Detecting mangrove deforestation using multi land use land cover change datasets: a comparative analysis in Southeast Asia

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Abstract. Mangrove forest grows on tropical coastal areas and has an ecological role for its surrounding environment. Mangrove forest protects the coast from large waves and becomes a habitat for various marine fauna. It stores the highest densities of carbon among any other ecosystem globally. In Southeast Asia, Mangrove forest is highly diverse and contributes to the sustainability of the ecosystem. However, based on previous studies, mangrove forests are experiencing deforestation due to high demands of commodities and land use. In this study, we analyzed changes of land cover in Southeast Asia using several global land cover products produced between 2001 and 2012 and their correlation with mangrove deforestation based on Mangrove Forest Watch (CGMFC-21) data. LULC data products applied in this study were ESA CCI LC, MODIS LC, GlobCover. The analysis was conducted by calculating the rate of increase in mangrove deforestation and comparing it with changes in land cover that replaced the mangrove area temporally. The results of this study were land cover classes that replaced mangrove forest areas in the study period. Based on the results it could be concluded that the methods and products used influenced the results. There are many sources of data products that might be used for future research, with other methods that are better so that they provide space for future research and development. Our study can be used as a consideration to implement policies that conserve mangrove forest across Southeast Asia.

1. Introduction
More than a third of the world's mangrove forests grow in southeast Asia with very high mangrove diversity [1]. Mangrove forests have ecological and economic functions for the surrounding environment. Ecologically, mangrove forests are a habitat for a variety of biodiversity, including for fauna such as aquatic and terrestrial insects, fish, mammals, amphibians, reptiles, and birds [2]. Economically, mangrove forests support the surrounding population through the provision of various needs such as fuel, food and construction materials [3]. Although it has an important function for the environment, the presence of mangrove forests is very threatened. Mangrove forests loss during the period 1980-2005 was more than 3 million ha with the rate of degradation during the period 1990-2000 estimated at 1% per year, two times greater than the rate of terrestrial rainforests degradation [4]. Regional degradation in Southeast Asia is the highest in the world, mainly due to human activities [5]. The triggers of degradation caused by human activities generate from the processes underlying population increase, industrialism, urbanization, and globalization, namely increasing demand for commodities [6]. Mangrove deforestation has implications for ecosystem service providers, because
mangrove forests store carbon with very high concentrations. So, changes in land cover that occur in mangrove forests can produce carbon emissions equal to 2-8% of emissions from deforestation in rainforests [7]. Meanwhile, some tropical developing countries still have the latest spatial deficiencies related to deforestation and their causes [8]. In fact, in recent years, the availability of global land cover data has increased with the development of monitoring technology through remote sensing [1]. Some global land cover products, for example, are MODIS land cover products, GlobCover, land cover products from the European Space Agency Climate Change Initiative (ESA CCI), and the Global Land Cover by the National Mapping Organization (GLCNMO). However, the relatively low spatial resolution of all these land cover products is not enough to observe deforestation on a high scale [9]. Therefore, a comparative study is needed to determine which land cover products are suitable for monitoring deforestation, especially mangroves in Southeast Asia. This research is a development of latest research related to mangrove deforestation, there are "evaluating mangrove forests deforestation causes in southeast Asia by analysing recent information and socio-economic data products" [10] and evaluation of Southeast Asia mangrove forests deforestation using long-term remote sensing index datasets” [11].

2. Datasets

2.1. Global Land Cover Datasets

This paper focuses on the global land cover datasets explained in detail below and summarized in Table 1.

The ESA’s Land Cover (LC-CCI) project delivered three consecutive GLC maps for three five-year epochs centred around 2000, 2005, and 2010, with a spatial resolution of 300 m. The classification combines supervised and unsupervised classification of MERIS Full Resolution (FR) time series, pre-processed in seven-day composites to generate a baseline LC map (from 2003 to 2012). Backdating and updating techniques, based on the SPOT-VGT time series, were adopted to obtain the three different epochs. In this study, we use the epoch 2010, which is representative of the 2008 to 2012 period, with a legend based on LCCS with 22 classes. The overall accuracy is 74.4% based on the same reference sample as the one used for the GlobCover-2009 validation [12] and [13].

MODISLC was developed by Boston University and is coordinated by the MODIS Land Team from the National Aeronautics and Space Administration (NASA) [14]; the first version became available in 2001. In this study, the MODIS Collection 5 Land Cover Type (MCD12Q1 V051) for 2001 and 2012 at 500 m spatial resolution is evaluated. MODIS land cover was produced using an ensemble supervised classification algorithm, based on a multi-temporal decision tree in conjunction with a boosting technique based on spectral and temporal information from MODIS bands 1 to 7, supplemented by the enhanced vegetation index and land surface temperature [15]. It contains five classification schemes, from which the International Geosphere-Biosphere Programme (IGBP), consisting of 17 classes [16], was created; IGBP is used in this study. Its overall accuracy reached 71.6% [15].

The first version of GlobCover was developed in 2005 by the European Space Agency (ESA) in cooperation with an international network of partners, including the European Environmental Agency (EEA), the United Nations Environment Program (UNEP), the Global Observation of Forest Cover and Land Dynamic (GOFC-GOLD), the Joint Research Center (JRC), and the IGBP [17]. In this paper, we evaluate GlobCover 2009. This product used as input, cloud-free, bi-monthly, and annual mosaics derived from MERIS Full Resolution (300 m spatial resolution) instrument onboard ENVISAT from January to December 2009. Per-pixel supervised classification was used to identify urban and wetland classes, and an unsupervised classification was used for the remaining classes to create similar spectral and temporal clusters that are labelled further. The global land cover map is made up of 22 land cover classes defined with the LCCS and has an overall accuracy of 67.5% [18].
GLCNMO2008 was generated by the Global Mapping Project organized by the International Steering Committee for Global Mapping (ISCGM). The Version II dataset has a spatial resolution of 500 m that is based on 16 days Bidirectional Reflectance Distribution Function (BRDF)-Adjusted Reflectance (MCD43A4) MODIS data for 2008, with 77.9% overall accuracy [19]. The legend has 20 classes defined under the LCCS. The method is a combination of supervised classification for fourteen of the twenty classes and an individual independent classification for the remaining six classes [19].

2.2. Global Mangrove Datasets

The most widely-used and referenced global mangrove dataset is Mangrove Forests of the World (MFW) by Giri et al. [1]. Giri et al. [1] was the first comprehensive global assessment of mangrove distribution produced using satellite imagery, providing spatially explicit information at a moderate spatial resolution (i.e., 30 m) for all countries/territories in the ROI circa 2000. The global dataset was produced using approximately 1000 Landsat images (specific sensor information not reported), subset to include areas where mangroves were likely to occur. A hybrid supervised/unsupervised classification approach, using the (Iterative Self-Organizing Data Analysis) ISODATA clustering algorithm, generated 50–150 spectral clusters and four land-cover classes: mangrove, non-mangrove, barren lands and water. The resulting database was evaluated against existing datasets (findings not reported), whilst qualitative validation by local experts employed high spatial resolution QuickBird and IKONOS imagery. Geometric correction reduced root mean square (RMS) error to ±1/2 pixel. MFW estimated 6,068,096 ha of mangrove within the ROI in 2000.

The CGMFC-21 product builds on (C)’s [20] use of Landsat ETM+ imagery to map global mangrove change from 2000–2014, at a spatial resolution of 30 m. Two global mangrove extent products were produced by masking GFC using MFW [1] and the Terrestrial Ecoregions of the World (TEOW) [21]. TEOW was not compiled using remote sensing methods so is not considered in this study. Areas of forest and annual change within the masked extent were identified from GFC annually to produce maps of canopy-cover (m2), resulting in continuous (rather than discrete) mangrove coverage. Areas of mangrove change outside of the baseline area are therefore excluded. Accuracy was tested by way of comparison with the only other study reporting similar resolution continuous forest cover available, the USGS National Land Cover Dataset over the United States. Comparison for mangroves in Florida identified a 3.6% disagreement, providing some assurance of accuracy for CGMFC-21. The positional error of the CGMFC-21 product is that of MFW [1], i.e., a published RMS error of ±1/2 pixel. The product estimated 4,477,769 ha of mangroves in the ROI in 2000, falling to 4,310,725 ha by 2014. This equals a 3.7% decline in extent between 2000–2014, or 0.27% per annum.

2.3. Reference Global Land Cover Datasets

Dominant Land Use of Deforested Mangrove Patch (DLUDMP) provide information about the function of dominant land use in mangrove areas which were deforested in 2012 with a spatial resolution of one degree. The function of the dominant land use is determined by calculating the area with the largest land use which caused the conversion of mangrove forests. This data product is produced through two main data processes. First, data on deforestation of mangrove forests between 2000-2012 was obtained through the integration of Global Forces Change (GFC) data [20], which presents information on annual global deforestation between 2000-2012, and MFW data [1], which presents information about the distribution of global mangrove forests. Second, the dominant land use in the mangrove forest area deforested was obtained through classification of Landsat satellite images in 2012 for each area of mangrove forest deforested with an area of more than 0.5 ha. In addition, four determinant geographical variables were used for each area of land deforested, the Normalized Difference Vegetation Index (NDVI), distance to the main road, and the climate suitability index for oil palm and rice fields obtained from FAO. Images obtained from Google Earth pro are also used to observe the dominant land functions in several mangrove forest areas. Then the function of land is categorized into eight classes, fisheries, rice fields, oil palm plantations, cities, mangrove forests, terrestrial forests, coastal erosion, and unobserved classes of conversion [6].
Table 1. Mangrove data and global land cover product specifications

| Product Data       | Data Type           | Spatial Resolution | Temporal Resolution |
|--------------------|---------------------|--------------------|---------------------|
| MFW-USGS [1]       | Mangrove Distribution | 30 meters          | 2000                |
| CGMFC-21 [20]      | Mangrove Deforestation | 30 meters          | 2001, 2005, 2009, 2012 |
| ESA CCI Land Cover [12]| Land Cover         | 300 meters         | 2001 and 2012       |
| GLCNMO [19]        | Land Cover          | 500 meters         | 2008 and 2012       |
| GlobCover [18]     | Land Cover          | 300 meters         | 2005 and 2009       |
| MCD12Q1 [14]       | Land Cover          | 500 meters         | 2001 and 2012       |
| DLUDMP [6]         | Dominant Land Use   | 1^0                | 2001 and 2012       |

3. Methods
One of the main challenges in the comparison of land cover is legendary reconciliation or harmonization, because each product defines mangrove forest in different ways and refers to different classifications. The number of classes referred to as mangrove forests is very different from one product to another. There are several obstacles in translating classes in each product as a class of mangrove forests, especially if these land cover products are not specifically designed for purposes oriented to mangrove forests. Therefore, land cover data is harmonized into two classes, the first class which is considered as mangrove forest, and the second class as the class which is considered to be the conversion of land cover due to mangrove deforestation. Mangrove forest is a typical forest that is overgrown by mangrove trees and is found along sloping beaches, river estuaries, deltas and bays that are affected by tides and are found in the tropics and subtropics [24, 25]. Referring to the definition of mangrove forest in the introduction section, ESA, GlobCover, and MODIS land cover products are taken from forest and wetland classes as classes defined as mangrove forests, while on GLCNMO land cover products, there is a mangrove class. The aquaculture industry has played a leading role in mangrove deforestation in Southeast Asia over the past 30 years [22]. Therefore, from each land cover product, residential class (Urban), Agriculture (Agriculture), and Wetland (Wetland), and waters (Water) which are considered as aquaculture, referring to the previous definition, taken as a class considered cover conversion land due to mangrove deforestation.

At this stage of harmonization, we find that the number of pixels of the class defined as mangrove forests varies between land cover products. The number of pixels of mangrove classes in MODIS Land Cover reaches 40000 pixels for the forest class, and 140000 pixels for the wetland class. At ESA CCI LC the number of pixels of the mangrove class reaches 60000 pixels for the forest class and 300000 pixels for the wetland class. In GlobCover the number of pixels of the mangrove class reaches 180000 pixels for the forest class and 115000 for the wetland class. In GLCNMO the number of pixels for the mangrove class reaches 150000 pixels that come from the mangrove class. This varied total pixel is due to the different data input methods, classification techniques, class definitions, spatial resolution, and production years among the different global land cover datasets [27].
After each product is generalized into a class of mangrove forests and land conversion classes, there are agriculture, urban, and aquaculture, then it is to compare each product in terms of the amount of mangrove deforestation caused by land cover conversion, and the location of the mangrove deforestation point. The amount of mangrove deforestation caused by land cover conversion is calculated referring to the difference in the number of pixels in the class of mangrove forest which turns into a class of land cover conversion for each land cover product with a certain time span. The number of pixels is then masked with the CGMFC-21 data with the same time span to get the match between the converted mangrove class to another class of land cover products with actual deforestation data.

The consistency of each of these land cover products was evaluated against Richard et al. [6] research in 2015 regarding the rate and triggers of mangrove deforestation in Southeast Asia in 2000-2012. For this purpose, the study of dominant land function data in the mangrove area deforested in 2001-2012 [6] was used as visual and quantitative comparative data to assess the suitability of the results of land cover conversion from mangrove deforestation obtained from each global land cover product. Visually, the results of the study were carried out by calculating the percentage of the number of data grid products in the same land cover class in the one-degree grid size. Whereas quantitatively, the area of mangrove deforestation converted into other land cover classes from the results of the study is compared with the dominant function area of land in the mangrove area deforested in 2001-2012. Thus, a general description of the overall capability of global land cover products is obtained in obtaining the same information as DLUDMP data.

4. Results & Discussions

4.1. Land Cover Conversion from Deforestation of Mangroves in Southeast Asia
Conversion of land cover from mangrove deforestation is obtained through a temporal comparison of each harmonized land cover product of the land cover class into a class of mangrove forests and conversion classes of mangrove forests (agriculture, aquaculture, and settlements). Then, the results of the temporal comparison were overlapped with mangrove deforestation products in the same period of time to get the results of land cover changes confirmed as mangrove deforestation. As illustrated in figure 2 and figure 3, GLCNMO 2008 and 2012 products can identify the extent of mangrove deforestation converted into other land cover classes that is higher than other products, where the
conversion of mangrove deforestation to agriculture and aquaculture reaches more than 1000 hectares respectively. Then, the ESA CCI Land Cover and MODIS Land Cover products in 2001 and 2012 can identify the conversion of deforestation of mangrove forests in excess of 500 hectares, of which the ESA CCI Land Cover converts mangrove deforestation to agriculture dominates with an area of more than 300 hectares, while in MODIS Land products Cover, the conversion of mangrove deforestation to aquaculture dominates with an area of more than 400 hectares. Meanwhile, GlobCover 2005 and 2009 products can only identify the conversion of deforestation of mangrove forests to no more than 50 hectares, where agricultural classes dominate with an area of more than 40 hectares.

**Figure 2.** Total mangrove deforestation due to land cover change by each global land cover.
4.2. Suitability of the Results with DLUDMP [6]

Each product of the mangrove data and land cover changes is overlapped to the land function class in DLUDMP data. Then, the percentage of the number grid in the land function class according to the one-degree grid size shows the level of suitability of the results of the study with DLUDMP [6]. Suitability level of the study show a general description of each global land cover product in obtaining the same information as DLUDMP data. In general, according to the percentage of suitability obtained based on table 2, MODIS Land Cover products of 2001 and 2012 have a very high suitability in the aquaculture class with 98.04%, while in urban and agricultural classes according to their suitability is low. Then, the 2008 and 2013 GLCNMO products had very high suitability in the agricultural class which reached more than 100%, and the aquaculture class with a contribution of 87.25%, while the suitability of urban class only reached 4.35%. For ESA CCI Land Cover products 2001 and 2012, and GlobCover 2005 and 2009, none of the products obtained more than 30% suitability, which was obtained highest by ESA CCI Land Cover products through agricultural classes with suitability of 30.96%.

**Table 2.** Percentage of suitability of each global land cover product with DLUDMP [6] in one-degree size grid
4.3. Agreement Level of Mangrove Conversion

Agreement level maps of mangrove conversion is obtained by combining all global land cover products with the same class of land cover conversion from the mangrove forest (agriculture, aquaculture, and urban classes). The level of agreement of the mangrove forest conversion class is visualized in a one-degree sized grid, as is the visualization of the distribution map of mangrove deforestation in Figure 3. The level of agreement is sorted from the lowest, which is level 1 which indicates that the land cover conversion class is recognized by one land cover product global and highest level 4 indicates that the land cover conversion class at that location is recognized by all global land cover products. Based on figure 4, the conversion class of mangrove forests to agriculture has the highest-level, level 3, recognized by a maximum of 3 land cover product. Where the grid with level 3 is located in Myanmar, Cambodia and Indonesia. In the class conversion of mangrove forest to aquaculture, a grid with level 4 is located in Cambodia and Myanmar and a grid with level 3 is widely found on the island of Borneo, Indonesia. In the conversion class of mangrove forests to urban areas, a level 3 grid is located on the border between Singapore and Malaysia. The agreement level maps cannot indeed show the magnitude of the accuracy of each global land cover product in detecting mangrove deforestation and land cover classes that convert it. However, the level of agreement can illustrate that spatially, at a location there has been a conversion of land cover classes to mangrove forests, as recognized by several global land cover products.
Figure 4. Agreement level maps of each mangrove conversion classes.

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