Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2020 doi:10.20944/preprints202012.0129.v1

Oil palm in the 2020s and beyond: challenges and solutions

Denis J Murphy[1*], Kirstie Goggin[1,2], R. Russell M Paterson[3,4]

[1] School of Applied Sciences, University of South Wales, Pontypridd, CF37 4AT, United Kingdom
[2] School of Pharmacy and Pharmaceutical Sciences, University of Cardiff, CF10 3NB, United Kingdom
[3] CEB – Centre of Biological Engineering, Gualtar Campus, University of Minho, Braga 4710-057, Portugal
[4] Department of Plant Protection, Faculty of Agriculture, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor D.E., Malaysia

*corresponding author: denis.murphy@southwales.ac.uk
Co-authors: kirstiegoggin@outlook.com; russell.paterson@deb.uminho.pt

Keywords: Oil palm, breeding, sustainability, certification, diseases, basal stem rot; *Phytophthora;* climate change, modelling; supply chains, biodiesel, covid-19

Abbreviations: BSR, basal stem rot; CVD, cardiovascular disease; FFB, fresh fruit bunches; GHG, greenhouse gas; GM, genetic manipulation (via transgenesis); IP, identity preservation; LCA, life cycle assessment (or analysis); Mt, million tonnes; ha, hectare; OP, oil palm; QTL, quantitative trait locus; RSPO, Roundtable on Sustainable Palm Oil; t, tonne.

Background
Oil palm (OP), *Elaeis guineensis*, is by far the most important global oil crop, supplying about 40% of total traded vegetable oil. Palm oils are key dietary components consumed daily by over three billion people, mostly in Asia, and also have a wide range of important non-food uses including in cleansing and sanitising products.
Main body
Oil palm is a perennial crop with a >25-year life cycle and an exceptionally small land footprint compared to annual oilseed crops. Oil palm crops globally produce an annual 81 million tonnes (Mt) of oil from about 19 million hectares (Mha). In contrast, the second and third largest vegetable oil crops, soybean and rapeseed, yield a combined 84 Mt oil but occupy over 163 Mha of increasingly scarce arable land. Despite this advantage, oil palm has acquired a poor environmental reputation, especially in Europe and North America, although soybean planting is now responsible for more deforestation. Oil palm crops face other challenges in the 2020s. On the demand side, these include changing consumer purchasing habits, threats to global trade systems, and diminishing demand for liquid fuels as transport systems become increasingly electrified. On the supply side, major issues include stagnant yields in ageing plantations, sluggish replanting of improved varieties, labour shortages, diseases and climatic/ environmental threats. The latter include the increasing incidence of new and existing pests/diseases and a general lack of climatic resilience, especially relating to elevated temperatures and increasingly erratic rainfall patterns. This review surveys the oil palm sector in the 2020s and beyond, its major challenges and options for future progress.
Conclusions
Oil palm crops face many future challenges, including emerging threats from climate change and new pests and diseases, that require more effective international collaboration.

Nevertheless, new breeding technologies are providing the promise of improvements, such as much higher yielding varieties, improved oil profiles, enhanced disease resistance and modified crop architecture to enable harvesting mechanisation. The industry also needs to redouble its efforts to engage with global consumers in a constructive dialogue aimed at addressing its image problem and explaining the many benefits of its products.

Introduction

Palms are highly significant to humans and to biodiversity (1). The African OP, *Elaeis guineensis*, is a member of the monocot order, Arecales, and is native to West Africa and is one of the world's most important palm species. The palm fruits, which are available year-round, have served as semi-wild food resources for traditional societies for >7,000 years, and the plant still has considerable significance to local people and for wider biodiversity (1–3). Cultivation of OP as a crop was originally an informal process mainly confined to its centre of origin in the West/Central African coastal belt between Guinea/Liberia and northern Angola (4). Globally, the best production levels of OP crops are achieved in the high rainfall areas in equatorial regions between 7° N and 7° S. During the 19th century, OP seeds were transported to the Dutch East Indies (modern Indonesia), and to the Malay States (modern Malaysia), as part of colonial ventures to grow new cash crops, such as rubber and cocoa, in the region. During the early 20th century, more systematic OP cultivation on plantations gradually became established in the Malay States. In terms of large-scale commercial production, however, OP is a relatively recent crop that only emerged into global prominence later in the 20th century, with an almost linear rise from 1990 to the early 2000s, followed by a plateau after 2007 (5). This was largely due to government initiatives in the 1970s and 80s aimed at improving the agriculture and economy of the newly independent nation of Malaysia (4,6). The subsequent rise of the OP industry in Indonesia occurred during the 21st century when there was a >5-fold increase in oil production from 8.3 Mt in 2000 to 43.5 Mt in 2020 (7). This was facilitated by greater political stability, relatively lax regulation often devolved to local authorities, and rapidly increasing global demand for palm oils.

Today, OP is crucial to the economies of many countries, especially Indonesia and Malaysia, from which large quantities of its products are exported in the form of oil, meal and other derivatives (8). More widely, OP is now cultivated in plantations across the humid tropics of Asia, Africa and the Americas, from where its products are exported to global markets. However, despite its increasing cultivation on three widely separated continents, the vast majority of OP is still grown in the two adjacent South East (SE) Asian countries of Indonesia and Malaysia (Table 1), that together generate about 85% of the entire global production (6,9–11). The major importing regions, collectively responsible for about 60% of total palm oil imports, are the Indian subcontinent (India, Pakistan, Bangladesh) with about 17 Mt, the EU-27 with 6.5 Mt, and China with 5 Mt (12). Smaller, but still significant, amounts of palm oils and/or their many downstream products are imported by almost every country in the world, meaning that OP can truly be described as a 'global' crop.

There are two contrasting types of oil found in the two principal tissues of palm fruits, namely 'palm oil' and 'palm kernel oil' (10). Palm oil, extracted from the fleshy mesocarp tissue, is a deep orange-red semi-solid fluid, whilst palm kernel oil is a white-yellow oil that is extracted mainly from the endosperm tissue of the kernel (seed). These two oils have very different fatty acid compositions (Table 2), which means they are used for different downstream applications in a range of industrial sectors (12). In general, the relatively high saturated fat content of palm

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2020 doi:10.20944/preprints202012.0129.v1

oil makes it particularly suitable for edible use as a solid vegetable fat (melting point ca. 35 °C). In contrast, palm kernel oil is a less dense product (melting point ca. 24 °C) that is mostly used for non-edible applications. A major application of palm kernel oil is as the key functional ingredient in many soaps, detergents and cosmetics. *E. guineensis* bear prolific numbers of oil-rich fruit bunches year-round, each containing between 1,000–3,000 individual fruits. Mesocarp-derived palm oil makes up about 89% the total fruit oil with the remaining 11% being derived from the seed or kernel. Because palm oil and palm kernel oil are extracted from fruits by different mechanical processes and have very different downstream uses, they enter separate supply chains immediately after extraction in mills.

Table 1. Major centres of global oil palm cultivation in 2020. Source: ref 11.

Rank	Country	Palm oil production	
		Mt	%
1	Indonesia	42.5	58.8
2	Malaysia	18.5	25.6
3	Thailand	2.8	3.9
4	Colombia	1.5	2.1
5	Nigeria	1.0	1.4
	Others	5.9	8.2
	Total	**72.3**	

Table 2. Principal fatty acid compositions of the nine major globally traded vegetable oils. Saturated fatty acids are in blue, monounsaturates in red and polyunsaturates in black. In each case, data reflect average vales from the main commodity varieties and do not reflect specialist niche varieties such as high-erucic rapeseed or high-oleic soybean oils. In 2019-20, the total production of these nine vegetable oils was about 204 Mt. Data from refs 14, 191.

Crop	% Global supply	Principal fatty acids						
		12:0 Lauric	14:0 Myristic	16:0 Palmitic	18:0 Stearic	18:1 Oleic	18:2 Linoleic	18:3 α-Linolenic
Oil palm (mesocarp)	35.5		1	43	4	40	10	0.3
Oil palm (kernel)	4.3	48	16	8	2	15	2.5	

Soybean	27.8			11	4	23	54	8
Rapeseed	13.4			4	2	60	20	10
Sunflower	10.4			7	5	19	68	
Peanut	3.0			12	5	48	30	
Cottonseed	2.5		1	24	2	18	54	0.5
Coconut	1.8	49	17	9	2	6	2	
Olive	1.5			13	2	70	13	0.6

In terms of annual production, the global OP industry is worth about US$ 60 billion, employing 6 million people directly and an additional 11 million indirectly. Most of these jobs are generated in rural areas where alternative employment can be scarce (13). Over 81.1 Mt of palm oils was produced globally in 2019-20, of which 72.3 Mt was mesocarp oil (hereafter referred to as 'palm oil') while 8.8 Mt was palm kernel oil (14). It is estimated that palm oil or palm kernel oil are present as ingredients in at least half of the products found in a typical supermarket. At least three billion people rely directly on palm oil as a regular part of their diet, and it is a staple cooking oil commonly used in African and Asian food preparation. As global populations increase, the demand for palm oil is likely to continue to rise (15). Estimates from various industry sources predict that between 93 and 156 Mt palm oil might be required by 2050 (16–18). However, these estimates do not consider the effect of climate change on production, which is likely to reduce ability of the sector to meet these demands unless there are substantial decreases in the magnitude of the forecast changes (19,20).

The above estimates of demand might also require adjustment depending on new factors that will operate in a post-covid-19 world (see final section for further discussion of this topic), but it remains likely that OP will continue to be a hugely important global crop, both in terms of food security and the provision of a wide range of renewable non-food products that also include animal feeds. These feeds are derived from the seeds or kernels, which contain a protein-rich meal that remains behind as a residue following oil extraction. Palm kernel meal is an often overlooked product of the crop, but is a useful livestock feedstuff that is exported globally (21). In 2019, about 7.6 Mt palm kernel meal was exported, almost exclusively (98%) from Indonesia and Malaysia. In order of importance, the major importing countries (75% of total 2019 imports) are the EU, New Zealand and Japan, where the meal is used in a variety of feed formulations, especially for ruminants.

The image of OP has been adversely affected by detrimental environmental consequences of its cultivation, especially with respect to deforestation and haze creation (22). There is also great public concern about the plight of iconic species and particularly the orangutan in SE Asia. However, deforestation and habitat loss is also associated the second most important global oil crop, soybean (23,24). The dramatic expansion of soybean cultivation in regions such as Amazonia has recently led to increasing scientific and public concerns about the ecological and health consequences (25,26), although these concerns have been more muted than for OP. Encouraging the use of oils with lower saturated fat content in ultra-processed foods may have a greater detrimental impact on the environment than palm oil, through further deforestation and loss of biodiversity. Policymakers may therefore need to consider ways to reduce the demand for oils more specifically and for unhealthy ultra-processed foods more broadly (13).

Rigorous scientific studies of the environmental and socioeconomic aspects of its cultivation are in their infancy, with Dislich et al (2017) being a notable exception. Such studies are fraught with problems due to the huge breadth, complexity, and interdisciplinary nature of the systems involved. These already formidable challenges are further exacerbated by the roles of vested interests from all sides of the debate. In some cases this leads to cherry picking of partial data from selected studies in order to substantiate already entrenched views. For example, many studies have focussed on sustainability parameters, such as water use efficiency, but only in OP systems. Such studies would be more valid if similar assessments of other crops were made in order to compile a comparative balance sheet of the plus and minus points of other cropping systems (e.g., soybean or rapeseed in the case of oil crops) in the context of environmental impact and sustainability. In this context, an important issue is that soybean and rapeseed are grown as normally rainfed crops in temperate climates where water availability can be limiting, especially in the summer growing season (28–30). In contrast, OP is normally grown in tropical regions with much higher year-round rainfall. For the major vegetable oil crops, the water footprints have been estimated at soybean oil 4200 m^3/t; rapeseed oil 4300 m^3/t; palm oil 5000 m^3/t; and sunflower oil 6800 m^3/t (29). This places OP in the middle part of the range, but it must also be set in the context of overall rainfall amounts, which are typically 250–300 cm/year in regions of OP cultivation (i.e., Malaysia and Indonesia), while summer rainfall in major soybean and rapeseed regions (the Americas and Europe, respectively) is only ca. 30–80 cm.

The dramatic increase in the use of palm oil for powering motor vehicles has been largely driven by a widely criticized EU policy originally devised to encourage use of renewable biofuels. This policy was launched with the laudable objective of reducing non-renewable fossil fuel consumption but has had the unfortunate (and presumably unforeseen) consequence of increasing overall demand for OP crops, hence accelerating the conversion of pristine tropical land to OP plantations. By diverting palm oil towards biofuel use, it has also reduced edible oil supplies and increased prices in a way that mainly impacts on poor people in Asia (31). Despite a recent rethink on the mandatory EU renewable fuels targets, palm oil continues to be imported in huge quantities for biodiesel use via a subsidy mechanism that is distorting other aspects of the supply chain, especially for edible and oleochemical markets, leading to increased prices across the board (9). The future prospects for the use of palm oil as a biofuel are discussed below.

In the remaining sections of this review, the current status of the global OP industry will be outlined, followed by an assessment of its environmental context and the management of pests and diseases, together with responses to abiotic stresses including newly emerging climatic factors plus recent progress in breeding and biotechnology for key traits such as oil yield and quality. Moving downstream, the operation of palm oil supply chains is discussed including the important role of consumer sentiment in framing responses to perceived environmental, sustainability and health issues relating to the industry. Finally, the immediate and longer term impacts of covid-19 and future prospects for OP in a rapidly changing world are examined.

Structure of the oil palm industry

Modern commercial OP cultivation began in Malaysia in 1917 (32) and over 88% of palm oil is still produced by Malaysia and the two neighbouring SE Asian countries of Indonesia and Thailand (11). From 2001 to 2016 the expansion of OP plantations was particularly marked in this region with a 2.5-fold increase in Malaysia and a 4.2-fold increase in Indonesia (33) . Over the past decade, OP crops have also been grown increasingly outside SE Asia (20), as suitable land in Asia is becoming scarce and the changing climate is less conducive to cultivation. For example, there is only an estimated 300,000 ha of available land for palm expansion remaining in Malaysia (34), with increasing government prohibitions for environmental reasons on further encroachment onto either forest and peatland in Indonesia (19,20,35–38). Continuing increases in global demand over the past five decades have meant that the cultivation of OP has been widely regarded by many tropical countries as a method to boost their economies (20,39–41).

In SE Asia, the primary regions for OP production in Indonesia are Sumatra (36) and Kalimantan (42) while in Malaysia the peninsula was the historical centre, although considerable expansion has occurred more recently in Sabah and Sarawak. Due their climatic suitability, OP cultivation has spread to other SE Asian countries, especially Thailand and Papua New Guinea (4,43–45), with Myanmar and the Philippines in the initial stages of development (4,46,47). The OP is important to the economies of each of these countries. Due to its profitability, there are also significant OP industries in much of tropical Africa with Nigeria, Ghana, Ivory Coast, Cameroon, Sierra Leon, Benin, Angola, and DRC as the main producers (in that order) (47). However, in most cases the crops are used for local consumption, with Cameroon and Ivory Coast as the only major palm oil exporters (4). Nigeria is the fifth highest producer globally, with an annual 1·0 Mt, although this is dwarfed by Indonesia with 42.5 Mt and Malaysia with 18.5 Mt (11).

In the Americas, the first OP plantations were established in Honduras and Costa Rica and currently the largest industries are in Colombia and Ecuador, although Brazil is also expanding its production (4,46,48). South and Central America are considered excellent areas for OP development in terms of their theoretical ability to produce palm oil. There is well over 1.5 Mha of planted OP in Latin America and Brazil has the largest potential overall, although currently the leading producer is Colombia with an annual 1.5 Mt. Although the environmental consequences of increasing cultivation of OP require careful consideration (9), these countries could potentially increase their market share in a sustainable manner as land in Malaysia and Indonesia becomes less available (22). However, there are also major climate change constraints for a sustainable future industry both in the Americas (19,47) and Africa (47).

A common misconception about OP is that it is only a ‘big business’ crop. In fact, smallholders account for between 30 and 40% of global land palm oil cultivation (49,50). In SE Asia there are more than three million smallholders, nearly all of whom farm individual family-owned and managed plots of less than 50 ha and often as little as 1-2 ha. In Indonesia, which is the largest OP producing country, smallholder plots account for 40% of the total crop area, where they only produce 30% of total output (51). However, although the larger commercial plantations tend to be more efficient in terms of oil yield and overall economics, smallholder units serve important social roles in providing income and employment to rural populations

(9,51). Smallholder units are also more likely to supply palm oil for local consumption rather than for export. This is particularly true for parts of Indonesia and Africa where the crops can be regarded as key elements in local food security and economic wellbeing (52). Interestingly, there is also evidence that smallholdings can have lower environmental impacts (53) and higher biodiversity levels (54) than commercial plantations. The relative profitability of OP versus other crops, such as rice, has encouraged many rural farmers to switch cultivation in regions such as Borneo (9,52,55). Studies in Sumatra, Indonesia have shown that smallholders switching to OP from alternative crops such as rubber and rice, benefit from as much as 17% higher levels of total household consumption (52,56). In South America, many of the newly established OP plantations that are located in former coca-growing regions of Columbia and in similarly marginalised post-conflict regions in Peru are also run by smallholder famers (57).

In contrast, commercial plantations tend to be part of large ventures that are often owned by multinational companies that can extend over tens of thousands of hectares with the largest totalling about one million ha. These plantations employ large numbers of workers for what is still a labour-intensive and largely unmechanized industry. For example, in Malaysia about 500,000 low-skilled and mainly overseas migrant workers are involved in producing 19 Mt of palm oil in commercial plantations. This is in addition to about 300,000 indigenous smallholder farmers and indicates the importance of OP as a contributor to basic rural livelihoods and to the wider more globalised economy of its host countries (10). In terms of global trade, palm oils from commercial plantations are by far the most important contributors. In some cases, the larger plantation companies also own or control some or all of the key downstream elements in palm oil supply chains, that include refineries, shipping operations and distribution networks to processors and retailers in export destinations. As discussed later, this form of vertical integration could be important in facilitating the future emergence of identity preserved (IP) supply networks as part of efforts to ensure the status of 'certified sustainable' palm oil products for consumers.

In summary, OP cultivation is still highly concentrated in SE Asia but the focus of future expansion is likely to be elsewhere in the tropics, especially in West Africa and northern regions of South America. While the majority of exported palm oil is produced on large commercial plantations for global export markets, even these ventures employ over a million low-income workers, many of them migrants. Moreover, a substantial area is owned and run by smallholder farmers who number in the millions. Therefore, in contrast with the major oilseed crops, the OP industry is a hybrid of large scale, globally focussed, commercial farming and small scale production of a cash crop, often for local consumption.

The environmental context

Despite its importance for human nutrition, health, and hygiene, the OP sector has been the subject of considerable criticism in several parts of the world, mostly in Europe and North America, over the past decade. This has been mainly due to the environmental and ecological impacts of some of the more recent land conversions to OP plantations, especially in Indonesia. In many cases these have displaced pristine tropical habitats and affected iconic wildlife species, such as orangutan (58,59). The poor perception of OP is hardly surprising because, over recent years, much of the media coverage of OP has included bleak images of displaced wildlife (60) and burning tropical forests producing atmospheric pollution (known somewhat euphemistically as 'haze') and releasing huge amounts of greenhouse gases (GHGs) (61). This perception means that many people in the West have decidedly negative opinions about OP. In contrast, some groups in Asia have questioned the motives of certain anti-palm NGOs, which they see as threatening a key aspect of economic growth in the region and even as a form of neo-colonialism (62).

For example, the EU is the second largest global importer of palm-based oils and this demand from consumers has been one of the drivers of the expansion of its cultivation over the past few decades. Despite this, some of the most vociferous criticism of the OP industry on environmental grounds has come from Europe. One of the major issues is that this expansion has often (but by no means always) been at the expense of tropical rainforest. However, a recent publication in *Science* has emphasised the highly problematic issue of deforestation in Brazil to produce soy (24), so the situation with OP is not unique. Since 2000, increased global demand for biofuels and other non-food products (mainly from Europe), and for food (mainly from India and China), were the major factors behind the conversion of land in SE Asia (mostly in Indonesia) to OP cultivation. In Indonesia the area of OP cultivation more than trebled from 2.5 Mha to over 8 Mha between 2000 and 2014 (63). In some cases this has led to significant habitat loss and reductions in biodiversity (53,60). There have also been more general reductions in overall species biodiversity as complex ecosystems are replaced with simpler plantation systems that host fewer species, plus concerns about increased GHG emissions as land is converted (64).

One of the most important limitations in developing robust policies for a sustainable and environmentally sound OP industry is a lack of hard facts about the precise eco-social impacts of palm oil production and utilization from 'cradle to grave'. As an example, the following quote is from a 2015 study on ecosystem services provided by OP plantations:
"Our review highlights numerous research gaps. In particular, there are significant gaps with respect to information functions (socio-cultural functions). There is a need for empirical data on the importance of spatial and temporal scales, such as the differences between plantations in different environments, of different sizes, and of different ages. Finally, more research is needed on developing management practices that can offset the losses of ecosystem functions." (27).

An important tool used by policymakers to assess the impacts of a particular cropping system is life cycle assessment (LCA) (65–67). This method seeks to estimate the impact of all aspects of the production process from planting seed, growing, harvesting and processing the crop (including fuel and labour costs); application of inputs such as water, fertilizer, herbicides, and pesticides; shipping of the oil overseas and downstream conversion into products such as foods and oleochemicals; transport to wholesalers, retailers, and consumers; and finally disposal of all products at the end of their lifetimes. Unfortunately, very few published studies manage to cover the entire system 'from cradle to grave'. Despite these caveats, some useful LCA data are now emerging where OP is compared with some of the other major oil crops. Examples include a 2015 study, showing that the overall environmental impact of OP is comparable to, and sometimes superior to, temperate oil crops (66) and data from analyses of comparative water use efficiencies by Mekonnen and Hoekstra (68) and Sadras et al. (69). Many more such studies are needed in order to inform better public debate and future policy about the true environmental impacts of oil crops in general and OP in particular.

More research data are also emerging on the comparative ecology of OP plantations versus other tropical habitats, the wider impacts of land-use change, and possible effects (both ongoing and in the future) of climate change, including a balance sheet for GHG dynamics during conversion of forest or peatland to plantations. Examples include the High Carbon Stock Science Study that was set up by five major OP growers (Asian Agri, IOI Corporation Berhad, Kuala Lumpur Kepong Berhad, Musim Mas Group, and Sime Darby Plantation), together with Cargill and Unilever, to increase their commitment to sustainable palm oil (for details see www.carbonstockstudy.com). This group, which is jointly chaired by the academic John Raison and well-known environmentalist Jonathon Porritt, issued a draft report for discussion in 2015, in which they produce values for various environmental impacts and list a series of recommendations for future conduct of the industry. The utility of this approach has been highlighted by Deere et al. (70), who conclude that environmental certification and reduction of emissions due to forest removal and degradation can be applied alongside with conservation efforts to mitigate agricultural impacts on tropical forest carbon stocks and biodiversity

Two other recent studies examined the potential impact of land use and climate change on biodiversity in Borneo where a great deal of OP planting has occurred during the past decade (71). Recommendations from these and other studies include the need to establish nature reserves in upland areas where climate change will be less severe and also to improve connections between reserves and plantations via wildlife corridors (72). One of the most controversial aspects of new palm cultivation in SE Asia is the use of tropical peatland, especially in Borneo. There are several ongoing studies of the impact of peatland conversion in terms of GHG emissions, and other environmental studies have been carried out in association with the Roundtable on Sustainable Palm Oil (RSPO). Examples include: (17,61,73–77). A review of several studies of the climatic effects of the conversion of peatland to OP plantations has also revealed inconsistencies and contradictions in some of the previous work, mainly due to differences in methodology and interpretation (78).

While there are clear negative climatic impacts of peatland conversion to OP, their magnitude remains unclear and it is important that such studies also take into account the mitigation of GHG emissions and the wider socioeconomic context of such land conversions (79). More studies by independent groups will be necessary in order to generate sufficient data for future meta-analyses that could provide robust policy options for the exploitation (or not) of peat soils. Other studies, including the systematic analysis of tropical peat soils (80), have demonstrated an unexpectedly complex picture with several different categories of peat, some of which can more readily support OP crops than others.

The conclusion is that it is not appropriate to impose blanket bans on the use of all peat soils for OP cultivation but rather to survey the soil first before making a better informed decision. Other studies suggest that limited OP expansion is still possible on already degraded land, without the need to convert mature tropical forests (37,81) and that smallholdings may have lower environmental impacts than commercial plantations (53). Despite these caveats, there is considerable pressure for governments to impose much stricter controls, and even outright bans, on the conversion of tropical peatlands and non-degraded forest to OP. Although there have been encouraging statements along these lines from politicians in the two major producing countries, these remain largely aspirational at present and more effective action is urgently required.

Pests and diseases

OPs crops are affected by several economically important pests and diseases, of which several of the most serious will now be considered (4).

Basal Stem Rot

Basal stem rot (BSR) caused by the fungus, *G. boninense* (Fig. 1) (82) is a serious disease of OP, which can reduce yields by 50–80%. It has increased over the past two or three decades due to its spread from infection foci at a greater rate following repeated cycles of crop planting on infested sites. In Malaysia, BSR is often reported now in young plants and seedlings, whereas previously only mature OPs were infected. By the time the palms are halfway through their ca. 25-year economic lifespan, BSR can kill 80% of a stand. Furthermore, expansion of industrial OP cultivation began early in Sumatra, where *G. boninense* adaption to the environment is most likely to occur. This region contains the highest levels of disease, implying an association between the duration of OP cultivation and higher disease concentrations. BSR is found increasingly in inland peninsular Malaysia and in Sabah, and in some cases was at high levels in places where it had not previously been detected. BSR was also reported at high levels in OP grown on inland lateritic soils and peat soils, irrespective of cropping history, whereas before such soils had been disease-free. By the time of replanting (every 25 years), 40–50% of palms were lost in some fields, with the majority of standing palms showing disease symptoms. The disease level in Asahan, Indonesia also indicated a possible climate change-related event. This information indicates a trend for increasing BSR with projected climate change. However, the climate for growing OP is currently optimal and has been so for many decades. The increase in disease previously reported will be from increased virulence of the fungus, rather than a possible increased susceptibility of OP due to a less suitable climate.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2020 doi:10.20944/preprints202012.0129.v1

Figure 1. *Ganoderma boninense* basidiomata on oil palm stems. Images are from the authors' personal collections (DP & DM).

BSR may increase further by natural selection of more virulent strains (82). OP cannot adapt rapidly enough to develop resistance to these changes in pathogen virulence (83,84). The BSR pathogen has the ability to infect OP plants at a rate of as much as 80% incidence over half of its economic life span of about 20-25 years (4). *Ganoderma* is a variable genus with poorly defined species concepts (85) . The fungus will adapt to climate change more readily than OP via natural selection of more virulent strains (86,87). In Indonesia, BSR is less severe in Kalimantan than in Sumatra, probably due to younger crop rotations (19,35,42). In Thailand, national BSR incidence is relatively low with a reported rate of 1.53%, although it is more widespread in the south (see: https://www.plantwise.org/knowledgebank/datasheet/24924). In southern Thailand, BSR incidence may be influenced by proximity to peninsular Malaysia where the disease rates are also high (36). In Papua New Guinea, the incidence of BSR is not as high as in other areas of SE Asian, although rates of 50% have been recorded in some regions. An average of 25% infection is a plausible scenario for this country as the initial incidence is lower than in Malaysia and Indonesia. BSR incidence is probably low in Myanmar as the plantations are more recent and distances between them are large. Myanmar has a distinctly different climate to the rest of SE Asia and is less capable of growing OP *per se* (20).

Fusarium oxysporum *f.sp.* elaeidis

The disease caused by *Fusarium oxysporum* f. sp. *elaeidis* (Foe) results in acute and chronic wilt of OP particularly in Africa. A major outbreak devastated OP in West and Central Africa where it has a particularly high incidence (88,89). However, Foe in Malaysia and Indonesia is controlled by quarantine procedures, although native strains can infect OP *in vitro*. Avoiding introduction from endemic areas is essential to prevent Foe in regions where it is does not normally exist. However, importation of breeding materials from Africa is required to expand genetic diversity in Malaysia and Indonesia, implying a risk from infested seed and pollen.

Quarantine procedures in Malaysia and Indonesia are undertaken, although the risk of spread remains (90), especially because climate change may increase disease (83).

In the Ivory Coast, 20% of palms planted from 1964 to 1967 displayed vascular wilt symptoms, with some crosses at 70% (91). But from 1976 to 1983 vascular wilt rates of < 2% were observed and in the 1990s, it was difficult to find symptoms in plantations. These reductions were attributed to breeding for resistance. Cooper et al. (89) found that Foe infection of OP was frequent in Ghana with incidences of 10.4% and 8.3% and also detected the presence of *Foe* in ca. 11% of symptomless palms in plantations. A potentially sustainable method for control is breeding OP for *Fusarium* wilt resistance. Decades of selection and breeding for resistance occurred in Ivory Coast where 20% of palms planted from 1964 to 1967 displayed vascular wilt symptoms, with some crosses at 70% (91). Rusli et al. (92) demonstrated that Malaysian OPs were susceptible to infection by Foe strains from Africa.

Phytophthora palmivora

Phytophthora palmivora is a fungus-like oomycete and a notorious pathogen of OP, causing severe damage in Latin American countries, such as Colombia (4). The disease has recently devastated >30,000 ha in South West Colombia and >10,000 ha in the Central Zone and the rapid increase in the disease may be related to climate change (20). Acute and chronic forms are found, and it is possible that several different diseases have been described under one name. The acute forms are present in Colombia and Ecuador, with the chronic forms found in Brazil (4). *P. palmivora* disease of OP is unreported in Malaysia and/or Indonesia, although a similar spear rot of OP has been reported in Africa and Thailand, which may involve *P. palmivora*. Many other hosts for the oomycete exist in Malaysia and Indonesia (e.g. durian) and, in view of a recent extreme outbreak in Colombia, *P. palmivora* presents a potentially severe threat to Malaysian and Indonesian plantations (36). More assessments of infectivity are essential given that outbreaks of *P. palmivora* could cause severe problems for major SE Asian OP industries.

Other fungi

A variety of lesser fungal diseases also cause problems for OP (4). Bunch failure is used to describe OP fruit bunches that fail to develop from anthesis to harvest and the disease can be caused by the basidiomycete *Marasmius palmivorus.* Another basidiomycete, *G. philippii,* is highly related to *G. boninense*. *G. philippii* is a trunk rot of *Acacia* trees and is listed as a pathogen of OP (93). The species may become more frequently isolated from OP under climate change and is probably a white rot fungus as are so many species within the genus. *Phellinus noxius* is a basidiomycete, partially responsible for upper stem rot of OP, occurring together with *G. boninense* in some cases (4). *Haematonectria haematococca* has been implicated in spear rot of OP *in vitro*. Dry basal rot of OP is caused by the ascomycete *Ceratocystis paradoxa* (anamorph = *Thielaviopsis paradoxa*), which also has been implicated in OP fatal yellowing in, for example, Colombia. *Cercospora ealidis* is widespread throughout Africa and causes *Cercospora* leaf spot. It is infrequent in Asia and is primarily a disease of nursery seedlings and frequently carried forward to plantations where it can survive for a long time (4). *Glomerella cingulata* is responsible for anthracnose disease in OP, although it is not severe currently. All these are diseases of OP and it is important to assess how they will be affected by climate change as discussed in the next section.

Pests

In general, pest species of OP do not have as much impact on the crop as diseases, with the possible exception of the rhinoceros beetle, *Oryctes rhinoceros*, which has emerged as the major pest of OP in SE Asia since the 1980s. Although chemical insecticides can be effective, they are expensive, they can affect beneficial insects, and the target organisms may develop resistance. This has led to development of biocontrol strategies, the most effective of which are the deployment of two pathogens of the beetle, namely the entomophagous fungus *Metarhizium anisopliae* and the *Oryctes* virus (94). Both pathogens are specific to rhinoceros beetles and as such will not affect other insects. The *Oryctes* virus appears to be endemic in the beetle population, and deliberate augmentation can raise its infection levels to above 75%. The *Metarhizium* fungal spores can be applied to areas of infestation as a spray that is highly effective at controlling, but not totally eradicating, the beetles. The combined use of these and other natural pathogens of the rhinoceros beetle have the potential to reduce its harmful impact on the crop, while also minimising risks of resistance development.

With the projected increase in OP replanting over the next few years, it will be important to consider the wider release of such biocontrol agents into areas where the incidence of rhinoceros beetles is particularly high. These and other forms of integrated pest management are being investigated as primary options in plantations across SE Asia (95). The rapid expansion of high intensity commercial plantations in new regions such as West Africa and South/Central America, plus climatic changes, are likely to result in the emergence of new pests and pathogens. Therefore, it will be important for the public sector and industry to work together in developing improved methods of surveillance and early detection of such threats. In the next section, the potential effects of ongoing climatic change in OP growing regions that may result in higher incidence and lowered resistance to such biotic threats, plus the emergence of new pests and diseases, will be discussed (83).

Impacts of climate change

The potential impact and significance of climate change is well documented in the scientific literature and is increasingly acknowledged by the general public. Climate change threatens many ecosystems with much evidence of its impact on species distributions (47,96,97), Such alterations are manifested phenologically (98), physiologically (96), morphologically (99), demographically (100) and ecologically (101). In addition, the rates of extinctions will accelerate (102,103). Conservation scientists, managers and environmental policy makers need to adapt guidelines and policies to mitigate the impact of climate change (104) and procedures have been discussed for ameliorating the effect of climate change on OP and *vice versa* (22).

Climate change threatens the sustainability of crop production via factors such as rainfall and disease patterns (105), although the effects on tropical crops remain less well known, especially in SE Asia, Africa and Latin America (106,107). Some recent papers have begun to address the situation for OP (19,20,35,36,41,47,108). However, research on climate change in tropical countries remains patchy and studies covering large areas are lacking with data on thermoregulatory behaviours being absent for tropical lowland plants. This deficiency is a fundamental problem because tropical plants will respond differently to climate change compared to temperate plants. Tropical plants should be a priority since in many cases there are no available substitutes to replace declining species, leading to biotic attrition with potentially negative consequences to ecosystem functioning (109).

The effects of climate change are manifested by phenology as noted by Thackeray et al. (98), who suggested that future climate warming may further disrupt many ecosystems and services. Walsh et al. (99) reported morphological changes in the chipmunk related to climate change and concluded that anthropogenic climate change was having a significant impact on physical and biological systems globally. Rosenzweig et al (96) determined that demographic changes will occur in changed climates that are suitable for species growth. Other studies indicate high levels of ecological changes by the use of scientific inference (101). Most studies extrapolate correlations between current climate and species distributions to novel conditions and omit important biological mechanisms, including species interactions, evolution, landscape dispersal barriers, habitat degradation, and intraspecific trait variation. Conservation scientists, managers and environmental policy makers need to adapt guidelines to mitigate the impact of climate change (104). Procedures for amelioration have been discussed for OP (22) as partially based on CLIMEX models of Paterson et al. (41,47). Climate change effects on natural systems require prediction to mitigate consequential changes in diversity and ecosystem function (107).

Experiments, analogies and models were used when estimating future climate-related risks, vulnerabilities and impacts in the 2014 Intergovernmental Panel on Climate Change (IPCC) report (110). Models can be predominantly descriptive narratives of possible futures, such as those used in scenario construction. Also, they can be numerical simulations of real-world systems, calibrated and validated from experiments or analogies, and then run using data representing future climate. The quantitative and descriptive models are often used together in a complementary manner. Impacts are modelled, *inter alia*, for ecosystem services and agricultural productivity including diseases of crops. Poleward movements in plant species' climate-related range are by far the most reported (111) and Paterson et al. (47) reported this direction of change in suitable climate for growing OP.

Mapping of plant disease distributions influence biosecurity planning, specifying areas that qualify for eradication or containment. The CLIMEX model has been developed for current and future species distribution where knowledge about the effects of climate change on species distributions is essential in mitigating negative impacts (47). How species may react under climate has been reported. Paterson et al (47) determined the detrimental effect on the suitability of future climate on OP growth in a global setting. Ramirez-Cabral et al (112) indicated that large areas that are suitable for global maize cultivation will suffer from heat and dry stresses that may constrain production. Shabani et al. (113) determined the future distribution of plant pathogenic *F. oxysporum* and indicated that the climate would become more suitable for the fungus in the future in some countries threatening more infection of crops.

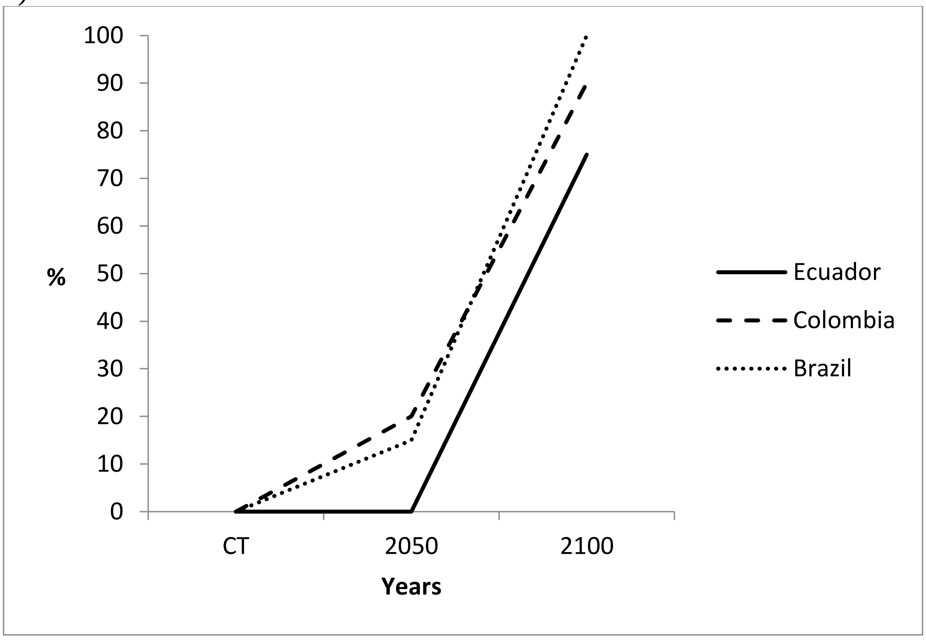
OP and climatic change

OP production creates climate change and this will affect detrimentally the ability to grow OPs and alter their distribution (22). OP is currently grown in optimal climatic conditions and has been for many decades (4,22,36,41,87,114–116). Koh and Wilcove (119) suggested that OP expansion occurs at the expense of forests acting as carbon sinks, which may also result in biodiversity loss. Dislich et al. (27) determined 11 of 14 ecosystem functions decreased in levels of function by the introduction of OP plantations. Fitzherbert et al (118) determined that OP plantations support many fewer species than forests and some other tree crops: Habitat fragmentation and increased pollution occur, increasing GHG emissions. The detrimental aspects of increasing numbers of OP plantations has been discussed in terms of deforestation and haze production from burning peat soil to clear ground for new plantations (27). These processes release GHGs contributing to climate change, which is an amoral situation (119). Climate change is likely to affect sustainable production of palm oil as the suitable climate for the palm will decrease (22,36,41,47,87,116), with the concomitant increases in economic and social problems in producing regions.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2020 doi:10.20944/preprints202012.0129.v1

Suitable OP climatic impact data were used to create schemes for OP mortality by postulating that large degrees of unsuitable and marginal climates in particular were likely to cause high amounts of OP mortality and *vice versa*. Also, reductions in highly suitable and/or suitable climate *per se* would not cause a significant effect on OP mortality. Simulation modelling and big data to determine suitable climate scenarios for growing OP (41,47), were employed herein to estimate how climate for growing OP would change and how many plants may be killed especially by increasingly unsuitable climatic conditions. The estimation of OP death in this manner is the first such data. Future percentage mortality of OP in (a) SE Asia (19) and (b) Latin American countries and extrapolated to Malaysia and Indonesia (20) (Fig. 2a,b). These percentages represent large numbers of OP in Malaysia, Indonesia, Thailand and Papua New Guinea because of the large numbers of OP growing in these countries. Finally, large scale conversion of tropical forest to OP plantations has detrimental effects on biodiversity.

a)



b)

doi:10.20944/preprints202012.0129.v1

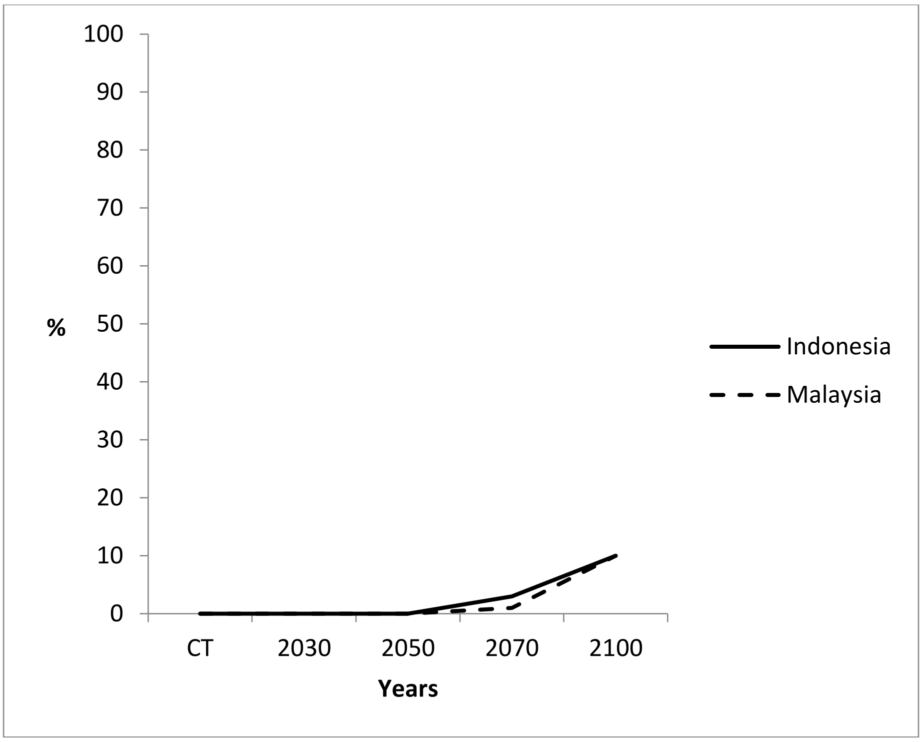


Figure 2. a) Oil palm mortality in Ecuador, Colombia and Brazil. b) Oil palm mortality in Malaysia and Indonesia. These data take into account projected future changes in suitable climate for growing oil palm. (Adapted from data provided in ref 19).

Paterson et al. (47) determined the detrimental effect of future climate on OP growth in a global setting while Paterson (84) considered future climate effects on OP mortality in Kalimantan, Indonesia and some other SE Asian countries, which provided information relevant to Malaysia (see Table 3). High OP mortalities were determined for Thailand, and Myanmar and low mortalities for Kalimantan and the Philippines while Papua New Guinea was intermediate. Paterson et al. (20) modelled OP mortality for three South American countries, Malaysia and Indonesia using similar methods to Paterson et al (19). The Latin American counties and particularly Brazil, were assessed to have high mortalities in the future, whereas the figures for Malaysia and Indonesia were much lower. These potential effects on mortalities will have detrimental consequences on future abilities to meet the demand for palm oil.

Table 3. Predicted oil palm mortalities (%) with climate change in various South American and SE Asian countries, plus the Kalimantan province of Indonesia. ND = not determined. (Adapted from data provided in ref 19).

		Years	
Countries	2050	2070	2100
Indonesia	0	3	10
Malaysia	0	1	10

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2020 doi:10.20944/preprints202012.0129.v1

Kalimantan	0	5	10
The Philippines	0	ND	10
Papua New Guinea	0	ND	40
Myanmar	5	ND	60
Thailand	10	ND	70
Colombia	20	ND	90
Ecuador	0	ND	75
Brazil	15	ND	100

By way of a comparison, African palms in general are likely more badly affected by climate change from increased GHGs and may under threat, although there appears a low extinction risk in the immediate future. OPs are of course African palms and, unusually for palms, grow in forests and in open plain. It is crucial to understand the climate change threats to these plants (1). African palm species will experience a decline in climatic suitability in >70% of their current ranges by 2080 (120), reducing to ca. 35% if migration to nearby climatically-suitable sites succeeds. However, this is difficult in latitudinal directions in the tropics because there are no temperature gradients in these directions. Furthermore, losses of palm habitats such as tropical rain forests are exacerbating the pressures on palm populations and palms and their ecosystem functions and services will be highly sensitive to climate change. OP cultivation itself involves deforestation (22,27), and hence the development of OP could threaten other palms. Blach-Overgaard et al. (120) predicted climate suitability losses across almost all terrains where palms occur in Africa. There is little information about species survival in tropical regions under climate change and data on species migration under climate change is required. CLIMEX modelling indicated that in the future Africa will have less suitable climatic conditions for OP cultivation (47).

Climate change threatens many aspects of crop production (105,112,113). Increased mortality of OP from climate change (19,20) and increased disease (19,20,35,36) have been noted. A significant negative relationship was found between annual average temperature and sea level rise and OP production in Malaysia (108): temperature rises of 1 to 4 °C can cause OP production to decrease by 10 to 41%. Paterson et al. (47) considered future changes to suitable climates for growing OP worldwide by using modelling based on temperature and soil moisture and water stress data. The general predictions were for a reduced level of suitable climatic regions by 2050 and even greater reductions by 2100. The projections indicate serious consequences to the OP industry generally. In Africa, the climate is predicted to become unsuitable for growing OP at the same rate, or faster than, in Malaysia and Indonesia. Uganda appears to be an exception to the overall trend in Africa as increases in climatic suitability were observed.

Climate has an important role in defining the range limits of OP distribution by exerting eco-physiological constraints (47). However, factors such as soil properties and biotic interactions may prevent plants from colonising sites that are otherwise suitable. Changes in climate will have broad-scale impacts on the distribution of OP. Alterations in cold, heat and dry stresses were largely responsible for the changes in climatic suitability for OP cultivation, while wet stress was unimportant, hence extending the range of parameters from temperature alone (47). Many climate change studies are limited in scope, including a lack of information on tropical species (106). Apart from temperature (107) and diseases, a wide range of factors (e.g. precipitation) still awaits consideration although studies on effects on crop production and diseases have been reported (105). Climate change effects in Malaysia were reviewed (121), and the effects on rice and general agriculture were discussed but not OP, despite it being the most important commodity in Malaysia. The effect of climate change on future OP growth in Malaysia and Indonesia is likely to be highly detrimental and threatens the sustainability of OP production (41,108) also reported potentially harmful effects of changes in temperature and sea level rise on Malaysian OP cultivation. Paterson et al. (47) considered the effect of climate change on the suitability of climate on OP growth globally which, overall, was negative.

Climate change impacts on basal stem rot and* Phytophthora palmivora *diseases

The OP industry is threatened by various OP diseases (4). The effect of climate change on OP disease by fungi and *P. palmivora* was discussed in (19,20,35,36) indicating a trend for increased BSR and *P. palmivora* incidence with projected climate change. The effect of changes in climate for growing OP on the infection levels of BSR in Sumatra, Indonesia, including quantitative BSR data, was determined. The developed scenario indicated that BSR would become even more serious after 2050 and that the climate for growing OP would deteriorate greatly. Weather is a major factor in crop maladies and, when crops suffer cold, heat or dry stress, they may be more susceptible. Mountain areas were considered in his assessment which affected some results considerably. For example, hilly regions in North Sumatra did not provide a suitable climate for OP.

Paterson (36) employed a similar ‘Agriculture 4.0’ methodology of big data and simulation modelling to produce a postulated scheme of how BSR would advance under future climates in Malaysia. However, the unsuitable climate associated with mountainous regions were not considered in the initial assessments of suitable climate, making it a different approach to Paterson (35) and that employed herein. The assessments of BSR were merely qualitative and indicated, nevertheless, that the levels of infection would also increase a great deal in the postulated situation after 2050. Paterson (20) considered future climate effects on BSR in Kalimantan and alternative countries in SE Asia. Kalimantan and the Philippines were assessed as sustainable, but Thailand and Myanmar were unsustainable while PNG was intermediate in sustainability (Fig. 3). The oomycete, *P. palmivora* is prevalent in South America and Paterson (19) extended the principles described above to the disease. Colombia and Ecuador were highly susceptible, while Brazil was less so. However, a severe threat to Malaysia and Indonesia was assessed, which would require increased future vigilance to control the disease.

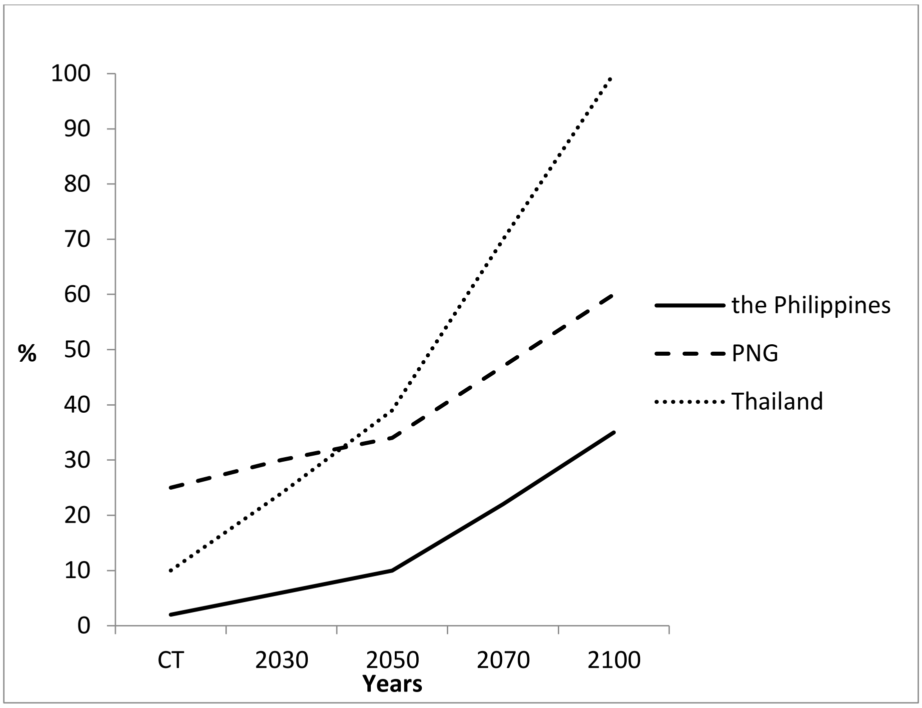


Figure 3. Basal stem rot in three S E Asian countries. The incidence of disease was determined from the changes in suitable climate for growing oil palm as described in ref 20

Amelioration of climate change effects on OP

Resistant OP cultivars to climate change, or environmental stress, may overcome the less favourable growth conditions imposed by climate change (122). However, it is impossible to know accurately what the climate changes will be to enable resistant cultivars development for the actual problematic future climate: A cultivar resistant to dry stress may be sensitive to high temperature. Paterson and Lima (22) described key areas which will reduce the effect of OP cultivation on climate change and the effect of climate change on OP agronomy. These areas included (a) inter-planting leguminous crops to increase nitrogen in the soil; (b) using empty OP bunches to enhance soil, (c) adding earthworms to improve soil, (d) employing arbuscular mycorrhizal fungi and (e) biochar to assist nutrition of OP. However, the most effective manner of addressing climate change is to adhere to the policies devised at the 2019 COP25 climate meeting in Spain, by reducing GHGs and keeping temperature rise to more manageable levels (file:///C:/Users/Russell/Downloads/cp2019_L10E.pdf). Conservation scientists, managers and environmental policymakers need to adapt their guidelines and policies accordingly to mitigate the impact of climate change (104).

Breeding and biotechnology

Recently, there have been several significant advances in breeding and biotechnology use for OP improvement. This is despite the challenges posed by the long-lived perennial nature of OPs, which are large plants typically grown for >25 years rather than as annual crops. Hence, such biological strategies are much more complex and lengthier to implement compared to the smaller, rapid cycling annual crops. Breeding efforts have tended to focus on major economic traits such as oil yield and composition, pest and disease resistance, and plant architecture. Until relatively recently, OP breeding was also disadvantaged by the restricted genetic pool of commercial varieties, most of which were derived from small numbers of plants imported from Africa to SE Asia in the 19th and 20th centuries. The available gene pool has now been greatly expanded, largely thanks to a series of germplasm collection expeditions to Africa and South America by pioneering breeders such as Rajanaidu et al (123). Recent breeding-related reviews include genomics (124,125), genomic selection (126), transgenics (6), genome editing (127), and marker-assisted selection (128,129). Following the publication of the OP genome sequence in 2013 (130), several detailed linkage maps have now become available for the use of breeders (131,132).

Genomics-based strategies such as marker-assisted selection are already generating several useful advances for a variety of important traits that include oil yield, fatty acid composition and crop morphology (132–134). One of the most exciting recent developments was the announcement in mid-2020 of new breeding lines that are capable of more than double the current average oil yield (135). These plants are part of a genomics-based programme called 'Genome Select' carried out by plantation company Sime Darby, with a claimed 9.9 t/ha average yield over 5 years in field trials under optimum conditions. Given that current average palm oil yields are less than 4 t/ha, and that soybean and rapeseed only yield 0.3 and 1.2 t/ha respectively, this could be a game changer for the industry if two important conditions are met. Firstly, the experimental lines will need to be assessed for their oil yield performance under commercial plantation conditions in a range of geographic regions and, if necessary, crossed with locally adapted varieties. Secondly, the new higher yielding varieties need to be part of an ambitious replanting programme that will potentially replace a significant proportion of the estimated 2.5 billion OPs that are currently under cultivation worldwide.

In terms of oil quality, the most important target trait for OP breeders is the oleic acid content in the mesocarp oil. Existing varieties of OP produce a mesocarp oil that typically contains only about 40-45% oleic acid, whereas competitor crops such as rapeseed, olive, soybean and sunflower have varieties containing well above 60%, and in some cases as high as 85%, oleate. The main reason for the low oleate content of palm oil is that the mesocarp has an active palmitoyl thioesterase that channels C16 palmitate towards oil accumulation instead of it being elongated to stearate and desaturated to oleate. This means that palm oil typically contains about 48% of palmitate + stearate, both of which are saturated fatty acids. For comparison, the saturated fatty acid contents of soybean, rapeseed and sunflower are in the range of 6-15% (see Table 2). In order to change the mesocarp oil into a high-oleate profile, it is necessary to manipulate at least three, and possibly several more, genes. Firstly, palmitoyl thioesterase needs to be downregulated to stop palmitate being diverted to oil. Secondly, the key elongation gene, KASII, needs to be upregulated so that the palmitate is efficiently converted to C18 stearate. Thirdly, the stearate desaturase needs to be upregulated so stearate is efficiently desaturated to oleate. Experience with other oil crops has shown that it may also be necessary to transfer additional acyltransferase genes to ensure that the new fatty acids are efficiently assembled onto triacylglycerols. For example, evidence from several plant species suggests that the type-2 acyl-CoA:diacylglycerol acyltransferase can stimulate accumulation of exotic fatty acids in storage oils (136,137).

Due to these complications, it is likely to be some time before an ultra-high oleate trait can be created in OP via a transgenic (genetically modified, GM) route, but this goal is still important due to the usefulness of oleate-rich feedstocks for both food and non-food applications (6). It also means that the engineering of OP for more minor fatty acid traits, such as high palmitate or palmitoleate, or for acyl derivatives such as bioplastics (138,139) is going to be even more problematic. In addition to oil modification, transgenic approaches can, in principle, be applied to any other trait where suitable genes have been identified. This means that there is a long list of possible GM varieties of OP, but at present, the high R&D and regulatory costs are likely to limit their development to traits with significant agronomic and commercial potential. For example, transgenic expression of Bt insecticidal proteins has been proven to be an effective strategy to control certain insect pests in a range of crops including major oilseeds including soybean, rapeseed and cottonseed, and this strategy is also being investigated in OP (140).

Routine methods for transforming OP with gene constructs optimized for commercial phenotypes will probably take several more decades. The initial target of having commercial transgenic OP varieties under cultivation in the 2020s is now looking decidedly optimistic. However, a target date in the late 2020s is not necessarily totally unrealistic, especially if new genome editing technologies such as CRISPR, prove useful. A major issue for transgenic OP is consumer acceptability of products from GM crops. Despite a lack of clear scientific evidence to support adverse claims from anti-GM activists, many politicians in Europe remain wary about allowing GM crops or products to be grown or imported into the region. Given that OP already suffers from an image problem (especially in Europe) due to its perceived environmental impacts, the industry is rightly cautious about possible future GM developments. Indeed, in many cases palm oil producers actually stress that the crop is entirely non-GM presently.

An alternative to transgenic crop manipulation is the used of so-called cisgenic approaches such as genome editing. Specific applications of genome editing to OP breeding via CRISPR have been reviewed recently by Yarra et al (127). Modern crop breeding is also able to profit from a host of advanced technologies such as association genetics (141), molecular mutagenesis including TILLING (TargetIng Local Lesions IN Genomes) and marker-assisted selection (142). Deployment of these technologies in OP is already enabling breeders to begin to address complex traits such as drought tolerance and disease resistance that are also relevant to adaptation to climate change as discussed below (143,144). Such genomic technologies could potentially be used in conjunction with transgenic methods in OP to develop useful traits such as dwarf trees (145), increased oil content in mesocarp and kernel tissues (133), and wider resistance/tolerance profiles to a range of pests and pathogens (6).

The recent success in applying molecular marker-based genomic selection to improve oil yield (135) raises the prospect of developing high-oleate oils via a non-transgenic route. As described above, fatty acid content in OP is a complex metabolic trait that has been recalcitrant to conventional breeding. This problem was made worse by a lack of genetic variation for oleate levels in the available commercial breeding materials. However, OP germplasm collections have now been much improved by incorporation of material from Africa and South America (123). In some of these lines, elevated oleate levels of 55-60% are present and quantitative trait loci (QTL) for this trait have been identified (134). The automatic metabolic consequence of higher oleate levels in palm oil is a corresponding reduction in saturated fatty acids, especially palmitate. Therefore a high-oleic palm oil (say 60-70%) would also be a relatively low-saturate oil that would be closer in composition to competitor oils from soybean and rapeseed (see Table 2). Such an oil would address some concerns around the nutritional consequences of high levels of dietary saturated intake, and a high-oleic palm oil would be very price-competitive with oils from other crops. The wider nutritional aspects of palm oil are discussed further below.

In terms of molecular genetics approaches to Basal Stem Rot mechanism and control, *G. boninense* genome and transcriptome data and now available with two *G. boninense* genome assemblies in the NCBI Depository (146). Wong et al. (146) provides a table listing publicly available genome and transcriptome data associated with the *G. boninense* and *G. boninense*-OP pathosystem. High-throughput next-generation sequencing and improved bioinformatics analyses has greatly facilitated *G. boninense* pathogenesis and house-keeping candidate gene identification. However, *G. boninense* remains poorly studied with respect to system-level gene function studies and biotechnology manipulation, with no available gene co-expression network models. Most studies have focused on host transcriptome data, whilst similar studies on the pathogen remain scarce. Ho et al. (147) utilised mass RNA sequencing and *de novo* assembly of RNA-seq and were able to detect a high number of *Ganoderma* transcripts involved in lignin metabolism, such as manganese peroxidase and laccases. Transcripts encoding cell wall degrading/modification enzymes, such as glycoside hydrolases and glycosyltransferases from various families, carbohydrate-binding modules, cellulases and polysaccharide lyase were also detected. This finding corroborates reports on the detection of corresponding enzyme activities in *G. boninense*.

The transcriptome of *G. boninense* at monokaryon, mating junction and dikaryon stages was reported (148). The data being made publicly available will be useful for investigation of the mating process of this fungus. However, annotation and functional studies of these differentially expressed genes at different stages have not been carried out . RNAi as a tool for functional genomics in to study developmental or virulent genes is lacking, although the genome has been sequenced. The role of genes involved in ergosterol biosynthetic pathway in *G. boninense* utilizing RNAi-mediated gene silencing is currently being investigated (146). The identification and verification of candidate genes are crucial for the application of these targets in RNAi-based crop protection, such as host-induced gene silencing (HIGS) or spray-induced gene silencing (SIGS). In addition, a study on the potential application of RNA silencing targeting DCL genes of *G. boninense* to confer protection against basa 581 stem rot is in progress (146). The availability of *G. boninense* genome data in public database (NCBI) enables potential candidate genes to be identified for testing and designing of efficient silencing constructs to avoid off-target transcripts, whilst the availability of the OP genome data helps to ensure the silencing constructs do not target and negatively affect the host. Because *G. boninense* on attacks OP by degrading lignin (Fig. 1), there is the possibility of modifying lignin to make OP plants more resistant (149). Alternatively, making the plant more resistant to initial fungal colonization by inhibiting carbohydrate metabolism first is a more logical approach that possibly overrides the emphasis on lignin *per se* (146).

Global supply chains and consumer sentiment

Palm oils are globally traded commodities with lengthy and complex supply chains. Their complexity is further increased by non-economic factors including sustainability, traceability, disease monitoring and pest management. As previously discussed, palm oil production has a largely negative media image (37). Particularly in Europe, this has led to consumer demand for improved production methods that minimise environmental and socioeconomic impacts. There have been criticisms that the OP industry initially responded slowly to these developments and, in some cases, there have been largely unproductive and polarised confrontations between NGOs and some media outlets on one side and industry and producer country governments on the other. In a few isolated cases, this has led to boycotts of products containing palm oil, despite clear evidence that there is no realistically sustainable replacement.

More recently, however, a more constructive dialogue has emerged as several NGOs and community groups have joined with bodies such as RSPO and some major industry players in exploring initiatives such as certification schemes, that seek to guarantee that palm oils are sourced from sustainable and environmentally friendly sources. It is also encouraging that

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2020 doi:10.20944/preprints202012.0129.v1

governments in OP growing regions have started to establish laws and regulations to better manage OP production, enabling mitigation of negative impacts. In the consumer-facing sector, manufacturers and retails have, in general, responded well to consumer demand, with many implementing sustainable palm oil policies and signing up to certification schemes such as RSPO. However, whilst there has been considerable movement towards sustainable production, there is still an active anti-palm oil movement with persistent calls to boycott palm oil entirely (despite the lack of a viable alternative), as discussed further below.

Palm oil supply chain structure

Due to increasing awareness of the wider impacts of OP crops, sourcing of palm oil from verified, certified sustainable/responsible sources is of growing interest. Supply chain traceability ensures that information about products can flow easily and enable consumers to have maximum information about product origins. Traceability is formally defined as '*the ability to trace a product from production to distribution*'. Palm oil supply chains are complex and have many components. For example, a traditional, non-certified palm oil supply chain usually consists of growers, millers, transporters, refiners and manufacturers (Figure 4). The reality can often be even more complex, depending upon whether plantations are managed by a commercial company that is often part of a large multinational enterprise, or by a self-managed smallholder farmer (150).

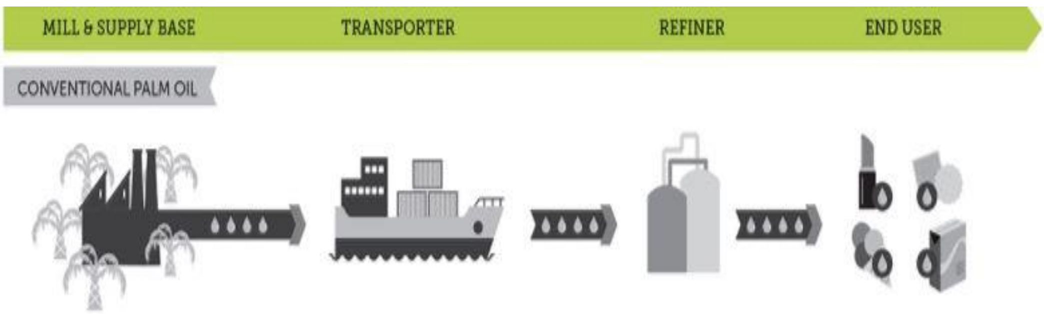


Figure 4. A conventional palm oil supply chain consisting of mill and supply base, transporter, refiner and end user (source: www.rspo.org).

A large company can typically manage several separate plantations in different countries and regions, as well as groups of smallholder farmers. Such companies usually have dedicated mills located close to the plantations and employ workers who harvest, transport and process 'Fresh Fruit Bunches' (FFBs) from their plantations. However, if the plantation is self-managed, e.g. by a smallholder, then middlemen are often involved in the supply chain. Middlemen will often negotiate a price for the FFBs produced by plantation owners and sell them on to whatever mill will purchase them for the best price. In this situation, traceability is very difficult as FFBs from multiple plantations are bulked together and, from day to day, the route travelled by the middleman may vary. Furthermore, in such cases documentation for these exchanges may be lacking, which means relying on a paper trail alone is often not sufficient. This makes supply chain traceability somewhat challenging.

Lyons-White and Knight (151) described the supply chain as "*being hourglass-shaped, with many different stakeholders at the supply and demand end and a small number of trading companies in the middle. At the production end of the supply chain, it was said that FFBs (*fresh fruit bunches*) were often traded between multiple smallholders and local traders before arriving at the mill, making the ability to trace the origin of third-party FFBs difficult or impossible*". Further downstream, it was reported that the rapid speed and large scale of palm oil trading on commodity markets hindered tracking of consignments, obstructing traceability to mills.

Sustainability and traceability

Certification schemes have mostly been established to improve sustainability within the industry, but for these to operate openly and transparently, supply chain traceability is an essential requirement. The most widely used sustainable certification scheme, which aims to improve traceability, is RSPO. This is a multi-stakeholder organisation, founded in 2004 in response to demand from consumers and manufacturers for increased sustainability and responsibility within the palm oil industry. It currently operates two certification systems. The first ensures that palm oil is produced sustainably (producer/grower certification). The second ensures the integrity of trade in sustainable palm oil, ensuring that palm oil sold as sustainable palm oil, has actually been produced by certified plantations. The certification systems are monitored by the four RSPO supply chain models listed below. A graphical overview of each model is also displayed in Figure 5 (152):

1. Identity Preserved (IP): sustainable palm oil is derived from a single source and kept separate from all other sources throughout the entire supply chain
2. Segregated (SG): sustainable palm oil is derived from multiple sources and mixed; it is then kept separate from conventional palm oil throughout the supply chain
3. Mass Balance (MB): sustainable palm oil is mixed with palm oil from non-certified sources in a controlled and regulated manner
4. RSPO credits: the supply chain is not monitored for the presence of sustainable palm oil. But manufacturers and retailers can buy credits from RSPO-certified growers, crushers and independent smallholders

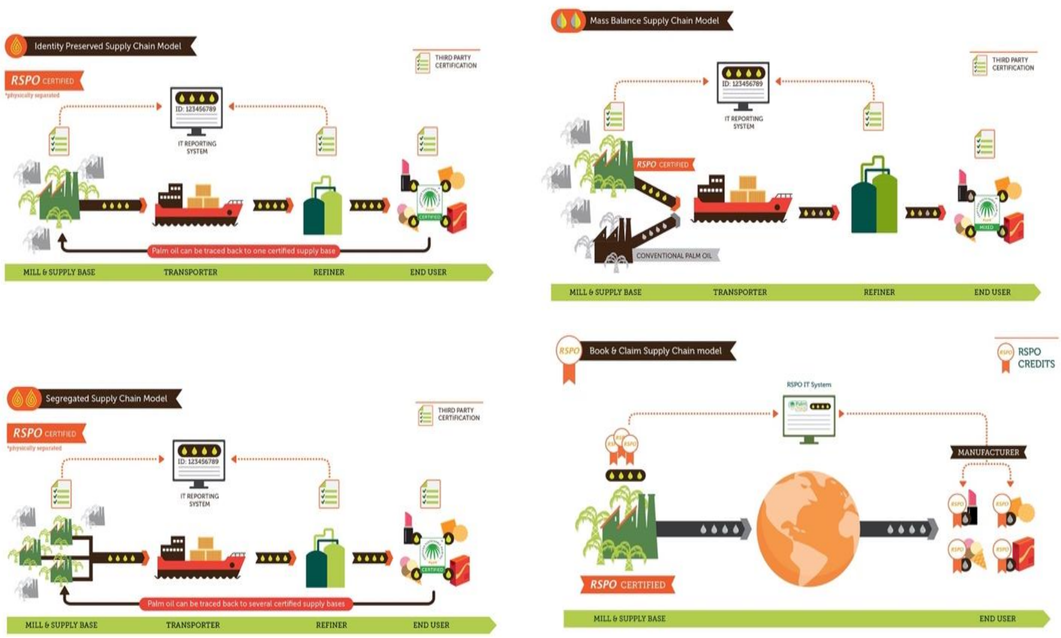


Figure 5. The four different RSPO supply chain models including Identity Preserved, Mass Balance, Segregated and Book and Claim (source: www.rspo.org).

Only an IP supply chain model enables palm oil to be traced back to its geographical origin, more specifically back to the plantation or mill of origin. However, this model is extremely expensive to implement and so is the least utilised (153). This means that whilst 21% of palm oil produced is RSPO certified sustainable (154), the majority of this is not traceable to its source, although it does carry a guarantee that it has been produced in line with RSPO sustainability criteria.

Labelling

Labelling has been shown to influence consumer purchasing habits and to have positive impacts on food production. All products carry some form of labelling to inform consumers about important product information such as ingredients, origin and production. However, outside of Asia, where it is sold as a cooking oil, palm oil is seldom sold as a stand-alone product and is invariably incorporated into more complex products, such as chocolate or processed foods, as one of several ingredients. In an increasing number of countries it is now required by law that the precise crop of origin is included on product labels, for example 'palm oil' instead of the generic 'vegetable oil'. When the food labelling law changed in 2014, RSPO reported a 65% increase in sales of certified sustainable palm oil in the first two quarters of the year compared with the previous year. However, such labelling requirements do not extend to non-food items such as detergents, cosmetics, toothpaste etc, where a term such as '*laureth*' or '*lauric*' is generally used to describe the active ingredient that is derived from palm kernel oil.

Some retailers have already included 'palm oil' on labels for several years, the British Retail Consortium (BRC) reported no discernible change "*in customer behaviour or sales or even any questions through customer lines*" and "*There seems to be a very strong move by consumers to claim their right to know what is in their food, and that labels are as clear as possible. But whether that translates into a change in consumer behaviour … is still to be seen. For example, people asserted their right to have country of origin information and that also hasn't seen any change in customer purchasing behaviour*". Many manufacturers using 100% certified sustainable palm oil choose not to put the RSPO certification trademark on product packaging, preferring instead to reference it only in CSR reports or corporate websites. The BRC attributed this to lack of consumer demand, stating "*it is not common because there are too many logos these days. The manufacturers have their own branding, other logos, ingredients, health information. The front of pack becomes completely crowded. What manufacturers are basically looking for is that the consumer trusts the brand*". On the other hand, however, RSPO believes that using its certification trademark on products will be central to raising awareness and driving demand.

Health and Nutrition

Palm oil is used for cooking and is also added to many ready-to-eat foods. Its taste is considered savoury and earthy, with some people describing its flavour as being similar to carrot or pumpkin. It has been a staple in West African and tropical cuisines for millennia (2). Nowadays in the commercial food sector, palm oil is often used for sautéing or frying because it has a high smoke point of 232 °C and remains stable under high temperatures. During the 1980s, in some countries including the USA, palm oil was replaced by hydrogenated oils from soybean or rapeseed, in many products due to concerns that it might jeopardise heart health. However, subsequent research concluded that the *trans* fats present in such hydrogenated oils actually posed a far greater risk to heart health than the saturated fats in palm oil. As a result, most manufacturers have now resumed use of palm oil, which contains no *trans* fats (155). As shown in Table 2, palm oil contains 50% saturated, 40% monounsaturated and 10% polyunsaturated fatty acids. The major saturated fat is palmitic acid, which contributes to approximately 44% of its calories. It also contains high amounts of oleic acid and smaller amounts of linoleic and stearic acid. The reddish-orange colour of palm oil is attributed to its carotenoid content, particularly ß-carotene, which is a vitamin A precursor.

There has been a perception that palm oil has adverse nutritional qualities, despite it having been an important human food product for millennia. However, this has been challenged by more recent meta-analyses and prospective observational studies, mainly conducted in North America and Europe, that failed to demonstrate a correlation between total saturated fat intake and risk of cardiovascular disease (CVD) (156). Other evidence using biomarkers, shows that low dietary levels of linoleic acid are associated with a 22% greater risk of CVD (157). Low intakes of linoleic acid are associated with consumption of red and processed meat products, which is consistently linked to elevated CVD risk. In contrast, palm oil contains about four time the amount of linoleic acid found in fat from ruminant animals and in other tropical oils (*e.g*. coconut, cocoa butter, shea). This may, in part, explain the lack of association of palm oil with CVD (37)j

Palm oil is also linked to several health benefits including protecting brain function, reducing heart disease risk factors and improving vitamin A status. Palm oil is an excellent source of tocotrienols, a form of vitamin E with strong antioxidant properties thought to support brain health. Animal and human studies suggest that the tocotrienols in palm oil may help protect polyunsaturated fats in the brain, slow dementia progression, reduce the risk of stroke and prevent the growth of brain lesions. Other research has shown that palm oil can improve vitamin A status in people who are deficient or at risk of deficiency (158). Studies in pregnant women in developing countries have shown that consuming red palm oil increases vitamin A levels in blood, as well as in their breastfed infants (159). Furthermore, people with cystic fibrosis who have difficulty absorbing fat-soluble vitamins, experienced an increase in vitamin A blood levels after taking two to three tablespoons of red palm oil daily for eight weeks (160).

To summarise, as stated in a recent review: "*Thus, while palm oil is important in meeting global food energy requirements especially in Asia and Africa, there is no evidence to support assertions that palm oil is associated with adverse nutritional outcomes in humans. The call for allies to join in 'evidence generation and advocacy around the detrimental impacts of palm oil on human and planetary heath' appears misguided"* (37).

Consumer sentiments

A recent study compared consumer knowledge, awareness, and perceptions of palm oil and its sustainability in Malaysia, Singapore and the UK (161). From an online survey, interviews and focus groups and building on consumer behaviour theories, several key differences and similarities were found between the three nationalities. Malaysians were generally more aware of palm oil and held more positive views, but all nationalities were less familiar with the concept of "sustainable palm oil". Only a small proportion of respondents from each country ruled out purchasing sustainably certified palm oil products. However, price was the major determining factor with most respondents unwilling to pay more for "green" products. The authors concluded that considering the disconnect felt by consumers towards the realities of palm oil production, improved consumer-focused information about environmental and socioeconomic issues is essential to influence consumption patterns. The study also highlighted the importance of consumer location in shaping their views of palm oil, and thus the need to better understand how positive information campaigns about the benefits of sustainable production can sit alongside more specific localised information flows about palm oil (161).

In recent years, the public debate on the health and sustainability of palm oil and its use by food industries has strongly influenced consumer choices. Consequently, "palm oil-free" products have asserted health and sustainability benefits that are largely vague and unproven. One study sought to contribute to the extant knowledge on consumers' perception of palm oil, particularly concerning preferences for food products carrying a "palm oil-free" label on their packaging (162). A web survey with a sample of 291 individuals was performed (162). Determinants of consumers' preferences towards the "palm oil-free" label were estimated with an ordered logistic model using as the dependent variable the purchasing frequency of palm oil-free foods and a set of independent variables. Results showed that respondents generally preferred palm oil-free products, perceiving these products as healthier or eco-friendly. Furthermore, individuals were strongly influenced by the available information on these foods that may guide their choices for palm oil-free foods, which may be perceived as 'cleaner'.

Other findings highlighted the dearth of reliable information on palm oil, underlining the need for public information and communication campaigns through different media, in order to emphasise that no scientifically proven negative health effect is currently attributed to palm oil consumption. The study draws on the assumption that consumers' avoidance of food products containing palm oil may be determined by different drivers. First, because palm oil is frequently associated with issues of social and environmental sustainability, as well as with concerns about its effects on human health, we might expect that consumers who ascribe great importance to these aspects to be more likely to choose palm oil-free foods. Second, given the poor reputation palm oil has gained over the years, consumers might have developed specific negative attitudes and beliefs that may guide their choice of products perceived as 'cleaner'. Third, palm oil-free products might be selected by those consumers more engaged in searching for information on food products, and thus keener to use food labels and more attentive to the information contained on food packaging.

One consumer-facing campaign that is having some effect is the "no palm oil" claim used in a few products including 'Divine Chocolate' and 'Meridian Peanut Butter'. Andrew Jenkins, sustainable development manager for products at Boots UK, stated that this took an overly narrow view, stating: *"If palm oil was no longer used, what would the unintended consequences on the environment be of whatever it is replaced with?". "In personal care many of the derivatives from palm could be and are manufactured from coconut instead*." But given that coconut plantations yield less than half the oil per hectare than palm, "*you are simply transferring the environmental problem elsewhere*". On this point, it is also interesting to note that, in July 2020, there were calls for boycotts of coconut products due to its claimed destructive effects on wildlife (163) and alleged poor harvesting practices involving trained monkeys (164). If heeded, such calls would effectively rule out the only possible (albeit far from satisfactory) replacement for palm kernel oil as a provider of lauric fats for products such as detergents and cosmetics. There is broad agreement from industry that certified sustainable palm oil is the only environmentally responsible solution, but diversification of supply chains is also desirable – although this is not necessarily achievable for lauric products except on a small scale, due to the low yield of alternative crops such as coconut.

To summarise, the world continues to need vegetable oils and, if the 40% of global production that currently comes from palm oil is ruled out, up to nine times more land would be required. This would likely lead to increased deforestation, more habitat conversion and even greater releases of GHGs. Therefore, the great majority of scientists and environmentalists agree that boycotting palm oil is not a viable proposition. Instead, production of sustainable palm oil is recommended so that consumers only buy from companies using palm oil certified under

RSPO, or similar certification schemes. Certification schemes improve consumer confidence and provide a high level of guarantee that that areas of high conservation value are preserved, local communities supported and that palm oil plantation managers are implementing best practices. Whilst many criticise certification schemes for not moving far or fast enough, researchers and NGOs such as WWF are working with schemes like RSPO, to facilitate greater progress and to include more progressive criteria for best practice, in order to increase the number of plantations certified.

Future prospects

Like many sectors of commercial agriculture, the global OP industry is facing significant future challenges. Some examples include:

- Immediate issues related to economic and other consequences of covid-19.
- Greatly reduced demand for crop-derived biofuels, especially in Europe in the 2020s.
- Immediate production issues related to plantation management, labour shortages, replanting with improved crop varieties, mechanisation etc.
- Ongoing environmental and sustainability issues including deforestation, biodiversity loss and GHG emissions due to crop expansion.
- Growing threats arising from climate change, including biotic factors, such as pests and disease, that could impact crop performance in unpredictable ways.
- Increasingly serious supply chain and consumer issues including potential trade barriers and boycotts.

In some cases, the short and medium term impacts of these challenges have been accelerated by the sudden shock created by the covid-19 pandemic of 2020, but in all cases they will require attention by the industry during the rest of this decade and beyond.

Impacts of covid-19

"Food markets will face many more months of uncertainty related to the COVID-19 pandemic. However, while most markets are braced for a major global economic downturn, the agri-food sector is likely to display more resilience to the crisis than other sectors" (165).

At the time of writing (July 2020), the full impact of the covid-19 pandemic on the OP sector, and indeed on agriculture as a whole, remains far from clear. Nevertheless, there is little doubt that there will be significant effects, both in the short and longer term. The immediate human mortality due to the 2020 outbreak is unlikely to exceed 0.02% of the global population so there will be very limited demographic impact, e.g. on overall food demand. However, as the virus becomes endemic, its wider socio-economic effects could be both significant and long lasting for the OP industry. The immediate effects of the covid-19 pandemic on OP were felt almost entirely in the supply chain and crop production sectors and were due to the sudden lockdowns that spread globally early in 2020. These lockdowns initially affected trade as activities were disrupted sequentially from January to March 2020 across the major importing regions. Despite an initial shock from the lockdowns, supply chains proved to be remarkably resilient with the transportation of millions of tonnes of palm oils continuing with relatively little interruption from the major producing hubs of SE Asia to importers in Europe, China and India. For example, key entry ports that serve as entrepôts for palm oil import and transhipment, such as Rotterdam (Europe), Kakinada (India) and Xiamen (China), treated palm oils as prioritised strategic commodities, hence ensuring their prompt offloading and distribution.

This was an important recognition that palm oils fulfil two particularly critical socio-economic functions. Firstly, palm oil is a major provider of edible calories to billions of people, especially in Asia. Secondly, palm kernel oil is the functional ingredient in vital cleaning, hygiene and personal care products, such as soaps, detergents and surface cleaners (166). These are essential tools in public health strategies to combat the covid-19 virus (SARS-CoV-2) and similar disease threats. While OP supply chains were relatively unaffected by the pandemic, there was significant disruption higher up the supply chain in some plantations, due to localised lockdowns and unavailability of sufficient labour. This could result in a reduction in palm oil production of about 10% during 2020 and into 2021 (167). However, this loss of production will be offset by a greatly reduced demand for palm biodiesel (see below), so supplies for the crucial food and personal care/cleaning markets are unlikely to be greatly impacted.

In the longer term, the covid-19 pandemic is likely to have considerable effects on the global economy, as well as accelerating some existing trends that are relevant to the OP sector. The most significant and easily predictable effect will be on palm biodiesel. Here, the probable disappearance of the EU market during the 2020s could wipe out over 6% of global demand for palm oil, as discussed below. The pandemic has also shone a spotlight on often-complex global supply chains and their vulnerability to sudden shocks. This could feed into existing nationalistic sentiments that are promoting protectionism in some countries and threatening global free trade. Examples relevant to agriculture include disputes over crop tariffs and quotas between major trade blocks such as USA, China and the EU.

The latter factors could encourage a search for local substitutes for OP products, such as use of solid animal fats instead of palm oil. In this case, the downsides for consumers include that these animal fats are non-vegetarian, have high stearic acid levels (bad for CVD), and might be prohibited by certain ethno-religious groups (eg lard from pigs or dripping from beef). As discussed above, there is currently no viable alternative to palm kernel oil, but this could change if temperate oilseed crops were bioengineered to accumulate high-lauric oils. During the early 1990s, the US biotech company, Calgene, created transgenic high-lauric rapeseed varieties, although these were neither agronomically nor economically successful (168). However, with more efficient modern genome editing technologies, and with possible support from a sympathetic government, it is possible that a protectionist trade bloc might develop such an OP substitute in a local annual oilseed crop. The aim would be to guarantee easy local access to what has now become a strategically essential product, namely high-lauric oil. In July 2020, the market price (fob, Rotterdam) of palm kernel oil was almost the same as that of soybean oil, at about \$680/t. This means that, once R&D costs had been written off, a putative high-lauric soybean variety could be in principle be available to be grown as a crop in a temperate region, such as the USA, and its oil could be priced similarly to the palm kernel oil that is currently imported from SE Asia. The success of such a ‘home grown’ lauric oilseed crop could be further guaranteed by the imposition of tariff barrier on the import of overseas palm kernel oil by a protectionist government.

Unintended consequences of land conversion to OP

The covid-19 pandemic has greatly increased the awareness of zoonotic disease threats to humans. A high proportion of zoonoses originates either directly from livestock or indirectly from wild animals displaced by human activities related to agriculture. The SARS-CoV-2 virus probably originated in a bat and was transmitted to humans via an as-yet unknown route - but it is clear that this was unrelated to the OP industry. However, there is a possibility that OP-related deforestation in SE Asia could have contributed to a previous fatal zoonotic viral infection (169). This outbreak involved a novel paramyxovirus, named Nipah after the village near to its centre of infection in Malaysia (170,171). In 1998, the Nipah virus first emerged in pigs and spread to humans, with over 100 fatalities requiring the emergency culling of over one million pigs by the Malaysian Army. A causal link between deforestation for pulpwood logging and OP planting in Sumatra has been reported, potentially causing the displacement of virus-laden fruit bats to pig farms in Malaysia, followed by transfer of the virus to pigs and humans (169,172,173). Subsequent Nipah virus outbreaks in Bangladesh (2001) and India (2018) were also associated with fruit bats but in these particular cases OP-related land conversion was not involved.

In the future, the global OP industry needs to take a broader and more holistic global view of the wider consequences of its actions. This will be particularly important as changing climatic conditions result in unpredictable ecological changes and the possible emergence of new biotic threats. The same considerations apply as OP cultivation expands into new regions of the tropics where the crop has never been grown previously and where there might be unforeseen zoonotic threats, such as the like of Nipah virus. These topics should now be reconsidered by the sector, including at government level, in the context of improved transnational biosecurity surveillance.

Uncertain future for palm-based biofuels

Over the past decade a growing proportion of palm oil has been used as a biofuel, mostly in the transport sector as biodiesel derived from methyl esters of the oil. Most palm biodiesel is consumed locally in Malaysia and Indonesia. This is due to government-supported mandates that enforce the mixing of palm biodiesel with petroleum-derived diesel. It has enabled palm biodiesel use to rise from 0.25 to 7.2 Mt between 2010 and 2019 – an almost 30-fold increase. However, the use of palm biodiesel as a carbon-neutral fuel in the transport sector has proved to be controversial, especially in the EU (174). Until very recently, a substantial and growing amount of palm biodiesel, totalling 4.9 Mt in 2018, was used in the EU. As shown in Fig 6, for over a decade the EU has steadily increased its imports of palm oil for fuel use while the amount used for food, feed and oleochemicals has declined from a high of almost 4 Mt to about 2.7 Mt (175). Recent data show that in 2018 the EU imported a total of 7.6 Mt palm oil but only 2.7 Mt (36%) of this was for food and personal care use, while the remaining 4.9 Mt (64%) was for use as transport biodiesel or fuel oil (e.g. for electricity generation).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2020 doi:10.20944/preprints202012.0129.v1

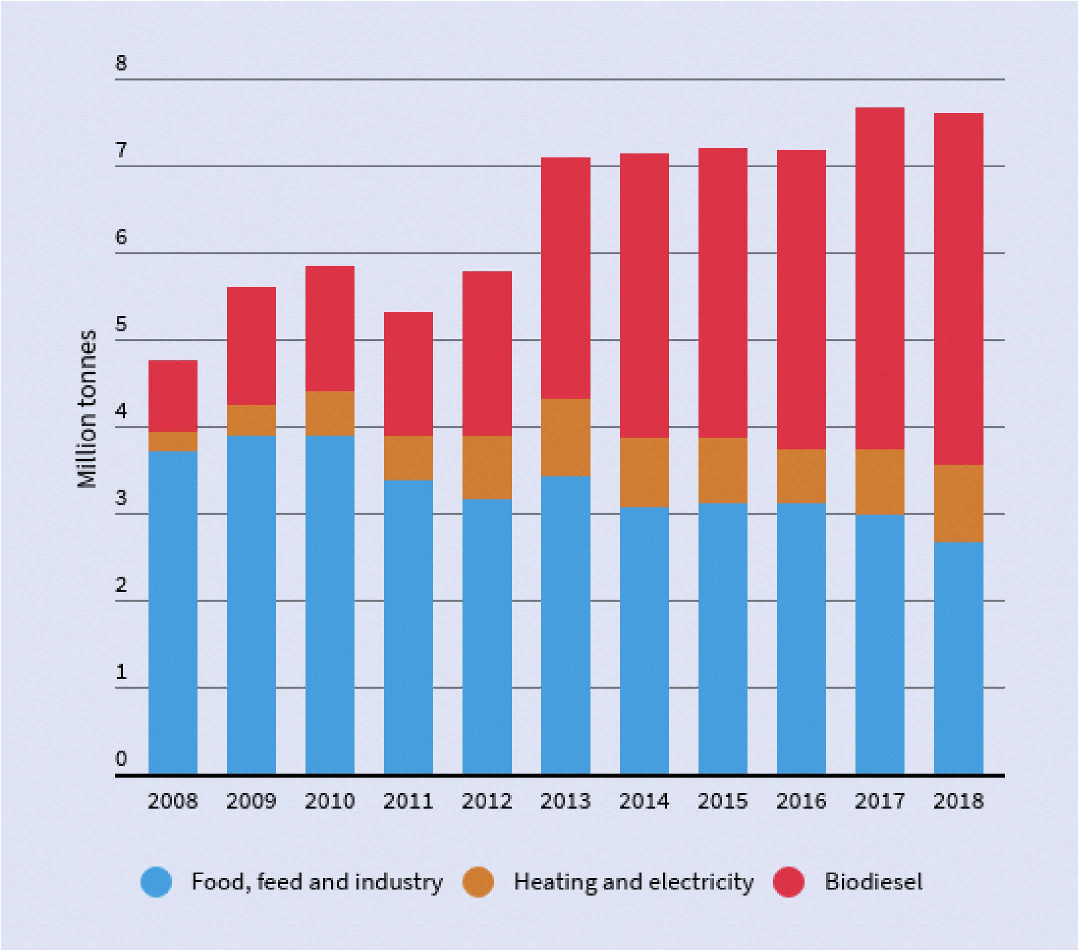


Figure 6. EU palm oil consumption by end use. A steady decline in food use is mirrored by an increase in biodiesel use for palm oil imported into the EU from 2008 to 2018. Source: ref 175.

As described above, concerns about the environmental impact of OP cultivation and the use of food crops for biofuel, coupled with recent advances in electric vehicle (EV) technologies, mean that the EU is now moving away from both crop-based biofuels and from fossil fuels. By 2019, EVs were rapidly increasing their market share in Europe, accounting for as much as half of all car sales in some countries, and this trend has been accelerated by the covid-19 pandemic. Longer term, most European countries are now phasing out carbon-based fuels, with the UK pledging in 2020 to move to a complete ban on sales of new diesel, petrol and hybrid cars by 2035 or earlier (176). This means that, irrespective of tariffs or other trade barriers on palm biodiesel imports, within a few decades there is likely to be no market for it anyway in the EU. Moreover, as vehicle manufacturers continue to move away from models with diesel engines, the entire global market for crop-based biodiesel fuels could disappear by mid-century.

Prior to 2020, the EU had already pledged to phase out palm-based biofuels by 2030, and this timetable will almost certainly be accelerated by the increasing pace of moves away from carbon-based vehicle fuels. Indeed, by April 2020, Malaysian biodiesel exports had already declined by over 90% (177). Palm biodiesel has also been adversely affected by the worldwide glut of petroleum, which led to a price collapse in early 2020. The likelihood of continuing low petroleum prices over the next few years means that more expensive biodiesel is uneconomic, even with government subsidies. For example, in 2020, bio-based aircraft fuel cost \$1.2/l, while fossil-based fuel <\$0.1/l, making the biofuel over 12-fold more expensive. In line with these developments, Malaysia and Indonesia have recently delayed the introduction of increased levels of palm biodiesel in vehicle fuels (178).

In the medium term, as fossil oil use continues to decline and its price remains low, there are few prospects that palm biodiesel will compete effectively on price in international markets. Therefore the only outlet for palm biodiesel, which currently accounts for about 18% of total palm oil production, will be as an expensive, locally-subsidised diesel admixture in the two major producing countries, Indonesia and Malaysia. But it seems unlikely that this would be politically or economically sustainable in the long term. However, there might be a silver lining here if, as expected, there is a future requirement for increased OP production as the global population continues to increase. Corley and Tinker (4) estimated that, by 2050, a further 6 Mha of land could be required to meet OP production requirements. But if most of the current palm that is diverted to biodiesel is switched to food use, about 3 - 4 Mha of this additional land would not be required.

Production issues

On the production or supply side, the OP sector faces several significant challenges, many of while are long-standing but have been brought into focus by recent events. The latter include new scientific advances, changing patterns of global trade and consumer sentiment, and the 2020 covid-19 pandemic. The efficiency and effectiveness of plantation management varies greatly across the sector both among large commercial enterprises and individual smallholders. One of the most remarkable features of the OP is the stagnation in yields at values around or under 4 t/ha over the past two decades (48,179). As shown in Figure 7, this is in marked contrast to other major crops, including oilseeds, which have shown consistent yield increases in response to factors such as biological improvements, improved management and more efficient transport and supply chain infrastructure (179).

In the case of OP, there has been an element of lethargy in tackling specific issues such as labour management, development of mechanised tools as a way of reducing labour costs, ageing crop processing equipment, and replanting with improved crop varieties that can yield over double the current average amount of oil (135). In some cases, modelling analysis can provide new insights into plantation management that suggest possible improvements. A recent example is the application of model optimisation and heuristic techniques that indicated significant potential for yield improvements by reducing the harvest cycle length from 19.6 to 8.3 days in a plantation in Columbia (180). Innovative new ideas for ‘smart’ OP mills have also been advanced (148) as well as the use of digital technologies, such as blockchain, to enhance the performance and transparency of supply chains (181).

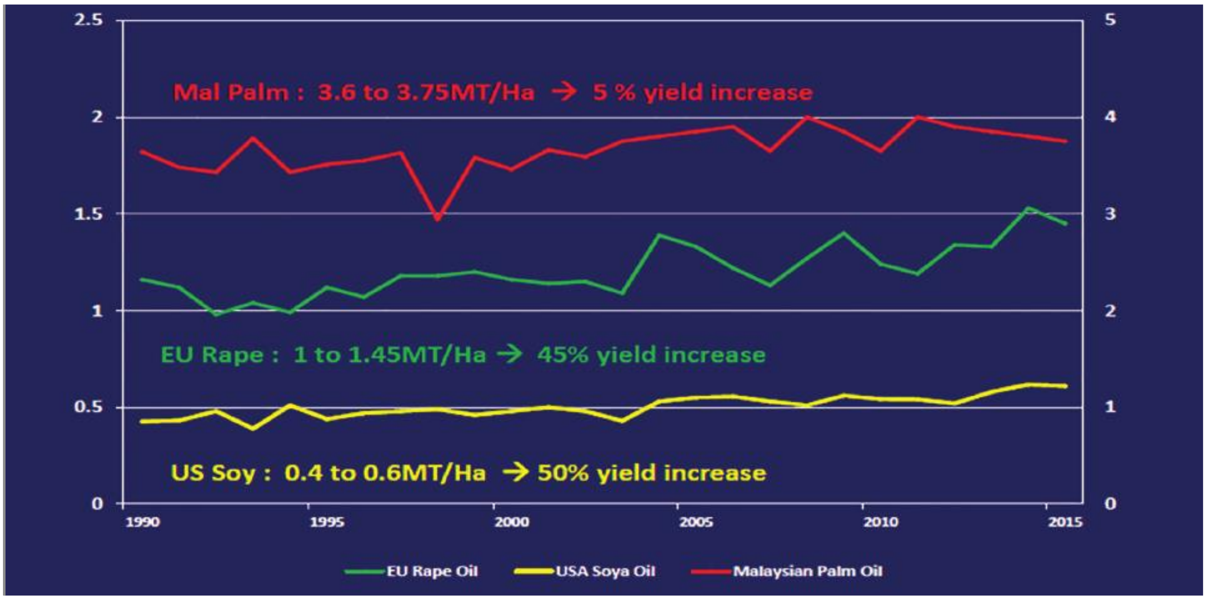


Figure 7. Stagnation of average oil yield in Malaysian OP crops compared to two major competitor oilseeds, rapeseed and soybean. Source: ref 179.

In the long term, the most realistic solution to the current labour problems that plague the sector (37) is the introduction of more effective mechanisation as has been done in other plantation crops (6). One way of facilitating mechanisation and increasing yield is to use modern molecular breeding approaches to modify crop architecture, for example to reduce trunk height as has been done with tree crops such as apples and major cereals such as wheat and rice (182,183). Interestingly, a very recent study has identified three major QTLs associated with OP height on chromosome 11, which could facilitate the breeding of shorter and more compact palms for enhanced yield and ease of harvesting (184). Replanting of ageing and/or poorly performing palms is a vitally important strategy for improving the yield, and hence the overall sustainability and environmental footprint of OP crops. This applies to both large commercial growers and smallholders, many of whom use inferior seeds bought from middlemen with no record of their provenance. While there have been government initiatives in Malaysia and Indonesia, these efforts need to be redoubled and made more effective as the threat from temperate oilseeds continues to increase.

Sustainability and environmental challenges

The issues surrounding the poor image of OP as discussed previously remain serious challenges that have the potential to impact the industry further in the future. Although some producers have addressed these issues, progress across the sector as a whole has been patchy. As seen in recent examples, such as the 2018 boycott by the UK supermarket chain, Iceland, poor practices by a few ‘rogue’ operators (in this case in West Kalimantan, Indonesia) led to the entire OP industry being tarred with the same brush as being a major cause of global deforestation. The industry should also be aware that the kinds of criticisms coming from Europe today might also come from other major importers such as China and India in the future. We have already seen how the levels of environmental awareness and concerns about food quality and safety are steadily increasing, especially among consumers in these Asian mega-economies.

It is evident that the use of OP as a food ingredient in the large EU market has been in steady decline over the past decade (Fig 6). There is little doubt that part of this decline has been due to adverse consumer sentiment about the OP industry in general. To make matters worse, there are now discussions in the EU to require verifiable 'point of origin' declarations for all food-grade palm oil (185). This could mean that any oil that cannot be reliably identified as from a sustainably certified source, such as RSPO, might not be imported into the EU. Clearly the industry needs to address these certification and authenticity issues in its supply chains to ensure that it becomes fully compliant with the requirements of its second largest customer, namely the EU.

On the plus side, there are indications that NGO and consumer sentiment is gradually moving away from consideration of blanket boycotts on all OP products and towards the acceptance of products that are reliably sourced from certified sustainable sources via a transparent and fully traceable supply chain. Encouragingly, there are some grassroots campaigns that support the use of certified sustainable OP in conjunction with action to improve biodiversity in producing countries. For example, in 2019, several UK towns and cities including Chester and Newquay branded themselves as supporters of sustainable palm oil in campaigns that engaged schools, retailers, food outlets and consumers. These are very positive developments but they remain isolated and not widely publicised, and could undone at any time by a new high-profile scandal. There are some analogies between the public perception of OP and that of GM crops, particularly in the often polarised and emotional debates where consideration of scientific evidence can be lacking. The OP sector can learn from such experience and one future priority should be to tackle its image problem in a more productive manner than previously.

Climatic and biosecurity threats

As discussed in detail above, in the past few years, evidence has grown of the existing and likely future impacts of anthropogenic climatic changes on the OP industry. Immediate priorities should include further research to understand climatic effects on OP in the many regions of the tropics where the crop is now grown, and to begin the implementation of mitigation strategies to minimise adverse effects. Most of the climatic threats identified to date involve periods of elevated temperature and reduced rainfall, both of which cause stresses that impact on overall crop performance, and in particular oil yield. Increasingly well documented impacts of climatic cycles such as El Niño and La Niña have underlined the crucial role of climate for OP performance and oil yield (186,187). One of the most important future threats is the emergence of new pests and diseases and/or the movement of existing diseases from one part of the world to another. The transfer of existing biotic threats could occur due to climatic factors but another mechanism is movement via trade, travel or other human agency where potential pathogens might elude current biosecurity measures.

For example, mention has already been made above of the serious impact of *Phytophthora palmivora* on plantations in S America, and if this pathogen were to reach the central growing regions of SE Asia, its impact could be devastating (188). Although there are biosecurity measures already in place, these tend to be focussed on known threats and may not be able to cover all of the many potential entry routes for a new pathogen. An example of an unexpected new form of pathogen of OP is the orange-spotting coconut cadang-cadang viroid variant (OSCCC-Vd) (189). Viroids were only discovered in the 1970s, and are the smallest and simplest known type of infectious pathogen, consisting of just one small, naked, circular single-strand of RNA that does not encode any proteins. The origin of viroids is unknown with some suggestions that they might date from an ancient non-cellular 'RNA world', although a more recent and parsimonious hypothesis is that they have arisen *de novo* on multiple occasions as plant-specific pathogens (190). OSCCC-Vd normally infects coconut plantations and is endemic in the Philippines, but early in 2011 a putative variant was found in OP plantations in Sabah, triggering a ban on the movement of OP materials to other parts of Malaysia. Although threat of OSCCC-Vd eventually receded in the 2010s, it exposed problems in the surveillance mechanisms and phytosanitary procedures in the face of a hitherto unknown pathogen.

The recent covid-19 pandemic has exposed many deficiencies at both local and global levels in terms of responses to novel pathogens, including variants of existing diseases that have mutated into new forms that behave very differently from their progenitors. It is therefore important that members of the global OP industry should establish additional data gathering, surveillance, communication, and if possible, joint policy approaches to discover, assess and combat the new biotic and abiotic threats that are likely to arise in the future.

Conclusions

The global OP industry is a major component of contemporary agriculture, supplying food to billions of people, plus a host of non-food products that include strategically vital cleaning products used in critical health care settings. Compared to other oil crops, OP produces much higher oil yields and has a correspondingly lower land footprint. However, there are well founded concerns about the expansion of OP plantations into sensitive habitats, such as highly biodiverse tropical forests and peatlands. There are no viable alternatives to OP in terms of its yield and delivery of a range of specific oils for human use. Rather than seeking bans or boycotts on OP products, it is therefore important to implement transparent and effective certification schemes right across the industry to guarantee that OP products can be labelled as being derived from environmentally sustainable and socially responsible sources. Such schemes should include the millions of smallholder farmers who make their living from the crop. The industry also needs to redouble its efforts to engage with global consumers in a constructive dialogue aimed at addressing its image problem and explaining the many benefits of its products. OP crops face many other future challenges, including emerging threats from climate change and the likelihood of new pests and diseases, that require more effective international collaboration. Nevertheless, new breeding technologies are providing the promise of improvements, such as much higher yielding varieties, improved oil profiles, enhanced disease resistance and modified crop architecture to enable mechanisation of fruit harvesting. Overall, therefore, while there are many challenges, we consider that the future is potentially bright for the world's most important vegetable oil crop.

Declarations

- The authors declare no competing interests
- All authors contributed to researching and writing the article which was coordinated by DM.
- Ethics approval and consent to participate: n/a
- Consent for publication: n/a
- Availability of data and materials: n/a
- Funding: n/a
- Acknowledgements: n/a
- Authors' information: already provided

References

1. Cosiaux A, Gardiner LM, Stauffer FW, Bachman SP, Sonké B, Baker WJ, et al. Low extinction risk for an important plant resource: Conservation assessments of continental African palms (Arecaceae/Palmae). Biol Conserv [Internet]. 2018

May;221:323–33. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0006320717317627
2. Reddy MT, Kalpana M, Sivaraj N, Kamala V, Pandravada SR, Sunil N. Indigenous Traditional Knowledge on Health and Equitable Benefits of Oil Palm (Elaeis spp.). Open Access Libr J [Internet]. 2019;06(01):1–25. Available from: http://www.oalib.com/paper/pdf/5302374
3. Okolo CC, Okolo EC, Nnadi AL, Obikwelu FE, Obalum SE, Igwe CA. The oil palm (*Elaeis guineensis* Jacq): nature's ecological endowment to eastern Nigeria. Agro-Science [Internet]. 2019 Oct 10;18(3):48. Available from: https://www.ajol.info/index.php/as/article/view/190222
4. Corley, R.H.V., Tinker PB. The Oil Palm. Chichester: Wiley Blackwell; 2015.
5. Malaysian Palm Oil Production by Year [Internet]. Indexmundi. 2020 [cited 2020 Jul 1]. Available from: https://www.indexmundi.com/agriculture/?country=my&commodity=palm-oil&graph=production
6. Murphy DJ. The Future of Oil Palm As a Major Global Crop : Opportunities and Challenges. J Oil Palm Res. 2014;26(March):1–24.
7. Indonseian Palm Oil Production by Year [Internet]. Indexmundi. 2020 [cited 2020 Jul 1]. Available from: https://www.indexmundi.com/agriculture/?country=id&commodity=palm-oil
8. Ommelna, BG, Jennifer, AN, Chong K. The potential of chitosan in suppressing Ganoderma boninense infection in oil-palm seedlings. J Sustain Sci Manag. 2012;7:186–92.
9. Murphy DJ. What is the future for oil palm as a global crop? World Agric. 2015;(5):24–34.
10. Murphy DJ. (2014) From bioinformatics to Brazil: the future of oil palm as a major 21st century global crop, *Malaysian Oil Science & Technology* 23, 1-12
11. Statista. Leading producers of palm oil worldwide from 2012/13 to 2019/20. Statista. 2020. Available from: https://www.statista.com/statistics/856231/palm-oil-top-global-producers/
12. Goggin K, Murphy DJ. Monitoring the traceability, safety and authenticity of palm oils imported in Europe. Oilseeds fats, Crop Lipids [Internet]. 2018;25(6):1–15. Available from: https://www.ocl-journal.org/articles/ocl/full_html/first/ocl180025/ocl180025.html
13. Klandale S, Marten R, Smith R. The palm oil industry and noncommunicable diseases. Bull World Heal Organ. 2019;97(2):118–28.
14. Statisa. Production of major vegetable oils worldwide from 2019/2020 [Internet]. Statista. 2020 [cited 2020 Jul 7]. Available from: https://www.statista.com/statistics/263933/production-of-vegetable-oils-worldwide-since-2000/
15. Murphy DJ. Oil palm: future challenges for a key global crop. In: Oxford Handbook of Water, Food and Society. Oxford University Press, Oxford, UK; Available from: 2018. 10.1093/oxfordhb/9780190669799.013.33
16. Frost and Sullivan. The European, the Middle East and African Oils & Fats Market for Food Applications, Forecast to 2021. Global Food Ingredients Database Series. 2017. Available from: https://store.frost.com/the-european-the-middle-east-and-african-oils-fats-market-for-food-applications-forecast-to-2021.html
17. Harris NL, Brown K, Netzer M, Gunarso P, Killeen TJ. Projections of oil palm expansion in Indonesia, Malaysia and Papua New Guinea from 2010-2050. Reports from the Technical Panels of the 2nd Greenhouse Gas Working Group of the

Roundtable on Sustainable Palm Oil (RSPO), 89-112. 2013. Available from: https://www.researchgate.net/publication/320024842_Projections_of_oil_palm_expansion_in_Indonesia_Malaysia_and_Papua_New_Guinea_from_2010_to_2050
18. Pirker J, Mosnier A, Kraxner F, Havlik P, Obersteiner M. What are the limits to oil palm expansion? Glob Environ Chang. 2016;40.
19. Paterson R. Future scenarios for oil palm mortality and infection by Phytophthora palmivora in Colombia, Ecuador and Brazil, extrapolated to Malaysia and Indonesia. Phytoparasitica. 2020 in press; https://doi.org/10.1007/s12600-020-00815-6
20. Paterson R. Oil palm survival under climate change in Kalimantan and alternative SE Asian palm oil countries with future basal stem rot assessments. For Pathol. 2020 in press;
21. Shahbandeh M. Palm oil: global production volume 2012/13-2018/19 [Internet]. Statista. 2019 [cited 2020 Jan 30]. Available from: https://www.statista.com/statistics/613471/palm-oil-production-volume-worldwide/
22. Paterson, RRM, Lima N. Climate change affecting oil palm agronomy, and oil palm cultivation increasing climate change, require amelioration. Ecol Evol. 2018;
23. Fehlenberg V, Baumann M, Gasparri NI, Piquer-Rodriguez M, Gavier-Pizarro G, Kuemmerle T. The role of soybean production as an underlying driver of deforestation in the South American Chaco. Glob Environ Chang. 2017;45:23–34.
24. Rajão R, Soares-Filho B, Nunes F, Börner J, Machado L, Assis D, et al. The rotten apples of Brazil's agribusiness. Science [Internet]. 2020;369(6501):246–8. Available from: http://www.ncbi.nlm.nih.gov/pubmed/32675358
25. Carvalho TS, Domingues EP, Horridge J. Controlling deforestation in the Brazilian Amazon: Regional economic impacts and land-use change. Land use policy. 2017;64:327–41.
26. Zimmer K. Deforestation is leading to more infectious diseases in humans [Internet]. National Geographic. 2019 [cited 2020 Jul 1]. Available from: https://www.nationalgeographic.com/science/2019/11/deforestation-leading-to-more-infectious-diseases-in-humans/
27. Dislich, C., Keyel, A. C., Salecker, J., Kisel, Y., Meyer, K. M., Auliya, M., … Wiegand K. A review of the ecosystem functions in oil palm plantations, using forests as a reference system. Biological Reviews of the Cambridge Philosophical Society, 49, 1539–1569. Biol Rev Camb Philos Soc. 2017;49:1539–69.
28. Aiken R, Lamm F, Aboukheira AA. Water use of oilseed crops. Proc 23rd Annu Cent Plains Irrig Conf. 2011;
29. Mekonnen MM, Hoekstra AY. The green, blue and grey water footprint of crops and derived crop products. Hydrol Earth Syst Sci Discuss. 2011;8(1):763–809.
30. Riar AS. Overcoming yield limitation of canola by improving water use efficiency. The University of Adelaide; 2015. Available from: https://digital.library.adelaide.edu.au/dspace/ bitstream/2440/98682/2/02whole.pdf
31. Van Noorden R. EU debates U-turn on biofuels policy. Nature. 2013;4(499):13–4.
32. Basiron Y. Palm oil production through sustainable plantations. Eur J Lipid Sci Technol. 2007;109(4):289–95.
33. Xu Y, Yu I, Le W, Ciais P, Cheng Y, Gong P. Annual oil palm plantation maps in Malaysia and Indonesia from 2001 to 2016. Earth Syst Sci Data. 2020;12.
34. Villela AA, Jaccoud DB, Rosa LP, Freitas M V. Status and prospects of oil palm in the Brazilian Amazon. Biomass and Bioenergy. 2014 Aug;67:270–8.
35. Paterson R. Ganoderma boninense disease of oil palm is expected to significantly reduce production after 2050 in Sumatra if projected climate change occurs. Microorganisms. 2019;In press.

36. Paterson RRM. Ganoderma boninense disease deduced from simulation modelling with large data sets of future Malaysian oil palm climate. 2019;47(2):255–62.
37. Jackson TA, Crawford JW, Traeholt C, Sanders TAB. Learning to love the world's most hated crop. J Oil Palm Res. 2019;31(3):331–47.
38. Marlier ME, Defries R, Pennington D, Nelson E, Ordway EM, Lewis J, et al. Future fire emissions associated with projected land use change in Sumatra. Glob Chang Biol. 2014;345–62.
39. Arrieta F, Teixeira F, Yanez E, Lora E, Castillo E. Cogeneration potential in the Columbian palm oil industry: Three case studies. Biomass and Bioenergy. 2007 Jul;31(7):503–11.
40. Ohimain EI, Izah SC. Energy self-sufficiency of smallholder oil palm processing in Nigeria. Renew Energy [Internet]. 2014 Mar;63:426–31. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0960148113005375
41. Paterson RRM, Kumar L, Taylor S, Lima N. Future climate effects on suitability for growth of oil palms in Malaysia and Indonesia. Sci Rep. 2015;5.
42. Suryantini R, Wulandari RS. Diversity of Ganoderma pathogen in Pontianak , West Kalimantan : Characteristics , virulence and ability to infect Acacia mangium seedlings. 2018;19(2):465–71.
43. Pornsuriya, C, Sunpapao, A, Srihanant N, Worapattamasri K, Kittimorakul J, Phithakkit S P V. A survey of diseases and disorders in oil palms in southern Thailand. Plant Pathol J. 2013;12:169–75.
44. Somnuek S, Slingerland MMA, Gr??nb??hel CM. The introduction of oil palm in Northeast Thailand: A new cash crop for smallholders? Asia Pac Viewp. 2016;57(1):76–90.
45. Woods K. Forest Trade and Finance March 2015 Commercial Agriculture Expansion in Myanmar : Links to Deforestation , Conversion Timber , and Land Conflicts. 2015;(March).
46. Nahum JS, Santos LS, Santos C. Formation of palm oil cultivation in Para's Amazon. Mecator (Fortaleza). 2020;19.
47. Paterson RRM, Kumar L, Shabani F, Lima N. World climate suitability projections to 2050 and 2100 for growing oil palm. J Agric Sci. 2017;155(5).
48. Murphy DJ. Growing palm oil on former farmland curs deforestation, Co2 and biodiversity loss [Internet]. The conversation. 2019 [cited 2020 Jul 7]. Available from: https://theconversation.com/growing-palm-oil-on-former-farmland-cuts-deforestation-co-and-biodiversity-loss-127312
49. Byerlee D, Falcon WP, Naylor RL. The tropical oil crop revolution: food, feed, fuel and forests. New Yotk: Oxford University Press; 2017.
50. Krishna VV, Euler M, Siregar H, Oaim M. Differential livelihood impacts of oil palm expansion in Indonesia. Agric Econ. 2017;48.
51. Euler M, Schwarze S, Siregar H, Qaim M. Oil Palm Expansion among Smallholder Farmers in Sumatra, Indonesia. J Agric Econ [Internet]. 2016 Sep;67(3):658–76. Available from: http://doi.wiley.com/10.1111/1477-9552.12163
52. Kubitza C, Khrishna VV, Alamsaya Z, Oaim M. The economics behind an ecolohical crisis: livelihood effects of oil palm expansion in Sumatra, Indonesia. Hum Ecol. 2018;46.
53. Lee JSH, Abood S, Ghazoul J, Barus B, Obidzinski K, Koh LP. Environmental impacts of large-scale oil palm enterprises exceed that of smallholdings in Indonesia. Conserv Lett. 2014;7(1):25–33.
54. Razak SA, Saadun N, Azhar BM, Lindenmayer D. Smallholdings with high oil palm yield also support high bird species richness and diverse feeding guilds. Environ Res

Lett. 2020;
55. Kato Y, Soda R. The impact of RSPO certification on oil palm smallholdings in Sarawak. In: Anthropogenic Tropical Forests, Advances in Asian Human-Environmental Research. Springer; 2019.
56. Euler M, Krishna V, Schwarze S, Siregar H, Oaim M. Oil palm adoption, household welfare and nutrition among smallholder farmers in Indonesia. World Dev. 2017;93.
57. Bennett A, Ravikumar A, McDermott C, Malhi Y. Smallholder oil palm production in the peruvian amazon: rethinking the promise of associations and partnerships for economically sustainable livelihoods. Front Glob Chang. 2019;2(14).
58. May-Tobin C, Boucher D, Decker E, Hurowitz G, Martyn J, Mulik K, et al. Recipes for success: solutions for deforestation-free vegetable oils. Union of Concerned Scientists, Boston. 2012. Available from: https://www.ucsusa.org/ global-warming/solutions/stop-deforestation/deforestation-free-vegetable-oils.html#. Wk5w3kuOnTQ
59. Gaveau DLA, Sloan S, Molidena E, Yaen H, Sheil D, Abram NK, et al. Four decades of forest persistence, clearance and logging on Borneo. PLoS One. 2014;9(7):1–11.
60. Wich SA, Fredriksson GM, Usher G, Peters HH, Priatna D, Basalamah F, et al. Hunting of Sumatran orang-utans and its importance in determining distribution and density. Biol Conserv [Internet]. 2012;146(1):163–9. Available from: http://dx.doi.org/10.1016/j.biocon.2011.12.006
61. Carlson KM, Curran LM, Asner GP, McDonald Pittman A, Trigg SN, Adeney JM. Carbon emissions from forest conversion by Kalimantan oil palm plantations. Nat Clim Chang. 2012;3.
62. Khor YL. The oil palm industry bows to NGO campaigns. Lipid Technol. 2011;23(5):102–4.
63. INDONESIA: Palm oil expansion unaffected by Forest Moratorium [Internet]. USDA. 2013 [cited 2020 Jul 1]. Available from: https://ipad.fas.usda.gov/highlights/2013/06/indonesia/
64. Barcelos E, Rios S de A, Cunha RN V., Lopes R, Motoike SY, Babiychuk E, et al. Oil palm natural diversity and the potential for yield improvement. Front Plant Sci [Internet]. 2015;6(March):190. Available from: http://www.frontiersin.org/Plant_Genetics_and_Genomics/10.3389/fpls.2015.00190/abstract
65. de Vries SC, van de Ven GWJ, van Ittersum MK, Giller KE. Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques. Biomass and Bioenergy [Internet]. 2010;34(5):588–601. Available from: http://dx.doi.org/10.1016/j.biombioe.2010.01.001
66. Schmidt JH. Life cycle assessment of five vegetable oils. J Clean Prod [Internet]. 2015;87(C):130–8. Available from: http://dx.doi.org/10.1016/j.jclepro.2014.10.011
67. Yee KF, Tan KT, Abdullah AZ, Lee KT. Life cycle assessment of palm biodiesel: Revealing facts and benefits for sustainability. Appl Energy [Internet]. 2009;86(SUPPL. 1):S189–96. Available from: http://dx.doi.org/10.1016/j.apenergy.2009.04.014
68. Mekonnen MM, Hoekstra AY. Water footprint benchmarks for crop production: A first global assessment. Ecol Indic. 2014;46:214–23.
69. Sadras VO, Grassini P, Steduto P. Status of water use efficiency of main crops. SOLAW Backgr Themat Rep TR07 [Internet]. 2010;42. Available from: http://www.fao.org/fileadmin/templates/solaw/files/thematic_reports/TR_07_web.pdf
70. Deere NJ, Guillera-Arriota G, Baking EL, Bernard H, Pfeifer M, Reynolds G, et al. High carbon stock forests provide co-benefits for tropical biodiversity. J Appl Ecol.

2017;55(2).
71. Scriven SA, Hodgson JA, McClean CJ, Hill JK. Protected areas in Borneo may fail to conserve tropical forest biodiversity under climate change. Biol Conserv [Internet]. 2015;184:414–23. Available from: http://dx.doi.org/10.1016/j.biocon.2015.02.018
72. Scriven SA, Carlson KM, Hodgson JA, McClean CJ, Heilmayr R, Lucey JM, et al. Testing the benefits of conservation set-asides for improved habitat connectivity in tropical agricultural landscapes. J Appl Ecol. 2019;56(10).
73. Gunarso P, Hartoyo ME, Agus F, Killeen TJ. Oil Palm and Land Use Change in Indonesia , Malaysia and Papua New Guinea. Reports from Tech Panels RSPOs 2nd Greenh Gas Work Gr [Internet]. 2013;(November):29–64. Available from: http://www.rspo.org/file/GHGWG2/4_oil_palm_and_land_use_change_Gunarso_et_al.pdf
74. Chase L, Henson I, Abdul-Manan A, Agus F, Bessou C, Canals LM i, et al. PalmGHG \rA Greenhouse Gas Accounting Tool for \rPalm Products: Accompanying document. http://www.rspo.org/file/RSPO_PalmGHG%20Beta%20version%201.pdf. 2012;
75. Dalal, Ram; Shanmugam S. Consulting Study 6: Practical guidance on how to estimate soil carbon stocks and soil greenhouse gas emissions following tropical forest conversion on mineral soil. Area. 2015;9434(407):9436.
76. Tonks AJ, Aplin P, Beriro DJ, Cooper H, Evers S, Vane CH, et al. Impacts of conversion of tropical peat swamp forest to oil palm plantation on peat organic chemistry, physical properties and carbon stocks. Geoderma. 2017;289:36–45.
77. Cook S. Fluvial organic carbon losses from tropical peatland oil palm plantations in Sarawak, Malaysia. University of Leicester; 2018.
78. Rehman S, Sabiham S, Sudadi U, Anwar S. Impacts of Oil Palm Plantations on Climate Change: A Review of Peat Swamp Forests’ Conversion in Indonesia. Int J Plant Soil Sci. 2015;4(1):1–17.
79. Veloo R, Van Ranst E, Selliah P. Peat Characteristics and its Impact on Oil Palm Yield. NJAS - Wageningen J Life Sci [Internet]. 2015;72:33–40. Available from: http://dx.doi.org/10.1016/j.njas.2014.11.001
80. Veloo R, Paramananthan S, Van Ranst E. Classification of tropical lowland peats revisited: The case of Sarawak. Catena [Internet]. 2014;118:179–85. Available from: http://dx.doi.org/10.1016/j.catena.2014.01.004
81. Wicke B, Sikkema R, Dornburg V, Faaij A. Exploring land use changes and the role of palm oil production in Indonesia and Malaysia. Land use policy [Internet]. 2011;28(1):193–206. Available from: http://dx.doi.org/10.1016/j.landusepol.2010.06.001
82. Paterson RRM. Ganoderma boninense. In: Crop Protection Compendium. Wallingford: CABI Publishing; 2020.
83. Paterson RRM, Sariah M, Lima N. How will climate change affect oil palm fungal diseases? Crop Prot. 2013 Apr;46:113–20.
84. Paterson R. Phytophthora present in oil palm? PLoS ONE, 2020. https://journals.plos.org/plosone/article/comment?id=10.1371/annotation/afcb5949-27bc-4e37-a8b0-bf4525e986f2 .
85. Zhou L-W, Cao Y, Wu S-H, Vlasák J, Li D-W, Li M-J, et al. Global diversity of the Ganoderma lucidum complex (Ganodermataceae, Polyporales) inferred from morphology and multilocus phylogeny. Phytochemistry. 2015;114:7–15.
86. Merciere M BR, C C, C K, YP L, JS T, SR SA, et al. About Ganoderma boninense in oil palm plantations of Sumatra and peninsular Malaysia : Ancient population expansion , extensive gene flow and large scale dispersion ability. Fungal Biol. 2017;121:529–40.

87. Paterson, RRM; Lima N. Ecology and biotechnology of thermophilic fungi on crops under global warming. In: Tiquia-Arashiro SM, editor. Fungi in extreme environments: Ecological and biotechnological significance. Springer Verlag; 2019.
88. Adusei-Fosu, K Dickinson, M Yankey EN. AFLP as a fingerprinting tool for characterising isolates of Fusarium oxysporum f. sp. elaeidis causal organism for fusarium wilt disease of oil palm in Ghana. J Plant Dis Prot. 2019;126:575–584.
89. Cooper RM. DISEASE EPIDEMIOLOGY AND GENETIC DIVERSITY OF Fusarium oxysporum f . sp . elaeidis , CAUSE OF Fusarium WILT OF OIL PALM (Elaeis guineensis Jacq .). 2017;29(DECEMBER):548–61.
90. Rusli MH, Seman IA, Norhana Z, Yusof B. Fusarium Vascular Infection of Oil Palm: Epidemiology, Molecular Diagnostic Tools and the Potential of Fusarium Suppressive Soil in Malaysia. 2013;2(January):578–85.
91. Cochard Amblard P, Durand-gasselin T. Oil palm genetic improvement and sustainable development. 2005;12:141–7.
92. Rusli MH, Idris AS, Cooper RM. Evaluation of Malaysian oil palm progenies for susceptibility , resistance or tolerance to Fusarium oxysporum f . sp . elaeidis and defence-related gene expression in roots. 2015;638–47.
93. Paterson RRM. Ganoderma philippii. In: Crop Protection Compendium. Wallingford: CABI Publishing;
94. Ramle M, Wahid MB, Norman K, Glare TR, Jackson TA. The incidence and use of Oryctes virus for control of rhinoceros beetle in oil palm plantations in Malaysia. J Invertebr Pathol. 2005;89(1):85–90.
95. Caudwell RW, Orrell I. Integrated pest management for oil palm in Papua New Guinea. Integr Pest Manag Rev. 1997;2:17–24.
96. Rosenzweig C, Karoly D, Vicarelli M, Neofotis P, Wu Q, Casassa G, et al. Attributing physical and biological impacts to anthropogenic climate change. Nature. 2008;453(7193):353–7.
97. Shabani F, Kumar L, Taylor S. Climate Change Impacts on the Future Distribution of Date Palms: A Modeling Exercise Using CLIMEX. PLoS One. 2012;7(10):1–12.
98. Thackeray SJ, Sparks TH, Frederiksen M, Burthe S, Bacon PJ, Bell JR, et al. Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. Glob Chang Biol. 2010;16(12):3304–13.
99. Walsh RE, Aprígio Assis AP, Patton JL, Marroig G, Dawson TE, Lacey EA. Morphological and dietary responses of chipmunks to a century of climate change. Glob Chang Biol. 2016;22(9):3233–52.
100. Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F. Impacts of climate change on the future of biodiversity. Ecol Lett. 2012;15(4):365–77.
101. Parmesan C. Ecological and Evolutionary Responses to Recent Climate Change. Annu Rev Ecol Evol Syst. 2006;37(1):637–69.
102. Sinervo B, Méndez-de-la-Cruz F, Miles DB, Heulin B, Bastiaans E, Cruz MVS, et al. Erosion of lizard diversity by climate change and altered thermal niches. Science (80-). 2010;328(5980):894–9.
103. Urban M. Accelerating extinction risk from climate change. Science (80-). 2015;348:571–3.
104. Brooke C. Conservation and adaptation to climate change. Conserv Biol. 2008;22(6):1471–6.
105. Lobell DB, Field CB, Cahill KN, Bonfils C. Impacts of future climate change on California perennial crop yields: Model projections with climate and crop uncertainties. Agric For Meteorol. 2006;141(2–4):208–18.
106. Ghini R, Bettiol W, Hamada E. Diseases in tropical and plantation crops as affected by

climate changes: current knowledge and perspectives. Plant Pathol. 2011 Feb;60(1):122–32.
107. Feeley KJ, Stroud JT, Perez TM. Most ‘ global ’ reviews of species ’ responses to climate change are not truly global. 2017;231–4.
108. Sarkar SK. Impacts of climate change on oil palm production in Malaysia. 2020;9760–70.
109. Lenoir J, Svenning J. Climate-related range shifts – a global multidimensional synthesis and new research directions. 2015;(April 2014):15–28.
110. IPCC. "AR5 Synthesis Report - Climate Change 2014. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 2014;
111. Fei S, Desprez JM, Potter KM, Jo I, Knott JA, Oswalt CM. Divergence of species responses to climate change. 2017;(May).
112. Ramirez-Cabral NYZ, Kumar L, Shabani F. Global alterations in areas of suitability for maize production from climate change and using a mechanistic species distribution model (CLIMEX). Sci Rep. 2017;(June):1–13.
113. Shabani F, Kumar L, Esmaeili A. Future distributions of Fusarium oxysporum f. spp. in European, Middle Eastern and North African agricultural regions under climate change. Agric Ecosyst Environ. 2014;197:96–105.
114. Paterson RRM. Climate change affects detrimentally oil palm growth and Ganoderma boninense disease of oil palm requiring amelioration. In: Shaping The Future Through Agricultural Innovation 13-15 November, Universiti Putra Malaysia, Malaysia. Selangor: Universiti Putra Malaysia; 2018. p. 49.
115. Paterson R. Climate change, oil palm and basal stem rot of oil palm. In: 3rd International Conference on Agricultural & Food Sciences, 26-28 November, Thailand. Bangkok: Agripace org; 2018. p. 8.
116. Paterson RRM. Climate change affecting oil palm agronomy , and oil palm cultivation increasing climate change , require amelioration. 2018;(September 2017):452–61.
117. Koh, L. P. & Wilcove DS. Is oil palm agriculture really destroying tropical biodiversity? Conserv. Lett. 1. 2008. p. 60–64.
118. Fitzherbert EB, Struebig MJ, Morel A, Danielsen F, Donald PF, Phalan B. How will oil palm expansion affect biodiversity ? Trends Ecol Evol. 2008;23(10):538–45.
119. Meijaar E, Sheil D. The moral minefield of ethical oil palm and sustainabel development. Front For Glob Chang. 2019;2(22):1–15.
120. Blach-Overgaard A, Balslev H, Dransfield J, Normand S, Svenning J. Global-change vulnerability of a key plant resource , the African palms. Nat Publ Gr. 2020;1–10.
121. Tang KHD. Climate change in Malaysia: Trends, contributors, impacts, mitigation and adaptations. Sci Total Environ. 2019;650:1858–71.
122. Rival A. Breeding the oil palm (*Elaeis guineensis* Jacq.) for climate change. Ocl. 2017;24(1):D107.
123. Rajanaidu N, Ainul M, Kushairi A. Historical review of oil palm breeding journey for the past 50 years- Malaysian journey. Proc Int Semin oil palm Breed. 2014;
124. Ithnin M, Kushari A. The oil palm genome. London: Springer; 2020.
125. Low L. The oil palm genome revolution. J Oil Palm Res. 2020;29.
126. Nyouma A, Bell JM, Jacob F, Cros D. From mass selection to genomic selection: one century of breeding for quantitative yield components of oil palm (Elaeis guineensis Jacq.). Tree Genet Genomes. 2019;15(60).
127. Yarra R, Cao H, Jin L, Mengdi Y, Zhou L. CRISPR/Cas mediated base editing: a practical approach for genome editing in oil palm. 3 Biotech. 2020;10.
128. Ting NC, Mayes S, Massawe F, Sambanthamurthi R, Jansen J, Alwee SSRS, et al.

Putative regulatory candidate genes for QTL linked to fruit traits in oil palm (Elaeis guineensis Jacq.). Euphytica. 2018;
129. Babu BK, Rani MK., Sahu SR., Mathur R., Kumar NP, Ravichandran G, et al. Development and validation of whole genome-wide and genic microsatellite markers in oil palm (Elaeis guineensis Jacq.): First microsatellite database (OpSatdb). Sci Rep. 2019;9(1899).
130. Singh R, Ong-Abdullah M, Low LET, Manad MAAM, Rosli R, Nookiah R, et al. Oil palm genome sequence reveals divergence of infertile species in old and new worlds. Nature. 2013;500.
131. Ong A, Teh C, Kwong Q, Tangaya P, Appleton DR, Massawe F, et al. Linkage-based genome assembly improvement of oil palm (Elaeis guineensis). Sci Rep. 2019;9.
132. Herrero J, Santika B, Herran A, Erika P, Sarimana U, Wendra F, et al. Construction of a high density linkage map in oil palm using SPET markers. Sci Rep. 2020;10(9998).
133. Osorio-Guarin JA, Garzon-Martinez GA, Delgadillo-Duran P, Bastidas S, Moreno LP, Enciso-Rodriguez FE, et al. Genome-wide association study (GWAS) for morphological and yield-related traits in an oil palm hybrid (Elaeis oleifera x Elaeis guineensis) population. BMC Plant Biol. 2019;19.
134. Xia W, Luo T, Dou Y, Zhang W, Mason AS, Huang D, et al. Identification and validation of candidate genes involved in fatty acid content in oil palm by genome-wide association analysis. Front Plant Sci. 2019;
135. Sime Darby. A quantum leap with genome select [Internet]. 2020 [cited 2020 Jul 7]. Available from: http://www.simedarbyplantation.com/sustainability/beliefs-progress/our-stories/a-quantum-leap-with-genome-select
136. Kroon JTM, Wei W, Simon WJ, Slabas AR. Identification and functional expression of a type 2 acyl-CoA:diacylglycerol aclytransferase (DGAT2) in developing castor bean seeds which has high homology to the major triglyceride biosynthetic enzyme of fungi and animals. Phytochemistry. 2006;67(23):2541–9.
137. Shockey JM, Gidda SK, Chapital DC, Kuan J, Dhanoa PK, Bland JM, et al. Tung Tree DGAT1 and DGAT2 have nonredundant functions in triacylglycerol biosynthesis and are localised to different subdomains of the endoplasmic reticulum. Plant Cell. 2006; 18, 2294-2313
138. Parveez GKA, Bahariah B, Ayub NH, Masani MYA, Rasid OA, Tarmizi AH, et al. Production of polyhydroxbutytate in oil palm (Elaeis guineensis Jacq.) mediated by microprojectile bombardment of PHB biosynthesis genes into emryogenic calli. Front Plant Sci. 2015; 6, 598
139. Yunus AMM, Chailing H, Parveez GKA. Construction of phb and phbv transformation vectors for bioplastics production in oil palm. J Oil Palm Res. 2008;2(SPEC. ISS. JULY):37–55.
140. Doveri S, O'Sullivan DM, Lee D. Non-concordance between Genetic Profiles of Olive Oil and Fruit : a Cautionary Note to the Use of DNA Markers for Provenance Testing. 2006;54(24):9221–6.
141. Rafalski JA. Association genetics in crop improvement. Curr Opin Plant Biol [Internet]. 2010;13(2):174–80. Available from: http://dx.doi.org/10.1016/j.pbi.2009.12.004
142. Ribaut JM, de Vicente MC, Delannay X. Molecular breeding in developing countries: challenges and perspectives. Curr Opin Plant Biol [Internet]. 2010;13(2):213–8. Available from: http://dx.doi.org/10.1016/j.pbi.2009.12.011
143. Tuberosa R, Salvi S. Genomics-based approaches to improve drought tolerance of crops. Trends Plant Sci. 2006;11(8):405–12.
144. Xu Y. Molecular Plant Breeding. Oxford: CABI Publishing; 2010.

145. Ong PW, Maizura I, Marhalil M, Rajanaidu N, Abdullah NAP, Rafii MY, et al. Association of SNP markers with heigh increment in MPOB-Angolan natural oil palm populations. J Oil Palm Res. 2018;30(1).
146. Wong MY, Govender NT, Ong CS. RNA-seq data of Ganoderma boninense at axenic culture condition and under in planta pathogen-oil palm (Elaeis guineensis Jacq.) interaction. BMC Res Notes [Internet]. 2019;12(1):10–2. Available from: https://doi.org/10.1186/s13104-019-4652-y
147. Ho CL, Tan YC, Yeoh KA, Ghazali AK, Yee WY, Hoh CC. De novo transcriptome analyses of host-fungal interactions in oil palm (Elaeis guineensis Jacq.). BMC Genomics [Internet]. 2016;17(1):1–19. Available from: http://dx.doi.org/10.1186/s12864-016-2368-0
148. Isaac J. Industrial revolution 4.0 for smart oil palm mills. Malaysian Oil Sci Technol. 2019;28:28–36.
149. Paterson RRM, Moen S, Lima N. The feasibility of producing oil palm with altered lignin content to control ganoderma disease. J Phytopathol. 2009;157(11–12):649–56.
150. Corley RH V., Tinker PBH. The Oil Palm. 4th ed. Wiley-Blackwell; 2008. 121–592 p.
151. Lyons-White J, Knight AT. Palm Oil Supply Chain Complexity Impedes Implementation of Corporate No-Deforestation Commitments. Glob Environ Chang. 2018;50:303–13.
152. RSPO Supply Chains [Internet]. RSPO. 2017 [cited 2017 Jun 19]. Available from: http://www.rspo.org/certification/supply-chains
153. RSPO. RSPO Supply Chain Certification Systems. 2009.
154. Meijaard E, Garcia-Ulloa J, Sheil D, Wich SA, Carlson KM, Juffe-Bignoli D, et al. Oil Palm and Biodiversity. A situation analysis by the IUCN Oil Palm Task Force. 2018.
155. Dhaka V, Gulia N, Ahlawat KS, Khatkar BS. Trans fats — sources , health risks and alternative approach - A review. 2011;20894.
156. Chowdhury R, Wamakula S, Kunutsor S, Crowe F, Ward HA, Johnson L, et al. Association of dietary, circulating, and supplement fatty acids with coronary risk. Ann Intern Med. 2014;160(6).
157. Marklund M, Wu JHY, Imamura F, Del Gobbo LC, Fretts A, De Goede J, et al. Biomarkers of Dietary Omega-6 Fatty Acids and Incident Cardiovascular Disease and Mortality: An Individual-Level Pooled Analysis of 30 Cohort Studies. Circulation. 2019;139(21):2422–36.
158. Dong S, Xia H, Wang F, Sun G. The Effect of Red Palm Oil on Vitamin A Deficiency : A Meta-Analysis of Randomized Controlled Trials. 2017;8223(01):22–3.
159. Maia SB, Sandro A, Souza R, Fátima M De, Caminha C, Lins S. Vitamin A and Pregnancy : A Narrative Review. 2019;24–5.
160. Sommerburg O, Spirt S De, Joachim C. Supplementation With Red Palm Oil Increases β - carotene and Vitamin A Blood Levels in Patients With Cystic Fibrosis National Center for Biotechnology Information. 2015;19.
161. Reardon K, Pad R. " Consumers don't see tigers dying in palm oil plantations ": a cross-cultural comparative study of UK , Malaysian and Singaporean consumer views of palm oil. Asian Geographer 36 (2), 117-141, 2019.
162. Borrello M, Annunziata A, Vecchio R. Sustainability of Palm Oil : Drivers of Consumers ' Preferences. Sustainability. 2020;
163. Alberts EC. That coconut oil you love? Species have gone extinct over it. True story [Internet]. Mongabay. 2020 [cited 2020 Jul 1]. Available from: https://news.mongabay.com/2020/07/that-coconut-oil-you-love-species-have-gone-extinct-over-it-true-story/
164. Supermarkets snub coconut goods picked by monkeys [Internet]. BBC News. 2020

[cited 2020 Jul 1]. Available from: https://www.bbc.co.uk/news/amp/business-53276071
165. FAO. Food outlook- biannual report on global food markets. Rome; 2020. Available from: http://www.fao.org/3/ca9509en/ca9509en.pdf
166. CPET. Sustainable palm derivatives in cleaning and personal care products [Internet]. CPET. 2015 [cited 2020 Jul 7]. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/444001/CPET_Palm_Oil_Derivatives_in_Cleaning_and_Personal_Care_Products_08_07_15_External_FINAL.pdf
167. Webinar on mitigating the impact of Covid-19 on Malaysian Palm Oil Trade [Internet]. MPOC. 2020 [cited 2020 Jul 1]. Available from: https://mpoc.eu/webinar-on-mitigating-the-impact-of-covid-19-on-malaysian-palm-oil-trade/
168. Voelker TA, Hayes TR, Cranmer AM, Turner JC, Davies HM. Genetic engineering of a quantitative trait: Metabolic and genetic parameters influencing the accumulation of laurate in rapeseed. Vol. 9, Plant Journal. 1996. p. 229–41.
169. Chua KB. Nipah Virus Outbreak in Malaysia. J Clin Virol. 2007;26.
170. Public Health England. Nipah virus: epidemiology, outbreaks and guidance [Internet]. Public Health England. 2019 [cited 2020 Jul 7]. Available from: https://www.gov.uk/guidance/nipah-virus-epidemiology-outbreaks-and-guidance
171. WHO. Emergencies, preparedness, response [Internet]. WHO. 2020 [cited 2020 Jul 1]. Available from: https://www.who.int/csr/disease/nipah/en/
172. Chua KB, Chua BH, Wang CW. Anthropogenic Deforestation, El Nino and the Emergence of Nipah Virus Outbreak in Malaysia. Malays J Pathol. 2002;24.
173. Looi LM, Chua KB. Lessons from the Nipah virus outbreak in Malaysia. Malays J Pathol. 2007;29.
174. Lim S. EU-Indonesia FTA Relations: Palm Oil- In for a Rough Ride? EU-Asia at a Glance [Internet]. European Institute for Asian Studies. 2018 [cited 2020 Jul 7]. Available from: http://www.eias.org/wp-content/uploads/2016/03/Selynn-EU-ASIA-AT-A-GLANCE.pdf
175. Muzii N. Almost two-thirds of palm oil consumed in the EU is burned as energy- new data. Transport and Environment. 2019.
176. Department for Transport. Open consultation: consulting on ending the sale of new petrol, dieals and hybrid cars and vans [Internet]. gov.uk. 2020 [cited 2020 Jul 1]. Available from: https://www.gov.uk/government/consultations/consulting-on-ending-the-sale-of-new-petrol-diesel-and-hybrid-cars-and-vans
177. Three ways that Covid-19 is impacting the biofuels sector. BloombergNEF. 2020.
178. Parmar A. Indonesia mulls future of B30 biodiesel mandate [Internet]. Argus. 2020 [cited 2020 Jul 1]. Available from: https://www.argusmedia.com/en/news/2106098-indonesia-mulls-future-of-b30-biodiesel-mandate
179. Chandran MR. Future viability and sustainability of plantation crops. Malaysian Oil Sci Technol. 2019;28:56–60.
180. Escallón-Barrios M, Castillo-Gomez D, Leal J, Montenegro C, Medaglia AL. Improving harvesting operations in an oil palm plantation [Internet]. Annals of Operations Research. Springer US; 2020. Available from: https://doi.org/10.1007/s10479-020-03686-6
181. Keong NW. Modernising sales and widening markets. Malaysian Oil Sci Technol. 2019;28:32–6.
182. Murphy DJ. Plants, Biotechnology and Agriculture. Oxford: CABI Publishing; 2011.
183. Nagai K, Mori Y, Ishikawa S, Furuta T, Gamuyao R, Niimi Y, et al. Antagonistic regulation of the gibberellic acid response during stem growth in rice [Internet].

Nature. Springer US; 2020. Available from: http://dx.doi.org/10.1038/s41586-020-2501-8
184. Teh CK, Ong AL, Mayes S, Massawe F, Appleton DR. Major qtls for trunk height and correlated agronomic traits provide insights into multiple trait integration in oil palm breeding. Genes (Basel). 2020;11(7):1–15.
185. Southey F. Enforcing sustainability in palm oil: what would mandatory due diligence look like? [Internet]. Food Navigator. 2020 [cited 2020 Jul 1]. Available from: https://www.foodnavigator.com/Article/2020/06/08/Enforcing-sustainability-in-palm-oil-What-would-mandatory-due-diligence-look-like
186. Rahutomo S. BMP's FOR FACING DROUGHT STRESS ON OIL PALM. 2016; Available from: http://www.iopri.org/wp-content/uploads/2016/09/ISOPA-Paper-I.pdf
187. USDA. El Nino drought reduces 2015/16 corn prospects in South Africa [Internet]. USDA. 2016 [cited 2020 Jul 1]. Available from: https://ipad.fas.usda.gov/highlights/2016/05/SouthAfricaElNino/index.htm
188. Mohamed Azni INA, Sundram S, Ramachandran V. Pathogenicity of Malaysian Phytophthora palmivora on cocoa, durian, rubber and oil palm determines the threat of bud rot disease. For Pathol. 2019;49(6):1–11.
189. Coconut cadang-cadang viroid (cadang cadang disease) [Internet]. CABI. 2020 [cited 2020 Jul 1]. Available from: https://www.cabi.org/isc/datasheet/13700
190. Catalán P, Elena SF, Cuesta JA, Manrubia S. Parsimonious scenario for the emergence of viroid-like replicons de novo. Viruses. 2019;11(5):1–20.
191. Gunstone FD, Harwood JL, Dijkstra AJ, eds, *The Lipid Handbook*, 3rd Edition, Taylor & Francis, UK

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2020 doi:10.20944/preprints202012.0129.v1

 doi:10.20944/preprints202012.0129.v1

 doi:10.20944/preprints202012.0129.v1

 doi:10.20944/preprints202012.0129.v1