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Benchmarking Yield for Sustainable Intensification of Oil Palm Production in Indonesia using PALMSIM

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The physiological oil palm growth model PALMSIM can be used to estimate yield ceilings that provide benchmarks for sustainable intensification of oil palm production, either by expansion of cultivation to degraded sites or by increasing production from areas under cultivation. This is demonstrated using two case studies. In the first case study, PALMSIM estimates of water-limited yield for Kalimantan was overlaid onto a recently published map showing degraded sites potentially suitable for oil palm cultivation. A large proportion (35.6%; or 115,300 km^2) of the identified areas fell into the potential productivity range of 35 to 40 tonnes FFB per hectare. In the second case study, PALMSIM was used to estimate potential yield for six plantation sites in Indonesia where best management practices (BMP) were assessed for yield intensification by the International Plant Nutrition Institute (IPNI) Southeast Asia Program (SEAP) and its collaborating plantation partners. Potential yields are generally higher in Sumatra than in Kalimantan due to higher solar radiation. Water deficit was a problem at two sites. The gap between water-limited yield and actual yield differs from location to location, and therefore requires a site-specific analysis. In these two case studies, the scope for sustainable intensification at regional and at plantation level was explored in a quantitative manner - a novel approach to oil palm production.

Keywords: *PALMSIM, oil palm intensification, yield benchmarking.*

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Driven by high productivity of up to 6 tonnes oil per hectare, oil palm production expanded rapidly in Indonesia, in particular in Sumatra and Kalimantan, over the last two decades. Land dedicated to oil palm doubled in the last ten years. Accordingly, Indonesia became the largest global producer of palm oil, reaching 31 million tonnes in 2013 (FAOSTAT, 2013).

Environmental concerns are mainly related to drainage of peatlands for conversion to plantations as a source of greenhouse gas emissions and clearance of biodiversity-rich forests for establishment of oil palm estates (Koh *et al.*, 2011). Non-governmental organisations accuse oil palm producers of land right crimes in relation to indigenous groups (Sayer *et al.*, 2012). However, studies also show that oil palm can be a driver of rural development (Feintrenie *et al.*, 2010; Rist *et al.*, 2010). Furthermore, global population growth will make a further increase in demand highly likely (Corley, 2009).

To minimise further rainforests conversion, the keys for future oil palm production are therefore to focus expansion to degraded sites and to close the yield gap between current and attainable yield by simultaneously increasing the resource use efficiency (Sayer *et al.*, 2012). Current oil palm statistics in Indonesia show scope for such sustainable intensification: Indonesian average national yield of 17 tonnes per hectare fresh fruit bunches (FFB) is below the Malaysian average of 21 tonnes per hectare. Field trial results for several sites in Sumatra and Kalimantan have shown that yields of over 30 tonnes FFB per hectare can be reached when optimally managed (Hoffmann *et al.*, 2014). Climatic conditions of these islands are classified mostly as favourable for oil palm with an average annual rainfall of 2 000 mm and solar radiation of 6 000-6 300 MJ per sq metre.

In a recent report, Gingold *et al.* (2012) aimed to identify degraded sites in Kalimantan. They used information on soil type, rainfall, nature parks, infrastructure and possible land rights to estimate the size of degraded sites. Although they had to admit that there is still some discussion over the definition of degraded land, they concluded that there is, even when very vaguely defined, a reasonable scope for oil palm expansion into degraded sites. However, no assessment of potential productivity of these sites was possible, which would further help to reduce the time spent to identify suitable land for oil palm.

Assessing the water-limited yield of a specific site would support both identifying degraded sites with potential high productivity and intensification measures in existing plantations. Field trials and highest yield records from plantations are valuable sources of data to set such yield targets. However, field trials are financially demanding, in time and labour, and are restricted to existing plantation sites. Furthermore, both highest yield records as well as field trial results are difficult to extrapolate to other sites and years, due to variations in weather conditions during the observed period or the management practices employed. Therefore, mechanistic crop growth modeling has become a standard method in annual crops to set yield targets and explore yield gaps (van Ittersum *et al.*, 2013).

For perennial crops, especially tropical plantation crops, the development of such process-based models is still in its infancy. This might be due to lack of information to parameterise (physiological data) and run (mainly climate and soil data) such data-demanding models (van Oijen *et al.*, 2010; Huth *et al.*, 2014). Furthermore, the complex development of perennials (for example, fruit development in oil palm needs four years) makes this challenging to describe in a model.

However, the growing interest in oil palm has led to the release of a few oil palm models. A very detailed model in terms of flowering, ECOPALM, was developed by Combres *et al*. (2013). A production model was implemented in APSIM (Huth *et al*., 2014). A slightly older model is OPRODSIM by Henson (2009). All these models need very detailed information in terms of weather, and partly soil and crop physiology to be applicable.

Another model recently developed by Hoffmann *et al*. (2014) called PALMSIM was built with the objective to make it simple enough to be applicable at a range of sites, but still capturing the main process determining yield. PALMSIM simulates the potential growth of an oil palm stand on a monthly step based on incoming solar radiation for the period of 30 years. Frond and yield data from field trials from a range of sites in Malaysia and Indonesia were successfully used to evaluate the model. Since then, a simple widely used water balance for oil palm has been added to the model to provide an assessment of water-limited yield taking solar radiation, rainfall, days of rain per month and an estimation of plant available water holding capacity into account. An application of the improved PALMSIM model can be found in Rhebergen *et al*. (2014).

Against this background, the aims of this study are to assess yield benchmarks for: (i) the potentially degraded sites in Kalimantan, identified by Gingold *et al*. (2012) and (ii) for six oil palm plantations in Sumatra and Kalimantan where best management practices (BMP) for yield intensification were implemented (Donough *et al*., 2009). Thereby, the scope for sustainable intensification at regional and at plantation level is explored in a quantitative manner - a novel approach to oil palm production.

MATERIAL AND METHODS

The PALMSIM model

The simulation model PALMSIM consists of a plant growth module, which simulates the potential growth and yield of an individual oil palm stand on a per hectare basis, and a radiation module. Potential production is defined by radiation under otherwise optimal environmentally determined growing conditions, no growth limitation in terms of water or nutrient availability, and no incidence of pests or diseases (van Ittersum *et al*., 2013). The model also assumes uniform planting material and recommended canopy management in terms of pruning. Planting density is set to 143 palms per hectare, which falls within the range (138 or 148 palms/ha) most commonly used in the oil palm industry (Corley & Tinker, 2003). However, planting density and also the pruning regime can be altered in the model. The growth and the radiation modules are linked through a manager module, which serves as the user interface. The oil palm growth module can also be used as a standalone tool for applications to individual sites when measured or estimated radiation values are available.

PALMSIM was successfully tested against a range of optimal field trial results across Malaysia and Indonesia in terms of frond and bunch production. For a detailed description and an evaluation including sensitivity and plausibility assessment of the model we refer to Hoffmann *et al*. (2014).

The effect of limiting water availability is now included in PALMSIM for this study. Due to the extended period of time bunches take to become mature, water deficits are thought to have an economical effect not only in the short but also in the medium and long term. PALMSIM uses a widely applied and simple method developed by CIRAD (Surre, 1968), in which a water balance is calculated for each month (*Figure 1*).

In the water balance, evapotranspiration is assumed as 150 mm when less than 10 days of rain per month and 120 mm otherwise. Soil water not used to fulfil evapotranspiration demand per month is stored until the upper limit of the available soil water capacity for the next month. Water supply above that upper limit leads to losses from the system representing drainage and runoff. Yield i.e. assimilates available for flowers and bunches is reduced by a factor (0.0288) derived from oil palm irrigation trials when evapotranspiration demand is not fulfiled (Carr, 2011).

Case study 1: Assessment of suitable degraded sites in Kalimantan for oil palm production

Gingold *et al*. (2012) did a desktop study to assess the scope of the degraded sites suitable for oil palm production in Kalimantan. Currently, Kalimantan is of major interest for oil palm production. It is regarded as a region of major oil palm expansion with high deforestation rates (Carlson *et al*., 2012). Land was classified by Gingold *et al*. (2012) - based on available information on land cover, peatland, conservation areas with buffer zones, erosion risk, groundwater recharge potential, water resource buffers, topography, rainfall, soil properties (depth, type, drainage, acidity, colour), size and accessibility of the land, and finally land owner rights - into three categories: high potential, potential and not suitable for oil palm cultivation.

In a second step, a field survey was done to control again size and accessibility of the land, and to investigate land classification and concessions. In the final stage, the data from field survey and desktop study were combined to create a map indicating suitable areas for oil palm cultivation. Land not suitable for oil palm production was defined as: peatlands, conservation areas, forests and settlement areas. Potential land suitable for oil palm production was defined as land which is currently used for mining, farming or timber production. High potential land was characterised by open land dominated by shrubs/bush and savannah. For detailed descriptions of the assessment we refer to Gingold *et al*. (2012). The created maps are

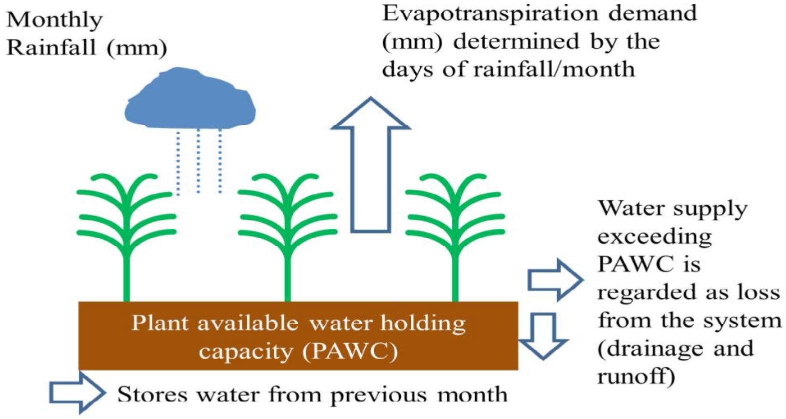

Figure 1 Illustration of the water balance implemented in the PALMSIM model

freely available from the web platform: http://www.wri.org/publication/how-identify-degraded-land-sustainable-palm-oil-indonesia.

PALMSIM was set up for Kalimantan on a 0.1° grid. Monthly cloudiness data to calculate solar radiation was available from NASA (http://earthobservatory.nasa.gov/). Average monthly rainfall data was used from the WORLDCLIM database (*Figure 2*). Soil type and plant available soil water capacity was extracted from the ISRIC-WISE soil database (Batjes, 2009) (*Table 1* & *Figure 3*). Suitable areas for oil palm from the Gingold *et al*. (2012) assessment were then related to the simulated yield of that region.

Case study 2: Yield intensification in existing plantations in Indonesia

From mid-2006 to mid-2011, the Southeast Asia Program (SEAP) of the International Plant Nutrition Institute (IPNI) implemented best management practices (BMP) at six oil palm plantation sites in Sumatra and Kalimantan with

TABLE 1
SOIL TYPES IN KALIMANTAN AND THEIR ASSOCIATED PLANT AVAILABLE WATER HOLDING CAPACITY FROM ISRIC-WISE SOIL DATABASE

Soil type	*Plant available water holding capacity (mm)*
Acrisol	150
Arenosols	100
Ferralsols	50
Fluvisols	150
Gleysols	150
Histosols	150
Nitisol	150
Luvisol	150
Lixisols	20
Podzols	100

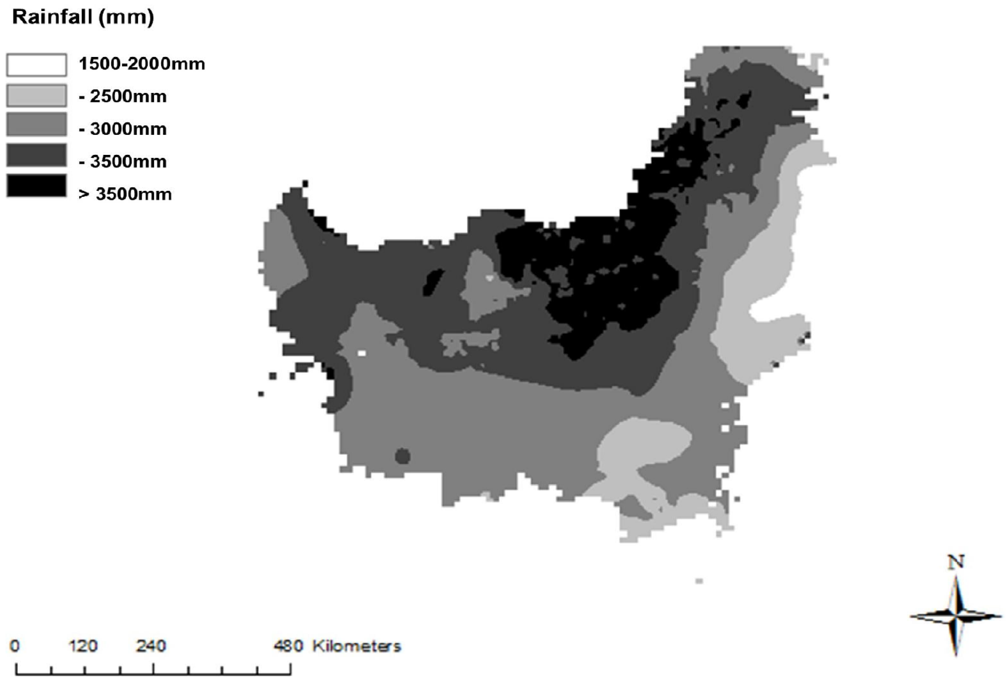

Figure 2 Average annual rainfall (mm) for Kalimantan. Data were derived from WorldClim

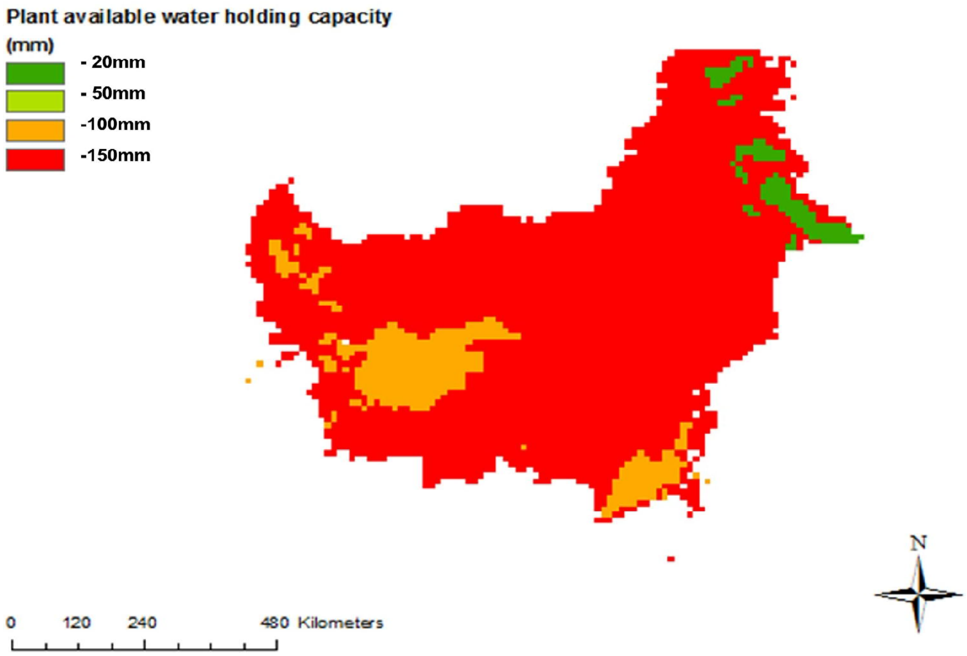

Figure 3 Plant available water holding capacity on a 0.1° grid for Kalimantan. Data were derived from soil type

the aim of improving productivity and preserving soil quality (*Table 2*) (Donough *et al*., 2010, 2011). The BMP implemented were classified into three functional categories *viz*. crop recovery, canopy management and nutrient management, details of which are given in *Table 3* (Donough *et al*., 2010).

In the experimental design, a parallel set of comparable blocks representative of a plantation are selected. Within the higher yielding block, standard commercial practices are maintained (REF blocks), while a set of

TABLE 2
SITES SELECTED FOR THE IMPLEMENTATION OF BMP BY THE INTERNATIONAL PLANT NUTRITION INSTITUTE (IPNI) SOUTHEAST ASIA PROGRAM (SEAP)

Site	*Location*	*Palm age range (years)*	*Previous yield level*[3] *(tonnes/ha)*
1	North Sumatra	5-12	26-29
2	North Sumatra	8-13	24-25
3	South Sumatra	15-18	16-24
4	West Kalimantan	8-9	16-17
5	Central Kalimantan	8-9	12-13
6	East Kalimantan	3-12	23-26

after Donough *et al.* (2010)

BMP are identified and introduced in the lower yielding block of each pair for comparison (*Table 3*). For both fields, an inventory of limiting factors is prepared, but corrective action is only taken for the BMP block.

Since July 2006, 60 paired blocks (total area 2 184 ha) have been selected, with BMP applied on 30 blocks (total area 1 080 ha). Five plantation groups collaborated on the BMP project at six different locations throughout Indonesia, covering a wide range of environments in which oil palm is grown in North and South Sumatra, and West, Central and East Kalimantan (*Table 2*). More information about the field trial design may be found in Donough *et al.* (2009, 2010) and Rhebergen (2012).

PALMSIM was setup for every plantation site as follows: Monthly solar radiation, rainfall and days of rain were created using the MARKSIM weather generator.

MARKSIM uses observed data from the WORLDCLIM data base and stochastically generates a range of possible annual weather scenarios (Jones & Thornton, 2013). As no long-term weather record was available for these sites, we used 99 years of generated possible weather conditions and run PALMSIM with each one.

Average weather data for each site is presented in *Figure 4*: Radiation is highest in northern Sumatra (sites one and two) and

TABLE 3
BEST MANAGEMENT PRACTICES (BMP) IMPLEMENTED BY THE INTERNATIONAL PLANT NUTRITION INSTITUTE (IPNI) SOUTHEAST ASIA PROGRAM (SEAP)

Crop recovery	*Canopy management*	*Nutrient management*
Harvest interval of 7 days.	Maintenance of sufficient fronds to support high palm productivity.	Spreading pruned fronds widely in inter-row area and between palms within rows.
Minimum ripeness standard = 1 loose fruit before harvest.	Removing abnormal, unproductive palms.	Eradication of perennial woody weeds.
Same day transport of harvested crop to palm oil mill.	In-filling unplanted areas.	Mulching with empty fruit bunches.
Harvest audits to monitor completeness of crop recovery and quality (ripeness) of harvested crop.	Selective thinning in dense areas.	Management of applied fertiliser.
Good in-field accessibility.	Monitoring and management of pests and disease.	Monitoring of plant nutrient status and growth.
Clean weeded circles.		
Palm platforms constructed and maintained whenever needed.		
Minimum under-pruning in tall palms to ensure crop visibility.		

after Donough *et al.* (2010)

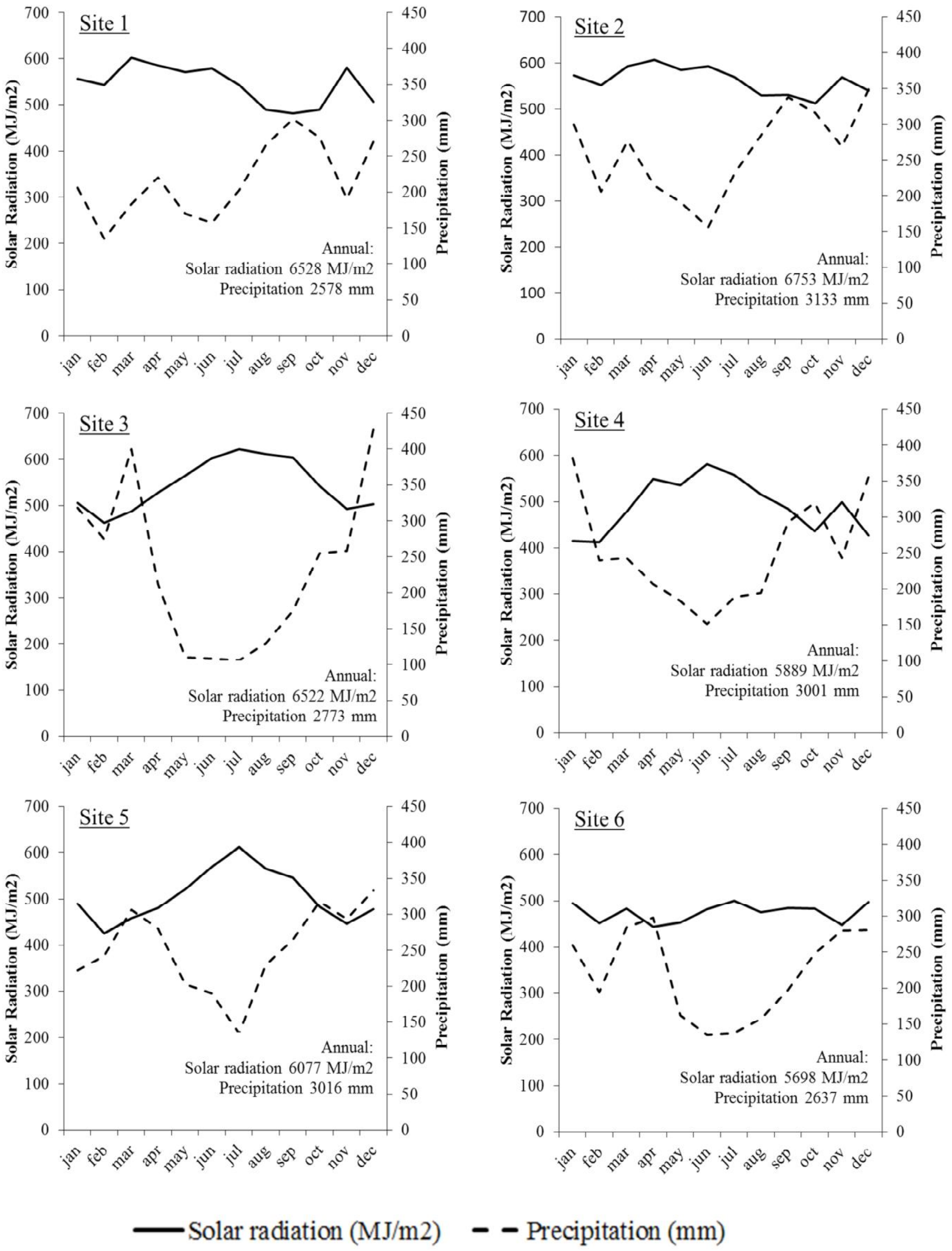

Figure 4 Average monthly solar radiation and rainfall for the six sites used in the study: site one (North Sumatra), site two (North Sumatra), site three (South Sumatra), site four (West Kalimantan), site five (Central Kalimantan), and site six (East Kalimantan) based on WorldClim data set and its use in the stochastic weather generator MarkSim

lowest in East Kalimantan (site six). Lowest average rainfall per year is suggested for site one in North Sumatra with 2 578 mm followed by site six in East Kalimantan (2 637 mm) and site three in South Sumatra (2 773 mm). The highest mean annual rainfall is generated for site two with 3 133 mm. PAWC was derived from the major soil texture class at the plantation site (*Table 4*).

RESULTS

Case study 1: A map of potential oil palm FFB yield for degraded sites in Kalimantan

PALMSIM simulated yields (limited by radiation and water only) for Kalimantan show a wide range from below 10 tonnes per hectare in the centre and the Northeast to very high levels of above 40 tonnes per hectare at the coastal sites (*Figure 5*). The low simulated yields for the centre and the Northeast present areas with higher altitude and intact rainforest - these are therefore not suitable. The very high simulated yields of above 40 tonnes per hectare for the south are for regions with peatlands, which are not regarded as suitable for oil palm cultivation due to their environmental importance (*Figure 5*).

Overlaying the suitable regions identified by Gingold *et al.* (2012) with the PALMSIM simulated potential yields (*Figure 6*) showed that 8.1 per cent of the suitable land has a potential productivity of more than 40 tonnes per hectare of FFB. The largest proportion (35.6% of the suitable land or 115 300 km^2) falls into the category between 35 and 40 tonnes FFB per hectare. Similar proportion of around 20 per cent (or 63 000 km^2) are simulated for the categories 25-30 and 30-35 tonnes FFB per hectare. Of minor importance is the category of 15-25 tonnes FFB per hectare, which covers an area of 56 500 km^2 (17.4%). Only 1 300 km^2 have very low yields below 15 tonnes FFB per hectare.

Case study 2: Assessed yield gaps for the BMP project of IPNI SEAP

Observed FFB yields from the BMP blocks are generally higher than the yields from REF blocks at sites two, three, four and five (*Figure 7*). At sites one and six, the BMP-REF yield gap is less pronounced. BMP FFB yield ranges from 25 to 38 tonnes per hectare at site one, from 21 to 33 tonnes per hectare at site two, 18 to 28 tonnes per hectare at site three, from 16 to 27 tonnes per hectare at site four, from 13 to 29 tonnes per hectare at site five and from 27 to 32 tonnes per hectare at site six.

PALMSIM simulated potential FFB yields differ from site to site (*Figure 7*): Potential

TABLE 4
CHARACTERISATION OF THE PLANTATIONS FOR PALMSIM SIMULATIONS

Location	*Main soil texture*	*PAWC*
Site 1	Sandy clay loam/sandy loam	157
Site 2	Sandy clay loam/sandy clay	142
Site 3	Sandy clay loam/sandy clay	140
Site 4	Loamy sand/loamy sand	107
Site 5	Loamy sand	40
Site 6	Clay loam	157

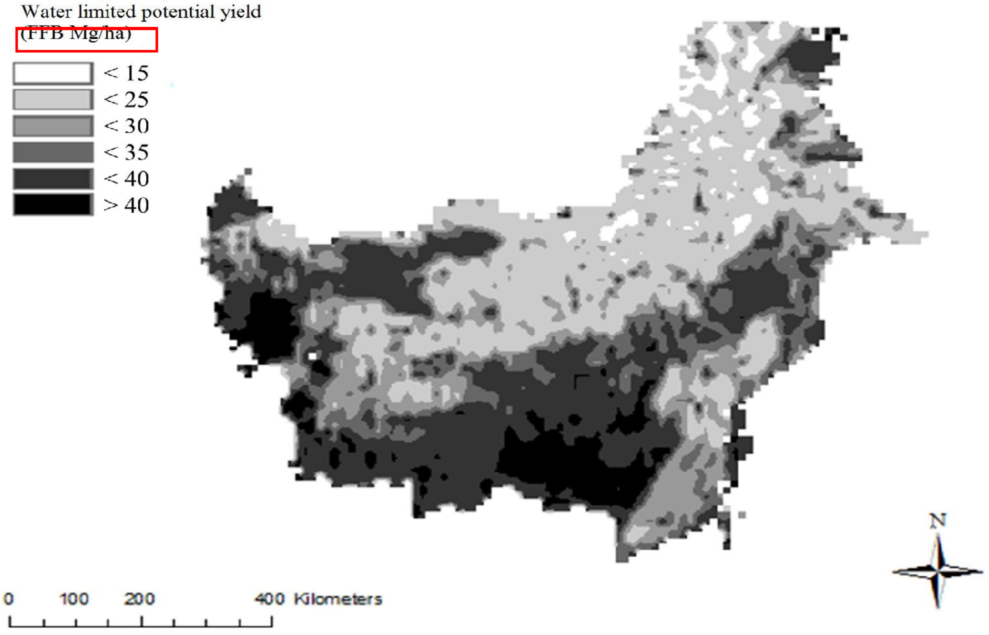

Figure 5 Simulated water and solar radiation limited potential yield for Kalimantan on a 0.1° grid based on PALMSIM runs

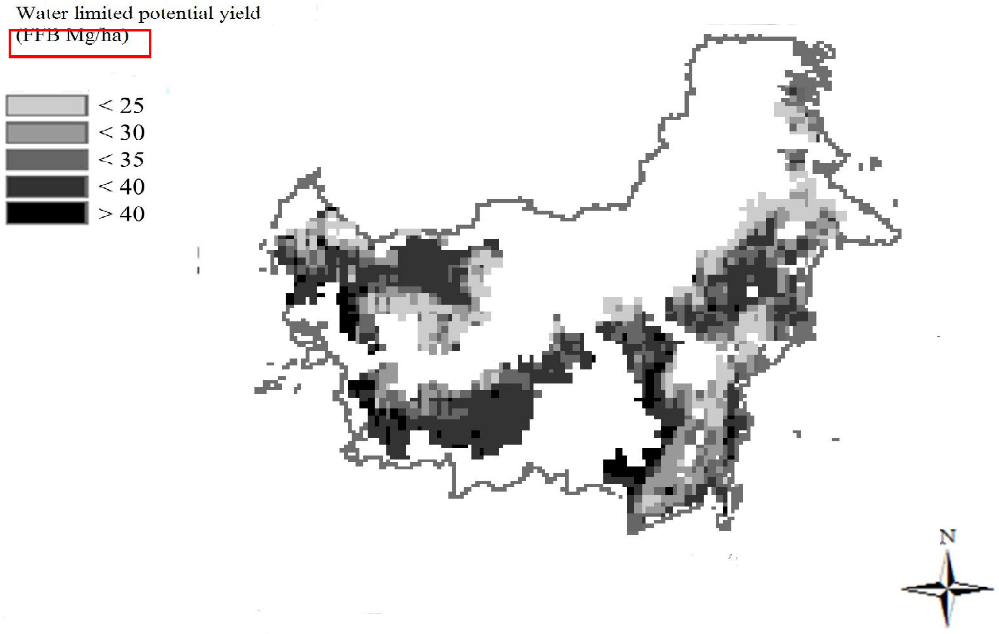

Figure 6 Simulated water and solar radiation limited potential yield for Kalimantan on a 0.1° grid based on PALMSIM runs. Sites which are not suitable for oil palm according to Gingold et al. *(2012) are excluded*

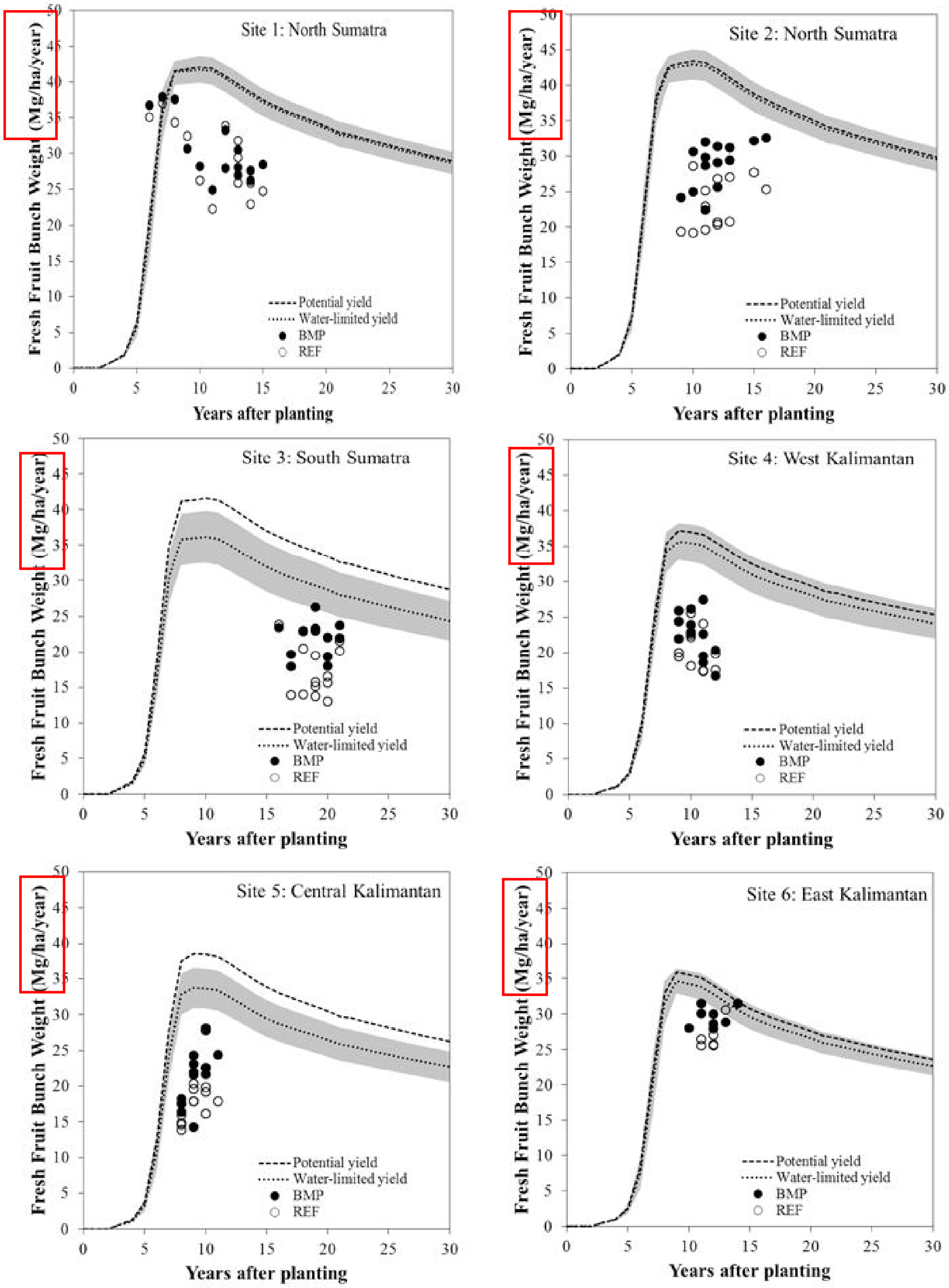

Figure 7 *Simulated mean potential and water-limited for six plantation sites in Indonesia based on 99-year runs with PALMSIM (data derived from MarkSim). The grey zone presents the standard deviation of the mean yield. Observed yields from blocks under best management practice and under reference practices are presented as points*

yields at plateau phase are highest at sites one and two, reaching 45 tonnes per hectare, and lowest at site six with 35 tonnes per hectare. At sites one, two, four and six, there is only a very weak simulated gap between potential yield (limited by solar radiation only) and water-limited yield. For sites three and five, there is a gap of 5 tonnes per hectare. In addition, the variability in possible yields indicated by the amplitude of the potential production zones (grey zone in *Figure 7*) is strongest in comparison with other sites.

DISCUSSION

Case study 1: Assessing potential productivity of degraded sites in Kalimantan for oil palm

The simulated water-limited yield map presents zones of high potential productivity (*Figure 5*). They are located in coastal and flat areas with higher solar radiation and less rainfall. With increasing altitude, higher cloud cover can be found (Corley &Tinker, 2003), which leads to low potential productivity. Lower temperatures (<20°C) associated with higher altitudes limit growth and bunch development (Corley & Tinker, 2003); areas with mean annual temperature less than 16°C are considered unsuitable for oil palm.

The high simulated potential yields (>40 tonnes/ha) for South Kalimantan have to be interpreted carefully as constraints of the dominant peatlands in that region are not captured by the model (cost of drainage, low nutrient status of the soil). Generally, these peatlands are of major environmental importance (sink of CO_2), and were consequently classified as unsuitable for oil palm production.

However in West Kalimantan, high solar radiation and sufficient rainfall lead, according to the model, to high water-limited yields, and according to Gingold *et al.* (2012) this region contains suitable land for oil palm. Surveys for oil palm land-use planning should take place in this region and in certain parts of East Kalimantan, where land classified as suitable matches high simulated yields. However, 43.7 per cent of the land classified as suitable and very suitable by Gingold *et al.* (2012) has simulated water-limited yields above 35 tonnes per hectare of FFB. This is mostly due to the high annual average rainfall of areas above 2 500 mm (*Figure 2*). Water deficiency will usually occur in dryer than average years or when soil conditions have a very low PAWC. Consequently, the solar radiation is often the limiting factor for growth in the simulation analysis.

In the literature, there is limited discussion about climate-related yield differences within Kalimantan. Usually, the climate of Kalimantan and Sumatra is seen as favourable for oil palm cultivation in comparison with other regions. However, more site-specific assessments beyond these large-scale agro-ecological zones are rarely found (Corley & Tinker, 2003).

Case study 2: Exploring management and climate related yield gaps in oil palm

Understanding climate-related production limitation is key when interpreting and comparing field trial results from several sites, as is the case of the BMP project of IPNI SEAP. Generally, solar radiation is higher in Sumatra than in Kalimantan, consequently the model results suggest potential yields (limited by solar radiation only) of more than 40 tonnes per hectare of FFB at the plateau phase for the sites in Sumatra. The simulation output for the sites in Kalimantan indicates potential yields below 40 tonnes per hectare. This might be due to higher cloud cover in Kalimantan.

The gap between attainable water-limited yield and potential yield differs from site to site: While for the two sites in North Sumatra no major water stress occurred throughout the simulation runs, minor stress events occurred for sites four and six in Kalimantan. Site three in southern Sumatra was affected by regular water deficiency where annual rainfall distribution was strongly seasonal (*Figure 3*) compared to the other sites. At site five in Central Kalimantan, water stress was due to low rainfall and soil (sand) with a very low PAWC.

Management-related yield gap, i.e. the difference between water-limited yield and observed BMP and REF yields, is smallest at site 6 (*Figure 7*). At this site, yields in many BMP and a few REF blocks match the potential production zone. Here, management already operates at the upper limit of production and differences between BMP and REF are not very pronounced. Therefore, further gains through improved management are not possible according to PALMSIM results. A similar situation is found for site one, where both BMP and REF yields are close to the production limits. At site three, FFB yields are low mainly due to the age of the palm stand. However, it was possible to increase yield close to water-limited yield by implementing BMP. Further yield gains are unlikely as water limits yield at that site more than at others. Site two offers a large yield gap. BMP implementation improved this, but there is still potential for exploitation. A major reason might be the poorer planting material (high dura contamination), which cannot be changed in the short run. The same reason might also explain the larger yield gap at site five.

To sum up the simulation, analysis suggests that sites one and six already operate at the upper limit of production, and at site three could be improved by replanting. For sites two, four and five, a larger management-related yield gap is present. Such analysis might help to understand better field trial results evaluating best management practices. There is a strong focus on nutrient caused yield gaps in oil palm research (Dubos *et al*., 2010; Rafflegeau *et al*., 2010; Webb, 2008; Webb *et al*., 2011), but there is limited literature about climate-related yield gaps for specific sites. Few studies aim to relate production to the weather conditions (Adam *et al*., 2011; Caliman & Southworth, 1998; Combres *et al*., 2013; Dufrêne *et al*., 1990; Legros *et al*., 2009). The current expansion of oil palm in Africa and South America with different climates to those in Southeast Asia will certainly increase interest in the climate-productivity relationship with oil palm. This study illustrates that even within Southeast Asia, differences in potential and water-limited yield can be found. However, these simulation results have to be used carefully, as data input for the model such as PAWC and, in particular, the simulated weather data cannot assure detailed accuracy. The recent attention on yield gap studies based on simulation modelling is so far limited to annual crops, as also stated by van Ittersum *et al*. (2013) as model and input data are rather scarce for tropical plantation crops (van Oijen *et al*., 2010).

The approach in this study using the low data input model PALMSIM showed some useful insights and provided the first yield gap analysis based on simulation modelling. However, this contains a certain amount of uncertainty as several factors, such as temperature, rainfall distribution within a month, and nutrient effects, are not captured. Despite these challenges, yield gap studies based on simulation modelling can potentially be even more beneficial for tropical plantation crops. Field trials for perennials are financially and logistically difficult to conduct; for uncultivated land it is missing. Oil palm climate change studies based on modelling analysis are so far lacking. Simulation modelling could help to evaluate whether a certain region is still suitable for the crop in 20 or 30 years, taking into account that this investment has to be made now.

Challenges for yield benchmarking in oil palm

For both proposed strategies of sustainable intensification - i.e. expansion into degraded land only and increasing productivity of land already under cultivation - yield benchmarking as shown above can be used as a valuable and supportive tool. However, defining water-limited yield is challenging in perennial crops. Such crops are heavily affected by long-term weather, which is not only restricted to one year. Instead, several years of weather define water-limited yield for a specific site (Carr, 2011).

In this study we dealt differently with this challenge: for the creation of the oil palm yield map of Kalimantan only average weather data was used. In the yield gap assessment, 99 years of possible weather scenarios were used for simulating water-limited yield. This first approach might be sufficient to give an overview on which sites are superior to others. However, for a better understanding of the potential productivity of a given site it is necessary to know about the range of possible production. To reflect this, we developed the concept of water-limited production zones (*Figure 7*), which represents the mean plus/minus the standard deviation of FFB yield as an output from 99 simulations. However, this approach is still far away from the accuracy of yield gap analysis in annual crops. This is firstly due to the simplicity of PALMSIM, especially in terms of the water balance, and secondly the lack of information in terms of long-term observed weather data.

CONCLUSION

To balance the large environmental impact of oil palm plantations and the increasing demand for palm oil, sustainable intensification - by expansion only into degraded sites and by the increase of productivity per unit land in existing cultivated areas - is highly desirable. For both strategies, yield benchmarking by simulation modelling can be a useful supportive tool. Therefore, the simple physiological oil palm model PALMSIM was used to set yield targets in two case studies illustrating these two options for sustainable intensification. Such a quantitative pathway towards benchmarking yield is - to our knowledge - a novel approach to oil palm production.

ACKNOWLEDGEMENT

More information about the model including the source code is available from: http://www.uni-goettingen.de/en/palmsim/499488.html. This article is part of the PhD thesis by Munir Hoffmann (2015) “Understanding potential yield in the context of the climate and resource constraint to sustainably intensify cropping systems in tropical and temperate regions” University of Göttingen, Germany.

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