported for the "Forest" class in the PALSAR-FNF map of Southeast Asia (0.993 User's Accuracy and 0.861 Producer's Accuracy (JAXA, 2022), however. This may be because the "Missing forest" areas were more difficult to classify than other, typically larger, forested areas which had already been correctly classified as "Forest" in the NAMRIA-2020 map (and thus were excluded from our accuracy assessment). Both our map and the PALSAR-FNF map have significantly lower commission errors than omission errors, suggesting that they underestimated forest extent. It is likely a result of the PALSAR-FNF map attempting to exclude oil palm and fruit tree plantations, which typically have lower L-band radar backscatter (due to lower above-ground biomass) than forest areas. The result is that forests with similarly low above-ground biomass may not have been mapped as "Forest" in the PALSAR-FNF map. The underestimation of forest extent in the integrated map was even clearer in the error matrix containing estimated area proportions (hereafter "area-weighted error matrix", Table 4), which was populated based on the area proportion of "Missing forest", "Other land with tree cover", and "Other land" in the integrated map. The Producer's and User's accuracies of the "Missing forest" class area-weighted error matrix were 0.723 and 0.905, respectively. The reason for the lower Producer's accuracy in this area-weighted error matrix is due to the much larger area of land mapped as "Other land" in the integrated map.

3.2. Mapped area, and bias-corrected area of "Missing Forest" and "Other land with tree cover" identified through map integration

The mapped area of "Missing forest" in the integrated map was 4.736 Mha, while the mapped area of "Other land with tree cover" was 3.881 Mha (Fig. 3). Out of the total mapped extent of "Other land with tree cover", 0.107 Mha (2.84%) consisted of tree cover in areas of urban land use, while the remaining 3.773 Mha (97.16%) was tree cover in areas of agricultural land use. Because these mapped areas may have been over- or underestimated, we also calculated bias-corrected area estimates of these two classes using good practices for land cover area estimation (Olofsson et al., 2014) (Table 4). The bias-corrected area estimate of "Missing forest" extent in the Philippines was 5.937 ± 0.217 Mha (approximate 95% confidence interval), while the bias-corrected area estimate of "Other land with tree cover" (excluding areas of agricultural tree cover) was 4.294 ± 0.258 Mha (approximate 95% confidence interval).

The bias-corrected estimated area of "Missing forest" in our integrated map was quite large considering that only 7.229 Mha was mapped as "Forest" in the NAMRIA-2020 map. However, even after adding the area of "Missing forest" to the area mapped as "Forest" in NAMRIA-2020 (i.e., 5.937 + 7.229 = 13.166 Mha), the result is less than the 15.8 Mha of land legally classified as "forest land" according to a 1987 law (Department of Environment and Natural Resources, 2022). Our bias-corrected estimate was also ~ 20% higher than the 10.9 Mha of forest cover in the Philippines estimated in a prior study based on visual analysis of 9,852 reference samples (Estoque et al., 2018). The prior study, however, used a higher minimum canopy cover threshold (greater than 50%) for identifying "Forest" areas, which may explain the difference.

Many of the "Missing forest" areas in the integrated map, particularly those found on areas classified as "Brush/Shrub" in NAMRIA-2020, are likely new areas of forests (mainly plantation forests) planted or degraded forests that were recently restored under the country's National Greening Program, as these replanted/restored areas were previously classified as "Brush/Shrub" in NAMRIA's 2015 LULC map (because they had not yet met NAMRIA's minimum tree height/canopy cover thresholds) (Quilloy, 2020). Our results, however, showed that 68% of the areas mapped as "Brush/Shrub" in NAMRIA-2020 were found to contain "Missing forest", indicating that the PALSAR-FNF map has detected that many of these areas are already exceeding the FAO-Forest thresholds. We found that there was also a substantial amount of"Missing forest" on lands classified as "Grassland" (36% of its mapped area), and "Marshland/Swamp" (34% of its mapped area) by NAMRIA-2020, and these are possibly regenerated forests (on grasslands) or wetland forests. Additionally, we estimated that 4.294 ± 0.258 Mha of land corresponded to the FAO category "Other land with tree cover" on areas classified as "Perennial Crop", "Annual Crop" and "Built-up", while no land was reported as "Other land with tree cover" in the Philippines' most recent FRA country report. These tree patches on areas under agricultural and urban land use lands (i.e., trees outside of forests) provide many important ecosystem services (Peros et al., 2022), so their

Table 4
Error matrix populated proportion of area coverage. *Note: User's and Producer's accuracies in this matrix are for the proportion of area mapped as each class.

	Forest	Other land with tree cover	Other land	Sum (classified pixels)	User's accuracy*
Forest	0.192	0.011	0.009	0.212	**0.905**
Other land with tree cover	0.003	0.146	0.028	0.176	**0.825**
Other land	0.071	0.038	0.503	0.612	**0.822**
Sum (reference samples)	0.265	0.194	0.540	1.000	
Producer's accuracy*	**0.722**	**0.746**	**0.932**		
Bias-adjusted area (Mha)	5.938	4.294	11.295		

Table 3
Error matrix populated with number of reference samples (n = 526); and accuracy metrics, total mapped area, and proportion of area coverage of each class in the integrated map.

	Missing forest	Other land with tree cover	Other land	Sum (classified pixels)	User's Accuracy	Total mapped area (Mha)	Proportion of area cover
Missing forest	143	8	7	158	**0.905**	4.736	0.212
Other land with tree cover	2	104	20	126	**0.825**	3.881	0.174
Other land	28	15	199	242	**0.822**	13.735	0.614
Sum (reference samples)	173	127	226	526		22.353	1.000
Producer's accuracy	**0.827**	**0.819**	**0.881**				

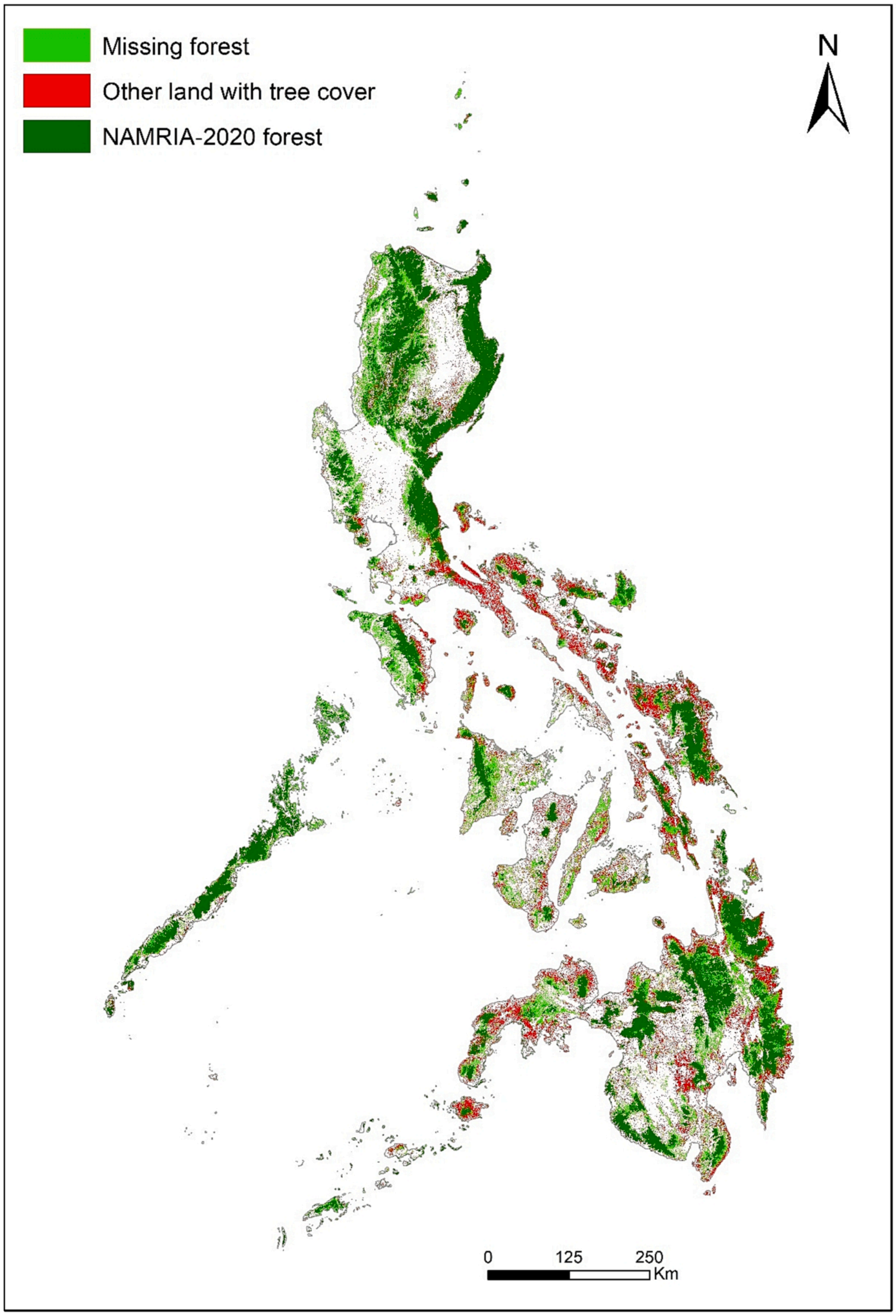

Fig. 3. "Missing forest" and "Other land with tree cover" areas in integrated map. Areas mapped as "Forest" in NAMRIA-2020 are also shown for reference.

area coverage is also important to quantify to support the FAO global FRA process, as well as for tracking of progress towards other global environmental goals and targets.

As noted in Section 2.4., in this study we focused our map accuracy assessment and bias-corrected area estimation on the "Missing forest" and "Other land with tree cover" classes, because these were the main outputs of the proposed map integration procedure. For countries' actual reporting of forest area estimates, however, they would need to combine the map of "Missing forest" with their official map of "Forest" areas (i.e., NAMRIA-2020 in the case of the Philippines) into a merged "Forest" map, and conduct the accuracy assessment/bias-corrected area estimation for this merged "Forest" class.

3.3. Additional CO_2 sinks in areas found to correspond to "Forest" and "Other land with tree cover" in the integrated map

As shown in Table 5, the CO_2 sinks in the areas of "Missing Forest" in the integrated map was estimated to be 87,085 ± 3,185 GgCO2/yr. Areas of "Other land with tree cover" were also found to contribute significant CO_2 sinks, estimated as 58,395 ± 3,512 $GgCO_2$/yr. The sum of the estimated CO_2 sinks for these two classes totaled 145,480 $GgCO_2$/yr, which is greater than the total reported CO_2 removals of the entire land use sector (105,111 $GgCO_2$/year) in the Philippines' most recent national GHG inventory, which was for the year 2000 (Government of the Philippines, 2014). However, it should be noted that the current calculation does not consider land use changes, e.g. forests converted to non-forests, because area data was available for a single year only.

Table 5
Additional annual CO_2 sinks by "Missing forest" and "Other land with tree cover" identified in our integrated map.

Category in integrated map	LULC Class in NAMRIA-2020 map	Assumed land cover/ use types	Bias-corrected area from integrated map (Mha)	Removal factor[1)] (tC/ha/yr)	Additional sink ($GgCO_2$/yr)
"Missing forest"	Brush/Shrubs, Grassland, Inland Water, Marshland/Swamp, Fishpond, Open/Barren	Second-growth forest	5.931 ± 0.217	4.0[2)]	87,085 ± 3,185
"Other land with tree cover"	Annual Crop, Perennial Crop	Agroforestry-Improved fallow	0.9716 * (4.294 ± 0.258)	3.7[3)]	58,395 ± 3,512[5)]
	Built-up	Tree cover in built-up area	0.0284 * (4.294 ± 0.258)	4.0[4)]	

1) Includes removals from above-ground (AGB) and below-ground biomass (BGB). BGB is assumed as 37% of AGB, according to Republic of the Philippines (2022). AGB values are taken from the literature 2)-4).
2) Environmental Management Bureau (2011) (Table 64 (Second-growth Forest)).
3) Environmental Management Bureau (2011) (Table 62 (Agroforestry- Improved fallow)).
4) IPCC (2006) (Table 8.1 (Default annual carbon accumulation per ha tree crown cover, global default)).
5) Bias-corrected area estimates and area-weighted CO_2 removal factors were calculated based on the proportion of "Other land with tree cover" located on urban (0.0284) vs. agricultural lands (0.9716) in the integrated map.

Existence of "Missing forest" and "Other land with tree cover" implies that these could also potentially be deforested or degraded, and thus become emission sources. Thus, our map integration approach can help for reporting of annual removals, while it would need to be implemented for multiple years (e.g., for 2015 and 2020, or 2020 and 2025) to provide additional support the entire National GHG Inventory process (i.e., by quantifying changes in C stocks by identifying changes in the area of "Forest" and "Other land with tree cover"). Future research could focus in this direction.

3.4. Sources of uncertainty in integrated map

The main sources of errors in this study were related to the LULC datasets used for this map integration process. One source of error was related to the definitions of "Forest" used in each of the LULC maps. Neither the NAMRIA-2020 nor PALSAR-FNF maps had definitions were completely consistent with FAO-Forest. Our map integration process mitigated errors present in the individual LULC datasets to some degree by identifying additional areas corresponding to FAO-Forest ("Missing forest") and "Other land with tree cover"), but it should be noted that some areas where tree cover does not currently, but is expected to exceed FAO-Forest thresholds in the future, were likely not mapped as "Forest". Another source of error in the LULC datasets relates to their thematic accuracy, i.e., how accurately they mapped each LULC class. Although the NAMRIA-2020 map has reportedly been ground validated, no official information is available yet on its accuracy. We used it in this study because it is the official national LULC map used in the Philippines' FRA country reports. As previously mentioned, the accuracy of the PALSAR-FNF map has been reported at the Southeast Asia regional level. The L-band SAR satellite data used to generate this map is sensitive to vegetation volume, but does not directly measure tree height, which is important to ensure that areas mapped as "Forest" have tree heights exceeding 5 m. High-resolution (~30 m) global tree height maps produced by fusing satellite Lidar data with other types of satellite imagery are becoming more common, with current maps having a mean average error of ~ 4.5 m (Potapov et al., 2021). As the accuracy of these global tree height datasets further improves, and/or as more accurate national/regional tree height datasets become available (Michez et al., 2020), they may provide additional useful information for detecting areas corresponding to FAO-Forest, and more generally for monitoring of forest changes of forests with different height ranges.

Finally, the accuracy of the estimated CO_2 sinks in areas of "Missing forest" and "Other land with tree cover" were affected by the accuracy of the integrated map as well as the accuracy of the CO_2 removal factors (national or IPCC default average values). We took into account the accuracy of the integrated map for these estimations by including the approximate 95% confidence intervals of the area estimates of "Missing forest" and "Other land with tree cover". Similarly to global tree height maps, high-resolution global above-ground forest biomass maps are also recently becoming available (Santoro and Cartus, 2023), and in the future they may be useful to reduce the uncertainty of CO_2 sink estimates.

3.5. Limitations of FAO's definition of "Forest" in the context of biodiversity conservation and forest GHG monitoring, and potential solutions

Finally, while we have discussed some advantages of using the FAO-Forest definition for reporting in the context of global environmental initiatives (e.g., it is widely-used, broad enough to ensure that few forest areas go unmapped, and compliant to the IPCC's Guidelines for National GHG Inventories), it has some important limitations. For example, it does not differentiate between natural forests and (non-agricultural) plantation forests, and its minimum tree canopy cover threshold may be too low for monitoring some types of forests, estimation of forest carbon stocks (Johnson et al., 2019), or to allow for detection of forest degradation (Estoque et al., 2022). Thus, forest assessments that only consider the area of FAO-Forest, without also considering additional important context information related to the forested area (e.g., how much of the forested area is natural forest vs. plantation forest, how much is open vs. closed forest, or how tree canopy cover is changing in areas mapped as "Forest") could potentially give a misleading impression of the biodiversity conservation benefits or carbon sinks associated with forest cover in a particular country. For this reason, it remains beneficial for countries to continue monitoring their forests using more appropriate nationally-specific definitions as well. This could be done in practice in various ways to also ensure interoperability with FAO definitions, e.g., by further separating areas identified as FAO-Forest into natural forests and plantation forests (to differentiate between these types of forests), by separating areas currently with and without tree cover (to better track the area that is currently forested in a particular year), or by applying a higher minimum canopy cover threshold or using continuous tree cover maps to better monitor denser forests and/or tree cover changes within areas corresponding to FAO-Forest (Estoque et al., 2022).

A benefit of our proposed approach is that it does not take much additional time/effort to integrate a national LULC map (containing nationally-specific forest classes) with the PALSAR-FNF map to generate a map more consistent with FAO definitions. This aspect is important, considering that countries have already made significant efforts (and allocated considerable resources) to meet with their reporting obligations to various international agreements (including those in Table 1) (Umemiya and White, 2023).

4. Conclusions

In this study, we proposed a map integration approach which combines two existing LULC products (including one global map and one national LULC map) to generate an integrated map more consistent with FAO definitions of "Forest" and "Other land with tree cover". The PALSAR-FNF map was selected as the most appropriate global LULC to complement the national LULC maps for this map integration procedure because it had a definition of "forest" that most closely matched that of the FAO. As a case study, the proposed approach was applied in the Philippines and used to integrate a national LULC map (NAMRIA-2020) with the PALSAR-FNF map.

Our integrated map identified an additional 5.937 ± 0.217 Mha of "Missing forest" land in the Philippines, i.e., land corresponding to the FAO definition of "Forest" that was not identified in the country's official LULC map. We further identified 4.294 ± 0.258 Mha of land corresponding with the FAO definition of "Other land with tree cover". Thus, our proposed approach can potentially be used to improve the reporting of these categories of land to the FAO, as well as in national reporting of progress towards global biodiversity goals/targets including the Kunming-Montreal Global Biodiversity Framework and the UN Sustainable Development Goals. Our integrated map could also identify significant additional CO_2 sinks on areas of "Missing forest" (estimated as 87,085 ± 3,185 $GgCO_2$/year) and "Other land with tree cover" (estimated as 58,395 ± 3,512 $GgCO_2$/year), demonstrating the utility of the approach for monitoring forest-related ecosystem services in the context of the UNFCCC Paris Agreement.

CRediT authorship contribution statement

Brian A. Johnson: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **Chisa Umemiya:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Project administration. **Damasa B. Magcale-Macandog:** Writing – original draft, Supervision. **Ronald C. Estoque:** Methodology, Writing – review & editing. **Masato Hayashi:** Conceptualization, Writing – review & editing, Supervision, Project administration. **Takeo Tadono:** Conceptualization, Writing – review & editing, Supervision, Project administration, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The georeferenced maps (.shp files) of "Missing forest", "Other land with tree cover", and NAMRIA-2020 "Forest" generated in this study are available for download at https://www.iges.or.jp/en/pub/forest-map-ph2020/en. Additional data will be made available on request.

Acknowledgements

This work was kindly supported by JAXA, and the Environmental Research and Technology Development Fund [JPMEERF20221C06] of the Environmental Restoration and Conservation Agency of Japan.

Appendix A

Table A1
Definitions of different FAO land categories.

FAO definition
Forest: "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. It does not include land that is predominantly under agricultural or urban land use. Explanatory notes 1. Forest is determined both by the presence of trees and the absence of other predominant land uses. The trees should be able to reach a minimum height of 5 m in situ. 2. Includes areas with young trees that have not yet reached but which are expected to reach a canopy cover of 10 percent and tree height of 5 m. It also includes areas that are temporarily unstocked due to clear-cutting as part of a forest management practice or natural disasters, and which are expected to be regenerated within 5 years. Local conditions may, in exceptional cases, justify that a longer time frame is used. 3. Includes forest roads, firebreaks and other small open areas; forest in national parks, nature reserves and other protected areas such as those of specific environmental, scientific, historical, cultural or spiritual interest. 4. Includes windbreaks, shelterbelts and corridors of trees with an area of more than 0.5 ha and width of more than 20 m. 5. Includes abandoned shifting cultivation land with a regeneration of trees that have, or is expected to reach, a canopy cover of 10 percent and tree height of 5 m. 6. Includes areas with mangroves in tidal zones, regardless whether this area is classified as land area or not. 7. Includes rubber-wood, cork oak and Christmas tree plantations. 8. Includes areas with bamboo and palms provided that land use, height and canopy cover criteria are met. 9. Excludes tree stands in agricultural production systems, such as fruit tree plantations, oil palm plantations and agroforestry systems when crops are grown under tree cover. Note: Some agroforestry systems such as the "Taungya" system where crops are grown only during the first years of the forest rotation should be classified as forest" (FAO, 2010).
Other wooded land: "Land not classified as Forest, spanning more than 0.5 ha; with trees higher than 5 m and a canopy cover of 5–10 percent, or trees able to reach these thresholds in situ; or with a combined cover of shrubs, bushes and trees above 10 percent. It does not include land that is predominantly under agricultural or urban land use. Explanatory notes 1. The definition above has two options: The canopy cover of trees is between 5 and 10 percent; trees should be higher than 5 m or able to reach 5 m in situ. or The canopy cover of trees is less than 5 percent but the combined cover of shrubs, bushes and trees is more than 10 percent. Includes areas of shrubs and bushes where no trees are present. 2. Includes areas with trees that will not reach a height of 5 m in situ and with a canopy cover of 10 percent or more, e.g. some alpine tree vegetation types, arid zone mangroves, etc. 3. Includes areas with bamboo and palms provided that land use, height and canopy cover criteria are met (FAO, 2010)."
Other land: "All land that is not classified as Forest or Other wooded land."
Other land with tree cover (sub-category of Other land): Land classified as Other land, spanning more than 0.5 ha with a canopy cover of more than 10 percent of trees able to reach a height of 5 m at maturity. Explanatory notes 1. The difference between Forest and Other land with tree cover is the land use criteria. 2. Includes groups of trees and scattered trees in agricultural landscapes, parks, gardens and around buildings, provided that area, height and canopy cover criteria are met. 3. Includes tree stands in agricultural production systems, for example in fruit tree plantations

(*continued on next page*)

Table A1 (*continued*)

FAO definition
and agroforestry systems when crops are grown under tree cover. Also includes tree plantations established mainly for other purposes than wood, such as oil palm plantations. 4. Excludes scattered trees with a canopy cover less than 10 percent, small groups of trees covering less than 0.5 ha and tree lines less than 20 m wide. (FAO. Guidelines for Country Reporting to FRA 2010)

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jag.2023.103452.

References

Ameray, A., Bergeron, Y., Valeria, O., Montoro Girona, M., Cavard, X., 2021. Forest Carbon Management: a Review of Silvicultural Practices and Management Strategies Across Boreal, Temperate and Tropical Forests. Curr. For. Rep. 7, 245–266. https://doi.org/10.1007/s40725-021-00151-w.

Balzter, H., Skinner, L., Luckman, A., Brooke, R., 2003. Estimation of tree growth in a conifer plantation over 19 years from multi-satellite L-band SAR. Remote Sens. Environ. 84, 184–191. https://doi.org/10.1016/S0034-4257(02)00106-2.

Belgiu, M., Drăguţ, L., 2016. Random forest in remote sensing: A review of applications and future directions. ISPRS J. Photogramm. Remote Sens. 114, 24–31. https://doi.org/10.1016/j.isprsjprs.2016.01.011.

Breiman, L., 2001. Random Forests. Mach. Learn. 45, 5–32.

CBD, 2022a. CBD/COP/15/L.25.

CBD, 2022b. CBD/COP/15/L.26.

Debele, S.E., Kumar, P., Sahani, J., Marti-cardona, B., Mickovski, S.B., Leo, L.S., Porcù, F., Bertini, F., Montesi, D., Vojinovic, Z., Di, S., 2019. Nature-based solutions for hydro-meteorological hazards : Revised concepts, classification schemes and databases. Environ. Res. 179, 108799 https://doi.org/10.1016/j.envres.2019.108799.

Department of Environment and Natural Resources, 2022. Philippine Forests at a Glance: 2022 Edition.

Environmental Management Bureau, 2011. Tracking Greenhouse Gases: An Inventory Manual.

Estoque, R.C., Pontius, R.G., Murayama, Y., Hou, H., Thapa, R.B., Lasco, R.D., Villar, M. A., 2018. Simultaneous comparison and assessment of eight remotely sensed maps of Philippine forests. Int. J. Appl. Earth Obs. Geoinformation 67, 123–134. https://doi.org/10.1016/j.jag.2017.10.008.

Estoque, R.C., Johnson, B.A., Dasgupta, R., Gao, Y., Matsuura, T., Toma, T., Hirata, Y., Lasco, R.D., 2022. Rethinking forest monitoring for more meaningful global forest landscape change assessments. J. Environ. Manage. 317, 115478 https://doi.org/10.1016/j.jenvman.2022.115478.

FAO, 2020. Global Forest Resources Assessment 2020: Main Report. FAO, Rome. https://doi.org/10.4060/ca9825en.

FAO, 2010. Guidelines for Country Reporting to FRA 2010.

Government of the Philippines, 2014. Second National Communication to the United Nations Framework Convention on Climate Change.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., 2013. High-resolution global maps of 21st-century forest cover change. Science 342 (6160), 850–853.

Intergovernmental Panel on Climate Change, 2006. Agriculture, Forestry, and Other Land Use, in: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. https://doi.org/10.1016/j.phrs.2011.03.002.

JAXA, 2022. Global 25 m Resolution PALSAR-2 Forest/Non-Forest Map (FNF) (Ver.2.0.0) Dataset Description.

Jensen, J.R., 2005. Introductory Digital Image Processing - A Remote Sensing Perspective. Pearson Prentice Hall, Upper Saddle River, USA.

Johnson, B.A., 2015. Combining national forest type maps with annual global tree cover maps to better understand forest change over time: Case study for Thailand. Appl. Geogr. 62, 294–300.

Johnson, B.A., Dasgupta, R., Mader, A.D., Scheyvens, H., 2019. Understanding national biodiversity targets in a REDD+ context. Environ Sci Policy 92, 27–33. https://doi.org/10.1016/j.envsci.2018.11.007.

Johnson, B.A., Kumar, P., Okano, N., Dasgupta, R., Shivakoti, B.R., 2022. Nature-based solutions for climate change adaptation: A systematic review of systematic reviews. Nat.-Based Solut. 2, 100042 https://doi.org/10.1016/j.nbsj.2022.100042.

Margono, B.A., Potapov, P.V., Turubanova, S., Stolle, F., Hansen, M.C., 2014. Primary forest cover loss in Indonesia over 2000–2012. Nat. Clim. Chang. 4, 730–735.

Michez, A., Huylenbroeck, L., Bolyn, C., Latte, N., Bauwens, S., Lejeune, P., 2020. Can regional aerial images from orthophoto surveys produce high quality photogrammetric Canopy Height Model? A single tree approach in Western Europe. Int. J. Appl. Earth Obs. Geoinformation 92, 102190. https://doi.org/10.1016/j.jag.2020.102190.

Naime, J., Mora, F., Sánchez-Martínez, M., Arreola, F., Balvanera, P., 2020. Economic valuation of ecosystem services from secondary tropical forests: trade-offs and implications for policy making. For. Ecol. Manag. 473, 118294 https://doi.org/10.1016/j.foreco.2020.118294.

Nesha, M.K., Hussin, Y.A., Van Leeuwen, L.M., Sulistioadi, Y.B., 2020. Modeling and mapping aboveground biomass of the restored mangroves using ALOS-2 PALSAR-2 in East Kalimantan, Indonesia. Int. J. Appl. Earth Obs. Geoinformation 91, 102158. https://doi.org/10.1016/j.jag.2020.102158.

Olofsson, P., Foody, G.M., Herold, M., Stehman, S.V., Woodcock, C.E., Wulder, M.A., 2014. Good Practices for Assessing Accuracy and Estimating Area of Land Change. Remote Sens. Environ. 148, 42–57.

Peros, C.S., Dasgupta, R., Estoque, R.C., Basu, M., 2022. Ecosystem services of 'Trees Outside Forests (TOF)' and their contribution to the contemporary sustainability agenda: a systematic review. Environ. Res. Commun. 4, 112002 https://doi.org/10.1088/2515-7620/ac9d86.

Pesaresi, M., Ehrlich, D., Florczyk, A.J., Freire, S., Julea, A., Kemper, T., Soille, P., Syrris, V., 2016. Operating procedure for the production of the Global Human Settlement Layer from Landsat data of the epochs 1975, 1990, 2000, and 2014. Publ. Off. Eur. Union 1–62. https://doi.org/10.2788/253582.

Potapov, P., Li, X., Hernandez-Serna, A., Tyukavina, A., Hansen, M.C., Kommareddy, A., Pickens, A., Turubanova, S., Tang, H., Silva, C.E., Armston, J., Dubayah, R., Blair, J. B., Hofton, M., 2021. Mapping global forest canopy height through integration of GEDI and Landsat data. Remote Sens. Environ. 253, 112165 https://doi.org/10.1016/j.rse.2020.112165.

Quilloy, I., 2020. Global Forest Resources Assessment 2020. Philippines, Report.

Republic of Indonesia, 2022. National Forest Reference Level for Deforestation, Forest Degradation and Enhancement of Forest Carbon Stock.

Republic of the Philippines, 2022. Philippines Forest Reference Level under the UNFCCC REDD+ Framework.

Romijn, E., Ainembabazi, J.H., Wijaya, A., Herold, M., Angelsen, A., Verchot, L., Murdiyarso, D., 2013. Exploring different forest definitions and their impact on developing REDD+ reference emission levels: A case study for Indonesia. Environ Sci Policy 33, 246–259.

Santoro, M, Cartus, O, 2023. ESA Biomass Climate Change Initiative (Biomass_cci): Global datasets of forest above-ground biomass for the years 2010, 2017, 2018, 2019 and 2020, v4. NERC EDS Cent. Environ. Data Anal. https://doi.org/10.5285/af60720c1e404a9e9d2c145d2b2ead4e.

Shimada, M., Itoh, T., Motooka, T., Watanabe, M., Shiraishi, T., Thapa, R., Lucas, R., 2014. New global forest/non-forest maps from ALOS PALSAR data (2007–2010). Remote Sens. Environ. 155, 13–31.

Sodhi, N.S., Posa, M.R.C., Lee, T.M., Bickford, D., Koh, L.P., Brook, B.W., 2010. The state and conservation of Southeast Asian biodiversity. Biodivers. Conserv. 19, 317–328.

Umemiya, C., White, M.K., 2023. National GHG inventory capacity in developing countries – a global assessment of progress. Clim. Policy 1–13. https://doi.org/10.1080/14693062.2023.2167802.

UNFCCC, 2016. FCCC/CP/2015/10/Add.1.

United Nations, 2015. A/RES/70/1.

United Nations, 2017. A/RES/71/313: Resolution adopted by the General Assembly on 6 July 2017.

van Weerd, M., Strijk, J., Snelder, D., 2003. The importance of forest fragments for birds and local communities in Northeast Luzon, Philippines. Sylvatrop Tech. J. Philipp. Ecosyst. Nat. Resour. 13, 1–30.

Zhang, S., Vega, C., Deleuze, C., Durrieu, S., Barbillon, P., Bouriaud, O., Renaud, J.-P., 2022. Modelling forest volume with small area estimation of forest inventory using GEDI footprints as auxiliary information. Int. J. Appl. Earth Obs. Geoinformation 114, 103072. https://doi.org/10.1016/j.jag.2022.103072.