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What are the limits to oil palm expansion?

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ABSTRACT

Palm oil production has boomed over the last decade, resulting in an expansion of the global oil palm planting area from 10 to 17 Million hectares between 2000 and 2012. Previous studies showed that a significant share of this expansion has come at the expense of tropical forests, notably in Indonesia and Malaysia, the current production centers. Governments of developing and emerging countries in all tropical regions increasingly promote oil palm cultivation as a major contributor to poverty alleviation, as well as food and energy independence. However, being under pressure from several non-governmental environmental organizations and consumers, the main palm oil traders have committed to sourcing sustainable palm oil. Against this backdrop we assess the area of suitable land and what are the limits to future oil palm expansion when several constraints are considered. We find that suitability is mainly determined by climatic conditions resulting in 1.37 billion hectares of suitable land for oil palm cultivation concentrated in twelve tropical countries. However, we estimate that half of the biophysically suitable area is already allocated to other uses, including protected areas which cover 30% of oil palm suitable area. Our results also highlight that the non-conversion of high carbon stock forest (>100 t AGB/ha) would be the most constraining factor for future oil palm expansion as it would exclude two-thirds of global oil palm suitable area. Combining eight criteria which might restrict future land availability for oil palm expansion, we find that 234 million hectares or 17% of worldwide suitable area are left. This might seem that the limits for oil palm expansion are far from being reached but one needs to take into account that some of this area might be hardly accessible currently with only 18% of this remaining area being under 2 h transportation to the closest city and that growing demand for other agricultural commodities which might also compete for this land has not been yet taken into account.

1. Introduction

Palm oil production has boomed over the last decades driven by increasing use as frying oil, as an ingredient in processed food and non-edible products (detergents and cosmetics), and more recently in biodiesel production (Thoenes, 2006). Most observers expect this trend to continue in the coming years, even though probably at a slower pace than the last decade (OECD and FAO, 2013). The share of palm oil in global vegetable oil production has more than doubled over the last twenty years, today representing more than 30%, outstripping soya oil production (OECD and FAO, 2013). Reasons for this strong expansion include the substantially higher oil yield of palm oil compared to other oilseeds – over four and seven times greater than rapeseed and soy, respectively (Product Board MVO, 2010) – and its lower price, which has made it the primary cooking oil for the majority of people in Asia, Africa and the Middle East (Carter et al., 2007; USDA-FAS, 2011). Schmidt and Weidema (2008) estimate that palm oil is today the “marginal oil”, i.e. future increases in demand for vegetable oils will be primarily satisfied by palm oil rather than by other vegetable oils.

This resulted in an expansion of the global oil palm planting area from 6 to 16 Million hectares between 1990 and 2010, an area which now accounts for about 10 percent of the world’s permanent cropland. Malaysia and Indonesia have been the epicenter of this dynamic development: in these two countries planted area has increased by 150% and 40%, respectively, over the last decade, and together they currently represent over 80% of the global palm oil production (FAO, 2016). As global demand increases and available land becomes increasingly scarce in the traditional production centers (Kongsager and Reenberg, 2012; USDA-FAS, 2011), governments of developing and emerging countries such as Brazil, Peru and Central and Western Africa increasingly promote oil palm cultivation as a major contributor to poverty alleviation, and food and energy independence (Carrere, 2010; Feintrenie, 2014; Gutiérrez-Vélez and DeFries, 2013; Pacheco, 2012; Villela et al., 2014).

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It is estimated that 17% of the new plantations in Malaysia and 63% of those in Indonesia came at the direct expense of biodiversity-rich tropical forests over the period 1990–2010 (Gunarso et al., 2013; Koh et al., 2011) and up to 30% of this expansion occurred on peat soils, leading to large CO_2 emissions (Carlson et al., 2012; Miettinen et al., 2012; Omar et al., 2010). These potential negative effects of oil palm cultivation have given rise to closer scrutiny from consumers (Greenpeace International, 2012). As a consequence, the palm oil sector developed in 2004 its own sustainable certification standard, the Roundtable on Sustainable Palm Oil (RSPO; von Geibler, 2013), and the European Union as well as the United States have also set-up some specific sustainability criteria on feedstock imports for biofuel production (Environmental Protection Agency, 2012; European Comission, 2010). However, RSPO-certified palm oil continues to be a niche product, holding about only 15% of the market, half of which is marketed as conventional palm oil, since demand for certifies oil is still too low (Balch, 2013; Round table on sustainable palm oil (RSPO), 2011). In 2014, five major oil palm growers initiated the Sustainable Oil Palm Manifesto which is preparing the ground for the establishment of a set of clearly defined and globally applicable thresholds to the definition of sustainable palm oil (Raison et al., 2015).

The broad objective of sustainable development is to “meet the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987). Some palm oil certification schemes like the RSPO, tackle the three pillars of sustainable development i.e. the environmental, social and economic dimensions while some other initiatives, like the EU directive on biofuels, focus on carbon savings and biodiversity protection (Frank et al., 2013). There is not an alignment among the different certification schemes on the most appropriate or useful set of indicators and there are different approaches for developing and using them (Pavlovskaia, 2014). However, two schemes are widely used in order to prevent emissions from the conversion of land with high carbon content or the destruction of biodiversity-rich natural habitats from palm oil production: the High Carbon Stocks (HCS) and the High Conservation Value indicator (HCV).

In the context of a continued boom in palm oil demand and the increasing sustainability commitment of the palm oil sector, the objective of this paper is to identify the potential available area for future expansion of palm oil plantations globally and more especially, how this might be affected by the implementation of some environmental sustainability criteria which are currently discussed by the sector. We first assess oil palm land suitability from a bio-physical perspective taking into account climate, soil and topography. Subsequently, we remove from the suitable area the land where conversion is currently not possible because being already under use or protection. Then, we exclude land which is of special value for biodiversity conservation or carbon storage. Finally, we assess the accessibility of the resulting potentially available land for future oil palm plantations expansion, as remoteness might reduce the profitability of palm oil production.

2. Materials and methods

2.1. Bio-physical suitability for oil palm

2.1.1. Climate

Oil palm trees grow in warm and wet conditions. Four climatic factors are crucial for oil palm cultivation: the average annual temperature, the average temperature of the coldest month of the year, the annual precipitation and the number of months which receive less than 100 mm of precipitation (Corley and Tinker, 2008). Optimal temperature conditions range between 24 and 28 °C, and the average temperature of the coldest month of the year should not fall under 15 °C (Corley and Tinker, 2008). Further, the length of the growing period (LGP) for oil palm is mainly determined by the length of the period with sufficient moisture supply. Optimal conditions for palm cultivation are 2000–2500 mm rainfall per year with a minimum of 100 mm per month. On well drained soils, i.e. soils which are classified as other than poorly drained according to the Harmonized World Soil Database (HWSD; Nachtergaele et al., 2012) annual rainfall up to 4000 mm is well supported, above this threshold diseases become more frequent and 5000 mm is considered the definite upper limit to oil palm cultivation. It is reported to be grown under precipitation conditions as low as 1000 mm per year (Yao and Kamagate, 2010) and up to five months of dry period. We present a review of suitability factors used by other studies in SM C. We do not consider irrigation schemes as a potential management option because for oil palm cultivation these schemes are still in the experimental phase. We use data from the WorldClim database (Hijmans et al., 2005) to compute climate suitability at the 30 arc seconds resolution level and data from the HWSD (Nachtergaele et al., 2012) to determine the drainage status of a site.

2.1.2. Soil

Oil palm is not very demanding in its requirements of the chemical and physical properties of the soil: it grows on a wide range of tropical soils, many of which are not suitable for the production of other crops. Constraining soil factors for oil palm cultivation can be either chemical (e.g. nutrient deficiencies) or physical (e.g. low water holding capacity) in nature. Optimal conditions are provided by finely structured soils with high clay content, though fairly good yields can also be achieved on loam and silt-dominated soils. Oil palm is also very sensitive to insufficiencies in water provision which are frequent on sand-dominated soils. We distinguish between those soil features that can be overcome by appropriate agronomic management and those that are unsuitable regardless of management (see SM A for more details). We make the assumption that appropriate soil management measures are applied in agro-industrial oil palm plantations and therefore non-permanent problematic soil features can be overcome and are not considered in the analysis. For soil information we rely on the HWSD (HWSD; Nachtergaele et al., 2012), as it provides globally consistent data and has become the standard soil dataset for global applications in recent years. The database is, however, incomplete concerning significant areas in Africa and Asia and to be conservative we classified these areas as not suitable. However, since these patches are located in arid areas unsuitable for oil palm cultivation, the partial lack of soil data does not affect our assessment.

2.1.3. Topography

Steep slopes restrict oil palm cultivation in different ways. They increase planting, maintenance and harvesting costs, and shallow soils mean weak anchorage of the plants and surface runoff of fertilizers. Topsoil erosion of exposed sites is also commonly associated with sloping land, which is an exclusion criterion in an assessment of High Conservation Values (HCVs; HCV Resource Network, 2015). Ideal conditions can be found on flat areas with 0–4° slope inclination – but palms can successfully be grown on slopes of up to 16°. The common opinion at present is that slopes above 25° should not be planted at all. Furthermore, in tropical regions, elevation is strongly correlated to temperature, with a lapse rate being around −6 °C per 1000 m and elevation is also often associated with slope inclination. We use data from the NASA Shuttle Radar Topography Mission (SRTM; http://srtm.usgs.gov) with a 90 m initial raster grid cell size resampled to 1 km using a nearest neighbor technique as this source provides a globally consistent dataset at high resolution and free of charge.

2.1.4. Overall suitability indicator

Soil and climate are the basic resources for growth of any crop whereas topography is a good proxy for the manageability of a mechanized production system, with the latter being particularly true for the oil palm. We defined an optimal range and minimum and maximum suitability values for oil palm growing conditions according to four climatic, three soil and two topography criteria and classified suitable land from 1 – marginally suitable to 5 – perfectly suitable. The approach to combine criteria into one overall suitability presented here is based on Liebig's fundamental "Law of the Minimum", which states that "a given factor can exert its effect only in the presence of and in conjunction with other factors" (Rübel, 1935). For instance, a soil may be rich in nutrients but these substances are useless if necessary moisture is lacking to sustain plant growth. Consequently, the overall suitability score reflects the score of that bio-physical variable which is least suitable for oil palm cultivation, e.g. overall suitability is zero if one or more variables are zero. In the following we use the term "suitable land" for all land that is suitable from a purely bio-physical viewpoint based on the criteria described in Table 1. Detailed information of the thresholds considered to classify bio-physical data into suitability bins is provided in the Supplementary material (SM A).

2.2. Land potentially available for oil palm expansion

We distinguish three types of limits to oil palm expansion: (i) land that is prevented from being converted to other uses such as built-up land, (ii) land which is already used such as cropland and pasture and (iii) non-protected areas which are nevertheless important for biodiversity conservation and carbon storage. The data sets used are available at varying spatial resolutions, in raster or polygon format. To allow for a consistent assessment, we converted the datasets to raster format at the spatial resolution of 30 Arc seconds, corresponding to ca. 1 km using a nearest neighbor technique.

2.2.1. Land that cannot be converted to other uses

We first exclude protected areas (PAs) from land potentially available for oil palm expansion since the law usually prevents land conversion in these areas. We opted to use PAs of all status classes from the World Database on Protected Areas (WDPA, version June 2015) to identify location and extent of protected areas. PAs of any status were picked in order to adopt a conservative approach and to ensure we did not omit PAs that might be delivering some conservation on the ground despite not being legally recognized as PA by the jurisdiction in place (Juffe-Bignoli et al., 2015). Generally, information about both location and extent of PAs was available as polygons. In some cases, point data was available from the WDPA indicating the approximate center and the reported area of each PA only. In those cases we calculated a circular shape of the PA corresponding to the reported size of each PA as suggested by Juffe-Bignoli et al. (2015) and added these circular polygons as a proxy of the actual extent of PAs to the dataset.

We consider that the timescale to convert built area to other uses goes beyond the scope of this study. Consequently, we also exclude urban areas from the land being potentially available for oil palm expansion. We used the crowdsourcing-based hybrid land cover map constructed by See et al. (2014) to identify urban areas (Table 2).

2.2.2. Land already under use

Suitable land for oil palm cultivation can be already used for food, animal feed or timber production. Substitution of palm oil plantations to these different uses is usually not forbidden, but this could potentially create some conflicts with other needs including food for local populations. Following a conservative approach, we decided to exclude this land from the available land for oil palm plantations expansion.

Existing cropland, pasture and cropland-forest mosaic area was identified based on the See et al. (2014) global land cover map. Furthermore, we also excluded existing industrial oil palm plantations for Indonesia, the Central African Republic, Equatorial Guinea, Cameroon, Democratic Republic of the Congo, Gabon, Liberia (World Resources Institute (WRI), 2013a), Cameroon (Nkongho et al., 2015), the Republic of the Congo (MEFDDE, 2015) and Guatemala (IARNA, 2012), for which we had access to spatial data. This approach allowed us to capture ca. 15 Mha of concession area. Spatial data were not available for important palm oil producing countries like Malaysia and Colombia.

Finally, forest concessions are usually attributed to timber harvests during a period longer than 25 years in the tropics. We exclude them from available land for seven countries worldwide where we had access to spatial data: Indonesia, the Central African Republic, Equatorial Guinea, Cameroon, Democratic Republic of the Congo, Gabon (World Resources Institute (WRI), 2013a,b) and the Republic of Congo (MEFDDE, 2015).

2.2.3. Land with a high value for biodiversity and carbon storage

High Conservation Values (HCV) dominate the discussion around sustainable palm oil and conducting assessments against HCV standards are obligatory for a number of certification schemes. However, HCV is a concept developed for local and case-to-case application and hence there is no global dataset of

Table 1
Criteria used for the construction of the bio-physical suitability map.

	Criterion	Unit/description	Suitable range	Original spatial resolution	Dataset used
Climate	Annual Precipitation	mm/m^2	1000–5000	30 arc seconds (ca. 1 km)	WorldClim (Hijmans et al., 2005)
	Number of dry months	Monthly precipitation less than 100 mm/m^2	0–4		
	Average Annual Temperature	° Celsius	18–38		
	Temperature of the coldest month	° Celsius	>15		
Soil	Pre dominant soil texture type	Soil texture classification	Sand–Clay-loam	30 arc seconds (ca. 1 km)	HWSD (Nachtergaele et al., 2012)
	Other problematic site features	Permanently waterlogged zones considered unsuitable	–		MODIS (Friedl et al., 2010)
Topography	Slope	Sloping degrees	0–25	3 arc seconds (ca. 90 m)	NASA SRTM (NASA, 2010)
	Elevation	Meters a.s.l	0–1500		

Table 2
Criteria used to exclude land from available land for oil palm expansion.

	Description	Generic Definition	Definition	Original spatial resolution	Data source
Land already under use or protection	Land not possible to convert	Urban areas	All urban areas	10 arc seconds (ca. 300 m)	See et al. (2014)
		Protected areas	All protected areas	n.a.	UNEP-WCMC and IUCN (2015)
	Land already under use	Cropland and pasture	Cropland, pasture, agriculture-forest mosaic	10 arc seconds (ca. 300 m)	See et al. (2014)
		Oil palm concessions	Existing plantations when spatial data available	n.a.	Indonesia, DRC, Gabon, Liberia (World Resources Institute (WRI), 2013a), Cameroon (Nkongho et al., 2015), the Republic of Congo (MEFDDE, 2015) and Guatemala (IARNA, 2012)
		Logging concessions	Existing forest concessions when spatial data available	n.a.	Indonesia, DRC, Gabon, Liberia, Cameroon (World Resources Institute (WRI), 2013a,b), Republic of Congo (MEFDDE, 2015)
Sustainability criteria	Biodiversity-rich areas	Global terrestrial biodiversity priority areas	≥4 overlapping priority areas	15 arc sec (ca. 500 m)	Kapos et al. (2008)
		Intact forest landscapes	≥20,000 ha of continuous forest	500 m	Potapov et al. (2008)
	Carbon-rich areas	Above ground biomass	≥100 t AGB/ha	930 m	Baccini et al. (2012)
		Peatlands	All histosols	30 arc seconds (ca. 1 km)	Nachtergaele et al. (2012)

Note: No scale or spatial resolution could be determined for the datasets marked as "n.a." in the column "Original spatial resolution".

HCVs. In an attempt to find substitutes for HCV data, we identified areas where at least four of the six global, terrestrial biodiversity priority areas overlap, following an approach put forward by Kapos et al. (2008) to cover HCV 1 and 3 (HCV Resource Network, 2015). The six priority areas include Conservation International's Hotspots (Mittermeier et al., 2004), WWF's Global 200 terrestrial and freshwater ecoregions (Olson and Dinerstein, 2002), Birdlife International's Endemic Bird Areas (Birdlife International, 2008), WWF/IUCN's Centers of Plant Diversity (Davis et al., 1998) and Amphibian Diversity Areas (Duellman, 1999).

The draft version of the sustainability commitment of the major oil palm growers mentions that "old-growth forests without evidence of recent human disturbance" should not be converted (Raison et al., 2015 p.9), which is related to HCV 2. For this purpose, we use the Intact Forest Landscape dataset that maps old growth forests with a minimum area of 20,000 ha (Potapov et al., 2008).

The sustainability commitment of the palm oil sector sets out very clear guidelines for the definition of what is to be considered land with high carbon stock (HCS) – including both above ground and below ground carbon – that should be permanently spared from conversion to oil palm plantations. The proposal is to consider as HCS any forest type with an above ground biomass (AGB) greater or equal to 100t/ha and peat soil with a thickness of its peat layer exceeding 12.5 cm (Raison et al., 2015). To that end, we use the pan-tropical AGB map produced by Baccini et al. (2012) to identify HCS forests, and the *histosols* soil category from the HWSD (HWSD; Nachtergaele et al., 2012) as a proxy for tropical peatlands.

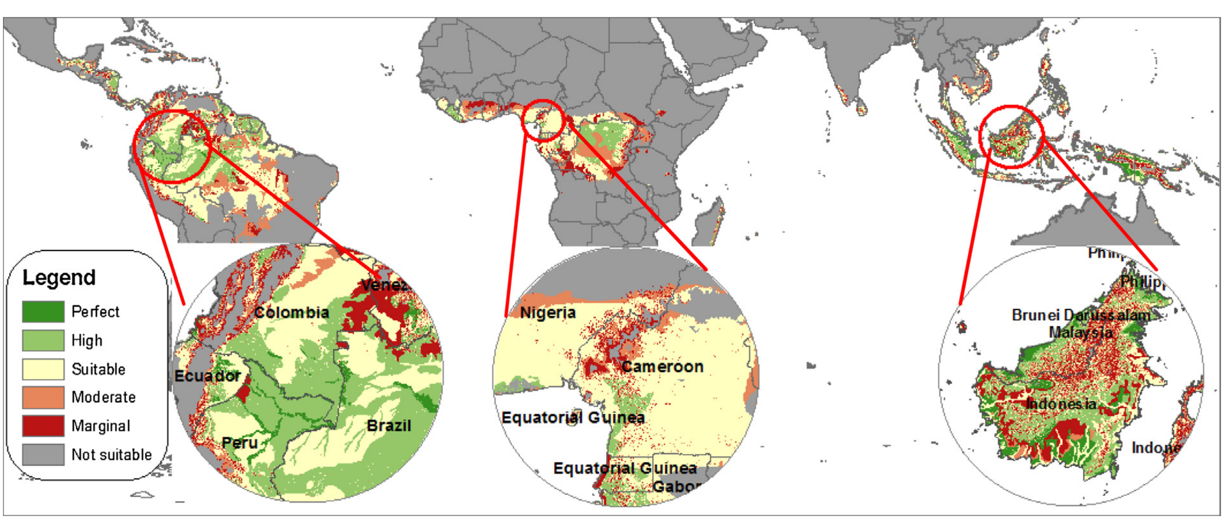

Fig. 1. Global suitability map and zoom into three oil palm focus areas (from left to right): The Amazon region; the coast of Central Africa and the island of Borneo.

2.2.4. Market accessibility

Finally, we overlay the potentially available land for sustainable oil palm cultivation that we obtain from the combination of all previously mentioned criteria, with the time to access the closest city above 50,000 inhabitants based on current infrastructure network (Nelson, 2008). This allows us to estimate how accessible and therefore economically attractive are the remaining areas identified for sustainable oil palm production and hence provides a first glimpse of the economic dimension of this assignment. The spatial resolution of this dataset is 30 arc seconds (ca. 1 km).

3. Results

3.1. Land suitable for oil palm cultivation

We find that some 1.37 billion hectares of land globally are suitable for oil palm cultivation. Suitable land is concentrated in twelve tropical countries, which together encompass 84% of the global suitable area (Fig. 1). Almost half of the land area of Brazil – essentially located in the Amazon – is to some extent suitable for oil palm planting, which corresponds to a total suitable area of 417 Mha, making it the number one country in terms of suitable land. The sheer size of the country determines the huge potential for oil palm expansion, in fact other countries have a higher proportion of suitable land relative to their total. The Supplementary material (SM D and E) provides an overview of the bio-physically suitable area for all tropical countries.

Suitability is essentially driven by climate. High temperatures over the year along with sufficient and steady rainfall are crucial to oil palm cultivation. Optimal climatic conditions are found in South East Asia and especially in Indonesia and Malaysia, with consistently high temperatures and precipitation throughout the year. However, when moving north to continental South East Asia away from the equator, a marked dry season diminishes climatic suitability for oil palm cultivation in countries such as Thailand, India and Cambodia.

In South America, large tracts of the Amazon region in Brazil, Colombia, Peru and Ecuador exhibit good climatic conditions for oil palm growth and so do parts of Central America and the Caribbean. The main limiting factor here is the Andean mountain chain stretching North-South and the climate which – in addition to the equatorial gradient – is too dry to bear oil palms in a good portion of the north of Brazil.

In Africa, the biggest area of suitable land is located in the Congo basin, essentially in DRC, but also the gulf of Guinea and West Africa harbor a relatively narrow stretch of suitable land along the coast. However, several months with less than 100 mm and lower annual precipitations than in the other tropical regions partly reduce the suitability for oil palm in the region.

Undulating slopes and elevated areas pose further constraints in mountainous areas such as the Andes in South America, the Albertine Rift in Eastern DRC and the New Guinea Highlands on the island of Papua.

About 70% of the potentially suitable cultivation area for oil palm according to climatic conditions could be negatively affected by problematic soil growing conditions, the most prominent problematic soil type being weathered and leached soils (*Acrisols* and *Ferralsols*) which are widespread over the whole tropical area, and especially in Africa. Poorly drained soils are common in depression zones of Indonesia, which are often identical to peat areas and other soils with high organic matter. These can also be observed along major rivers in South America. However, most of these constraints could be overcome by applying optimal management, even if it will entail some additional production costs.

3.2. Land available for oil palm cultivation

Starting from the total suitable area for oil palm cultivation, we first exclude one by one the land which falls under each individual criterion to determine how each of them impacts the land availability for oil palm expansion. In a second step, we combine all the criteria to determine their joint impact on land availability, since it is important to note that many of the criteria overlap (Fig. 3).

3.2.1. Suitable land already taken

Of the total of 1370 Mha of suitable land, urban areas reduce available land for oil palm expansion by 5 Mha which is equivalent to 0.38% of total suitable area. Conversely, 30% of the globally suitable area for oil palm production is currently occupied by PAs, reducing the available land for oil palm plantations expansion by 417 Mha worldwide. PA coverage of suitable land for oil palm production ranges from less than 2% in Papua New Guinea (PNG) to as much as 67% in Venezuela, with the majority of the countries covering 15-20% of their suitable area.

About 216 Mha of agricultural land is located on suitable areas. This number comprises cropland and pasture (47 Mha) as well as areas covered with cropland-forest mosaic (168 Mha). Oil palm is currently grown on a total area of 18 Mha according to available spatial information, among which 20% is already classified as agricultural land. This means that about 14 Mha of current oil palm concessions have to be added to the agricultural area to account for the area already under agricultural use. For the countries where data was available – basically the Congo basin countries and Indonesia – logging concessions could further reduce oil palm plantations expansion by almost 70 Mha with Indonesia holding the largest area with a total of 24.9 Mha of suitable land being under forest concession.

Since the overlaps between the above criteria are quite limited (exclusive use), we calculate that 723 Mha of suitable area for oil palm expansion is already taken by other uses, reducing the land availability for future expansion by half compared to the biophysically suitable area.

3.2.2. Suitable land with high environmental value

Highly biodiverse areas cover 125 Mha of suitable land for oil palm cultivation and are relatively concentrated in a handful of countries with Indonesia (22.3 Mha), Peru (16 Mha), Brazil (9 Mha) and Venezuela (8 Mha) making up for almost 45% of all highly biodiverse areas in suitable areas for oil palm cultivation. We also note that highly biodiverse areas would almost completely prevent oil palm plantation expansion in some countries, such as Madagascar (99%) and Liberia (92%). A similar concentration on a few countries is true for intact forests, where Brazil (227 Mha), DRC (62 Mha) and Peru (48 Mha) account for two thirds of the global suitable area, which amounts to a total of 507 Mha. Forest storing more than 100 tons AGB per ha is the most constraining criterion in terms of land availability for oil palm expansion, covering about 1 billion ha i.e. leaving 370 Mha suitable for potential expansion worldwide. The suitable area for oil palm is strongly correlated with this criterion as 83% of carbon-rich forests are located in the twelve countries that also have the largest suitable area. This criterion would especially reduce land availability in Brazil, with more than 300 Mha dropped from the suitable area. Peatlands, by contrast, are very much concentrated on South-East Asia with Indonesia (16.7 Mha) and Malaysia (2.4 Mha) harboring almost all the world's known peatlands (21.7 Mha).

3.2.3. Total potentially available land for oil palm plantations expansion

The combination of all above mentioned criteria and suitable land for oil palm cultivation yields an estimate of available land for oil palm plantations of 233.82 Mha worldwide, only 17% of what we have estimated as the total suitable area (Fig. 3 and SM E).

Brazil, with 43.4 Mha, has by far the largest area of available land for oil palm expansion followed by the DRC (38.4 Mha), Colombia (21.1 Mha) and Indonesia (18.2 Mha). That being said, the application of sustainability criteria will restrict oil palm cultivation in some countries more than in others (See SM D and E). There are countries which could develop as much as 49% (Nigeria, 9.5 Mha), 53% (Cote d'Ivoire, 9.3 Mha) and even 69% (Uganda, 5.1 Mha) of their suitable land while adhering to the full set of sustainability criteria. On the other end of the spectrum countries such as Peru, Guyana, Suriname and French Guyana could only develop a marginal share of less than 4% of the countries' suitable area for sustainable palm oil production. The extensive and biomass-rich forest cover is by far the single most constraining factor in these countries.

Whereas overall potential availability of suitable land is ca. 17% (233.82 Mha) globally, only 5% of the 'very suitable' areas remain (suitability classes 4 and 5 – dark and light green in Figs. 2 and 3). In absolute terms, this corresponds to 19.3 Mha of very suitable land which could be available for sustainable oil palm cultivation in the future, a number which would still allow doubling the current extent of 18.1 Mha of oil palm worldwide. Once overlap of criteria is taken into account, the combination of existing agricultural land and 100 t/ha above ground biomass cover would be enough to cover 88% of the total excluded area globally based on the combination of the eight criteria considered in this study. However, this could not be the case locally, where other criteria, like biodiversity hotspots could significantly reduce area for oil palm expansion beyond carbon and agricultural land.

3.2.4. Market accessibility

Analysis of accessibility of potentially available lands yields the results presented in Fig. 4. Just less than 1/5th (18%) of the area is in reach in less than 2 h from the closest city and 50% are accessible in less than 5 h. On the other hand, 20% of all available areas are located at 10 h or more from cities. Variation among suitability classes is minor, yet land in the highest suitability class tends to be somewhat more remote than land in other classes.

4. Discussion and conclusion

We have generated a new global bio-physical oil palm suitability map which differentiates between five suitability classes. This dataset could be one useful layer of information to guide future oil palm expansion according to different objectives. Our results indicate that ten countries encompass 75% of the global suitable area. Countries in South East Asia – the current center of palm oil production – have the highest share of suitable land in relation to the size of the countries, while countries in Latin America and Central and Western Africa have the largest tracts of potentially suitable land. Suitability is essentially driven by climate, and in particular high temperatures with sufficient and steady rainfall over the year. The choice of thresholds to categorize categorical data (soil) and discrete data (climate, topography) to form suitability classes has been made upon a detailed literature review. However, this could remain a potential source of debate.

The suitability map produced for this study is comparable with previous studies, yet regionally strong differences exist between the products which mainly relate to differences in the way water availability in particular during dry seasons are being taken into account. We think that this study better captures the impact of seasonality by using the number of dry months over the year and the lowest temperature in the coldest month rather than the lowest mean monthly relative humidity (RHlow) of the driest month of the year which is used in the GAEZ study, where dry

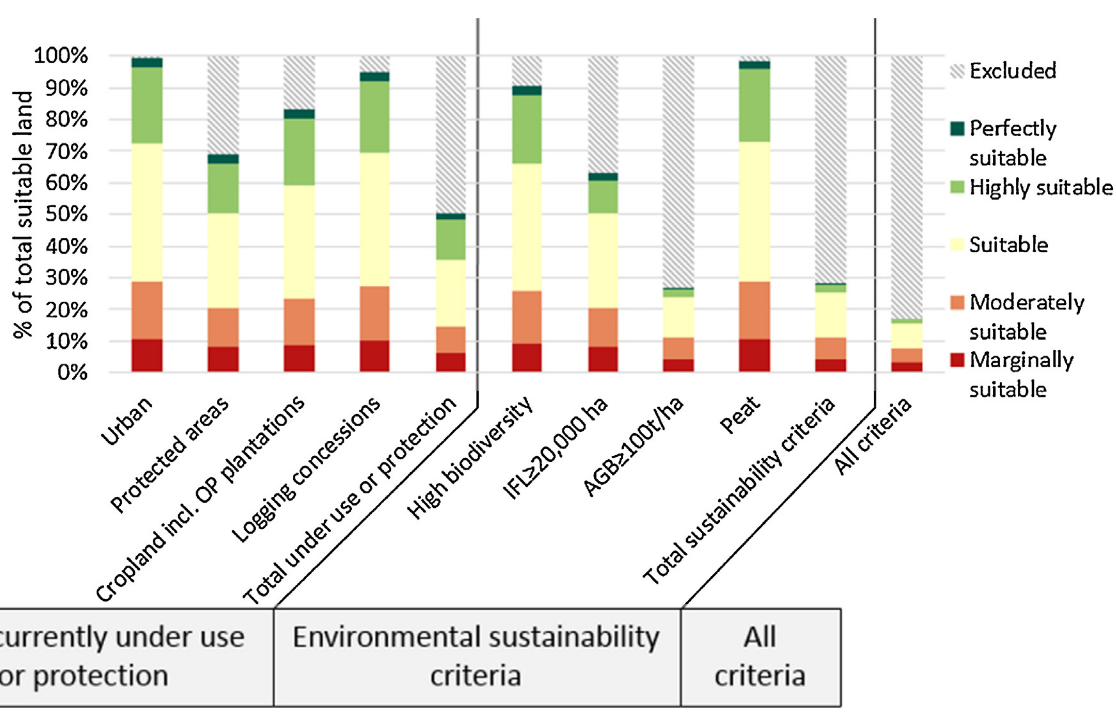

Fig. 2. Exclusion of suitable area for future oil palm expansion according to different criteria (black diagonal hatching) and remaining potentially available area by suitability class (green, yellow, red) on a global scale. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

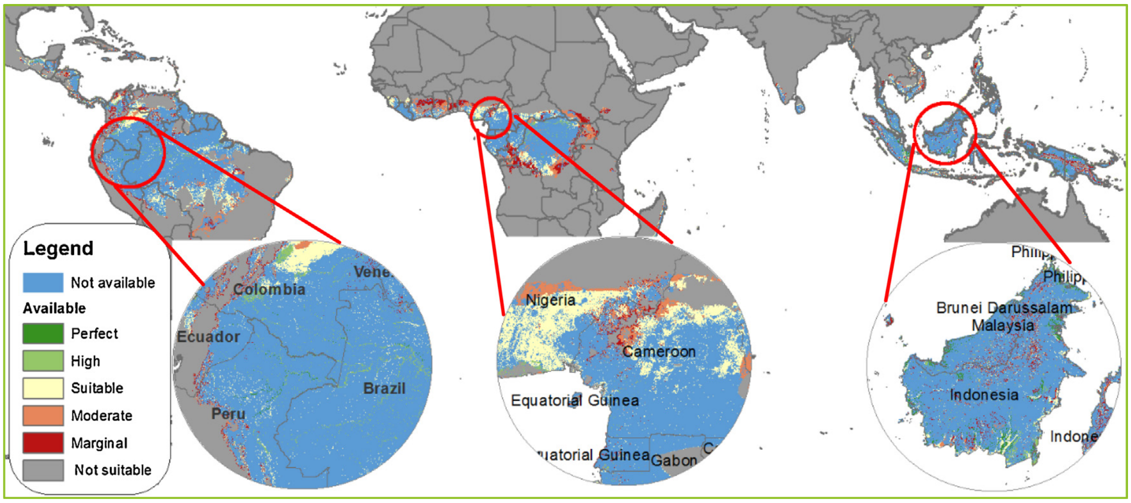

Fig. 3. Locations of remaining potentially available area for oil palm expansion by suitability class (green, yellow and red) once areas already used or protected and which do not meet environmental sustainability criteria have been excluded (in blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

spells are not reflected explcitly. This study also tends to consider a wider area to be suitable than the WRI study because we use a lower minimum annual rainfall: 1000 mm instead of 1400 mm. Since there is empirical evidence of oil palm being cultivated under less favorable climatic conditions (Corley, 2009; PALMCI, 2011; Yao and Kamagate, 2010), we are confident in using a lower minimum threshold value. We present a comparison of the both the GAEZ product and our new suitability map in the Supplementary material (SM G). One limiting factor to the reliability of the suitability map is the quality of input data. As we assessed suitability on a global scale, the data is often the result of an interpolation process from in situ measurements. Climactic information is collected in a network of climate stations around the globe, however, in tropical areas this network is particularly thin and the quality of the final product is thus diminished (see http://www.worldclim.org/methods). Both availability and quality of soil data also vary greatly among regions. The authors of the Harmonized World Soil Database acknowledge that soil data for West Africa and South Asia is especially less reliable (Nachtergaele et al., 2012).

The suitability map has been realized under optimal management i.e. assuming that most of the soil constraints are overcome by better practices including for instance ploughing, soil water management techniques, mulching or fertilization. Consequently, suitability area on problematic soils is higher than without management but the total suitable area is not affected by assumptions made about the management. In fact the suitable area could be expanded if irrigation could be used to overcome

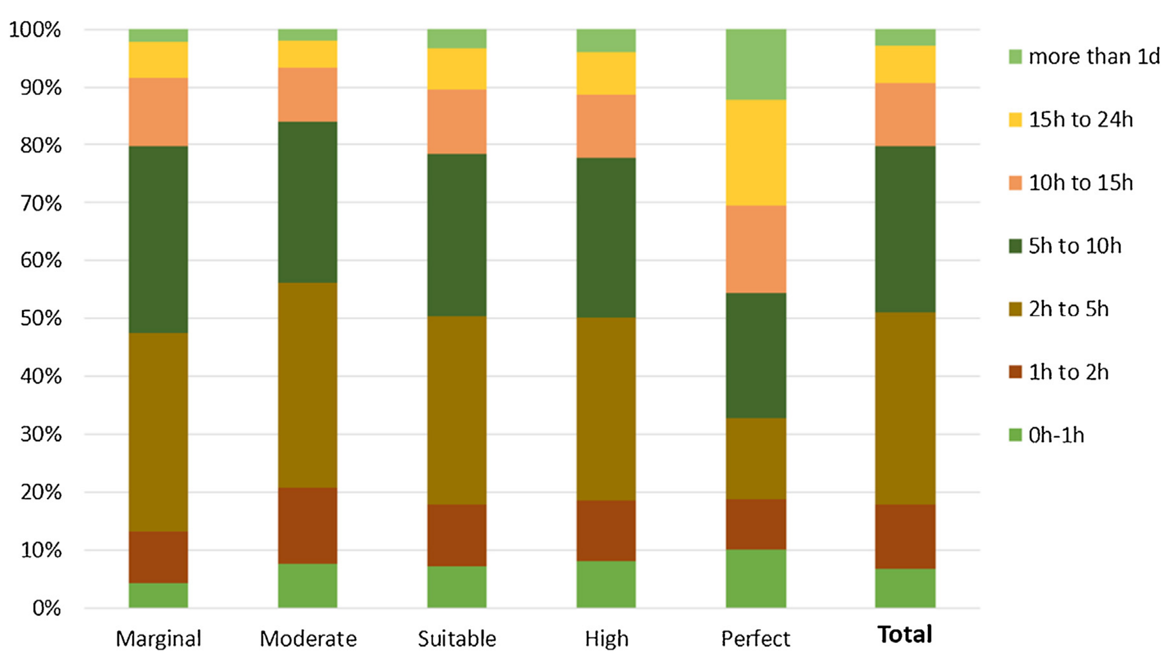

Fig. 4. Accessibility (in h and days) of potentially available land separated by suitability classes.

water deficit. However, there is currently almost no agro-industrial plantation which uses irrigation so we decided to not use this management option. Yet, an alternative suitability map could be built in the future to allow for irrigation. Ultimately, all these management options should not only be considered through increase in the potential yield per hectare but also through higher production costs. This would allow exploring which palm oil price level would be necessary to adopt certain management options.

One of the limits of future oil palm expansion is the competition for land with other uses. We have shown that by removing the area under current use or protection, we reduce by half the total suitable area potentially available for future oil palm expansion. In reality, an important share of plantation has been developed on agricultural land in the past (Gunarso et al., 2013). But since the global population is expected to continue growing until at least 2050 (Lutz et al., 2001), we likely underestimate the area which will be allocated to other uses and overestimate the available area for future oil palm cultivation. We envisage to investigate this issue of increasing competition for land in the future between oil palm and other commodities by using an economic model with a detailed representation of land-based activities and market interactions such as GLOBIOM (Valin et al., 2014). Our results also highlight the need to reinforce control in existing protected areas as 30% of current protected areas are located in areas suitable for oil palm.

Major palm oil producing companies and countries are more and more committed to reduce their environmental impacts. From 1.37 billion hectares of land being suitable for oil palm cultivation, only 17% remains when land currently allocated and environmental sustainability criteria are taken into account, including 19 million hectares of highly suitable area. High carbon stocks criteria alone reduces by 73% the suitable area for oil palm expansion and encompasses 88% of the land excluded by the sum of all other environmental criteria. This suggests that this criterion could be prioritized in future studies if data on other criteria is not available (Raison et al., 2015). However, if several global datasets on aboveground biomass are available (Avitabile et al., 2016; Baccini et al., 2012; Saatchi et al., 2011), there is a high uncertainty associated with the biomass information which is derived from satellite images (Mitchard et al., 2013).

The remaining suitable, sustainable and potentially available land that we estimate in this study is still large if we compare with the current 17 million hectares under oil palm cultivation globally. A study commissioned by the Indonesian government finds 18 Mha of available land for oil palm expansion which is similar to our results (The Jakarta Post, 2009). For the Brazilian Amazon, Ramalho Filho et al. (2010) identified 31.2 Mha which is about 12 Mha less than our study and for the Republic of the Congo Feintrenie et al. (2014) found available land of 1.28 Mha as opposed to 6.3 in our study. This can partly be explained by the explicit focus of Ramalho Filho et al. on previously deforested sites and the fact that buffer zones around villages, rivers, and protected areas are also excluded in Feintrenie's assessment. It should also be noted that the biodiversity sustainability criteria used in this study are likely less rigorous than a detailed HCV assessment. In our assessment we explicitly cover HCV 1-3 by considering global terrestrial biodiversity priority areas and intact forest landscapes. But we lack criteria on ecosystem services, social and cultural well-being of local communities or indigenous peoples (HCV 4-6) which can only be identified through engagement at the local level.

However, our results also show that the potentially available land for oil palm expansion using a limited number of environmental sustainability criteria becomes quite scarce in some countries, especially for highly suitable area. There is almost no area left for the development of oil palm plantations in Liberia and Madagascar. Moreover, diverting oil palm production to lower suitable areas will also lead to lower economic profitability which could be partly offset by higher plantations area. A careful cost-benefit analysis must be done to ensure that new oil palm plantations meet the three dimensions of sustainable development.

Finally, the oil palm business model has very much focused on expansion as the means to satisfy increasing demand and yields have stagnated over the last decade in Malaysia and Indonesia (Murphy, 2007). However, novel breeding technologies are expected to allow for attaining higher yields and longer productive rotation periods, which might contribute to a reduction in future expansion of plantations. Further research should therefore also address the possible role of agronomic intensification and yield increases.

5. Implications of the results

Focusing on the current centers of oil palm production, Indonesia with available land in the order of 18.2 Mha and currently planted area of 10 Mha might face looming land scarcity for sustainable oil palm production and Malaysia with 2.1 Mha of available land and 4.6 Mha of currently planted area has already exceeded its sustainable area (FAO, 2016). On the other hand, our findings also support the feasibility of a number of countries' future oil palm expansion plans (SM F), although they should be considered as an upper boundary to sustainable oil palm expansion as fine-scale economic and social criteria must also be taken into account.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2016.06.007.

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