Supplementary information for "Fostering a climate-smart intensification for oil palm" by Monzon *et al*.

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I. Additional methods to estimate water-limited yield potential for oil palm

A. Site selection and plantation area coverage

Following the protocols of the Global Yield Gap Atlas[31,52,71], we seek a compromise between reaching a reasonable coverage of national mature plantation area while minimizing the number of sites for which Yw needs to be estimated (Extended Data Fig. 3). We used an oil palm area distribution map for Indonesia for year 2015, which includes both smallholder and large plantations[72]. This map was clipped by a peatland distribution map[73] to develop a map that only includes oil palm area located in mineral soils. As a first step, climate zones accounting for >5% of national oil palm area were selected. Each climate zone corresponds to a unique combination of annual growing-degree days, water balance, and temperature seasonality[74]. Subsequently, buffer zones (radius: 100 km) were defined around existing weather stations, with their borders clipped so that the buffers do not extent into different climate zones (Extended Data Fig. 3). Weather stations with long-term weather records are required to estimate Yw and its variability. Buffers were selected successively, starting from the one with highest share of national oil palm area, and then eliminating those buffers that overlap with the selected buffer by more than 20%. The process was repeated, and more buffers were selected until reaching a coverage of *ca.* 50% of national oil palm area. We created additional buffers (hereafter called 'hypothetical buffers') to cover important oil palm producing areas that were not selected because of absence of weather stations. Overall, the 22 selected buffers accounted for 60% of national oil palm area (Extended Data Fig. 3). In turn, these buffers were located in agro-climatic zones that accounted for 93% of national oil palm area.

B. Sources of weather and soil data

Fourteen of the 22 buffers have an associated weather station from the national meteorological service[75], with long-term daily weather records needed to estimate long-term Yw and its variability. Gridded weather data from the NASA LaRC POWER Project database[76] were used to estimate Yw for the remaining eight "hypothetical" buffers (sites #1, #3, #4, #7, #16, #19, #21, and #22) (Extended Data Fig. 3). In all cases, daily weather data included incident solar radiation, maximum and minimum air temperature, relative humidity, wind speed, and precipitation from the past 28 years (1990-2018).

Soil texture, depth, and slope for dominant mineral soils identified in each buffer were derived from soil maps at scale 1:250,000 from the Indonesian Centre for Agricultural Land Resources Research and Development[77]. In all cases, selected soil(s) accounted for >60% of total oil palm area in mineral soils within each buffer. Pedo-transfer functions calibrated for tropical soils were used to retrieve upper and lower soil water retention limits[78]. In absence of soil constraints to root growth, we assumed a maximum soil depth for soil water extraction of 1.5 m[79]. These soil parameters were inputted into the crop model to simulate the soil water balance.

C. Retrieval of average actual yield and management data by farmer typology

Regency-level data for average actual yields were retrieved from official national statistics for the period 2012-2016[9]. In all our calculations, FFB yields were derived from CPO yields at regency and national level, using an OER of 20%[7,9,62]. Available data were already disaggregated by farm type: large plantations (>25 ha) and smallholders (<25 ha). In practice, smallholder farmers manage one to two hectares planted with oil palm. Large plantations included both private and state (government-owned) plantations. We did not attempt to differentiate between private and state plantations given the similarity in yield and management practices between them and the small area of state plantations (*ca.* 7% of national oil palm area[9]). In the case of smallholders, they can be further disaggregated into supported and independent smallholders, depending on the degree of engagement with large plantations. Supported smallholders typically engage *via* contract with a large plantation, with a large-scale oil palm plantation ('nucleus') surrounded by smallholder plantations ('plasma'). The large plantation supports smallholders in acquiring inputs and proper planting material who, in turn, sell their FFB output to the mill managed by the large plantation. In contrast, independent smallholders operate without any formal connection with large plantations[26]. Yields are estimated to be 10-24% lower in independent *versus* supported smallholder farmers[26,29]. Unfortunately, current official statistics on oil palm yield and area are not disaggregated into supported and independent smallholders; instead, statistics are reported for the pooled smallholder category[9].

For each year and farm typology, a weighted Ya for productive plantations was calculated for each buffer based on the mature area in each regency that overlap with the buffers' extent. For the calculation of Ya in a given buffer, we only used yield data from regencies that have >33% of their total area inside a given buffer. Data from large plantations in 2016 were not available; hence, for that year, we estimated yields for large plantations based on smallholders' yields by year 2016 and the yield ratio between large plantations and smallholders in the previous four years (2012-2015). Official statistics on actual yields do not differentiate among mineral soils and peatlands.

Data on average palm age were collected for each buffer and farm typology (smallholder and large plantations) by professionals from the Indonesian Oil Palm Research Institute (IOPRI). Average palm age is relevant for estimating yield gap as it influences the Yw and needs to be accounted for in the estimation of yield gap for oil palm. Hence, for robust estimation of yield gap in oil palm, it is important to know what the average age of the plantation for each buffer and farm type is, so that the Ya can be compared against the corresponding Yw at that same age (Extended Data Figure 5).

D. Estimation of water-limited yield potential and yield gaps for the 22 sites

Crop models are tools that allow to estimate Yw. In the present study, simulations were performed using PALMSIM v2.0 model[53,80], which is a modified version of PALMSIM v1.0[28,81]. The earlier versions of PALMSIM (2010–2014) were entirely radiation-driven. In short, the known site-specific incoming solar radiation is used to determine the amount of photo-assimilates available and used by the crop for maintenance and growth. Next, yield is determined by considering partitioning of assimilates between vegetative and generative organs based on constant biomass fractions. Hekman et al.[53] have taken steps to improve the model. PALMSIM v2.0 is coupled now to a water balance routine that includes water fluxes *via* precipitation, evapotranspiration, and drainage. A transpiration reduction factor, in combination with the incoming radiation and light use efficiency, determines the amount of assimilates produced. Subsequently, assimilates available for plant growth are partitioned to the vegetative (roots, trunk, fronds) and generative part (male/female inflorescences) based on age-dependent potential growth rates, which determine the sink strength of a certain organ. The ratio between supply and demand (potential growth rate) is used to simulate yield-determining mechanisms like male/female inflorescences ratio, bunch abortion, and bunch failure[53,79, 80, 82, 83]. The current model can therefore be used to estimate Yw accounting for the effects of water stress on reproductive organs. The model provides estimates of Yw on a field-scale level at a daily time resolution requires specification of climate and soil properties. When simulating Yw, PALMSIM assumes no limitation by nutrients and no yield reductions due to incidence of weeds, pathogens, and insect pests.

Model calibration and testing was performed using monthly FFB yield, bunch number, and average bunch weight data from 14 high-yielding mature commercial blocks located in Sumatra and Kalimantan. These blocks were explicitly selected to portray well-managed plantations across a wide range of soil and climate conditions. Long-term average annual FFB yield ranged from 24.4 to 35.3 t ha^{-1} across blocks, with annual FFB ranging from 18.2 to 41.6 t ha^{-1} across all site-year combinations. On-site soil and weather data were also provided. In those cases where weather data were not available (or were incomplete), we used data from the nearby BMKG weather station[75] or NASA LaRC POWER Project database[76], if there was no nearby weather station. For the simulations, no limitations to crop growth by nutrients or biotic stress were assumed and planting density and configuration were set according to recommended best practices (141 palms per ha and an optimal frond count of 50 and 40 for young and mature plantations, respectively). Four commercial plots, with the most completed and detailed data, were selected for model calibration. First, a boundary line analysis was performed to obtain potential bunch weights at different palm ages. The remaining parameters were calibrated in a subsequent step using the same subset of (four) blocks. The other 10 blocks available in the database were used, together with the four blocks used for model calibration, to assess uncertainty in our estimates of Yw and Yatt (Supplementary Information Section II).

The model was subsequently used to predict Yw across the 22 target sites based on local weather and soil, average palm age, and best available planting material. Commercial plantations are usually replanted every 25 years; hence, for each buffer, we simulated Yw for the entire 25-year plantation cycle. For a given palm age, Yw can still vary because of variation in weather. To account for weather-driven variation in Yw at a given palm age, multiple 25-year simulations were performed for a given buffer using the same weather data but with different arrangements (Extended Data Fig. 4). Briefly, we started the 25-year simulations at different years (filling the missing years at the end with the early years of the weather file if needed). We performed these (25-year) simulations of the plantation cycle starting in 28 different years (1990 to 2018); hence, for a given palm age, we obtained 28 values of Yw (Extended Data Fig. 4).

Separate simulations of Yw were performed for each mineral soil type in each buffer and resulting values were aggregated to buffer level based on the share of each soil type to the total oil palm area located in mineral soils within each buffer (Supplementary Table 1). Yw was upscaled to national level based on the proportion of oil palm area located in each buffer in relation to national mature area (in mineral soils in both cases). Yw for oil palm in Indonesia averaged 44 t ha^{-1} (average of smallholders and large plantations, weighed by their respective areas), with relatively small variation across the 22 sites as quantified using the coefficient of variation (CV = 11%) (Supplementary Table 1).

The Yatt was estimated as 70% of Yw, while the exploitable yield gap was calculated as the difference between the Yatt and Ya (Extended Data Fig. 1 and 5). The exploitable yield gap was computed for each of the 22 sites, separately for large plantations and smallholders, and also at the national level (Supplementary Table 1). In each case, for the calculation of the exploitable yield gap, we used the Yatt that corresponded to the average palm age reported for each specific buffer and farmer type (Supplementary Table 1). We note that the Yatt was slightly smaller for smallholder compared with large plantations (29.1 *versus* 31.6 t ha^{-1}) because Yw declines with age[51] and smallholder plantations are older than large plantations, averaging 18 and 15 years, respectively (Supplementary Table 1). Replanting cycles are often longer for smallholders compared to large plantations due to economic constraints delaying replanting[20,26].

II. Limitations and sources of uncertainty

A. Estimation of exploitable yield gap

There are some possible sources of error associated with the average actual yields. Official statistics do not disaggregate yield by type of soil (mineral *versus* peatland); average actual yield is typically lower in peatlands. Peatlands account for a relatively small portion (20%) of national oil palm area[54,55], which would lead to a relatively small overestimation of the yield gap for mineral soils. Similarly, average actual yield reported for smallholders is not disaggregated between supported and independent smallholders. Hence, the yield gap will be underestimated and overestimated in the case of independent and supported smallholders, respectively; the yield gap will be 10 to 24% larger for independent smallholders[26,29]. Because our goal was not to quantify the yield for every single type of smallholder, this limitation will not affect the overall findings from our study.

There was also intrinsic uncertainty associated with the accuracy of the data inputs used for the crop simulations. In the case of weather data, quality control and filling/correction was performed based on correlations between the target meteorological station and one to three adjacent weather stations. Number of corrections/filled data was always <3% of the total amount of data. Also, in relation with weather data, we decided not to evaluate effects of long-term climate change because of large uncertainty in the degree of climate change impacts at local scales and because the climate change impact by 2035 projected for the region is expected to be relatively small compared with the large yield gaps that we found here[84]. Data on soil type, average palm age, and average nutrient fertilizer rates were cross-validated with expert opinion from oil palm agronomists and plantation managers through workshops and personal meetings and data from the literature[29, 62].

It is difficult to validate our simulated values of Yw as long-term trials where management practices have been optimized to eliminate all possible yield limiting and reducing factors do not exist for oil palm. Still, our range of simulated Yw (Supplementary Table 1) was consistent with highest recorded yields in blocks in Indonesia and Malaysia [79,81,85-91] were the influence of yield-limiting and reducing factors was minimized *via* management, ranging from 31 to 55.5 t ha^{-1} (Extended Data Fig. 7). The difference between the two sources of Yw values was not statistically different from zero (two-tailed Student's t-test; $p = 0.35$). Similarly, there is uncertainty in our assumption of 70% of Yw for the calculation of Yatt. That approach is difficult to validate without a thorough economic analysis and the data required for this evaluation are not available. Fortunately, similarity in range of attainable yield derived from crop modelling *versus* long-term average actual yields measured across 14 well-managed commercial blocks during >10 years in Indonesia suggests that our estimates of Yatt are robust (Extended Data Fig. 7). Similar to the comparison of Yw, the difference between the two sources of Yatt values was not statistically different from zero (two-tailed Student's t-test; $p = 0.72$), indicating that our estimates of Yatt are robust. Finally, our estimates of CPO production by 2035 may be pessimistic if there is progress in elevating the genetic yield potential of oil palm[92]. However, this would also imply that an even larger exploitable yield gap than the already large gaps reported herein needs to be close. Additionally, we noted the long replanting cycle in oil palm (25 years), which would slow adoption of new materials with higher yield potential.

B. Oil palm production in peatlands

Quantification of yield gaps in peatlands is not possible with current crop simulation models[81], and management practices needed to increase yield have not been so well documented as those for mineral soils. Perhaps more importantly, there are concerns about the long-term sustainability of oil palm production in peatlands[93]. On the one hand, this means that our estimated extra production potential could be higher than the one estimated here if average actual yields for oil palm in peatland increases. On the other hand, if oil palm plantations in peatland are gradually taken out of production, for example, for restoration purposes or when the peat reaches non-drainable level due to subsidence[94], that would reduce oil palm area and put further pressure on closing the exploitable yield gap in mineral soils in order to meet the national CPO goal by year 2035. Given this uncertainty, we decided not to account for any yield gain derived from crop intensification in peatland and we also ignored any potential net loss in oil palm area in peatlands that might occur in the future.

C. Oil palm demand and estimation of oil extraction rate (OER)

We are aware of possible sources of uncertainty in relation to the estimated demand for palm oil in Indonesia around 2035, including global demand for vegetable oils, restrictions to oil palm exports, biodiesel demand, and extra palm oil supply from other countries where oil palm area is growing. Despite these uncertainties, the 36%-demand increase in CPO by year 2035 is consistent with those reported by other independent sources, such as OECD[23] and IFPRI[22], reporting increases in oil palm demand in Indonesia (OECD) and East Asia Pacific (IFPRI) of 35 and 38%, respectively. These estimates considered the extra palm oil production from South America and Africa.

Improvements in OER, *via* higher efficiency in the extraction process and/or use of planting material with higher oil content would reduce the land requirement and yield gains required to reach the CPO goal by year 2035. Indeed, existence of elite parents with oil content higher than 28%[95] and widespread presence of *Dura* palms (with lower oil content) in smallholders plantations[40] highlights the potential room for increasing CPO production through use of planting material with higher oil content. Considering the short timeframe of our scenario assessment (17 years), the relatively long replanting cycle (25 years), and constraints to adopt proper planting material in smallholder farms[20,26], we used a conservative OER value of 20%, which is similar to the national average for Indonesia during the 2002-2018 period.

D. Estimation of land use change and GHG emissions

The BAU and INT-TE assumed that the productivity of new land is similar to that of existing plantation area when, in fact, it tends to be lower[96]. Hence, the extra production derived from new land converted for oil palm production may be overestimated in our analysis, highlighting the need to complement target expansion with intensification on existing plantation area. Further GHG emissions from peatland may occur as the result of forest fires[97]. Due to the difficulty to distinguish between natural *versus* human-induced fires and the amount of peatland area affected by fire in each year, together with very limited availability of data on forest fires, our estimation of GHG from peatland only includes those areas associated with land conversion and the subsequent emissions from peat decomposition[57]. There is uncertainty also in the emission factors used for estimating GHG_{LUC}. In the case of peat decomposition, emission factors can vary as a result of peat depth and water management in the oil palm plantation and in the preceding land use[98]. In all cases, we used the tabulated values from the literature for our computation of GHG_{LUC}[57]. While we acknowledge that there may be opportunities in the future to reduce GHG emissions from peat decomposition on existing oil palm plantations in peatlands (*e.g.*, *via* improved water management), it is at the moment impossible to know the exact impact this could have on the associated emissions and what the timeline for evaluation and adoption of these new management options are. Hence, for our scenario assessment, we did not consider any reduction in the GHG emissions derived from peat decomposition as a result of improved water management. Similarly, other studies on life-cycle assessment of palm-oil biodiesel have explored more radical changes in the plantation management (e.g., lengthening the plantation cycle and use of early-yielding varieties) as means to reduce the overall GWP[68]. Given the relatively short timeframe of our study (15 years), and agronomic, logistics, and economic constrains limiting adoption of these practices[26], we did not include these options in our scenario assessment.

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Supplementary Table 1. *Average palm age (years after planting [YAP]), water-limited yield potential (Yw), attainable yield (Yatt), average actual yield (Ya), and exploitable yield gap (Yg, expressed as percentage of Yatt) across 22 sites in Indonesia. Average values at country level are shown at the bottom of the table. Buffers are mapped in Extended Data Fig. 3. Parenthetic values indicate the standard deviation. Yw, Yatt, and Ya are expressed in tons of fresh fruit bunches (FFB) per hectare per year. Data on Yw, Yatt, and yield gaps are available through the Global Yield Gap Atlas website (http://www.yieldgap.org/indonesia-oil-palm).*

Buffer ID	Name	Large plantations					Smallholders				
		Palm age	Yw	Yatt	Ya	Yg	Palm age	Yw	Yatt	Ya	Yg
		(YAP)		---- t FFB ha^{-1} ----		%	(YAP)		----- t FFB ha^{-1} -----		%
1	Seruway	19	35.4 (4.9)	24.8 (3.4)	21.7 (1.2)	12	15	38.9 (5.6)	27.2 (3.9)	15.9 (0.6)	42
2	Tuntungan	18	38.1 (2.8)	26.7 (2.0)	23.6 (1.2)	12	22	34.7 (2.4)	24.3 (1.7)	17.1 (0.3)	29
3	Batahan	17	46.6 (2.6)	32.6 (1.8)	17.9 (2.3)	45	15	49.2 (2.5)	34.4 (1.8)	15.8 (0.5)	54
4	Bagansinemba	18	45.1 (2.7)	31.6 (1.9)	21.5 (0.6)	32	20	42.8 (2.5)	30.0 (1.8)	17.0 (0.4)	43
5	Pekanbaru	15	43.5 (3.3)	30.5 (2.3)	19.8 (1.2)	35	20	38.6 (2.7)	27.0 (1.9)	14.3 (2.5)	47
6	Japura	16	41.7 (2.3)	29.2 (1.6)	23.9 (3.6)	18	18	39.7 (2.5)	27.8 (1.8)	19.3 (0.5)	30
7	Muko Muko	18	44.1 (4.3)	30.9 (3.0)	19.5 (0.7)	37	16	46.5 (4.9)	32.6 (3.4)	17.5 (0.3)	46
8	Jambi	16	40.1 (3.5)	28.1 (2.5)	17.1 (1.9)	39	15	40.9 (3.9)	28.6 (2.7)	14.8 (0.5)	48
9	Palembang	11	46.4 (5.2)	32.5 (3.6)	19.2 (1.4)	41	18	40.6 (4.3)	28.4 (3.0)	12.5 (0.9)	56
10	Kota Bumi	15	41.8 (5.5)	29.3 (3.9)	20.6 (1.5)	30	14	43.2 (5.3)	30.2 (3.7)	15.3 (1.1)	49
11	Liku	15	40.9 (3.6)	28.6 (2.5)	16.5 (2.0)	43	21	35.2 (2.7)	24.6 (1.9)	11.5 (1.0)	53
12	Pontianak	16	45.7 (2.8)	32.0 (2.0)	16.9 (1.3)	47	25	37.4 (2.1)	26.2 (1.5)	10.9 (1.0)	58
13	Sintang	14	47.3 (3.5)	33.1 (2.5)	15.5 (1.6)	53	25	36.3 (2.8)	25.4 (2.0)	12.9 (1.1)	49
14	Kota Ketapang	13	48.9 (4.3)	34.2 (3.0)	16.3 (1.8)	52	25	38.5 (3.2)	26.9 (2.2)	11.1 (0.7)	59
15	Pangkalabuun	19	41.1 (3.6)	28.7 (2.5)	21.6 (2.0)	25	10	52.0 (4.7)	36.4 (3.3)	12.0 (0.7)	67
16	Parenggean	15	47.0 (4.8)	32.9 (3.4)	21.7 (2.2)	34	11	52.4 (5.7)	36.7 (4.0)	15.5 (3.1)	58
17	Sampit	15	44.7 (5.2)	31.3 (3.6)	20.3 (2.0)	35	12	48.6 (5.9)	34.0 (4.1)	17.7 (4.2)	48
18	Banjar Baru	16	41.2 (3.6)	28.8 (2.5)	17.3 (1.7)	40	11	46.5 (3.8)	32.5 (2.7)	16.3 (0.8)	50
19	Karangdajoe	15	43.5 (5.1)	30.4 (3.6)	17.0 (2.0)	44	10	49.3 (6.8)	34.5 (4.8)	14.3 (4.3)	59
20	Balikpapan	15	41.1 (3.5)	28.8 (2.5)	16.4 (1.5)	43	15	41.1 (3.5)	28.8 (2.5)	12.0 (2.7)	58
21	Muara A.	12	53.4 (4.8)	37.4 (3.4)	18.6 (2.6)	50	9	58.5 (6.0)	41.0 (4.2)	16.5 (2.4)	60
22	Kabalamin	14	53.2 (5.9)	37.3 (4.1)	22.1 (1.2)	41	10	59.0 (6.8)	41.3 (4.8)	17.3 (1.6)	58
Country		15	45.0 (4.0)	31.6 (2.8)	19.7 (0.6)	38	18	41.7 (3.7)	29.1 (2.6)	15.3 (0.2)	47

***Supplementary Table 2.** Predicted annual total oil palm area expansion (M ha) by land cover type*[63] *for the business as usual (BAU) and the intensification plus target expansion (INT-TE) scenarios, disaggregated for mineral soils and peatland, during the 2018-2035 study period*[63]*. M ha: million ha.*

Land cover type	Scenario		
	BAU		INT-TE
	Mineral soil	Peatland	Mineral soil
Primary forest	0.005	0.002	0
Secondary forest	0.039	0.019	0
Scrubland	0.137	0.043	0.136
Grassland	0.008	0.002	0.007
Bareland	0.070	0.023	0.069
Annual crops	0.058	0.009	0
Paddy rice	0.009	0.004	0
Perennial tree	0.097	0.008	0
Timber plantation	0.004	0.003	0
Total	0.427	0.113	0.212

Supplementary Table 3. Carbon (C) stocks in aboveground dry matter (ADM) by land use type[65] and emission factors (EF) for peatland under different land use types[79].

Land cover type	ADM (t C ha^{-1})	EF peat (t CO_2 ha^{-1} y^{-1})
Primary forest	130	0
Secondary forest	93	19
Scrubland	30	19
Grassland	4	35
Bareland	2.5	51
Annual crops	10	51
Lowland rice	2	34
Perennial tree	30	51
Timber plantation	49	73
Oil palm plantation	40	40