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Global oil palm suitability assessment

Pirker, J. and Mosnier, A.

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Interim Report **IR-15-006**

Global oil palm suitability assessment

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Contents

Abstract

The palm oil boom of recent years has brought about both positive – economic development – and negative impacts – deforestation, habitat losses and increased GHG emissions – in the main producer countries in South-East Asia. As global demand for palm oil is still increasing, governments of developing and emerging countries increasingly promote oil palm cultivation as a major contributor to economic development, but there are concerns about the potential negative impacts of oil palm expansion on the natural environment in these countries.

Against this backdrop, we present a global oil palm suitability map on the spatial resolution of 0.5 arc minutes (approximately 1 km) in order to i) help land use planning for production and conservation in tropical and sub-tropical areas, and ii) provide insights about the sustainability of further oil palm production expansion in the future iii) help identify potential trade-offs between further oil palm plantation expansion, forest conservation, and use planning at the regional level.

By combining climate, soil and topography data, we find that global suitable areas are concentrated in nine tropical countries, with Brazil harboring the largest tracts of suitable land, followed by the Democratic Republic of the Congo and Indonesia. We conclude that this map will most useful to achieve the goals stated above when combined with a number of socio-economic factors that also drive of oil palm expansion dynamics.

Résumé

L’explosion de la production d’huile de palme des dernières années a apporté des impacts positifs – contribution au développement économique – ainsi que des impacts négatifs – déforestation, perte d’habitats naturels et hausse d’émissions de gaz à l’effet de serre – dans les pays producteurs principalement en Asie du Sud-Est. Alors que la demande globale pour l’huile de palme continue de croître, de nombreux gouvernements de pays en développement et des pays émergeants promeuvent de plus en plus la culture de palmier à huile comme moyen de contribuer au développement économique. Cependant, l’expansion potentielle de la culture de palmier à huile a suscité l’inquiétude majeure due à l’impact potentiel sur l’environnement naturel.

Dans ce contexte, nous présentons une carte de potentiel global de palmier à huile dotée d’une résolution spatiale de 0.5 minutes arc (approximativement 1 km) afin de i) contribuer à l’aménagement du territoire pour la production et la conservation dans des zones tropicales et subtropicales, ii) donner une idée à propos de la durabilité d’une nouvelle expansion de la production de l’huile de palme dans l’avenir et iii) aider à identifier les compromis potentiels entre une nouvelle expansion de palmier à l’huile, la conservation de forêts et l’aménagement du territoire à l’échelle régionale.

En combinant des donnés de climat, de sol et de la topographie on constate que les zones adéquates pour la culture du palmier se concentrent dans 9 pays tropicaux, dont le Brésil qui abrite les plus grandes zones adéquates, suivi par la République Démocratique du Congo et l’Indonésie. Nous concluons que cette carte-ci sera particulièrement utile en la combinant avec des facteurs socio-économiques entraînant la dynamique de l’expansion du palmier à huile.

Global oil palm suitability assessment

Johannes Pirker
Aline Mosnier

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, and most observers expect this trend to continue in the coming years. The share of palm oil in global vegetable oil production has more than doubled over the last twenty years, outstripping soya oil production and representing today more than 30% of the global vegetable oil production (OECD & FAO, 2013). Some reasons for this strong expansion are the substantially higher oil yield of palm oil compared to other oilseeds – over 4 and 7 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 & Weidema (2008) estimate that palm oil is today the "marginal oil", i.e. a 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 10 to 17 Million hectares between 2000 and 2012, an area which now accounts for one tenth 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 2014, see annex 1). 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, Hartoyo, Agus, & Killeen, 2013; Koh, Miettinen, Liew, & Ghazoul, 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, Abd Aziz, Tarmizi, Harun, & Kushairi, 2010). The potential negative effects of OP cultivation on the world climate and biodiversity has given rise to closer scrutiny from consumers about the sustainability of palm oil production (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 15% of the market (Balch, 2013; RSPO, 2011) and experts estimate that biofuels make too up for 15% of the palm oil market (Thoenes 2014, per. comm.; see annex 1). As global demand increases and available land becomes increasingly scarce in the traditional production centers (Kongsager & 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, food- and energy independence (Carrere, 2010; Feintrenie, 2014a; V. H. Gutiérrez-Vélez & DeFries, 2013; Pacheco, 2012; Villela, Jaccoud, Rosa, & Freitas, 2014). In this light, the role of certification standards and sustainability criteria to avoid deforestation from new plantations remains uncertain.

Here we present a global oil palm suitability map in order to i) help land use planning for production and conservation in tropical and sub-tropical areas, ii) provide insights about the sustainability of further PO production expansion in the future, and iii) help identify potential trade-offs among further OP plantation expansion, forest conservation, and land use planning at the regional level. The palm oil sector is dominated by large plantations but still an important area – e.g. 44% in Indonesia and even 76% in Thailand - is cultivated by smallholders (Feintrenie, 2012; The World Bank & IFC, 2011). Taking into account unequal management capacities of large-scale plantations and smallholders, we compute two distinct suitability maps at the 30 arc seconds (ca. 1km^2) resolution level. The first one is the natural land suitability without soil preparation and the second one is the land suitability under optimal management conditions i.e. when all currently available techniques are used to mitigate biophysical constraints.

Our study differs from existing literature in several aspects. First, we produce a global map using high-resolution input data while other studies mainly focus on national or sub-national areas (Gingold et al., 2012; Harris, Killeen, Brown, Netzer, & Gunarso, 2013; Mantel, Wösten, & Verhagen, 2007; Ramalho Filho, Ferreira da Motta, Naime, Goncalves Ortega, & Claessen, 2010; Yui & Yeh, 2013). Only a global suitability map can be used for the global assessment of future oil palm expansion, including possible leakage phenomena through international trade. As compared to existing global suitability maps, our methodology has the advantage of explicitly taking into account seasonal variability. Our map represents different management systems and several suitability classes, allowing for more insights on productivity potentials compared to the binary assessment proposed by Stickler et al. (2007). We rely on purely bio-physical factors to determine oil palm suitability, notwithstanding the fact that socio-economic criteria are key to determining future expansion of oil palm. However, we aim at clearly distinguishing bio-physical from socio-economic suitability, as their evolution over time is not affected by the same underlying causes (Geist & Lambin, 2002). Both can be later combined in an economic land use model or for land use planning purposes.

2. Methodology

We compute suitability maps for oil palm according to each relevant bio-physical factor and we then compute the overall suitability for oil palm cultivation by combining them. Literature review is used to set-up minimum, optimal and maximum suitability values of oil palm growing conditions according to each factor. Since many biophysical constraints can be overcome by appropriate management practices, we compute two distinct suitability maps: one under optimal management conditions i.e. where all currently available techniques are used to mitigate biophysical constraints (further referred to as “Optimal management”) and one which is under no or minimum management i.e. close to natural growing conditions (further referred to as “Minimum management”).

2.1. Biophysical criteria limiting oil palm cultivation

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 (Table 1). Optimal temperature conditions range between 24-28°C, and the average temperature of the coldest month of the year should not fall under 15°C (Corley & Tinker, 2008). The length of the growing season (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 not attributed the value "Poor drainage" 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 & Kamagate, 2010) and up to five months dry period, but these conditions cause both lower yield and cessation of production in dry periods (Corley & Tinker, 2008). We do not consider irrigation schemes as a potential management option because for OP cultivation these schemes are still in the experimental phase. We use data from the WorldClim database (www.worldclim.org) to compute current climate suitability (average over the 1950-2000 period) at the 30 arc seconds resolution level and data from the Harmonized World Soil Database (HWSD) (Nachtergaele et al., 2012) to determine the drainage status of a region.

Table 1: Palm oil suitability classes thresholds according to climatic factors

Climatic Characteristics	Management	Suitability classes (from perfectly suitable = 5 to not suitable = 0)					
		5	4	3	2	1	0
Annual Precipitation (mm/m^2)	All	2000-2500	1750 - 2000	1500 - 1750	1250 - 1500	1000 - 1250	<1000
	All	2000-2500	2500-2875	2875-3250	3250 -3625	3625-4000	>4000
Annual Precipitation on well-drained soils (mm/m^2)	All	<4000	4000- 4250	4250 - 4500	4500 - 4750	4750 - 5000	>5000
Number of dry months (monthly precipitation <100 mm/m^2)	All	0	1	2	3	4-5	>5
Average Annual Temperature (degree Celsius)	All	24.0 – 33.0	21.6 – 24.0	20.4 - 21.6	19.2 - 20.4	18.0 - 19.2	<18.0
	All	24.0 – 33.0	33.0 - 34.0	34.0 - 35.0	35.0 - 36.0	36.0 - 38.0	>38
Average temperature of the coldest month (degree Celsius)	All	>15					<15

Soil- The oil palm is not very demanding in its requirements to the chemical and physical properties of the soil: it grows on a wide range of tropical soils many of which could not be used for the production of other crops. Constraining soil factors for oil palm cultivation can be either of chemical (e.g. nutrient deficiencies) or physical (e.g. low water holding capacity) 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. The oil palm is also very sensitive to insufficiencies in water provision. Several soils types and soil features are problematic for oil palm and require particular attention before they can be planted:

- Soils which are naturally poor in nutrients -very leached and weathered soils such as ferrasols and acrisols, but also poor tropical peat soils- entail plant nutrition problems;
- Saline soils (Electrical conductivity >4 dS[1] m^{-1}) which are typically present in coastal areas are not supported by oil palm;
- Very sandy -mostly referred to as podsols-, gravelly, rudic, lateritic and stony soils have very little water holding capacity and boulders or outcrops in the surface layers make the use of mechanized agriculture equipment impracticable;
- Strong presence of gravel, stones or compacted layers of clay impede root penetration which renders palms prone to wind damage;
- Peat soils and other soils with a high content of organic matter, especially those which exhibit a peat layer deeper than 100cm, lead to weak anchorage of palms in the fibrous peat and tropical peat soils frequently pose problems of plant nutrition;
- Permanently flooded areas.

In most cases these soils can be reclaimed by applying adequate management measures. For instance, nutrient deficiencies can be overcome by applying soil amendments such as empty fruit bunches and mineral fertilizers. The site can be protected against sea water inundation by constructing dams, flushing of the sites with sufficient fresh water or planting on ridges. Appropriate mitigation measures are maintenance of a permanent ground cover, mulching with empty fruit bunches, and construction of terraces for planting. The chemical and physical shortcomings of peat soils can also be overcome by management measures including functional systems to manage water and fertilization. For the construction of the two suitability maps – one for minimal management, one for near-optimal management – we assume that temporary problematic soil properties (specified in Table 2) can be completely overcome by appropriate agronomic management as provided under optimal management. We provide an overview of the most common management practices for marginal soils in .

For soil information we rely on the Harmonized World Soil Database (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 areas which are not suitable from a climatic viewpoint e.g. in Mali, Niger, Chad, Namibia and Yemen, the lack of soil data remains without consequences for our assessment.

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[1] Salinity is measured in as electrical conductivity, measured in Siemens per meter.

Table 2: Palm oil suitability classes thresholds according to soil factors

Soil Characteristics	Management type	Suitability classes (from perfectly suitable = 5 to not suitable = 0)					
		5	4	3	2	1	0
Pre-dominant soil texture type	Minimum	• Clay loam • Sandy clay loam • Silty clay loam	• Sandy loam • Silt loam • Silt	• Loam	• Clay (heavy) • Loamy sand	• Sand	
	Optimal	Same as under minimum management scenario	Same as under minimum management scenario	Same as under minimum management scenario	Same as under minimum management scenario	Same as under minimum management scenario	
Problematic soil properties	Minimum	-	• Weathered and leached soils • Acid and sulfate soils	• Gravelly stony or lateritic • High content of organic matter	• Deep sandy soils	• Poorly drained soils	• Saline soils
	Optimal	-	-	-	-	-	-
Other permanent site properties	Minimum	-	-	-	-	-	• Wetlands
	Optimal	-	-	-	-	-	• Wetlands

Topography- Steep slopes restrict oil palm cultivation in different ways. They increase planting, maintenance and harvesting costs; shallow soils imply weak anchorage of the plants and surface runoff of fertilizers; and topsoil erosion of exposed sites are commonly associated with sloping land. Ideal conditions can be found on flat areas 0-4 degrees slope inclination - but palms can successfully be grown on slopes of up to 16 degrees. The common opinion at present is that slopes above 25 degrees should not be planted at all (Table 3). Furthermore, in tropical regions, elevation is strongly correlated to temperature, with a lapse rate being around -6°C per 1000m 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 45m raster grid cell size as this source provides a globally consistent dataset at high resolution and free of charge.

Table 3: Palm oil suitability classes thresholds according to topography factors

Slope Characteristics	Management	Suitability classes (from perfectly suitable = 5 to not suitable = 0)					
		5	4	3	2	1	0
Slope in degrees	All	<4	4-9	9-13	13-18	18-25	>25
Elevation a.s.l.	All	<500	500-850	850-1050	1050-1280	1280-1500	>1500

2.2. Overall suitability assessment

Suitability maps for oil palm were created by computing the oil palm-specific site quality taking into account climate, soil and topography variables. The approach 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 OP cultivation, e.g. overall suitability is zero if one or more variables are zero. Overall suitability is expressed as index of six classes ranging from not suitable (zero) to perfectly suitable (five). Figure 1 below shows the computation scheme of the suitability map.

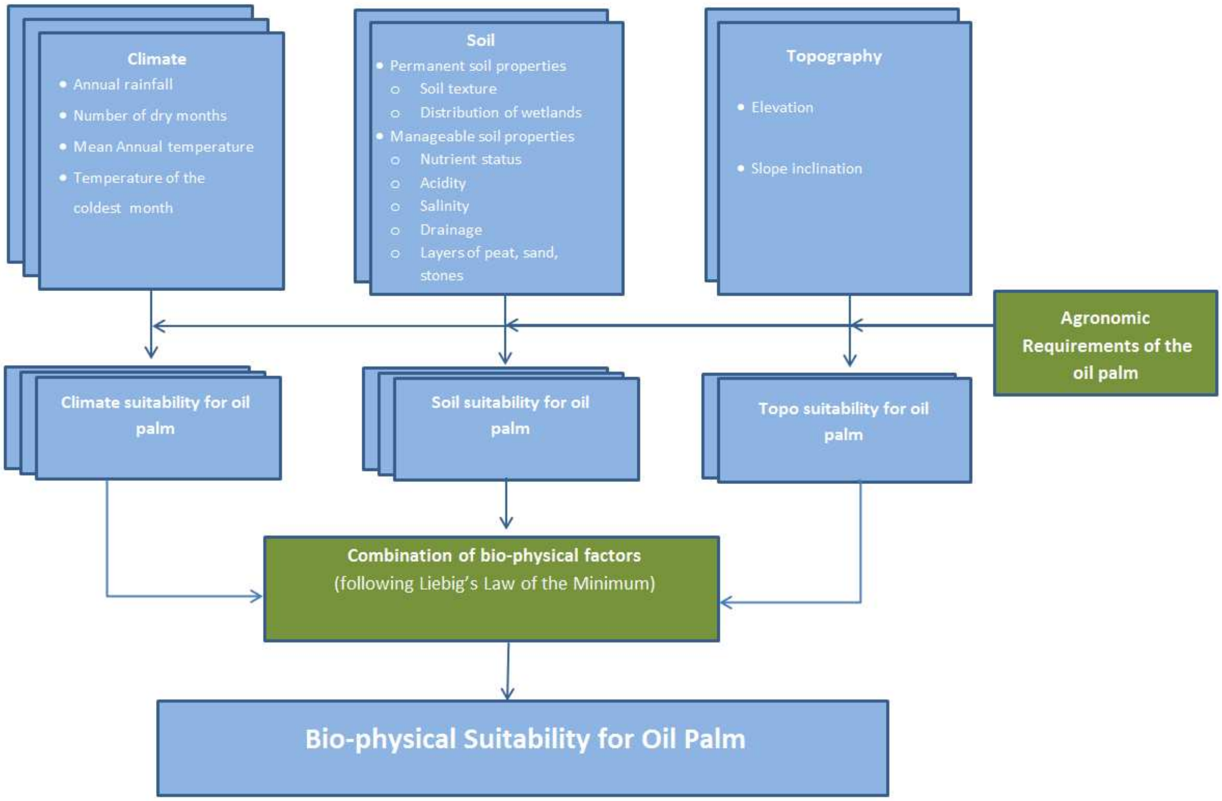

Figure 1: Scheme of the computation of the suitability map. Blue rectangles represent spatial data, green rectangles represent non-spatial information.

3. Results

3.1. By biophysical criterion

Climate- The four variables which determine climate suitability are presented in Figure 2 below. The average temperature criterion limits oil palm cultivation to the tropical and sub-tropical areas across Southern and Central America, Africa, Asia and Oceania. The suitable area is further restricted by the coldest month criterion and the precipitation patterns which are only satisfied in the tropics. Optimal climatic conditions are found in South East Asia and especially in Indonesia and Malaysia, with consistently high temperatures and precipitation throughout the year. But when moving north to continental South East Asia and thus 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, the North-Eastern part of Brazil has a drought period of several months, yet large tracts of the Amazon region in Brazil and its neighboring countries Colombia, Peru and Ecuador exhibit good climatic conditions for oil palm growth and so do parts of Central America and the Caribbean. In Central Africa, the home of the oil palm, the Congo Basin is the most suitable area. However, several months with less than 100mm and lower annual precipitations than in the other tropical regions partly reduce oil palm suitability in the region.

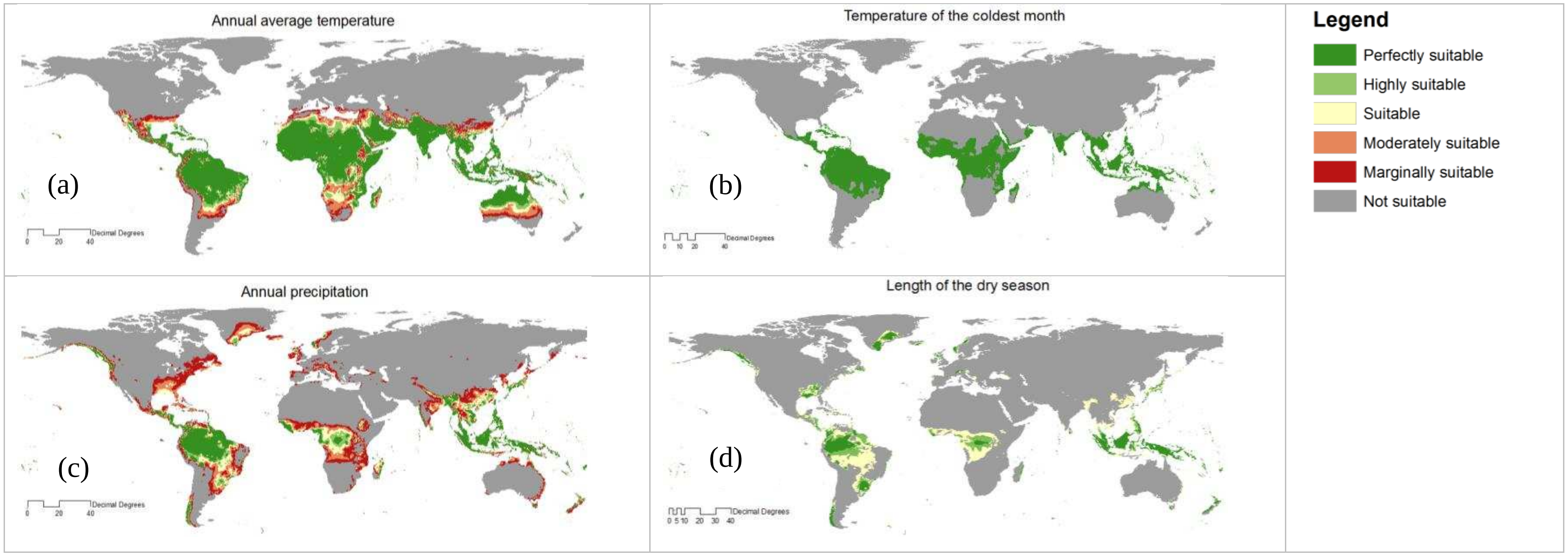

Figure 2: Suitability maps for climate variables: a) the average annual temperature, b) the temperature of the coldest month of the year c) annual precipitation (mm) and d) the number of months which received less than 100mm of precipitation.

Soil About 70% of the potentially suitable cultivation area for oil palm according to climatic conditions could be negatively affected by problematic soil growing conditions (Figure 3). The most prominent problematic soil type is 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 with peat areas and other soils with high organic matter. These can also be observed along major rivers in South America. Less common limiting soil features are stony, gravelly and lateritic soils, soils dominated by a thick layer of sands, very acid soils and salt-influenced soils. The latter ones are typically located in coastal areas. Besides the common problem of poor soil drainage, saline soils pose the most severe constraint to the salt-sensitive oil palm. Nutrient-poor and acidic soils, by contrast, can be relatively well supported. A comparison between the minimum management scheme presented in map (a) and the optimal management scheme in map (b) reveals the important role played by soil management. Soil suitability in the majority of the areas increases when applying optimal management. In India, for example, soils can experience a major improvement through management.

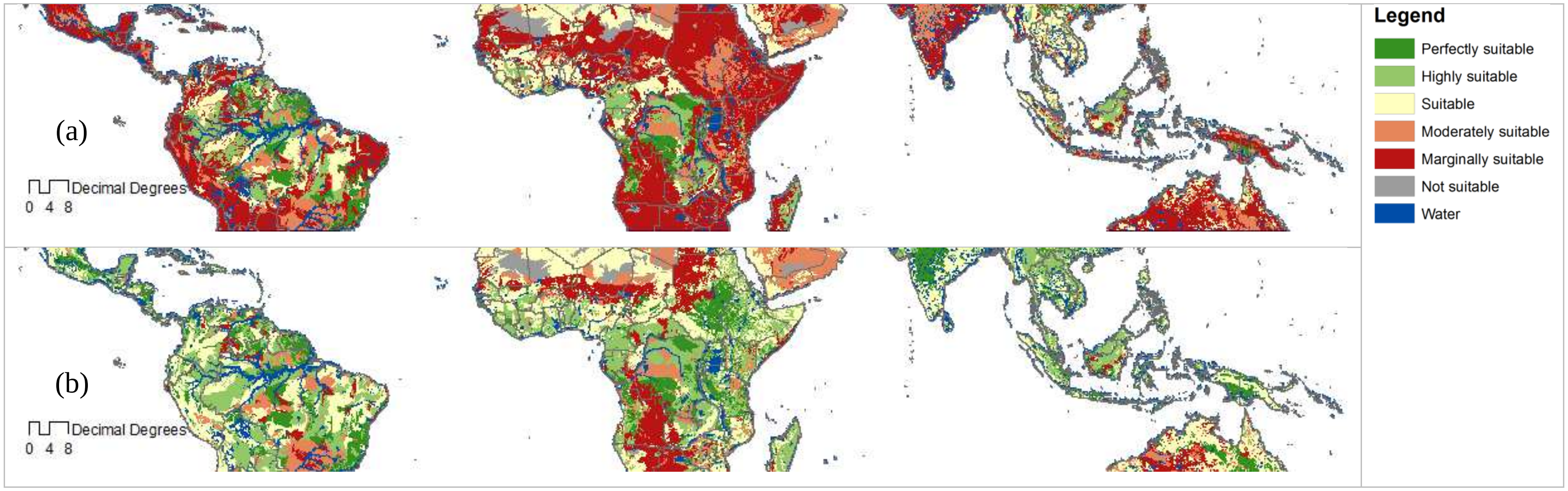

Figure 3: Soil suitability in the pan-tropics under (a.) conditions of minimum management and (b.) optimal management.

Topography Topography is a common regional limiting factor in some parts of the potential cultivation area. It mainly renders mountain areas unsuitable, such as large tracts of the Andean region, parts of East Africa and the hinterland of the islands of Borneo and Papua (Figure 4).

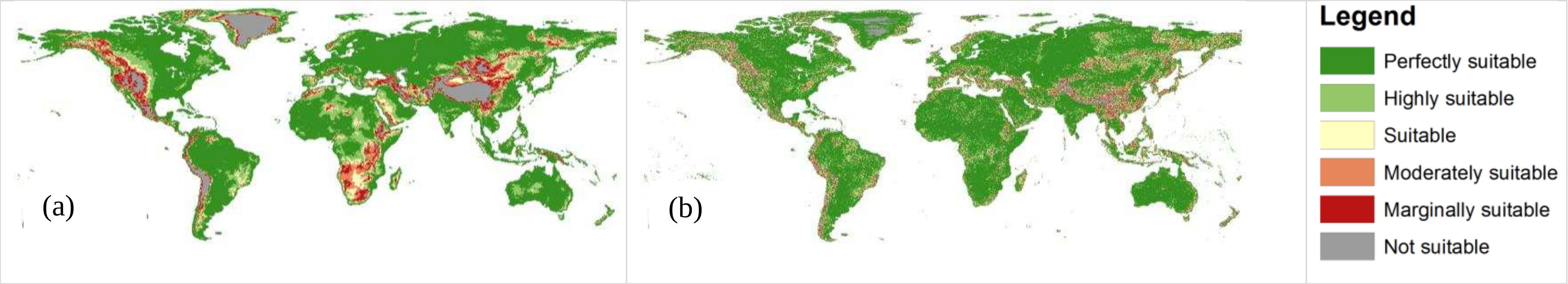

Figure 4: Suitability maps according to topography variables relevant for oil palm cultivation; (a) elevation above sea level and (b) slope (Source: NASA SRTM)

3.2. Combined oil palm suitability map

Under the assumption that no real agronomic management is performed, large tracts of land on all continents are only marginally or moderately suitable for oil palm cultivation (Figure 5a). In the Amazon region, large tracts of land show a high degree of suitability. Along main rivers, soil drainage is insufficient to bear oil palm and soil acidity also plays an important role in this region. Outside the Amazon region, potential cultivation areas in South America are limited by unfavorable temperatures and precipitation regimes in the Andean region in parts of Brazil. In Central Africa, by contrast, the marked dry season along with locally sand and stone-rich soils are the predominant limiting factors. Hence, the areas in Africa that suit best the needs of the moisture-depending oil palm are located in the Congo Basin, mainly in the Democratic Republic of the Congo (DRC) and in the coastal region of Western Africa – mainly Sierra Leone and Liberia. The highest natural potential can be observed in South East Asia, the current center of oil palm production. Favorable distribution of precipitation is the most important asset of the region. Locally, unfavorable soil conditions are the major constraint to oil palm in South East Asia: large parts of Borneo and Sumatra are covered by water-logged soils, which in fact often are peat soils. As one moves away from the equator, suitability decreases due to the increasing length of the dry season and the highland stretching over Papua.

If appropriate management measures are taken (Figure 5b), most of the unfavorable soil features can be overcome so that climate is the main remaining limiting factor. As compared to the minimum-management scheme, notably in South America and South East Asia, soil drainage and fertilization schemes can lead to substantial improvements of suitability. Suitability in Africa tends to remain generally lower than in the other regions since agronomic management in the case of oil palm can barely substitute for poor climatic conditions.

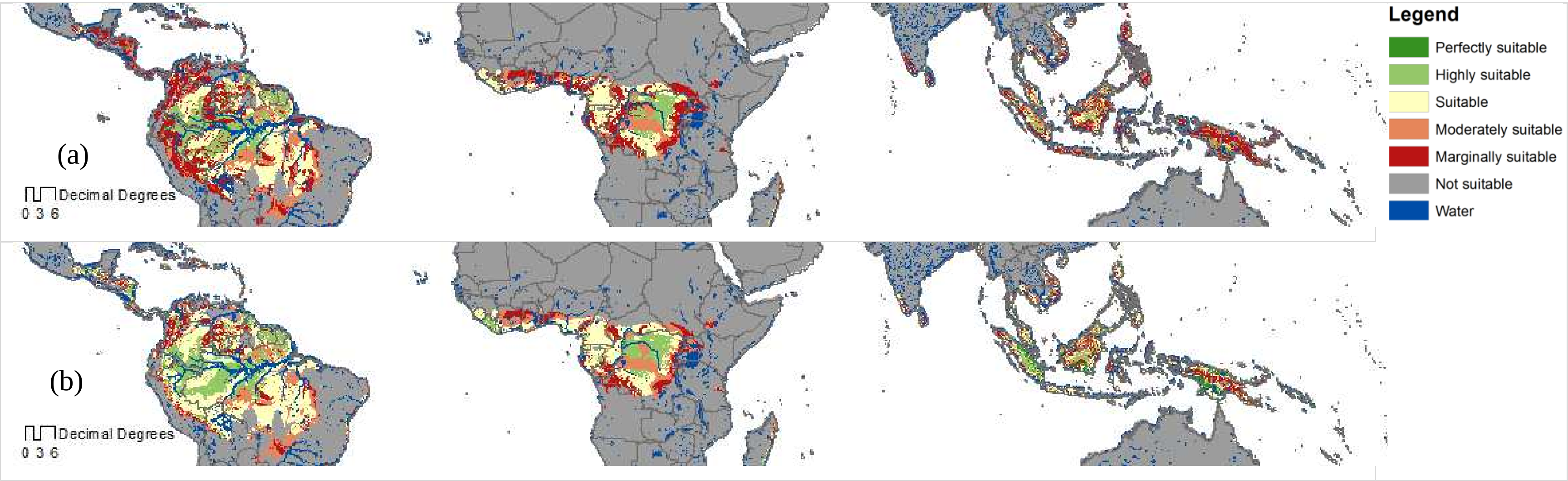

Figure 5: Combined suitability map under (a) a minimum management and (b) an optimal management scheme.

We find that under the optimal management scenario 1.1 billion hectares of land globally are suitable for oil palm cultivation. This land is concentrated in nine tropical countries representing 86% of the globally suitable area (Figure 6). The highly suitable area (in blue) corresponds to the classes 4 (highly suitable) and 5 (perfectly suitable) whereas other suitable areas (in red) represent the classes one, two and three. Almost 50% of the area of Brazil is to some extent suitable for oil palm planting, which corresponds to a total suitable area in the range of 400 million hectares, 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, whereas other countries have a higher share of suitable land - expressed by the ratio of suitable area vs. total country area - such as DRC (71%), Colombia (72%), Indonesia (71%) and Malaysia (88%).

On a second level of analysis, Figure 6 also highlights that Indonesia and Malaysia benefit from very favorable bio-physical conditions for oil palm cultivation, which is expressed as the high share of very suitable areas among all suitable areas. However, countries like Colombia (35%), Peru (44%) and PNG (37%) have similarly high values. Annex 3 provides a tabular overview of the presented data including the current extent of plantations per country.

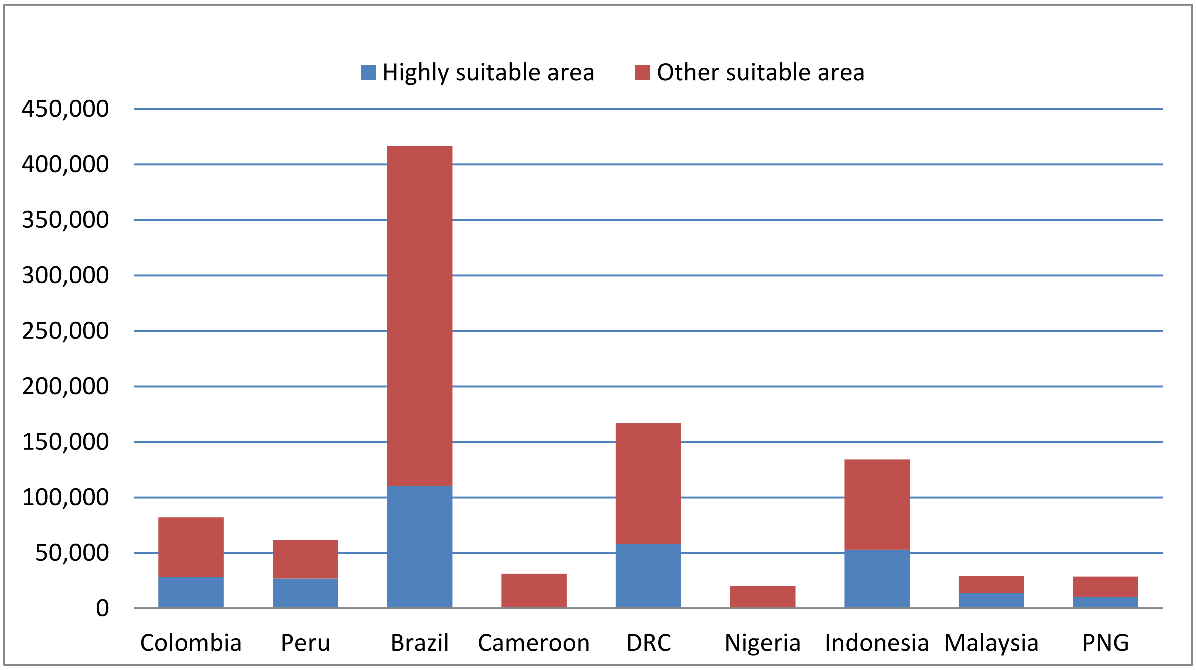

Figure 6: Area (in millions of ha) per country with high degree of suitability (blue) and other suitable land (red) of selected countries under the optimal management scenario.

3.3. Comparison with existing suitability maps

We compared our optimal management suitability map with two other studies which also assessed oil palm suitability on a global scale: A global assessment of suitability for a series of crops in the framework of the REDD+ mechanism conducted by the World Resources Institute (WRI) (Stickler et al., 2007) and the Global Agro-Ecological Zones (GAEZ) product hosted by IIASA and the FAO (van Velthuizen et al., 2007). We aggregated all three maps to binary suitability maps in order to make the three products comparable. Then we overlaid them in order to compute areas of agreement and disagreement, respectively, between the three products. These overlays are presented in Figure 7, where map 7a depicts the comparison against the WRI-assessment and map 7b contains the comparison against the GAEZ product. “Agreement” (green) hereby means areas that are deemed suitable by both products; “Disagreement – only WRI/GAEZ” (orange) means areas which are marked not suitable by our approach and suitable by the WRI or GAEZ; “Disagreement – only our product” (yellow) represents areas which are considered suitable according to the present product and not suitable according to WRI or GAEZ.

The overall agreement between WRI and our map is 70%, and the general pattern over all regions is that the present assessment considers a wider area to be suitable than the WRI-product does. This is unsurprising given that the WRI assessment adopts a different minimum precipitation threshold than ours. WRI assumed that oil palm requires at least 1400 mm rainfall annual, which is the most commonly cited value in the literature but since we also found empirical evidence that in practice oil palm is still cultivated under less favorable climatic conditions (Corley, 2009; PALMCI, 2011; Yao & Kamagate, 2010), we decided to use a lower minimum threshold value of 1000 mm. By contrast, the GAEZ-map generally has been constructed based on relatively flexible climatic assumptions. Large tracts of areas are considered suitable which are according to our assessment dropped out mainly due to the seasonality constraint (too long dry season) or the temperature constraint (too low temperatures in the coldest month of the year). Thus, the greatest source of disagreement is in mainland South East Asia and East Africa where GAEZ overestimates suitable areas as compared to our assessment. It should be noted, however, that in both products these areas of disagreement are attributed marginal suitability only.

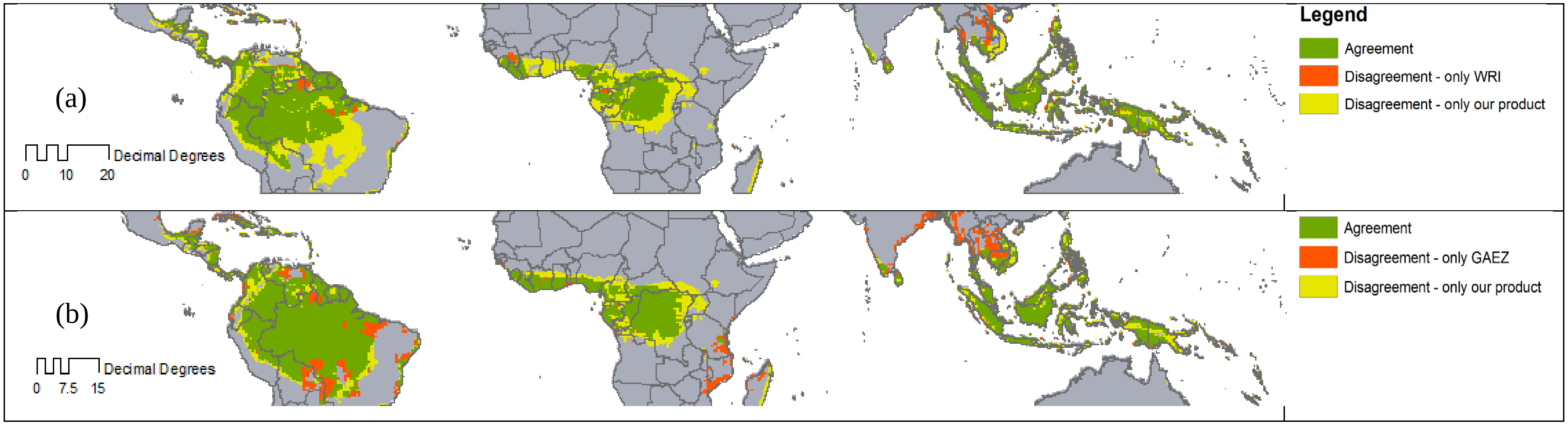

Figure 7: Comparison of our assessment with the similar products from (a) WRI (Stickler et al., 2007) **and (b) GAEZ** (van Velthuizen et al., 2007)**. Areas of agreement are depicted in green, areas of disagreement in yellow and orange.**

4. Discussion and conclusion

We have generated a new global bio-physical oil palm suitability map which differentiates between five suitability classes and two management systems. The results indicate that nine countries encompass 86% of the global suitable area with countries in South East Asia - the current center of palm oil production - having the highest share of suitable land in relation to the size of the countries, while countries in Latin America and Central and Western Africa having the largest tracts of potentially suitable land. Suitability is essentially driven by climate. High temperatures over the year along with sufficient and steady rainfall are crucial to OP cultivation. 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. Soil constraints, by contrast, can be overcome by optimal management practices except for permanently water-logged sites which are common in the vicinity of major rivers. However, these large suitable areas should not be confused with available land, as significant shares of this area might be currently under other use, stocked by forest or harbor significant biodiversity values.

One limiting factor to the reliability of the present product 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 relatively unreliable, whereas Southern and Eastern Africa along with Latin America are considered trustworthy (Nachtergaele et al., 2012). In order to partly overcome this constraint, for identification of unfavorable wetlands we relied on a hybrid approach by taking soil features from both the soil sample based Harmonized World Soil database (Nachtergaele et al., 2012) and the MODIS remote sensing product (NASA, 2009). This approach brought some significant improvements, notably for the detection of permanent water bodies and wetland areas which are common along the Amazon and the Congo River.

Subsequent data processing from bio-physical variables to suitability maps is a potential source of debate too. We defined thresholds to categorize categorical data (soil) and discrete data (climate, topography) to suitability classes upon review of the relevant literature. For climate variables we chose threshold values that are slightly less rigid as compared to the most commonly cited thresholds (>1000 mm annual precipitation instead of >1400 mm and up to five months of dry season instead of four months. The location of existing plantations confirms our assumption since oil palm plantations can be found in areas that would be considered unsuitable when applying conventional climate thresholds.

Besides bio-physical suitability, a range of political and economic factors has shaped the development of the sector in the current major producer countries: direct and indirect government support in various forms (e.g. trade promotion programs); capital availability through domestic and foreign investors; the industry’s focus on continuous research and development; availability of skilled labor; and the strong presence of general infrastructure and shipping facilities (Thoenes, 2006). Therefore, it will be imperative to address the socio-economic settings in order to achieve fully the objectives stated at the beginning of this report. On a local scale (Gingold et al., 2012) up to national scale (Feintrenie, 2014b) this issue has been addressed by several studies. In addition, oil palm production under optimal management is related to higher production costs which would have to be taken into account to decide on where to expand OP plantations. Hence, the next step will be to combine the suitability map with socio-economic data on a global scale in order to adequately represent the constraints to OP expansion beyond those imposed by the bio-physical environment.

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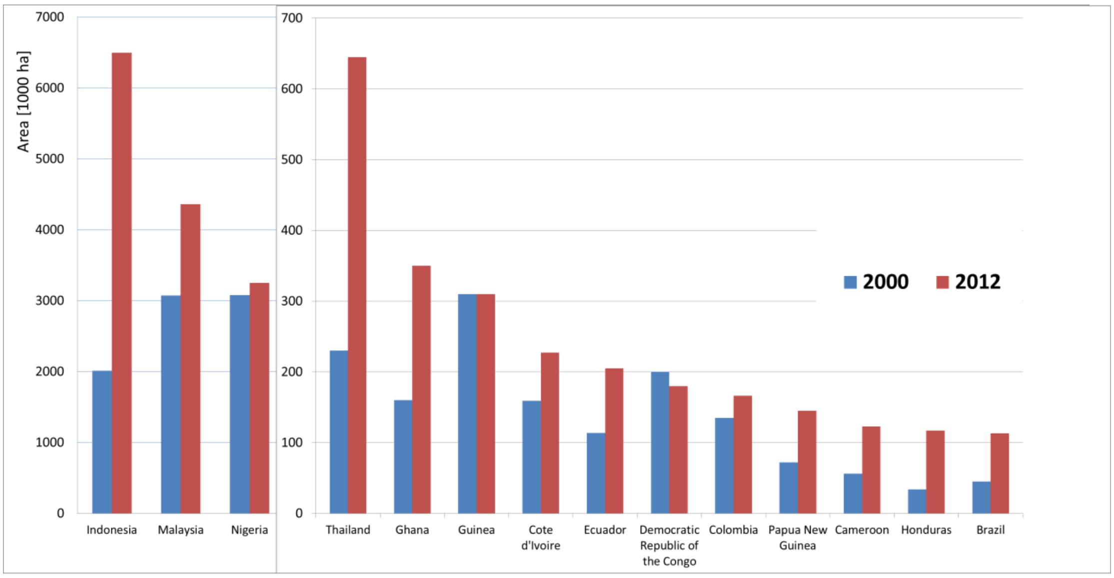
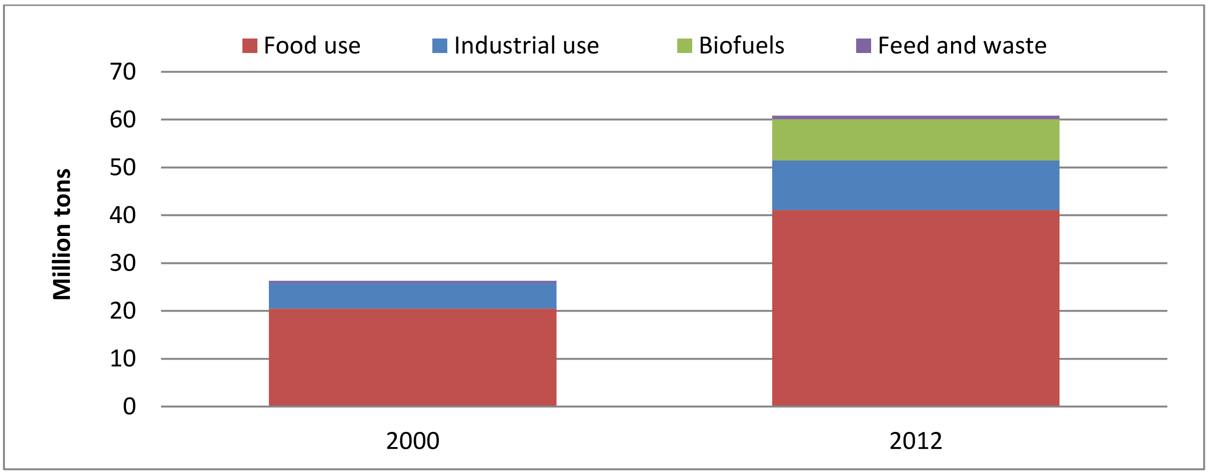
6. Annexes

Annex 1: Planted area (a) and consumption patterns (b) in 2000 and 2012.



a) **Area (1000 ha) cultivated in the 14 main producer countries in 2000 and 2012. Source: FAO (2014)**



b.) **Global consumption in 2000 and 2012 by usage-type (in Million tons). For 2000, biofuels are part of the industrial use fraction, as no separate data was available for that year**. Source: USDA-FAS 2014 and Thoenes, FAO, personal communication.

Annex 2: Marginal soils and respective soil amelioration techniques

	Activities occurring at plantation establishment		Activities occurring regularly	
	Ploughing/ excavation	**Soil water management (drainage, flushing, or damming)**	**Other soil amelioration[2]**	**Fertilization**
Gravelly, stony and lateritic soils	X		X	X
Very acid and sulfate soils		X		
Saline soils		X		
Deep sandy soils			X	X
Soils with high organic matter content (histosols and peatlands)		X		X
Poorly drained soils (including peatlands)		X		
Weathered and leached soils (Ferralsols and Acrisols)			X	X

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[2] Examples are: Establishment of a permanent crop cover of the soil and mulching with empty fruit bunches.

Annex 3: Country statistics of currently cultivated area, suitable areas and the ratio of both

Country	Current oil palm cultivated area [1000 ha]*	Highly suitable area [1000 ha]	Total suitable area [1000 ha]	Share of the country territory suitable [%]
Indonesia	6,500	52,812.48	134,278.95	71%
Malaysia	4,360	13,736.51	28,916.85	88%
Papua New Guinea	145	10,542.08	28,704.48	62%
Subtotal: Asia (including Oceania)	11,606			
Nigeria	3,250	279.20	20,217.24	22%
Democratic Republic of Congo (DRC)	180	58,201.28	166,933.38	71%
Cameroon	123	1,366.92	31,233.65	66%
Subtotal: Africa	4,614			
Colombia	166	28,388.40	81,896.86	72%
Brazil	113	110,218.67	416,739.88	49%
Peru	32	27,054.11	61,839.29	48%
Subtotal: Americas	864			

*Source: FAO 2014

Annex 4: Overview of relevant case studies and methodology used by region.

Source	Study region	Climate						Topography		Soil							
		Rainfall	Temperature	Seasonality indicator	Water deficiency	Solar radiation	Wind speed	Elevation a.s.l.	Slope	Soil type	Soil depth	Soil drainage	Soil texture	Soil fertility	Soil erosion risk	Level of the water table	Other soil property
Latin America																	
Ramalho Filho et al., 2010	Legal Amazon / Brazil	X	X	X		X			X		X	X	X	X	X		
Yui & Yeh, 2013	Pará State / Brazil	X	X						X			X	X				
Gutiérrez-Vélez et al., 2011	Peru							X	X								
Inter-American Development Bank, 2012	Colombia	X	X			X	X		X		X	X	X				

Fernandez Vargas, 2010	Nicaragua	X	X	X		X		X			X	X				X	
INIFAP, 2008	Mexico	X						X	X				X				
Africa																	
Wyrley-Birch et al, 1982	South-West Cameroon					X	X					X					X
Feintrenie ,2014	Republic of Congo	X	X														
Asia																	
Mantel et al., 2007	Kalimantan / Indonesia	X	X			X	X	X	X								X
Harris et al., 2013	Indonesia, Malaysia, Papua New-Guinea	X	X					X	X	X							

Gingold et al., 2012	Kalimantan and Papua / Indonesia	X						X	X	X	X	X		X			
									Global								
van Velthuizen et al., 2007	Global	X	X	X	X				X		X	X	X				X
Stickler et al., 2007	Global	X	X	X													X