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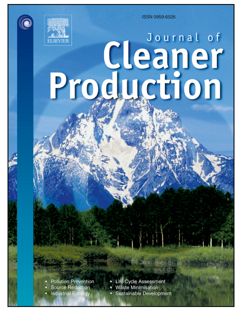

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Credit author statement

Michele De Rosa and Jannick Schmidt conceived and designed the study.

Michele De Rosa drafted and revised the manuscript.

Haskarlianus Pasang provided primary data. Michele De Rosa and Jannick Schmidt provided literatre data.

Jannick Schmidt and Haskarlianus Pasang approved the manuscript to be published.

Industry-driven mitigation measures can reduce GHG emissions of palm oil

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ABSTRACT

Tropical peatland stores a large amount of carbon. In the last 20 years, drainage of Asian peat soil has increased to satisfy the demand of land for plantation agricultures. Industrial oil palm plantations occupy large areas of peatland in Indonesia and Malaysia, with associated GHG emissions and biodiversity loss, here referred to as nature occupation impact. This study performs a detailed Life Cycle Assessment (LCA) of 1 kg of palm oil for two case studies: PT SMART's Hanau and Sungai Rungau facilities in Central Kalimantan, Indonesia. The objective is to quantify the reduction in GHG emissions and nature occupation that has been achieved by implementing the following industry-driven measures: reducing the area of cultivated peat soil, reducing the peat drainage depth, and setting aside part of the land-bank for nature conservation. The results show that 1 kg of palm oil causes 2.72 and 2.25 kg CO_2-eq./kg palm oil from Hanau and Sungai Rungau facilities respectively. These are 20%-34% lower than average RSPO certified palm oil and 49%-58% lower than average non-certified palm oil. Sungai Rungau achieves the reduction mainly due to a completely peat soil-free supply base. Hanau's peat emissions are instead 0.28 kg, compared to the 0.77 and 2.36 kg CO_2-eq for RSPO certified and non-certified palm oil respectively, due to a very low drainage depth (18-25 cm compared to 57-73 cm in average of RSPO certified and non-certified respectively) and an overall lower share of oil palms on peat land. The impact on nature occupation is 24%-43% lower in Hanau and Sungai Rungau compared to non-certified oil and 4%-29% lower compared to RPSO certified respectively. About 8% of the total land bank of the Hanau supply-base has been set aside for nature conservation, reducing GHG emissions by 2% and nature occupation by 9%. Both Hanau and Sungai Rungau could also significantly reduce GHG emissions in the palm oil milling stage, by implementing biogas capture in palm oil mill effluent (POME) treatment.

Keywords: Palm oil, Life Cycle Assessment, peatland, GHG emissions, carbon footprint.

1. Introduction

The area covered by oil palm plantations has doubled in the last two decades (Vijay et al. 2016), with most of the expansion occurring in Indonesia and Malaysia, together supplying approximately 85% of the global palm oil production (FAOSTAT 2020). This trend means that the development of new plantations is more likely to occur on peat soil, due to the limited mineral soil now available. The tropical peatland in Southeast Asia contains 11-14% of the global carbon pool of peat land (IPCC 2014a). The drainage of peat soil for cultivation allows oxygen to access the soil, resulting in the decomposition of the organic material and the consequent emissions of CO_2 and N_2O (Tonks et al. 2017). The consequence is the increase of Greenhouse Gas (GHG) emissions related to the crop production and of the impact on biodiversity (Wicke et al. 2011). The palm oil industry has responded to the public demand of sustainable palm oil production with voluntary initiatives such as the Roundtable for Sustainable Palm Oil (RSPO) certification schema, aiming at reducing the environmental impacts of palm oil (RSPO 2018a). RSPO is currently the most widely used global standard for palm oil certification. Other certification schemes adopted by the palm oil sector are: the International Sustainability and Carbon Certification (ISCC), often pursued by growers selling to the European biofuel market (ISCC 2019); the Rainforest Alliance Sustainable Agricultural Standard, a stringent certification standards for biodiversity protection (Deanna and Milder 2018); the Sustainable Agriculture Network (SAN 2019); and the Roundtable on Sustainable Biomaterials (RSB 2019). Industries play a key role in applying best management practices: for example, it is acknowledged that nature conservation areas within estates are vital for the development of a biodiverse and properly functioning oil palm landscape in oil palm plantations (Foster et al. 2011). However, most existing publications focus on quantifying the impact of palm oil production, rather than the potential impact reductions achievable with good land use practices.

Evidence shows that peat soil drainage for land cultivation accelerates peat decomposition (Sangok et al. 2017, Tonks et al. 2017). Therefore, palm oil derived from oil palms cultivated on peat soil is significantly more GHG emission-intensive (Cooper et al. 2019). Few studies investigate mitigation options to reduce GHG emissions in oil palm cultivation: some suggest reducing the peat drainage depth when oil palm is cultivated on peat soil (Othman et al. 2011, Hashim et al. 2018) and to cultivate already degraded peat land (Hashim et al. 2018). While the reduction of the peat drainage depth is a measure worth further investigation, the occupation of already degraded land only reduces the direct Land Use Change (dLUC) GHG emissions and does not affect the indirect Land Use Change (iLUC) GHG emissions. Indirect LUC emissions occur because of increasing global land demand (IPCC 2014a) and the occupation of already degraded or cleared land does not reduce the total global demand of land (Schmidt et al. 2015). Currently, there are no studies in the scientific literature investigating the effectiveness of nature conservation in oil palm plantations to reduce both GHG emissions and nature occupation due to palm oil production. However, research quantifying the benefits of industry-driven GHG mitigation measures in oil palm plantations is limited. A systematic and verifiable assessment of the benefits achieved through enhancing production practices is crucial for businesses investing environmental impact reduction measures.

In this paper we carry out a life cycle assessment (LCA) of palm oil produced by PT SMART, a subsidiary of Golden Agri Resources (GAR), at two palm oil mills (POMs) and their supply base. The objective is to quantify the benefits achieved by industry-driven measures in terms of mitigating the peat GHG emissions of oil palm and the nature occupation (loss of biodiversity). PT SMART is an industrial producer of RSPO certified palm oil, i.e. it is committed to reducing the share of peatland in its supply-base and to preserve biodiversity by reducing deforestation and nature occupation (RSPO 2018b). The company developed a Forest Conservation Policy in 2011 to halt development on high conservation value (HCV) forests and to preserve critical areas such as peat land, water catchments and riparian zones (PT SMART 2018). We test the effectiveness of peat soil management and avoiding peatland occupation in oil palm plantations and the effect of setting aside HCV land in order to reduce GHG emissions and the impact on nature occupation of palm oil production.

In 2017, PT SMART launched a pilot project at two of its POMs: Hanau and Sungai Rungau mill. In this paper, we perform a detailed LCA of Refined, Bleached and Deodorized (RBD) palm oil refined in Jakarta, processed and cultivated at Hanau and Sungai Rungau POMs, and supplying estates in Central Kalimantan, Indonesia. LCA systematically quantifies a variety of environmental impacts of products/services. Here we focus on two impact categories: global warming (caused by GHG emissions) and nature occupation (land use changes causing biodiversity losses). This paper also analyses the potential of further improvement options, i.e. the effect of good peat soil management (reducing the peat drainage depth), reducing or avoiding the cultivation of peatland, and increasing the land set aside for HCV nature conservation. The study is carried out according to the specifications of the ISO standards on life-cycle assessment ISO 14040/ and ISO 14044 (ISO 14040, 2006; ISO 14040, 2006).

The GHG emissions and the nature occupation associated with the palm oil production at Hanau and Sungai Rungau mill are compared to the average RSPO certified and non-certified palm oil in Indonesia and Malaysia in 2016 documented in Schmidt and De Rosa (2020). The comparison allows benchmarking PT SMART performances against average certified and non-certified oil.

Although this paper refers to a specific case study, the identified hotspots of the palm oil system and the potential improvement options analysed may be relevant for other palm oil producers seeking options to reduce the environmental impacts associated to palm oil production on peat soil and for the most effective climate mitigation options.

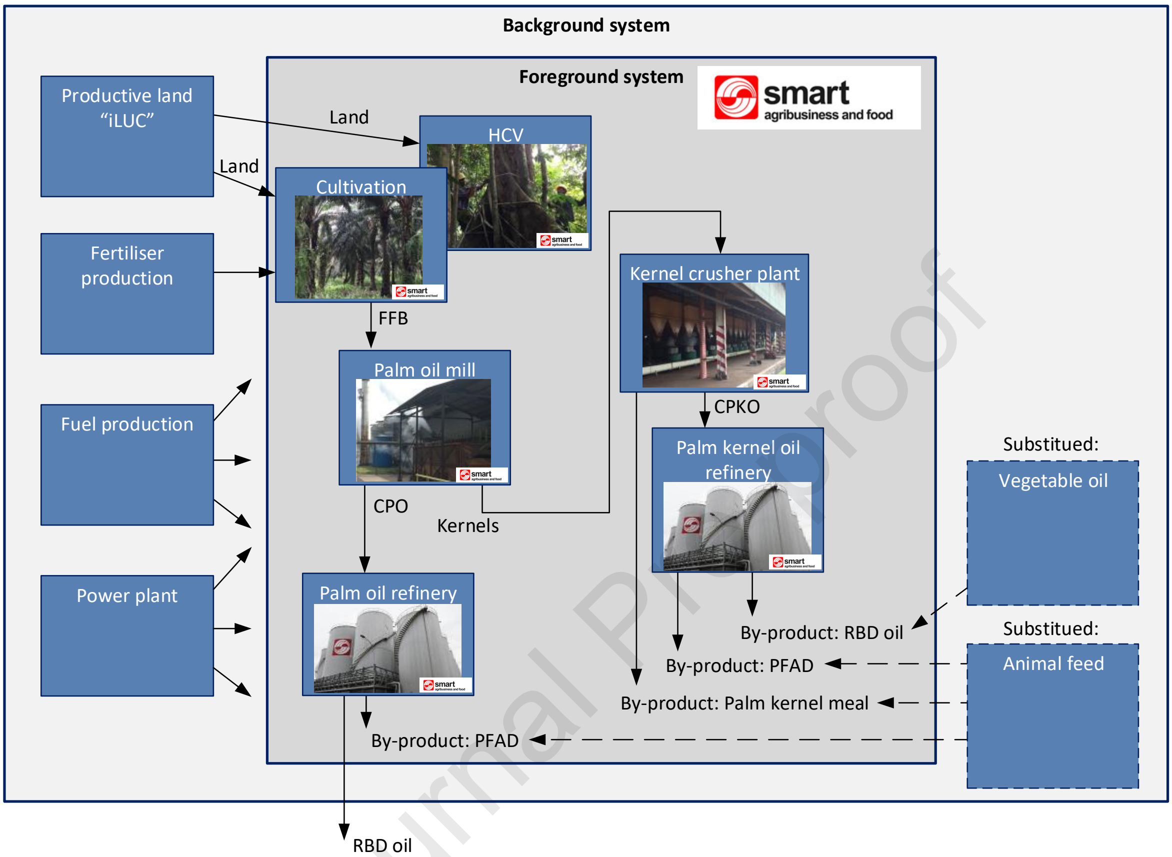

***Figure 1**: The main stages of the product system for palm oil production. Dotted lines and dotted boxes represent negative flows and substituted processes. HCV: High Conservation Value; FFB: Fresh Fruit Bunches; CPO: Crude Palm Oil; CPKO: Crude Palm Kernel Oil; RBD: Refined Bleached and Deodorized; PFAD: Palm Fatty Acid Distillate.*

2. Materials and methods

2.1. Goal and scope

The study carries out a Life Cycle Assessment (LCA) of palm oil in 2017, cultivated and processed at Hanau and Sungai Rungau palm oil mills and their supply-base in Central Kalimantan and refined at the Marunda refinery in Jakarta, Java. The results are presented for a functional unit of "1 kg of Refined Bleached and Deodorised (RBD) palm oil". The functional unit is the reference unit to which the calculated performance of the product system refers. The LCA framework quantifies the environmental impacts of products and services throughout their entire life cycle. The LCA performed in the current paper is compliant with the international standards on LCA ISO 14040 (2016) and ISO 14044 (2016). In LCA terminology, the study is carried out using the consequential approach to modelling in life cycle inventory (Weidema et al. 2003), which means that it quantifies the consequences of a change in demand for the functional unit. It intends to provide information on the environmental consequences of producing/purchasing an additional amount of the functional unit of 1 kg RBD palm oil. The consequential approach allows consumers, business users and suppliers to be informed about the environmental impacts caused by the production with and without the analysed mitigation efforts.

The LCA includes the product's life cycle stages from resource extraction to the factory gate i.e. it is a cradle-to-gate study. The foreground system includes the following life cycle stages: oil palm cultivation, oil mill, refining (of palm oil as well as palm kernel oil), kernel crushing, and nature conservation, see Figure 1. The product's packaging is not included because typically RBD palm oil is handled as bulk. Capital goods and services are included. The foreground system groups the LCA activities for which data are collected and modelled in the study. The background system contains other required activities for which generic data are drawn from LCA databases. Main by-products of the product system are palm/palm kernel fatty acid distillate (PFAD/PKFAD) and palm kernel meal, both used for animal feed. Figure 1 shows the by-products and the market affected by the product substitution, i.e. the market for vegetable oils and animal feeds.

Table 1*: Key data for the four estates supplying Hanau POM: Hanau estate (HNAE); Lengadang estate (LNGE); Tasik Mas estate (TMSE); Tanjung Paring estate (TPRE).*

Data	Unit	HNAE	LNGE	TMSE	TPRE
Estate					
Oil palm planted area	ha	4,177	2,040	4,285	3,936
Other land: roads, ditches, buildings etc.	ha	713	370	363	781
Share of planted area on peat	%	1%	28%	0%	21%
Peat drainage depth	cm	24.96	14.53	-	17.91
Nature conservation (HCV)					
Land set-aside as HCV	ha	376	246	318	331
Above ground biomass (carbon)	t C/ha	27	5	57	16
Below ground biomass (carbon)	t C/ha	10	2	21	6
Dead organic matter (carbon)	t C/ha	0.7	0.3	1.3	0.5
Soil organic matter* (carbon)	t C/ha	105	120	83	113
Share of HCV on peat	%	0%	43%	0%	30%

2.2. Case study

The LCA is performed on the RSPO certified crude palm oil from the Hanau and Sungai Rungau palm oil mills and their respective supply-base. The refining takes place at the Marunda refinery in Jakarta, Java. The supply-base of FFB to the Hanau POM includes five estates, located west of the Seruyan River (**Figure 2**) of which four are RSPO certified. The estates occupy an area of 18,000 ha of which 14,400 ha are mature oil palms. No immature stands are currently present at Hanau's supply-base estates (**Table 1**). Three of the four estates supplying Hanau mill have shares of the oil palm plantations on peatland, ranging from 1 to 28%. In total, the estates set aside 1,300 ha of land for nature conservation. In addition, the Hanau mill also receives external FFB. For the current study, only the RSPO certified estates are included since this refers to certified palm oil supplied by the Hanau POM under a mass balance certification scheme (RSPO 2014).

The Hanau POM has a capacity of 80 tonnes FFB/hour. In 2017, it processed 392,137 tonnes of FFB and it produced 83,288 tonnes of crude palm oil (CPO) and 22,786 tonnes of kernels. About 80% of the processed FFB are from the four RSPO certified estates supplying Hanau POM.

Data on carbon stock of the HCV land set aside for nature conservation and oil palm plantations have been collected with a detailed on-site survey including data on carbon stocks in biomass, soil and Decomposing Organic Matter (DOC). In Hanau's supply base, the survey has been carried out on 25 plots: 12 plots for conservation area on peat soil; 12 for conservation area on mineral soil; and 1 plot for oil palm plantations on mineral soil. The 24 HCV plots are distributed among three estates. In total, 480 measurements of Diameters at Breast Height (DBH) have been measured in the HCV land to assess the biomass carbon content. For each of the 25 plots surveyed, data on Decomposing Organic Matter (DOC) and soil carbon have also been collected.

Five estates, located east of the Seruyan River (**Figure 3**), supply FFB to the Sungai Rungau POM. The area occupied by each estate ranges between 2,750 and 4,660 ha (**Table 2**). In total, the oil palm plantations occupy 19,000 ha of mature oil palms with no immature stands. Four of the five estates set aside HCV land for a total of 1,505 ha for permanent nature conservation, i.e. 7% of the total land bank of 20,500 ha. The remaining land is covered by roads, airstrips, offices etc. Data on carbon stock of the HCV land set aside for nature conservation were collected in July 2017, in 25 plots, among four estates: 2 plots in Sungai Rungau Estate (SRGE), 10 plots in Sungai Seruyan Estate (SSRE), 1 plot in Bukit Tiga Estate (BTGE) and 12 plots in Tangar Estate (TNGE). Carbon stock assessment was conducted using biomass calculation approach (Hairiah et al. 2011). The HCV area in BAP concession is categorized as a secondary forest dominated by stands with high wood density and a diameter of mostly between 20 and 39 cm. The forest seems in a process of regeneration, and the abundance of sapling and pole per hectare (1,533 and 611 individual per ha, respectively) seems to confirm this status. Sungai Rungau POM has a capacity of 80 tonnes/hour. Palm kernels are crushed at the Perdana kernel crusher plant, which has a capacity of 400 tonnes/day, receiving palm kernels from several others mills. In 2016 Sungai Rungau POM produced around 100,000 tonnes of crude palm oil and 25,000 tonnes of palm kernel oil.

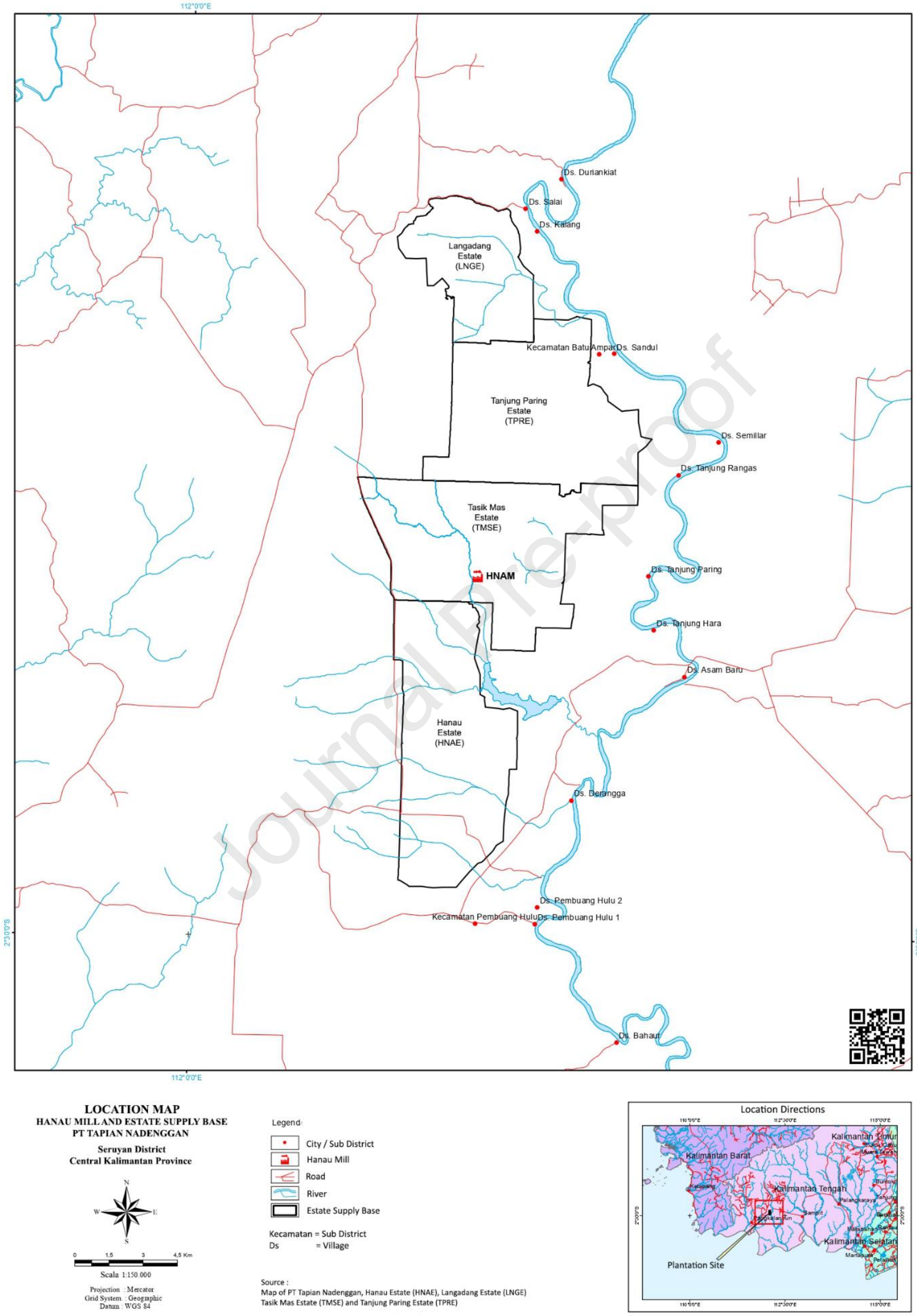

Figure 2*: Location of the four estate supplying to the Hanau mill. The estates are located in central Kalimantan, Indonesia.*

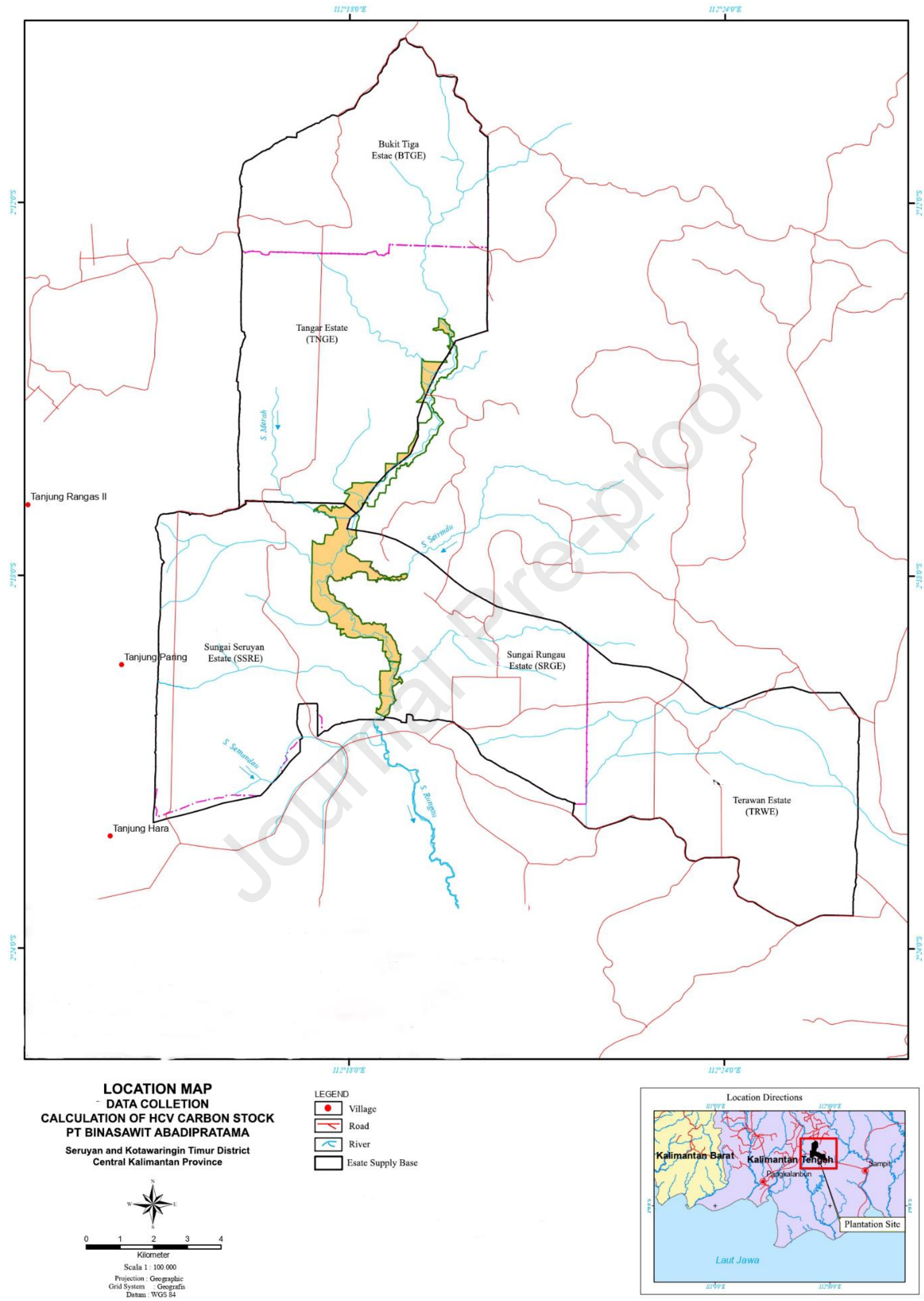

***Figure 3**: Location of the five estate supplying to the Sungai Rungau mill. The estates are located in central Kalimantan, Indonesia.*

2.3. Life Cycle Inventory

The Life Cycle Inventory (LCI) model is divided in the foreground and the background systems. The foreground system includes detailed on-site data for all relevant input and output flows of the three main production stages: oil palm cultivation, palm oil milling and palm oil refining. Data have been collected for the estates suppling Hanau and Sungai Rungau POMs, the POMs, the kernel crushing plant at the Perdana palm oil mill, bulking at the Bagendang and Bumiharjo bulking stations and refining at the Marunda refinery. The data describes the inputs of materials (fertilisers, packaging, fuels, pesticides, chemicals); energy (purchased electricity from the grid, own steam and electricity generation, boiler characteristics); the treatment of palm oil mill effluent (POME); the utilization of FFB residues; transport (distances, load factors, and vehicle specific diesel use/km). The key inventory data describing Hanau and Sungai Rungau production are summarised in **Table 3** and compared to RSPO certified and non-certified data.

Table 2*: Key data for the five estates included in this study supplying Sungai Rungau POM. The estates are Terawan Estate (TRWE), Sungai Rungau Estate (SRGE), Sungai Seruyan Estate (SRSE), Tangar Estate (TNGE) and Bukit Tiga Estate (BTGE).*

Data	Unit	TRWE	SRGE	SSRE	TNGE	BTGE
Estate						
Oil palm planted area	ha	4,660	3,392	4,205	3,971	2,752
Other land: roads, ditches, buildings etc.	ha	168	217	145	440	310
Share of planted area on peat	%	0%	0%	0%	0%	0%
Nature conservation (HCV): values representing the whole Sungai Rungau's estates						
Land set-aside as HCV	ha	0	197	649	411	248
Above ground biomass (carbon)	t C/ha			190.9*		
Below ground biomass (carbon)	t C/ha			93.88*		
Dead organic matter (carbon)	t C/ha			0.46*		
Soil organic matter (carbon)	t C/ha			9.05*		
Share of HCV on peat	%			0%		

*Average value among estates.

Table 3*: Data for palm oil production at Hanau POM, Indonesian and Malaysian industry average palm oil. PT SMART data are based on the data collection of the current study. Data for RSPO certified and non-certifies are drawn from Schmidt and De Rosa (2020). The organic fertiliser is obtained from the land application of EFB and POME.*

Data	Unit	PT Smart Hanau POM	PT Smart Sungai Rungau	RSPO certified	Non-certified
Estate					
FFB yield (mature)	ton/ha*year	21.6	24.3	21.1	18.9
Share of oil palm on peat	%	12%	0%	11%	19%
Drainage depth of peat	cm	17	-	57	75
Land bank set-aside as HCV nature conservation	%	8%	7%	3.1%	0%
Share of nature conservation on peat	%	16%	0%	n.a.	n.a.
Carbon stock of HCV nature conservation (above and below ground)	ton C/ha	143	213	226	0
N-fertiliser	kg N/ha*year	148	116	176	104
of which organic N fertiliser	kg N/ha*year	7	27	23	-
P-fertiliser	kg P_2O_5/ha*year	133	75	138	69
of which organic P fertiliser	kg P_2O_5/ha*year	49	11	31	-
K-fertiliser	kg K_2O/ha*year	422	287	407	294
of which organic K fertiliser	kg K_2O/ha*year	187	104	152	-

Palm oil mill					
Oil extraction rate (OER)	%	21.2%	22.2%	21.9%	19.8%
Kernel extraction rate (KER)	%	5.8%	5.6%	5.6%	5.4%
Empty fruit bunches (EFB) to land application	Kg/t FFB	235	211	-	-
POME treated with biogas capture	%	0%	0%	16%	2.4%
Refinery					
Electricity	kWh/ton RBD oil	13	12	16.7	16.7
PFAD to CPO	%	5.0%	5.2%	4.61%	4.61%
Oil loss relative to CPO	%	0.7%	0.7%	n.a.	n.a.

Data on capital goods, such as vehicles and machinery, equipment, construction, furniture and data on services (lawyers, sales support, business travel, accounting etc.) are obtained from the background input-output (IO) database EXIOBASE v3 (Stadler et al. 2018; Merciai and Schmidt 2017). Specific inputs to industrial sectors (cultivation of oil crops and processing of vegetable oils and fats) are represented by Indonesian capital goods and services data. EXIOBASE data are more aggregated than traditional process-based LCI data, but they are globally consistent and available for 164 product categories, 43 countries and 5 aggregated regions covering the remaining countries. The database allows operation with no cut-off because all inputs are included for all activities. EXIOBASE is trade-linked which means that data describe the products supplied by each country and their destinations. The hybrid version of EXIOBASE applies substitution to model the by-products, following the same approach of consequential LCA applied in this study. Product substitution allows modelling the connection between the palm oil market and global animal feed market. Those are linked because the palm oil milling by-products palm kernel meal and PFAD/PKFAD are used as animal feed. Inventory data for product substitution and data for average RSPO certified and non-certified palm oil are obtained from Schmidt and De Rosa (2020).

2.4. GHG emissions modelling

The main sources of emissions in the palm oil system are: nitrous oxide emissions occurring during fertiliser application and cultivation of peatland, carbon dioxide from cultivation of peatland and methane emissions from POME treatment. The N_2O account is based on detailed N-balances following the IPCC tier 2 approach (IPCC 2006). Indonesian climate and precipitation data are obtained from Albanito et al. (2017) in order to calculate N_2O emission factors specifically adapted to local conditions. IPCC (2014a) peat emission factors of 41.4 t CO_2/ha*year are used to calculate peat emissions proportionally to the peat drainage depth. The largest share of emissions in the palm oil milling stage occurs during POME treatment. These are calculated based on UNFCCC (2010). The procedure is further described in Schmidt and De Rosa (2020).

2.5. Indirect land use changes (iLUC)

The LCA model presented in the current paper includes a detailed inventory of LUC emissions, direct and indirect, based on the method described in Schmidt et al. (2015) and Schmidt and Muñoz (2014). The method is among the most performant to assess LUC in LCA (De Rosa et al. 2016). About 11% of the global GHG emissions are caused by LUC (IPCC 2014b), occurring when land is converted to different uses with a lower carbon stock (direct LUC). Indirect LUC emissions occur as a consequence of increasing the land demand globally and of crop displacement: the displaced crops are produced somewhere else in the world (IPCC 2014a) occupying further land (‘land occupation’), and/or by increasing the production inputs such as fertilisers and pesticides on already harvested land (‘land intensification’). Most of the global crop production occurs on land already used for agriculture, i.e. land that does not require a change in land use, particularly deforestation. However, the demand of agricultural land contributes to the global land demand thus contributing to indirect changes of land-use somewhere else (Schmidt et al. 2015). The key concept of the LUC framework is that the market for the production capacity of land is global; and land demand always leads to an indirect change in land use in other geographical regions, and therefore results in indirect emissions, regardless of the purpose for which the land is occupied. The iLUC model (Schmidt et al. 2015) is also the framework used to model the effect of nature conservation, as described in section 2.8.

The benefit of avoiding land transformation is quantified based on the difference in carbon stock and species richness of the conserved land and of the potential land conversion avoided. Therefore, the identification of the land use changes, and of its consequences on biodiversity, is strictly linked to the iLUC model. A beneficial effect is achieved every year that the nature conservation area is maintained (i.e. land conversion is avoided). For a more detailed description of the nature conservation model see Schmidt and de Saxcé (2016).

2.6. Oil palm crops on peat soil

While the changes in mineral soil carbon in oil palm plantations are assumed as insignificant, the peat soil CO_2 emissions due to peat oxidation are a major source of GHG emissions. When managing organic soil, carbon dioxide can arise from on-site emissions due to peat decomposition, off-site emissions from dissolved organic carbon transported in water, and from peat fire (IPCC 2014a). Emissions from peat decay vary significantly, depending on whether the peat is drained and on the drainage depth. The drainage depth of oil palms on peat soil is often deeper than required. A better management of the water table may therefore reduce the peat aeration and, hence, reduce emissions from peat oxidation. This aspect is relevant for Hanau's oil palm estates, where a share of the planted area is on peat soil (**Table 1**). We performed a literature review to identify existing assessments of peat emissions in the scientific literature (**Table 4**). According to Hooijer et al. (2006), the annual CO_2 emissions per hectare from peat drainage can be roughly estimated by multiplying the drainage depth (DD, in cm) by a fixed coefficient of 0.9, valid with DD between 25 cm and 110 cm. However, the authors point out that this simplified approach is highly uncertain: the CO_2 emissions from root respiration should be excluded from the quantification. Furthermore, the approach is based on insufficient information on water table and soil moisture. Henson (2004) identified a mean annual emission from peat soils of 27.5 t CO_2 ha^{-1} yr^{-1}, though also measured much higher values (44 to 66 t CO_2 ha^{-1} yr^{-1}). He found that carbon CO_2 emissions are higher immediately after peat drainage and decrease gradually afterwards, due to soil subsidence. Hooijer et al. (2012) confirmed this finding with field studies measuring subsidence in Indonesian peatland drained for wood and oil palm plantations, finding that over 25 years, emissions are approximately 100 t CO_2 ha^{-1} yr^{-1}. The higher emissions compared to the literature are because earlier studies assumed constant peat oxidation rates while Hooijer et al. (2012) confirms higher loss rates in the first few years after drainage. Similarly, Page et al. (2011) argue that other studies underestimate the peat emissions because they do not consider the very high emissions that occur the first 5 years following peat drainage. Page et al. (2011) identified three ranges (**Table 4)**, representing: 1) the recommended min and max values, 2) the emissions for 60 cm drainage depth and 3) the emissions for a drainage depth of 85 cm.

Agus et al. (2013b) calculated an emission factor based on the 0.91 t CO_2 ha^{-1} cm^{-1} from Hooijer et al. (2006), corrected using a coefficient to account for the root emissions according to Jauhjainen et al. (2012). They assume a mean water table for oil palm on peat between 50 cm and 70 cm, resulting in an average of 43 (36-50) t CO_2 ha^{-1} cm^{-1}. This value is similar to the 37-55 t CO_2 ha^{-1} yr^{-1} peat drainage, reported by Reijnders and Huijbregts (2006).

Concerning Southeast Asia, Hooijer et al. (2010) found that the CO_2 emissions range from 6 to 100 t CO_2 ha^{-1} yr^{-1}, depending on a number of parameters such as the size of the peat area, the drainage depth, the type of vegetation and the human activities. They found that the weighted average emission factor for the region including Indonesia, Malaysia, Brunei and Papua New Guinea in the period 1985 – 2006 was 53 (29.8 - 71.8) t CO_2 ha^{-1} yr^{-1} of drained peatland, and that CO_2 emissions from fires can be even higher than those from drainage of peat land.

The Intergovernmental Panel on Climate Change (IPCC 2006) show a wide range of CO_2 emissions factors depending on the cultivation practice. Oil palm plantations are probably drained deeper than managed forests, and therefore it is likely that the CO_2 emissions from oil palm are between managed forests and cropland. The 2014 update (IPCC 2014a) divides emissions into CO_2 emissions and CH_4 emissions. Methane emissions are further addressed in the following section. CO_2 emissions include on-site emissions from peat decay, off-site emissions from dissolved organic carbon transported in water via drains and emissions from peat fire. The on-site emissions are specified as 40.3 t CO_2 ha^{-1} yr^{-1} (ranging from 20.5 to 62.3 t CO_2 ha^{-1} yr^{-1}) for drained oil palm plantations. The reported off-site emissions from drained soils in the tropics are 1.1 t CO_2 ha^{-1} yr^{-1} (IPCC 2014a, p 2.20).

***Table 4**: Summary of values of CO_2 emissions from oil palm on drained peat found in literature.*

Reference	t CO_2 ha^{-1} $year^{-1}$	Drainage depth (cm)	Description
Agus et al. (2013b)	43 (36 - 50)	50 - 70	For peat fire, emission factors of 330 t CO_2 ha^{-1} for plantations established on forest landscapes and 110 t CO_2 ha^{-1} on shrub land. These are one-time emissions that needs to be allocated according to the plantation lifetime.
Henson (2004)	27.5	-	Mean annual emission. Higher values were also found (44 to 66 t CO_2 ha^{-1} yr^{-1}).
Hooijer et al. (2006)	63	70	Based on equation: CO_2 emission = 0.9*DD (valid within 25 cm – 110 cm DD).
Hooijer et al. (2010)	53 (29.8 - 71.8)		CO_2 emissions ranging from 6 to 100 tonne CO_2 ha^{-1} yr^{-1}.
Hooijer et al. (2012)	100	-	Higher figures compared to literature because earlier studies assumed that peat oxidation rates are constant while the authors confirms higher emission rates in the first few years after drainage.
IPCC (2006)	5 (3.0 - 14.0) 73 (7.3 - 139)	-	5.0 t CO_2 ha^{-1} yr^{-1} for drained managed tropical forests (2006, p 4.53) 73 t CO_2 ha^{-1} yr^{-1} for tropical cultivated organic soils (2006, p 5.19).
IPCC (2014a)	41.4 (21.6-63.4)	-	IPCC (2014a) updates IPCC (2006) values. The reported off-site emissions from drained soils in the tropics are 1.1 t CO_2 ha^{-1} yr^{-1} (IPCC 2014a, p 2.20).
Page et al. (2011)	54-115 67 ± 15 95 ± 21	- 60 85	1) recommended min and max values 2) emissions for 60 cm drainage depth 3) emissions for 85 cm drainage depth
Reijnders and Huijbregts (2006)	37 - 55	-	Values for oil palm on peat

In the current study, these IPCC values are applied and adjusted according to the peat drainage depth measured in the estates, as described in Hooijer et al. (2006). The carbon dioxide emissions from peat are therefore described by the following equation:

$$PE = 41.4 - (41.4 / 73) * (73 - DD) \qquad \textbf{Equation 1}$$

where PE are the CO_2 emission from peat in t CO_2/ha year, DD is the drainage depth in cm. The emission value 41.4 t CO_2 ha^{-1} yr^{-1} calculated with average drainage depth at 73 cm is associated with substantial uncertainties. Therefore, this parameter is investigated by a sensitivity analysis in section 4.3.

2.7. Modelling methane emissions from crops on peat soil

CH_4 emissions from soil are assumed zero while carbon emissions from drainage ditches are assumed to be 2,259 t CO_2 ha^{-1} yr^{-1} according to IPCC (2014b, p 2.25). The drainage ditches account for 2% of the area of typical drained organic soils: hence, the methane (CH_4) emissions are 45 kg CH_4 ha^{-1} yr^{-1}. These emissions are modelled as fossil emissions because the methane originates from peat.

Methane emissions from peat drainage reduce when draining the peat, because CH_4 emissions from peat are higher in anaerobic conditions than in aerobic conditions, occurring when the water table is reduced by peat drainage (Hergoualc'h and Verchot 2012). This aspect is not addressed by the IPCC (2014b). Hergoualc'h and Verchot (2012) provide an equation describing the relationship between drainage depth and CH_4 emissions from virgin/non-drained tropical peat forests:

$$ME = \frac{16}{12} * e^{0.11*WT4.04} - e^{4.04} \quad \textbf{Equation 2}$$

where ME are the methane emissions [kg CH_4 ha^{-1} yr^{-1}] and WT is the water table depth. The water table is equal to the negative drainage depth in Equation 1 (WT = - DD). Hergoualc'h and Verchot (2012) stress the fact that the reduction in methane emissions occurring because of the peat drainage would never offset the simultaneous increase in soil carbon dioxide emissions due to accelerated peat decomposition. The CH_4 emissions from peat drainage are modelled as fossil emissions, consistent with CH_4 emissions from drainage ditches.

2.8. Quantifying the effect of nature conservation

Nature conservation (also referred to as nature preservation) is a voluntary action to set aside a share of the land bank, in order to increase the biodiversity richness and avoid the conversion of oil palm in HCV areas into agricultural land. The current study accounts for the effects of nature conservation both in terms of global warming (GHG emissions/sink) and in terms of impact on biodiversity.

We account for both direct LUC and iLUC GHG emissions from nature conservation: direct emissions are the difference between the carbon stock of the HCV area and the carbon stock of the oil palm, converted in terms of CO_2. The iLUC emissions are the remote effect induced by avoiding the conversion of the conserved land into productive land. The potential productivity of the HCV land is accounted for, to estimate the land equivalent that needs to be supplied somewhere else. The amount of land equivalent calculated is then linked to the iLUC model described in section 2.5.

We used the detailed survey data collected in the estates to estimate the carbon stock of the HCV land set aside for nature conservation. For Hanau's estates, we used the average carbon stock of these estates to represent the estates for which no survey data are available. The carbon stock included the above and below ground biomass carbon, the soil carbon and the carbon content of the decomposing organic matter. This allowed us to accurately model the actual carbon stock in the HCV areas, for which detailed plot-specific data are typically missing. The net avoided GHG emissions achieved by nature conservation is the difference between the calculated carbon content in HCV land and in oil palm plantations in the estates. This methodology is further described in Schmidt (2015b, 2017). We modelled peat soil carbon as a separate carbon pool from soil organic carbon and below ground carbon. The avoided peat emissions are calculated as a function of the peat drainage depth of the oil palm plantations, as described in section 2.7, because the area would have been converted to oil palm plantation if nature conservation did not occur.

Biodiversity impacts from land occupation are expressed in Potentially Disappearing fraction (PDF) per year, measured in m^2*year. A value of 1 PDF represents the occupation of 1 m^2*year of global average land with the highest impact, e.g. a type of land occupation completely hostile to species. The biodiversity modelling is described in detail in Schmidt and de Saxcé (2016). When impact on biodiversity is caused by iLUC, the model estimates the effect as the global average effect in terms of PDF. When the impact on biodiversity is caused by direct on-site LUC such as nature conservation activities, the model estimates instead the on-site PDF. Due to lack of primary data for species richness in PT SMART's nature conservation sites, a rough proxy has been estimated: the global PDF effect has been weighted by the potential net primary productivity (NPP_0) in Indonesia relative to global average for arable land. This means that nature conservation in PT SMART's estates contain 1.97 more species than the global average of land that is typically converted to arable land.

2.9. Life Cycle Impact Assessment (LCIA)

In accordance with the goal and scope of this paper, we assess the global warming effect (carbon footprint) and the nature occupation due to palm oil production, the two most relevant impact categories in palm oil production (Schmidt and De Rosa 2020), by applying the impact assessment method Stepwise version 1.7. The climate metric used to measure global warming is Global Warming Potential (GWP100) with unit CO_2-eq. (IPCC 2013). The typical sources of GHG emissions in the palm oil production system are carbon dioxide, methane, and nitrous oxide. In GWP100, 1 kg methane corresponds to 27.75 kg CO_2-eq. (Muñoz and Schmidt 2016) and 1 kg N_2O corresponds to 265 kg CO_2-eq. Biogenic CO_2 flows are excluded with the exception of indirect land use changes (iLUC) and nature conservation-related CO_2 flows.

3. **Results**

3.1. Global warming

Figure 4 shows that the carbon footprint of palm oil produced at Hanau and Sungai Rungau is significantly lower than the average non-certified palm oil. The carbon footprint is also lower than the average RSPO-certified palm oil calculated by Schmidt and De Rosa (2020). The production of 1kg of RBD palm oil in the Hanau system causes 2.72 kg CO_2-eq/kg RBD palm oil. **Table 5** shows that the oil crop cultivation stage, including iLUC, generates 77% of the GHG emissions (2.09 kg CO_2-eq/kg), followed by the oil mill stage with 27% (0.73 kg CO_2-eq/kg). The refinery stage decreases the impact by 4% (-0.05 kg CO_2-eq/kg) due to the contribution of the by-products PFAD/PKFAD (**Table 5**).

In the oil palm cultivation stage, the largest contribution to Hanau's GHG emissions are the field emissions (0.66 kg CO_2-eq/kg), and iLUC (**Table 5**). The GHG emission contribution of iLUC is 20% (0.56 kg CO_2-eq/kg) of the total emissions. Although peat emissions are a significant share of Hanau's oil palm cultivation stage (10%), those are still significantly lower than the peat emissions in RSPO certified (- 88%) and non-certified palm oil (- 64%) due to the lower share of cultivated peat and the lower peat drainage depth (**Table 5**). Nature conservation activities result in a negative contribution (carbon sink in biomass) of -0.05 kg CO_2-eq/kg (avoided emissions) which lowers the emissions by 2% (**Table 5**).

The production of 1kg of RBD palm oil in the Sungai Rungau system causes 2.25 kg CO_2-eq/kg RBD palm oil. In Sungai Rungau, the oil crop cultivation stage (including iLUC) generates only 44% of the GHG emissions (1.00 kg CO_2-eq/kg), while the palm oil milling stage is the highest contributor (**Table 5**) with 59% of the GHG emissions (1.33 kg CO_2-eq/kg). The refinery stage decreases the impact by 2% (-0.05 kg CO_2-eq/kg) due to the contribution of the by-products PFAD/PKFAD (**Table 5**). In the oil palm cultivation stage, the largest contribution to Sungai Rungau's GHG emissions are the field emissions (0.40 kg CO_2-eq/kg) and the iLUC contribution. Peat emissions are not present, because no peat soil is cultivated in Sungai Rungau. The GHG emission from iLUC is 18% (0.41 kg CO_2-eq/kg) of the total emissions. Nature conservation activities result in a negative contribution (carbon sink in biomass) of -0.02 kg CO_2-eq/kg (avoided emissions) which lowers the emissions by 1%.

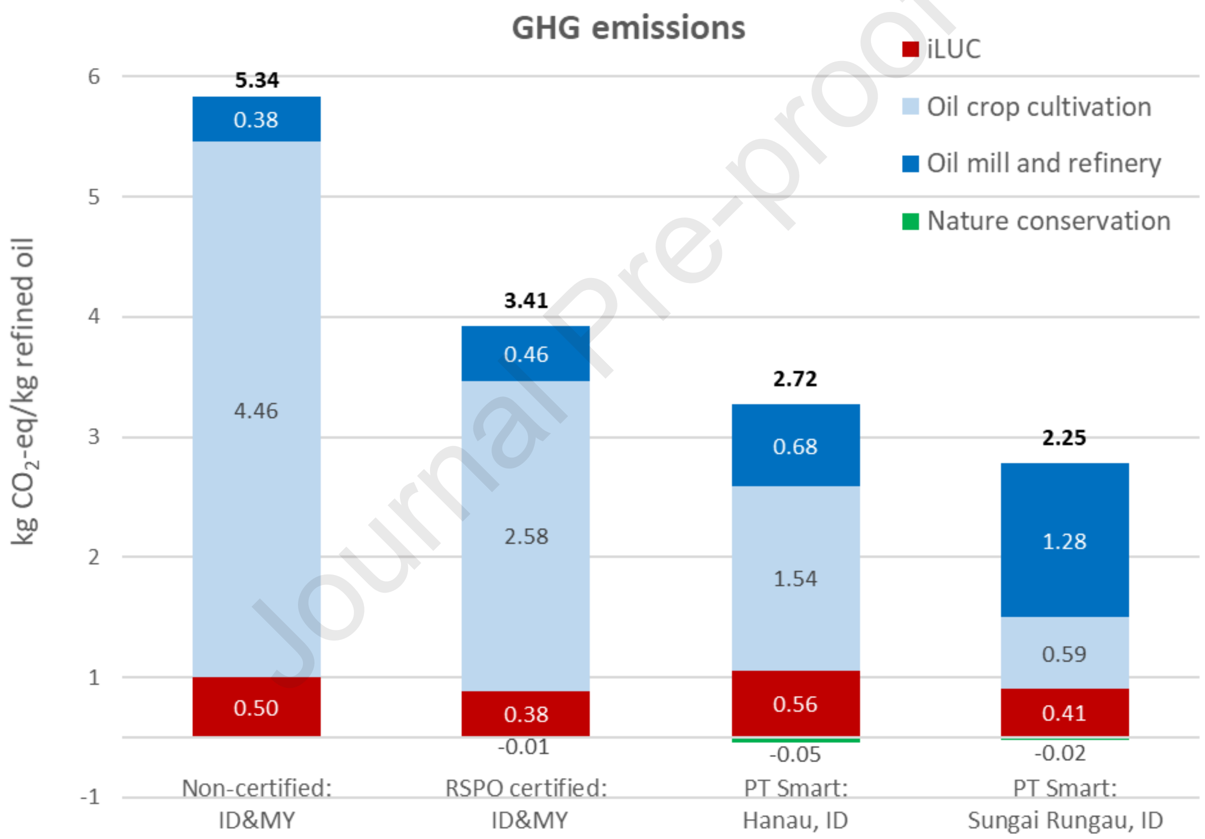

Figure 4*. GHG emissions per kg Refined Bleached and Deodorised (RBD) palm oil for average RSPO certified and non-certified palm oil produced in Indonesia & Malaysia (first and second column) and PT SMART's RBD palm oil produced at Hanau and Sungai Rungau's facilities (third and fourth column).*

The production of Hanau's RBD oil emits 20% less GHGs than average RSPO-certified palm oil and 49% less than non-certified palm oil. The production of Sungai Rungau's RBD oil emits 34% less GHGs than average RSPO-certified palm oil and 58% than non-certified palm oil (**Table 5**). The largest GHG emission reduction is achieved in the oil palm cultivation stage, where Hanau's GHG emissions are 19% lower than average RSPO-certified production and 53% lower than average non-certified, while Sungai Rungau's GHG emissions are 61% lower than average RSPO-certified production and 78% lower than average non-certified. The most significant emission reduction in the oil palm cultivation stage is achieved due to the lower share of oil palm cultivated on peatland in Hanau and complete absence of peatland in the Sungai Rungau supply base (**Table 5**). This result confirms the importance of avoiding the cultivation of tropical peatlands to reduce GHG emissions, or reducing the peat drainage depth where peat soil is cultivated.

Table 5. *Contribution analysis: GHG emissions per kg Refined Bleached and Deodorised (RBD) palm oil produced at PT SMART's facilities of Hanau and Sungai Rungau compared to Indonesian and Malaysian average RSPO certified and non-certified palm oil. Unit: kg* CO_2*-eq.*

GHG contribution analysis	**Industry average ID&MY**		**PT SMART**	
	Non-cert.	**RSPO-cert**	**Hanau**	**Sungai Rungau**
Crop cultivation				
Field emissions (related to nutrient cycle)	0.92	0.72	0.66	0.40
Field emissions (related to peat drainage)	2.36	0.77	0.28	0
Indirect land use changes (iLUC)	0.62	0.49	0.56	0.41
Materials: Fertilisers, chemicals and packaging	0.21	0.33	0.27	0.11
Energy	0.08	0.07	0.07	0.03
Other (transport, waste treatment, assets and services)	0.27	0.20	0.26	0.06
Total Crop Cultivation	**4.46**	**2.58**	**2.09**	**1.00**
Nature conservation				
HCV nature conservation	0.00	-0.01	-0.05	-0.02
Palm oil mill				
POME treatment	1.51	1.19	1.45	1.61
Energy	-0.06	-0.03	-0.05	-0.03
Other (transport, waste treatment, assets and services)	0.18	0.17	0.20	0.12
By-products: Kernels	-0.70	-0.43	-0.38	-0.31
By-products: Utilization of EFB and excess shell	-0.04	-0.04	**-0.49**	-0.06
Total Palm Oil Mill Stage	**0.89**	**0.86**	**0.73**	**1.33**
Refinery				
Materials: chemicals and water	0.02	0.02	0.01	0.01
Energy	0.03	0.03	0.11	0.11
Other (transport, waste treatment, assets and services)	0.02	0.02	0.00	0.00
By-products: PFAD/PKFAD	-0.08	-0.08	-0.17	-0.17
Total Refinery Stage	**-0.01**	**-0.01**	**-0.05**	**-0.05**
Sum	**5.34**	**3.41**	**2.72**	**2.25**

The GHG emission reduction achieved through conservation of HCV land in Hanau and Sungai Rungau, shown separately in **Figure 4** and **Table 5**, is both higher than average RSPO-certified and non-certified palm oil (more negative values) due to the higher share of nature conservation in Hanau's supply-base. The GHG emission reduction from conservation in Hanau is also higher than the reduction in Sungai Rungau, due to the presence of (and therefore avoided emissions from) peat soil.

The oil milling stage shows a slightly lower contribution for Hanau POM compared to average certified production, but a significantly higher contribution for Sungai Rungau POM. The POME treatment emissions in Hanau and Sungai Rungau are higher than average RSPO-certified, because Hanau and Sungai Rungau POMs do not have biogas capture facilities and the biogas is treated in open ponds, which causes higher methane emissions. The improvement potential through installing biogas capture facilities is discussed in section 4.4 below. Nevertheless, in the case of Hanau, the total POM GHG emissions are still lower than average certified and non-certified, because Hanau POM uses a large amount of the by-products empty fruit bunches (EFB) and excess shells as a fuel substitute. This results in a significant negative contribution (avoided emissions) as shown in **Table 5**. For Sungai Rungau, the POM GHG emissions are higher than average certified and non-certified, because the POME GHG emissions are higher than in Hanau, while the avoided emissions from the by-products are very low: in Sungai Rungau the shells are not exported for electricity production. Instead, they are used less efficiently in the oil mill boiler.

The palm oil refinery stage contributes with net negative GHG emissions for both Hanau and Sungai Rungau. The refinery's contribution is identical for the two systems per kg of RBD oil, because they both refine the oil at the Marunda refinery, in Jakarta, as discussed in section 2.2. The negative contribution from the by-products in the refinery stage is higher for Hanau and Sungai Rungau than in average certified and non-certified palm oil (Schmidt and De Rosa 2020). In Schmidt and De Rosa (2020) the by-products PFAD/PKFAD are modelled as substituting animal feed. In the Marunda refinery, the PFAD/PKFAD are used for biodiesel production, hence substituting fuel.

3.2. Nature occupation

Hanau's production system shows a nature occupation of 1.56 PDF m^2/kg RBD palm oil, 4.4% lower than average certified production and 24% lower than non-certified. Sungai Rungau's production system shows a nature occupation of 1.16 PDF m^2/kg RBD palm oil, 29% lower than average certified production and 43% lower than non-certified. This means that the impact is lower in terms of natural area occupied and biodiversity loss. The result in **Figure 5** shows that the contribution of nature conservation in Hanau and Sungai Rungau's supply-base estates is crucial to achieve the impact reduction. This is calculated by the iLUC model, triggered when a production system requires land as a production input. The negative contribution indicates the avoided nature occupation and the avoided loss of biodiversity. **Figure 5** shows a small contribution of nature conservation for RSPO-certified production as well, while non-certified production systems do not set aside any share of the land bank for conservation activities (Schmidt and De Rosa 2020).

In terms of actual land occupied to produce 1 kg of RBD palm oil from Hanau POM, 2.22 m^2*year are required instead of the 2.35 m^2*year for RSPO-certified and 2.95 m^2*year for non-certified palm oil. The area required for Hanau POM's production is the sum of 2.22 m^2*year of land occupied in Indonesia for the cultivation of oil palms and -0.004 m^2*year of avoided use of land in other countries due to the substitution effect of animal feed obtained using the by-products PFAD. The inventory data for nature occupation show that 1 kg of RBD palm oil from Sungai Rungau requires 1.87 m^2/year. The area of 1.87 m^2/year is obtained by summing 1.97 m^2/year required in Indonesia, where the actual cultivation of palm oil occurs, and -0.1 m^2/year of avoided land use in other countries caused by the substitution of animal feed due to the by-products PFAD.

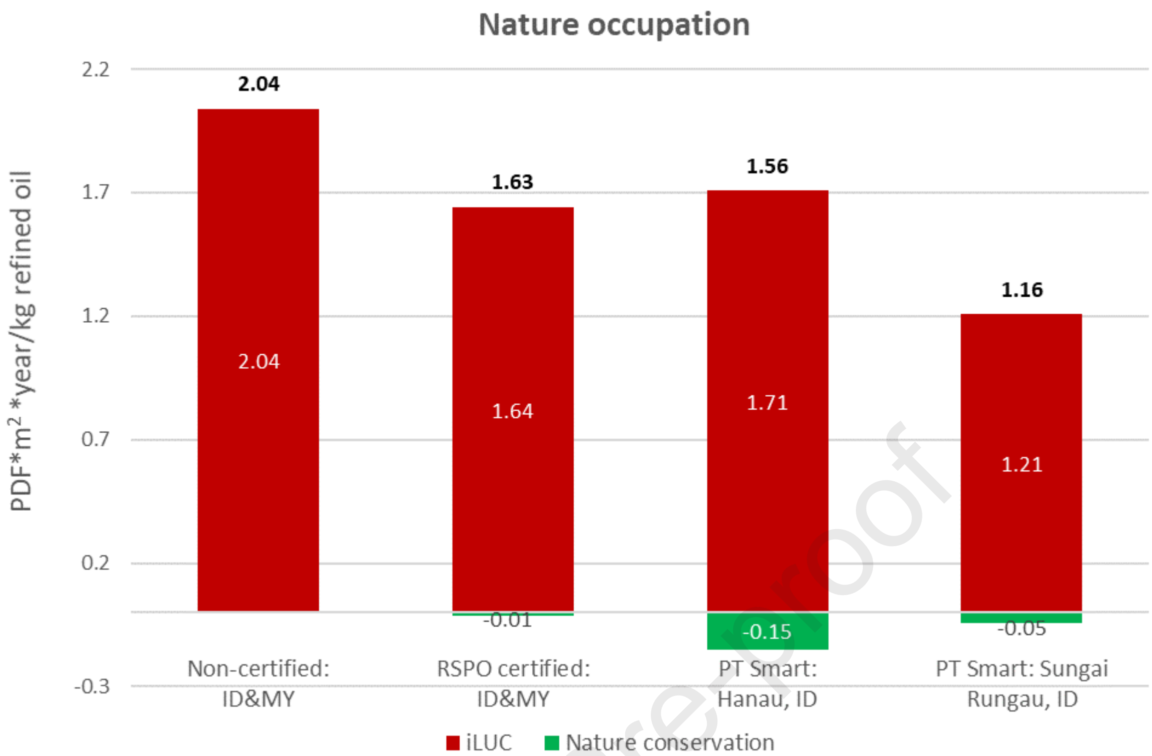

Figure 5*. Nature occupation per kg Refined Bleached and Deodorised (RBD) palm oil for average RSPO certified and non-certified palm oil produced in Indonesia & Malaysia (first and second column) and PT SMART's RBD palm oil produced at Hanau and Sungai Rungau's facilities (third and fourth column).*

4. Discussion

The results presented above show that the major contribution to GHG emissions in PT SMART's Hanau and Sungai RungauPOMs originates from the oil crop cultivation in the oil palm estates and from the treatment of POME in the oil milling stage. The thickness of the flows in **Figure 6** and **Figure 7** below shows the contribution of GHG emissions from estates and palm oil mills with respect to the other sources, demonstrating how reducing the emissions from estates and POME treatment is crucial in reducing the GHG emissions per kg of palm oil.

In the crop cultivation stage, avoiding the use of tropical peatland is a key factor in reducing the GHG emissions. Due to the lower peat share and to higher share of land set aside for nature conservation, the palm oil of Hanau's POM system shows a lower impact both in terms of GHG emissions and biodiversity loss than certified and non-certified average palm oil production. Currently 12% of the palm oil cultivation area is on peatland and 8% of the land bank is set aside for nature conservation. The potential GHG reduction achievement by avoiding cultivation of peat soil is even clearer in Sungai Rungau (**Figure 7**), where no peat soil is present in the supply-base. The higher yields of Hanau and Sungai Rungau's supply-base are also crucial to reduce the impact per kg of product. Yet, the figures also show potential margins for further improvements. These could be achieved by increasing the area reserved for nature conservation, thus reducing the GHG emissions and the nature occupation, reducing the area of cultivated peat and reducing POME GHG emissions.

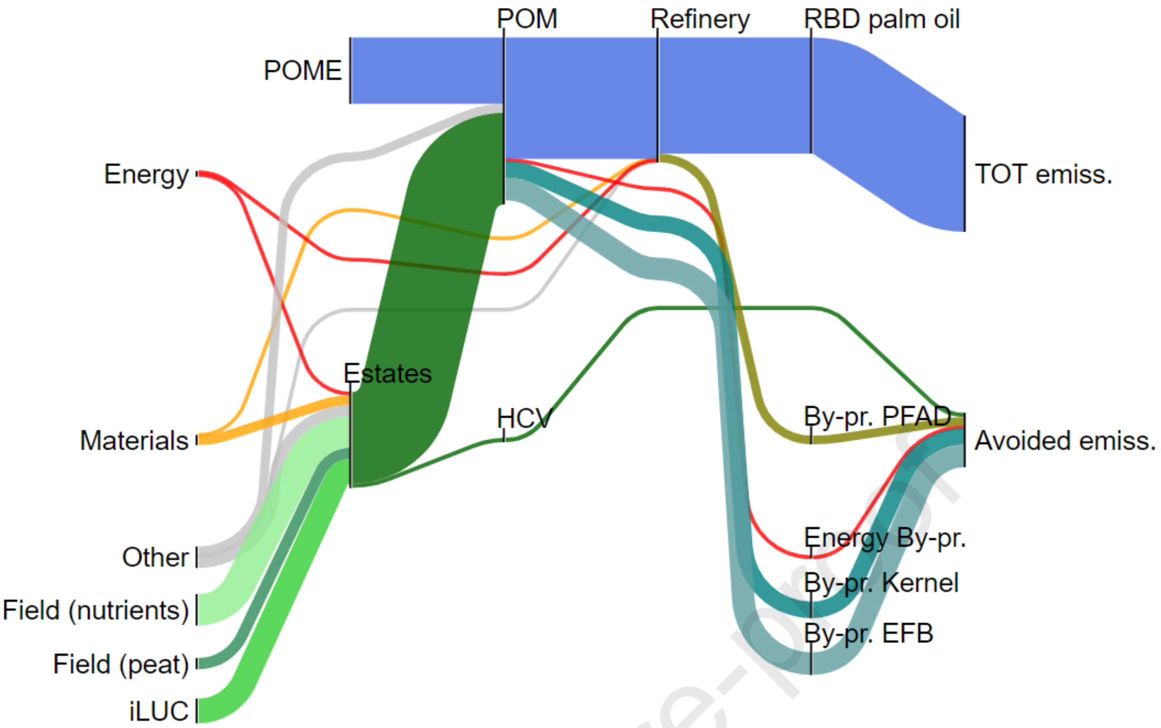

Figure 6. *GHG emissions flows per kg refined bleached and deodorised (RBD) palm oil produced at PT SMART's mill of Hanau. Unit: kg* CO_2*-eq. The thickness of the flows is proportionate to the flows in this figure and cannot be compared with the thickness of the flow in Figure 7.*

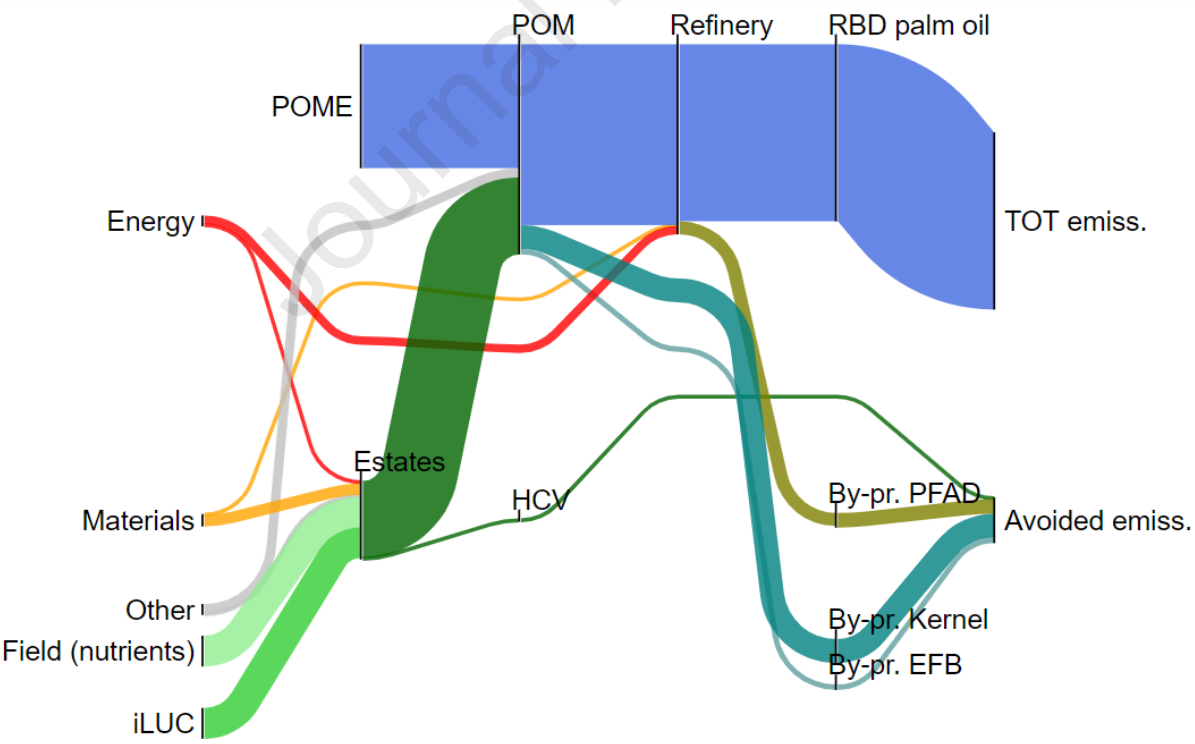

Figure 7. *GHG emissions flows per kg refined bleached and deodorised (RBD) palm oil produced at PT SMART's mill of Sungai Rungau. Unit: kg* CO_2*-eq. The thickness of the flows is proportionate to the flows in this figure and cannot be compared with the thickness of the flow in Figure 6.*

To investigate the potential reduction achievable by implementing these solutions, we performed an improvement analysis. The analysis assesses the variation of the results when the following improvement option are implemented: increasing the share of nature conservation areas to achieve both lower GHG emissions and lower nature occupation (section 4.1); reducing the share of cultivated peat soil to reduce GHG emissions (section 4.2); biogas capture and utilisation options to reduce GHG emissions, distinguishing four different options (section 4.4). We also performed a sensitivity analysis to test the GHG emission reduction obtained assuming a higher or lower carbon content of the area set aside for nature conservation than the value used to calculate the results above (105t C/ha) (section 4.4).

4.1. Nature conservation

Section 2.8 showed that nature conservation affects both global warming and nature occupation. This section discusses the improvements achieved in Hanau and Sungau Rungau's supply-base with the current level of nature conservation, and the feasible further improvements throughfurther increasing the nature conservation area.

Currently 8% and 7% of the Hanau and Sungai Rungau land banks are set aside for nature conservation, reducing GHG emissions by 2% and 1% respectively. The reduction achieved in Hanau is more prominent due to the presence of peat soil in the land set aside for nature conservation. We investigated the further potential reductions by increasing the area dedicated to nature conservation to 15% and 30%, and compared the results with the scenario where no nature conservation is carried out.

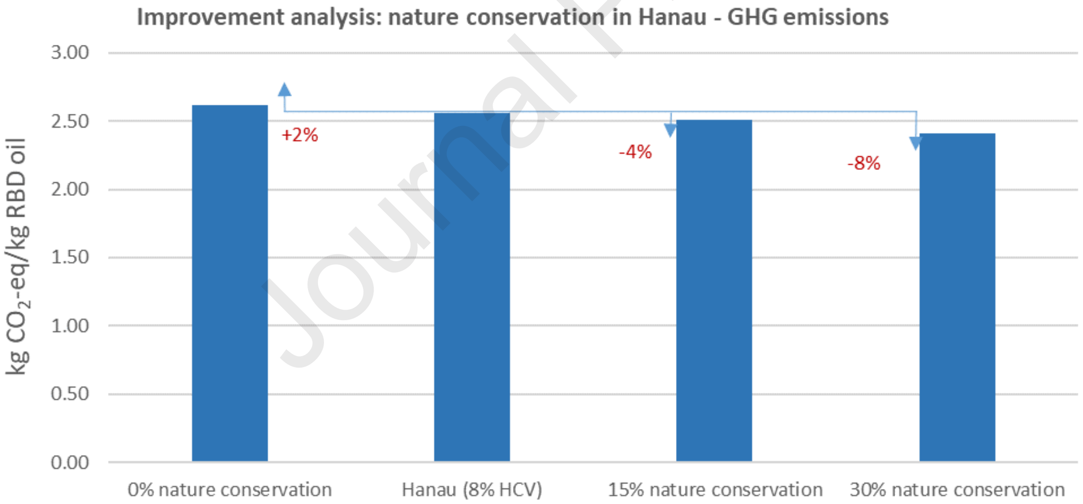

Figure 8. *GHG emissions reduction achieved HCV land set-aside for nature conservation in Hanau's land bank. The baseline shows the current scenario, where 8% of the land bank is set-aside for nature conservation. The two scenarios on the right show the potential reduction achievable by setting-aside 15% and 30% of the land bank respectively for nature conservation. Unit: kg CO_2-eq.*

Increasing the area of the land bank set aside for nature conservation in Hanau's supply-base to 15% would decrease the emissions by a further 4% compared to the current scenario. A reduction of 8% of the current emissions would be obtained if 30% of the total Hanau land bank were dedicated to nature conservation (**Figure 8**). Increasing the area of land bank set aside for nature conservation in Sungai Rungau's supply-base to 15% would decrease the emissions by a further 1% compared to the current scenario. A reduction of 3% of the current emissions would be obtained if 30% of the total Sungai Rungau land bank were dedicated to nature conservation (**Figure 9**). The higher potential reduction in Hanau is due to the presence of peat soil in the area set aside for nature conservation.

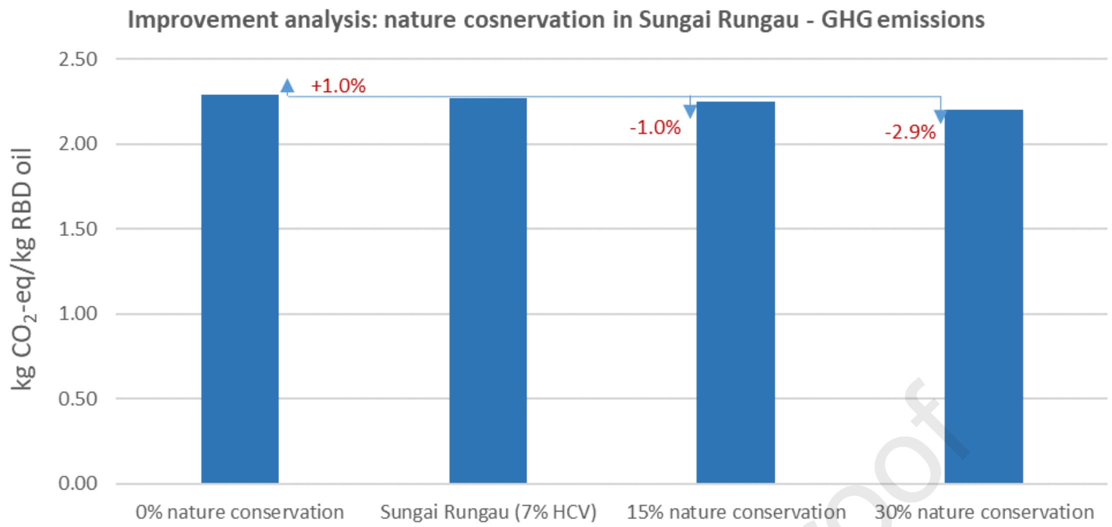

Figure 9.*GHG emissions reduction achieved HCV land set-aside for nature conservation in Sungai Rungau's land bank. The baseline shows the current scenario, where 7% of the land bank is set-aside for nature conservation. The two scenarios on the right show the potential reduction achievable by setting-aside 15% and 30% of the land bank respectively for nature conservation. Unit: kg CO_2-eq.*

The area set aside for nature conservation also has an effect in terms of nature occupation (biodiversity). **Figure 10** and **Figure 11** show how biodiversity loss might be further mitigated by increasing the area for nature conservation. Currently, the nature occupation impacts are already reduced by 10% in Hanau and 14% in Sungai Rungau thanks to the current share of land set aside for nature conservation (8% and 7% respectively). The nature conservation impact would further reduce by 10% and 14% increasing the share of land set-aside for nature conservation to 15% of the total, and would further reduce by 29% and 43% respectively if increasing the share of land set-aside to 30% of the land bank in Hanau and Sungai Rungau respectively. The higher reduction potential in Sungai Rungai depends on the current HCV, which presents a higher forestation as shown by the carbon content of the HCV in Sungai Rungau (**Table 2**).

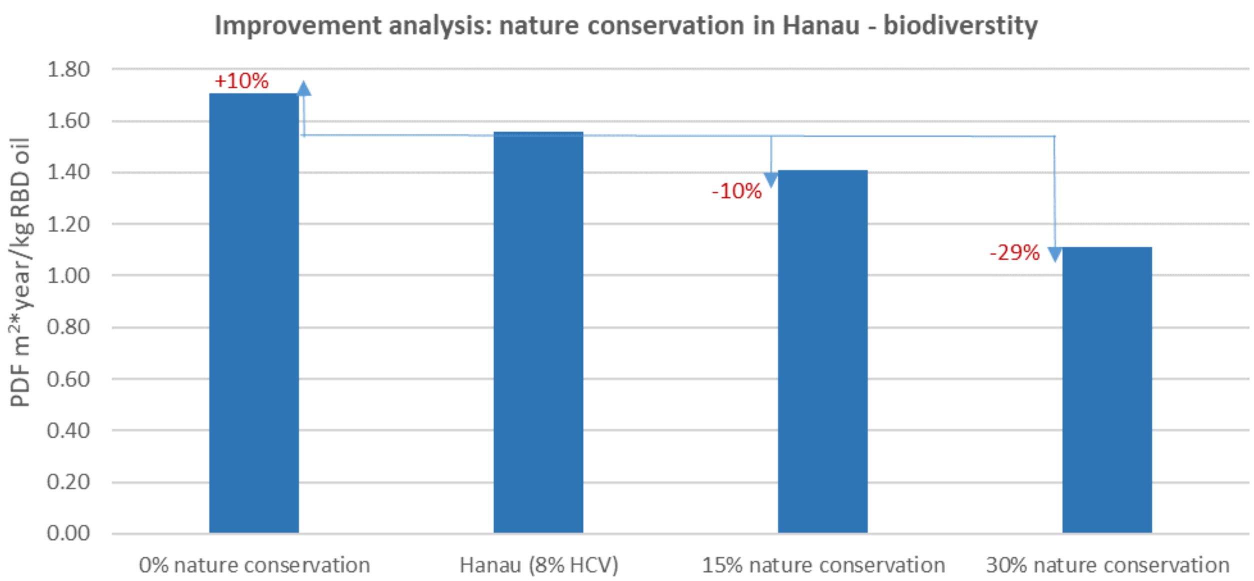

Figure 10*. Biodiversity impacts for palm oil production with different shares of land-bank set-aside for nature conservation in Hanau. The baseline shows the current scenario where 8% of the land bank is set-aside for nature conservation. Unit: Potentially Disappearing Fraction (PDF) m*^{2}**year.*

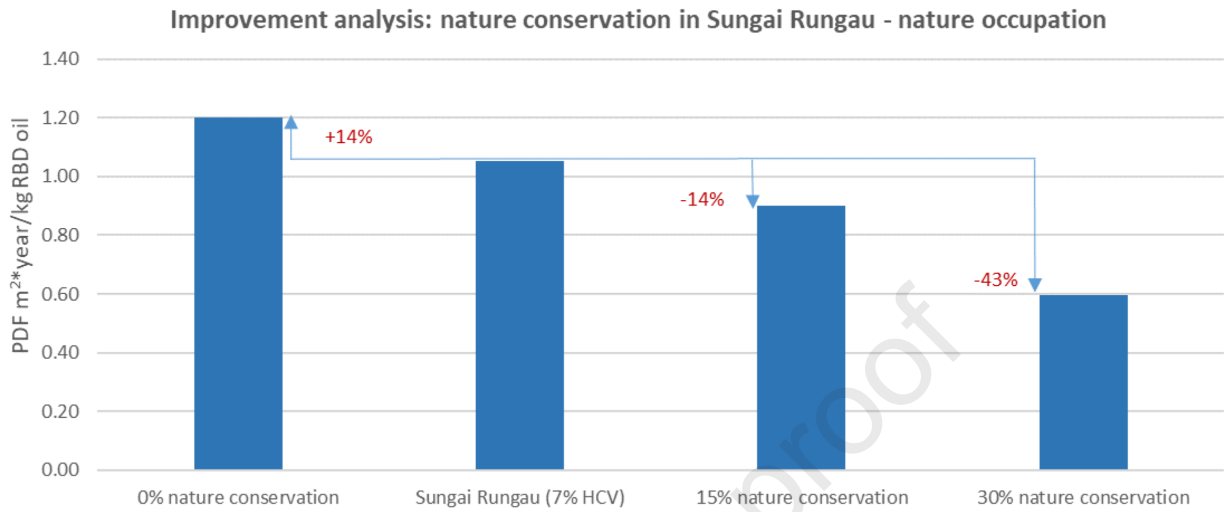

Figure 11*. Biodiversity impacts for palm oil production with different shares of land-bank set-aside for nature conservation in Sungai Rungau. The baseline shows the current scenario where 7% of the land bank is set-aside for nature conservation. Unit: Potentially Disappearing Fraction (PDF) m*^{2}**year.*

4.2. Reducing the cultivation on peat soil: Hanau

Currently 12% of the oil palm in Hanau's supply-base is on peat soil. No peat soil is cultivated in Sungai Rungau. We calculated the reduction achieved with a share of peat soil as found in the average RSPO certified palm oil (11%) and compared the current emissions with further reduction achievable if the peat share is halved (6%) and if peat soil is completely avoided.

Reducing the peat share by 1% would already harvest a GHG emission reduction of 2%, while halving the peat share would result in a GHG emission reduction of 5% (**Figure 12**). Completely avoiding the cultivation of oil palm peat soil in Hanau's supply-base would reduce the emissions by 8%. Although there is a large potential for further lowering the global warming effect of palm oil production by avoiding cultivation on peat soil, this is becoming increasingly difficult as oil palms continue to be established in South-East Asia.

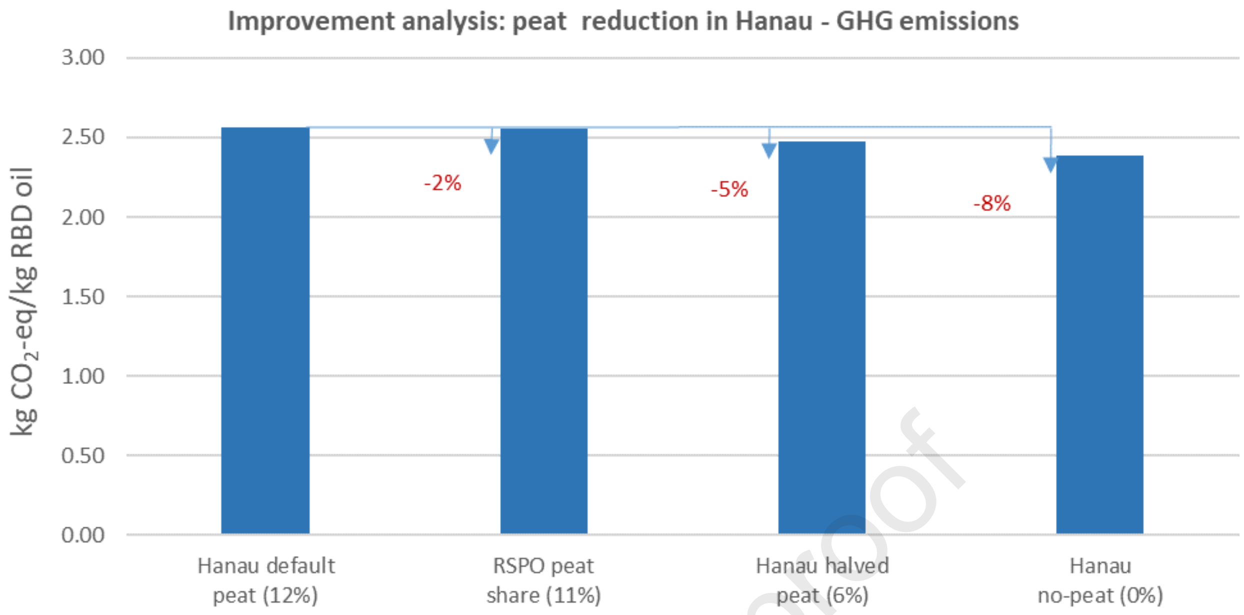

Figure 12*. GHG emissions reduction achieved in Hanau by decreasing the share of cultivated peats soil and further improvement analysis. Unit: kg CO_2-eq.*

4.3. Nature conservation and peat soil: sensitivity analysis

The results presented in **Figure 8** and **Figure 9** are calculated by using the default IPCC (2006) average values for carbon content in tropical forest. However, average figures may not represent the actual carbon content in the area set aside for nature conservation in a determined estate. Moreover, when peat land is present, the potential GHG emission reduction also depends on the share of peat land and the peat drainage depth of the land set aside for nature conservation. This is the case of Hanau's estates, due to the presence of peat soil in the land set aside, which is absent in Sungai Rungau's land bank. **Figure 13** shows the potential GHG emission reduction using a higher or lower carbon content value than the value used to calculate the results above (105t C/ha). **Figure 13** also shows the potential GHG emission reduction if the set-aside land is fully on peat soil, or if no peat soil is present, and if the drainage depth found is as in the average non-certified estates (73 cm) or RSPO-certified estates (57cm), according to Schmidt and De Rosa (2020). Combined, the figure shows twelve GHG emissions reduction scenarios. The highest GHG emission reduction is achievable by converting the currently cultivated peat land with deep peat drainage and the highest carbon content to nature conservation. However, the figure also shows that drainage depth is a key factor in reducing GHG emissions. Therefore, if avoiding peat land cultivation is not possible, a better management of the peat drainage can also have a significant contribution in reducing the carbon footprint.

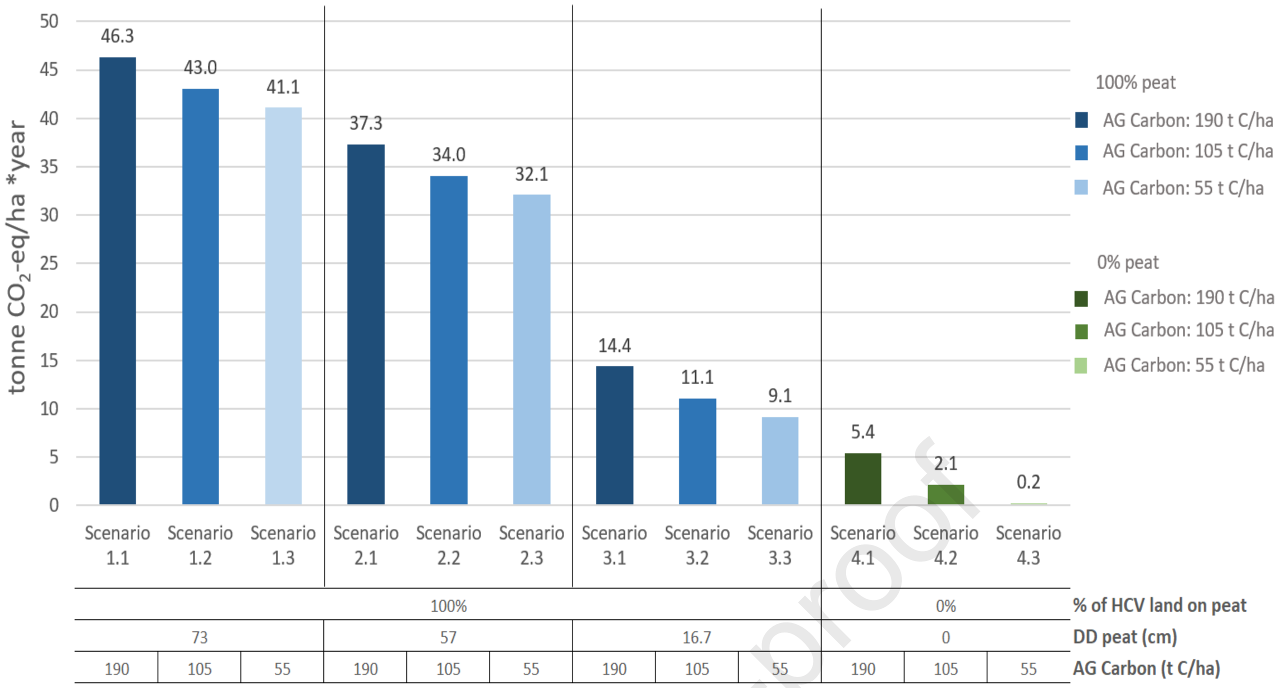

Figure 13. *GHG emissions reduction achievable by setting aside 1 ha of HCV land under in different conditions. The scenarios test the following parameters: the share of set-aside land on peat soil (100% or 0%); the peat drainage depth (DD, in cm); the above ground (AG) carbon (C).*

Table 6. *GHG emissions reduction obtained with lower and higher carbon stock in nature conservation for Sungai Rungau palm oil. Results are shown for GHG emissions as kg CO_2-eq./kg RBD palm oil and as a percentage variation compared to the result obtained with the default value.*

Investigated parameter	**GHG emissions kg CO_2-eq.**	**% Increase/Decrease**
Low carbon stock: 107 t C/ha	2.31	2.6%
Default: 213 t C/ha	2.25	-
High carbon stock: 427 t C/ha	2.18	-3.1%

The share of peat soil in the land set aside for nature conservation and the peat drainage depth are parameters determined by the management choices and practices. The variability of the carbon content in tropical forest is a parameter often difficult to estimate, and thus a potential source of uncertainty. In order to investigate that, we performed a sensitivity analysis on Sungai Rungau results (where no peat land is present) by doubling and halving the default carbon stock value. **Table 6** shows that carbon stock value could decrease the GHG emissions by -3.5% or increase them by +2.2% in the case of Sungai Rungau. However, the emission reduction obtained by nature conservation would still be significant when assuming halved carbon content in the conserved area and the GHG emissions per kg RBD oil would still be substantially lower than the average RSPO-certified palm oil emissions. A carbon stock twice as high as the default scenario would yield a further reduction of 0.08 kg CO_{2eq}.* year/ha. This parameter only affects global warming, not nature occupation.

4.4. Biogas capture facilities

The contribution analysis in **Table 5** showed that both Hanau and Sungai Rungau POME GHG emissions are higher than average RSPO certified POME GHG emissions. Sungai Rungau POME GHG emissions are also higher compared to average non-certified palm oil. Therefore, there are large margins for reducing POME emissions in both the mills. **Figure 14** presents the GHG emission reduction per kg RBD palm oil achievable in Hanau by installing biogas capture facilities compared with the baseline scenario which uses an open pond system, represented by the current GHG emissions. Biogas capture significantly reduces the POM's GHG emissions and the overall emissions. We analysed four biogas capture options. Biogas capture with open flare, i.e. openly combusting the captured biogas and thus avoiding methane emissions, reduces the emissions by 30%. A more expensive solution is enclosed flaring, where the biogas is combusted at a higher temperature to destroy the toxic elements contained in the biogas. Enclosed flare would achieve a reduction of 47% compared to the baseline scenario. The highest reductions are achieved when the biogas is captured and used in the POM boiler or in biogas engines for electricity generation with a net GHG emissions reduction of 60% and 59% of GHG emissions, respectively (**Figure 14**).

Figure 15 presents the GHG emission reduction per kg RBD palm oil by installing biogas capture facilities in Sungai Rungau compared with the baseline scenario, represented by the current GHG emissions obtained with an open pond system. As for Hanau, the figure shows that capturing biogas significantly reduces the POM's GHG emissions and, in turn, the total emissions per kg RBD oil compared to the baseline scenario. Four biogas capture options are analysed. **Figure 15** shows the different improvement options based on the descending order of their performances: biogas capture with open flare, i.e. openly combusting the captured gas to avoid methane emissions, would reduce the emissions by 31%. Enclosed flaring, which combusts the biogas at a higher temperature to destroy the toxic elements contained in the biogas, is generally a more expensive solution than open flaring. Enclosed flaring would achieve an even more substantial GHG emission reduction of 52% compared to the baseline scenario. Flaring does not allow utilization of the captured biogas. However, once captured, the biogas could be used as a fuel. The two last biogas treatment solutions analysed show the emission reduction achieved when the captured biogas is used in the POM boiler or in biogas engines for electricity generation. These options yield the best results, with a net GHG emission of 60% and 59% respectively.

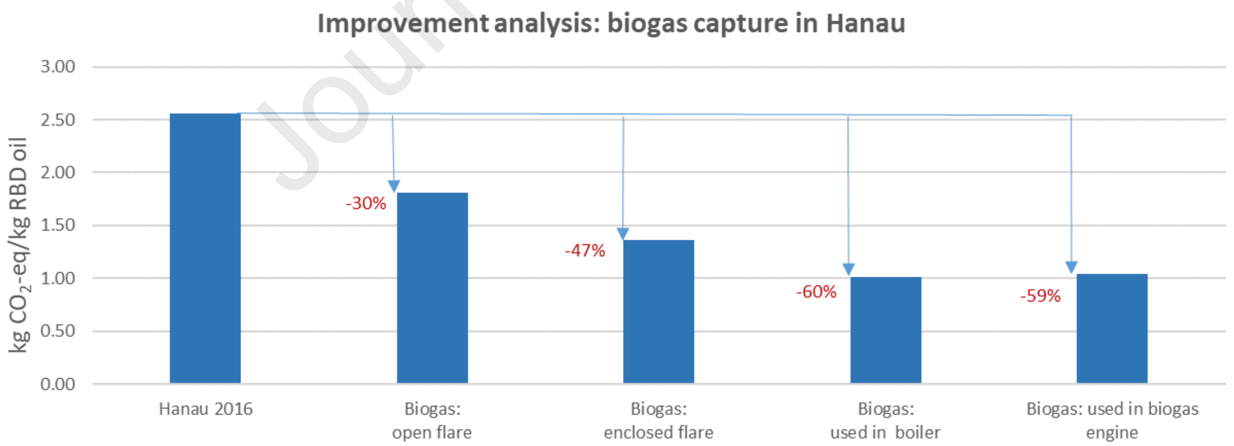

Figure 14. *Reduction of GHG emissions for 1kg of RBD palm oil production achievable by implementing four different biogas treatment options in Hanau POM: biogas capture with open or enclosed flaring and utilization in boilers or biogas engine. The Hanau's baseline scenario, 'Hanau 2016', does not include any biogas capture facility, because POME are currently treated in an open pond system.*

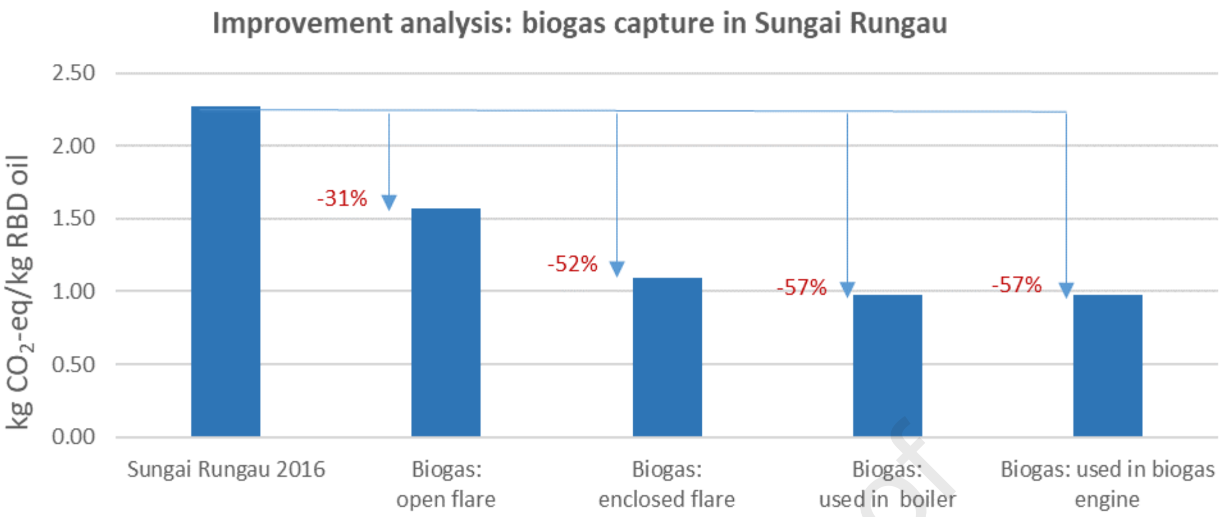

***Figure 15**. Reduction of GHG emissions for 1kg of RBD palm oil production achievable by implementing four different biogas treatment options: biogas capture with open or enclosed flaring, and biogas capture and utilization in boilers or biogas engine. The Sungai Rungau's baseline scenario, 'PT SMART 2016'. does not include any biogas capture facility, because POME are currently treated in an open pond system.*

5. Conclusions

The results show that industry-driven mitigation measures can reduce, to a large extent, the carbon footprint and the impact on biodiversity of palm oil production. The effects of reducing or avoiding peat soil in oil palm plantations and of setting aside part of the land-bank for nature conservation are assessed by performing a Life Cycle Analysis of two detailed case studies, i.e. the palm oil produced at PT SMART's Hanau and Sungai Rungau facilities. The GHG emissions in Hanau and Sungai Rungau are 2.72 and 2.25 kg CO_2-eq. *year/kg RBD oil respectively. The nature occupation is 1.56 and 1.16 PDF m^2*year/kg RBD oil respectively.

Compared to the Indonesian and Malaysian industry average, Hanau's GHG emissions are 49% lower than the non-certified GHG emissions and 20% lower than RSPO-certified GHG emissions. The reductions are achieved mainly in the palm oil cultivation stage. In particular, Hanau shows lower GHG emission from peat soil, i.e. lower peat soil share in the estates and shallower peat drainage, and from nature conservation measures. Hanau's supply-base and part of the land set aside for nature conservation includes peat soil. Reducing the peat drainage depth appears to be an effective solution to reduce GHG emissions in estates where avoiding cultivation of peat soil is not possible. This is becoming particularly relevant due to the increasing scarcity of mineral soil for agricultural conversion in Indonesia and Malaysia.

Sungai Rungau's GHG emissions are 58% lower than the non-certified production and 34% lower than the RSPO-certified production. The reductions are achieved in the palm oil cultivation stage, mainly by completely avoiding the cultivation of peat soil. Sungai Rungau's palm oil production is exclusively on mineral soil.

The results show that the benefit of nature conservation is twofold: reducing GHG emissions and reducing the impact on biodiversity. In Hanau, nature conservation reduces the biodiversity impacts by 4% and 24%

compared to RSPO-certified and non-certified respectively. In Sungai Rungau, the biodiversity impact decreases by 28% and 43% compared to RSPO-certified and non-certified respectively.

There is potential to reduce the carbon footprint and the biodiversity impact even further by increasing the area dedicated to nature conservation. Currently, Hanau and Sungai Rungau's nature conservation sites occupy 8% and 7% of the land bank respectively, ensuring a GHG emission reduction of 2% and 1%, and a biodiversity impact reduction of 10% and 14% respectively. If the area set-aside for nature conservation is increased to 15%, the impacts from nature occupation could be further reduced by 10% in Hanau and 14% in Sungai Rungau. By increasing the area set aside for nature conservation to 30%, the nature occupation impacts could instead be reduced by 29% in Hanau and 43% in Sungai Rungau. Nature conservation in particular reduces GHG emissions and nature occupation in estates with peat soil and HCV land.

In Hanau's production system, a significant GHG emission reduction is also achieved in the palm oil milling stage, by exporting the by-product empty fruit bunches to produce energy. This is not the case in Sungai Rungau, where the empty fruit bunches are instead burned in the oil mill boiler.

The comparison of the results with average non-certified and RSPO-certified performances shows that there are potential for further improvements in the palm oil mill stage. In particular, there are margins to reduce the GHG emissions from POME by implementing biogas capture facilities, both in Hanau and Sungai Rungau's POM. If the captured biogas is used as a fuel for the POM boiler or in biogas engines for electricity generation, the carbon footprint could be reduced to less than half of current results, i.e. reducing the GHG emissions by a further 57% and 59% in Hanau and Sungai Rungau respectively.

The refinery stage provides only a minor contribution to the GHG emissions of palm oil production. However, the GHG emissions of the Maruda refinery, where Hanau and Sungai Rungau's palm oil is refined, are lower than the average palm oil refinery, due to the larger negative contribution of the by-product. In the Maruda refinery, the by-product PFAD/PKFAD is utilized to produce biodiesel, while typically PFAD/PKFAD are used as feed substitute.

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- Avoiding the cultivation of peat soil reduces the GHG emissions of palm oil production
- When oil palms are on peat soil, reducing the peat drainage depth reduces the GHG emissions
- Nature conservation initiatives reduce GHG emissions and nature occupation of palm oil production
- Capturing the biogas produced in palm oil mill effluents (POME) treatment reduces GHG emissions
- Using the captured biogas in boiler or biogas engine further abates the GHG emissions of palm oil

Declaration of interests

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

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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