



# Mitigation of unwanted direct and indirect land-use change – an integrated approach illustrated for palm oil, pulpwood, rubber and rice production in North and East Kalimantan, Indonesia

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## Abstract

The widespread production of cash crops can result in the decline of forests, peatlands, rice fields and local community land. Such unwanted land-use and land-cover (LULC) change can lead to decreased carbon stocks, diminished biodiversity, displaced communities and reduced local food production. In this study, we analysed to what extent four main commodities, namely, palm oil, pulpwood, rice and rubber, can be produced in North and East Kalimantan in Indonesia without such unwanted LULC change. We investigated the technical potential of four measures to mitigate unwanted LULC change between 2008 and 2020 under low, medium and high scenarios, referring to the intensities of the mitigation measures compared with those implemented in 2008. These measures are related to land sparing through (i) the improvements of yields, (ii) chain efficiencies, (iii) chain integration and (iv) the steering of any expansion of these commodities to suitable and available underutilised (potentially degraded) lands. Our analyses resulted in a land-sparing potential of 0.4–1.2 Mha (i.e. 24–62% of the total land demand of the commodities) between 2008 and 2020, depending on the land-use projection of the four commodities and the scenario for implementing the mitigation measures. Additional expansion on underutilised land is the most important mitigation measure (45–62% of the total potential), followed by yield improvements as the second most important mitigation measure (32–46% of the total potential). Our study shows that reconciling the production of palm oil, pulpwood, rice and rubber with the maintenance of existing agricultural lands, forests and peatlands is technically possible *only* (i) under a scenario of limited agricultural expansion, (ii) if responsible land zoning is applied and enforced and (iii) if the yields and chain efficiencies are strongly improved.

**Keywords:** deforestation, degraded lands, land sparing, land-use and land-cover change, North and East Kalimantan, palm oil, rice, tropical forests, underutilised lands, yield improvements

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## Introduction

The widespread production of food and nonfood cash crops in tropical rural areas often provides more prosperity to producers than subsistence crops (Sayer *et al.*, 2012). However, in the past few decades, land-use and land-cover (LULC) changes for the production of cash crops, such as oil palm and rubber, have led to the conversion of forests, peatlands, rice fields and the agricultural lands of local communities (Gibbs *et al.*, 2010; Wicke *et al.*, 2011; Susanti & Burgers, 2012; Inoue *et al.*, 2013; Abood *et al.*, 2014; Laurance *et al.*, 2014). Such LULC change can be classified as ‘unwanted’ because it

leads to decreased carbon stocks, diminished biodiversity, reduced local food production and the displacement of local communities (Fargione *et al.*, 2008; Koh & Wilcove, 2008; Hooijer *et al.*, 2010; Sodhi *et al.*, 2010; Abood *et al.*, 2014; Immerzeel *et al.*, 2014; Laurance *et al.*, 2014).

In Indonesia, the logging, pulpwood, palm oil and mining industries have been identified as the main contributors to unwanted LULC change, particularly on the islands of Kalimantan, Sumatra and Papua (Wicke *et al.*, 2011; Susanti & Burgers, 2012; Gaveau *et al.*, 2013, 2014; Abood *et al.*, 2014). Although the palm oil industry is currently identified as only the third main contributor to forest loss (Abood *et al.*, 2014), its contribution to LULC change in Indonesia is expected to increase substantially in the coming years (Koh & Ghazoul, 2010;

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OECD/FAO, 2015). This expectation is based on the strong rise of oil palm plantations in recent decades (FAOSTAT, 2014) and the growing domestic and global demand for palm oil for food and nonfood products, including biodiesel (Carriquiry *et al.*, 2010; OECD/FAO, 2015).

In 2012, almost half of the global crude palm oil (CPO) was produced in Indonesia, specifically, 26 million tonnes (Mt) CPO of 53 Mt CPO (FAOSTAT, 2014). Approximately 18 Mt CPO was exported, with the two largest importing countries being China and India. The European Union (EU) was the third largest importer of CPO from Indonesia in 2014 (4 Mt). The total demand for palm oil in the EU increased from 4.5 to 6.4 Mt CPO between 2006 and 2012 (Gerasimchuk & Yam Koh, 2013). In 2012, the largest share of palm oil imported in the EU was for the production of food, personal care and oleochemical products (61%), followed by the production of biodiesel (29%) and electricity and heat (9%) (Gerasimchuk & Yam Koh, 2013). Meanwhile, the domestic demand in Indonesia is expected to rise; the Ministry of Energy and Mineral Resources (MEMR) has planned to double the mandatory biodiesel blending for transportation and industry in only 5 years from 15% in 2015 to 30% in 2020 (MEMR Regulation 12/2015) (Wright & Rahmanulloh, 2015). These expected increases in the demand for palm oil for food and non-food purposes will result in a large expansion of oil palm plantations, and concerns have been raised regarding the associated occurrence of unwanted LULC change and its aforementioned environmental and social impacts in the tropics (Gerasimchuk & Yam Koh, 2013).

Methods such as the Responsible Cultivation Method (Smit *et al.*, 2013) and the Suitability Mapper (Gingold *et al.*, 2012) have been developed to mitigate the adverse social and environmental impacts of LULC change during the development of oil palm plantations. These methods aim to identify underutilised (degraded) lands that are suitable and available for oil palm and have low carbon stocks and low biodiversity levels, while community land use is respected. Smit *et al.* (2013) found that oil palm expansion in West Kalimantan does not have to result in deforestation and degradation if it complies with the above-mentioned criteria. However, as described above, palm oil production is not the only contributor to unwanted LULC change in Indonesia. Thus, reconciling the production of all contributing commodities while maintaining forests, peatlands and local food production is important.

In addition to strategies that identify suitable and available underutilised lands, analysing the potential of other approaches to mitigate unwanted LULC change, such as land sparing through the improvement of yields

and supply chain efficiencies, is important (Gutiérrez-Vélez *et al.*, 2011; Hodges *et al.*, 2011; Phalan *et al.*, 2013). Studies have shown that land sparing can benefit the maintenance of forests, carbon stocks and biodiversity, particularly of species that are sensitive to disturbances (Burney *et al.*, 2010; DeFries & Rosenzweig, 2010; Phalan *et al.*, 2011; Grau *et al.*, 2013; Law *et al.*, 2015). The amount of land that can be spared by yield improvements has been analysed on a regional scale for oil palm (Lee *et al.*, 2014a) and on a global scale for multiple crops (Tilman *et al.*, 2011). However, the land-sparing potential of yield improvements for multiple commodities has not yet been integrated with the development of suitable and available underutilised lands or responsible land-use planning and zoning at a regional scale. The integration of such strategies is important to mitigate unwanted LULC change and displacement effects (Angelsen & Kaimowitz, 2001; DeFries & Rosenzweig, 2010; Gutiérrez-Vélez *et al.*, 2011; Abood *et al.*, 2014; Laurance *et al.*, 2014; Lee *et al.*, 2014b).

In this article, we analysed whether and how the production of palm oil can be reconciled with the production of a set of other main commodities while mitigating unwanted direct and indirect LULC change. We applied a whole-landscape and multisector approach for the production of palm oil, pulpwood, rubber and rice in North and East Kalimantan to estimate the potential of a set of measures to mitigate unwanted LULC change. These two Indonesian provinces are rich in natural resources and are affected by widespread unwanted LULC change from the production of the aforementioned commodities, with an increasing proportion of palm oil (Hoffmann *et al.*, 1999; Van Nieuwstadt, 2001; Harris *et al.*, 2008; Müller *et al.*, 2014; Van der Laan *et al.*, 2014). To avoid potential displacement effects, we focused our analyses on reconciling the production of these four commodities under different growth scenarios with the maintenance of agricultural lands for local food production, forest cover and peatlands.

## Materials and methods

### Study area

North and East Kalimantan are situated in the north-eastern part of Borneo (Fig. 1). The province of North Kalimantan was previously part of East Kalimantan and was officially established on 25 October 2012. Because most of the available data are from the period up to 2012, both these provinces in Indonesian Borneo are included in the analyses. Henceforth, these provinces are indicated in this article as North-East Kalimantan. The two provinces are rich in natural resources, such as oil, natural gas and coal, and have large tracts of forests in the lowland and mountainous areas. These characteristics make

the province attractive for exploitation and development. Because of logging, forest fires and peatland conversion, the North-East Kalimantan provinces are currently the third largest greenhouse gas-emitting provinces in Indonesia, with 255 Mt CO<sub>2</sub> emitted per year (GCF-TF Indonesia, 2011). In 2008, ca. 60% of the greenhouse gas emissions was related to agricultural expansion, including the development of oil palm plantations (GCF-TF Indonesia, 2011).

### *Mitigating unwanted LULC change*

The analyses were composed of four main steps that are based on the method developed by Brinkman *et al.* (2015) and were specified for this case study. The steps are shown in Fig. 2 and described in the following paragraphs. In sections Projected land-use demand for the commodities between 2008 and 2020 to The potential of the measures to mitigate unwanted LULC change, we examine the data, assumptions and analyses in these steps in greater detail.

In step 1, we estimated the extra land-use demands of the main commodities in the region for the period 2008–2020 by subtracting the land-use demands in 2008 from the land-use demands that were projected for 2020, assuming that no mitigation measures are implemented. Because of great variations in

production growth rates in the past, we defined two contrasting projections for the future land-use demands of these commodities (section Projected land-use demand for the commodities between 2008 and 2020).

In step 2 (section Assessment of the four mitigation measures under the low, medium and high scenarios), we estimated the technical potential of four key mitigation measures under a low, medium and high mitigation intensity scenario. These low, medium and high scenarios refer to low, medium and high development intensities for the mitigation measures compared with those implemented in 2008. We used a low, medium and high scenario to account for variations in the possible future implementation of the measures and to test the variability and uncertainty in the data. We first estimated the land-sparing potential of measure 1 improvement of yields, measure 2 integration of by- and coproducts in the palm oil production chain and measure 3 improvement of the production chain efficiency. The 'land-sparing potential' refers to the land area that can be prevented from being converted for the production of the selected commodities. After estimating the land-sparing potential, we assessed how much land was suitable and available for the production of the selected commodities by measure 4 responsible land zoning and potential agricultural development on underutilised lands. These mitigation measures are explained further in section Assessment of the four mitigation measures under the low, medium and high scenarios. The land-sparing potential is the result of the subtraction of the land-use demand in 2020 under the low-high scenarios from the land-use demand under the baseline scenario. In the baseline scenario, we assume that no measures have been implemented between 2008 and 2020.

In step 3 (section The potential of the measures to mitigate unwanted LULC change), we estimated the land-use demand for the period 2008–2020, assuming the implementation of the three land-sparing mitigation measures. We subtracted the land-sparing potential from the land-use demand of the commodities for 2008–2020.

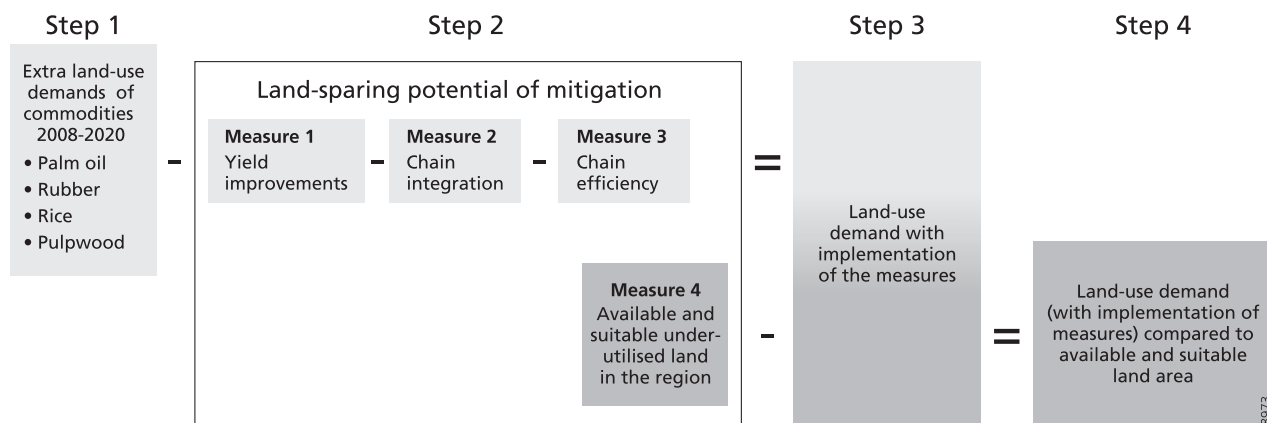
In the final step (step 4, section The potential of the measures to mitigate unwanted LULC change), we compared the projected land-use demand for the period 2008–2020 to the suitable and available land area that resulted from measure 4. Thus, we could assess whether the mitigation measures have sufficient potential to mitigate unwanted LULC change from the potential future production of palm oil, pulpwood, rice and rubber in the study area.



**Fig. 1** North and East Kalimantan provinces and their location in Indonesia.

### *Projected land-use demand for the commodities between 2008 and 2020*

Four agricultural commodities were included in the analyses, including palm oil, pulpwood, rice and rubber. The largest proportion of land in 2008 (~1.2 Mha; BPS, 2012) was cultivated for the production of pulpwood from industrial pulpwood plantations, or 'Hutan Tanaman Industri' (HTI) in Bahasa Indonesia (Fig. 3). HTIs are monoculture tree-based plantations, often *Acacia mangium* and *Eucalyptus* spp., which are mainly developed for the production of pulp and paper, timber and materials for other wood industries (henceforth

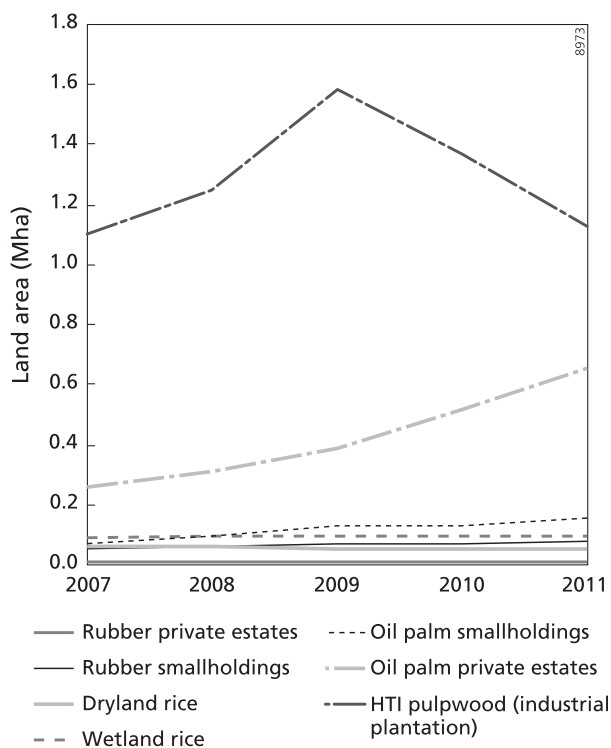


**Fig. 2** Analytical framework with the four steps of the analyses. In step 1, the extra land-use demands of the commodities palm oil, rubber, rice and pulpwood are defined for the period 2008–2020; in step 2, the land-sparing potential of mitigation measures 1–3 and the suitable and available land of mitigation measure 4 are defined; in step 3, the land-sparing potential (step 2) is subtracted from the extra land-use demand 2008–2020 (step 1); and in step 4, the land-use demand with implementation of the measures (step 3) is compared with the suitable and available land area (from step 2).

referred to as ‘pulpwood plantations’). Eighty per cent or ca. 0.7 Mha of the remaining cultivated land in 2008 was used for the production of palm oil, dryland and wetland rice, and rubber (BPS 2012; Fig. 3).

The estate types, cultivation area and production volumes of the selected land uses for 2008 were based on the regional agricultural statistics, that is the Dalam Angka data from the Bureau of Statistics (Badan Pusat Statistik, BPS) of North and East Kalimantan (BPS, 2009, 2012), and are shown in Table S1 (Appendix S1). The BPS data consist of primary and secondary data that were collected by censuses, surveys and inputs from related local government services and private institutions. Although these BPS data may contain some inaccuracies, they provide the best available statistical data at a regional scale. The HTI pulpwood production volume for 2008 could not be extracted from the BPS data. Therefore, the volume estimations were based on data from Obidzinski & Dermawan (2012) (Table S2 in Appendix S1).

We projected the production volume and land-use demand for palm oil, pulpwood, rice and rubber for 2020 under two different scenarios. Palm oil, rice and rubber production were projected by applying the business-as-usual (i.e. BAU84) scenario of the MIRAGE model (Modelling International Relationships in Applied General Equilibrium; Laborde, 2011). The MIRAGE business-as-usual scenario projects a growth in production volume and land area as a result of strong yield increases and the implementation of the EU biofuel mandate that was defined by the EU-RED. Because MIRAGE defines demand only at a highly aggregated scale – the relevant area for this study is Indonesia and Malaysia combined – we disaggregated the projected production volumes to North–East Kalimantan in the following way. For the rice and rubber 2020 projections, we applied the MIRAGE regional volume growth rates for ‘Rice’ (25% from 2008 to 2020) and ‘OthCrop’ (13% from 2008 to 2020) to the respective production volumes of these commodities in 2008. The rice and rubber projections resulted in a projected production volume of 0.73 Mt of rice and 0.06 Mt of



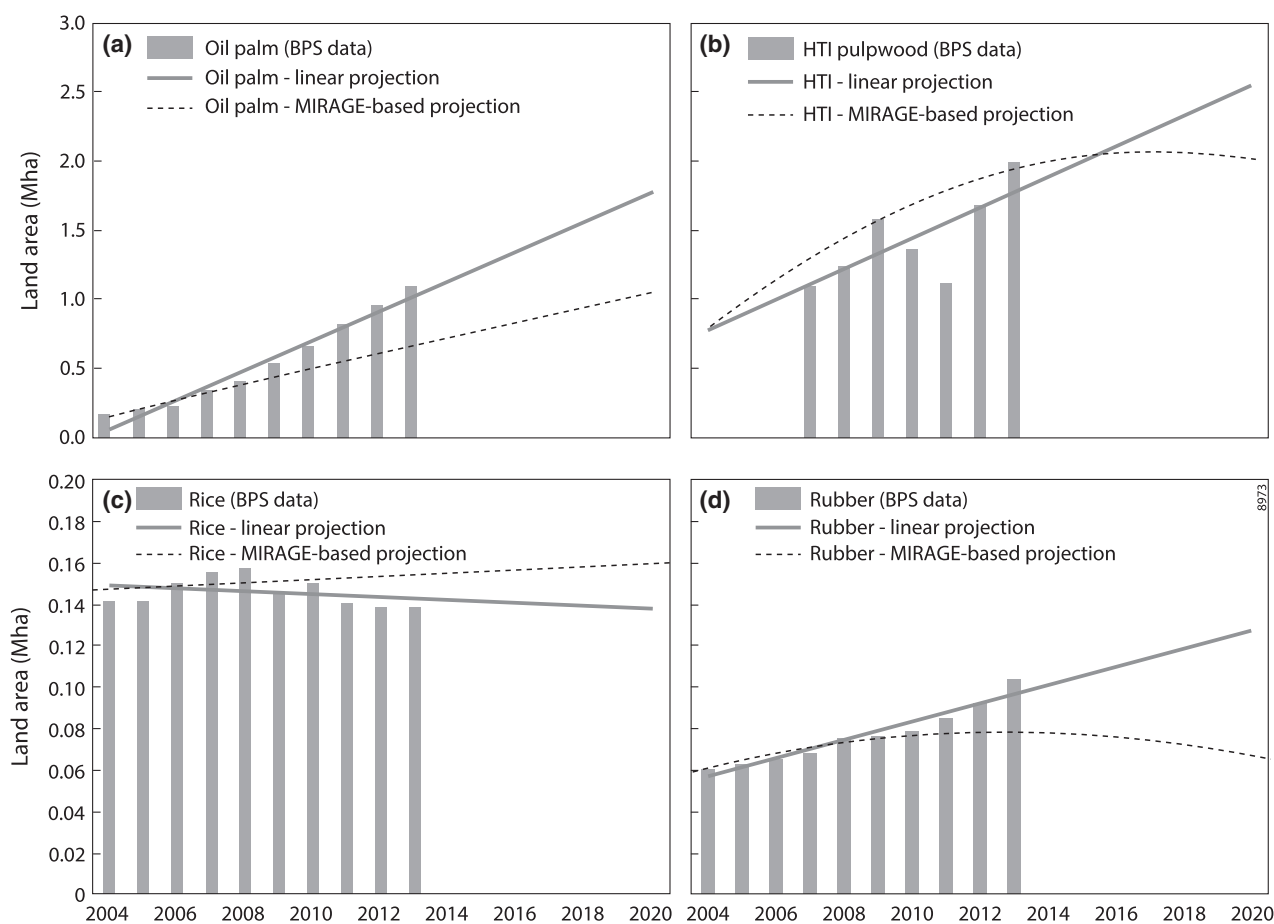
**Fig. 3** Cultivation area (ha) of HTI pulpwood industrial plantations and oil palm, rice and rubber production systems in North–East Kalimantan between 2007 and 2011 (based on BPS, 2009, 2012). For the oil palm, rice and rubber plantations, a distinction is made between large private estates and smallholdings. Production volumes are presented in Table S1 in Appendix S1.

rubber in the study area for 2020. To obtain the 2020 land-use demand for rice and rubber, we divided these projected production volumes by the projected yields from MIRAGE

(Table 2). For palm oil, we applied the MIRAGE 2008–2020 growth rate of 'PalmFruit' (79%) to the 2008 production volume of oil palm fresh fruit bunches (FFB; ~2.1 Mt), which resulted in a production volume of 3.6 Mt. This value is substantially lower than expected from the historical growth rate of oil palm in the study area (Fig. 3). Therefore, we used an alternative disaggregation method, which is explained in Appendix S2. The oil palm projection resulted in a land-use demand of ca. 1.1 Mha in 2020 under the MIRAGE scenario when using the corresponding average FFB yield from MIRAGE (Table 2). Additionally, we accounted for 20% of immature plantations by adding an extra 20% of plantation area. This share of immature plantations was estimated by extrapolating the percentage of immature plantations in 2010–2012 for smallholdings (60%) and private estates (~50%, BPS 2012) to 2020. No projection was available for the development of pulpwood plantations in MIRAGE. Therefore, we defined a scenario under which the pulpwood plantation area would stabilise from 2013 onwards at ca. 2 Mha, assuming that the extension of the moratorium on new licence issuance for primary natural forest and peatland by the Indonesian government, following Presidential Instruction

No. 6/2013, would result in a limited development of new forest plantations (Republic of Indonesia, 2013). For simplicity reasons, we hereafter call this projection the MIRAGE-based projection.

For the second land-use demand projection, we linearly extrapolated the land area for oil palm, pulpwood rice and rubber plantations following historical trends. We used the period of 2004–2013 for oil palm, rice and rubber and the period of 2007–2013 for pulpwood based on available data (Fig. 4). Under this projection, oil palm expansion would increase to 1.8 Mha in 2020, which is plausible given the strong historical oil palm expansion in the region between 2004 and 2013 (Fig. 4; BPS, 2008, 2014) and the increasing demand for palm oil, for example for the production of biodiesel (Gerasimchuk & Yam Koh, 2013; Wright & Rahmanulloh, 2015). The expansion of rubber would also increase under the linear projection to 0.13 Mha in 2020 (Fig. 4), an expectation that is based on the increasing global demand for natural rubber (Warren-Thomas *et al.*, 2015). A linear extrapolation of the historical trends revealed an increase in HTI pulpwood plantations to 2.55 Mha in 2020 and a decrease in rice cultivation to ca. 0.14 Mha in 2020.



**Fig. 4** Land area (Mha) for the production of (a) palm oil, (b) HTI pulpwood (data 2004–2006 missing), (c) rice and (d) rubber in 2004–2013 (bars) (based on BPS, 2008, 2012, 2014a,b), and projected land-use demand for 2020 under a MIRAGE-based projection (dotted line) and a linear projection (continuous line) for North–East Kalimantan.



Finally, the extra land-use demands for oil palm, HTI pulpwood, rice and rubber for the period 2008–2020 were defined by subtracting the land-use demands in 2008 from the land-use demands in 2020 (see Table 1).

#### *Assessment of the four mitigation measures under the low, medium and high scenarios*

**Measure 1: yield improvement.** Yield improvement has land-sparing potential because relatively less land is required for the production of the commodities in the study area. The aim of this measure was to estimate the land-sparing potential by implementing the yield improvement of oil palm, pulpwood, rice and rubber above the baseline yields. Under the baseline scenario, we assumed that no yield improvement measures would be implemented until 2020, given that yields have historically changed only marginally (BPS, 2009, 2012) and thus that the yields would remain similar between 2008 and 2020. The baseline yields were calculated by dividing the 2008 production volume by the 2008 cultivation area of each commodity (BPS 2009, 2012; see Table S1 in Appendix S1).

To estimate the oil palm FFB yields, we only included the mature plantations at private estates and smallholdings throughout the analysed time period. Because the proportion of mature plantations in 2008 was unknown, a correction factor was defined by extrapolating the percentage of mature plantations in 2010–2012 for smallholdings (~40%) and private estates (~50%; BPS 2012) to 2008 (50% and 35%, respectively). This step resulted in an average 2008 yield of 10.4 t ha<sup>-1</sup> for smallholdings and 15.2 t ha<sup>-1</sup> for private estates in the baseline scenario (Fig 5).

Rice yields remained stable between 2008 and 2011 at ca. 2.5 t ha<sup>-1</sup> for dryland rice and 4.5 t ha<sup>-1</sup> for wetland rice. The yields of smallholder rubber estates also remained stable

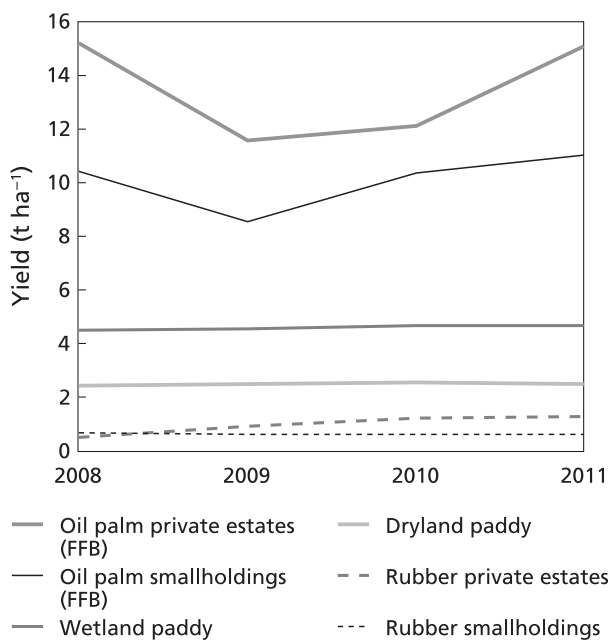
**Table 1** Cultivation area (ha) in 2008 and extra land-use demand (ha) projected for pulpwood, oil palm, rice and rubber in 2020 under a MIRAGE vs. a linear projection

	Cultivation area 2008* (ha)	Extra land-use demand projections 2020* (ha)	
		MIRAGE-based projection	Linear projection
HTI pulpwood	1 246 000	654 110	1 305 400
Oil palm†	404 600	654 000	1 373 900
Rice	157 300	0	-19 400
Rubber	74 700	-9900	52 100
Total land area	1 882 600	1 289 200	2 712 100

\*Based on the average 2008 yields (see Table 2) and a 20% proportion of immature oil palm plantations in 2020 (sections Projected land-use demand for the commodities between 2008 and 2020 and Measure 1: yield improvement).

†Based on the baseline oil extraction rate of 20% in 2008 (Table 3).

Data sources: BPS, 2009, 2012; Laborde, 2011; FAOSTAT, 2014.



**Fig. 5** Yields (t ha<sup>-1</sup>) of the land uses in North-East Kalimantan between 2008 and 2011 (BPS, 2009, 2012). For the estimation of oil palm yields, only mature oil palm plantations were taken into account by applying the correction factor in section Measure 1: yield improvement.

between 2008 and 2011 at ca. 0.7 t ha<sup>-1</sup>. The yields of private rubber estates increased between 2008 and 2011 from 0.6 to 1.4 t ha<sup>-1</sup> (Fig. 5). The estimated yields were lower than both the national average (FAOSTAT, 2014) and best practice yields in Malaysia and much lower than the maximum attainable yields (Table 2).

The productivity of HTI pulpwood plantations in Indonesia is uncertain because of unreliable data (Arets *et al.*, 2011; Obidzinski & Dermawan, 2012). Because local yield data for HTI plantations were not available for 2008, we estimated these values by dividing the national HTI pulpwood production volume of 22.3 million m<sup>3</sup> in 2008 by the national HTI pulpwood concession area of 4.2 Mha in 2008 (Obidzinski & Dermawan, 2012). This step resulted in an HTI pulpwood yield of 5.3 m<sup>3</sup> ha<sup>-1</sup>. This yield estimation is low compared to the average national yields that are found in the literature (e.g. 30–250 m<sup>3</sup> ha<sup>-1</sup>; Arets *et al.*, 2011) because we assume that a share of the concessions is still covered with natural forest and that only a part of the concessions is planted.

Yield improvements until 2020 are considered possible based on (i) the relatively low yields in 2008 compared to the current yields in other parts of Indonesian or Malaysian Borneo and the maximum attainable yields (Table 2) and (ii) the causes of and potential solutions to existing yield gaps, as described for the four commodities in this study in the following paragraphs. We defined three yield improvement scenarios, recognising the potential ranges of future developments in efforts and investments in improving yields. The projected annual yield growth rates between 2008 and 2020 and the

**Table 2** Yields projected for 2020, based on the baseline and scenario calculations

	Baseline yields Yields in North- East Kalimantan in 2008	Low scenario 1% annual yield increase above baseline yield	Medium scenario MIRAGE yield increase (BAU84 scenario)	High scenario 2% annual yield increase above baseline yield	Yields Indonesia 2008 (FAOSTAT, 2014)	Yields Malaysia 2008 (FAOSTAT, 2014)	Maximum attainable yields
Oil palm private estates (FFB) (t ha <sup>-1</sup> )	15.2	17.1	19.0	19.3	17.1	22.7	36.7*
Oil palm smallholdings (FFB) (t ha <sup>-1</sup> )	10.4	11.7	13.0	13.2	14.0†	22.7	36.7*
Wetland rice (t ha <sup>-1</sup> )	4.5	5.1	5.7	5.7	4.9	3.6	6‡
Dryland rice (t ha <sup>-1</sup> )	2.4	2.7	3.0	3.1	4.9	3.6	6‡
Rubber smallholdings (t ha <sup>-1</sup> )	0.7	0.8	0.9	0.9	0.8	0.9	1.5
Rubber private estates (t ha <sup>-1</sup> )	0.5	0.6	0.7	0.7	0.8	0.9	1.5
HTI pulpwood plantations (m <sup>3</sup> ha <sup>-1</sup> )	5.3	6.0	6.3	6.7	5.3	–	–

\*In North and East Kalimantan, assuming best management practices (Donough *et al.*, 2010).†Molenaar *et al.* (2010).

‡IRRI (2011).

resulting yields for all land uses for 2020 for all three scenarios are shown in Table 2.

We chose yield growth rates for oil palm, rice and rubber of 1% annually in the low scenario and 2% annually in the high scenario. For the medium scenario, we applied the yield growth rates as defined under the MIRAGE (BAU84) scenario, namely, 24.8% for oil palm, 25.4% for rice and 26.4% for rubber between 2008 and 2020, or ca. 1.9% per year for all commodities. Overall, the yields in the three scenarios in 2020 were similar to the current national averages and lower than the maximum attainable yields. The yields of the oil palm smallholdings, specifically, 13.2 t ha<sup>-1</sup> projected for 2020, are conservative compared to the average yields in Indonesia and Malaysia and the maximum attainable yields (Donough *et al.*, 2010; FAOSTAT, 2014).

In line with the projections of the other production systems, we also assumed an annual yield improvement for pulpwood plantations of 1%, 1.5% and 2% until 2020 in the three scenarios. These rough estimates resulted in 2020 yields of 6.0, 6.3 and 6.7 m<sup>3</sup> of pulpwood per ha per year in the low, medium and high scenarios, respectively.

Multiple strategies exist to improve crop yields. Several studies have shown that FFB yields can be increased by continuously improving and evaluating best management practices (BMPs) in oil palm plantations (Fairhurst & McLaughlin, 2009; Donough *et al.*, 2010; Lee *et al.*, 2014b). Three broad BMP categories exist, which focus on crop recovery, canopy management and nutrient management (Donough *et al.*, 2010). Ownership status, access to financial capital, access to reliable technical information and coping with market risks are fundamental to maximising the oil palm cultivation potential, especially for smallholdings (Vermeulen & Goad, 2006; Molenaar *et al.*, 2010).

Despite strong public sector investment over the past few decades, most food crop yields have stagnated (USDA, 2012). Nonetheless, rice yield gaps can be bridged by strong guidance and improvement in technical skills (IRRI, 2011), high-quality seeds and rice varieties (IRRI, 2011), crop and nutrient management (IRRI, 2011), drainage and irrigation systems (Makarim, 2000; Laborte *et al.*, 2012) and rodent control (John, 2014).

During the mid-1990s, international agencies promoted high-yielding monoculture rubber plantations (Pye-Smith, 2011). Partly because of this international promotion, large-scale monocultures have been replacing smallholder rubber gardens, thus increasing the average national yields and income (Pye-Smith, 2011). However, the yields of smallholder rubber gardens can also be improved while maintaining the cultural character and biodiversity of the rubber gardens. This approach is possible through, for example, the provision of high-yielding clones and capacity building that is focused on improved weeding and optimal tapping, as shown by Pye-Smith (2011).

The management of pulpwood plantations in Indonesia is generally poor because of topography, poor weather conditions, poor accessibility, conflicts with neighbouring communities and the lack of skilled manpower (Pirard & Cossalter, 2006; Arets *et al.*, 2011). Tackling some of these aspects creates the potential to improve yields.

Having determined the baseline and projected 2020 yields (Table 2), we estimated the land-sparing potential by applying Eqn (1).

$$\text{LSP}_{\text{crop}} = \text{LUD}_{\text{baseline}} - \text{LUD}_Y = \sum_{i=1}^n \frac{P_i}{Y_{\text{baseline},i}} - \sum_{i=1}^n \frac{P_i}{Y_{\text{projected},i}} \quad (1)$$

where  $\text{LSP}_{\text{crop}}$ , land-sparing potential (ha), which results from yield increases above the baseline 2008 yield;  $\text{LUD}_{\text{baseline}}$ , land-use demand (ha) for projected crop cultivation in 2020 (Table 1) when applying the baseline yield (Table 2);  $\text{LUD}_Y$ , land-use demand (ha) for projected crop cultivation in 2020 when applying the improved yields;  $P_i$ , projected production (t) for crop  $i$ , which is derived from the MIRAGE-based and linear projections;  $Y_{\text{baseline},i}$ , projected baseline yield for crop  $i$  ( $\text{t ha}^{-1} \text{yr}^{-1}$ ); and  $Y_{\text{projected},i}$ , projected yield for crop  $i$  ( $\text{t ha}^{-1} \text{yr}^{-1}$ ).

**Measure 2: integration of by- and coproducts in the palm oil production chain.** Improving the utilisation of by- and coproducts in the CPO production chain can reduce the need for other agricultural products and potentially result in lower land-use demand and, thus, land sparing. Oil palm trunks (OPTs) and oil palm fronds are generated at the plantation, while empty fruit bunches, palm oil mill effluent, palm kernel oil, palm kernel shell and palm kernel fibre are generated at the mill. We aimed to estimate the land area that can be spared by utilising by- and coproducts in the palm oil production chain. We included OPTs in the analyses. The other by- and coproducts were not considered in this analysis for reasons that are explained in Appendix S3.

Oil palm trunk was selected for evaluation because OPT plywood has the potential to be used as an alternative to softwood timber from pulpwood plantations (Wahab *et al.*, 2008; Sulaiman *et al.*, 2012; UNEP, 2012), and as such can generate land sparing. Additionally, the rotting processes of trunks at the plantation site can be prevented, thus mitigating the spread of fungi and diseases. Research and development on plywood from OPTs has been conducted at a local scale in Malaysia, and the results have been promising (UNEP, 2012). The production and utilisation of OPT plywood as a nonconstruction material is, however, still in the experimentation phase and not yet commercially available. We conducted first-order estimates of the amount of OPT that can be used for this purpose under three scenarios and compared the output to the baseline scenario, which assumes that no OPT is used between 2008 and 2020. The method to estimate the land-sparing potential of using OPT plywood as an alternative to softwood from pulpwood plantations for the period 2008–2020 can be found in Appendix S4.

**Measure 3: improved efficiency of the palm oil and rice production chain.** We aimed to estimate the land-sparing potential of improving the efficiency of the production processes of palm oil and rice. We did not evaluate potential efficiency improvements in the rubber and HTI pulpwood production chains because of a lack of data.

**Palm oil.** A key aspect in increasing the efficiency of palm oil production is increasing the oil extraction rate (OER) so that more CPO can be produced from FFBs. Globally, the range of the OER is 17–27%, depending on the region (FAOSTAT, 2014). Because no OER data were available for the study area, we assumed an OER for 2008 that was slightly lower than the Indonesian national average and similar to the Malaysian national average for the same period, namely, 20% (see Table S4 in Appendix S5, FAOSTAT 2014).

Poor plantation management, suboptimal harvesting and poor milling operations can negatively impact the OER. Key measures to increase the OER in North-East Kalimantan include capacity building for plantation management, particularly for smallholdings (MPOB, 2014); harvesting FFBs at an optimal ripeness to obtain the maximum quantity of oil (Sheil *et al.*, 2009); and the delivery of FFBs to mills within 24 h of harvesting to ensure that the amount of free fatty acid in the CPO is as low as possible (Santosa, 2008).

We varied the OER under the three scenarios and calculated the difference between the resulting land-use demand and the land-use demand under the baseline scenario (Eqn 2) to estimate the land-sparing potential in 2020 by increasing the OER. In the baseline scenario, we assumed that the OER between 2008 and 2020 would remain constant at 20%. In the low scenario, we assumed that the OER would increase to ca. 21% by 2020 based on the average OER for Sabah/Sarawak in Malaysian Borneo. In the high scenario, we assumed that capacity building programs on BMPs that involved harvesting, transporting and milling can increase the OER to 22% in 2020. This result is slightly higher than the 2008–2012 average OER in Indonesia and Malaysia combined (Table S4) but is considered feasible because of the OER of 27% in other regions in Indonesia (FAOSTAT, 2014). For the medium scenario, we selected an intermediate OER of 21.5%.

$$\text{LSP}_{\text{OER},2020} = \text{LUD}_{\text{oil palm},2020} - \left( \frac{\text{LUD}_{\text{oil palm},2020} \times \text{OER}_{2020,\text{baseline}}}{\text{OER}_{2020,\text{scenario}}} \right) \quad (2)$$

where  $\text{LSP}_{2020}$  is the land-sparing potential by increasing the OER (ha);  $\text{LUD}_{\text{oil palm},2020}$  is the land-use demand for oil palm cultivation that is projected for 2020 under the baseline scenario (ha) (Table 1);  $\text{OER}_{2020,\text{baseline}}$  is the OER under the baseline scenario (%); and  $\text{OER}_{2020,\text{scenario}}$  is the increased OER under the low, medium and high scenarios (%).

**Rice.** The postharvest rice losses in Indonesia were 7.8% in 2008 and 7.9% in 2011 (FAOSTAT, 2014), which were higher than the average rice losses in South-East Asia (Table S5). We applied these national rice loss percentages to North-East Kalimantan because region-specific data of postharvest rice losses were not available. In the postharvest stage, rice is lost during drying, storage and transportation. To minimise rice losses, these processes should occur under dry, cool and well-ventilated conditions, preferably during the dry season to protect from moisture, spoilage and self-heating (GDV, 2015). During the preharvest stage, rodents contribute to high quantities of rice losses in Indonesia (John, 2014). We excluded preharvest



losses from this analysis because the implementation of rodent control included in the yield improvement measure.

We varied the rice loss percentages under the three scenarios and compared these values to the baseline scenario to estimate the land-sparing potential in 2020 by minimising the postharvest rice losses. Under the baseline scenario in 2020, we assumed a postharvest rice loss percentage in the study area that was similar to the rice loss percentage in Indonesia in 2008–2011 (7.8%; FAOSTAT, 2014). Under the low scenario, we assumed the rice losses in North–East Kalimantan in 2020 to be similar to the regional average in South-East Asia (7%; FAOSTAT, 2014; see Table S5). For the high scenario, the rice losses were assumed to be reduced to the lowest level of rice loss that is currently experienced in South-East Asia, specifically, 6% in the Lao People's Democratic Republic (FAOSTAT, 2014; see Table S5). An intermediate rice loss percentage (6.5%) was selected in the medium scenario. The amount of rice that was saved by reducing postharvest losses and the resulting land-sparing potential were determined by Eqn (3).

$$\text{LSP}_{\text{rice},2020} = \text{LUD}_{\text{rice},2020} - \left( \frac{\text{LUD}_{\text{rice},2020} \times L_{2020,\text{scenario}}}{L_{2020,\text{baseline}}} \right) \quad (3)$$

where  $\text{LSP}_{2020}$  is the land-sparing potential by minimising rice losses;  $\text{LUD}_{\text{rice},2020}$  is the land-use demand for rice production that is projected for 2020 under the baseline scenario (Table 1);  $L_{2020,\text{scenario}}$  is the proportion of rice that is lost in 2020 after efficiency improvements (%) under the low, medium and high scenarios; and  $L_{2020,\text{baseline}}$  is the proportion of rice that is lost from the baseline in 2020 (no efficiency improvements since 2008) (%).

*Measure 4: responsible land zoning and potential agricultural development on underutilised lands.* We aimed to estimate the amount of land that is suitable and available for the production of the selected commodities by assuming responsible land zoning and the use of underutilised lands to mitigate negative ecological, social and economic impacts. Underutilised land includes set-aside land, abandoned land, marginal land and degraded land, as long as it is both suitable and available. In this study, *suitable land* refers to land that is (i) biophysically suitable in terms of climate, terrain and soil variables and (ii) environmentally suitable, that is avoiding high carbon stock and high conservation value areas, such as peatlands and forests. *Available land* refers to land that is not used for agriculture or other purposes and is not traditionally and/or legally owned or used by local communities.

We accounted for the land-zoning regulations in Indonesia and a set of biophysical, environmental and land ownership criteria for the expansion of oil palm because this commodity has the most restrictions in terms of social, biophysical and environmental requirements. Two methods were identified, namely, the Responsible Cultivation Areas (RCA) method (Smit *et al.*, 2013) and the Suitability Mapper tool of the World Resources Institute (WRI) (Gingold *et al.*, 2012). Although the RCA method and the Suitability Mapper tool are closely related from a methodological perspective, we selected the

Suitability Mapper because it is an online tool that is readily applicable (World Resources Institute, 2015).

Three scenarios were defined to account for differences in suitability (see Table S6 in Appendix S6 for details on the settings that were applied to the Suitability Mapper). In all three scenarios, peatland and forests were excluded to minimise carbon emissions and carbon payback time (Gibbs *et al.*, 2007). Settlements, plantations and agricultural lands were also excluded because the production of the selected commodities in these areas may induce displacement and unwanted LULC change if the original land use or commodity is relocated elsewhere. Although agricultural croplands were not considered available, extensively used lands that cannot be identified by remote sensing data may not have been included. Therefore, local field assessments are required to confirm or reject site suitability and availability. The field assessments for West Kalimantan that were conducted by Gingold *et al.* (2012) showed that 9 of 22 potentially suitable sites were actually available, which indicated that ca. 40% of the initially selected sites were available and suitable. We applied this percentage to the study area because no data for North–East Kalimantan were available.

### *The potential of the measures to mitigate unwanted LULC change*

In the previous paragraphs, we described the land-sparing potential of mitigation measures 1–3 and the suitable and available land potential of measure 4 for the cultivation of oil palm, HTI pulpwood, rice and rubber under low, medium and high scenarios. Table 3 presents an overview of the settings of each measure per scenario.

Subsequently, we subtracted the land-sparing potential from the total land-use demand of the commodities for 2008–2020 under the MIRAGE-based and linear projections. Finally, we defined whether the available and suitable land that was generated by mitigation measure 4 was sufficient to accommodate the land-use demand of the commodities for 2008–2020, with and without the implementation of measures 1–3. If the available and suitable land from measure 4 is higher than the land-use demand under these scenarios, it would be technically possible to produce the four main commodities with a low risk of unwanted LULC change. If this land is lower than the land-use demand that is estimated under each of the scenarios, the study area would not be able to provide the required palm oil, pulpwood, rice and rubber without unwanted LULC changes, such as the conversion of forests, peatlands, food crops or community lands.

## Results

### *Measure 1: yield improvement*

The impact of yield improvements on the projected land-use demand and land-sparing potential is shown in Fig. 6. The results show a total land-use demand of ca. 2.5 Mha (high scenario, MIRAGE projection) to ca. 4.3 Mha (low scenario, linear projection). This range is

**Table 3** Settings of the baseline and the low, medium and high scenarios analysed in this study for each of the mitigation measures

	Yield improvements	Improved chain integration	Increased production chain efficiency	Land zoning and biofuel feedstock production on underutilised lands
Baseline	Yields remain the same as in 2008	No additional chain integration compared to 2008; no additional utilisation of by- or coproducts	No increased chain efficiency compared to 2008; Crude palm OER = 20%; Rice losses of 7.8%	No use of available and suitable underutilised lands
Low	1% annual yield increase until 2020	10% of selected by- and coproducts is additionally utilised	Crude palm OER = 21% (average Indonesia); Rice losses of 7%	Use of land zoning and suitable and available land, optimal growth conditions
Medium	~1.5–2% annual yield increase until 2020	40% of selected by- and coproducts is additionally utilised	Crude palm OER = 21.5% (intermediate OER); Rice losses of 6.5%	Use of land zoning and suitable and available land, additional measures needed to obtain similar or higher yields compared to 2008
High	2% annual yield increase until 2020 (results in yields that are lower than the maximum attainable yields)	70% of selected by- and coproducts is additionally utilised	Crude palm OER = 22% (assuming the implementation of a nationwide programme) Rice losses of 6%	Use of land zoning and suitable and available land, additional measures needed to obtain similar or higher yields compared to 2008

lower than the 3.2–4.8 Mha of land that is needed under the baseline scenario (Fig. 6a). HTI pulpwood and oil palm plantations still showed the highest land-use demands, specifically, 0.8–2.3 Mha under the low to high scenarios (Fig. 6).

Yield improvements from 1% to 2% above the baseline under the low to high scenarios have a land-sparing potential of ca. 1 Mha in 2020 (Fig. 6). The linear projection shows the largest land-use demand in 2020 and a land-sparing potential of 0.5–1 Mha (Fig. 6a). The largest land sparing under this growth projection can be generated by yield improvements of HTI pulpwood (53%) and oil palm (~42%). Assuming a MIRAGE-based growth for the commodities results in land sparing from 0.4 to 0.7 Mha (Fig. 6b).

#### *Measure 2: integration of by- and coproducts in the palm oil production chain*

Our estimates under the low, medium and high scenarios resulted in ca. 2500 ha, 10 000 ha and 18 000 ha, respectively, of oil palm plantation area that can be harvested for OPT plywood production and subsequently replanted with oil palms. Assuming a harvest of 235 m<sup>3</sup> stems per ha (Hromatka & Savage, 2010) and a 40% suitability rate of OPTs for plywood production for nonconstruction materials (UNEP, 2012), ca. 235 000–1 645 000 m<sup>3</sup> of OPT plywood can be produced under the low to high scenarios, respectively.

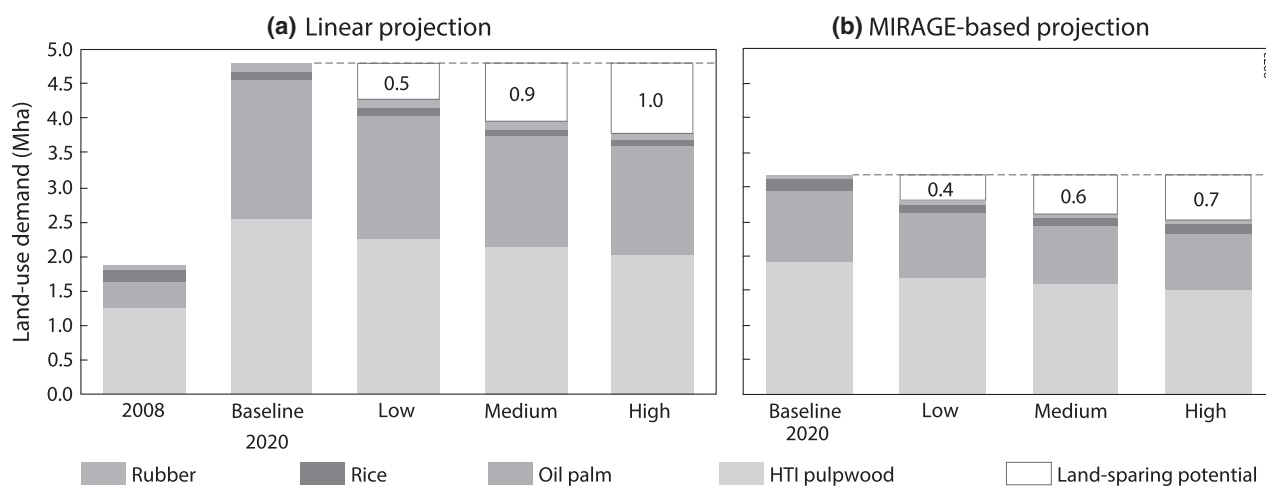
This approach would result in ca. 3000 to 24 000 ha of land sparing in the low to high scenarios.

#### *Measure 3: improved efficiency of the production chain*

Increasing the OER above the baseline in North-East Kalimantan under the low, medium and high scenarios results in ca. 135 000–269 000 t of extra CPO in 2020, assuming MIRAGE-based palm oil growth, and in ca. 228 000–456 000 t of extra CPO in 2020, assuming linear palm oil growth (Table S7). Under the low to high scenarios, this process resulted in a land-sparing potential of 50 000–95 000 ha and 85 000–162 000 ha for the MIRAGE-based and linear growth in palm oil demand, respectively. Minimising rice losses in North-East Kalimantan resulted in prevented rice losses between 4000 and 10 000 t depending on the scenario for efficiency improvements and the land-use demand projections (Table S7). This process resulted in a land-sparing potential of ca. 15 000–34 000 ha. The improved efficiencies in both the production of rice and palm oil can result in 66 000–194 000 ha of land sparing (Table 4).

#### *Measure 4: responsible land zoning and potential agricultural development on underutilised lands*

The Suitability Mapper considered an estimated availability of 40% underutilised land (Gingold *et al.*, 2012),



**Fig. 6** Land-use demand estimated for 2008 (BPS, 2012) and projected for 2020 (Mha) with yield improvements for North-East Kalimantan under the baseline, low, medium and high scenarios and considering the linear and MIRAGE-based projections of the commodities. The land-sparing potential (subtraction of the land-use demand under the low–high scenarios from the land-use demand under the baseline scenario) is indicated by the figures at the top of the bars (in Mha).

which resulted in ca. 0.7 to 1.0 Mha of land that was suitable and available for the expansion of the commodities in North-East Kalimantan under the low to high scenarios (Table S8).

#### *The potential of the measures to mitigate unwanted LULC change*

The total potential of the three mitigation measures for land sparing is ca. 0.4–0.8 Mha (i.e. 33–62% of the total land demand of the commodities) for the MIRAGE projection and 0.6–1.2 Mha (i.e. 24–45% of the total land demand of the commodities) for the linear projection under the low to high scenarios (Table S9). Subtracting this land-sparing potential from the total land-use demand for 2008–2020, and thus assuming the implementation of measures 1–3, results in a land-use demand of ca. 0.5–2 Mha (Table S10, Fig. 7). Comparing the resulting land-use demand with the suitable and available land area of measure 4 shows that palm oil, HTI pulpwood, rice and rubber can only be produced with a low risk of unwanted LULC change under the MIRAGE-based projection and only under the medium to high scenarios (Table S11, Fig. 7). The linear projection results show that the mitigation measures are insufficient (Table S11 and Fig. 7).

Table 4 shows that the total potential of all the mitigation measures together is ca. 1.1–1.8 Mha for the MIRAGE-based projection and 1.3–2.2 Mha for the linear projection under the low to high scenarios (Table 4). Measure 4, 'land zoning and development on underutilised land', resulted in the largest mitigation potential in terms of land area, specifically, 0.7–1 Mha of land,

which is 45–52% of the total potential under the MIRAGE-based projection and 55–62% under the linear projection (Table 4). Measure 1, 'yield improvement', contributed ca. 32–37% and 40–46% under these projections. Measures 2 and 3 resulted in much lower potential, specifically, less than 10% of the total potential under the different scenarios and projections. Measures 1 and 4 were therefore identified as the most important mitigation measures in this study. Combining the use of underutilised lands, land zoning and yield improvements allows substantial additional production with a low risk of unwanted LULC change.

#### **Discussion**

Our study shows that reconciling the production of palm oil with the production of other main commodities while mitigating unwanted direct and indirect LULC change is technically possible. However, this process is only possible under the MIRAGE-based projection, which showed a limited agricultural expansion of these commodities, and only if the mitigation measures on land sparing, land zoning and development on underutilised lands are implemented as described under the medium and high scenarios. The MIRAGE-based projections for the commodities resulted in relatively low land-use demands in 2020 compared to actual land use in recent years (BPS, 2014a,b). For example, oil palm and HTI pulpwood are estimated to use ca. 1 and 2 Mha of land in 2020, respectively, which are similar to their associated land use in 2013 (BPS, 2014a,b). Furthermore, the land-use demand that is projected for rubber in 2020 is almost 40% lower than the land area that was

**Table 4** Overview of the mitigation potential of the four measures and their contribution to the total potential in terms of ha and %

Projections and measures	Low		Medium		High	
	ha	% of total potential	ha	% of total potential	ha	% of total potential
Linear projection						
1. Yield improvement	541 100	40	867 200	45	1 016 800	45
2. Chain integration	3400	0	13 400	1	23 500	1
3. Chain efficiency	98 800	7	147 100	8	193 500	9
Total land-sparing potential (measure 1–3)	643 300		1 027 700		1 233 800	
4. Responsible land zoning and potential agricultural development on underutilised lands	700 000	52	900 000	47	1 000 000	45
Total potential of the mitigation measures	1 343 300	100	1 927 700	100	2 233 800	100
MIRAGE-based projection						
1. Yield improvement	357 000	32	564 700	36	670 800	37
2. Chain integration	3400	0	13 400	1	23 500	1
3. Chain efficiency	66 100	6	99 500	6	131 700	7
Total land-sparing potential (measure 1–3)	426 500		677 600		826 000	
4. Responsible land zoning and potential agricultural development on underutilised lands	700 000	62	900 000	57	1 000 000	55
Total potential of the mitigation measures	1 126 500	100	1 577 600	100	1 826 000	100

used in 2013, while the demand for rice is only slightly higher than the land area that was used in 2008 (BPS, 2009, 2014a,b). Overall, whether the MIRAGE-based projections for 2020 are realistic for this study region is questionable, particularly given the expected increases in these commodities according to the literature (e.g. Koh & Wilcove, 2008; Obidzinski & Dermawan, 2012; Ahrends *et al.*, 2015; Warren-Thomas *et al.*, 2015). Thus, while our projections emphasise the importance of limited agricultural expansion in the study area, this approach must not come at the price of displacing LULC change to other regions. For example, whether sufficient rice can be produced to feed the growing population in North-East Kalimantan (BPS, 2009, 2014a,b) or whether rice production will be displaced to areas outside these provinces are uncertain according to our projections. This after-effect could have implications for LULC change elsewhere and would thus only shift the problem.

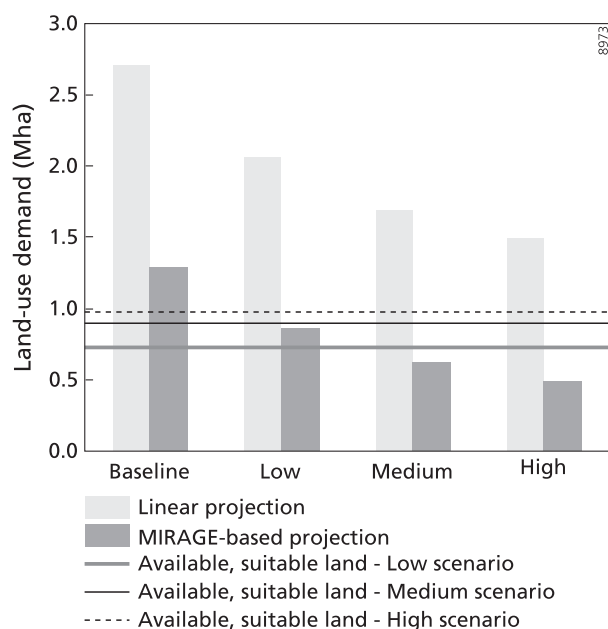
Land zoning and the use of underutilised lands (0.7–1 Mha, 45–62% of the total mitigation potential) were identified in this study as the most important mitigation measure. This result was expected because the North-East Kalimantan provinces have been affected in previous decades by widespread logging activities, large-scale fires for land development and/or large-scale fires because of El Niño (e.g. Hoffmann *et al.*, 1999; Siegert & Hoffmann, 2000; Abood *et al.*, 2014; Gaveau *et al.*, 2014). However, thorough field research is required to improve our rough estimates of underutilised lands and to verify these estimates in the field. These ground checks can also support the alignment of

spatial planning and land allocation zoning and the responsible selection of suitable and available lands, for example by the RCA method of Smit *et al.* (2013), to stimulate expansion onto underutilised land that is either degraded or not. The use of underutilised lands can be incentivised, for example by subsidies or financial programs to support land and soil restoration and plantation development. Monitoring the landscape is required to support the identification and potential use of these underutilised or degraded lands. This approach can be conducted by regular analyses of local and regional remote sensing data and intensive ground checks.

The second most important measure was yield improvements (0.4–1 Mha or 32–46% of the total mitigation potential). This large potential to improve yields is the result of the currently very low yields in North-East Kalimantan compared to other nearby regions (BPS, 2014a,b). Local support is required with regard to credit facilities and technical assistance to smallholders, who generally have lower access to capital and knowledge of BMPs. Independent and trustworthy sources for funding and information are important to ensure the success of this type of support. Technical assistance can consist of providing better planting material and capacity building on BMPs (specifically regarding better plantation design, harvesting and nutrient management). Yield developments would need to be monitored on an annual basis to determine the efficacy of such programs and support.

A large amount of regional statistics and spatial data were required for this study. Improvements in accuracy, reliability, coverage and temporal resolution are a





**Fig. 7** Land-use demand of oil palm, HTI pulpwood, rice and rubber under the baseline scenario in 2020 (no implementation of measures), and under the low, medium and high scenarios in 2020 (with implementation of measures) (bars), compared to available and suitable land-area potential in 2020 (lines) under the low to medium scenarios, assuming the MIRAGE-based and linear projections.

prerequisite for further analysis on strategies to mitigate unwanted LULC change. Provincial statistical data were missing for crop yields, OER, HTI pulpwood volumes and rice losses. Therefore, most of these key parameters were estimated based on regional or national data, such as the BPS dataset, which may have created uncertainties in the outcomes. For this reason, we conducted a scenario analysis to analyse a bandwidth of possible outcomes. Specifically, ambiguity is present in the BPS data regarding the exact data sources and collection methods. However, this collection is the most extensive regional dataset that is available for the study area and allows for comprehensive regional-level estimates. Spatial data, which were required in this study to assess the suitable and available area of underutilised land, are widely available for the region and have been made available online by research institutes such as ESRI (ESRI, 2015), SarVision (SarVision, 2015) and the WRI (World Resources Institute, 2015). However, land use, land-use regulations and spatial planning are constantly changing in Indonesia, so spatial data are required on a more regular basis, preferably annually. This solution is challenging, particularly in tropical areas, where permanent cloud cover hampers the use of optical remote sensing data for the production of LULC maps. New radar-based technologies are under development and

will contribute to more accurate and more frequently available spatial data in the near future.

In our study, we analysed four mitigation measures to approach the mitigation of unwanted LULC change from different angles. The importance of yield improvements (Lee *et al.*, 2014a) and of land zoning and the use of underutilised lands (Smit *et al.*, 2013) has also been indicated in previous studies. With this study, we contributed to the existing literature as we integrated the mitigation measures, accounting for a variety of commodities and projected land-use demands in the future and at a regional scale. By conducting this whole-landscape and multisector approach, we were able to address unwanted LULC change in an integrated manner, thus accounting for direct and indirect LULC changes and displacement effects that are related to the production of food, feed, fibre and fuels.

The land-sparing potential that was estimated in this study is a technical potential that considers important ecological aspects, such as the exclusion of forest and peatlands. However, a sustainable implementation potential may be lower because it must also consider additional ecological, social, legal and economic considerations. These factors must be analysed at the local level. Nonetheless, the measures that were presented in this article have considerable potential to mitigate unwanted LULC change in these and other tropical regions. This result is particularly true in areas with a high rate of agricultural expansion and large areas of underutilised land because of large-scale deforestation and degradation during the past few decades. However, mitigating unwanted LULC change is only possible if the close link between the agricultural, forestry and bio-fuel sectors is recognised. Therefore, an integrated perspective on land use must be established for all purposes during the planning and implementation of general land-use policies, particularly on the mitigation of unwanted LULC change. Thus, the focus of improvements, capacity building and other support programmes for all measures should not only be on cash crop commodities such as palm oil and pulpwood but also on food crops. Moreover, an integrated perspective means that the measures are implemented simultaneously to maximise their potential. Responsible land zoning and land-use planning are fundamental because the improvement of yields can increase the financial returns per hectare and thus motivate established farmers and migrants to convert more land for agriculture (Angelsen & Kaimowitz, 2001; Laurance & Balmford, 2013; Carrasco & Larrosa, 2014). An integrated perspective for mitigating unwanted LULC change entails significant efforts in (i) halting the projected linear or even exponential expansion of oil palm and other commodities in the region, (ii) implementing responsible land zoning

and enforcement so that only available and suitable underutilised land is used for land development and (iii) increasing the resource efficiency and productivity of agricultural production by improving the capacity of smallholdings and their access to finance and markets. However, if these conditions are not met, the four mitigation measures that were analysed in this study will not be sufficient to mitigate unwanted LULC change. Moreover, the implementation and success of these measures strongly depend on political and societal awareness and willingness to mitigate unwanted LULC change. Thus, strong law enforcement, policy implementation and the tackling of corruption are fundamental to the success of the mitigation of unwanted LULC change in North–East Kalimantan and elsewhere.

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## Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

### Appendix S1. Cultivation/plantation area and production volume of the production systems

**Table S1.** The land uses and estate types, current cultivation area (for oil palm, only mature areas were accounted for), proportion of mature oil palm plantations in and current production volume (in t) in North–East Kalimantan in 2008.

**Table S2.** Plantation area and annual production volume of pulpwood in Indonesia in 2010, planned for 2030, and projected for 2020, and projected for North–East Kalimantan in 2020 and 2030.

**Appendix S2.** Disaggregation of FFB production volume from Indonesia–Malaysia to North–East Kalimantan

**Figure S1.** Proportion (%) of the production volume North–East Kalimantan to production volume Indonesia and Malaysia.

**Table S3.** Production volume of oil palm FFB and CPO for 2008 and projected extra production volume demand for 2020 in the Indonesia–Malaysia region.

**Appendix S3.** Integration of by- and coproducts in the palm oil production chain

**Appendix S4.** Potential surplus land generated by the utilisation of oil palm trunks

**Figure S2.** Oil palm cultivation area in North–East Kalimantan extrapolated (year\* and trendline) based on data from 1998 (Casson, 1999) and 2004–2011 (BPS, 2009, 2012).

**Equation S1.** Land-sparing potential

**Appendix S5.** Improvement of the rice and palm oil production chain efficiency

**Table S4.** CPO (Oil, palm) and FFB (Oil, palm fruit) production volumes and the calculated oil extraction rates, for Indonesia and Malaysia.

**Table S5.** Rice production volumes and losses in Indonesia and nearby countries and regions between 2008 and 2011.

**Appendix S6.** Input information mitigation measures

**Table S6.** Selected input settings of the WRI Suitability Mapper, indicating suitability and oil palm crop criteria under the low, medium and high scenario (for data descriptions, data layer resolutions and data sources see WRI)

**Table S7.** Extra CPO production and rice loss prevented (t) and the land-sparing potentials (ha) in 2020 by improving the OER and minimising rice losses under the selected scenarios compared to the baseline.

**Table S8.** Amount of suitable and available underutilised land for expansion of the commodities in North–East Kalimantan.

**Table S9.** Estimated land-sparing potential (ha) of the measures under the two expansion projections.

**Table S10.** Land-use demand in 2020 with and without implementation of the measures.

**Table S11.** Difference between (i) available and suitable land and (ii) the land-use demand under different growth projections and scenarios for implementing the measures.