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CLIMATE CHANGE AND AGRICULTURE RESEARCH PAPER

World climate suitability projections to 2050 and 2100 for growing oil palm

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SUMMARY

Palm oil (PO) is a very important commodity used as food, in pharmaceuticals, for cooking and as biodiesel: PO is a major contributor to the economies of many countries, especially Indonesia and Malaysia. Novel tropical regions are being explored increasingly to grow oil palm as current land decreases, whilst recent published modelling studies by the current authors for Malaysia and Indonesia indicate that the climate will become less suitable. Countries that grow the crop commercially include those in Latin America, Africa and Asia. How will climate change (CC) affect the ability to grow oil palm in these countries? Worldwide projections for apt climate were made using Climex software in the present paper and the global area with unsuitable climate was assessed to increase by 6%, whilst highly suitable climate (HSC) decreased by 22% by 2050. The suitability decreases are dramatic by 2100 suggesting regions totally unsuitable for growing OP, which are currently appropriate: the global area with unsuitable climate increased from 154 to 169 million km^2 and HSC decreased from 17 to 4 million km^2. This second assessment of Indonesia and Malaysia confirmed the original findings by the current authors of large decreases in suitability. Many parts of Latin America and Africa were dramatically decreased: reductions in HSC for Brazil, Columbia and Nigeria are projected to be 119 000, 35 and 1 from 5 000 000, 219 and 69 km^2, respectively. However, increases in aptness were observed in 2050 for Paraguay and Madagascar (HSC increases were 90 and 41%, respectively), which were maintained until 2100 (95 and 45%, respectively). Lesser or transient increases were seen for a few other countries. Hot, dry and cold climate stresses upon oil palm for all regions are also provided. These results have negative implications for growing oil palm in countries as: (a) alternatives to Malaysia and Indonesia or (b) economic resources *per se*. The inability to grow oil palm may assist in amelioration of CC, although the situation is complex. Data suggest a moderate movement of apposite climate towards the poles as previously predicted.

INTRODUCTION

Palm oil (PO) is an extremely important commodity. Oil palm (*Elaeis guineensis* Jacq.) is the highest yielding oil plant and PO is used in (a) cooking, (b) *c.* 30% of supermarket goods, (c) cosmetics, (d) pharmaceuticals and (e) biodiesel (Paterson *et al.* 2013): it is the most produced of vegetable oils (Villela *et al.* 2014). Demand for PO increased to 61·0 million tonnes in 2012/2013 and 6·2 million tonnes were used as biofuels in 2012. The high productivity of *E. guineensis* is enabled by adaptation to the tropical climate (Villela *et al.* 2014).

Oil palm is amongst the most in demand of crops (Paterson *et al.* 2015). The exponential economic development of Malaysia, the second largest producer in 2008 at 83 million tonnes, is linked to large-scale oil palm cultivation: the largest, Indonesia, produced 85 million tonnes. However, highly significant economic development in many equatorial countries derives from the PO industry (Margono *et al.* 2014). Indonesian PO production generated US$11.1 billion in 2010 and the country plans to double production mainly by increasing holdings in Kalimantan

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and Papua (Carlson *et al.* 2013). In the case of Malaysia, oil palm cultivation and PO production increased from $5{\cdot}4\times10^4$ to $4{\cdot}7\times10^6$ ha and $9{\cdot}4\times10^4$ to $1{\cdot}8\times10^7$ tonnes, respectively from 1960 to 2009. Exports increased from $2{\cdot}17\times10^7$ to $2{\cdot}24\times10^7$ tonnes from 2008 to 2009 (Paterson *et al.* 2013).

Indonesia and Malaysia remain the most important countries by far for oil palm production. However, land for expansion of cultivation is scarce: in Malaysia there are only $3{\cdot}0\times10^5$ ha remaining (Villela *et al.* 2014). The country has also pledged to decrease greenhouse gas (GHG) emissions, largely by reducing deforestation, and forest and peat-land degradation (Austin *et al.* 2015). In addition, issues concerning burning of forests and peat land are of great relevance (Marlier *et al.* 2015). Growing oil palm in Malaysia and Indonesia may become difficult as climate change (CC) progresses. Furthermore, there may be a pole-ward movement of *E. guineensis* to countries with currently sub-tropical climates (Paterson & Lima 2010, 2011; Paterson *et al.* 2013, 2015). High-quality information on the impacts of CC on oil palm is unavailable (Ghini *et al.* 2011; Paterson *et al.* 2013). Previous modelling studies focused on: (a) carbon accumulation rates of oil palm plantations (Germer & Sauerborn 2008), (b) economic aspects of oil palm cultivation in Malaysia and Indonesia (Abram *et al.* 2014), (c) impact of emissions from oil palm plantations on air quality and climate (Hewitt *et al.* 2009), (d) carbon sequestration and GHG emissions associated with oil palm cultivation and land-use change within Malaysia (Henson 2009) and (e) impacts of oil palm plantations on Brazilian land-use changes (Lapola *et al.* 2010), and did not consider climate suitability.

However, Paterson *et al.* (2015), employed (a) Commonwealth Scientific and Industrial Research Organisation Mark 3·0 (CSIRO-Mk3·0) and (b) Model for Interdisciplinary Research On Climate (MIROC-H) models to explore the impacts of CC until the years 2030, 2070 and 2100 on climate suitablility in the most important countries for PO production, Indonesia and Malaysia, which represented the first such study. These data demonstrated that suitability was unaffected by 2030, but was decreased dramatically by 2100 with highly negative implications for the industry in these countries and globally. The rest of the world accounts for 14% of the world's supply of PO and oil palm may be grown increasingly in other countries as suitable land becomes scarce and climate is unconducive to growth in these two countries. In addition, other nations will naturally produce PO to boost their economies, forming potential competitors to Indonesia and Malaysia. In general, 95% of existing plantations are located in a latitude range of 10° north and south of the Equator, restricting the plant to some countries in sub-Saharan Africa, Latin America and Southeast Asia. How will CC affect these other countries?

Many countries have plans to increase the amount/area of oil palm grown (Arrieta *et al.* 2007; Ohimain & Izah 2014; Paterson *et al.* 2015). Thailand (Chavalparit *et al.* 2006; Saswattecha *et al.* 2015) and Nigeria (Abila 2010) are novel PO-producing nations and the third and fourth highest manufacturers, respectively: the average yield of PO in Nigeria is $1{\cdot}3\times10^6$ million tonnes and the country produced biodiesel at $6{\cdot}0\times10^3$ litres/ha oil palm in 2007. The estimated potential biodiesel production in the same year was $1{\cdot}9\times10^{10}$ litres from $3{\cdot}1\times10^6$ ha cultivated land (Abila 2010). Furthermore, there are many instances of land being bought, or attempts made to purchase land, in Africa to reintroduce the plant, such as in Madagascar, where a large land acquisition for this purpose was unsuccessful. Columbia is currently the fifth highest producer and may soon be overtaken by Brazil, which has huge potential for land procurement for oil palm in the Amazon region (Villela *et al.* 2014).

Brazil's massive agriculture sector exemplifies how agriculture will expand further into production in tropical countries. Currently, Brazil is a minor producer and a net importer of PO, although it possesses deforested land with soil and climate currently suitable for oil palm cultivation, most of which is Amazonian. This amounts to twice that being employed worldwide. The area of cultivated land has doubled from 2004 to 2010 and is projected to grow even faster until 2015 (Villela *et al.* 2014). The Brazilian plans for oil palm may transform the Amazon region in Brazil and particularly the state of Pará, the largest producer (Villela *et al.* 2014). Also, research and production projects are employed in the states of Roraima, Amazonas, Rondônia and Mato Grosso. Hence, there are numerous initiatives in Brazil in relation to oil palm development which require consideration when discussing sustainability, where a continuing suitable climate is crucial.

The current authors utilized the CLIMEX modelling package to develop a model of the climate responses of oil palm using parameters slightly modified from those in Paterson *et al.* (2015). The modified values were for 'limiting low soil moisture', 'limiting high soil moisture', 'cold stress temperature threshold', 'cold stress temperature rate', 'degree-day cold stress

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rate', 'heat stress temperature rate' and 'dry stress rate' of 0·38, 2·3, 16, −0·006, 0·0006, 16 and 0·008, respectively. The semi-mechanistic modelling method CLIMEX (Sutherst *et al.* 2007*a*) models the relationships between distributions of a species, its growth patterns and climate. Empirically measured parameters together with point distribution records are used to fit models. As CLIMEX integrates generalized eco-physiological parameters, simple trait evolution may also be studied by changes in the parameters of the model, to match observations. CLIMEX may be described as a dynamic model, in that it integrates the population's weekly responses to climate into an annual series of indices. Furthermore, the model has been used to illustrate, amongst other things: (a) the potential distribution of *Lantana camara* L., (b) the distribution of Queensland fruit fly (Yonow & Sutherst 1998), (c) the modelling of pests (Sutherst & Floyd 1999), (d) the susceptibility of animal and human health to parasites under future climates (Sutherst 2001) and (e) the distribution of date palm under future climates (Shabani *et al.* 2012).

The distribution of species is defined crucially by climate exerting eco-physiological constraints. The various factors that influence this spread can be complex since the spatial scale may vary widely. Climate acts at a broad scale to limit the distribution of agricultural species such as oil palm: soil texture and nutrient content, as well as topography, may become significant at local scales and can be investigated using ecological niche modelling approaches. The ecological niche describes how an organism or population responds to the distribution of resources and competitors and how it in turn alters those same factors. It should be noted that the type and number of variables comprising the dimensions of an environmental niche vary from one species to another and the importance of particular environmental variables for a species may vary according to the geographic and biotic contexts. The impacts of non-climatic factors can be considered in a stepwise manner after the climate modelling has been completed using Geographical Information Systems (GIS; Shabani *et al.* 2014*a*, *b*, 2016; Paterson *et al.* 2015).

The CLIMEX model was used to project the potential distribution of oil palm under current and future CC for Latin America, sub-Saharan Africa and Asia and the results are reported herein, which represent the first such reports of global data. To make the comparison more straightforward, two future time periods (2050 and 2100) were selected. In addition, Paterson *et al.* (2015) indicated that 2030 was too soon from the present to show significant changes and 2050 was a useful compromise between 2030 and 2070. The year 2100 was used because highly significant changes were observed in Paterson *et al.* (2015).

CLIMEX is climate-based and does not cover other biophysical factors such as soil, vegetation cover and disturbance activities. Human inputs such as improved pest and weed management will also impact where a crop will grow; however, these aspects are not included in CLIMEX modelling.

MATERIALS AND METHODS

Elaeis guineensis distribution

The Global Biodiversity Information Facility (GBIF) (http://www.gbif.org/, accessed 9 November 2015) and additional literature on the species in CAB Direct (http://www.cabdirect.org/web/about.html, accessed October 2015), formed the basis for the collection of data on *E. guineensis* distribution. While the GBIF database returned 2851 oil palm records, 386 of these lacked the necessary geographic coordinates and were removed. Therefore, 2465 records were utilized in fitting the parameters. These records may be described as geographically representative of known distribution of the species (Fig. 1).

Climate data and future projections

For a comparison of the ability of mechanistic and correlative bioclimatic modelling methodologies, CliMond 10′ gridded climate data (Kriticos *et al.* 2012) was employed for the different methods, guaranteeing uniformity of data relating to climatic factors. CliMond 10′ records are based on the averages of different climatic parameters between the years 1950 and 2000 (Sutherst *et al.* 2007*a*), facilitating the modelling of current distributions of a species. Parameters of climate incorporated in the meteorological database are the mean monthly temperature maxima and minima (T_{max} and T_{min}), mean monthly precipitation level (P_{total}) and relative humidity at 09:00 h ($RH_{09:00}$) and 15:00 h ($RH_{15:00}$). The same parameters were also used to project the possible future climates.

Scenario of climate change

The current study used CSIRO-Mk3·0 and MIROC-H GCM global climate models (GCMs), and in

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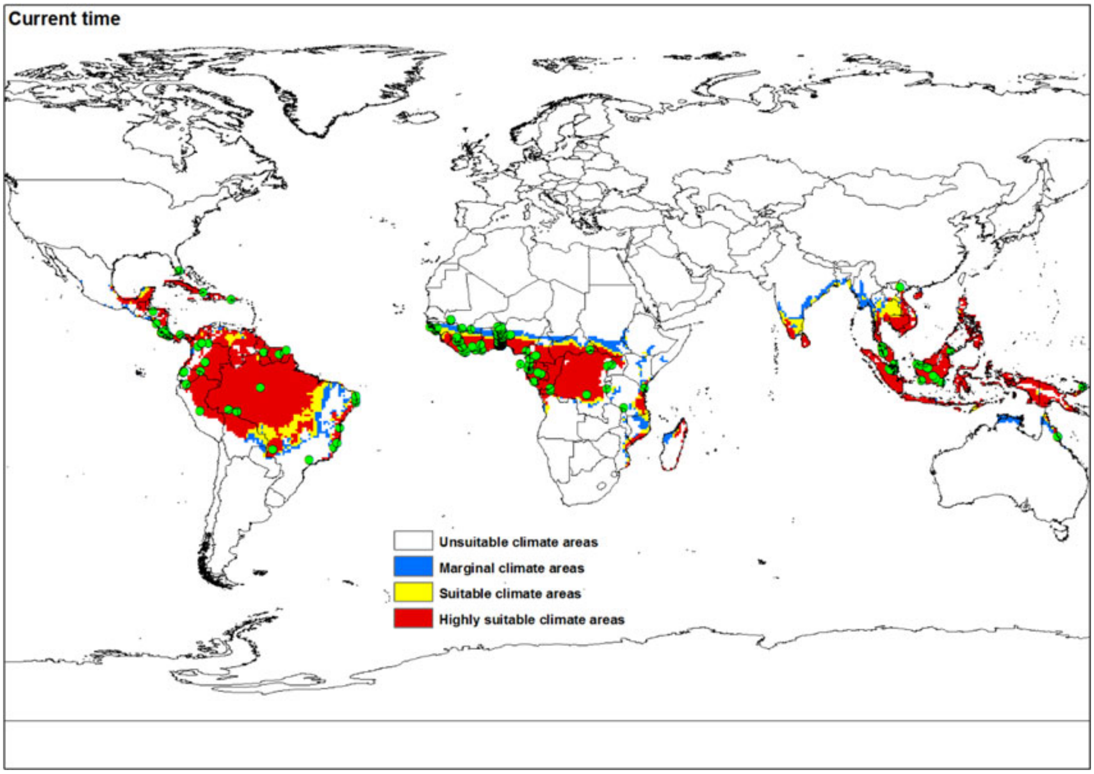

Fig. 1. Current worldwide suitability of climate for growing oil palm. The green dots represent existing oil palm occurrence. Colour online.

conjunction with the A2 Special Report on Emissions Scenarios (SRES) scenario (IPCC 2000), to model potential future distribution of oil palm. This scenario was selected because it incorporates economic, technological and demographic factors that impact on global GHG emissions (IPCC 2007; Shabani *et al.* 2015*a*, *b*). It includes various issues such as demography and the financial and technological forces driving GHG emissions. Moderate global GHG emissions are assumed compared with others such as A1F1, A1B, B2, A1T and B1 (IPCC 2000) by 2100. The projection date of 2100 was chosen since it assumes a moderately increasing GHG, set around the midpoint of lower- and higher-level projections.

CLIMEX, a mechanistic niche model

CLIMEX software supports ecological research incorporating the modelling of species' potential distributions under differing climate scenarios and assumes that climate is the paramount determining factor of plant and poikilothermal animal distributions (Sutherst *et al.* 2007*a*, *b*). CLIMEX enables users to determine geographically relevant climatic parameters describing the responses of an organism to climate (Sutherst *et al.* 2007*b*). Thus, it models mechanisms imposing limitations to the geographical distribution of a species and determines seasonal phenology and abundance (Sutherst *et al.* 2007*a*). Species growth potential in the favourable season is denoted by the Annual Growth Index (GI_A), while the impact of population reduction during an unfavourable season is established by the cold, hot, wet and dry Stress Indices and their interactions (Sutherst *et al.* 2007*a*). The Ecoclimatic Index (EI), the product of the GI_A and Stress Indices, rates the level of suitability for species' occupation of a particular location or year. The EI is thus an annual average index, derived from weekly data of the growth and stress indices of suitability levels of climatic factors, denoted by a value on the scale 0 to 100. A species may be established where $EI > 0$. The current research used CLIMEX to model present and future distributions of *E. guineensis*. CLIMEX output categorized areas according to high suitability, suitability and marginal suitability based on other studies through CLIMEX (Sutherst *et al.* 2007*b*; Shabani *et al.* 2012, 2013; Shabani & Kumar 2013, 2015; Castellanos-Frías *et al.* 2015).

In the present study, temperature index (DV0 = Limiting low temperature, DV1 = Lower optimal temperature,

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Table 1. *CLIMEX parameter values used for oil palm modelling*

Parameter	Mnemonic	Values	Reference
Limiting low temperature	DV0	19 °C	Hartley (1988), Paterson *et al.* (2015)
Lower optimal temperature	DV1	24 °C	
Upper optimal temperature	DV2	28 °C	
Limiting high temperature	DV3	36 °C	
Limiting low soil moisture	SM0	0·38	Corley & Tinker (2008), Paterson *et al.* (2015)
Lower optimal soil moisture	SM1	0·6	
Upper optimal soil moisture	SM2	1·6	
Limiting high soil moisture	SM3	2·3	
Cold stress temperature threshold	TTCS	16 °C	Goh (2011), Paterson *et al.* (2015)
Cold stress temperature rate	THCS	−0·006	
Minimum degree-day cold stress threshold	DTCS	20 °C days	Paterson *et al.* (2015)
Degree-day cold stress rate	DHCS	−0·0006/week	Paterson *et al.* (2015)
Heat stress temperature threshold	TTHS	36 °C	
Heat stress temperature rate	THHS	0·002/week	
Dry stress threshold	SMDS	0·4	
Dry stress rate	HDS	−0·008/week	
Wet stress threshold	SMWS	2	Corley & Tinker (2008), Paterson *et al.* (2015)
Wet stress rate	HWS	0·0023/week	
Degree-day threshold	PDD	1500	Corley & Tinker (2008), Paterson *et al.* (2015)

DV2 = Upper optimal temperature, DV3 = Limiting high temperature); moisture index (SM0 = Limiting low soil moisture, SM1 = Lower optimal soil moisture, SM2 = Upper optimal soil moisture, SM3 = Limiting high soil moisture); cold stress (TTCS = Cold stress temperature threshold, THCS = Cold stress temperature rate, DTCS = Minimum degree-day cold stress threshold, DHCS = Degree-day cold stress rate); heat stress (TTHS = Heat stress temperature threshold, THHS = Heat stress temperature rate); dry stress (SMDS = Dry stress threshold, HDS = Dry stress rate); wet stress (SMWS = Wet stress threshold, HWS = Wet stress rate) and Degree-day threshold (PDD) were fitted according to global distribution data, iteratively adjusted to achieve satisfactory agreement between known and projected species' distributions globally. Detailed justification of these parameters, and the manner by which they were obtained, are provided in Paterson *et al*. (2015). See Table 1 for CLIMEX parameter values used in oil palm modelling.

RESULTS

Current climate

The current climate in Latin America is appropriate over large areas and numerous countries (Fig. 1). Columbia has a large area of highly suitable climate (HSC) and many instances of oil palm occurrences. Approximately 65% of Brazil has HSC involving much of the Amazonian region and associated states and a considerable amount represents unsuitable climate, which is a broad region on the east coast. Some oil palm growth already occurs within Brazil (Fig. 1). The countries to the west and north of Brazil have large regions or whole countries with HSC, e.g. Venezuela, Guyana, French Guiana and Suriname (Fig. 1), and HSC is present in the lower altitudes of Ecuador, Colombia, Peru and Bolivia. Occurrences of *E. guineensis* are frequent in Guyana, Suriname, French Guiana, Colombia, Ecuador and Peru. Highly suitable climates are present in Central America, with large areas in countries such as Nicaragua, Costa Rica, Panama, Guatemala and in South Mexico, and island countries such as Cuba, Haiti and the Dominican Republic. The occurrence of the crop is frequent in Nicaragua, Costa Rica, Guatemala, Cuba and Puerto Rica.

There is a large area of HSC in Africa, extending east from Sierra Leone and Liberia in a wide band to almost all of DR Congo and the north of Uganda (Fig. 1). Highly suitable climate appears on the coasts of Tanzania stretching into Kenya, and Mozambique. Many of the other countries in this zone have HSC for almost all areas of the countries, although only *c.* 35% of Nigeria has the HSC rating. In Madagascar, HSC regions occur along approximately

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65% of a thin strip of coast. A large number of occurrences of *E. guineensis* are recorded in Africa (Fig. 1). Virtually all of Malaysia and Indonesia are currently highly appropriate, with numerous occurrences of oil palm (Fig. 1). The Philippines, Vietnam, Cambodia, Papua New Guinea, Sri Lanka and Chinese Hainan have HSC, while Thailand is designated as suitable climate. Highly suitable climates also exist in the south west of India. Finally, there is a small area of HSC in northern Queensland, Australia, with evidence of the plant's presence.

Decreases in suitability by 2050

Unsuitable climate was projected to increase by 6% and HSC to decrease by 22% globally by 2050 (Table 2; Fig. 2). The largest negative change was consigned to Latin America and especially Brazil and Columbia. For example, in Brazil, HSC was projected to decrease from 5 to 1·5 million km^2. A large decrease in suitability was observed visually in the Venezuela region and Central America in general (Fig. 2). The projected change was not as great in Africa as Latin America in 2050. However, the north of the currently large central HSC zone was reduced considerably by 2050 as was the HSC on the east coast: HSC in Nigeria was reduced on average by 70% by 2050 (Table 2). Merely suitable climate decreased from 14 400 to 3600 km^2 in Madagascar, although HSC increased from 72 000 to 123 000 km^2. Unsuitable climate increased for Indonesia by 2050 by an average of 47% (Fig. 2). There was a small decrease in HSC projected for Malaysia, but suitable climate increased by 100% (Table 2). There were large average decreases in suitable climate and HSC of 409 and 96% respectively in Thailand (Table 2; Fig. 2).

Decreases in suitability 2100

In 2100, the projected scenario is one of high decreases throughout most of the regions, with large areas of marginal climate and unsuitable climate predominating from HSC (Table 2; Fig. 3). Unsuitable climate increased from 154 to 170 million km^2 and HSC decreased from 17 to 4 million km^2 globally. Areas in the Americas that are currently HSC (Fig. 1) were almost all projected to be unsuitable by 2100 including in the Amazon region (Fig. 3). Unsuitable climate increased from 2 to 5·5 million km^2 in Brazil and HSC decreased from 5 million to 122 000 km^2. Unsuitable climate increased from 70 to 152 km^2 in Columbia and HSC decreased from 219 to 39 km^2. Also, there was a great reduction in appropriate climate in most areas of Africa although less so than

Table 2. *Percentage change in suitable or unsuitable area for growth of oil palm globally and in key countries for 2050 and 2100*

Country/global	2050	2100
Global		
Unsuitable	6·4	11·1
Marginal	52·4	61·1
Suitable	39·1	16·0
Highly suitable	−22·0	−267·6
Indonesia		
Unsuitable	47·3	36·1
Marginal	68·3	97·9
Suitable	61·7	95·6
Highly suitable	1·1	−100·0
Malaysia		
Unsuitable	0·0	−70·0
Marginal	0·0	100·0
Suitable	100·0	100·0
Highly suitable	−3·1	−270·5
Thailand		
Unsuitable	−32·3	70·1
Marginal	81·0	−19·1
Suitable	−409·8	−325·0
Highly suitable	−96·2	−825·0
Brazil		
Unsuitable	0·4	67·7
Marginal	72·0	61·6
Suitable	49·6	−303·4
Highly suitable	−163·1	−3957·6
Columbia		
Unsuitable	−17·5	61·2
Marginal	75·7	80·5
Suitable	94·1	36·4
Highly suitable	−55·5	−493·6
Paraguay		
Unsuitable	−29·9	−49·1
Marginal	−6·2	6·2
Suitable	64·9	69·3
Highly suitable	90·1	95·0
Nigeria		
Unsuitable	7·7	41·1
Marginal	13·1	−65·4
Suitable	10·0	−1025·0
Highly suitable	−70·6	−6800·0
Madagascar		
Unsuitable	−14·6	−17·7
Marginal	−27·5	−51·1
Suitable	−150·0	−166·7
Highly suitable	41·2	45·2

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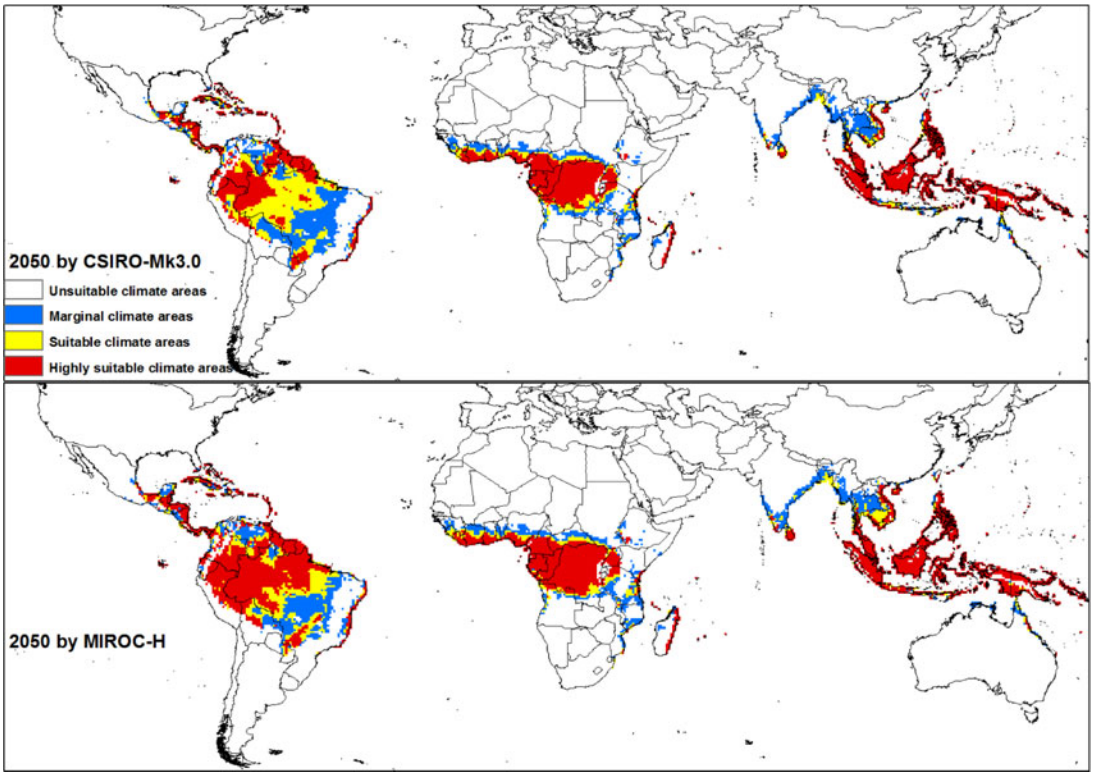

Fig. 2. Ecoclimatic Index suitability 2050 under the CSIRO-Mk3·0 and MIROC-H GCMs running the SRES A2 scenario. Colour online.

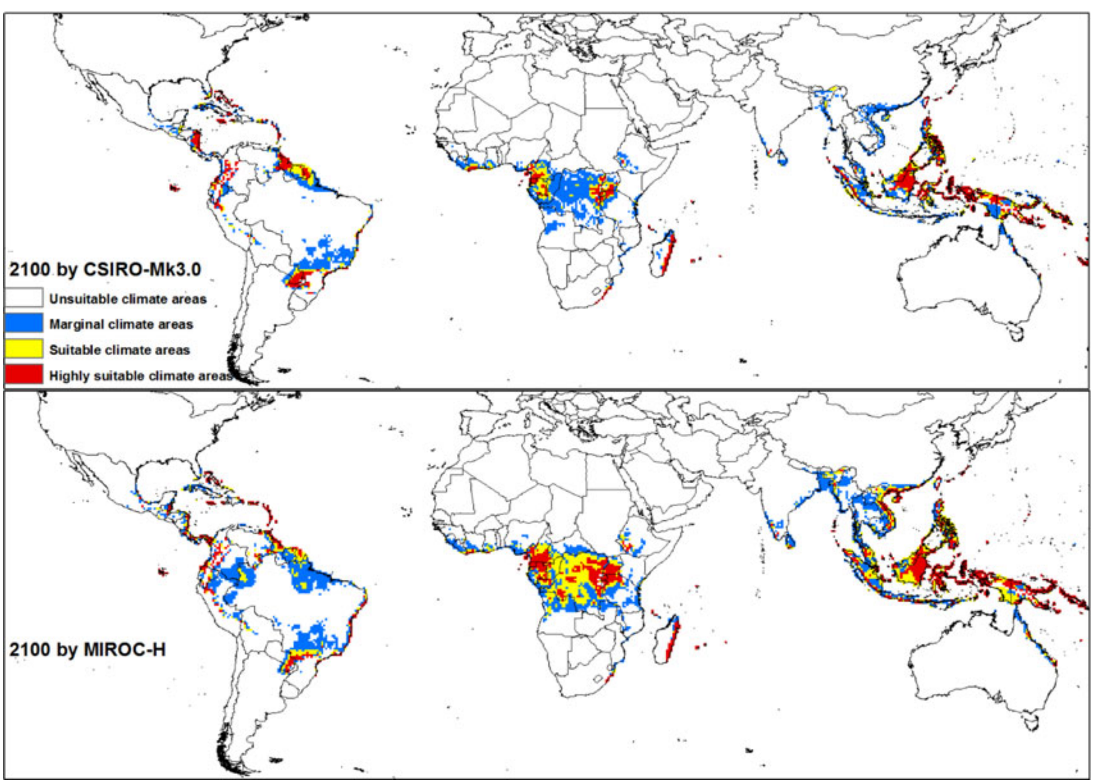

Fig. 3. Ecoclimatic Index suitability 2100 under the CSIRO-Mk3·0 and MIROC-H GCMs running the SRES A2 scenario. Colour online.

in the Americas. Unsuitable climate increased from 119 to 213 km^2 in Nigeria with extremely large decreases in HSC and suitable climate from 69 to 1 km^2. The aptness is dramatically reduced, especially in Sumatra and Java in the case of Indonesia (Fig. 3): HSC decreased by 100% whereas unsuitable climate increased, averaging 36·13% (Table 2). Decreases in HSC for Malaysia averaged 300 000 to 86 000 km^2 with increases in suitable and marginal climate from 0 to 140 000 km^2. Unsuitable climate area increased from 86 000 to 450 000 km^2 for Thailand and HSC decreased from 126 000 to 7000 km^2. In South India and Sri Lanka, the decreases in suitability were quite pronounced (Fig. 3).

Increases in suitability 2050

The unsuitable climate decrease was 30% in Paraguay: suitable climate and HSC increased by 65 and 90%, respectively (Table 2). The Bahamas, Nassau, the Turks and Caicos Islands and the other islands constituting this region were projected to become HSC. Florida in the USA appeared to become more appropriate, as did the islands south of Puerto Rico (Fig. 2). There were indications of an increase in Africa, especially towards the south and southwest of the main oil-palm-growing zone (Figs 1 and 2). Highly suitable climate increased in North Angola, Uganda in the north east and Sudan, while HSC increased by 41% for Madagascar; unsuitable climate decreased by 14% (Table 2). There were increases in marginal from unsuitable climate in Myanmar and Bangladesh (Fig. 2).

Increases in 2100

There were average increases in HSC and suitable climate of 95 and 69% in Paraguay with decreases in unsuitable climate of 49% (Table 2). Increases of HSC were apparent in North Argentina and the southern coastal states of Brazil by 2100 (Figs 1 and 3). The HSC increases in 2050 in Florida and the islands represented by The Bahamas and Barbados were not maintained by 2100 (Fig. 3). Areas where aptness increased were small in Africa but included a novel area of HSC in Eastern South Africa. There was a decrease in unsuitable climate in Madagascar from 425 000 to 378 000 km^2 and increases in HSC from 72 000 to 130 000 km^2, although suitable climate decreased from 14 400 to 3 600 km^2. The increases observed by 2050 in Angola, DR Congo, Uganda, Tanzania and Sudan were not maintained by 2100. The increases were less pronounced in Asia than in the Americas and Africa. Increases in aptness were further north in Bangladesh and in South China, and represent predominantly marginal climate with a little HSC. There was a further increase in suitable climate in Australia by 2100 (Fig. 3). There were no indications of a directly east/west worldwide increase in suitability compared with the north/south situation (Figs 1–3), and it was more a retreat from the western or eastern regions by 2100.

Climate stress

Figure 4 illustrates areas of climatic stress for 2050 and 2100. By 2050 there were projected to be few or no stress factors in the oil-palm-growing regions of Latin America, Africa and Asia. Also, India was projected to have no stress factors. Heat stress in particular was projected in South America by 2100. The dry and cold stress around Paraguay and North Argentina was reduced by 2100 (Table 2). Also, there was much more heat stress in Africa, although the cold stress towards more southerly regions had largely disappeared by 2100. The projected cold stress in South Africa in 2050 was much less by 2100. Interestingly, much of India was heat stressed by 2100. Cold stress in Bangladesh was much reduced by 2100 (Table 2; Figs 1–3). There was little indication of stress in other areas of Asia, except for cold stress in Papua New Guinea and Papua, Indonesia in 2050, which was not apparent in 2100. Heat stress appeared in Java by 2100. There was a great deal of stress of all climatic kinds in 80% of Australia, although in the north east there was none (Fig. 4).

DISCUSSION

This present work demonstrates clearly that the projections for suitable climate for growing oil palm will decrease in area by 2050 and more so by 2100 in many regions globally. However, there were limitations in the study that must be noted:

(i) The modelling was purely climate-based and did not take into account non-climatic factors such as use of land, type of soil, biotic interactions, competition and diseases;
(ii) Current broad-scale climatic data were employed, and thus results present purely broad-scale shifts;
(iii) Results are subject to the uncertainties surrounding future GHG emission levels;

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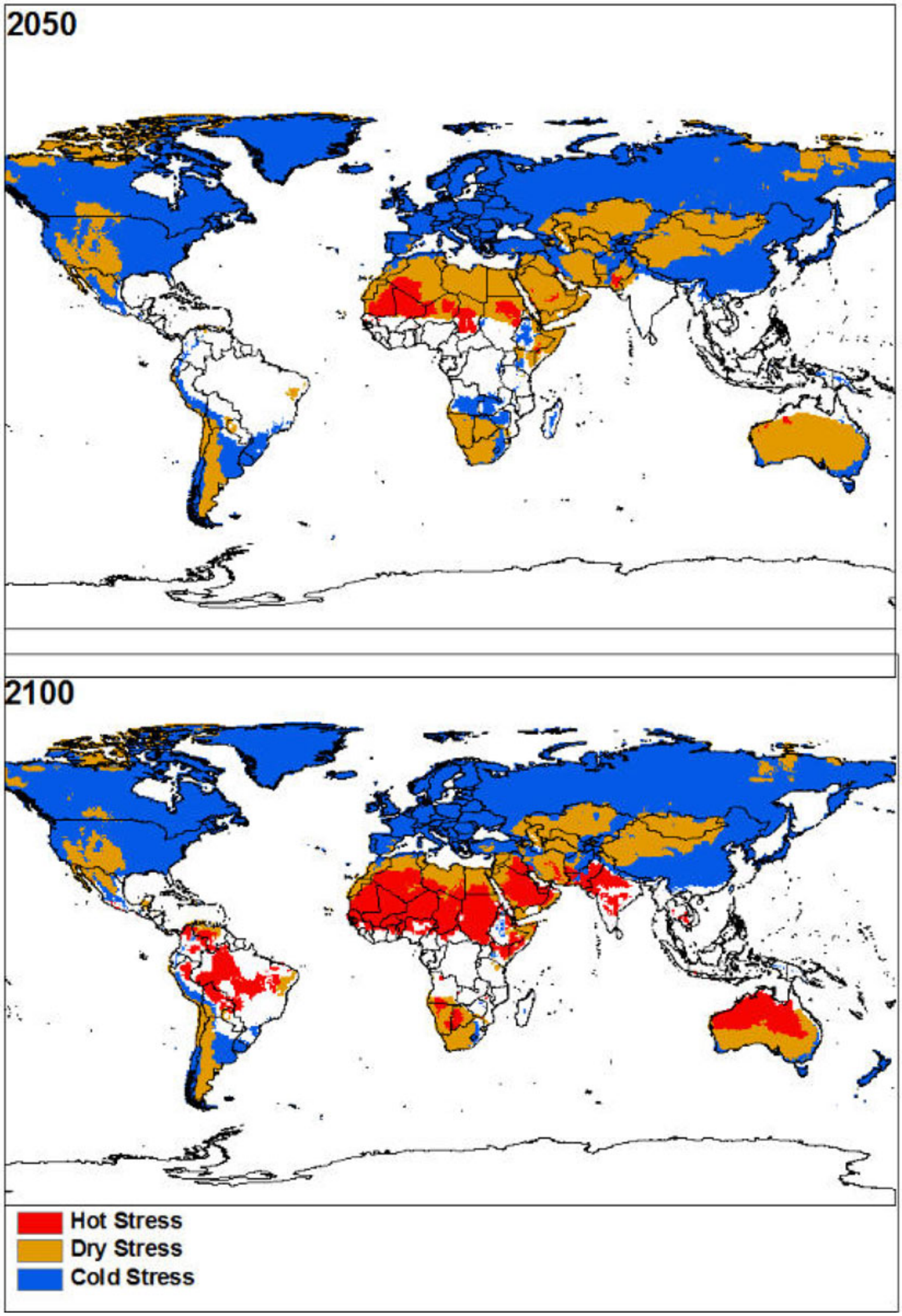

Fig. 4. Effect of hot, cold and dry stresses by 2050 and 2100 on future oil palm distribution. Colour online.

(iv) Similar modelling should be carried out for oil palm models using nitrogen, soil properties and irrigation; and

(v) Carbon dioxide (CO_2) enrichment and potential genetic progress were not taken into account.

Table 3. *Countries or regions where an increase in suitability of climate was observed, as indicated by a '+', between the current situation and (a) 2050 and (b) 2100 based on Figs 1–3*

	Climate suitability			
	Now-2050		Now-2100	
Country/region	HS	M	HS	M
Americas				
Paraguay	+		+	
The Bahamas; Nassau; Turks & Caicos; etc.	+			
Florida, USA	+f	+		
British Virgin Islands, Antigua and Barbuda, Barbados and Grenada	+			
Argentina			+	
Brazil (towards south only)			+	+
Africa				
Angola	+			
DR Congo		+		
Sudan	+	+		
Uganda	+	+		
Tanzania		+		
Madagascar	+		+	
South Africa			+	
Asia				
Myanmar		+	+f	+
Bangladesh		+	+f	+
China (south)		+f	+	+
Australia				+

HS, highly suitable climate; M, marginal climate; f, a faint increase.
A blank space indicates an increase in the particular climate parameter was not indicated by the data.

Nevertheless, the situation appears to become very severe by 2100 with dramatic losses in suitable climate, limiting the opportunities for growing in other areas to compensate for potential shortfalls in Indonesia and Malaysia. There is a severe reduction in appropriateness in Latin America in general. Some of the largest decreases in appropriate climate were in Thailand, Columbia and Nigeria, which are currently high producers of OP, implying that large changes in exisiting production will occur, although only 35% of Nigeria has HSC at present despite being the fourth largest PO producer. The projections indicate serious consequences to the economies of many countries and the PO industry generally, and that the climate will become unsuitable for growing oil palm in many tropical regions at a rate equal to, or faster than, Malaysia and Indonesia.

Pole-ward movement of climate

Paterson *et al.* (2013, 2015) and Paterson & Lima (2010, 2011) have suggested that there will be a pole-ward movement of crops, including oil palm, to accommodate changing climate, as it becomes less appropriate in the tropics. It is clear that the gains in suitability are far less than the losses, but are nevertheless interesting. Table 3 lists geographical areas that provide evidence of such developments. The various increases in suitability in the Americas may represent progress of appropriate climate towards the North Pole by 2050. The large increases in apposite climate in Africa by 2050 are surprising, and may indicate suitability for new plantations. The marginal climate zones in 2050 near Tanzania and Madagascar may represent movement towards the South Pole. However, in Sudan, Myanmar and Bangladesh the progression by 2050 is towards the North Pole.

The increases in South America, including especially Paraguay, by 2100 may represent development towards the poles of appropriate climate, although they do not compensate for the overall reductions. The HSC in Florida and in the representative islands of the Bahamas and Barbados indicated a movement of apt climate towards the North Pole by 2050, although this was not maintained to 2100. This may reflect the negative effects of CC between 2050 and 2100. On the other hand, the maintained increase within Paraguay until 2100 represents a persistent movement towards the South Pole, indicating this country is suitable for oil palm development within this period.

Increased areas of HSC in Madagascar and South Africa for 2100 may be indicative of a general movement of suitable climate to the South Pole. Many of the increases observed by 2050 in Africa that were not maintained until 2100 represent a temporary displacement of suitable climate towards the South Pole. On the other hand, the increase in acceptable climate in Sudan in 2050 indicates a change towards the North Pole, although again it was not maintained until 2100, reflecting the possible negative influence of CC during this period. The increases in Asia were less pronounced than in the Americas and Africa. However, increases in aptness in Bangladesh and South China may reflect a slight movement towards the North Pole and only the increase in Australia by 2100 represented a movement towards the South Pole within this region.

There are no indications of a directly east/west worldwide increase in suitability, which would be expected if the increases to the north and south were simply random. Hence, the increasing trend appears to be a genuine progress towards the poles.

Dry and cold stress

The dry and cold stress in the proximity of Paraguay and North Argentina was projected to reduce by 2100, perhaps explaining the increase in suitable climate for *E. guineensis* in these regions. Also, the cold stress towards more southerly regions of Africa largely disappeared by 2100, indicating suitable climate moving towards the South Pole as suggested in the previous section. The reduction of cold stress in Bangladesh by 2100 may explain the increase in suitable climate mentioned previously. There was little indication of stress in other areas of Asia, and in Paterson *et al*. (2015) there was a slightly greater indication of the three stresses in Malaysia and Indonesia, but they were not extensive. Correlating these stresses with climate suitability is not always absolute for various reasons such as complications from the length of the growing season, obligate vernalization and the fact that other stresses can have an impact, e.g. cold–dry, hot–dry, cold–wet and hot–wet amongst others.

Malaysia and Indonesia

The situation for Malaysia and Indonesia has been discussed in Paterson *et al*. (2015) using different CLIMEX parameters and the data presented herein are now compared. The 2030 data (Paterson *et al*. 2015) indicated a small increase in merely suitable climate from HSC in Java in 2030, which is similar to the 2050 data presented in the present paper, although a slight boost in marginal climate was also apparent. There was a general increase in marginal climate from HSC in Java for the 2070 data (Paterson *et al*. 2015), especially with the CSIRO maps, and there was more suitable climate over HSC in Kalimantan and Sumatra. This is consistent with an expected decrease in suitability from 2050 to 2070 and a more general reduction in suitability countrywide. There is a general similarity between the data presented in the present paper and those in Paterson *et al*. (2015) by 2100, depending to some extent on which representation is considered (i.e. CSIRO cf. MIROC). However, the large areas of unsuitable climate in the current data for 2100 were not apparent in Paterson *et al*. (2015), indicating the situation may be even less favourable than previously considered.

General

The data for distribution of date palm under CC in Shabani *et al*. (2012) are dissimilar to those presented herein. The Latin names of the two palms indicate that they are unrelated plants (i.e. *E. guineensis* and *Phoenix dactylifera*) and are likely to have disparate physiological and genetic characteristics. This is confirmed when the parameter values for the two are considered for the present paper and Shabani *et al*. (2012), where upper and lower growth temperatures, optimal soil moisture contents, etc. are different. In addition, the current distribution of the two palms contrasts with date palms being prevalent in, for example, the Middle East, Spain and Portugal and parts of the USA, where oil palms are missing. Conversely, oil

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palm covers a great deal of Southeast Asia where date palms are absent. Hence, the data provided in the present paper for oil palm provide unique insights into that crop.

There is a current dominance of soybean and tallow for biodiesel in Brazil, although long-term governmental scenarios indicate they will be overtaken by PO by 2030. The climate for the crop is projected to become increasingly unsuitable as indicated herein, and soybean and tallow production will themselves be affected by CC. Hence, it is difficult to speculate what the true situation will be in terms of new oil palm regions: perhaps oil palms will be grown more in Paraguay and possibly Argentina, where more suitable climates are projected in the present paper. The assumption is that Brazil will increasingly compete with Malaysia and Indonesia as their available land decreases (Villela *et al*. 2014), although this may not be possible according to the present data.

Paterson *et al*. (2015) concluded that the large reduction in the ability to grow *E. guineensis* because of CC in Indonesia and Malaysia may ameliorate the effects of CC, from reduced logging and burning of peat land: there will be less clearing of indigenous forests to grow oil palm and more of these trees will be available to provide a carbon sink hence reducing GHGs, because oil palm will not grow satisfactorily under the changed conditions. Peat is an even greater carbon sink than the indigenous trees and there would be reduced burning of peat to produce land suitable for oil palm. Hence, CC may be ameliorated. An argument against this possibility is that alternative crops may be grown on the land currently used for oil palm, meaning that forests and peat could still be cleared, but these other crops would also be subjected to CC and may grow poorly, reducing the pressure to clear land. Modified crops that could cope with CC could be considered if they become available, but all would grow better in other regions not currently in the tropics, leaving little incentive to grow in Malaysia and Indonesia. Increased logging of rainforests to compensate for the reduced ability to grow oil palm could occur. However, the rainforests would also be affected by CC and yields may become low, making logging unviable. Hence, the reduced ability to produce oil palm would tend to ameliorate CC, although the situation is multifaceted and impossible to predict accurately.

Similarly, the reduced ability to grow the plant in the Amazon as reported in the present paper may decrease pressure to clear the rainforest to produce oil palm, although the rainforest will be under threat in any case from CC. It is conceivable that *E. guineensis* provides a large carbon sink, but planting does not, in fact, compensate for the removal of the indigenous plants and would contribute to CC (Fargione *et al*. 2008; Danielsen *et al*. 2009; Ziegler *et al*. 2012; Austin *et al*. 2015; Busch *et al*. 2015). Most oil palm expansion in Indonesia has occurred at the expense of forests, resulting in significant GHG emissions and fires (Marlier *et al*. 2015). Indeed, the decrease of CO_2 emissions in the period from 2000 to 2012 is possibly due to the enforcement of a moratorium on deforestation. There may be a decrease in CO_2 emission if deforestation is decreased and conversely if it is increased for oil palm plantations then CO_2 will increase (Ramdani & Hino 2013). Ramdani & Hino (2013) demonstrated that in the Riau Province, Indonesia, the industry boomed in the period from 1990 to 2000, with transformation of tropical forest and peat land as the primary source of emissions, and so oil palm did not compensate as a carbon sink. Finally, the reduced ability to produce oil palm may ameliorate the effects of smog from forest fires and CC more generally.

CONCLUSIONS

The climate projections provided herein suggest that growing oil palms will be increasingly difficult at least until 2100 and especially in the five main PO producer countries. Developing plantations in other countries apart from Indonesia and Malaysia does not appear viable in the long term, despite some indication of movement of suitable climate to the Poles. The inability to grow oil palm may ameliorate the effects of CC as discussed above. Finally, severe economic consequences may result from any significant increase in difficulty to produce PO.

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