Analysis for improvement of Indonesia FREL–2016

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WORKING PAPER 26

Working Paper 26

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CIFOR-ICRAF

Working Paper 26

DOI: 10.17528/cifor-icraf/009106

Manuri S, Murdiyarso D, Hergoualc’h K, Bhomia R. 2024. *Analysis for improvement of Indonesia FREL–2016*. Working Paper 26. Bogor, Indonesia: CIFOR; Nairobi, Kenya: ICRAF.

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We would like to thank all donors who supported this work through their contributions to the CGIAR Trust Fund. A list of donors is available at: http://www.cgiar.org/about-us/our-funders/

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List of acronyms

AD	Activity data
AGB	Above-ground biomass
BGB	Below-ground biomass
C	Carbon
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DOC	Dissolved organic compounds
ECS	Enhancement of carbon stocks
EF	Emission factor
ER	Emission reduction
FREL	Forest Reference Level
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
MoA	Ministry of Agriculture
MODIS	Moderate resolution imaging spectroradiometer
MoEF	Ministry of Environment and Forestry
MRV	Monitoring, reporting, and verification
N_2O	Nitrous dioxide
NDC	Nationally Determined Contribution
NFI	National Forest Inventory
PDF	Probability density function
REDD+	Reducing emissions from deforestation, forest degradation, enhancement of forest carbon stock, sustainable management of forests and conservation of forest carbon
SFM	Sustainable forest management
U%	Percent of uncertainty
UNFCCC	United Nations Framework Convention on Climate Change

Foreword

Parties of the United Nations Framework Convention on Climate Change (UNFCCC) must develop Forest Reference Emission Levels (FREL) or Forest Reference Level. As Indonesia ranks among the world's top holders of high-carbon reservoirs in wetland ecosystems, including peatlands and mangroves, a number of under-represented sources and sinks need to be included to improve FREL and national monitoring, reporting, and verification systems.

While Indonesia's first FREL submitted to the UNFCCC secretariat is a laudable effort, UNFCCC reviewers nevertheless recommended technical improvements that included peatland fires and emissions of non-CO_2 gases. Emissions are reported at a Tier 2 level using country-specific data. In addition to the already adopted emission factor, Indonesia uses its own high-resolution land-cover dynamics, known as activity data, for the most important land-cover categories.

This study identified the missing actvities, pools, and gases in FREL–2016 and used the 2013 IPCC Wetlands Supplement to fill gaps for estimating emissions in mangrove and peatlands. We hope this paper can inform the potential improvement of Indonesia's FREL. Unless otherwise stated, the authors have generated some of the information in the tables and figures.

Bogor, December 2023

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Summary

The first Indonesian Forest Reference Emission Level (1st FREL) was submitted to the United Nations Framework Convention on Climate Change (UNFCCC) in 2015 and revised in 2016 (FREL–2016). The 1st FREL was used to assess emission reduction resulting from deforestation, forest degradation, enhancement of forest carbon stock, sustainable management of forests, and conservation of forest carbon (REDD+) mitigation action post-2012. The Green Climate Fund approved Indonesia's proposals for accessing REDD+ payment for USD 103.8 million for 2014–2016. The Government of Indonesia identified gaps and potential improvements, which were documented in FREL–2016 and by the UNFCCC technical assessment team for the FREL–2016 review.

This study identified the missing activities, pools, and gases in FREL–2016 based on its improvement plan, as well as recommendations of its technical assessment. Indonesian stakeholders identified key gaps during the April 2020 workshop on "Capacity building on the IPCC 2013 Wetlands Supplement" and FREL diagnostic. In addition, we used the 2013 IPCC Wetlands Supplement to identify gaps for estimating emissions and removals from forest-cover change and fires in mangrove and peat soils.

Proposed subactivities of REDD+ identified in the analysis include peat fires and mangrove conversion. Notably, emissions from peat fires have emerged as the largest source of emissions, surpassing both deforestation and peat decomposition. Furthermore, the analysis incorporates additional carbon pools and gases following the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (Wetlands Supplement). Specifically, non-CO_2 gases such as methane, nitrous oxide, and carbon monoxide were included in estimated emissions from peat decomposition and peat fires. Estimates of peat decomposition emissions also accounted for dissolved organic carbon loss. The findings suggest additional emissions of about 30% compared with the 2016 estimates for peat decomposition, while peat fire emissions were 58% higher than the 2016 baseline.

To assess the uncertainty of the estimated emissions, we combined Propagation of Error (PEA) and Monte Carlo Simulation (MCS) methods. The uncertainty level of peat decomposition emissions was found to be higher than that of FREL–2016, with the MCS deemed preferable for uncertainty analysis based on the 2016 IPCC guidelines. These findings underscore the importance of considering previously unaccounted activities, and additional carbon pools and gases, and of conducting uncertainty analysis to enhance the accuracy and reliability of emissions estimates within the context of REDD+ and the 1st FREL.

1 Background

The first Indonesian Forest Reference Emission Level (1st FREL) was submitted to the United Nations Framework Convention on Climate Change (UNFCCC) in 2015 and revised in 2016 (FREL–2016). The 1st FREL aimed to set a reference or baseline of emissions from deforestation, forest degradation, and peat decomposition based on historical data from 1990 to 2012. It was used for assessing emission reduction resulting from REDD+ mitigation action post-2012. The Green Climate Fund approved Indonesia's proposals for accessing REDD+ payments for USD 103.8 million for 2014–2016.

The Government of Indonesia identified gaps and potential improvements, which were documented in FREL–2016 and by the UNFCCC technical assessment team for the FREL–2016 review. These include improvement of emission factors (EFs) and activity data (AD) through more accurate data and better methodology, as well as inclusion of peat emissions from fire and other REDD+ activities, such as sustainable forest management (SFM) and enhancement of carbon stock (MoEF 2016).

FREL–2016 identified deforestation as the major source of emissions. Deforestation is defined as the conversion of forest-cover classes into non-forest classes. To estimate emissions from deforestation, we generated the EFs based on total carbon stock of each forest class, assuming that all carbon stock will be loss after deforestation.

FREL–2016 recognized the importance of peat fire emissions due to their significant contribution to national greenhouse gases (GHGs) inventory. Due to the unavailability of accurate AD and EFs, FREL–2016 excluded emissions from peat fire. However, they were included in the FREL–2016 annex. The method for estimating peat fires followed the 2014 IPCC guidelines. AD in the annex was a proxy for burned area based on hotspot distribution, following MRI (2013), which posed high uncertainty.

Indonesia has about 23% of global mangrove – about 3 million hectares (ha) — making it the largest source in the world. Murdiyarso et al. (2015) suggested that until 2015 loss of Indonesia's mangrove equals 31% of global emissions originating from coastal ecosystems. Hence, the ecosystem plays a crucial role for climate change mitigation in Indonesia. FREL–2016 includes emissions from deforestation and forest degradation in mangrove forests but only in changes of above-ground biomass (AGB). Thus, emissions from soil mangrove due to development of aquaculture should be included in the calculation.

CIFOR's project seeks to support improvement of the Indonesian FREL and monitoring, reporting, and verification (MRV) systems for wetlands to further characterize under-represented dynamics, such as peatland fires and mangrove deforestation, degradation, and regeneration. This pathway should be in line with efforts to enhance Indonesia's reporting in relation to the transparent, accurate, consistency, comparability, and completeness principles as part of a commitment to its Nationally Determined Contribution (NDC) stipulated in the Paris Agreement. More detailed assessment on missing activities, pools, and unaccounted for non-CO_2 gases is required to be conducted so that the potential emissions are well understood and uncertainties in emission calculation can be reduced

This analysis aims to contribute to the effort to improve FREL-2016 that incorporates missing key wetland emissions and sinks.

The document has two parts. First, it identifies missing activities, carbon pools, and gases of FREL-2016, as well as potential improvement of EF and AD, particularly for estimating emissions from wetlands. Second, it estimates the potential exclusion of emissions, particularly for wetlands from FREL–2016 based on the Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (Wetlands Supplement) (IPCC 2014).

2 Method

2.1 Identification of missing activities, pools, and gases

We identified the missing activities, pools, and gases in FREL–2016 based on its improvement plan (MoEF 2016), as well as the recommendations of its technical assessment (UNFCCC 2016). Indonesian stakeholders identified key gaps during the April 2020 workshop on "Capacity building on the IPCC 2013 Wetlands Supplement" and FREL diagnostic. Also, we received recommendations during the meeting and workshop organized by the Ministry of Environment and Forestry (MoEF) in 2019.

2.2 Compilation of activity data and emission factors

We based AD in this analysis on the database provided by MoEF unless the data were access-restricted or unavailable. The database is mostly in tabular format and comprises:

- forest and land-cover change during 1990–2017 from MoEF
- peatland distribution from the Ministry of Agriculture (MoA) (Ritung et al. 2011)
- burned areas in 2001–2019 from moderate resolution imaging spectroradiometer (MODIS) data derived from Giglio et al. (2018).

EFs were compiled from FREL–2016 and the 2014 IPCC guidelines to fill gaps in estimated emissions.

2.2.1 Emission factors

2.2.1.1 Emission factor for peat fires

For peat fires, FREL–2016 provides a preliminary assessment of carbon dioxide (CO_2) emission. Additional emission estimates for methane (CH_4) and carbon monoxide (CO) could also be included. All non-CO_2 GHGs are converted into CO_2 equivalent (CO_2e) using global warming potential over a 100-year horizon with climate-carbon feedback from the IPCC–Fifth Assessment Report. Since CO is not a GHG, it is not converted into CO_2e. EFs for peat fires were derived from Chapter 2 of the 2013 Wetlands Supplement (see Table 1).

Table 1. Emission factors for peat fires

Gas	Mean	95% CI	Unit
CO_2	601	[290; 913]	t CO_2 ha^{-1}
CO	74	[36; 113]	t CO_2 ha^{-1}
CH_4	252	[48; 132]	t CO_2 ha^{-1}

Source: Drösler et al. 2014.

2.2.1.2 Non-CO_2 emission factors for peat decomposition/drainage

FREL–2016 includes on-site peat CO_2 emissions from soil organic matter decomposition but excludes other GHGs (CH_4 and N_2O). It also excludes off-site CO_2 emissions as dissolved organic compounds (DOC) losses. To complete estimates of emissions in peatlands, we used the EF from the 2013 IPCC supplement (see Table 2 , Table 3, Table 4 and Table 5).

Table 2. Emission factors for on-site CO_2 emissions from peat decomposition

Land cover	IPCC class	EF (t CH_4 ha^{-1} y^{-1})	Percent of uncertainty (U%)
Primary dry land forest	Drained forest land and shrubs	1.7	90.6
Secondary dry land forest/logged forest	Drained forest land and shrubs	1.7	90.6
Primary mangrove forest	Drained forest land and shrubs	1.7	90.6
Primary swamp forest	Drained forest land and shrubs	1.7	90.6
Plantation forest	Drained forest plantation	1.6	152.2
Dry shrub	Drained forest land and shrubs	1.7	90.6
Estate crop	Oil palm plantation	1.5	73.5
Settlement areas	Croplands	1.8	120.7
Bare ground	Grasslands	1.8	120.7
Savanna and grasses	Grasslands	1.8	120.7
Open water/water body	Paddy rice	6.3	92.3
Secondary mangrove forest/logged forest	Drained forest land and shrubs	1.7	90.6
Secondary swamp forest/logged forest	Drained forest land and shrubs	1.7	90.6
Wet shrub	Drained forest land and shrubs	1.7	90.6
Pure dry agriculture	Croplands	1.8	120.7
Mixed dry agriculture	Croplands	1.8	120.7
Paddy field	Paddy rice	6.3	92.3
Fish pond/aquaculture	Paddy rice	6.3	92.3
Transmigration areas	Croplands	1.8	120.7
Port and harbour		-	-
Mining areas		-	-
Open swamps	Paddy rice	6.3	92.3

Source: Drösler et al. 2014.

Table 3. Emission factors for on-site N_2O emissions from peat decomposition

Land cover	IPCC class	EF (t N_2O ha^{-1} y^{-1})	Percent of uncertainty (U%)
Primary dry land forest	Drained forest land and shrubs	1.1	45.8
Secondary dry land forest/ logged forest	Drained forest land and shrubs	1.1	45.8
Primary mangrove forest	Drained forest land and shrubs	1.1	45.8
Primary swamp forest	Drained forest land and shrubs	1.1	45.8
Plantation forest	Plantations, oil palm	0.6	-
Dry shrub	Drained forest land and shrubs	1.1	45.8
Estate crop	Plantations, oil palm	0.6	-
Settlement areas	Croplands	2.3	54.0
Bare ground	Croplands	2.3	54.0
Savanna and grasses	Croplands	2.3	54.0
Open water/water body	Croplands	2.3	54.0
Secondary mangrove forest/ logged forest	Drained forest land and shrubs	1.1	45.8
Secondary swamp forest/ logged forest	Drained forest land and shrubs	1.1	45.8
Wet shrub	Drained forest land and shrubs	1.1	45.8
Pure dry agriculture	Croplands	2.3	54.0
Mixed dry agriculture	Croplands	2.3	54.0
Paddy field	Paddy rice	0.2	112.5
Fish pond/aquaculture		-	-
Transmigration areas	Croplands	2.3	54.0
Port and harbour	Croplands	2.3	54.0
Mining areas	Croplands	2.3	54.0
Open swamps		-	-

Source: Drösler et al. 2014.

Table 4. Emission factors for on-site CH_4 emissions from peatlands

Land cover	IPCC class	EF (t CH_4 $ha^{-1}y^{-1}$)	Percent of uncertainty (U%)
Primary dry land forest	Drained forest land and shrubs	1.7	90.6
Secondary dry land forest/logged forest	Drained forest land and shrubs	1.7	90.6
Primary mangrove forest	Drained forest land and shrubs	1.7	90.6
Primary swamp forest	Drained forest land and shrubs	1.7	90.6
Plantation forest	Drained forest plantation	1.6	152.2
Dry shrub	Drained forest land and shrubs	1.7	90.6
Estate crop	Oil palm plantation	1.5	73.5
Settlement areas	Croplands	1.8	120.7
Bare ground	Grasslands	1.8	120.7
Savanna and grasses	Grasslands	1.8	120.7
Open water/water body	Paddy rice	6.3	92.3
Secondary mangrove forest/logged forest	Drained forest land and shrubs	1.7	90.6
Secondary swamp forest/logged forest	Drained forest land and shrubs	1.7	90.6
Wet shrub	Drained forest land and shrubs	1.7	90.6
Pure dry agriculture	Croplands	1.8	120.7
Mixed dry agriculture	Croplands	1.8	120.7
Paddy field	Paddy rice	6.3	92.3
Fish pond/aquaculture	Paddy rice	6.3	92.3
Transmigration areas	Croplands	1.8	120.7
Port and harbour		-	-
Mining areas		-	-
Open swamps	Paddy rice	6.3	92.3

Source: Drösler et al. 2014.

Table 5. Emission factors for off-site CO_2 emissions as dissolved organic carbon losses

Land-use category	EF (t CO_2 ha^{-1} y^{-1})	Percent of uncertainty (U%)
Tropical zone	3.0	35.4

Source: Drösler et al. 2014.

2.2.1.3 Emission factor for conversion to aquaculture

We used the EF from the 2013 IPCC Supplement for estimating mangrove soil extraction for aquaculture, which use 1-m depth as the basis for measurement (see Table 6). The conversion of mangrove into aquaculture involves soil excavation, which we assume will lead to emissions from 1-m depth excavated soils.

Table 6. Mean soil organic carbon in mangrove based on various types of soil, derived from Table 4.11 2013 IPCC guidelines (IPCC 2014)

Soil types	Mean SO_{before} (t CO_2 ha^{-1})	95% CI (t CO_2 ha^{-1})
Organic soil	1,727	128;138
Mineral soil	1,049	143;161
Aggregated soil	1,415	128;139

2.2.2 Activity data

A new method for generating AD will be required to include the missing activities, such as net deforestation, peat fires, mangrove conversion, and enhancement of C stock. The previous method for generating AD using the MoEF forest and land-cover maps will be maintained for forest degradation and peat decomposition. A new peatland map is available for peat decomposition, but was not yet published when the report was being prepared. The similar dataset used in FREL–2016 will most likely be used for the next FREL. This analysis used the peat map datasets in FREL–2016, which were produced by Ritung et al. (2011).

2.2.2.1 Mangrove conversion

For mangrove conversion into aquaculture, we used the MoEF annual forests and land-cover maps that FREL–2016 used to generate AD of deforestation and forest degradation. One can extract the aquaculture or fishponds class from the dataset. Figure 1. Mangrove cover transition from 1990 to 2018 depicts the mangrove forest cover over time. About 15% of forested mangrove in 1990 was deforested in 2018. Between 1990-2018, about 210,000 ha, out of 3.6 million ha of mangrove forests, were converted into aquaculture, with an average of 7,350 ha annually (see Figure 2).

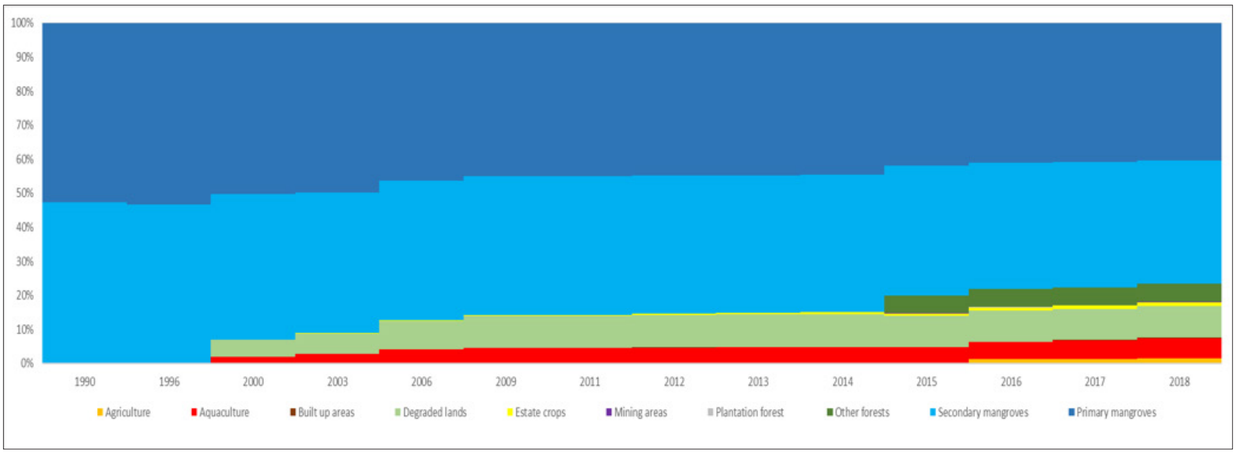

Figure 1. Mangrove cover transition from 1990 to 2018

Note: The colour red depicts the annual extent of aquaculture.

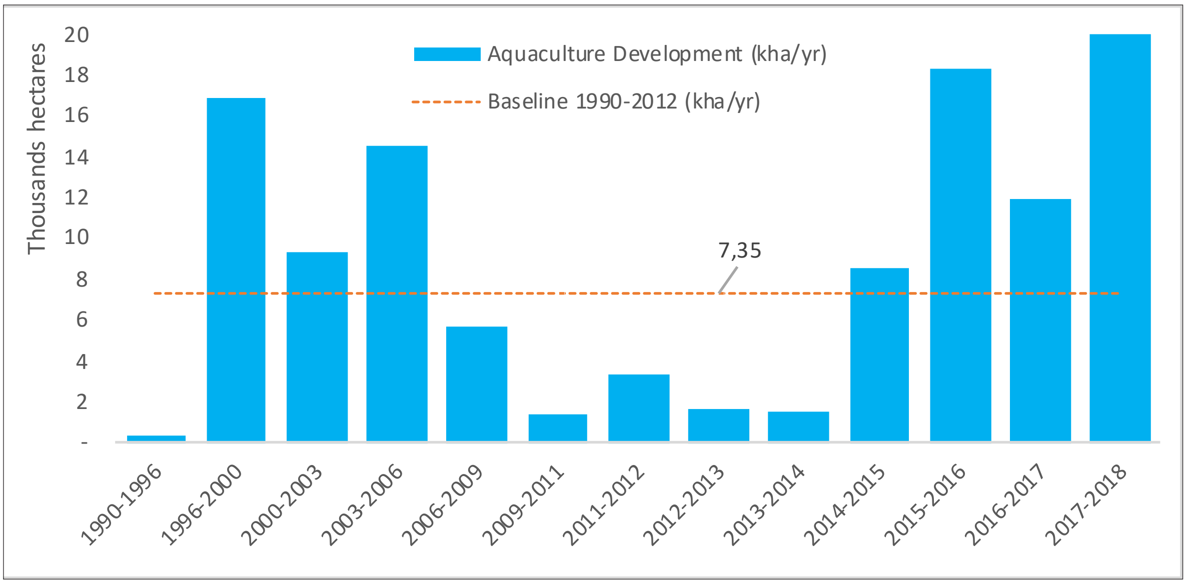

Figure 2. Annual development of aquaculture in Indonesia

The average deforestation in mangrove forests is more than 23,338 ha annually, but only 6,228 ha were converted to aquaculture annually (see Figure 3). For this analysis, we used data on aquaculture development in forested mangrove in 1990, regardless of the forest and land-cover types post-1990. Not all deforestation in mangrove results from aquaculture development (see Figure 3). Also, not all aquaculture was developed directly from mangrove forests. Often, aquaculture develops years after mangrove deforestation.

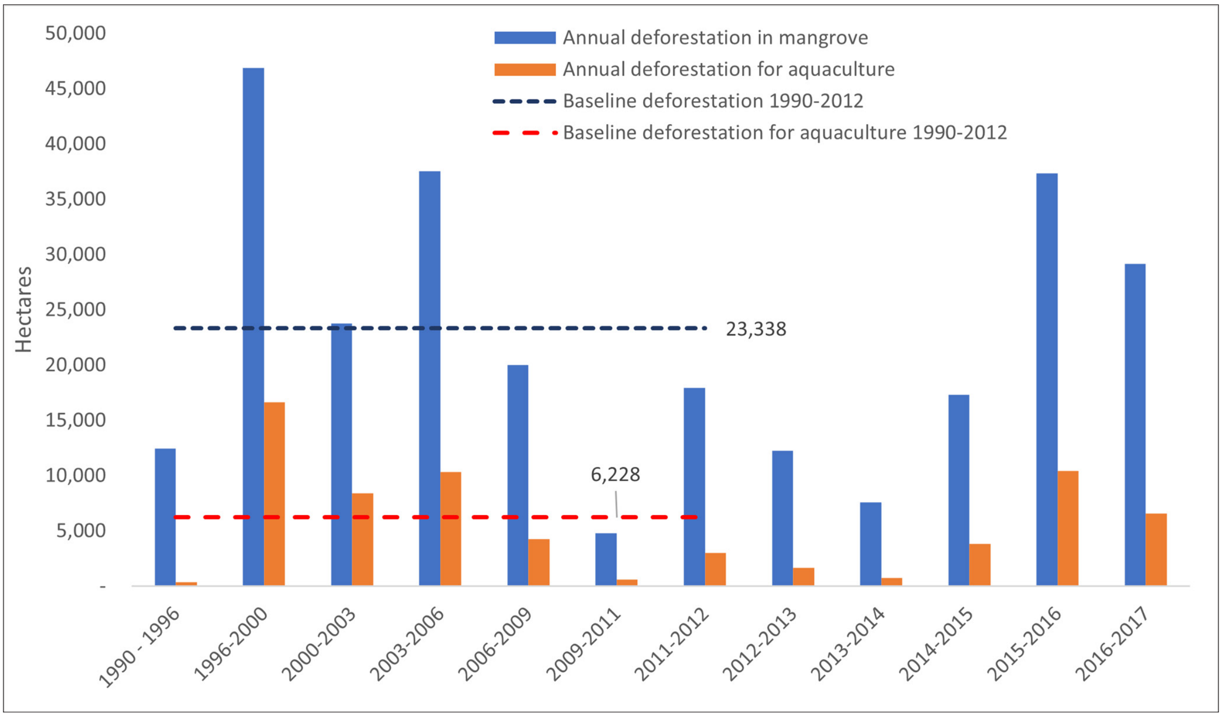

Figure 3. Annual mangrove deforestation (blue bars) and mangrove conversion for aquaculture (orange bars) in thousand hectares

For this analysis, we used the conversion of mangrove forests as AD, with an average of 23.3 ha annually from 1990 to 2012. The largest deforestation of mangrove forests occurred in 1996–2000 (47,000 ha annually). The lowest mangrove deforestation was in 2009–2011.

2.2.2.2 Land cover over peatland

The AD for peat decomposition was generated from the forest and land-cover maps, overlaid with a peat land distribution map. All peatlands forested in 1990 are included in the calculation of peat decomposition emissions. Figure 4 shows the forest and land-cover change trend in peatlands from 1990 to 2012. Once the peat swamp forests are deforested and converted to other land use and land-cover classes, they will release higher emissions than the forest classes. The emissions from non-forest classes will continue to be considered in the next monitoring period, which refers to inherited emissions. Similarly, if forest degradation occurs in primary peat swamp forest and becomes secondary forests, it will also release emissions due to canal development for logging accessibility.

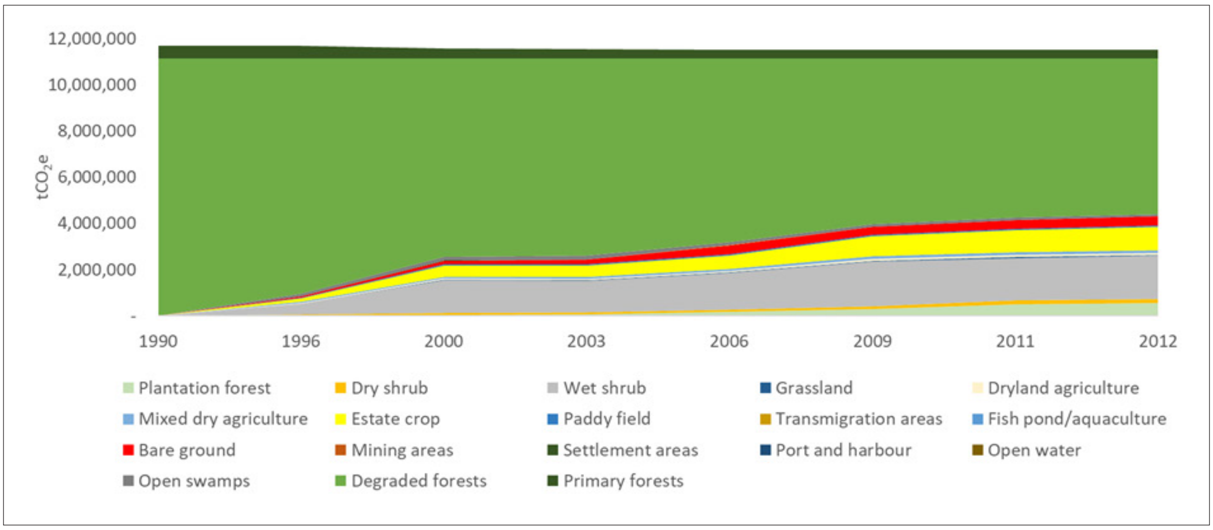

Figure 4. Forest and land-cover change trend in peatlands during baseline period

2.2.2.3 Burn scar data of peatland fires

In this analysis, we used dummy data of burned areas in peatlands derived from MODIS data (University of Maryland 2019) (see Figure 5). This dataset was an improved version of burned areas using a new algorithm that covers more burned areas than the previous version (Giglio et al. 2018). However, these data are only available beginning in 2001, and thus cannot be used to reconstruct FREL–2016 using the baseline period of 1996–2012. A quantitative analysis on error properties of this dataset suggested the MODIS burn area has uncertainty of 57.37% in the Southeast Asia region (Brennan et al. 2019).

Between 2001-2012 peatland fires were 377,000 ha/year (based on MODIS burn scar data). These data differ significantly from the FREL–2016 annex, which identified 29,000 ha of peatland lost to fire annually. However, in terms of an annual trend, the data are similar. For example, both datasets indicated the highest number of burned areas during the baseline period of 2001–2012 occurred in 2016.

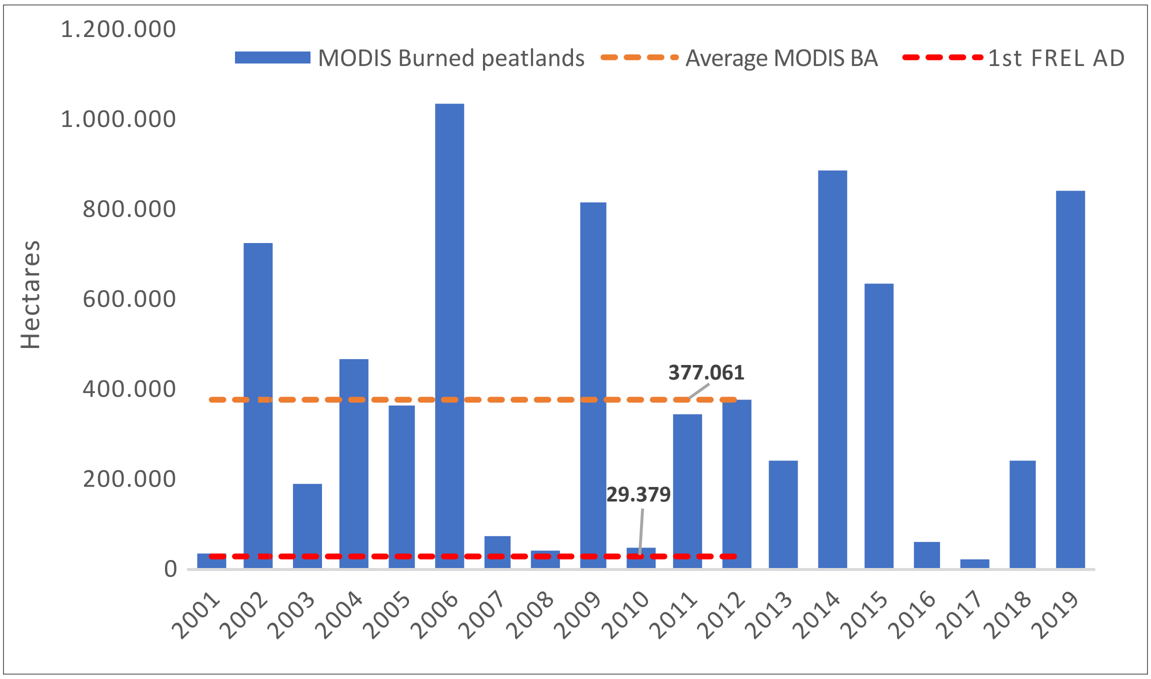

Figure 5. Annual burned area in peatlands (in hectares)

2.3 Estimating annual emissions and emission baselines

For estimating emissions, we used the same approaches as FREL–2016, ensuring consistency and comparability. Emission is generated by multiplying the AD in hectares and the EFs in tCO_2e per hectare. The analysis used the same sources of AD as FREL–2016.

Emission baselines of mangrove conversion and peat fires were based on the average of historical emissions from the baseline period, which is similar to the method used in FREL–2016. Emission baseline of peat decomposition was based on the average of annual emission increase, which differs from the linear regression used in FREL–2016. The baseline period for mangrove conversion and peat decomposition was 1990–2012, while for peat fires it was 2001–2012 due to limited availability of historical data. Summary of data sources and methods used for calculating the emissions, removals, and baselines can be seen in Table 7.

Table 7. Summary of data sources and methods used for calculating the emissions, removals, and baselines

Activities	Activity data	Emission factor	Method
Peat decomposition	Same dataset as FREL–2016 and ER Report, covering forest and landcover changes from 1990 to 2018	CO_2 EF from FREL–2016 and additional EF for non-CO_2 GHG	Same approach as deforestation and forest degradation in estimating mean baseline emissions.
Peat fires	MODIS burned areas from 2001 to 2018, as the modified MODIS hotspot used as proxy data for burn scar in the FREL–2016 annex is imprecise	Peat fires EF from the 2014 IPCC guidelines	Included inherited emissions; used average increase of annual peat decomposition.
Mangrove conversion	Same dataset as FREL–2016 and ER Report, covering forest and landcover changes from 1990 to 2018	IPCC 2014. Table 4.11. Soil carbon stocks for mangroves, tidal marshes, and seagrass meadow for extraction activities	For estimating the emissions, we used the stock difference approach. For generating the baseline, we used historical average.

2.4 Uncertainty analysis

Our uncertainty analysis combined approach 1 and approach 2. Approach 1, based upon PEA, is used to estimate uncertainty in individual categories in the inventory. Approach 2, based on MCS, is suitable for detailed category-by-category assessment of uncertainty. This is especially relevant where uncertainties are large, distribution is non-normal, the algorithms are complex functions, and/or some of AD, EFs, or both, have correlations. Both approaches are suggested in the 2016 IPCC guidelines.

2.4.1 Approach 1: Error propagation

In approach 1, uncertainty in emissions or removals can be propagated from uncertainties in the AD and EF through the PEA. Approach 1 also theoretically requires the standard deviation divided by the mean value to be less than 0.3. In practice, however, the approach will give informative results even if this criterion is not strictly met and some correlations remain.

Improved uncertainties analysis of FREL–2016 using approach 1 requires estimates of the mean and the standard deviation for each AD and EF, as well as the approach used to estimate emissions at subcategory and category levels. Once the uncertainties in the categories were determined, they were combined to provide uncertainty estimates for the entire country in any period. As discussed here, these uncertainty estimates were combined using two convenient rules for combining uncorrelated uncertainties under addition and multiplication.

Approach 1 estimates uncertainties by using the error propagation equation in two steps. First, the IPCC Equation 3.1 approximation was used to combine EF and AD by category. Second, the IPCC Equation 3.2 approximation was used to arrive at the overall uncertainty in national emissions each year.

EQUATION 3.1

COMBINING UNCERTAINTIES – APPROACH 1 - MULTIPLICATION

$$U\ total = \sqrt{U1^2 + U2^2 + \cdots + Un^2}$$

Where:

U_{total} = the percentage uncertainty in the product of the quantities (half the 95% confidence interval divided by the total and expressed as a percentage).

U_1 = the percentage uncertainties associated with each of the quantities.

EQUATION 3.2

COMBINING UNCERTAINTIES – APPROACH 1 – ADDITION AND SUBTRACTION

$$U\ total = \frac{\sqrt{(U1+X1)^2 + (U2+X2)^2 + \cdots + (Un+Xn)^2}}{|X1+X2+...Xn|}$$

Where:

U_{total} = the percentage uncertainty in the sum of the quantities (half the 95% confidence interval divided by the total (i.e., mean) and expressed as a percentage). This term 'uncertainty' is thus based upon the 95% confidence interval.

X_1 and U_1 = the uncertain quantities and the percentage uncertainties associated with them, respectively.

2.4.2 Approach 2: Monte Carlo simulation

According to IPCC (2006), pseudo-random samples of model inputs are generated in MCS according to the probability density functions (PDFs) for each input. The samples are referred to as 'pseudo-random' because they are generated by an algorithm, referred to as a pseudo-random number generator. It can provide a reproducible series of numbers for which any series has properties of randomness. If the model has two or more inputs, then random samples are generated from the PDFs for each input. One random value for each input is entered into the model to arrive at one estimate of the model output. This process is repeated over a desired number of iterations to arrive at multiple estimates of the model output. The multiple estimates are sample values of the PDF of the model output. By analysing PDF samples for the model output, one can infer the mean, standard deviation, 95% confidence interval, and other properties of the output PDF. Because MCS is a numerical method, results typically become more precise with more iterations.

There are several cases where: (i) uncertainties of annual emissions from peat decomposition (mainly due to degradation and secondary forest) at transition level are large and distributions are non-normal; and (ii) distributions of annual emissions from degradation at transition level are non-normal. Consequently, to improve the uncertainties analysis of FREL–2016, numerical statistical techniques, particularly MCS, are preferred to approach 1.

To run MCS, we defined the PDF of AD and EF; selected random values of AD and EF within their individual probability density functions; and estimated emission values using the random values of AD and EF. This procedure was repeated many times, and the results of each calculation built up the overall emission PDF. MCS analysis was performed at the subcategory level (forest type and land-cover transitions), for aggregations of categories (deforestation, degradation, and peat decomposition) or for the FREL as a whole.

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3 Results

3.1 Missing activities, carbon pools, and gases for FREL–2016

3.1.1 List of missing activities

REDD+ activities include avoiding deforestation, forest degradation, sustainable management of forest, enhancement of forest carbon stock and the role of conservation. FREL–2016 includes only avoiding deforestation and forest degradation, including subactivities of peat decomposition that relate to forest and the land-use sector. Below, listed in priority, are REDD+ activities/subactivities that need to be included to follow the completeness principle of GHG emission reporting:

1. peat fires
2. mangrove conversion for aquaculture
3. enhancement of carbon stock
4. sustainable management of forests
5. conservation of forest carbon.

Apart from the above-mentioned key missing activities, mangrove conversion to aquaculture is also relevant, given that Indonesia is one of the largest mangrove countries in the world (Giri et al. 2011). In addition, some partial improvements of previously included activities are relevant, such as other carbon pools, gases, and other land-cover classes (see Table 8. List of carbon pools and gas used in FREL–2016 and potential inclusion for the next FREL).

FREL–2016 excluded enhancement of forest carbon stock due to the unavailability of accurate EFs. During the technical assessment process, the review team suggested the existing database could generate removals from the reverse conversion of forest and land-cover change. This is possible when carbon stock information for each land-cover class is available. Improving carbon stock values for non-natural forest classes will be useful for estimating not only the removals from enhancement of carbon stock but also emissions from deforestation that consider post-conversion land-cover classes.

3.1.2 List of missing carbon pools and gases

FREL–2016 was based on a stepwise approach, which includes both the most significant carbon pools and gases in the emission estimates, and what data are most available. This led to the selection of prioritized carbon pools and gases for FREL–2016. Therefore, inclusion of other significant pools and gases should be a priority area for improvement in the next FREL (see Table 8).

Table 8. List of carbon pools and gas used in FREL–2016 and potential inclusion for the next FREL

	FREL–2016	Potential improvement
Carbon pools	• AGB for deforestation and forest degradation • Soil carbon for peat decomposition	• AGB for enhancement of C stocks • Below-ground biomass (BGB) for deforestation and forest degradation • Soil carbon for mangrove conversion to aquaculture
Gas	• CO_2 for emissions from deforestation, forest degradation, and peat decomposition	• CH_4 and N_2O emissions and DOC from peat decomposition • CO_2, CH_4, and CO emissions from peat fires

3.1.3 Other improvements

During the technical assessment of FREL–2016, the team suggested improving uncertainty analysis of the AD to further differentiate forest and land-cover classes. The team had assessed the uncertainty of FREL–2016 AD only for forest and non-forest classes. During the Forest Carbon Partnership Facility implementation in East Kalimantan Province, MoEF considered the accuracy of forest and land-cover changes rather than the accuracy of forest and land-cover mapping in its uncertainty analysis of AD for deforestation and forest degradation. This method was adapted to the Indonesian context by applying manual classification. This will significantly improve the credibility of the FREL if the uncertainty analysis is carried out for change mapping of all Indonesia for the previous 10–15 years. However, this method may not be implemented for FREL–2016 data.

Table 9. Potential REDD+ activities and potential improvement for the improved FREL

No.	REDD+ activities to be included or improved	IPCC land-use change description	Carbon pools and GHG included in FREL–2016	Types of improvement proposed or mentioned in FREL–2016 proposed or mentioned in the FREL TA report proposed or mentioned in the ER report, 2018 proposed or mentioned in this report based on IPCC 2014	Required data and method	Issues
1	Deforestation	Forest land converted to other land	Pools • AGB • Soil* GHG • CO_2	1.1. Improved AD through hybrid approach, combining visual and automatic classification	• Algorithm for automatic classification	Methodological change of forest and land-cover change requires a huge effort over the long term.
				1.2. Improved AD through automatic classification and direct comparison of time series satellite imageries (change detection)	• Algorithm for change detection	The results are not suitable for assessment of post-conversion removals.
				1.3. Inclusion of post-conversion removals	• C stocks for non-forest classes • AD for net deforestation	
				1.4. Inclusion of additional pools and non-CO_2 gases	• EF that includes additional pools and non CO_2 gases • Existing AD of deforestation	Not all pools and gases are significant. Additional significant pools include BGB and deadwood.
				1.5. Inclusion of data from additional mangrove plots	• Sampling plots in mangrove forests	
				1.6. Faster data input and validation of measured biomass plots	• Data input and processing platform	This requires a robust and integrated system.
				1.7. Use of Tier 2 allometric equations or the improved Tier 1 equation	• Tier 2 allometric equations, which are already available	This requires recalculation of thousands of National Forest Inventory (NFI) plots.

* For on-site emissions from decomposition of drained organic soils.

continued on next page

Table 9. Continued

No.	REDD+ activities to be included or improved	IPCC land-use change description	Carbon pools and GHG included in FREL–2016	Types of improvement proposed or mentioned in FREL–2016 proposed or mentioned in the FREL TA report proposed or mentioned in the ER report, 2018 proposed or mentioned in this report based on IPCC 2014	Required data and method	Issues
				1.8. Estimation of EF based on detailed land-cover and forest stratification in several types of peatland	• EF for each detailed land-cover classes	There are limited studies on EF from peat decomposition.
				1.9. Baseline calculation for peatland emissions	• New approach for developing peat emission baseline	
				1.10. Additional gases and other off-site pools for peatland emissions	• EF for non-CO_2 peatland emissions and other off-site emissions	
				1.11. Justification and evidence for drainage in deforested area and degraded forests	• Justification based on literature review	
				1.12. Inclusion of emissions from soil mangrove extraction	• AD of mangrove conversion • EF on soil extraction	
				1.13. Inclusion of soil emissions from fires in peatlands	• AD of burned areas • EF for burned peatlands	
				1.14. Improvement of AD for burned peatland	• Improved AD	It is difficult to differentiate wild fires with prescribed burning in Indonesia using satellite imageries. Most burned areas delineated by MoEF are predominantly wildfires.
				1.15. Improved EF for burned peatland, especially burned depth	• Use EF from IPCC 2014[+]	
2	Forest degradation	Forest land remaining forest land	• AGB • CO_2 • Soil carbon for peatlands and mangrove	2.1. Inclusion of further forest degradation in secondary forests	• Method for assessing second level of forest degradation • AD of further (second level) forest degradation	Further forest degradation (second level of forest degradation) is hard to detect, especially with current method of visual interpretation.

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Table 9. Continued

No.	REDD+ activities to be included or improved	IPCC land-use change description	Carbon pools and GHG included in FREL–2016	Types of improvement proposed or mentioned in FREL–2016 proposed or mentioned in the FREL TA report proposed or mentioned in the ER report, 2018 proposed or mentioned in this report based on IPCC 2014	Required data and method	Issues
3	Enhancement of carbon stock (within an existing forest/ afforestation and reforestation)	Forest land remaining forest land/ Other land converted to forest land		3.1. Additional activities	• AD of afforestation and reforestation • AD of forest gain • Removal factors for afforestation, reforestation, and forest growth	
4	Sustainable management of forests	Forest land remaining forest land		4.1. Additional activities	• AGB and below-ground biomass, deadwood • AD on SFM, e.g., forest degradation, boundary of implemented SFM • EF on the impact of SFM	FREL–2016 identified some issues, especially related to EF and the boundary of implementation.
5	Conservation of forest carbon stocks	Forest land remaining forest land		5.1. Additional activities	• AGB, BGB, and deadwood • AD • EF on the impact of conservation	This activity has basically been covered in the deforestation and forest degradation.
6	General			6.1. comprehensive uncertainty analysis, which includes all potential and significant errors, as well as using MCS 6.2. consistent approach in calculating mean of annual emissions from deforestation and peat decomposition		

Organic soils refer to peatlands in this context as mangroves in Indonesia grow on mineral soils according to national peatland and land-cover maps (REF MAPS)

Note: above-ground biomass: AGB; AD: Activity data; below-ground biomass: BGB; Emission factor: EF; National forest inventory (NFI); Monte carlo simulation (MCS); Sustainable forest management (SFM)

3.2 Estimates of annual emissions

3.2.1 Emissions from peat decomposition

Emissions from peat decomposition were calculated not only for the CO_2 gas, as in FREL–2016, but also for other non-CO_2 gases (CH_4, N_2O, and DOC loss). Total emissions from peat decomposition in FREL–2016 and this analysis were 3.9 $GtCO_2$ and 5.4 $GtCO_2$, respectively. The emissions from the other gases added up to 38.8% of the previous FREL estimates of CO_2 generated only from peat decomposition (see Table 10).

Table 10. Peatland emissions from improved FREL and the additionality to the FREL–2016 peat emissions

	Average emissions	Total emissions
FREL–2016 (tCO_2)	177,502,645	3,905,058,186
Improved FREL (tCO_2)	246,296,821	5,418,530,065
Additional emissions (tCO_2)	68,794,176	1,513,471,879
Additional emissions (%)	38.8%	

Annual emissions from the 2016 baseline and this analysis show similar trends. The 2016 annual emissions from peat decomposition in 1991 and 2012 were 151.8 $MtCO_2$ and 226.2 $MtCO_2$, respectively. This analysis found that annual emissions from peat decomposition in 1991 and 2012 were 220.3 $MtCO_2$ and 294.7 $MtCO_2$, respectively (see Figure 6).

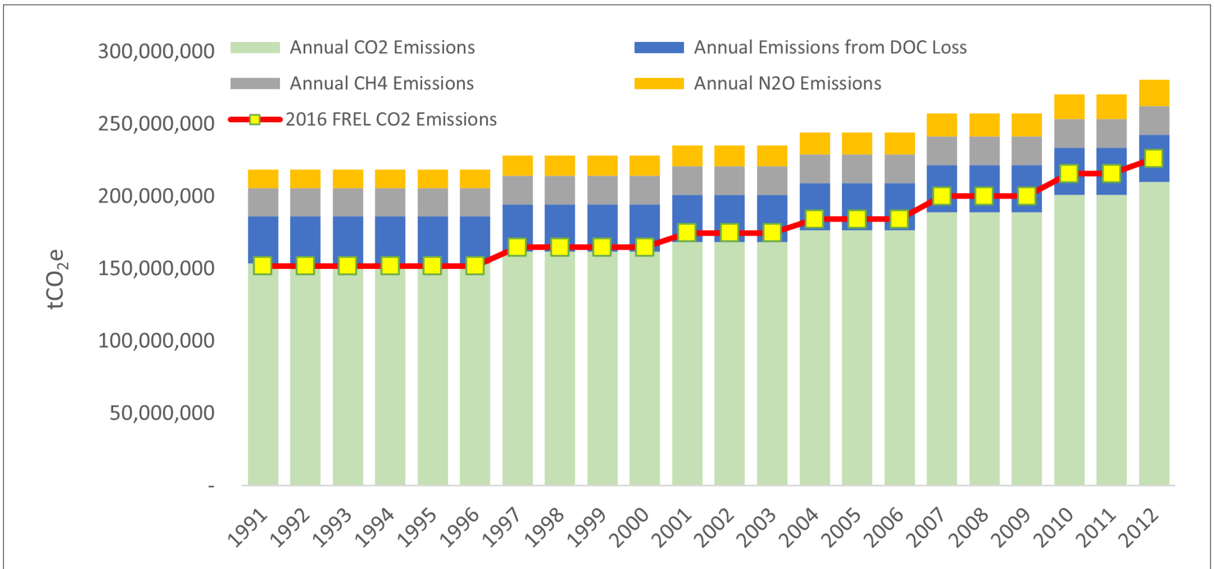

Figure 6. Annual emissions from peatlands

3.2.2 Emissions from peat fires

Due to lack of long-term historical data, baseline emissions from peat fires were estimated from 2001 to 2012 instead of from 1990 to 2012. The average annual emissions from peat fires were 344 million tCO_2, which is 12 times higher than the average from annual peat fires stated in the FREL–2016 annex. The highest emissions occurred in 2006, one of the strong El Nino years. The lowest emissions occurred in 2001, a La Nina year. Similar to 2001, emissions in 2007, 2008, and 2010 were also low due to La Nina. Peat fire emissions from CO_2 gas were the largest, with a 66% contribution. Meanwhile, CH_4 and CO contribute to only 26% and 8% of total peat fire emissions, respectively (see Figure 7).

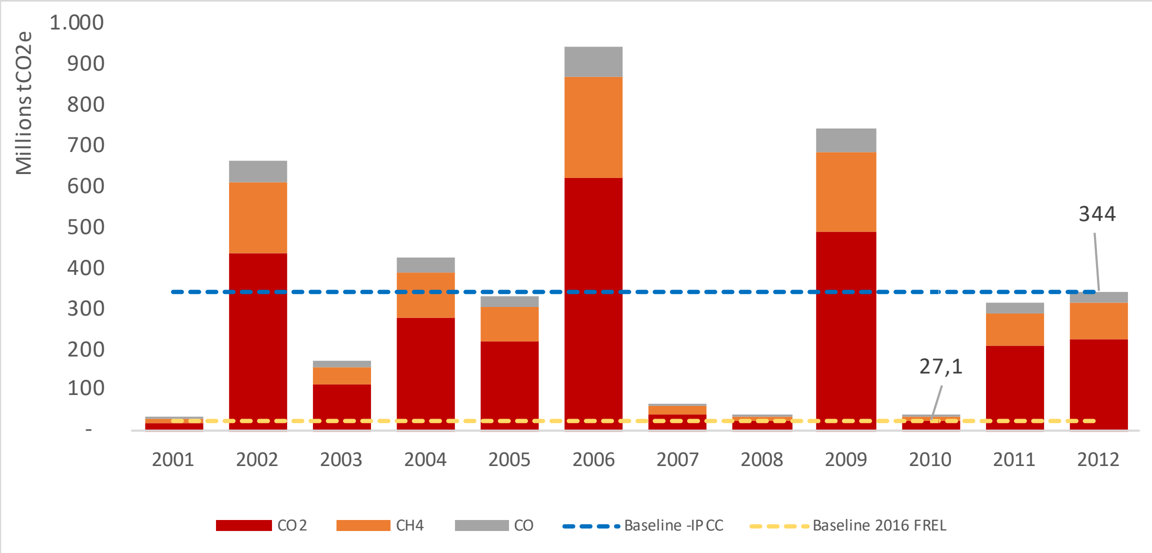

Figure 7. Annual emissions from peat fires

3.2.3 Emissions from mangrove conversions

Annual average emissions from deforestation of mangroves was 34.3 million $tCO_2\ y^{-1}$. The largest annual emissions occurred during 1996–2000, while the lowest occurred in 2009–2011. Development of aquaculture, as well as rampant logging to clear mangroves, were the main drivers of mangrove deforestation in 1997–2000. The annual emissions from mangrove soil due to the conversion can be seen in Figure 8.

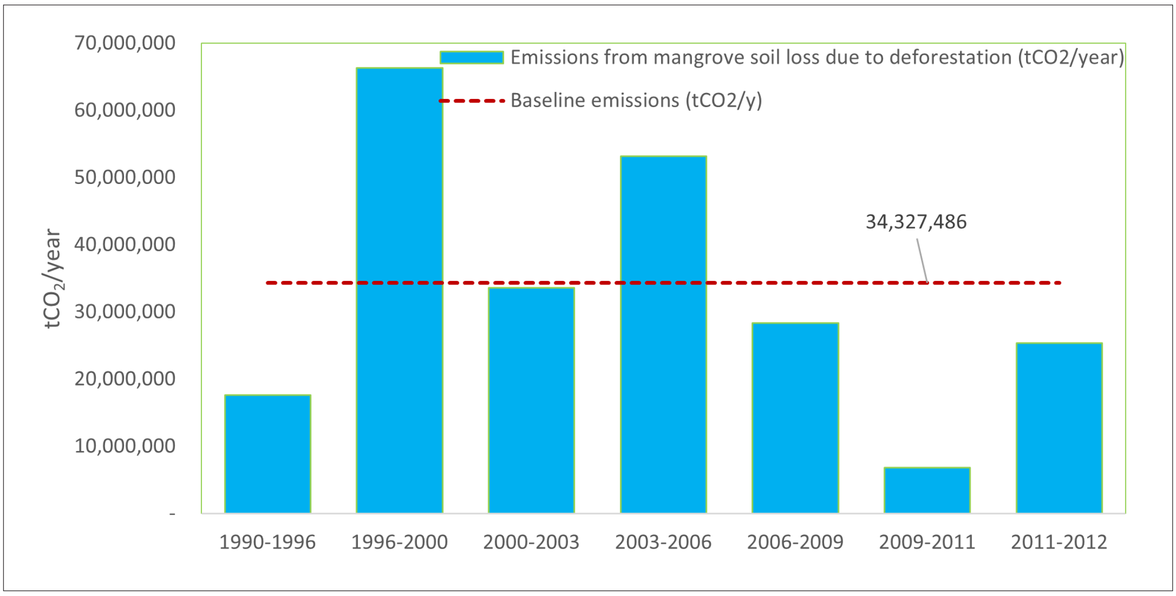

Figure 8. Annual emissions from mangrove soil loss due to conversions

3.3 Emission baselines

Total baseline emissions from deforestation, forest degradation, peat decomposition, peat fires and mangrove conversion in 2013 and 2020 were 1,028 $MtCO_2$ and 1,051 $MtCO_2$, respectively. They are almost twice as high as emissions reported in FREL–2016, which were 569 $MtCO_2$ and 593 $MtCO_2$, respectively, during the same periods (see Figure 9).

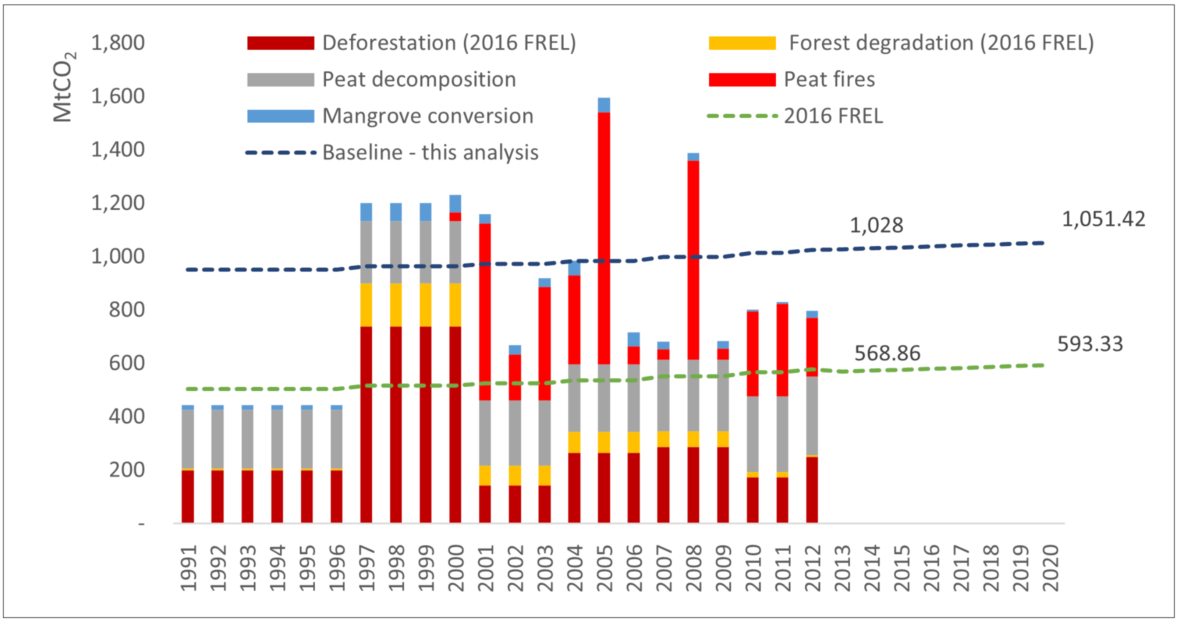

Figure 9. Annual emissions from REDD+ activities and comparison with national FREL

Table 11. Comparison of baseline emissions between this analysis and FREL–2016

	FREL - 2016 ($MtCO_2$)	Improved FREL 2016 ($MtCO_2$)
Deforestation	293	293
Forest degradation	58	58
Peat decomposition	218	298
Peat fires	27	344
Mangrove conversion		34
Total	596	1,028

The largest sources of emissions are peat fires, peat decomposition, and deforestation, which contributed 33%, 29%, and 29%, respectively. Meanwhile, emissions from forest degradation and mangrove conversion accounted for only 6% and 3%, respectively. The largest additional source of emissions was from peat fires (317 $MtCO_2$). Non-CO_2 emissions from peat decomposition and mangrove soil emissions contributed another 80 $MtCO_2$ and 34 $MtCO_2$, respectively (see Table 11).

3.4 Uncertainty analysis

In this analysis, emissions from peat decomposition have lower uncertainty between 29% to 62%, and upper uncertainty from 35% to 73%. On the other hand, the uncertainties of emissions from peat decomposition reported in FREL–2016 have values between 31% and 36%. The uncertainties of emissions from peat decomposition reported in FREL–2016 seem to have been underestimated at least by 1.5 times in the first four periods (1990–1996, 1996–2000, 2000–2003, and 2003–2006). Uncertainties in the last three periods (2006–2009, 2009–2011, and 2011–2012) were only slightly underestimated. However, the lower overall uncertainty was 15.8%, while the upper uncertainty has a value of 19%. The uncertainty analysis of emissions from peat decomposition can bee seen in Table 12.

Table 12. Uncertainty analysis of emissions from peat decomposition

Year	Gas	Emissions (tCO_2e)	Lower U (%)	Upper U (%)	Total emissions (tCO_2e)	Lower U (%)	Upper U (%)
1990	CO_2 emissions	155,092,164	88	102	220,310,086	62	73
	CH_4 emissions	19,267,715	62	71			
	N_2O emissions	12,480,714	34	41			
	DOC emissions	33,469,493	29	35			
1996	CO_2 emissions	168,114,882	74	89	233,708,021	54	65
	CH_4 emissions	19,707,666	54	64			
	N_2O emissions	12,419,576	32	39			
	DOC emissions	33,465,898	27	33			
2000	CO_2 emissions	178,172,542	56	68	243,882,089	41	50
	CH_4 emissions	19,835,872	46	55			
	N_2O emissions	12,411,373	29	35			
	DOC emissions	33,462,303	25	30			
2003	CO_2 emissions	187,483,511	54	67	253,203,269	41	50
	CH_4 emissions	19,736,481	46	55			
	N_2O emissions	12,520,331	28	35			
	DOC emissions	33,462,946	25	30			
2006	CO_2 emissions	203,386,046	47	58	268,975,209	36	44
	CH_4 emissions	19,635,013	44	52			
	N_2O emissions	12,488,584	27	33			
	DOC emissions	33,465,566	24	29			
2009	CO_2 emissions	219,070,680	42	51	284,466,570	32	39
	CH_4 emissions	19,594,411	41	49			
	N_2O emissions	12,333,936	26	32			
	DOC emissions	33,467,543	24	28			
2011	CO_2 emissions	229,426,400	38	46	294,722,620	30	36
	CH_4 emissions	19,549,973	40	48			
	N_2O emissions	12,277,729	26	31			
	DOC emissions	33,468,518	23	27			
2012	CO_2 emissions	116,029,676	37	45	148,666,445	29	35
	CH_4 emissions	9,772,879	40	48			
	N_2O emissions	6,129,144	26	31			
	DOC emissions	16,734,746	24	27			

Table 13. Uncertainty analysis of emissions from peat fires

Year	Gas	Emissions (tCO_2e)	Lower U (%)	Upper U (%)	Total emissions (tCO_2e)	Lower U (%)	Upper U (%)
2001	CO_2 emissions	21,466,123	53	63	870,721,742	30	35
	CH_4 emissions	8,506,805	51	61			
	CO emissions	2,644,973	53	63			
2002	CO_2 emissions	437,343,856	53	62			
	CH_4 emissions	173,314,888	51	60			
	CO emissions	53,887,822	53	62			
2003	CO_2 emissions	114,219,547	52	63			
	CH_4 emissions	45,264,036	51	61			
	CO emissions	14,073,692	53	62			
2004	CO_2 emissions	279,922,348	53	63	1,705,094,188	24	28
	CH_4 emissions	110,930,358	51	60			
	CO emissions	34,490,952	53	62			
2005	CO_2 emissions	220,162,907	53	62			
	CH_4 emissions	87,248,304	52	60			
	CO emissions	27,127,624	53	62			
2006	CO_2 emissions	622,052,010	53	62			
	CH_4 emissions	246,512,836	51	60			
	CO emissions	76,646,848	53	62			
2007	CO_2 emissions	44,520,230	53	63	850,892,194	33	39
	CH_4 emissions	17,642,911	51	60			
	CO emissions	5,485,611	53	62			
2008	CO_2 emissions	25,197,566	53	62			
	CH_4 emissions	9,985,537	51	61			
	CO emissions	3,104,747	53	62			
2009	CO_2 emissions	490,261,733	53	63			
	CH_4 emissions	194,285,700	51	60			
	CO emissions	60,408,159	53	62			
2010	CO_2 emissions	26,614,864	53	62	357,272,629	33	39
	CH_4 emissions	10,547,198	51	61			
	CO emissions	3,279,381	53	63			
2011	CO_2 emissions	208,509,351	53	62			
	CH_4 emissions	82,630,119	51	60			
	CO emissions	25,691,718	53	62			
2012	CO_2 emissions	227,148,738	53	62	345,153,846	38	44
	CH_4 emissions	90,016,717	51	60			
	CO emissions	27,988,391	53	63			

Table 14. Uncertainty analysis of emissions from mangrove conversion

Period	Annual emissions (tCO_2e)	Lower U (%)	Upper U (%)
1990–1996	17,589,069	29	33
1996–2000	66,330,649	24	28
2000–2003	33,606,304	28	32
2003–2006	53,164,664	28	33
2006–2009	28,348,341	28	32
2009–2011	6,807,219	27	31
2011–2012	25,376,558	26	30

Table 15. Summary of uncertainty analysis for each activity

Activity	Emissions (tCO_2e)	Lower U (%)	Upper U (%)
Peat decomposition	1,799,267,865	15.8	19.0
Peat fires	4,129,134,597	14.2	16.7
Mangrove conversion	231,222,804	11.5	13.2
Total	**6,159,625,267**	**10.6**	**12.5**

The lower uncertainty of estimated emissions from peat fires ranged from 24% to 38% in 2004–2006 and 2012, respectively. The upper uncertainty of the estimated peat fire emissions varied between 28% to 44%. The overall lower and upper uncertainties of estimated emissions for the whole baseline period were 14.2% and 16.7%, respectively. Estimated emissions from peat fires have lower uncertainty of 14.2% and upper uncertainty of 16.7% (see Table 13). Emissions from mangrove conversion have the lowest uncertainty among all activities, with a lower uncertainty value of 11.5% and upper uncertainty of 13.2% (see Table 14). Combined uncertainty for all emission estimates from all periods was 10.6% and 12.5% for lower and upper uncertainties, respectively. The overall uncertainty of total emissions from the FREL–2016 was 16.5%, higher than this analysis (see Table 15).

4 Discussion

Emissions from wetlands, i.e., emissions from peat fires, peat decomposition, and mangrove conversion, were revisited and added to improve FREL–2016 (which only addressed emissions from deforestation and forest degradation). The total revised baseline was twice as large as the FREL–2016 baseline. This analysis of emissions and baselines made use of existing EFs from IPCC guidelines for organic soil-related disturbances, which can be integrated into the FREL. Non-CO_2 gases were also included in the estimate of emissions, particularly for peat fires and peat decomposition. Emissions from peat fires significantly increase the total baseline.

Peat fires

The CO_2 EF used for estimating emissions from peat fires in FREL–2016 was higher than the IPCC EF used in this analysis. The estimated emissions of peat fires in this study became the largest source, outnumbering emissions from deforestation. The burn area data for this analysis were 13 times larger than the burn area data used for estimating emissions in the FREL–2016 annex. This is due to the different method of generating burn area.

The uncertainty of the MODIS burn area for Southeast Asia was 57.37%, which is quite large compared with uncertainty of the same dataset in other regions. Large uncertainties of burn area data from remote sensing products often result from spatial resolution and representation of training data. The MODIS burn area product was generated using medium resolution imageries (250 m) based on a global training dataset. The burn area used in the FREL–2016 annex was based on coarser resolution of the MODIS hotspot, i.e., 1 km and based on a model developed from relationship of hotspots and burn scar (MRI 2013). Unfortunately, no uncertainty property has been reported for this dataset.

MoEF (2021) found that the burned area in this analysis was higher than from its own maps. However, the two analyses share a similar trend in annual dynamics. The burned area produced by MoEF was generated based on visual interpretation of Landsat imageries. The comparison of burned areas is available in Figure 10.

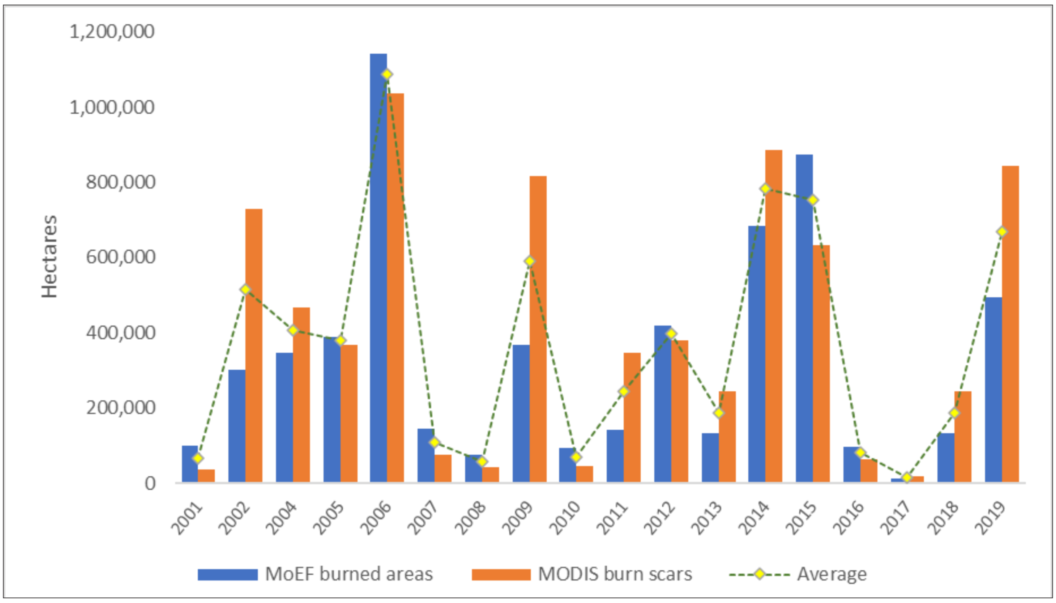

Figure 10. Comparison of burned areas produced by MODIS burned area product and MoEF

Additional non-CO_2 gases were also included in the estimated emissions from peat fires, which contribute to 26% and 8% for N_2O and CO, respectively. The inclusion of CO in the emission baseline estimate may not be necessary or overestimated; CO is not one of the GHGs. However, among other GHGs, CO contributes the fewest emissions.

Peat decomposition

Other additional non-CO_2 gas emissions in this analysis are from peat decomposition, which help increase the average emission baseline value to 38% of total emissions from peat decomposition. The uncertainties of emissions from peat decomposition reported in FREL–2016 seem to be underestimated by at least 1.5 times in some years within the baseline periods. However, the lower overall uncertainty of estimated emissions from peat decomposition was 15.8%, while the upper uncertainty has a value of 19%. Combined uncertainty for all emission estimates from all periods was 10.6% and 12.5% for lower and upper uncertainties, respectively. The overall uncertainty of total emissions from FREL–2016 was 16.5%, higher than this analysis.

5 Conclusions

A list of missing activities and subactivities of REDD+, carbon pools, and gas has been identified for improvement of the first FREL. The list was developed based on previous reports and documents from MoEF and UNFCCC. Proposed subactivities of REDD+ in this analysis include peat fires and mangrove conversion. Emissions from peat fires were the largest source of emissions after deforestation and peat decomposition.

Additional carbon pools and gases included in this analysis follow the 2013 IPCC Wetlands Supplement. Non-CO_2 gases, i.e., CH_4, N_2O, and CO, were included in this analysis for estimating emissions from peat decomposition and peat fires. In addition, DOC loss was included to estimate emissions from peat decomposition; this increased emissions to 30% higher than the first FREL estimates. Meanwhile, emission estimates from peat fires increased the baseline to 58% higher than the 2016 baseline.

Uncertainty analysis has been performed using a combination of PEA and MCS. This resulted in a higher uncertainty level of estimated peat decomposition emissions than in FREL–2016. However, according to 2016 IPCC guidelines, MCS is preferred over PEA for uncertainty analysis.


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DOI: 10.17528/cifor-icraf/009106

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Indonesia submitted its first Forest Reference Emission Level (FREL) to the United Nations Framework Convention on Climate Change in 2015, revising it in 2016 (FREL–2016). FREL–2016 was used to assess the impact of mitigation actions post-2012 implemented through REDD+ (Reducing emissions from deforestation, forest degradation, enhancement of forest carbon stock, sustainable management of forests, and conservation of forest carbon). While the UNFCCC considered FREL–2016 a laudable effort, its reviewers recommended technical improvements, such as including peatland fires and emissions of non-CO_2 gases.

This study identifies activities, pools, and gases absent from FREL–2016, and offers recommendations for its technical assessment. To that end, it combines Propagation of Error and Monte Carlo Simulation to assess the uncertainty of estimated emissions. The results reaffirm the importance of considering previously unaccounted activities, and additional carbon pools and gases. They also underscore the need for uncertainty analysis to enhance the accuracy and reliability of emissions estimates within the context of REDD+ and FREL–2016.