WWF Deutschland

# Impacts of rewetting and reforestation on greenhouse gas emissions and removals in Sebangau National Park, Central Kalimantan, Indonesia, 2015-2018.

Prepared by

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## EXECUTIVE SUMMARY

The Krombacher Climate Protection Project (German: Krombacher Klimaschutzprojekt; managed by WWF) in Sebangau National Park (Central Kalimantan, Indonesia) aims to reduce greenhouse gas (GHG) emissions and enhance carbon sequestration through rewetting of drained peatland, avoidance of peatland fires and restoration of peat swamp forest. Sebangau National Park has a long history of both legal and illegal logging with associated drainage and fires, which have resulted in large losses of biomass and peat carbon stocks.

The current study estimates avoided GHG emissions and GHG removals for the period 2015-2018 by determining

- land cover change and associated carbon stock changes in Sebangau between 2015 and 2018,
- and the extent of burned area in Sebangau and, as a reference, Tanjung Puting National Parks for the years 2015-2018 in order to estimate avoided carbon losses by fire.

Land cover categories were classified using Landsat-8 and Sentinel-2 satellite imagery. Above-ground biomass (AGB) values were assigned to these classes using data from LiDAR transects inside Sebangau National Park. The FORCLIME AGB database from Southeast Asia was used as an independent comparison value. Carbon stock changes (and associated $CO_2$ fluxes) were calculated from the land cover changes, using a root-to-shoot ratio of 37% to estimate below-ground biomass (BGB) and a biomass carbon content of 50%.

Burned areas were mapped using Sentinel-1 radar data. Emissions from peat fires were calculated taking into account fire frequency (determined by hotspots data since 2010), and using a dry peat bulk density of 0.1 g $cm^{-3}$ together with a peat carbon content of 58%. Emissions from the fires during the strong El Niño year 2015 were excluded from emission assessment because the low temporal frequency of such strong El Niño events is incompatible with the short length of the analyzed time series.

During the study period, deforestation and forest degradation were most prevalent in the northernmost section of the park, where the park status is contested by local authorities. Some areas in the northernmost section, which had burned in 2015, were in 2018 found to have been converted to agriculture. From 2015 to 2018, most of Sebangau area showed no change in land cover. Some areas showed both low vegetation regeneration after fire (27,231 ha) and forest regeneration (27,893 ha), whereas smaller areas showed conversion (non-forest areas to agriculture and channels, 700 ha) and forest degradation (499 ha). The assumption that canal blocking has avoided degradation and facilitated regeneration is supported by the observation that from 2016 to 2018, deforestation, conversion and forest degradation mainly took place outside the project areas.

In 2015, fires associated with the strongest El Niño event of the last half century affected Sebangau National Park, but much less than Tanjung Puting National Park. An estimated 31,733 ha (6% of the total park area) burned in Sebangau against 114,467 ha (>30%) in Tanjung Puting. From 2016-2018, fire occurrence was much less in both parks, corresponding to wetter meteorological conditions. Despite this, fires were more abundant in Tanjung Puting than in Sebangau also during these years, where very few newly burned areas were detected in 2018. In Sebangau, fires occurred mainly along rivers, in non-forested areas, and along the northeastern and southeastern park borders.

Net GHG emission reductions and removals for the WWF-Krombacher project areas (288,677 ha) over the period 2016-2018, i.e. excluding the extreme fire year 2015, are estimated at 11.6 t $CO_2$-e $ha^{-1}yr^{-1}$ using Tanjung Puting National Park as a baseline. The study concluded that the historical Tanjung Puting baseline is the best available comparative scenario to express what might have happened within Sebangau National Park without the WWF-Krombacher project activities and WWF engagement since 2007. The magnitude of these emission reductions was supported by calculations that included 2015, but used the longer period 2000-2018 as a baseline.

If, instead of Tanjung Putting, the 2000-2012 situation in Sebangau National Park is used as a baseline, emission reductions amount to 4.4 t $CO_2$-e $ha^{-1}yr^{-1}$. This would be the second best scenario for the assessment of carbon emission reductions and removals. However, this baseline also includes effects of project activities and WWF work since 2007 in Sebangau National Park, making it less appropriate for a comparison. The calculations do not include the effects of peatland rewetting on microbial decomposition of drained peat, which could account on average for another 0.8 t $CO_2$-e $ha^{-1}yr^{-1}$ but were omitted in order to remain conservative.

## ABBREVIATIONS

| | |
|---|---|
| a.s.l. | – above sea level |
| AGB | – above-ground biomass |
| BGB | – below-ground biomass |
| C | – Carbon |
| CHIRPS | – Climate Hazards Group InfraRed Precipitation with Station data |
| $CO_2$-e | – Carbon Dioxide Equivalent |
| ESA | – European Space Agency |
| FORCLIME | – Forests and Climate Change Programme |
| GHG | – Green House Gas |
| ha | – hectare |
| IPCC | – Intergovernmental Panel on Climate Change |
| LiDAR | – Light Detection and Ranging |
| m | – meter |
| MODIS | – Moderate Resolution Imaging Spectroradiometer |
| NP | – National Park |
| SAR | – Synthetic Aperture Radar |
| t | – ton |
| TRMM | – Tropical Rainfall Measuring Mission |
| WWF | – World Wide Fund for Nature |

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# 1. INTRODUCTION

The WWF-Krombacher project (Figure 1) in Sebangau National Park (Central Kalimantan, Indonesia) aims at reducing greenhouse gas emissions and stimulating carbon sequestration by rewetting of drained peatland and afforestation. The BIOCARBON project is funded jointly by Krombacher and Deutsche Post and comprises the watersheds Rasau, Bakung and Bangah. In 2015, WWF Germany commissioned a scoping study (Ballhorn and Navratil, 2015) to calculate the effect of its project activities. The current study aims to assess the carbon project effects for the period 2015-2018, with special attention to changes in biomass carbon stocks and carbon losses by peat fires.

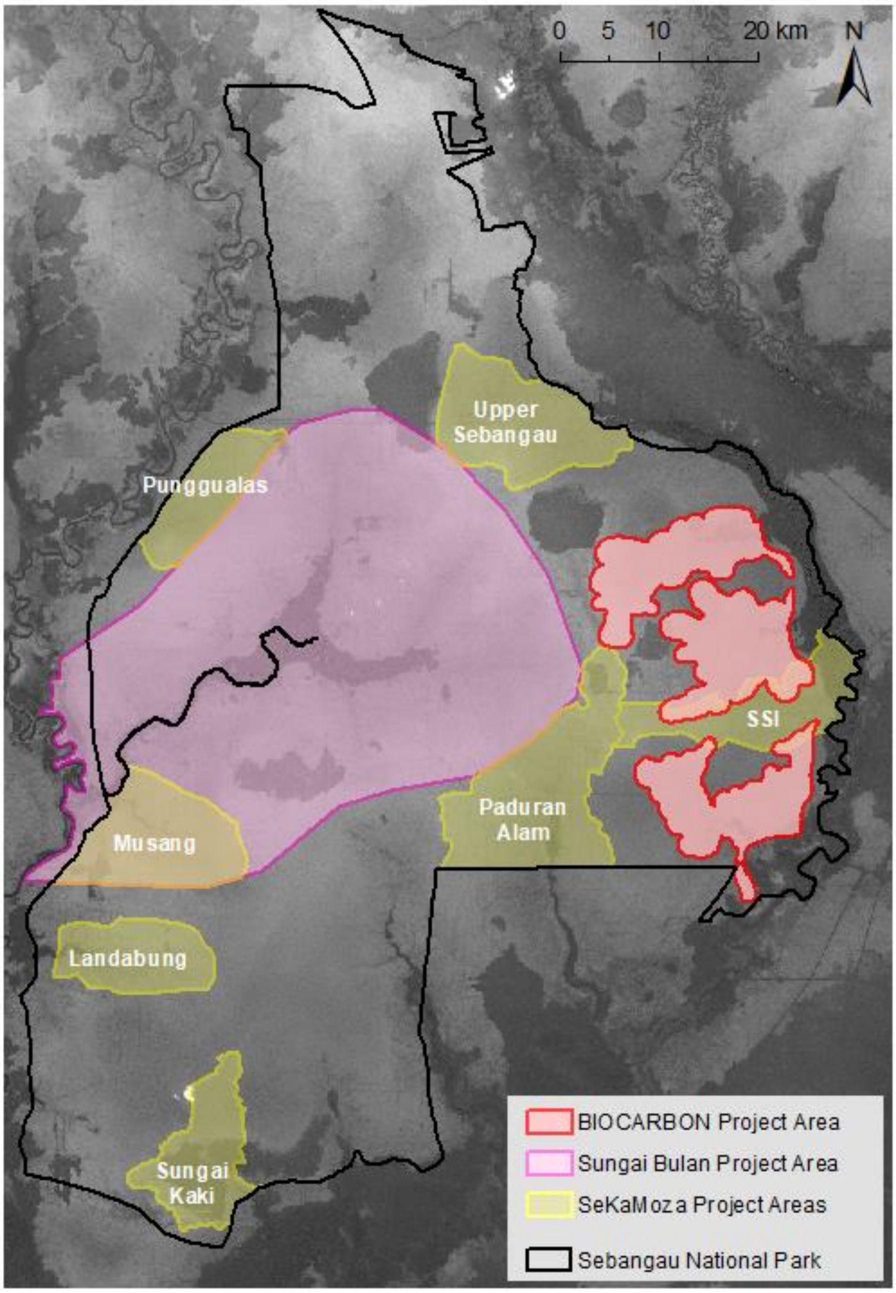


*Figure 1: Location of the WWF-Krombacher project areas Sungai Bulan (151,165 ha), SeKaMoza (97,273 ha), and BIOCARBON (40,239 ha) within the Sebangau National Park (2012 border, SK. 529 Menhut-II/2012) in Central Kalimantan, Indonesia.*

Fire activity within WWF-Krombacher project areas has historically been quite high due to accessibility through canals together with combined high drainage and degradation rates during the commercial logging period from 1970-1995 and the following illegal logging period that continued until 2004. Figure 2 shows that between 2000 and 2012, 44,607 ha of peatland burned in Sebangau National Park and 46,398 ha of peatland in Tanjung Puting.

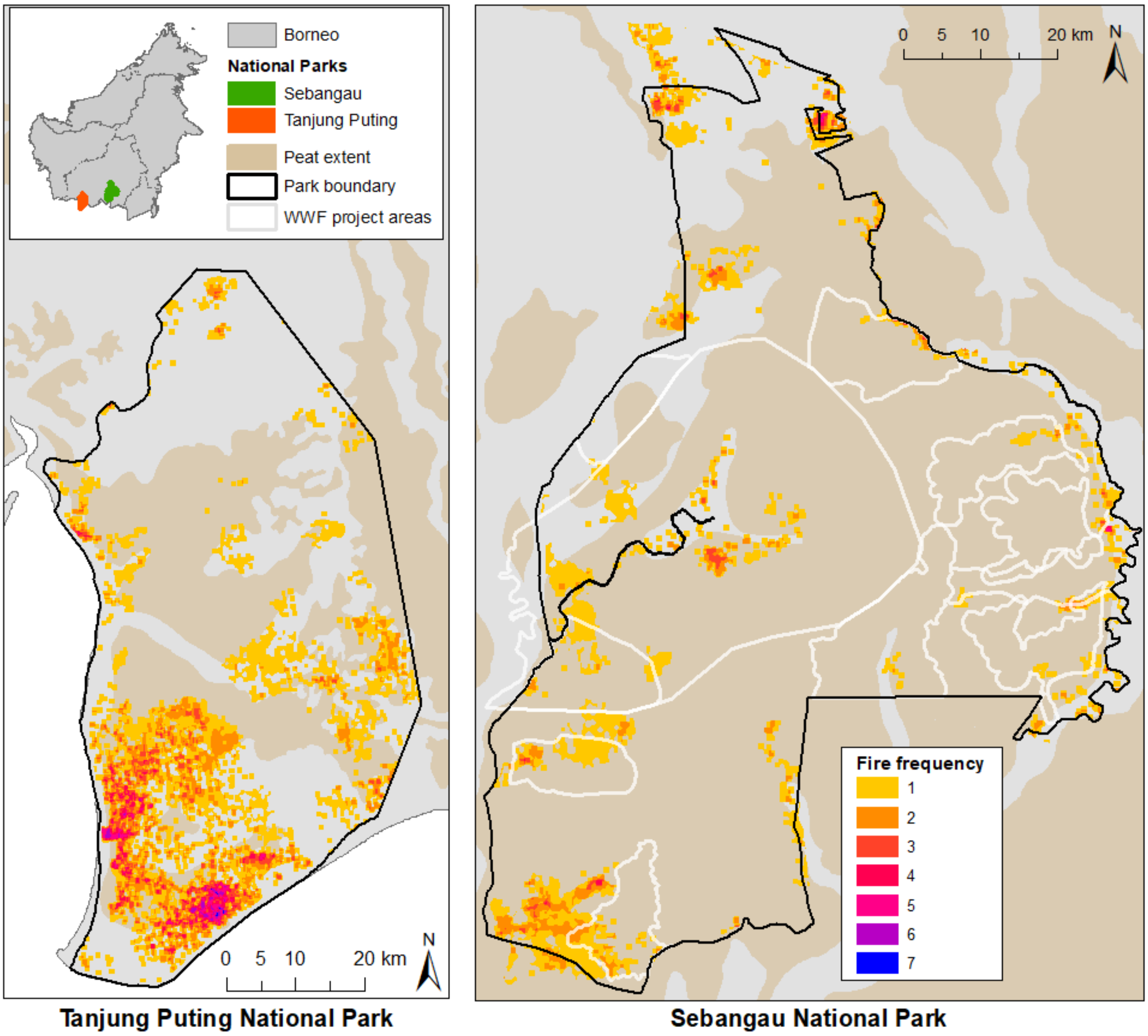


*Figure 2: Fire history based on hotspot data (AVHRR, MODIS and VIIRS data from 2000-2012) for the Tanjung Puting and Sebangau National Parks, represented as fire frequency (after Ballhorn and Navratil, 2015). Also shown (in white) are the outlines of the WWF project areas and peatland extent over each park in brown (based on Wahynto et al., 2004). Fire activity within the WWF-Krombacher project areas has historically always been quite high.*

# 2. METHODS

## *2.1. Biomass*

To assess changes in above-ground biomass, land cover was classified and mapped for the years 2015 and 2018, using Landsat-8 (30 m spatial resolution) and Sentinel-2 (10 m spatial resolution) multispectral satellite imagery. Next to having a high spatial resolution, Sentinel-2 also covers the mid-infrared wavelengths, making it particularly suitable for vegetation characterization and the detection of forest degradation. Image pre-processing included geometric correction, where necessary, and atmospheric correction. The analysis was conducted for the entire Sebangau National Park in order to detect potential leakage due to land use activity shifting.

**Multispectral sensor platform background**

The Sentinel-2 mission is a constellation of two identical satellites, with Sentinel-2A launched in June 2015 and Sentinel-2B in March 2017. Both platforms are mounted with a single Multispectral Instrument (MSI) sensor that detects in the optical, near- and shortwave-infrared spectrum. Imagery is provided in the spatial resolutions 10, 20 and 60 m, dependent on the spectral band. The Sebangau study area lies in the overlap of two orbit paths, so that revisit time is reduced (down to 2-3 days) compared to the usual 5 days. Two Sentinel-2 images had to be used to cover the entire area.

The Landsat-8 satellite was launched February 2013 and provides data with a spatial resolution of 30 m. Two sensors are mounted onboard: the Operational Land Imager (OLI) sensor, detecting in the optical to shortwave-infrared spectrum, and the Thermal Infrared (TIR) sensor. The entire Sebangau study area is covered by a single image with a 16-day repeat cycle.

The land cover map for 2015 was made using a Landsat-8 scene with very low cloud cover on 19 August 2015, i.e. during the dry season. Sentinel-2 imagery could not be used because only three images with less than 100% cloud coverage were available for 2015, all from November and December. If combined, these three images would only provide useful coverage for 30.6% of the Sebangau study area. The next suitable Sentinel-2 image, still with 50% cloud cover, was only available for April 2016, i.e. six months after the 2015 fires when much of the optical signal from burned areas was already obscured by vegetation regrowth.

The land cover map for 2018 was made using two Sentinel-2 images from 4 and 6 May 2018, at the end of the rainy season. Sentinel-2 images from August 2018 were also considered but these had at least double the cloud cover. No Landsat-8 scenes with acceptable cloud cover over Sebangau were available until at least mid-October 2018. The minimum mapping unit for both land cover maps was set to 0.81 ha (equivalent to nine Landsat pixels) to ensure comparability between 2015 and 2018.

Land cover was classified using the software eCognition (v9.2, Trimble Germany GmbH), which explicitly distinguishes different canopy cover densities. The algorithm first generates “objects”, also termed “segments”, and then classifies them. A bottom up multi-resolution segmentation was applied to create meaningful objects with respect to size and delineation of land cover classes (Sentinel-2 images: segmentation scale 30, shape 0.7, compactness 0.8; Landsat-8 image: segmentation scale 30, shape 0.1, compactness 0.1). The classification scheme has a hierarchical structure with four levels of detail (Table 1). On the first level, Vegetation and Non-Vegetation are distinguished. In the second level, Vegetation is subdivided into Peat Swamp Forest (PSF) and Non-Forest, Non-Vegetation into Burned Area, Water and Sparse Vegetation. This last class represents burn scars not yet converted to bush/shrub. Within the third level, the classification scheme distinguishes three Non-Forest classes (Agriculture, Shrub and Wetland). The Peat Swamp Forest (PSF) class is differentiated into Low Pole and Other Peat Swamp Forest. These peat swamp forest types could not be differentiated on the basis of Sentinel-2 imagery, thus a Landsat scene was used to discriminate between these types. The fourth level finally discriminates two forest degradation stages within each Peat Swamp Forest subclass: Slightly Degraded (crown cover 70-90%) and Highly Degraded (crown cover 25-70%).

*Table 1: Land cover classes used for the object-based land cover classification.*

| Classification level 1 | Classification level 2 | Classification level 3 | Classification level 4 |
|---|---|---|---|
| Vegetation | Peat Swamp Forest (PSF) | Low Pole PSF | Low Pole PSF - Slightly Degraded (crown cover 70-90%) |
| | | | Low Pole PSF - Highly Degraded (crown cover 25-70%) |
| | | Other PSF (such as medium/tall pole) | Other PSF - Slightly Degraded (crown cover 70-90%) |
| | | | Other PSF - Highly Degraded (crown cover 25-70%) |
| | Non-Forest | Shrub | |
| | | Wetland | |
| | | Agriculture | |
| Non-Vegetation | Burned Area | | |
| | Sparse Vegetation | | |
| | Water | | |

The types of land cover change between 2015 and 2018 are defined in Table 2. The change class “forest regeneration” is defined as highly degraded forest class areas that remained highly degraded forest and did not change to an even more degraded land cover class such as shrub, sparse vegetation or agriculture. All other land cover classes that did not change from 2015 to 2018 are grouped into the “no change” class.

*Table 2: Types of land cover changes in Sebangau National Park from 2015-2018*

| Name of change | Land cover class in 2015 | Land cover class in 2018 |
|---|---|---|
| Deforestation | Highly Degraded Forest | Non-Forest |
| Conversion | Non-Forest | Agriculture or roads/large canal clearings |
| Forest degradation | Slightly Degraded Forest | Highly Degraded Forest |
| No change | Class remained the same (except highly degraded forest) | |
| No data (cloud cover) | | |
| Reforestation (very rare) | Shrub | Highly Degraded Forest |
| Regeneration | Burned Area | Shrub or Sparse Vegetation |
| Forest regeneration | Highly Degraded Forest | Highly Degraded Forest |

The Landsat-8 scene from 19 August 2015 was taken before the peak of the 2015 fire season. To capture the many large areas burned within the park after August 2015, we used a burned area map developed in Atwood et al. (2016), which is based on Landsat scenes from 19 August, 23 November, 1 and 9 December 2015. Areas in the final land cover class map that burned later than 19 August 2015, identified using the Atwood et al. burned area map, were reclassified as "Additional Burned Area".

## *2.2. Burned area*

The extent of burned area was assessed for the years 2015, 2016, 2017 and 2018 for both Sebangau and Tanjung Puting National Parks using a SAR-based methodology. Both parks are located on the southern coast of Borneo and contain peat swamp forest ecosystems. Tanjung Puting was used as a proxy area because both areas:

- have a similar protection status (national park),
- are situated close to one another,
- have a similar location (near to the coast) providing analogous ecological conditions,
- largely consist of coastal peatlands, which are hydrologically and ecologically different from inland peatlands,
- have similar socioeconomic conditions both within and surrounding the parks, leading to comparable environmental pressures:
    - both national parks are located within the same province (Central Kalimantan) which entails a similar political framework,
    - proximity (about 10 km) to the next biggest city (Palangka Raya for Sebangau National Park and Pangkalan Bun for Tanjung Puting National Park) and population size of those cities (in the order of 200,000) are very similar for both national parks,
    - both areas have suffered massive forest conversion outside park boundaries (Mega Rice Project near Sebangau National Park and the decade long establishment of palm oil plantations surrounding Tanjung Puting National Park),
    - both national parks have a long history of illegal logging, game hunting and collection of animals plus other non-forest timber products, and
    - access to both national parks is predominantly via rivers
- can be assumed to have a highly comparable fire history and vulnerability (see Figure 2), given these similar hydrological, ecological and socioeconomic conditions.

Burned areas were mapped using Sentinel-1 radar data, which allows for cloud free, full area coverage mapping. For the years 2015 and 2016, Sentinel-1 burned area maps were already available for entire Kalimantan from the ESA Fire CCI project (www.esa-fire-cci.org, method detailed in Lohberger et al., 2018), which were utilized for the current project. It should be noted that the land cover classification from section 2.1 based on optical Landsat-8 and Sentinel-2 data, which also included a burned area class, was only conducted for Sebangau National Park and thus could not be used to compare changes in burned area over both national parks. For the years 2017 and 2018, the same algorithm was applied for both national parks in order to produce a consistent time series. The resulting burned area maps were used to analyze the spatial distribution and extent of burned areas within and outside the project rewetting areas. The results for Sebangau National Park were then compared to those for Tanjung Puting.

**SAR sensor platform background**

Sentinel-1 is a two-platform SAR (Synthetic Aperture Radar) satellite constellation with sensors operating at a center frequency of 5.405 Gigahertz. Sentinel-1A was launched in April 2014, Sentinel-1B in April 2016. Our study used the Interferometric Wide swath, the primary operational mode over land, which acquires data with a 250 km swath at 5 m by 20 m spatial resolution. We used Ground Range Detected Level-1 data with mid swath incidence angles between 38.85° and 39.26° in the Vertical-Horizontal polarization with a spatial resolution of 10 m. Figure 3 shows Sentinel-1 coverage over the two study areas and Table 3 provides an overview of the images used.

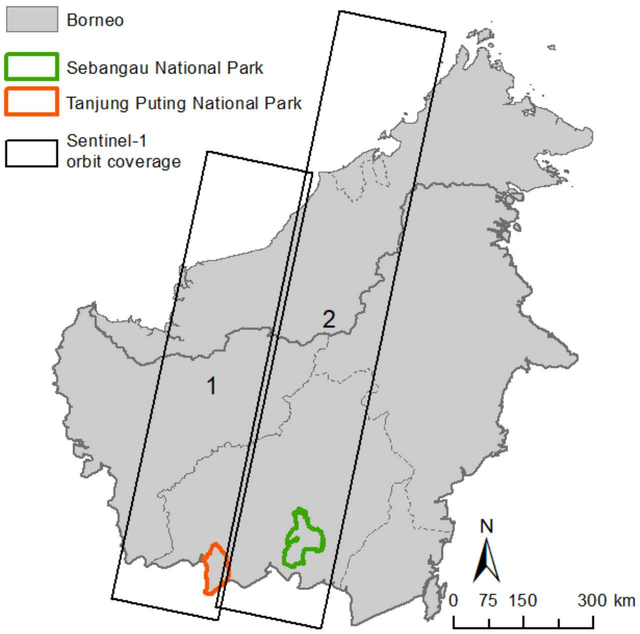


*Figure 3: Overview of Sentinel-1 coverage for both Sebangau and Tanjung Puting National Parks.*

*Table 3: Image acquisition dates of Sentinel-1 data used in the study. Note that the 2015 and 2016 data were processed for entire Kalimantan as part of the ESA Fire CCI project, see text for further details.*

| 2015 acquisitions | 2016 acquisitions | 2017 Sebangau NP acquisitions | 2017 Tanj. Put. NP acquisitions | 2018 Sebangau NP acquisitions | 2018 Tanj. Put. NP acquisitions |
|---:|---:|---:|---:|---:|---:|
| 01.07. | 09.04. | 22.01. | 03.01. | 05.01. | 22.01. |
| 20.07. | 14.04. | 03.02. | 08.02. | 17.01. | 15.02. |
| 05.10. | 14.07. | 04.04. | 16.03. | 29.01. | 27.02. |
| 24.10. | 07.08. | 16.04. | 28.03. | 06.03. | 11.03. |
| | 12.08. | 10.05. | 09.04. | 18.03. | 23.03. |
| | 24.09. | 22.05. | 21.04. | 11.04. | 04.04. |
| | 23.10. | 03.06. | 03.05. | 05.05. | 16.04. |
| | 05.12. | 15.06. | 15.05. | 27.06. | 28.04. |
| | | 21.07. | 27.05. | 04.07. | 03.06. |
| | | 02.08. | 08.06. | 16.07. | 09.07. |
| | | 14.08. | 02.07. | 09.08. | 21.07. |
| | | 26.08. | 09.07. | 02.09. | 02.08. |
| | | 07.09. | 14.07. | 14.09. | 14.08. |
| | | 19.09. | 26.07. | 26.09. | 26.08. |
| | | 13.10. | 31.08. | | 07.09. |
| | | 25.10. | 24.09. | | |
| | | 30.11. | 06.10. | | |
| | | 24.12. | 18.10. | | |
| | | | 11.11. | | |
| | | | 23.11. | | |
| | | | 05.12. | | |

Since SAR backscatter is highly sensitive to water content of the surface, both daily TRMM (Tropical Rainfall Measuring Mission, spatial resolution 0.25°) and CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data, spatial resolution 0.05°) precipitation data were used to select SAR data gathered during dry weather conditions. A digital elevation model from the Shuttle Radar Topography Mission flown in February 2000 (spatial resolution 1 arc-second = approx. 30 m over this region) was used to calculate slopes exceeding 15°, which were excluded from the burned area mapping because of relief displacement effects on the SAR backscatter signal (Lillesand et al., 2015). Error-prone water bodies were excluded using ESRI World Water Bodies, a high spatial resolution vector file for lakes, oceans and large rivers.

For 2015, only Sentinel-1A data were available and thus an image from before the fire season (1 July) was compared with an image from as close as possible to the end of the fire season (24 October). With the availability of Sentinel-1B data starting in 2016, data coverage improved significantly and the methodology was modified to a time series approach. This approach detects burned areas for each time interval between two image acquisitions (Figure 4) and allows for much more comprehensive detection, in particular for the years following 2015, which were considerably wetter.

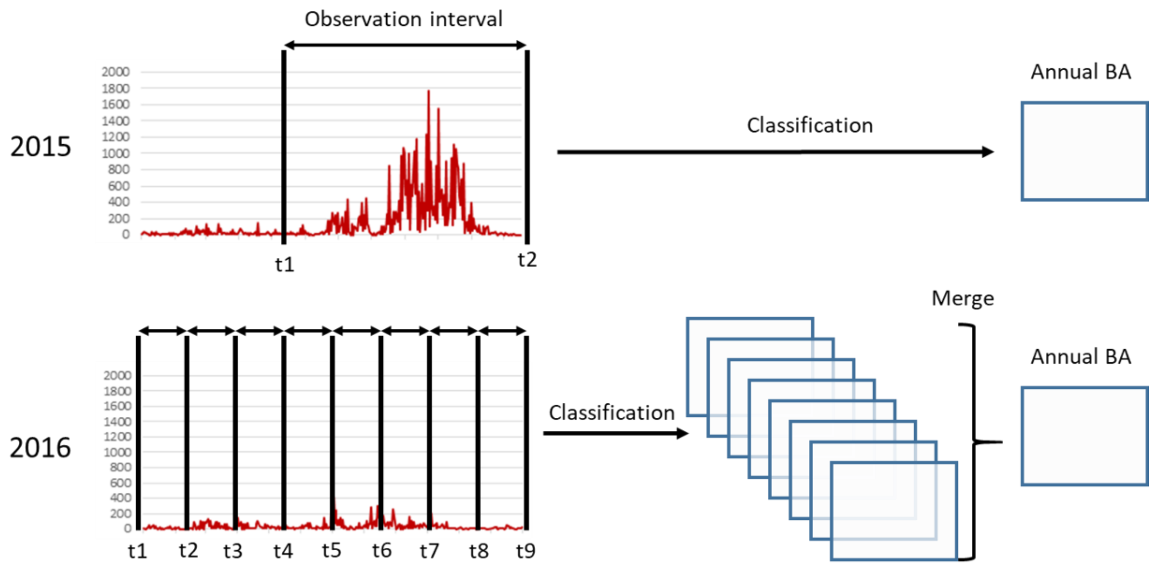


*Figure 4: Improvement in detection methodology from 2015 to 2016 and thereafter. BA = burned area.*

Sentinel-1 single-pole (Vertical-Horizontal polarization) data from 2017 and 2018 (up until September) were processed using the Sentinel-1 Toolbox implemented in the Sentinel Application Platform, provided by ESA. First, all images were checked for quality and influence of precipitation. Images with extensive cloud cover and from times with much precipitation (identified with TRMM and CHIRPS data) were excluded in order to reduce errors. Pre-processing of the imagery included calibration, radiometric and geometric correction as well as speckle filtering following Quegan et al. (2000). Only calibrated images allow sensible comparison between different sensors, acquisition times or locations (Oliver and Quegan, 2004).

Single tiles from the same date were first mosaicked and then multi-temporal SAR images were co-registered per orbit to one image (all years, 2015-2018). SAR imagery was processed using normalized radar cross-section gamma-naught backscatter coefficients.

A bottom up multi-resolution segmentation was applied with eCognition (v9.2) to create meaningful objects with respect to object size and delineation of burned areas (segmentation scale 50, shape 0.9, compactness 0.9). Input for the segmentation were T1 (first time-step) and T2 (second time-step) backscatter layers.

After segmentation, objects were classified based on Vertical-Horizontal (VH) "mean differences" and "custom brightness" using

$$VH\ Difference = (VH_{T1}) - (VH_{T2})$$

$$VH\ Custom\ brightness = \frac{(\overline{VH_{T2}} + \overline{VH_{T1}})}{2}$$

For classification, these features were used in a fuzzy logic procedure, which resulted in each object being assigned a certain probability that it belongs to the class 'Burned Area'. The classification and objects were lastly refined using "find enclosed by", "relations to neighbors", and "pixel-based resizing" procedures.

## 2.3. Carbon stock changes – carbon fluxes

Carbon stock changes (and associated $CO_2$ fluxes) for the period 2015-2018 were calculated on the basis of land cover changes and extent of burned area. Default above-ground biomass (AGB) values for all relevant land cover types were derived from LiDAR studies within Sebangau National Park (

Table 4). Independent comparison AGB values from the FORCLIME program (Navratil, 2012) for the same land cover classes were also considered. The FORCLIME values are based on an extensive databank (>200 literature sources as well as numerous field measurements) generated by RSS - Remote Sensing Solutions GmbH, covering a wide range of land cover types (grass/fern lands to almost intact peat swamp forests) throughout Southeast Asia at varying levels of detail.

For 'forest regeneration' (Highly Degraded Forest remaining Highly Degraded Forest, but without signs of further degradation), an AGB sequestration rate of 5 t $ha^{-1}yr^{-1}$ was assumed (Ballhorn and Navratil, 2015). No growth rate (0 t $ha^{-1}yr^{-1}$) was assumed for the Slightly Degraded Forest classes, in order to keep emission reduction estimates conservative. To estimate below-ground biomass (BGB), a root-to-shoot ratio of 37% was used (IPCC, 2006). An average biomass carbon content of 50% was assumed (Gibbs et al., 2007; Goetz et al., 2009). Land cover changes from the 2015 fires were excluded.

*Table 4: Land cover classes and ascribed AGB values (in tons per hectare), based either on LiDAR or FORCLIME data (Ballhorn and Navratil, 2015). PSF: Peat Swamp Forest.*

| Satellite-based Land Cover Classification | LiDAR Class | AGB LiDAR (t $ha^{-1}$) | FORCLIME Class | AGB FORCLIME (t $ha^{-1}$) |
|---|---|---|---|---|
| Other PSF - Slightly Degraded | Slightly Degraded Peat Swamp Forest | 230.93 | Peat Swamp Forest | 215.32 |
| Other PSF - Highly Degraded | Highly Degraded Peat Swamp Forest | 103.23 | Secondary Peat Swamp Forest | 151.66 |
| Low Pole PSF - Slightly Degraded | Slightly Degraded Low Pole Peat Swamp Forest | 229.96 | Peat Swamp Forest | 215.32 |
| Low Pole PSF - Highly Degraded | Highly Degraded Peat Swamp Forest | 103.23 | Secondary Peat Swamp Forest | 151.66 |
| Shrub | Shrub | 15.93 | Shrubs, Shifting Cultivation, Smallholder Agriculture, Grassland | 47.44 |
| Sparse Vegetation | Shrub | 15.93 | Shrubs, Shifting Cultivation, Smallholder Agriculture, Grassland | 47.44 |
| Wetland | Wetland | 4.78 | Wetland | 14.96 |
| Water | Water | 0.00 | Water | 0.00 |
| Burned Area | Burned Area | 3.46 | Bare Area | 0.00 |

Fire frequency of every burned area since 2000 was determined using the MODIS hotspot approach (see Ballhorn and Navratil, 2015). In order to keep reduction estimates conservative, all areas under investigation in Sebangau National Park (shown in Figure 1) were assumed to be located completely on peat. For Tanjung Puting, only fires on peat were considered. Peat extent in Tanjung Puting was determined using the Wetlands International peatland map (Wahyunto et al., 2004).

Emissions from peat fires were calculated taking into account fire frequency, using a loss of 0.17 m, 0.10 m, 0.06 m, and 0.02 m of peat after the first, second, third, and fourth or more fires, respectively (Konecny et al., 2016). For the peat carbon content, a dry peat bulk density of 0.1 gram per cubic centimeter (g $cm^{-3}$) and a peat carbon content of 58% were used (Neuzil, 1997; Ballhorn et al., 2009). Emissions from the 2015 fires were excluded from the assessment because the frequency of such strong

El Niño events (occurring on the scale of 10-20 years; Huang et al., 2016) is incompatible with the short length of the analyzed time series (3 years).

## *2.4. Emission reductions*

Emission reductions from reduced fire occurrence in Sebangau National Park 2016-2018 were calculated against three different baselines, including

a) the 2000-2012 fire history of Sebangau National Park (Ballhorn and Navratil, 2015), amounting to an annual average emission of 3.7 t $CO_2$-e $ha^{-1}yr^{-1}$,

b) the 2000-2012 fire history of Tanjung Puting National Park (Ballhorn and Navratil, 2015) amounting to an annual average emission of 10.9 t $CO_2$-e $ha^{-1}yr^{-1}$, and

c) the 2015-2018 fire history of Tanjung Puting National Park amounting to an annual average emission of 1.2 t $CO_2$-e $ha^{-1}yr^{-1}$.

# 3. RESULTS

## *3.1. Land cover change 2015-2018*

The land cover map of Sebangau National Park for 2015 (Figure 5) clearly shows the effects of the 2015 fire season through the "Additional Burned Area". Burned areas are concentrated along rivers, in non-forested wetland areas, and along the northeastern and southeastern park borders. Three large burned areas (labelled A, B and C in Figure 5) in the northern half of the park are not located near a river, and occur over formerly slightly and highly degraded forest classes.

Comparison of the 2015 and the 2018 land cover maps (Figure 6) shows that deforestation and forest degradation are highest in the northern section of the park outside the project areas. Some burned areas in this section appeared to have been converted to agricultural areas since 2015. Deforestation and forest degradation in the southern section of the park are also concentrated outside the project areas and are primarily attributable to access ways created by earlier legal logging concessions. In the 2018 map (Figure 5), almost all burn scars from 2015 are still visible, either as Shrub or Sparse Vegetation. Very little new burned area was detected, and neither the MODIS hotspots nor the Sentinel-1 analysis (see below) give reason to believe that substantial fires occurred after May 6, 2018, the latest dates of the applied Sentinel-2 imagery.

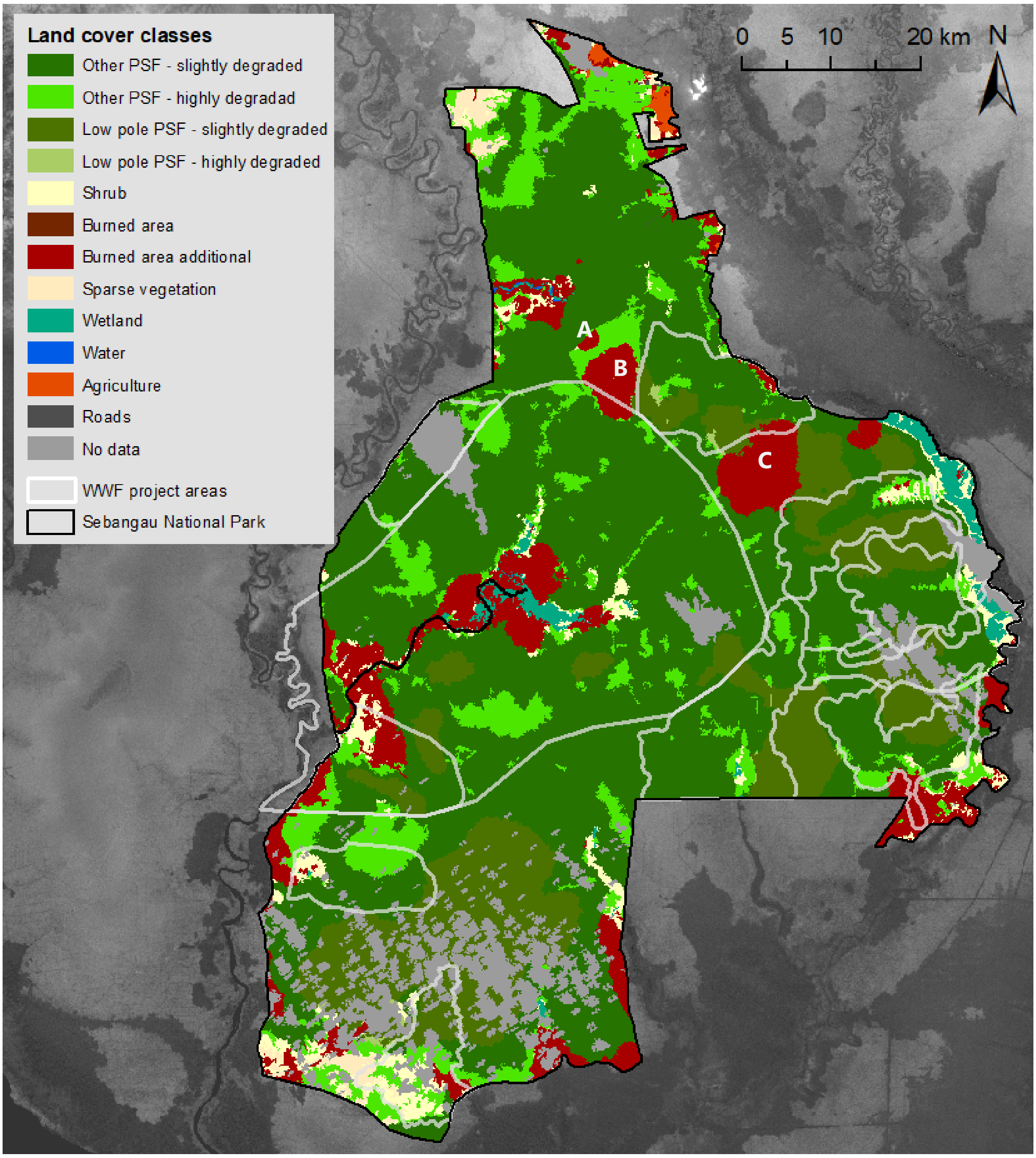


*Figure 5: Land cover map for 2015 of the Sebangau National Park study area, WWF-Krombacher project areas outlined in light gray. No data are due to cloud cover. Areas A, B and C are discussed in the text. For description of land cover classes see Table 1 and paragraph above Table 1.*

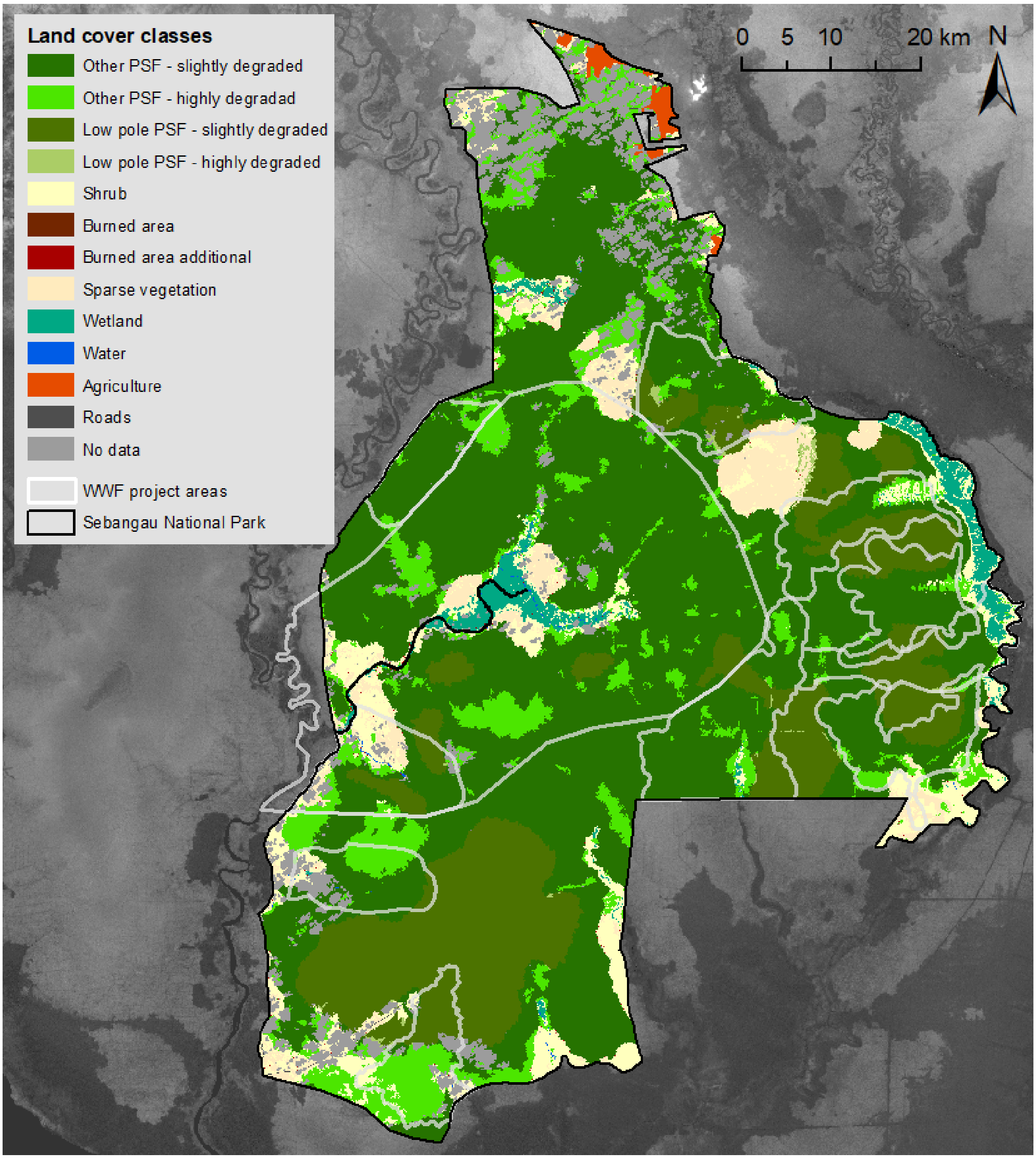


*Figure 6: Land cover map for 2018 of the Sebangau National Park study area, WWF project areas outlined in light gray. No data are due to cloud cover.*

The changes in land cover from 2015 to 2018 are presented in Figure 7 and Table 5.

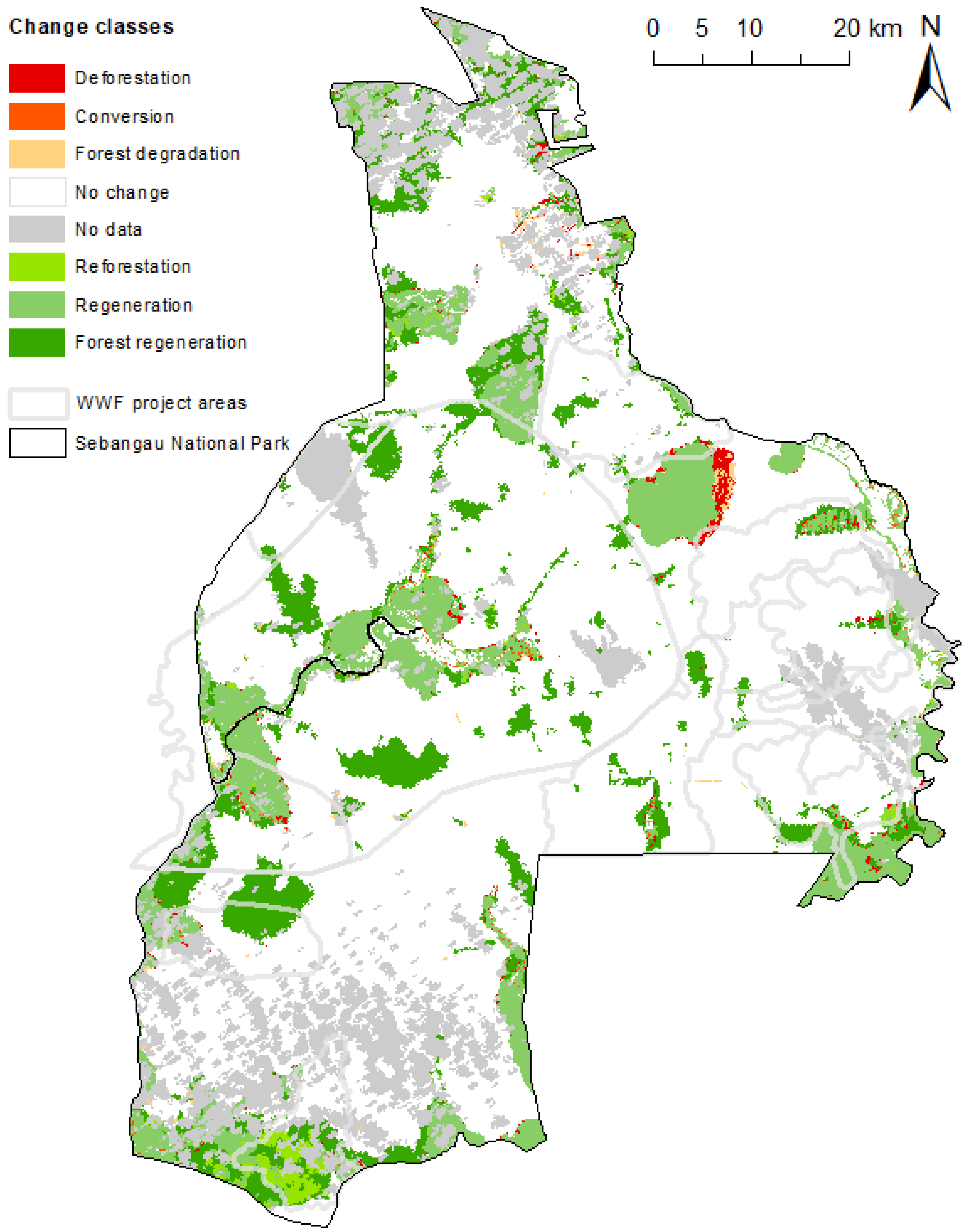


*Figure 7: Change in land cover classes from 2015 to 2018 within the Sebangau National Park study area, WWF-Krombacher project areas outlined in light gray. Class change definitions are provided in Table 2. No data are due to cloud cover.*

*Table 5: Land cover class changes (in ha and %) between 2015-2018 within the WWF-Krombacher project areas (see Figure 1). Change classes are defined in Table 2.*

| **Change class** | **WWF-Krombacher project areas** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Total (285,772 ha)** | | **BIOCARBON (40,239 ha)** | | **Sungai Bulan (151,165ha)** | | **SeKaMoza† (97,273 ha)** | |
| | **ha** | **%** | **ha** | **%** | **ha** | **%** | **ha** | **%** |
| Deforestation | 1,466 | 0.5 | 436 | 1.1 | 609 | 0.4 | 428 | 0.4 |
| Conversion | 700 | 0.2 | 35 | 0.1 | 499 | 0.3 | 165 | 0.2 |
| Forest degradation | 499 | 0.2 | 25 | 0.1 | 300 | 0.2 | 184 | 0.2 |
| No change | 198,834 | 69.6 | 31,997 | 79.5 | 106,102 | 70.2 | 62,902 | 64.7 |
| No data (cloud cover) | 26,137 | 9.1 | 3,380 | 8.4 | 8,936 | 5.9 | 14,464 | 14.9 |
| Reforestation | 3,012 | 1.1 | 216 | 0.5 | 507 | 0.3 | 2,289 | 2.4 |
| Regeneration | 27,231 | 9.5 | 1,804 | 4.5 | 18,848 | 12.5 | 6,579 | 6.8 |
| Forest regeneration | 27,893 | 9.8 | 2,346 | 5.8 | 15,363 | 10.2 | 10,262 | 10.5 |

† This includes the SeKaMoza catchment SSI overlap with the BIOCARBON study area, which was accounted for when making calculations for all project areas.

**Land cover change in Sebangau between 2015 and 2018:**

- Deforestation and forest degradation were most prevalent in the northernmost section of park
- Largest land cover changes in all project areas were 'regeneration' (27,231 ha) and 'forest regeneration' (27,893 ha)
- Smallest land cover changes in all project areas were 'conversion' (700 ha) and 'forest degradation' (499 ha)
- Very little new area burned in 2018, burn scars from 2015 were still visible as shrub and sparse vegetation in 2018

### 3.2. Burned area 2015-2018

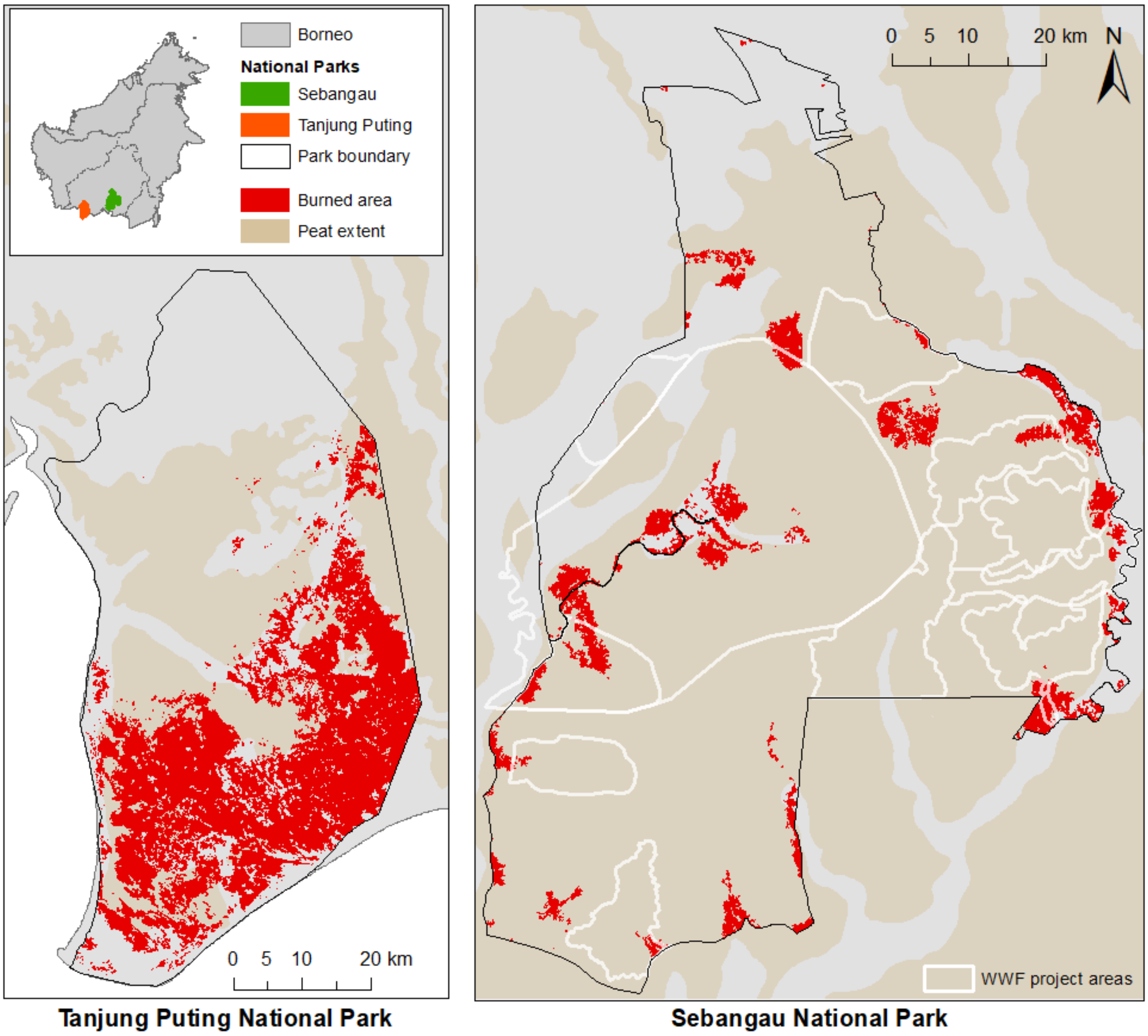


*Figure 8: Burned areas in 2015 within Tanjung Puting and Sebangau National Parks, together with peat extent (Wahynto et al., 2004). Location of both national parks on the island of Borneo is shown in the inset map.*

The effect of fires in the long dry season of 2015 and resulting burned areas can be observed in both national parks (Figure 8). Fire occurred more often per unit area in Tanjung Puting National Park. Within Sebangau National Park, fire occurrence was observed to be higher close to rivers and within non-forested wetland areas. This pattern has been observed before and is attributable to the continued (or even increasing) accessibility to forest areas and the deliberate burning of riverbank overgrowth. Fire occurrence was also higher along the eastern border, positively correlating with vicinity to more heavily populated regions. Two large fire areas in the northern section of Sebangau National Park did not follow either of these patterns.

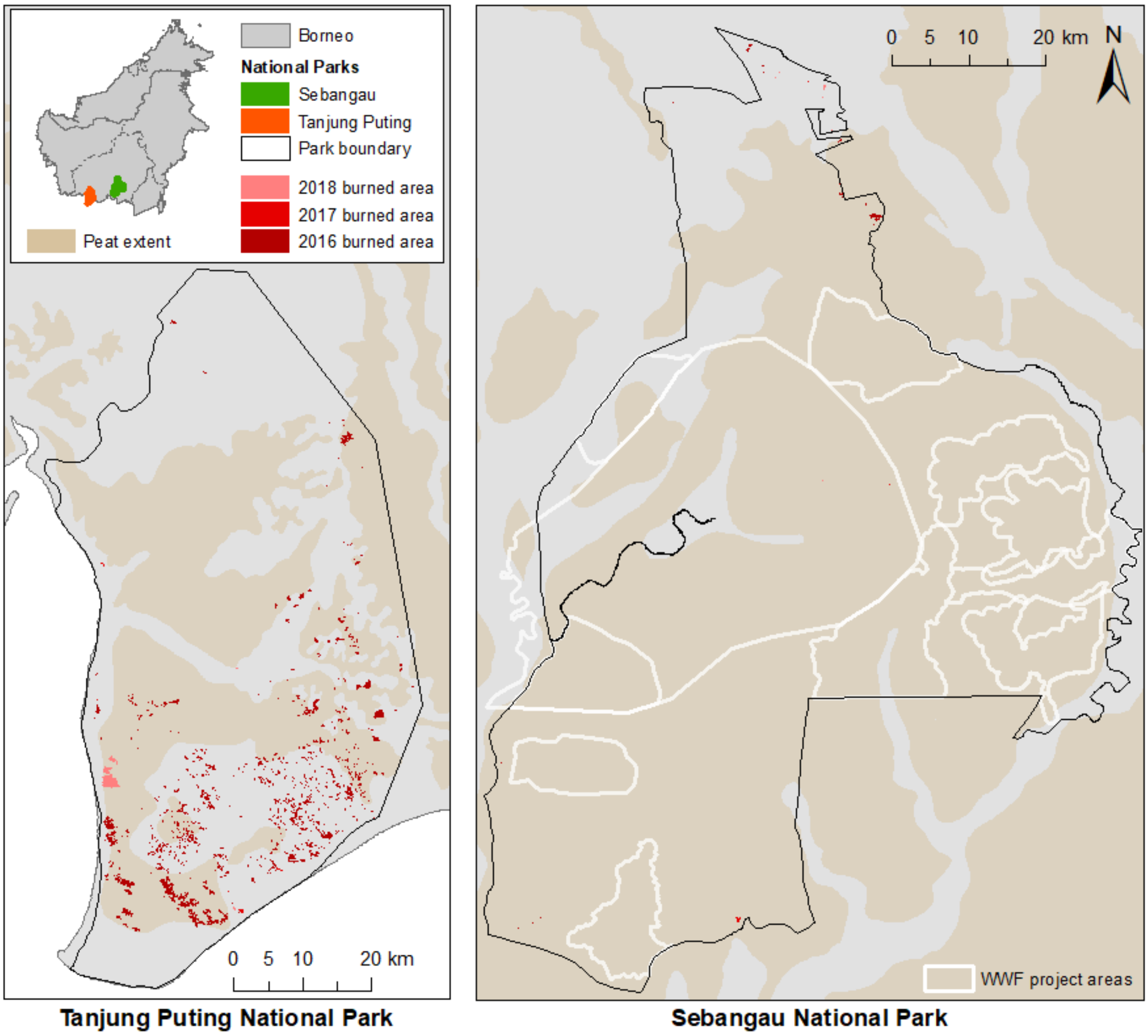


*Figure 9: Burned areas in the period 2016-2018 within Tanjung Puting and Sebangau National Parks. Location of both national parks on the island of Borneo is shown in the inset map.*

Fire occurrence was much less in both national parks for the years 2016 to 2018 (Figure 9), although fires continued to be more abundant in Tanjung Puting National Park (both within and outside of peatland areas). Fires in Sebangau National Park were very rare and occurred predominantly along the northeastern park border. Causes of fires included illegal logging and land clearing for agriculture and encroachment, i.e. pressures, which are presumably very similar between the two national parks (see arguments in section 2.2). Historical fire occurrence in Sebangau National Park has been quite high (Figure 2). WWF has been active in Sebangau since 2007, it is therefore assumed that WWF activities have greatly helped reduce fire occurrence not only within project areas but rather over the entire park (please refer to Figure 9).

The total burned area per park per year is presented in

Table 6. While a significant area (31,733 ha) burned in Sebangau National Park in 2015, the percentage burned area in the park (5.86%) was five times less than in Tanjung Puting (30.81%). A smaller area and lower percentage burned area was also observed in Sebangau compared to Tanjung Puting in the wetter years 2016 and 2018.

*Table 6: Burned area (in ha and %) for the years 2015-2018 for both national parks. Figures for Sebangau National Park refer to the 2012 boundary (SK. 529 Menhut), as depicted in Figure 1.*

| Burned area per park | 2015 | | 2016 | | 2017 | | 2018 | |
|---|---|---|---|---|---|---|---|---|
| | Area (ha) | % | Area (ha) | % | Area (ha) | % | Area (ha) | % |
| Sebangau | 31,733 | 5.86% | 174 | 0.03% | 37 | 0.01% | 40 | 0.01% |
| Tanjung Puting | 114,467 | 30.81% | 7,741 | 2.08% | 73 | 0.02% | 3,157 | 0.85% |

**Fires in Sebangau and Tanjung Puting 2015-2018:**

- Massive fires occurred in Sebangau in 2015, mainly along rivers and in non-forested wetland areas, as well as along the northeastern and southeastern park borders
- The percentage park area that burned in 2015 was much less in Sebangau (5.86%) as compared to Tanjung Puting (30.81%)
- Fire prevalence was very low in both parks in the wetter years 2016-2018
- Over 2016-2018, fires affected proportionally much less area in Sebangau than in Tanjung Puting

## 3.3. GHG emissions and removals

Table 7 and Table 8 display the estimated AGB and BGB gains/losses between 2015 and 2018 for the various WWF-Krombacher project areas (see Figure 1).

*Table 7: Gains (+) and losses (-) of above- (AGB) and below-ground biomass (BGB) carbon (C) and carbon dioxide equivalents ($CO_2$-e) in tons (t) over the period 2015-2018 in all WWF-Krombacher project areas together† (see Figure 1).*

| Land Cover Change | Area (ha) ∑285,772 | AGB Gain/Loss (tC) using AGB assessment with | |
|---|---|---|---|
| | | LiDAR | FORCLIME |
| Forest degradation | 499 | -31,808 | -15,892 |
| Deforestation | 1,466 | -108,176 | -100,463 |
| Conversion | 700 | -2,969 | -7,715 |
| No change | 198,834 | 0 | 0 |
| No data (cloud cover) | 26,137 | 0 | 0 |
| Low vegetation regeneration | 27,231 | +159,897 | +476,431 |
| Reforestation | 3,012 | +131,494 | +156,980 |
| Forest regeneration | 27,893 | +209,196 | +209,196 |
| | **Sum C AGB** | **+357,634** | **+718,537** |
| | **Sum C BGB (=0.37 x Sum C AGB)** | **+132,325** | **+265,859** |
| | **C AGB + C BGB** | **+489,959** | **+984,395** |
| | **$CO_2$-e AGB + $CO_2$-e BGB** | **+1,798,150** | **+3,612,730** |
| | **$CO_2$-e AGB + $CO_2$-e BGB per ha/year** | **+2.1** | **+4.2** |

† The SeKaMoza catchment SSI overlap with the BIOCARBON project area is accounted for only once in these calculations.

*Table 8: Gains (+) and losses (-) of above- (AGB) and below-ground biomass (BGB) carbon (C) and carbon dioxide equivalents ($CO_2$-e) in tons (t) over the period 2015-2018 in all WWF-Krombacher project areas separately† (see Figure 1).*

| **Project area** | BIOCARBON | | | Sungai Bulan* | | | SeKaMoza† | | |
|---|---|---|---|---|---|---|---|---|---|
| **Land Cover Change** | **Area (ha)** | **Gain/Loss AGB (tC)** | | **Area (ha)** | **Gain/Loss AGB (tC)** | | **Area (ha)** | **Gain/Loss AGB (tC)** | |
| | | **LiDAR** | **FORCLIME** | | **LiDAR** | **FORCLIME** | | **LiDAR** | **FORCLIME** |
| Total area | 40,239 | | | 151,165 | | | 97,273 | | |
| Forest degradation | 25 | -1,615 | -811 | 300 | -19,170 | -9,557 | 184 | -11,693 | -5,861 |
| Deforestation | 436 | -33,435 | -30,036 | 609 | -45,981 | -42,613 | 428 | -29,093 | -28,267 |
| Reclamation | 35 | -197 | -575 | 499 | -2,160 | -5,764 | 165 | -612 | -1,376 |
| No change | 31,997 | 0 | 0 | 106,102 | 0 | 0 | 62,902 | 0 | 0 |
| No data | 3,380 | 0 | 0 | 8,936 | 0 | 0 | 14,464 | 0 | 0 |
| Low vegetation regeneration | 1,804 | +12,122 | +30,569 | 18,848 | +104,170 | +337,230 | 6,579 | +43,605 | +108,632 |
| Reforestation | 216 | +9,421 | +11,247 | 507 | +22,151 | +26,444 | 2,289 | +99,923 | +119,289 |
| Forest Regeneration | 2,346 | +17,593 | +17,593 | 15,363 | +115,225 | +115,225 | 10,262 | +76,962 | +76,962 |
| **Sum C AGB** | | **+3,890** | **+27,987** | | **+174,233** | **+420,964** | | **+179,093** | **+269,379** |
| **Sum C BGB** | | **+1,439** | **+10,355** | | **+64,466** | **+155,757** | | **+66,264** | **+99,670** |
| **C AGB + C BGB** | | **+5,329** | **+38,343** | | **+238,699** | **+576,721** | | **+245,357** | **+369,050** |
| **$CO_2$-e AGB + BGB** | | **+19,557** | **+140,717** | | **+876,027** | **+2,116,567** | | **+900,459** | **+1,354,412** |
| **$CO_2$-e AGB + BGB per ha/year** | | **+0.2** | **+1.2** | | **+1.9** | **+4.7** | | **+3.1** | **+4.6** |

† Includes the SeKaMoza catchment SSI overlap with the BIOCARBON study area.
* Excluding the Musang catchment

The notable difference between the LiDAR and FORCLIME estimates of low vegetation AGB gain in Table 7 and Table 8 are attributable to differences between the LiDAR and FORCLIME AGB estimates presented in Table 4. Low vegetation regeneration is one of the largest area change classes detected and thus contributes heavily to this difference. No AGB emissions estimates were made for Tanjung Putting National Park because this was not relevant for calculating the biomass gains and losses in the project area.

Emissions estimates were based solely on calculated peat burning, as these represent the major component in total emissions from peatland fires. The 2015 fires in Tanjung Puting National Park released far more $tCO_2$-e $ha^{-1}$ from peat than the fires in the WWF-Krombacher project areas. Hardly any differences existed between the project areas and the total of Sebangau National Park (

Table 9), which is largely attributable to the Sungai Bulan project area, where emissions per ha were even larger than the average over the entire national park (Table 10).

*Table 9: Emissions from fires over peat for the years 2015-2018 for Sebangau National Park, all WWF-Krombacher project areas, and Tanjung Puting National Park. Note that some very small parts of the project areas extend outside of the park boundary (see Figure 1), which explains the occasionally higher burned area estimates within the project areas as compared to Sebangau National Park.*

| Fire year | | Sebangau National Park | | | WWF-Krombacher project areas† | | | Tanjung Puting National Park | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Burned area (ha) | Emissions | | Burned area (ha) | Emissions | | Burned area (ha) | Emissions | |
| | | | tC | $tCO_2$-e | | tC | $tCO_2$-e | | tC | $tCO_2$-e |
| 2015 | | 31,733 | 2,521,625 | 9,254,363 | 16,044 | 1,219,433 | 4,475,320 | 47,884 | 3,097,784 | 11,368,868 |
| 2016 | | 173 | 8,684 | 31,869 | 178 | 11,473 | 42,107 | 3,680 | 153,118 | 561,942 |
| 2017 | | 37 | 1,710 | 6,276 | 4 | 414 | 1,518 | 0 | 0 | 0 |
| 2018 | | 40 | 2,221 | 8,150 | 111 | 7,784 | 28,568 | 496 | 13,943 | 51,172 |
| Sum (all years) | | | 2,534,239 | 9,300,659 | | 1,239,104 | 4,547,513 | | 3,264,845 | 11,981,982 |
| Sum (without 2015) | | | 12,615 | 46,296 | | 19,671 | 72,194 | | 167,061 | 613,114 |
| per ha and year | all years | | 1.2 | 4.3 | | 1.1 | 4.0 | | 4.7 | 17.4 |
| | without 2015 | | 0.0 | 0.0 | | 0.0 | 0.1 | | 0.3 | 1.2 |

† The SeKaMoza catchment SSI overlap with the BIOCARBON project area is only accounted for once in these calculations

*Table 10: Peat fire emissions for the years 2015, 2016, 2017 and 2018 in all WWF-Krombacher project areas separately.*

| Project areas | BIOCARBON | | | Sungai Bulan | | | SeKaMoza† | | |
|---|---|---|---|---|---|---|---|---|---|
| Fire year | Burned area (ha) | Emissions | | Burned area (ha) | Emissions | | Burned area (ha) | Emissions | |
| | | tC | $tCO_2$-e | | tC | tCO2-e | | tC | tCO2-e |
| 2015 | 1,422 | 106,651 | 391,407 | 10,648 | 833,638 | 3,059,451 | 3,974 | 279,145 | 1,024,461 |
| 2016 | 0 | 0 | 0 | 178 | 11,473 | 42,107 | 0 | 0 | 0 |
| 2017 | 0 | 0 | 0 | 4 | 414 | 1,518 | 0 | 0 | 0 |
| 2018 | 0 | 0 | 0 | 111 | 7,784 | 28,568 | 0 | 0 | 0 |
| Sum (all years) | | 106,651 | 391,407 | | 853,309 | 3,131,645 | | 279,145 | 1,024,461 |
| Sum (without 2015) | | 0 | 0 | | 19,671 | 72,194 | | 0 | 0 |
| per ha and year (all years) | | 0.7 | 2.4 | | 1.4 | 5.2 | | 0.7 | 2.7 |
| per ha and year (without 2015) | | 0.0 | 0.0 | | 0.0 | 0.2 | | 0.0 | 0.0 |

† This includes the SeKaMoza catchment SSI overlap with the BIOCARBON study area.

Biomass estimates (LiDAR or FORCLIME, section 2.3) and baseline assumptions (section 2.4) were used to make all emission reduction estimates. The results range for all project areas together from 0.5 to 16.7 $tCO_2$-e $ha^{-1}yr^{-1}$ (Table 11), showing how estimates can differ for the same situation by more than a factor 30. Baseline estimates without 2015 are more realistic because the frequency of strong El Niño events is incompatible with the short length of the analyzed time series, as discussed above. Furthermore, it is expected that the LiDAR-biomass baseline estimates are more realistic given the higher precision of this methodology. Further discussion of which baseline estimate is the most realistic is presented in section 4 below.

*Table 11: Comparison of average annual emission reduction/carbon sequestration (in $tCO_2$-e $ha^{-1}yr^{-1}$) for the various project areas in Sebangau National Park over the period 2015-2018 using different baselines, both with and excluding the year 2015, and using LiDAR or FORCLIME biomass assessment methodologies. The most realistic values are depicted in green (see discussion in section 4).*

| | **2000-2012 baseline** | | | | | | | | **2015-2018 baseline** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **of Sebangau** | | | | **of Tanjung Puting** | | | | **of Tanjung Putting** | | | |
| | **without 2015** | | **with 2015** | | **without 2015** | | **with 2015** | | **without 2015** | | **with 2015** | |
| | LiDAR | FOR. | LiDAR | FOR. | LiDAR | FOR. | LiDAR | FOR. | LiDAR | FOR. | LiDAR | FOR. |
| **All project areas** | 4.4 | 6.8 | 0.5 | 2.9 | 11.6 | 14.0 | 7.7 | 10.1 | 1.9 | 4.3 | 14.3 | 16.7 |
| **Sungai Bulan** | 4.2 | 7.2 | -0.8 | 2.2 | 11.3 | 14.4 | 6.3 | 9.4 | 1.7 | 4.7 | 12.9 | 15.9 |
| **Biocarbon** | 2.6 | 3.9 | 0.1 | 1.4 | 9.7 | 11.0 | 7.3 | 8.6 | 0.1 | 1.4 | 13.9 | 15.2 |
| **SeKaMoza** | 5.5 | 7.3 | 2.8 | 4.7 | 12.7 | 14.5 | 10.0 | 11.9 | 3.0 | 4.9 | 16.6 | 18.4 |

# 4. DISCUSSION

The methods utilized in this study differ somewhat from those used in Ballhorn and Navratil (2015). Land cover classification was partially adapted to the Sentinel-2 sensor, which allowed for higher resolution mapping. Detection of burned area was not based on MODIS+VIIRS hotspots, but rather on a Sentinel-1 SAR based method, which has been shown to be more accurate (Lohberger et al., 2018).

The key objective of this study was to evaluate the effect of the WWF-Krombacher project activities in Sebangau National Park (Central Kalimantan, Indonesia) on greenhouse gas fluxes, especially to test the assumption that canal blocking has avoided further forest degradation and facilitated regeneration by limiting access for illegal logging activity. This is at least partially confirmed by the observation that between 2015 and 2018, the changes in deforestation, conversion and forest degradation mainly took place outside project areas. This result is even more convincing when considering that project sites were selected from areas with formerly high degradation rates due to the construction of canals for legal and illegal timber harvesting (see Figure 2 for fire history prior to WWF-Krombacher project activities). Differences in calculated emission reductions plus carbon sequestration of more than a factor 30 (see Table 11) illustrate the sensitivity of the outcome to baseline assumptions and choice of methodology; this indicates both require serious scrutiny.

LiDAR-based AGB estimates resulted in lower positive results than FORCLIME-based estimates. However, the LiDAR values are considered to be more realistic because they are based on site specific inventory data that were scaled up with the help of LiDAR transects covering all relevant land cover types in Sebangau National Park.

Fire occurrence was very high in 2015. Excluding 2015 from the evaluation period leads to much higher emission reduction estimates. Whereas these losses have been very real, exclusion of 2015 is appropriate because the frequency of such strong El Niño events (occurring on the scale of once every 10-20 years; Huang et al., 2016) is incompatible with the short length of the analyzed time series 2015-2018 (3-4 years).

Net GHG emission reductions and removals for the project areas (288,677 ha) over the period 2016-2018 are estimated at 11.6 t $CO_2$-e $ha^{-1}yr^{-1}$ using historic Tanjung Puting National Park as a proxy area.

The study concluded that the 2000-2012 Tanjung Puting baseline is the best available comparative scenario to what might have happened within the Sebangau National Park without WWF engagement starting in 2007 and following expanded WWF-Krombacher project activities. This conclusion is based on the following arguments: (1) the long temporal extent of the baseline, (2) Tanjung Puting and Sebangau National Parks have similar protection status, location, peatlands types/extent and socioeconomic conditions, (3) WWF-Krombacher project activities and earlier WWF work in Sebangau led to positive effects (e.g. lower fire occurrence) outside of project areas, disqualifying these areas as baseline, and (4) using a proxy area is a well-accepted method for emission reduction estimates. WWF-Krombacher dam installations began large-scale in 2013.

The 2000-2012 baseline of Sebangau National Park was concluded to represent the second-best scenario for carbon emission reduction estimation, which would lead to emission reductions of 4.3 t $CO_2$-e $ha^{-1}yr^{-1}$. This scenario not only covers a long temporal extent, but also focuses on the same area as the project areas. However, this baseline includes effects of other WWF work since 2007 in Sebangau National Park, making it less appropriate for comparison. Comparing emissions from both National Parks over the entire period 2000-2018, i.e. including the fire year 2015 (but excluding the years 2013 and 2014 for which no data were collected), shows that over that period Sebangau had on average 8.9 t $CO_2$- e $ha^{-1}yr^{-1}$ less emissions than Tanjung Putting. This value, which includes the extreme year 2015, strongly supports the conclusion that the activities of Krombacher since 2013 have indeed had an annual effect as was calculated for the period 2016-2018, which excluded 2015.

Peat fire emissions for the years 2015-2018 (i.e. including the 2015 El Niño fire year) differed only slightly between the WWF-Krombacher project areas (4.0 t $CO_2$-e $ha^{-1}yr^{-1}$) and the total Sebangau National Park area (4.3 t $CO_2$-e $ha^{-1}yr^{-1}$), whereas emissions in Tanjung Puting National Park were four times higher (17.4 t $CO_2$-e $ha^{-1}yr^{-1}$). Contrary to this, from 2000-2012, i.e. prior to most project activities, a similarly sized peatland area in both parks burned at least once (Figure 2). The emission estimates from 2015-2018 suggest that WWF-Krombacher activities had effects reaching far beyond the project area boundaries within Sebangau National Park.

All calculations do not include the effects of peatland rewetting, which could account for another 0.8 t $CO_2$-e $ha^{-1}yr^{-1}$ on average (Ballhorn and Navratil, 2015), but were left unaccounted for in order to remain more conservative in emission reductions estimations.

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# ANNEX I: GAIN/LOSS AGB AND BGB WITHIN SEKAMOZA CATCHMENTS

*Table 12: Landabung catchment within the SeKaMoza project area. Gain (+) and Loss (-) of Carbon (C) and Carbon Dioxide Equivalents ($CO_2$-e) in tons (t) in the above-ground biomass (AGB) and below-ground biomass (BGB) for the time period between 2015 and 2018. AGB values for the different land cover classes are based on the LiDAR and FORCLIME values (see Table 4 and Ballhorn and Navratil, 2015). BGB values are based on a default root-to-shoot ratio of 37% (IPCC, 2006).*

| Land Cover Change | Area (ha) ∑10,111 | LiDAR Gain/Loss AGB (tC) | FORCLIME Gain/Loss AGB (tC) |
|---|---|---|---|
| Deforestation | 52 | -4,055 | -3,713 |
| Forest Degradation | 10 | -610 | -304 |
| Degradation | 11 | -37 | -76 |
| Reforestation | 6 | +244 | +291 |
| Forest Regeneration | 2,199 | +16,492 | +16,492 |
| Regeneration | 485 | +3,398 | +5,391 |
| No Change | 5,468 | 0 | 0 |
| No Data | 1,882 | 0 | 0 |
| **Sum C AGB** | | **+15,433** | **+18,081** |
| **Sum C BGB** | | **+5,710** | **+6,690** |
| **C AGB + C BGB** | | **+21,143** | **+24,771** |
| **$CO_2$-e AGB + $CO_2$-e BGB** | | **+77,595** | **+90,910** |
| **$CO_2$-e AGB + $CO_2$-e BGB per ha/year** | | **+2.6** | **+3.0** |

*Table 13: Musang catchment within the SeKaMoza project area. Gain (+) and Loss (-) of Carbon (C) and Carbon Dioxide Equivalents ($CO_2$-e) in tons (t) in the above-ground biomass (AGB) and below-ground biomass (BGB) for the time period between 2015 and 2018. AGB values for the different land cover classes are based on the LiDAR and FORCLIME values (see Table 4 and Ballhorn and Navratil, 2015). BGB values are based on a default root-to-shoot ratio of 37% (IPCC, 2006).*

| Land Cover Change | Area (ha) ∑15,013 | LiDAR Gain/Loss AGB (tC) | FORCLIME Gain/Loss AGB (tC) |
|---|---|---|---|
| Deforestation | 141 | -8,204 | -8,429 |
| Forest Degradation | 37 | -2,372 | -1,186 |
| Degradation | 70 | -151 | -117 |
| Reforestation | 64 | +2,815 | +3,361 |
| Forest Regeneration | 1,716 | +12,868 | +12,868 |
| Regeneration | 3,337 | +21,958 | +64,372 |
| No Change | 8,060 | 0 | 0 |
| No Data | 1,588 | 0 | 0 |
| **Sum C AGB** | | **+26,913** | **+70,868** |
| **Sum C BGB** | | **+9,958** | **+26,221** |
| **C AGB + C BGB** | | **+36,871** | **+97,089** |
| **$CO_2$-e AGB + $CO_2$-e BGB** | | **+135,318** | **+356,317** |
| **$CO_2$-e AGB + $CO_2$-e BGB per ha/year** | | **+3.0** | **+7.9** |

*Table 14: Punggualas catchment within the SeKaMoza project area. Gain (+) and Loss (-) of Carbon (C) and Carbon Dioxide Equivalents ($CO_2$-e) in tons (t) in the above-ground biomass (AGB) and below-ground biomass (BGB) for the time period between 2015 and 2018. AGB values for the different land cover classes are based on the LiDAR and FORCLIME values (see Table 4 and Ballhorn and Navratil, 2015). BGB values are based on a default root-to-shoot ratio of 37% (IPCC, 2006).*

| **Land Cover Change** | **Area (ha) ∑8,854** | **LiDAR** | **FORCLIME** |
|---|---|---|---|
| | | **Gain/Loss AGB (tC)** | **Gain/Loss AGB (tC)** |
| Deforestation | 0 | 0 | 0 |
| Forest Degradation | 0 | 0 | 0 |
| Degradation | 0 | 0 | 0 |
| Reforestation | 0 | 0 | 0 |
| Forest Regeneration | 965 | +7,237 | +7,237 |
| Regeneration | 34 | +173 | +690 |
| No Change | 4,567 | 0 | 0 |
| No Data | 3,288 | 0 | 0 |
| | **Sum C AGB** | **+7,410** | **+7,927** |
| | **Sum C BGB** | **+2,742** | **+2,933** |
| | **C AGB + C BGB** | **+10,152** | **+10,860** |
| | **$CO_2$-e AGB + $CO_2$-e BGB** | **+37,257** | **+39,857** |
| | **$CO_2$-e AGB + $CO_2$-e BGB per ha/year** | **+1.4** | **+1.5** |

*Table 15: SSI catchment within the SeKaMoza project area. Gain (+) and Loss (-) of Carbon (C) and Carbon Dioxide Equivalents ($CO_2$-e) in tons (t) in the above-ground biomass (AGB) and below-ground biomass (BGB) for the time period between 2015 and 2018. AGB values for the different land cover classes are based on the LiDAR and FORCLIME values (see Table 4 and Ballhorn and Navratil, 2015). BGB values are based on a default root-to-shoot ratio of 37% (IPCC, 2006).*

| **Land Cover Change** | **Area (ha) ∑13,124** | **LiDAR** | **FORCLIME** |
|---|---|---|---|
| | | **Gain/Loss AGB (tC)** | **Gain/Loss AGB (tC)** |
| Deforestation | 23 | -1,102 | -1,361 |
| Forest Degradation | 34 | -2,173 | -1,092 |
| Degradation | 50 | -251 | -704 |
| Reforestation | 90 | +3,948 | +4,713 |
| Forest Regeneration | 372 | +2,794 | +2,794 |
| Regeneration | 724 | +4,906 | +6,945 |
| No Change | 8,330 | 0 | 0 |
| No Data | 3,500 | 0 | 0 |
| | **Sum C AGB** | **+8,121** | **+11,296** |
| | **Sum C BGB** | **+3,005** | **+4,179** |
| | **C AGB + C BGB** | **+11,126** | **+15,475** |
| | **$CO_2$-e AGB + $CO_2$-e BGB** | **+40,831** | **+56,793** |
| | **$CO_2$-e AGB + $CO_2$-e BGB per ha/year** | **+1.0** | **+1.4** |

*Table 16: Upper Sebangau catchment within the SeKaMoza project area. Gain (+) and Loss (-) of Carbon (C) and Carbon Dioxide Equivalents ($CO_2$-e) in tons (t) in the above-ground biomass (AGB) and below-ground biomass (BGB) for the time period between 2015 and 2018. AGB values for the different land cover classes are based on the LiDAR and FORCLIME values (see Table 4 and Ballhorn and Navratil, 2015). BGB values are based on a default root-to-shoot ratio of 37% (IPCC, 2006).*

| **Land Cover Change** | **Area (ha) ∑16,350** | **LiDAR** | **FORCLIME** |
|---|---|---|---|
| | | **Gain/Loss AGB (tC)** | **Gain/Loss AGB (tC)** |
| Deforestation | 95 | -9,052 | -7,438 |
| Forest Degradation | 79 | -5,006 | -2,512 |
| Degradation | 4 | -20 | -59 |
| Reforestation | 23 | 982 | 1,172 |
| Forest Regeneration | 1,018 | 7,633 | 7,633 |
| Regeneration | 914 | 5,344 | 19,333 |
| No Change | 13,719 | 0 | 0 |
| No Data | 499 | 0 | 0 |
| | **Sum C AGB** | **-120** | **18,129** |
| | **Sum C BGB** | **-44** | **6,708** |
| | **C AGB + C BGB** | **-164** | **24,836** |
| | **$CO_2$-e AGB + $CO_2$-e BGB** | **-603** | **91,149** |
| | **$CO_2$-e AGB + $CO_2$-e BGB per ha/year** | **0.0** | **+1.9** |

*Table 17: Paduran Alam catchment (only area within Sebangau National Park) within the SeKaMoza project area. Gain (+) and Loss (-) of Carbon (C) and Carbon Dioxide Equivalents ($CO_2$-e) in tons (t) in the above-ground biomass (AGB) and below-ground biomass (BGB) for the time period between 2015 and 2018. AGB values for the different land cover classes are based on the LiDAR and FORCLIME values (see Table 4 and Ballhorn and Navratil, 2015). BGB values are based on a default root-to-shoot ratio of 37% (IPCC, 2006).*

| **Land Cover Change** | **Area (ha) ∑22,525** | **LiDAR** | **FORCLIME** |
|---|---|---|---|
| | | **Gain/Loss AGB (tC)** | **Gain/Loss AGB (tC)** |
| Deforestation | 103 | -5,579 | -6,357 |
| Forest Degradation | 16 | -988 | -496 |
| Degradation | 25 | -138 | -402 |
| Reforestation | 11 | +502 | +599 |
| Forest Regeneration | 2,219 | +16,641 | +16,641 |
| Regeneration | 180 | +1,319 | +1,496 |
| No Change | 19,972 | 0 | 0 |
| No Data | 0 | 0 | 0 |
| | **Sum C AGB** | **+11,756** | **+11,481** |
| | **Sum C BGB** | **+4,350** | **+4,248** |
| | **C AGB + C BGB** | **+16,106** | **+15,729** |
| | **$CO_2$-e AGB + $CO_2$-e BGB** | **+59,110** | **+57,724** |
| | **$CO_2$-e AGB + $CO_2$-e BGB per ha/year** | **+0.9** | **+0.9** |

*Table 18: Sungai Kaki catchment (only area within Sebangau National Park) within the SeKaMoza project area. Gain (+) and Loss (-) of Carbon (C) and Carbon Dioxide Equivalents ($CO_2$-e) in tons (t) in the above-ground biomass (AGB) and below-ground biomass (BGB) for the time period between 2015 and 2018. AGB values for the different land cover classes are based on the LiDAR and FORCLIME values (see Table 4 and Ballhorn and Navratil, 2015). BGB values are based on a default root-to-shoot ratio of 37% (IPCC, 2006).*

| **Land Cover Change** | **Area (ha) ∑11,295** | **LiDAR** | **FORCLIME** |
|---|---|---|---|
| | | **Gain/Loss AGB (tC)** | **Gain/Loss AGB (tC)** |
| Deforestation | 14 | -1,101 | -969 |
| Forest Degradation | 9 | -543 | -271 |
| Degradation | 6 | -14 | -18 |
| Reforestation | 2,095 | +91,432 | +109,153 |
| Forest Regeneration | 1,773 | +13,297 | +13,297 |
| Regeneration | 905 | +6,508 | +10,405 |
| No Change | 2,787 | 0 | 0 |
| No Data | 3,707 | 0 | 0 |
| | **Sum C AGB** | **+109,579** | **+131,598** |
| | **Sum C BGB** | **+40,544** | **+48,691** |
| | **C AGB + C BGB** | **+150,123** | **+180,289** |
| | **$CO_2$-e AGB + $CO_2$-e BGB** | **+550,951** | **+661,661** |
| | **$CO_2$-e AGB + $CO_2$-e BGB per ha/year** | **+16.3** | **+19.5** |

## ANNEX II: PEAT FIRE EMISSIONS WITHIN SEKAMOZA CATCHMENTS

*Table 19: Landabung catchment within the SeKaMoza project area. Peat fire emissions for the years 2015, 2016, 2017 and 2018.*

| Fire year | Burned area (ha) | Emissions | |
|---|---|---|---|
| | | tC | $tCO_2$-e |
| 2015 | 159 | 5,071 | 18,612 |
| 2016 | 0 | 0 | 0 |
| 2017 | 0 | 0 | 0 |
| 2018 | 0 | 0 | 0 |
| **Sum (all years)** | | 5,071 | 18,612 |
| **Sum (without 2015)** | | 0 | 0 |
| **per ha peat/year (all years)** | | **0.1** | **0.5** |
| **per ha peat/year (without 2015)** | | **0.0** | **0.0** |

*Table 20: Musang catchment within the SeKaMoza project area. Peat fire emissions for the years 2015, 2016, 2017 and 2018.*

| Fire year | Burned area (ha) | Emissions | |
|---|---|---|---|
| | | tC | $tCO_2$-e |
| 2015 | 2,463 | 182,866 | 671,119 |
| 2016 | 0 | 0 | 0 |
| 2017 | 0 | 0 | 0 |
| 2018 | 0 | 0 | 0 |
| **Sum (all years)** | | 182,866 | 671,119 |
| **Sum (without 2015)** | | 0 | 0 |
| **per ha peat/year (all years)** | | **3.0** | **11.2** |
| **per ha peat/year (without 2015)** | | **0.0** | **0.0** |

*Table 21: Punggualas catchment within the SeKaMoza project area. Peat fire emissions for the years 2015, 2016, 2017 and 2018.*

| Fire year | Burned area (ha) | Emissions | |
|---|---|---|---|
| | | tC | $tCO_2$-e |
| 2015 | 19 | 1,131 | 4,150 |
| 2016 | 0 | 0 | 0 |
| 2017 | 0 | 0 | 0 |
| 2018 | 0 | 0 | 0 |
| **Sum (all years)** | | 1,131 | 4,150 |
| **Sum (without 2015)** | | 0 | 0 |
| **per ha peat/year (all years)** | | **0.0** | **0.1** |
| **per ha peat/year (without 2015)** | | **0.0** | **0.0** |

*Table 22: SSI catchment within the SeKaMoza project area. Peat fire emissions for the years 2015, 2016, 2017 and 2018.*

| Fire year | Burned area (ha) | Emissions | |
|---|---|---|---|
| | | tC | $tCO_2$-e |
| 2015 | 618 | 49,099 | 180,194 |
| 2016 | 0 | 0 | 0 |
| 2017 | 0 | 0 | 0 |
| 2018 | 0 | 0 | 0 |
| **Sum (all years)** | | 49,099 | 180,194 |
| **Sum (without 2015)** | | 0 | 0 |
| **per ha peat/year (all years)** | | **0.9** | **3.4** |
| **per ha peat/year (without 2015)** | | **0.0** | **0.0** |

*Table 23: Upper Sebangau catchment within the SeKaMoza project area. Peat fire emissions for the years 2015, 2016, 2017 and 2018.*

| Fire year | Burned area (ha) | Emissions | |
|---|---|---|---|
| | | tC | $tCO_2$-e |
| 2015 | 370 | 12,562 | 46,104 |
| 2016 | 0 | 0 | 0 |
| 2017 | 0 | 0 | 0 |
| 2018 | 0 | 0 | 0 |
| **Sum (all years)** | | 12,562 | 46,104 |
| **Sum (without 2015)** | | 0 | 0 |
| **per ha peat/year (all years)** | | **0.2** | **0.7** |
| **per ha peat/year (without 2015)** | | **0.0** | **0.0** |

*Table 24: Paduran Alam catchment (only area within Sebangau National Park) within the SeKaMoza project area. Peat fire emissions for the years 2015, 2016, 2017 and 2018.*

| Fire year | Burned area (ha) | Emissions | |
|---|---|---|---|
| | | tC | $tCO_2$-e |
| 2015 | 0 | 0 | 0 |
| 2016 | 0 | 0 | 0 |
| 2017 | 0 | 0 | 0 |
| 2018 | 0 | 0 | 0 |
| **Sum (all years)** | | 0 | 0 |
| **Sum (without 2015)** | | 0 | 0 |
| **per ha peat/year (all years)** | | **0.0** | **0.0** |
| **per ha peat/year (without 2015)** | | **0.0** | **0.0** |

*Table 25: Sungai Kaki catchment (only area within Sebangau National Park) within the SeKaMoza project area. Peat fire emissions for the years 2015, 2016, 2017 and 2018.*

| Fire year | Burned area (ha) | Emissions | |
|---|---|---|---|
| | | tC | $tCO_2$-e |
| 2015 | 345 | 28,415 | 104,282 |
| 2016 | 0 | 0 | 0 |
| 2017 | 0 | 0 | 0 |
| 2018 | 0 | 0 | 0 |
| **Sum (all years)** | | 28,415 | 104,282 |
| **Sum (without 2015)** | | 0 | 0 |
| **per ha peat/year (all years)** | | **0.6** | **2.3** |
| **per ha peat/year (without 2015)** | | **0.0** | **0.0** |