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Climate, soil and land-use based land suitability evaluation for oil palm production in Ghana

Tiemen Rhebergen[a,b,*], Thomas Fairhurst[c], Shamie Zingore[a], Myles Fisher[d], Thomas Oberthür[e], Anthony Whitbread[f,g]

[a] International Plant Nutrition Institute Sub-Saharan Africa Program (IPNI SSAP), C/O IFDC – East & Southern Africa Division, ICIPE Compound, Duduville – Kasarani, Thika Road, P.O. Box 30772-00100, Nairobi, Kenya
[b] Plant Production Systems Group, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands
[c] Tropical Crop Consultants Ltd, 26 Oxenturn Road, Wye, Kent TN25 5BE, United Kingdom
[d] International Center for Tropical Agriculture (CIAT), Cali, Colombia
[e] International Plant Nutrition Institute Southeast Asia Program (IPNI SEAP), C/O The World Fish Center, Jalan Batu Maung, Bayan Lepas, Penang 11960, Malaysia
[f] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502324, Telangana, India
[g] Crop Production Systems in the Tropics George-August-Universität, Göttingen, Grisebachstraße 6, 37077 Göttingen, Germany

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ABSTRACT

In the past decade, oil palm (*Elaeis guineensis* Jacq.) has become the world's most important oil crop. The large demand for palm oil has resulted in a rapid expansion of oil palm cultivation across the globe. Because of the dwindling availability of land in Southeast Asia, most expansion of the industry is expected in Central and South America and sub-Saharan Africa, where land with suitable agro-ecological conditions is available. Using Ghana as a case study, a method for evaluating areas that are both suitable and available for oil palm production is presented. Our assessment used spatial data and GIS techniques, and showed that areas with suitable climatic conditions (annual average water deficit <400 mm) is about 20% greater than was previously identified. The observed differences are the result of using different methods to determine suitability, and climate change. A major climatic factor limiting suitability for oil palm production in Ghana is the annual water deficit, with the most suitable areas located in the rainforest and semi-deciduous forest zones with higher rainfall in southern Ghana. Opportunities for large-scale oil palm plantation development is limited, however, because of the lack of availability of large and contiguous tracts of land that are required for commercial plantation oil palm development. A feasible strategy for oil palm expansion is therefore smallholder production, which can make use of smaller parcels of land. Alternatively, oil palm production in Ghana can be increased by yield intensification on land already planted to oil palm. This can also reduce the requirement for further land clearance for new plantations to meet the growing demand for palm oil. Such assessments will be essential for guiding government policy makers and investors considering investments in oil palm development.

1. Introduction

In the past decade, oil palm (*Elaeis guineensis* Jacq.) has become the world's most important oil crop, contributing nearly 30% of the world's edible vegetable oil requirements (Corley, 2009; Hansen et al., 2015). The large demand for palm oil has resulted in a rapid expansion of oil palm cultivation across the globe. Because of the dwindling availability of suitable land in Southeast Asia, most future expansion is expected in Central and South America and sub-Saharan Africa (SSA), where large areas with agricultural potential are available (Laurance et al., 2014).

In West Africa (WA), the consumption of palm oil and derived products is expected to increase as the population grows. Strong demand for vegetable oil in Africa has resulted in the expansion of the oil palm sector in WA. This has a large economic impact in producer countries by providing employment for millions of workers. In addition, palm oil is now a major source of income and trade along border districts (Ofosu-Budu and Sarpong, 2013). In the

* Corresponding author at: International Plant Nutrition Institute Sub-Saharan Africa (IPNI SSA), C/O IFDC – East & Southern Africa Division, ICIPE Compound, Duduville – Kasarani, Thika Road, P.O. Box 30772-00100, Nairobi, Kenya.
E-mail address: trhebergen@ipni.net (T. Rhebergen).

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Ghanaian economy for example, oil palm is the second most important perennial crop after cocoa (Angelucci, 2013; Ofosu-Budu and Sarpong, 2013). The yield of fruit bunches (FB) in Ghana is poor, however, and has decreased from 6.5 t ha^{-1} in 1990 to 5.4 t ha^{-1} in 2012 (FAO, 2014a). By contrast, FB yields in the major producing countries in Southeast Asia and Latin America, where the climate is more favourable, are more than three times greater at 18.5–19.0 t ha^{-1} (FAO, 2014a). In response to increasing local demand for palm oil and the present requirement for costly palm oil imports (for example, Ghana imported 74,431 t palm oil at a cost of US$ 83 million in 2011) (FAO, 2014a), the governments of some West African countries are encouraging both national and foreign investors to plant more oil palm (Ofosu-Budu and Sarpong, 2013). Area expansion is therefore proposed to increase local production and to reduce imports of crude palm oil.

An analysis of the availability of suitable land for oil palm plantations and the obtainable yields is essential information for government policy makers and investors. Some 45 years ago, van der Vossen (1969) identified areas in Ghana with suitable climatic conditions for oil palm based on 400 and 250 mm mean annual water deficit isolines. As in much of SSA, climatic conditions in the oil palm belt in Ghana have changed since the 1960s (Lemoalle and de Condappa, 2012). Rainfall isohyets and water-deficit isolines have been displaced to the south by about 1° latitude (i.e., about 110 km), possibly due to climate change and the impact of deforestation. Furthermore, total annual rainfall has also become more variable over the past three decades (Manzanas et al., 2014; Owusu, 2009; Stanturf et al., 2011). Whilst total annual rainfall has remained similar, rainfall distribution has changed, with more rainfall now occurring in what was formerly the dry season (Abdul-Aziz et al., 2013; Owusu, 2009). At a local scale, the amount of land with climatic conditions suitable for oil palm production may have either expanded or diminished due to changes in rainfall patterns (Gilbert, 2013).

In this paper, we provide an up to date and more accurate assessment of land suitability and availability for oil palm based upon geographic information systems (GIS) using spatial data that was not available when van der Vossen (1969) developed his suitability map. Using Ghana as a case study, we describe the agro-ecological conditions and, using information from the literature, derive environmental parameters that define whether or not areas are suitable for oil palm cultivation. We used these parameters together with the spatial data on climate to develop a land suitability classification and estimate the amount of suitable land that is available for oil palm development.

We determine the main constraints to oil palm production in Ghana based on an analysis of land characteristics that limit productivity, and conclude by providing recommendations for the sustainable development of the oil palm sector in Ghana.

2. Material and methods

2.1. Agro-ecological conditions in Ghana

Ghana is located in the middle of the West African coast along the Gulf of Guinea (4.5–11.5°N, 3.5°W–1.3°E), and is bordered by Côte d'Ivoire to the west, Burkina Faso to the north, and Togo to the east. The climate of Ghana is strongly influenced by the movement of the tropical rain belt, known as the inter-tropical convergence zone (ITCZ). The ITCZ oscillates between the northern and southern tropics in the course of a year, transporting a dry continental air mass to the north, and a tropical, maritime air mass to the south (Hayward and Oguntoyinbo, 1987). As a result, northern and southern regions of Ghana have distinct climates (McSweeney et al., 2010a, 2010b). Six distinct agro-ecological zones have been identified in Ghana, with a gradient of increased aridity from south to north (Antwi-Agyei et al., 2012). In order of increasing aridity they are: rainforest, semi-deciduous forest, coastal savanna, forest-savanna transition, Guinea savanna, and Sudan savanna (Antwi-Agyei et al., 2012) (Fig. A1). Rainfall decreases from the southwest (> 2000 mm $year^{-1}$) to the northeast (< 1000 mm $year^{-1}$) (Environmental Protection Agency (EPA) and Ministry of Environment, 2011). In the south, the annual mean relative humidity (RH) is ±80% (except for some days during the 'Harmattan' in the dry season), while in the north RH is lower at ±40% (Oppong-Anane, 2006). Northern Ghana has a single wet season between May and November, while the southern regions of Ghana have two wet seasons with long rains usually from March–July and short rains from September–November.

With the exception of the Kwahu Plateau, which runs along the southern edge of the Volta River Basin, the topography in Ghana is relatively flat and low-lying, with more than half the area <150 masl. Because Ghana is in the equatorial belt, mean monthly temperatures below 25 °C are seldom recorded. Mean annual temperature ranges from 26 °C in the south to 29 °C in the north (FAO, 2005). Minimum temperatures less than 18 °C only occur in the highlands above 400 masl (e.g., on the Kwahu Plateau) (van der Vossen, 1969). The diurnal temperature range is small in the south (5–9 °C) due to maritime influence from the Atlantic, and greater in the north (7–14 °C) due to hot and dusty air brought in from the Sahara desert during the Harmattan (McSweeney et al., 2010a, 2010b). As a result, climatic conditions are hot and seasonally dry along the southeast coast, hot and humid in the southwest, and hot and dry in the north.

Little solar radiation data is available for West Africa, and Ghana, because of the lack of solar radiation recording stations in the region (Stout, 1990). As a surrogate, sunshine hours are used as an estimate of solar radiation because it is easier to measure and data are more readily available. While solar radiation and sunshine hours are generally well-correlated, the effects of the Harmattan and atmospheric pollution under West African conditions prevents accurate recording of sunshine, even when conditions are cloudless. As a result, much solar radiation is reflected by the atmosphere, and reaches the earth's surface predominantly as diffuse radiation (Corley and Tinker, 2003; Hayward and Oguntoyinbo, 1987). Nevertheless, taking these factors into account, the total hours of sunshine per annum in WA is considerably less than in other oil palm growing regions such as Southeast Asia or Central and South America (Corley and Tinker, 2003; van der Vossen, 1974). In WA, sunshine hours increase with latitude from the Guinea Coast up to the Sahel and the margins of the Sahara, albeit not in a regular pattern. In Ghana, for example, a large land pocket with less sunshine occurs in the west central region (Hayward and Oguntoyinbo, 1987). In general, there are more sunshine hours during the dry season and less during the rainy season because of the effect of cloud cover. However, sunshine hours during the dry season are periodically reduced due to the effect of dust in the atmosphere during the Harmattan.

Soils in the higher rainfall zones in the south of Ghana are generally strongly weathered and highly leached with low pH, and poor soil fertility status (Swaine, 1996). Soil type is strongly related to topography and slope position. The topography in the oil palm belt is undulating to rolling, with slopes ranging from 2 to 9°. Some relatively flat areas are found with moderate slopes (<5°) but rolling to hilly terrain (5–17°) is more common, with low-lying and poorly drained swamps enclosed by upland areas. In the oil palm belt, the predominant soils are free-draining Acrisols and Ferralsols (Fig. A2). These two soil types are often found together, with Acrisols on eroded slopes of low hills, Ferralsols on nearby stable pediments and uplands. Soils in enclosed, low-lying swamps are commonly Gleysols (FAO, 2014b).

The most common soils in the semi-deciduous forest and parts of the forest-savanna transition zones of the oil palm belt are Orthic Acrisols. They are deep, well drained soils with sandy clay loam texture, strongly weathered, leached, and acid (pH <5.1–6.5). Acrisols are characterized by a distinct argillic B horizon, in which clay particles have accumulated from the upper soil layer. Acrisols are easily eroded once the forest cover vegetation has been removed (Adjei-Gyapong and Asiamah, 2002; Buringh, 1979; FAO, 2014b). Xanthic Ferralsols derived from acid rocks with high quartz content are more common in the high rainfall forest zone of Southwestern Ghana (Buringh, 1979; FAO, 2014b; van Wambeke, 1974). Xanthic Ferralsols have a typically yellowish or pale yellow B horizon, due to low iron content. As a result of their relatively coarse texture and high rainfall, they are strongly leached, acid and poor in nutrients. Well-developed soil micro-aggregates reduce the water holding capacity in these soils. Orthic Acrisols and Xanthic Ferralsols are acid (pH < 5.5) low fertility status soils containing small amounts of plant available nutrients (particularly nitrogen (N), phosphorus (P) and potassium (K)), with low cation exchange capacity (e.g., Ferralsols < 16 cmol kg^{-1}) and base saturation (e.g., Acrisols < 50%). Drainage is related to topography, with poorly drained, flood prone clay to loamy sand textured Gleysols in valley bottoms, and well drained Acrisols and Ferralsols respectively on lower and upper slopes (Annan-Afful et al., 2004; Annan-Afful et al., 2005; Owusu-Bennoah et al., 2000).

2.2. *Land suitability classification and approach*

We used land suitability evaluation methods to identify areas that are both suitable and available for oil palm production in Ghana. Land suitability is defined as '*the fitness of a given type of land for a defined use*' and land suitability evaluation (LSE) is the '*process of assessment of land performance for a specific purpose*' (FAO, 1976). For agriculture, LSE evaluates the ability of a piece of land to meet the agro-ecological requirements of a given crop for maximum yield (Abdel Kawy and Abou El-Magd, 2012). LSE assesses how well all relevant land characteristics such as soil, climate, and topography (FAO, 1976, 1985) match the requirements of a particular crop.

For the objectives of this study, computer-assisted overlay mapping is a suitable LSE method, in which the evaluation criteria are recorded as superimposed layers (Malczewski, 2004). These layers are then integrated in a single data layer, which can then be used to produce a map showing land suitability classes. We used this method to define suitable locations for oil palm in Ghana.

2.2.1. *Suitability classes*

LSE was conducted in three-steps. In the first step, we defined climatically suitable areas for oil palm based on mean annual water deficit. Water deficit is considered to be the most important climatic factor affecting oil palm yield (Corley and Tinker, 2003). Severe water deficits are particularly common in WA because of seasonal droughts. In extreme areas, such as Pobé in Benin, average annual water deficits can vary between 300 and 900 mm year^{-1}, with an average of 550 mm year^{-1} (Caliman and Southworth, 1998). The relationship between water deficit and FB yield is complex. Water stress, as well as other environmental factors, reduces FB yield via a time-lagged effect on floral initiation, sex differentiation, and abortion rate (Corley and Tinker, 2003). As a result, yield reduction may only become evident several months or even years after the incidence of drought or other stress events (Caliman and Southworth, 1998). With prolonged water stress, vegetative as well as generative growth is impaired and, in extreme cases, may lead to palm death (Caliman, 1992). The extents to which water deficits affect FB yield have been reported in several studies. In WA, Hartley (1988) found a 10% yield reduction with every 100 mm year^{-1} water deficit in the year of harvest. In contrast, Olivin (1968) and Ochs and Daniel (1976) reported a 10–20% yield reduction with every 100 mm year^{-1} water deficit, depending on the soil's water holding capacity. Caliman and Southworth (1998) found an 8–10% yield reduction in the first year, and a 3–4% yield reduction in the second year with a 100 mm year^{-1} water deficit. Mean annual water deficit is thus a useful parameter in delineating and grouping areas that are climatically similar in terms of oil palm production (Olivin, 1968; van der Vossen, 1969). In general, areas with water deficits >400 mm year^{-1} are considered unsuitable for oil palm production because low yields do not provide an economic return (Olivin, 1968; van der Vossen, 1969). The critical water deficit, after which oil palm growth and yield start to be affected is assumed to be 200 mm year^{-1} (Corley and Tinker, 2003). Based upon these assumptions, and following the suitability assessment methods of Olivin (1968) and van der Vossen (1969), we defined four categories of water deficit as follows

i Optimal: areas with a mean annual water deficit <150 mm;
ii Favourable: areas with a mean annual water deficit <250 mm;
iii Suitable: areas with a mean annual water deficit <400 mm; and
iv Unsuitable: areas with a mean annual water deficit >400 mm

Table 1
Suitability for oil palm production based on climate and topography parameters (Paramananthan, 2003).

Limitation	Units	Suitable	Unsuitable
Climate			
Solar radiation	MJ m^{-2}	7–21	<7, >21
Temperature	°C	18–37	<18, >37
Topography			
Slope	°	<20	>20

In the second step, we overlaid the areas that were climatically suitable with biophysical and topographic constraints categorized as either 'suitable' or 'not suitable' (Table 1). We included solar radiation, temperature, and slope because, after water deficit, they are the most important factors that determine oil palm yields (Paramananthan, 2003). The amount of solar radiation suitable for oil palm production is not defined precisely, however, because it is difficult to isolate its effect from other factors affecting productivity. Oil palm grows best where solar radiation is >16 MJ m^{-2}, but excessive amounts of solar radiation can affect stomatal aperture and leaf temperature, limiting the rate of CO_2 absorption and therefore photosynthesis (Corley and Tinker, 2003; Paramananthan, 2003). Additionally, high levels of solar radiation can cause photodamage to plants (Kasahara et al., 2002). Of these constraints, only topography can be modified by costly management interventions (e.g., installation of individual terraced platforms on moderate to strongly sloping land (5°–10°) and continuous terraces on steep terrain (10°–20°).

In the third and final step, we integrated the most current land-use and excluded protected areas, which include national parks, forest reserves, World Heritage sites, and Ramsar Wetlands. Protected areas are defined according to IUCN as '*a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long term conservation of nature with associated ecosystem services and cultural values*' (Dudley, 2008). Urban settlements, which were distinguished from rural areas based on a combination of population counts (persons), settlement points and the presence of nighttime lights, were also excluded. Urban settlements are defined as '*contiguous lighted cells from the nighttime lights or approximated urban extents based on buffered settlement points for which the total population is greater than* 5000 *persons* (Balk et al., 2006; CIESIN and IFPRI, 2011). Because of national differences in distinguishing urban from rural areas, the criteria for urban settlements are country specific (UN, 2013). In SSA, for example, the urban population threshold ranges from settlements of 20,000 to as few as 500 inhabitants for certain areas in South Africa and Zimbabwe (Foote et al., 1993). In Ghana, an urban area is defined as a settlement with >5000 inhabitants (Ajaegbu, 1979).

2.2.2. Data used

We used historical climate data from the WorldClim database (www.worldclim.org) (Hijmans et al., 2005), including monthly minimum, maximum and average temperature (°C) and average monthly rainfall (mm $month^{-1}$) for the period 1950–2000. The WorldClim data are generated through interpolation of average monthly climate data from meteorological stations distributed throughout Ghana. Elevation data was obtained from the SRTM 90 m database (http://srtm.csi.cgiar.org) (Jarvis et al., 2008) and soil properties, including soil texture and soil type from the ISRIC/WDC-Soils database (http://soilgrids1km.isric.org) (ISRIC, 2013) and the Harmonized World Soil Database v1.2 (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/) (FAO et al., 2009). Data on protected areas and urban settlements were obtained from (http://protectedplanet.net) (IUCN and UNEP-WCMC, 2014) and (http://sedac.ciesin.columbia.edu/data/set/grump-v1-urban-extents/data-download) (CIESIN and IFPRI, 2011). The data were compiled in a geographic information system using ArcMap 10. The climatic, biophysical, topographic, and soil spatial datasets were raster files on 30- and 3″ grids (~1 km and 100 m). Data of urban settlements and protected areas were imported as shapefiles. Data sources are listed in Table A1.

2.2.3. Data analysis

We clipped all raster grids and shapefiles to the extent of Ghana's national boundaries and derived slope maps from elevation contours (with Z factor = 9.12×10^{-6}). We estimated solar radiation at a 30″ resolution for each month from latitude and day of the year (Allen et al., 1998), and then converted solar radiation into water equivalents to calculate monthly potential evapotranspiration (ETP) following Läderach et al. (2013):

$$ETP = 0.0023 \times R_a \times (T - t)^{0.5} \times (t_m + 17.8) \quad (1)$$

where ETP = evapotranspiration (mm day^{-1}); R_a = extraterrestrial solar radiation expressed in water equivalent (mm day^{-1}); T-t = the monthly mean diurnal temperature range (°C); and t_m = mean air temperature (°C).

We estimated terrestrial solar radiation (R_s) (Hargreaves and Samani, 1982):

$$R_s 0.16 \times R_a \times (T - t)^{0.5} \quad (2)$$

where R_s = terrestrial solar radiation (MJ m^{-2} $month^{-1}$); and R_a and T-t are as defined in equation (1).

We converted ETP to mean annual water balances (B) (Surre, 1968):

$$B = S_{res} + P - \text{ETP} \quad (3)$$

where B = monthly water balance (mm); S_{res} = residual soil water from the previous month (mm); P = monthly rainfall (mm); and ETP = monthly potential evapotranspiration (mm).

Epebinu and Nwadialo (1993) found a high correlation (multiple R = 0.980) between available water capacity (AWC) and the soil particle size distribution in Nigeria:

$$AWC = 0.93 + 0.54 \times silt + 0.13 \times clay \quad (4)$$

We used equation (4) to estimate AWC for five layers (0–5 cm, 5–15 cm, 15–30 cm, 30–60 cm, and 60–100 cm depth) for each soil texture class. The sum estimates the maximum amount of available soil water (ASW) in the top 100 cm of soil, which is the zone exploited by the majority of the roots of oil palm (Nelson et al., 2006). We assumed that excess water was lost as runoff or drainage to depth. Negative values for monthly water balance (B) indicate a water deficit, in which case S_{res} for the following month is zero. If S_{res} was greater than the soil's maximum water storage capacity, it was set to the maximum. Annual water deficit was calculated as the sum of all negative monthly water balances for the year.

Rainfall data for the period 2010–2014 were obtained from five meteorological stations. Three of the stations were located at the commercial plantations Benso Oil Palm Plantation (BOPP), Twifo Oil Palm Plantation (TOPP) and Norpalm Ghana Ltd. located in the Western and Central Regions. The other two sites are Bogoso, a smallholder oil palm project, and the Ghana Oil Palm Research Institute (OPRI) at Kade, respectively in the Eastern and Western Regions. BOPP and Bogoso are located within the rain forest zone, while the other sites are found within the semi-deciduous forest zone. The five production sites cover a wide range of rainfall distribution (mm $month^{-1}$) within the oil palm belt. For all sites, we calculated average annual water deficits using the method of Surre (1968) and evaluated this against the results of our suitability assessment. In the final analysis, we integrated land use information to delineate areas that were suitable on land potentially available for oil palm production. We generated maps of land suitability after excluding land in protected areas and urban settlements.

Table 2
Land area falling within different suitability classes compared with the results of van der Vossen (1969).

Suitability class	Size		Difference	
	Climatic zones	van der Vossen (1969)		
	,000 ha	,000 ha	,000 ha	%
Suitable (AWD < 400 mm)	7354	6100	1254	+21
Favourable (AWD < 250 mm)	5049	1889	3160	+167
Optimal (AWD < 150 mm)	580	Not defined	–	–

3. Results

3.1. Areas suitable for oil palm production

We estimated the area suitable (deficit <400 mm $year^{-1}$) for oil palm in Ghana to be 7,350,000 ha, or 31% of the total land area (Fig. 1). The area unsuitable for oil palm production, due to poor water availability, is 16,500,000 ha. Optimal areas for oil palm (water deficit <150 mm $year^{-1}$) are in the south of the Western Region and a smaller area west of Koforidua in the Eastern Region. Optimal areas are estimated at 580,000 ha (Fig. 1).

Based on our assessment, the area that has climatic conditions suitable for oil palm (deficit <400 mm $year^{-1}$) is 20% greater than that identified by van der Vossen (1969) (Table 2). The additional area suitable for oil palm is found in the southwestern coast and east of Lake Volta (Fig. 1). Climatically favourable areas are 170% greater than van der Vossen's (1969) assessment (Table 2). The difference is found largely in the Western and Central Regions and the southern parts of the Ashanti and Eastern Regions (Fig. 1).

Average water deficits for five production sites in Ghana ranged between 130 mm $year^{-1}$ for BOPP and 390 mm $year^{-1}$ for Norpalm for the period 2010–2014 (Table A2). All five sites are located within climatically suitable areas, but only BOPP is located in the area with optimal climate (Fig. 1).

The uplifted edges of the Volta Basin lie along the northeastern edge of the semi-deciduous forest zone. They are found at

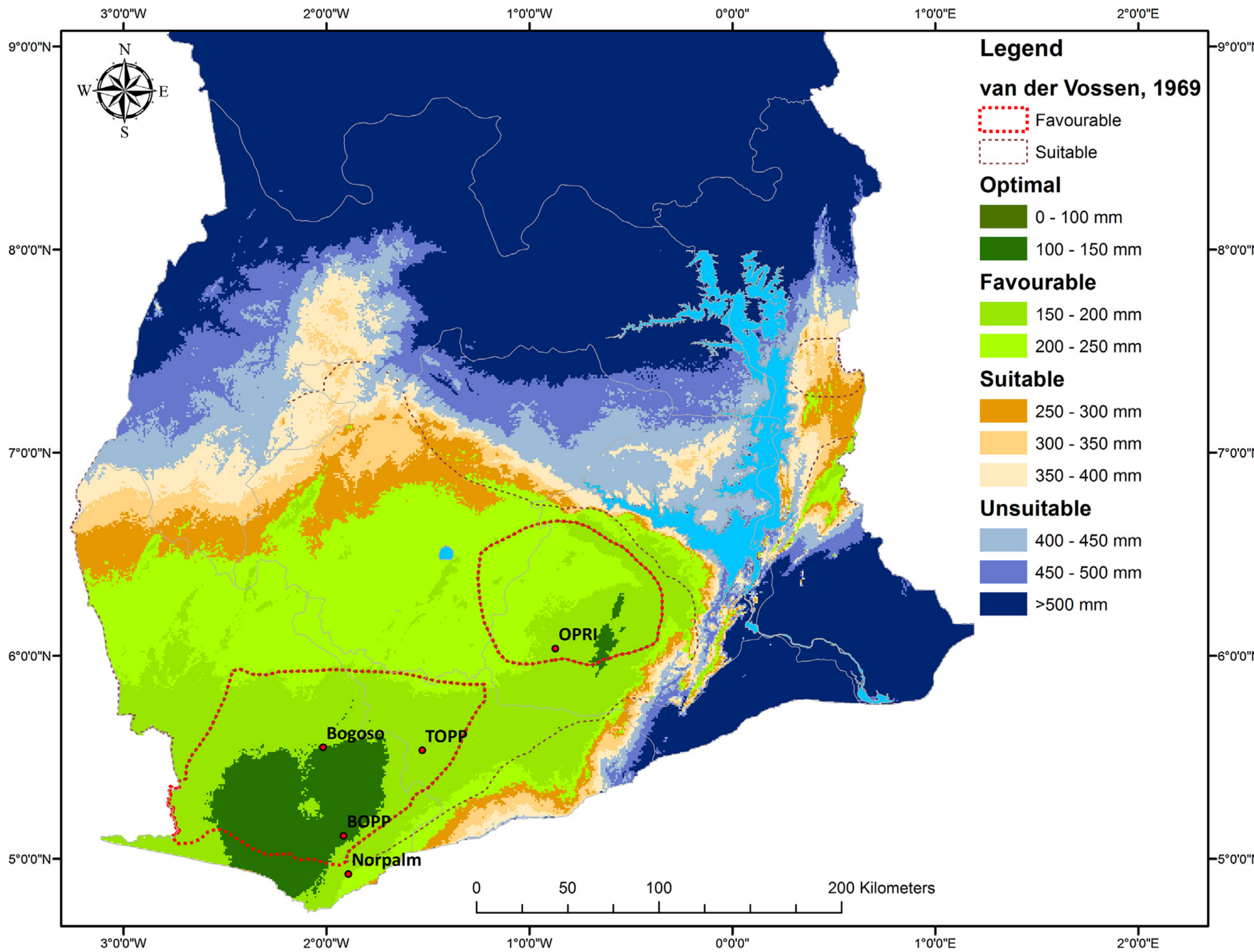

Fig. 1. Map of southern Ghana showing areas climatically suitable for oil palm production (≤400 mm year^{-1} water deficit) in steps of 50 mm water deficit, compared to suitable areas identified by van der Vossen (1969).

elevations >350 masl and have mean monthly minimum temperatures below 18 °C, which is the lower limit for oil palm (Table 1). We removed them from the area classified as climatically suitable (Fig. 2).

In the areas with suitable climate, estimated solar radiation was within the limits for oil palm (7–21 MJ m^{-2}) proposed by Paramananthan (2003) (Table 1). Slopes >20°, which occur around the edges of mountainous outcrops, are not suitable for cultivation of oil palm, and were removed from the climatically suitable areas. Hilly and undulating terrain with slopes 10–20° occur throughout the oil palm belt, mostly in the favourable and optimal climate zones.

When we excluded urban settlements and protected areas, the area suitable for oil palm production reduced with 9% to 6,720,000 ha. The reduction was mostly in the optimal area (-30%), where there are large areas of forest reserve and urban settlements (Table 3).

Few large, contiguous tracts of land remain available for oil palm within this zone. Areas of land suitable and available for expansion of oil palm in Ghana are shown in Fig. 3.

4. Discussion and conclusions

4.1. Suitability analysis

We used a simple approach to estimate the amount of suitable and available land for oil palm production in Ghana that can be used to guide investment decisions. The results provide a basis for discussion of the current large-scale expansion of oil palm in Ghana and underlines the importance of evaluating the climatic factors that determine the current and future potential production of oil palm.

Our assessment shows a larger area to be suitable for oil palm production in Ghana than identified by van der Vossen (1969). The observed differences are the result of different methods used to determine suitability, but also because of climate change. We were able to source more detailed climate, soils and topographical data than was available to van der Vossen (1969). Newer techniques (GIS), methodologies (calculation of ETP and AWC) and improved knowledge of the effects of environmental parameters on oil palm production also help to explain the observed differences. To enhance, but also verify the suitability assessment, crop modelling would be of great benefit to simulate and analyze crop responses to the various climate conditions.

In addition, meteorological data shows that the climate in the oil palm belt has changed over the past 40 years. Temperatures increased and there was less rainfall, which was more variable, throughout Ghana between 1960 and 2000. In our assessment, we used the WorldClim climate data derived from actual data for 1960–2000 (Hijmans et al., 2005) to take account of temporal variation.

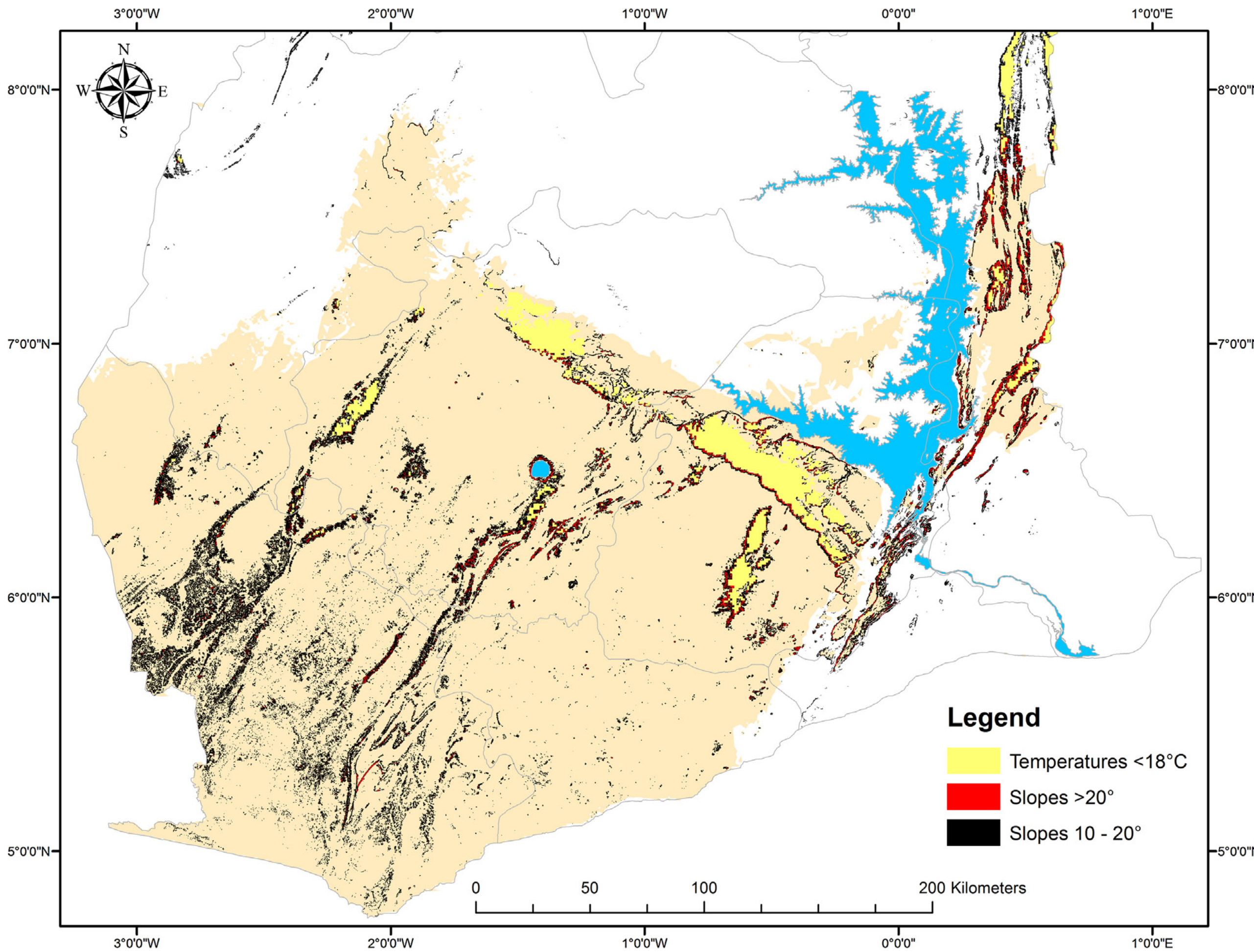

Fig. 2. Map showing areas with temperatures <18 °C and slopes >10° within the climatically suitable area for oil palm production in Ghana. Land with slopes of 10–20° are suitable for oil palm production, but land with slopes >20° is unsuitable.

Table 3
Reduction in the areas climatically suitable for oil palm production in Ghana after removing topographic and biophysical constraints, and urban settlements and protected areas.

Suitability class	Area								
	Climatic zones	Topographic and biophysical constraints			Protected areas	Urban settlements	Suitable and available land	Reduction	
		Temperature	Slope						
			10–20°	>20°					
	000 ha	000 ha	000 ha	000 ha	000 ha	000 ha	000 ha	000 ha	%
Suitable	7354	49	72	20	473	107	6720	635	−9
Favourable	5049	158	265	32	961	202	3786	1263	−25
Optimal	580	22	72	2.4	152	24	408	172	−30

4.2. Climate change and climate predictions in Ghana

The onset and the duration of the dry and rainy seasons and the annual rainfall varies from year to year and between decades (Stanturf et al., 2011). This is caused by variations in the movements and intensity of the ITCZ, which affects the timing and intensity of the West African monsoon. Overall, the climate in the oil palm belt in Ghana has become drier (i.e. decline in annual rainfall) and more variable (onset and duration of the dry seasons) since the 1960s, which were wetter than average (Manzanas et al., 2014; Owusu, 2009; Stanturf et al., 2011). In the late 1970s and early 1980s, annual rainfall decreased substantially but increased again from 1986 to 2000. During this period, there was less rainfall and fewer rain days per month during the short rains and at the beginning of the long rains, whilst there was more rainfall during the short dry season (Owusu, 2009). Similarly, rainfall was greater during the main dry season, but decreased during the short rain season between 1974 and 2010 in the Ashanti region (Abdul-Aziz et al., 2013). Expert opinion confirms that rainfall has become more unpredictable, but previously dry months have become wetter.

Projected climate trends predict that mean annual rainfall will decrease further by the year 2050, while temperatures will increase. Mean annual rainfall is expected to decrease by ±10% and temperatures increase by 2.5 °C and 2.0 °C within the semi-deciduous forest zone, and rainforest zone respectively (Environmental Protection Agency (EPA) and Ministry of

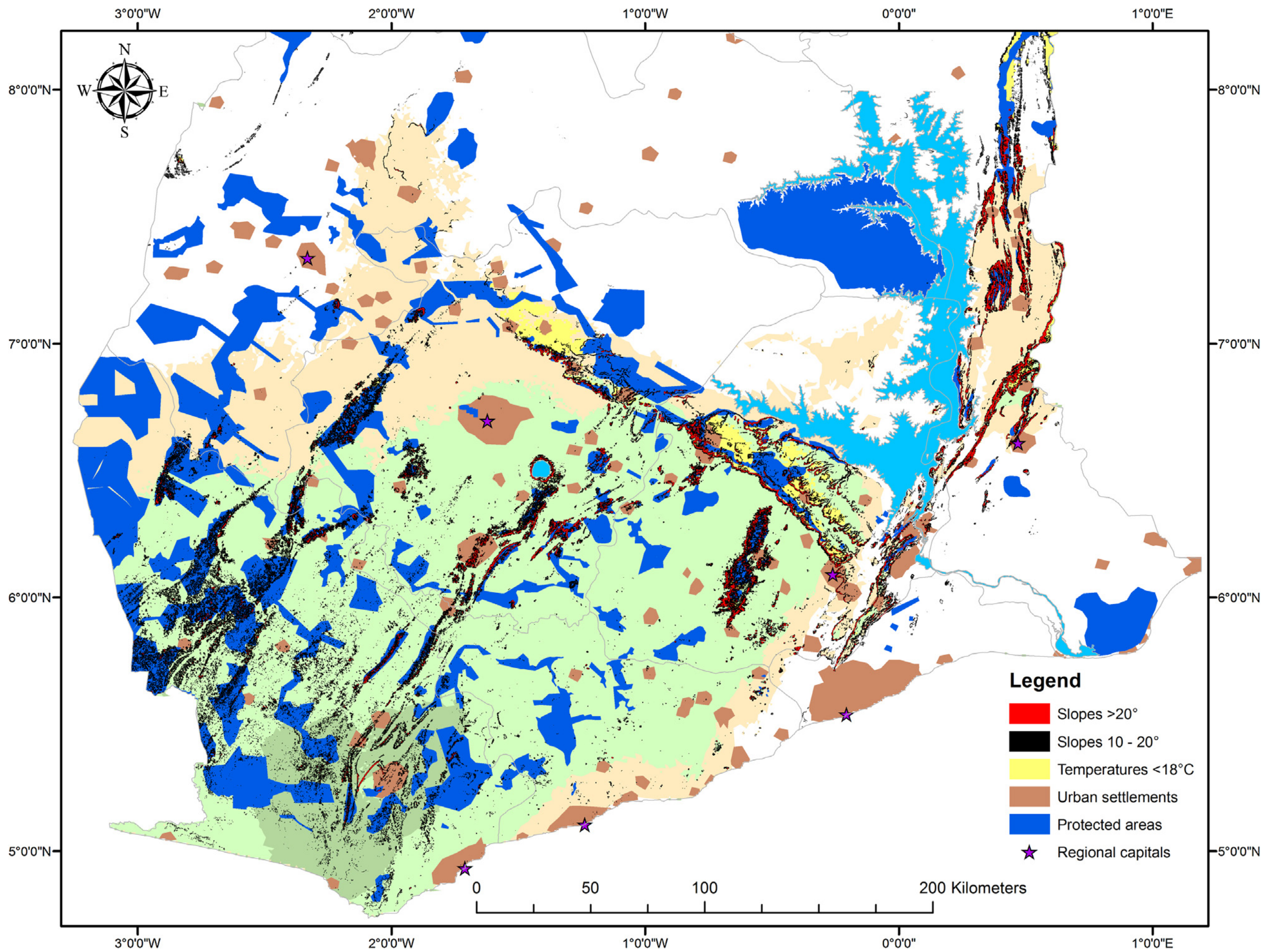

Fig. 3. Map of southern Ghana showing suitable and available areas with potential for oil palm expansion, after excluding urban settlements and protected areas.

Environment, 2011). By contrast, other workers predict that southern Ghana will become slightly wetter, especially in the coastal regions (Läderach et al., 2013). Total annual rainfall is predicted to increase by 20–30 mm year^{-1}, while the number of cumulative dry months (rainfall < 100 mm month^{-1}) is predicted to decrease from 4 to 3 months per year by 2050. Mean annual temperatures are expected to increase by between 1.7–2.1 °C in the southern (forest) regions, while mean daily temperature ranges are predicted to remain constant up until 2050.

The current and predicted changes in climate suggest that growing conditions for oil palm in Ghana will become more favourable. Although annual rainfall has decreased, it is distributed more evenly with less dry months (rainfall < 100 mm month^{-1}). Oil palm grows best where rainfall is distributed more evenly throughout the year with no water deficits (Corley and Tinker, 2003). An increase in temperature, on the other hand, will increase evapotranspiration and aggravate soil-moisture conditions during periods of drought. This might adversely affect oil palm production within the semi-deciduous and forest zones.

Weather data from the five production sites in Ghana showed large variability in annual rainfall and water deficits over a period of five years (Table A2). At the TOPP plantation, for example, annual rainfall was largest in 2010 with 1990 mm (annual water deficit 100 mm year^{-1}), and least in 2013 with 980 mm (annual water deficit 820 mm year^{-1}). A more accurate assessment of inter-annual variability on the water balance therefore needs to be taken into account to understand the dynamics of climate and its impact on oil palm production. The current WorldClim dataset does not allow for such an approach.

Evaluation of actual annual water deficits against the suitability assessment only resulted in an accurate prediction for the BOPP site. To test the validity of the current methodology, we need comprehensive climate data for sites across Ghana. These datasets are mostly lacking or difficult to find. This is mostly because of an inadequate number of meteorological stations for climate data collection. Also, much data that exists is not digitized and therefore not readily available (UNDP, 2011).

4.3. *Key constraints to the production of oil palm in Ghana*

Although oil palm originated in West Africa, the suboptimal amount and distribution of rainfall are major factors limiting its production (Corley and Tinker, 2003; Quencez, 1996). Oil palm grows best where rainfall is 2000–2500 mm year^{-1} and evenly distributed throughout the year with no months with < 100 mm rainfall (Goh, 2000; Hartley, 1988; Paramananthan, 2003). In Ghana, the rainforest and semi-deciduous forest zones therefore have the most suitable conditions for oil palm cultivation (Gyasi, 1992; van der Vossen, 1969). Based on our suitability assessment, three of the major plantations are located in the favourable growing areas in the southwest and east of the semi-deciduous forest zone. Only one major plantation is located in the rainforest zone within what we have defined as the optimal growing area. The opportunities to expand oil palm production within the optimal zone are likely limited due to competition from both large-scale mining and smallholder cocoa production. Smallholder farms and small-scale processing mills, on the other hand, are scattered throughout the entire oil palm belt.

In general, water deficit is the main constraint to oil palm production in West Africa (Caliman, 1992; Danso et al., 2008; Olivin, 1968; van der Vossen, 1969). Olivin (1968) found that average FB yields in oil palm plantations in West Africa correlated well with mean annual water deficit. In Ghana, Danso et al. (2008) found an almost linear inverse relationship between FB yield and water deficit. They concluded that availability of soil water is critical for oil palm production to be profitable.

Each 100 mm increase of water deficit reduces yields of FB by 10–15% (Corley and Tinker, 2003; Olivin, 1968). The reduction in yield can be as much as 40–50% if the palms were subjected to severe water stress in the preceding year (Caliman and Southworth, 1998). This emphasizes the need to explore the frequency and intensity of water deficits and the occurrence of drought as prerequisites to planning expansion of the area of oil palm (Caliman, 1992). Nevertheless, smallholders in Ghana grow oil palm in areas that we classify as unsuitable with mean annual water deficits up to 600 mm yr^{-1}. In areas with water deficits > 400 mm $year^{-1}$, no economic oil palm production can be expected (Olivin, 1968). These areas are considered to be unsuitable for oil palm in Ghana, except in areas where irrigation might be possible, such as the area surrounding Lake Volta.

Rainfall in southern Ghana is distributed bimodally, with long rains March–July and short rains September–November, separated by a short dry spell in August that is quite consistent across years. The dry season occurs between December and February, with less than 50 mm rainfall in January and less than 100 mm in both December and February (Table A2) (van der Vossen, 1969). The main period of water deficit, which occurs between November and March when radiation is high and rainfall is low, causes irregular distribution of palm yield. The extent of water stress within these months is considered the main yield-limiting factor for oil palm production in Ghana (van der Vossen, 1974). Across five sites in 2014, 50% of the annual crop from palms aged 7–15 years was harvested during the five-month period of the long rains. Only 23% was harvested in the dry season (Fig. 4). This imposes both logistical and operational problems, such as labour shortages during the long rains and underutilized mill capacity in the dry season.

Temperature does not appear to limit land suitability for oil palm in Ghana, except at elevations above 350 masl where monthly minima can drop below 18 °C. Cold-tolerant oil palm hybrids, such as produced by ASD de Costa Rica, are successful in higher, cooler elevations and provide a possible option to extend the area suitable for oil palm production (Chapman et al., 2003). Most higher elevations in Ghana are in mountainous areas with steep (>20°) slopes, which are unsuitable for cultivation.

Solar radiation was within the limits suitable for oil palm. After rainfall, it is considered the second most important climatic factor for oil palm. Whilst solar radiation is of course essential for photosynthesis, the oil palm's requirements, in terms of sunshine hours or photosynthetic active radiation (PAR) are poorly defined (Corley and Tinker, 2003; Paramananthan, 2003). Physiological models can be used to assess the effect of solar radiation on crop production (e.g., Hoffmann et al., 2014). Chan (1991) showed a decrease in yield of 4.8 t FB ha^{-1} $year^{-1}$ with a decrease in solar radiation of 1 GJ m^{-2} $year^{-1}$ for Malaysia. Lamade et al. (1996) reported an even larger effect of solar radiation on yield: only 0.73 GJ m^{-2} $year^{-1}$ more solar radiation in North Sumatra than in Côte d'Ivoire resulted in 13.6 t FB ha^{-1} $year^{-1}$ more yield. The authors mention that this large difference is likely partly explained by differences in rainfall and management practices between the two sites. Annual solar radiation measured at three sites in Ghana, Indonesia, and Guatemala for 2014 with similar meteorological stations is shown in Fig. 5.

Average annual solar radiation in Ghana is slightly lower than that received in Indonesia, with periods of high solar radiation in the dry season. Periods of high radiation coupled with a suboptimal water availability and distribution in Ghana undoubtedly lower the yield potential of oil palm compared with other oil palm growing regions (Hoffmann et al., 2014; van Ittersum et al., 2013). Further research is needed on the effect of solar radiation and its interaction with water on yield. While the amount of solar radiation sets the maximum yield potential of oil palm (Lim et al., 2011; van Ittersum et al., 2013), it is modified by other (climatic) factors such as rainfall and management. These factors need to be taken into account as well when assessing yield gaps. A useful parameter combining both water availability and sunshine hours is effective sunshine defined as the number of sunshine hours during periods of moisture sufficiency. Sparnaaij et al. (1963) found a strong positive and time-lagged correlation between total annual effective sunshine and annual bunch yield of mature palms 28–30 months later.

Slopes steeper than 10° occur throughout the oil palm belt, mostly in the southwestern rainforest, which is the optimal production zone. Oil palm is best planted on slopes <12°, but is sometimes grown on slopes ≤20°. On slopes exceeding 2°, substantial amounts of water are lost through runoff. This negatively affects the water balance and surface water flow can also cause severe erosion (Caliman, 1992). Careful management, including the establishment of legume cover crops and mulching with pruned fronds and empty fruit bunches is required to avoid erosion, and to conserve water. Other options include the installation of terraced planting and silt pits, which increase water infiltration and reduce soil erosion (Paramananthan, 2003).

Oil palm can be cultivated successfully on a wide range of soils, provided the soils are deep enough (> 50 cm soil) and properly drained (Paramananthan, 2003, 2011). Soil physical properties are more important than chemical properties because they are not easily changed by management and because they control the soil's ability to supply water to the crop. Where rainfall distribution is not uniform, soils with high water-holding capacity will be less affected by water deficits than those with low water holding capacity. In Benin, with rainfall less than 1200 mm and 4–5 dry months (Hartley, 1977), oil palm was viable because of the soils' high ASW content. In areas with only 100 mm water deficit, yields on a soil with low ASW can be half those on a soil with high ASW (Olivin, 1968). Soils that have high ASW content are therefore desirable to cope with West Africa's climates, but are limited within the oil palm belt of Ghana.

Poor fertility soils can be managed by applying mineral fertilizers and returning crop residues. We did not consider drainage criteria in the assessment, because most soils in the oil palm belt are well-drained. Landscapes in Ghana's oil palm belt are undulating to rolling terrain, with poorly-drained swamps in enclosed valleys that are difficult to drain. These pockets of poorly drained low-lying areas were not identified in the GIS assessment because the resolution of the raster grids was not fine enough to allow for an accurate analysis. The valleys have fertile soils with high ASW (Annan-Afful et al., 2005), and therefore have a high yield potential but often need costly drainage to prevent flooding and water-logging in periods of high rainfall (Rhebergen et al., 2014).

4.4. Opportunities to increase oil palm production in Ghana

The annual deficit in crude palm oil (CPO) will likely increase from 35,000 t to 127,000 t by 2024 (MASDAR, 2011) if current production levels are maintained. To meet the projected oil demand in Ghana, suitability mapping provides opportunities for area expansion into the most suitable lands for higher yields. In Ghana, land

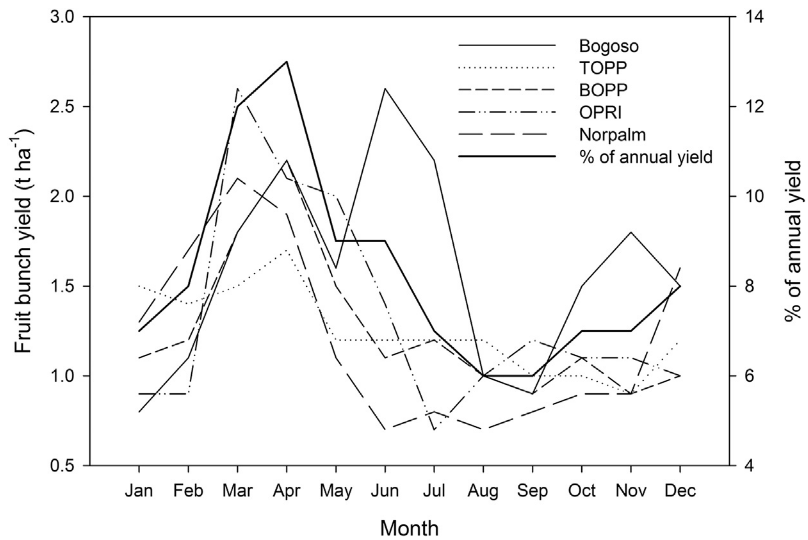

Fig. 4. Monthly average fruit bunch yields (t ha^{-1}) for 7–15 year old palms at five Ghanaian oil palm sites in 2014, and the average yield distribution (%) across all sites for 2014.

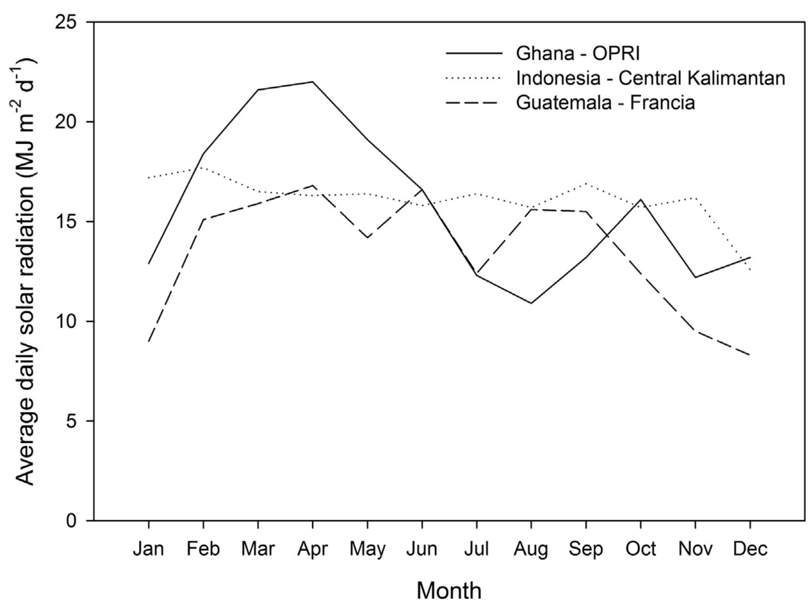

Fig. 5. Annual variation in monthly averages of daily solar radiation at oil palm plantations in Eastern region, Ghana, Central Kalimantan, Indonesia, and the Atlantic coast of Guatemala in 2014. Average annual solar radiation (in GJ m^{-2} $year^{-1}$) is 5.7 for Ghana, 5.9 for Indonesia, and 4.9 for Guatemala.

that is suitable for oil palm is found in the rainforest and semi-deciduous forest zones in southern Ghana, known as the 'oil-palm belt' (Gyasi, 1992; Quencez, 1996; van der Vossen, 1969). Suitable and available land is estimated at 6,720,000 ha. Although it is difficult to obtain accurate data, the total area currently under oil palm in Ghana is estimated at 330,000 ha. This is about 5% of the land area suitable and available to grow oil palm. About 40,000 ha (~12%) of this is managed in plantations, including smallholder and out-grower schemes linked to them. About 140,000 ha (~42%) is cultivated by independent medium- and small-scale farmers, and the remaining 150,000 ha (~45%) is found in wild oil palm groves (MASDAR, 2011; Ofosu-Budu and Sarpong, 2013). The minimum size for an oil palm plantation equipped with a 45-tph mill and an average annual yield of 18 t FB ha^{-1} is about 10,000 ha. The establishment of such a plantation is thus not only dependent on land suitability and availability, but also on milling technology. Whilst area expansion is possible for oil palm plantations, large continuous tracts of areas of suitable and available land are limited, particularly in the optimal growing zone. This land is possibly even more fragmented by other types of land-use that were not taken into account in the assessment. This includes for example land under cocoa and rubber production, but also annual crops, mining, high conservation value (HCV) areas (RSPO, 2013), and fallow land that is part of slash and burn agriculture. Moreover, land acquisition is further complicated by complex land tenure arrangements that prevail in southern Ghana that make it difficult for investors to acquire land for the development of large-scale plantations (Ahiable, personal communication). Such obstacles to land acquisition do not apply to the same extent, however, to the acquisition of smaller parcels of land (<100 ha) by local people. Due to the fragmented nature of available and suitable land, and increasingly complex land tenure with larger parcels of land, a feasible strategy for expansion is smallholder production. That is provided there are enough and efficient milling facilities available to process the fruit.

Alternatively, production in Ghana can be increased by improving productivity (Rhebergen et al., 2014). To identify entry points in improving yields, yield gap analysis (YGA) is a useful tool. YGA partitions yield gaps between different causes, such as environment and management, thus providing a systematic process to assess opportunities in increasing yields. Under good climatic conditions in Ghana, the maximum average attainable bunch yield is estimated at 25 t ha^{-1} (Rhebergen et al., 2014). With a country average bunch yield of 5.4 t ha^{-1}, current yield gaps are mostly the result of inadequate crop agronomic management, and poor crop recovery. Opportunities for increasing production can therefore be sought in improving current management practices. Yield intensification on land already planted to oil palm may therefore be an important policy for sustainable oil palm development in Ghana and West Africa. Adapting 'Best Management Practices (BMPs)' to local conditions can identity the management practices that are responsible for yield gaps (Donough et al., 2010). Improving agronomic management of existing palm stands shows considerable scope for yield intensification in Ghana which can alleviate pressure for further land clearance for new plantations.

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Appendix A.

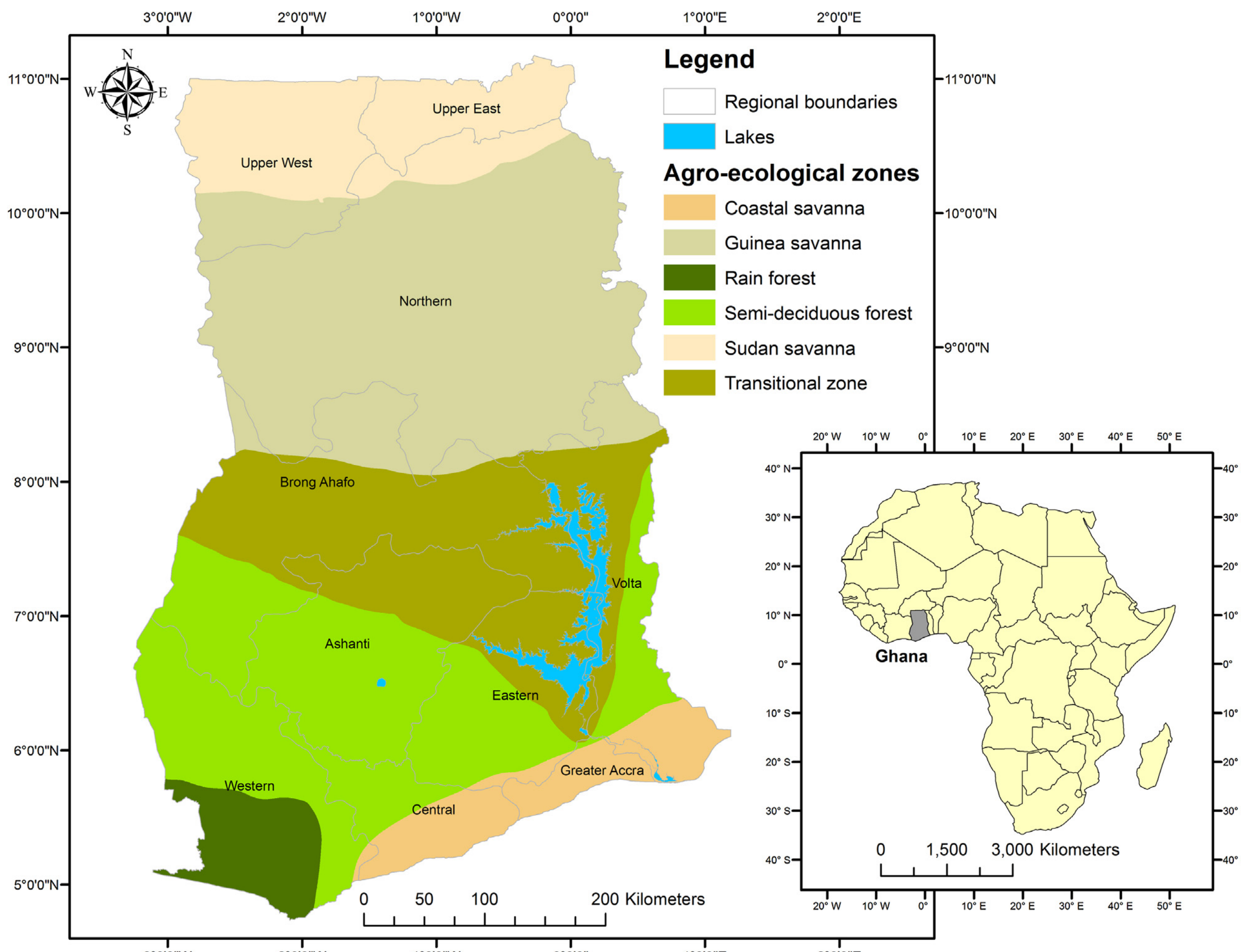

Fig. A1. Map showing six agro-ecological zones in Ghana.

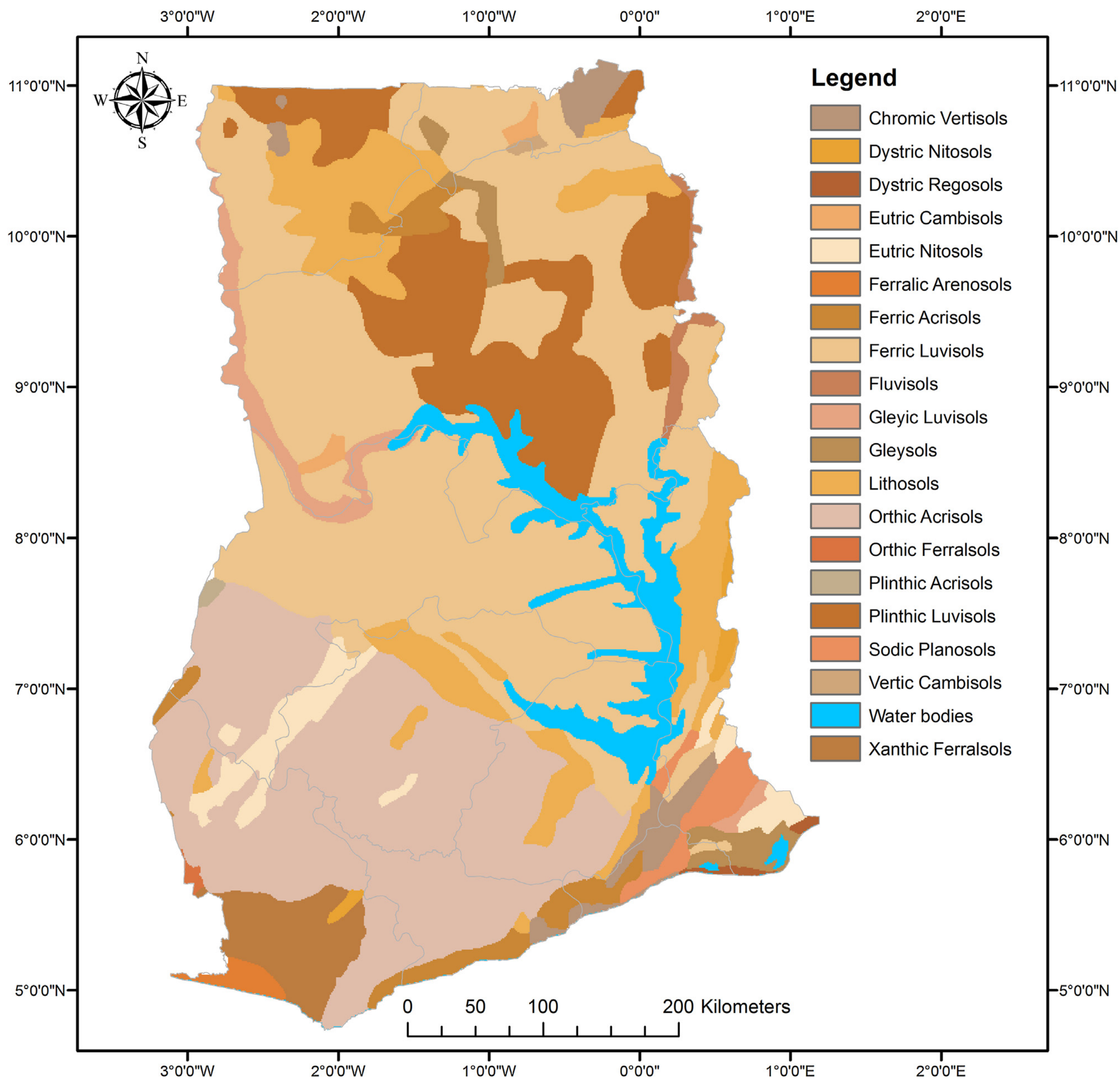

Fig. A2. Soil units of Ghana (FAO, ISRIC).

Table A1
Data sources.

Data	Variable	Unit	Format	Resolution	Period/year	Source
Protected areas	Protected areas	–	Shapefile	–	–	Protectedplanet; http://protectedplanet.net Accessed on 09/10/2014
Land cover	Agro-ecological zones	–	Shapefile	–	–	(Antwi-Agyei et al., 2012)
Urban extent	Urbanized places (places with 5000+ inhabitants)	–	Raster	30 arc-seconds (~1 km)	2000	NASA; http://sedac.ciesin.columbia.edu/data/set/grump-v1-urban-extents/data-download Accessed on 09/10/2014
Rainfall	Average monthly rainfall	mm month^{-1}	Raster	30 arc-seconds (~1 km)	1950–2000	WorldClim; http://www.worldclim.org Accessed on 29/08/2014
Temperature	Monthly min-, max-, and mean temperature Min temp of the coldest month Max temp of warmest month	°C	Raster	30 arc-seconds (~1 km)	1950–2000	WorldClim; http://www.worldclim.org Accessed on 29/08/2014
Elevation		M ASL	Raster	3 arc-seconds (~100 m)	2008	CGIAR; http://srtm.csi.cgiar.org Accessed on 29/08/2014
Soil properties	Soil texture	% Silt % Clay	Raster	30 arc-seconds (~1 km)	–	ISRIC; http://soilgrids1km.isric.org Accessed on 02/10/2014
	Soil type	unit	Raster	30 arc-seconds (~1 km)	2012	FAO; http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/ Accessed on 01/09/2014

Table A2
Average rainfall, rain days, water deficits (calculated using the method of Surre, 1968) and their standard deviation (σ) at five sites in Ghana from 2010 to 2014.

Site	Region and geo-reference	Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Bogoso	Western region	Rainfall (mm)	41	71	113	175	243	258	179	60	211	194	83	42	1670
	5°34′06.81“N	σ	*27*	*31*	*70*	*76*	*63*	*122*	*99*	*31*	*128*	*83*	*32*	*11*	*368*
	2°00′58.94“W	Rain days	4	8	10	12	19	16	16	14	20	20	14	4	157
		σ	*2*	*1*	*5*	*2*	*1*	*3*	*3*	*4*	*6*	*2*	*4*	*2*	*16*
		Water deficit (mm)	−70	−65	−23	76	193	253	198	62	147	173	73	−35	−193
		σ	*80*	*47*	*84*	*113*	*120*	*128*	*98*	*30*	*163*	*111*	*60*	*57*	*174*
BOPP	Western region	Rainfall (mm)	46	111	114	140	214	268	166	67	159	194	158	106	1743
	5°06′47.65“N	σ	*48*	*38*	*14*	*50*	*46*	*96*	*59*	*53*	*69*	*77*	*58*	*64*	*413*
	1°54′55.09“W	Rain days	2	6	6	7	12	12	9	6	11	12	10	6	99
		σ	*2*	*1*	*1*	*1*	*2*	*3*	*2*	*4*	*3*	*4*	*1*	*3*	*11*
		Water deficit (mm)	−58	−33	−29	−10	100	225	124	17	61	134	115	51	−131
		σ	*63*	*39*	*19*	*50*	*76*	*171*	*94*	*73*	*98*	*125*	*70*	*93*	*191*
Norpalm	Western region	Rainfall (mm)	32	34	56	117	220	335	107	44	127	132	98	65	1367
	4°55′26.84“N	σ	*28*	*18*	*29*	*56*	*109*	*90*	*44*	*29*	*74*	*49*	*29*	*34*	*261*
	1°53′31.54“W	Rain days	1	3	3	5	8	13	7	4	12	8	6	3	74
		σ	*1*	*1*	*2*	*2*	*3*	*2*	*2*	*3*	*7*	*3*	*1*	*1*	*6*
		Water deficit (mm)	−88	−110	−94	−33	96	302	96	−9	10	32	0	−60	−394
		σ	*65*	*19*	*29*	*56*	*124*	*152*	*34*	*56*	*88*	*75*	*60*	*36*	*185*
TOPP	Central region	Rainfall (mm)	40	41	62	138	201	290	140	84	122	225	92	44	1479
	5°32′40.10“N	σ	*24*	*30*	*43*	*97*	*98*	*112*	*38*	*62*	*96*	*66*	*83*	*27*	*368*
	1°31′12.38“W	Rain days	2	3	4	6	8	11	7	6	7	11	6	4	74
		σ	*1*	*2*	*3*	*3*	*3*	*2*	*3*	*2*	*5*	*3*	*3*	*2*	*19*
		Water deficit (mm)	−65	−92	−88	−12	95	235	135	60	49	159	57	−56	−314
		σ	*82*	*48*	*43*	*97*	*158*	*123*	*37*	*50*	*138*	*98*	*129*	*76*	*258*
OPRI	Eastern region	Rainfall (mm)	43	70	131	162	163	211	168	72	225	250	89	50	1634
	6°2′7.15“N	σ	*40*	*46*	*29*	*70*	*31*	*78*	*50*	*54*	*110*	*120*	*19*	*42*	*301*
	0°52′17.04“W	Rain days	3	7	10	9	13	16	12	11	15	18	15	6	135
		σ	*2*	*2*	*3*	*3*	*3*	*3*	*2*	*6*	*3*	*3*	*2*	*3*	*17*
		Water deficit (mm)	−47	−59	−8	34	91	176	173	69	185	225	96	−4	−118
		σ	*85*	*60*	*41*	*85*	*50*	*67*	*70*	*93*	*159*	*131*	*37*	*73*	*153*

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