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ARTICLE

Future Scenarios for CO_2 Sequestration by Oil Palm in Southeast Asia Versus Other Regions to Reduce Climate Change

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ABSTRACT

Carbon dioxide (CO_2) emissions from fossil fuels are a significant contributor to climate change. Concentrations of CO_2 were in balance when emissions were controlled by the photosynthetic capabilities of organisms on land and in oceans. Palm oil is a valuable commodity, and vast plantations of oil palm (OP) have been created, especially in Malaysia and Indonesia, which have involved destroying rainforests and growing palms on peat soil, which increases CO_2 emissions. However, OPs are effective at sequestrating CO_2, and growing OPs on degraded land may allow sequestration to combat climate change. Future scenarios for CO_2 sequestration are presented in this report by employing a CLIMEX computer programme, climate models, and narratives to determine optimal future sequestration. High levels of CO_2 sequestration by OP will be maintained generally until 2070, but this will decrease dramatically by 2100. Parts of Malaysia and Indonesia will have significantly greater sequestration than others. Some novel regions of high sequestration may occur in Paraguay and Uganda. Overall, it cannot be assumed that the OP will continue to sequester CO_2 in the same places where it currently grows well. The modelling provides a basis for making decisions regarding where to grow OP for CO_2 sequestration in the future. More modelling of future OP growth is required, focusing on the CO_2 sequestration potential.

Keywords: *Elaeis guineensis*; CLIMEX; Narrative Model; Carbon Dioxide; Climate Change; Sequestration; Malaysia

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1. Introduction

Carbon dioxide (CO_2) levels in the atmosphere have increased significantly. The main cause is the indiscriminate use of fossil fuels since the industrial revolution, which cannot be reduced to safe levels by normal photosynthetic processes [1], leading to climate change. Urgent remedial action is required [2,3]. Furthermore, the average annual global temperature in 2024 was the hottest year on record, with a value of 1.6 °C above preindustrial levels. The global target average is 1.5 °C over a 20-year period [4]; hence, high levels of warming are already occurring. Suggestions to combat climate change have been provided [3].

Climate change is likely to affect the growth and yields of many crops in the future [5–8]. For example, climate change is expected to negatively affect coffee until 2050 and will have a more nuanced effect on avocado and cashews [5]. Colozza [2] emphasised the potential negative effect of climate change on crops such as coffee and oil palm (*Elaeis guineensis*) (OP) on the health and wellbeing of children in Indonesia: OP will be badly affected in other OP growing countries in addition [9,10]. Soy, which competes with OP in the vegetable oil market, will be significantly affected, especially by drought and high temperatures in Ghana [7], and will have diverse effects worldwide [11]. Tropical forests, where OP has often been grown, will also be subjected to climate change [12]. For example, forests in Brazil may convert into Savannas in the future [13].

A potential method for decreasing CO_2 in the atmosphere is to increase CO_2 sequestration by growing more trees. However, this will not contribute to geological net zero requirements [14]: Passive CO_2 capture from newly grown trees is somewhat uncertain as the trees will be subjected to fire damage, temperature changes, precipitation alterations, pests and disease, unlike engineered CO_2 capture and geological storage. On the other hand, the technology for engineered carbon capture has inherent problems, such as a requirement for unrealistically large carbon capture facilities [3], and numerous R&D projects have failed to result in functioning technology ready for usage at scale [15]. Meanwhile, there remains the urgent requirement to reduce the use of fossil fuels drastically.

Deforestation can lead to significant reductions in CO_2 sequestration [16]. The OP industry has contributed to deforestation and peat land clearance, which has led to frequent peat fires and peat decomposition, resulting in high CO_2 emissions. OP has grown most in Indonesia, followed by Malaysia, which together supply 85% of the palm oil to the vegetable oil market. On the other hand, OP sequesters CO_2, although at a rate that does not compensate for the loss from deforestation and peat utilisation [16,17] that occur, especially in Indonesia and Malaysia. If OP were grown on (a) degraded pasture and (b) soil used to grow low-carbon annual crops, then overall sequestration may be positive [1,18], and there is a requirement to more clearly indicate where these areas may occur globally. The oil palm companies in Southeast Asia may be able to benefit from this information by growing OP in these regions in the future. The CO_2 sequestration potential of OP has been reported [19,20]. OPs are replaced in plantations when they become unproductive, whereas in natural forests, the old and dying trees remain, which reduces the overall CO_2 sequestration potential [1]. In addition, OP, are large trees that sequester much more CO_2 than annual crops such as soy or sunflower, which are much smaller plants. Furthermore, Paterson [21] indicated that there may be refuges from climate change in continents that grow OP, where sequestration would be higher in these sanctuaries. Increased sequestration by OP will improve the OP industry's environmental credentials, aligning with other schemes being introduced as part of the circular economy [22].

The ability to sequester CO_2 is highly related to the suitability of the climate for growing plants, and the climate is very likely to change a great deal in the future [3], which is also likely to affect OP. Large parts of Malaysia, Indonesia, Thailand, Colombia, and Nigeria, which are OP-growing countries, will become less suitable [23], and sequestration will decrease, although some parts of each country will decrease more than others [9,10]. In addition, CO_2 fertilisation may be possible, whereby high concentrations of CO_2 in the atmosphere lead to increased plant growth. This may result in higher yields from crops, although the fertilisation rates are often less than predicted levels [24]. Walker et al. [25] indicated a definite C sink from increased CO_2, but the magnitude was uncertain, and Way et al. [26] commented that there is little confidence in attributing gross primary productivity, instantaneous water use efficiency, and biomass production to increasing CO_2 concentrations. Nevertheless, high CO_2

levels' effects on OP have been modelled [27], which indicated a large increase in palm oil yields in various countries, including Malaysia, although Paterson [28] commented that the effects of future climate and disease require more consideration. In reality, palm oil yields have stagnated over the past few decades [29] despite CO_2 levels increasing [30], although other reasons may be involved (e.g., depleted soils, disease, and climate change growth effects), which will likely become more severe. Palm oil yields are currently very low compared to the potential [1] and modelling suggests that future suitable climate for growing OP would indicate reduced yields, especially by 2100 [8]. More consideration of CO_2 fertilisation is required in future climate schemes.

In the current paper, scenarios are provided for future percentage living OP (LOP) and potential sequestration (pSEQ) determined from climate suitability data for growing OP [9,10]. Narratives for (a) climate change, (b) fungal diseases, and (c) a fungus-like disease are also provided to indicate how CO_2 sequestration by OP in the future may develop and where oil palm companies based in Southeast Asia could develop in the future.

2. Materials and Methods

The computer modelling in the current paper was based on the results of Paterson et al. [9,10]. In brief, the Global Biodiversity Information Facility (GBIF) (http://www.gbif.org/, accessed November 13, 2024) was employed. Additional literature on OP was in CAB Direct (http://www.cabdirect.org/web/about.html, accessed of Paterson et al. [9,10]. In brief, the Global Biodiversity Information Facility (GBIF) (http://www.gbif.org/), November 13, 2024) was employed and formed the basis for the collection of data on *E. guineensis* distribution. CLIMEX for Windows, Version 347 (Hearne Scientific Software Pty Ltd., Melbourne, Australia, 2007) was used to determine the distribution models for OP for 2050 and 2100, and climate data and climate change scenarios used the CliMond 10′ gridded climate data. The data collection was based on the distribution of OP records used in fitting the parameters [9,10]. A mechanistic niche model using CLIMEX software (Version 347) supported ecological research, incorporating the modeling of species' potential distributions under differing climate scenarios and assuming that climate was the paramount determining factor of plant distributions. The CLIMEX output categorized areas according to climate, designating highly suitable, suitable, marginal, and unsuitable climates, based on other studies conducted through CLIMEX. Parameters of climate incorporated in the meteorological database are the mean monthly temperature maxima and minima (Tmax and Tmin), mean monthly precipitation level (Ptotal), and relative humidity at 09:00 h (RH09:00) and 15:00 h (RH15:00). The narrative modelling was developed as follows:

2.1. Living Oil Palm

LOP was considered to be 100% in the initial years of 2015/2017. The percentage of LOP after exposure to a changing suitable climate was determined by changes in suitable climate as presented in previous papers using the averages of two climate models (CIROC Mk 3 and MIROC-H) [31–34]. The percentage of OP that remained living after the disease was calculated by taking into account the effect on OP mortality of fungal diseases from changes in suitable climate. The fungal diseases considered were basal stem rot by *Ganoderma boninense* [30], OP bud rot by *Phytophthora palmivora* [35], and fusarium wilt by *Fusarium oxysporum* f. sp. *elaeidis* [34].

2.2. Potential Sequestration

The change in suitable climate data from 2015 to 2100 was determined as previously described and used to obtain pSEQ. The change in CO_2 sequestration was determined using a 1% change in CO_2 sequestration per 1% change in suitable climate. The change in sequestration due to climate-induced fungal diseases was calculated as a 1% change in sequestration per 1% change in BSR and bud rot. A 4% change in sequestration per 1% change in suitable climate was used for Fusarium wilt, which is more lethal. A greater than 100% pSEQ does not imply that the existing OP utilises CO_2 more efficiently, but rather that there is more land available on which to grow more OP in the future. The percentage of living OP capable of healthy sequestration was also determined by calculating the percentage of living OP that would sequestrate, using the percentage sequestration factor [**Equation (1)**].

$$\frac{\text{LOP}}{100} \times \text{pSEQ} \tag{1}$$

3. Results

Figure 1 indicates that the LOP in Malaysia decreased to 90% and 61% by 2070 and 2100, respectively. The percentage change in pSEQ demonstrated a slight increase to 104% by 2050, which then decreased to 90% by 2070 and further to 24% by 2100. The percentage of OP that could undertake pSEQ maintained a constantly high level of 100% until 2050 and then decreased to 84% by 2070, with a large decrease to 15% by 2100. In Sabah, the LOP figures were 100% until 2070, which decreased to 71% by 2100 (**Figure 2**). pSEQ increased to 103% by 2050 and decreased to 101% and 80% by 2070 and 2100, respectively. The percentage of OP with healthy pSEQ was 100% in 2030, increasing to 103% by 2050, and then decreasing to 95% and 57% by 2070 and 2100, respectively.

Figure 1. The effect of changes in suitable climate on the future percentage of living oil palm, the percentage of potential CO_2 sequestration, and the percentage of healthy oil palm capable of CO_2 sequestration in Malaysia.

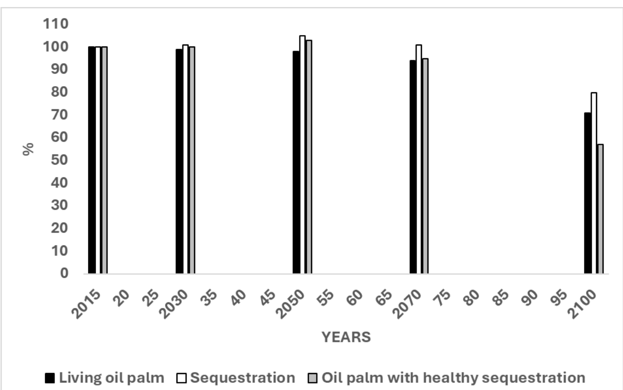

Figure 2. The effect of changes in future suitable climate on the future percentage of living oil palm, the percentage of potential CO_2 sequestration, and the percentage of healthy oil palm capable of CO_2 sequestration in Sabah, Malaysia.

The percentage LOP decreased gradually to 88% and 63% by 2070 and 2100, respectively, in the scenario for Indonesia, from values of 99% and 96% in 2030 and 2050, respectively (**Figure 3**). The pSEQ was 100% by 2030 and increased to 105% by 2050, which then decreased to 100% and 50% in 2070 and 2100, respectively. OP with healthy pSEQ increased to 101% by 2050 and then fell to 88% and 31% by 2070 and 2100, respectively. LOP was 100% for Sulawesi until 2100 (**Figure 4**). pSEQ increased to 115% until 2050 and then decreased to 108% by 2070, remaining at this value until 2100. The values for OP capable of healthy pSEQ remained at 100 % until 2100.

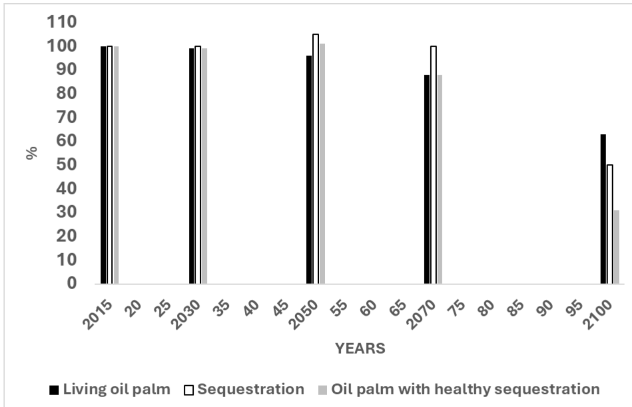

Figure 3. The effect of changes in future suitable climate on the percentage of living oil palm, the percentage of potential CO_2 sequestration, and the percentage of healthy oil palm capable of CO_2 sequestration in Indonesia.

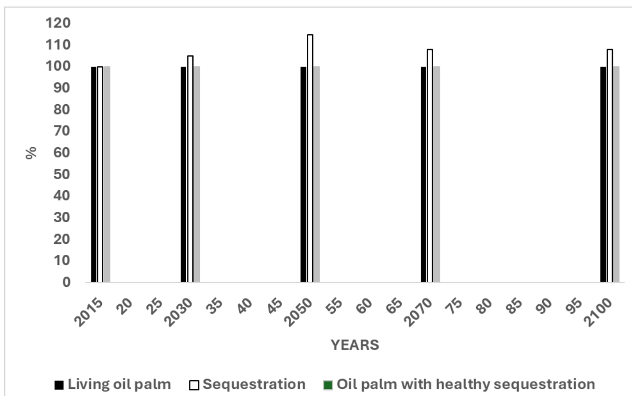

Figure 4. The effect of changes in suitable climate on the future percentage of living oil palm, the percentage of potential CO_2 sequestration, and the percentage of healthy oil palm capable of CO_2 sequestration in Sulawesi, Indonesia.

Figure 5 indicates that the LOP in Colombia decreased to 70% by 2050 and then to zero by 2065, and pSEQ decreased at a similar rate. The OP's capability of healthy pSEQ decreased to 51% by 2050 and was zero by

2065. LOP in Paraguay (**Figure 6**) was at 100% from 2015 to 2100. However, pSEQ increases dramatically to 115% and 128% by 2050 and 2100, respectively. The LOP capable of sequestration was 100% throughout.

Figure 5. The effect of changes in suitable climate on the future percentage of living oil palm, the percentage of potential CO_2 sequestration, and the percentage of healthy oil palm capable of CO_2 sequestration in Colombia.

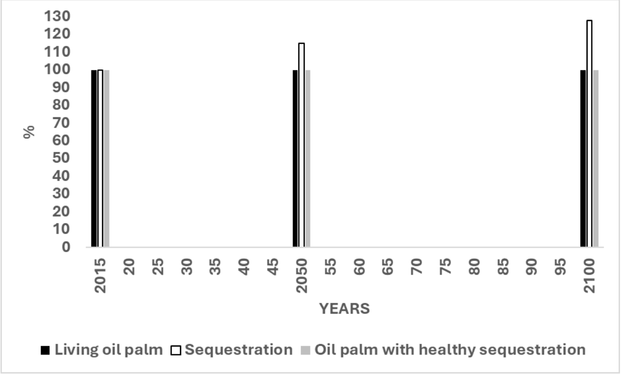

Figure 6. The effect of changes in suitable climate on the future percentage of living oil palm, the percentage of potential CO_2 sequestration, and the percentage of healthy oil palm capable of CO_2 sequestration in Paraguay.

Figure 7 demonstrates that the LOP for Nigeria decreased to 45% by 2050 and then to zero by 2060. pSEQ was 45% by 2050, which corresponded to 20% of LOP with healthy sequestration. All OPs were determined to be dead by 2060. **Figure 8** depicts the situation for Uganda: LOP remained at 100% until 2100. pSEQ increased remarkably to 155% by 2050 and remained at 120% by 2100. LOP with healthy sequestration was 100% throughout.

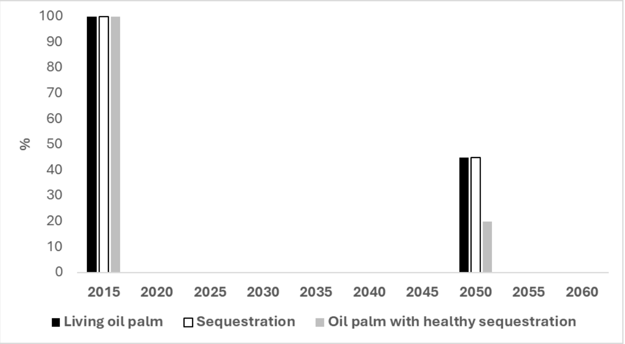

Figure 7. The effect of changes in suitable climate on the future percentage of living oil palm, the percentage of potential CO_2 sequestration, and the percentage of healthy oil palm capable of CO_2 sequestration in Nigeria.

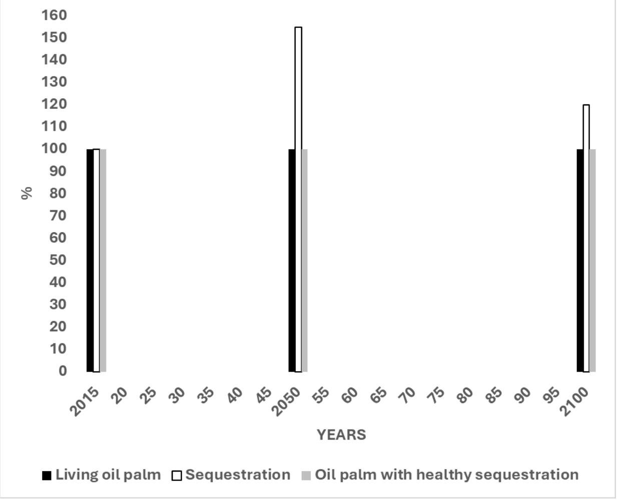

Figure 8. The effect of changes in suitable climate on the future percentage of living oil palm, the percentage of potential CO_2 sequestration, and the percentage of healthy oil palm capable of CO_2 sequestration in Uganda.

4. Discussion

The ability of OP to sequestrate CO2 in the future varies depending on which country or region is considered, according to the present scenarios. It is clear that the locations suitable for growing OP in the future, with the implied ability to sequestrate CO2, will differ from the current optimal locations for growing OP in many cases. This implies that some far-reaching planning and decisions will be required in the near future for the oil palm industry, involving where to grow OP as climate change occurs. The information in this paper will assist in making these decisions. No other directly relevant data exist.

The situations for Malaysia and Indonesia, the world's two largest palm oil producers, are mixed. For example, Sulawesi, Indonesia, has a high level of pSEQ until 2070 according to the present results. In Malaysia, sequestration is maintained until 2050, at which time high percentages of sequestration may occur. However, sequestration decreased in Malaysia by 2070 and further by 2100 to a low level. In Sabah, the situation was of high pSEQ until 2070 and a more moderate reduction by 2100. Hence, Sabah is more suitable for sequestration than Peninsular Malaysia and Sarawak [32]. The situation for Malaysia is somewhat similar to that of Indonesia. Sulawesi, Indonesia, maintained a high sequestration potential until 2100 (**Figure 4**), and other islands such as Sumatra and Java will experience reduced sequestration [33]. The situations in Malaysia and Indonesia can be compared to those other regions globally.

The suitable climate for growing OP in South America is dramatically lower in 2100 than in current time (CT). In CT, there are substantial amounts of suitable climate. The decrease implies there are fewer areas where an increase in CO_2 sequestration would be possible. In Africa, the decreases are also dramatic, although larger areas for OP development remain compared to South America. Some countries within these large areas of South America and Africa, which produce significant amounts of OP, such as Nigeria and Colombia, have limited prospects for growing OP in the future, according to the schemes described herein. Colombia will be severely affected by climate change, more so than countries in Southeast Asia. There is a considerable decrease in the sequestration potential by 2050, and thereafter, OP will not be able to grow after 2065. Consequently, there is very little opportunity to grow OP for sequestration purposes in Colombia. The situation is worse for Nigeria, where rapid decreases in pSEQ were observed until 2050, and no OP would be living by 2060. Hence, there is little opportunity to grow OP for increased sequestration in this country, according to the present data.

Interestingly, some countries with small palm oil industries currently (i.e., Uganda and Paraguay) have scenarios where more OP could be grown, with the potential for higher CO_2 sequestration. The situation in Paraguay appears remarkably advantageous for sequestration until 2100, which could be achieved by planting more OP. Uganda also has a high potential for growing OP until 2100 for sequestration purposes, and the development of more plantations may be advantageous in this country. Furthermore, a region roughly corresponding to the Congo Basin in Africa, from Cameroon to Uganda, maintains a high level of suitable climate according to the MIROC-H model, and consequently, would remain an area with high CO_2 sequestration potential by 2100 [9]. The CSIRO MK3 model has much more marginal climate in parts of this zone than the MIROC-H model and consequently indicates less favourability. In addition, there was evidence of enhanced suitability in (a) the west coast of Sumatra, Indonesia, (b) the border between Sabah, Sarawak, and northern Kalimantan, and (c) West Papua, Indonesia [9], permitting enhanced sequestration in these regions. Given the potential severity of climate change in the future under current trajectories, it is remarkable that areas of increased suitability remain and somewhat reassuring that areas of high CO_2 sequestration persist, although the general scenario is one of decline.

Beringer et al. [27] reported high yields due to CO_2 fertilisation, although they do not appear to consider the effects on fertilisation of unsuitable climate and disease [28]. A dataset for Thailand for the 2070 to 2099 period revealed an approximate 98% increase in palm oil yield, with an average increase of approximately 70%. This appears remarkably high, especially when considering the authors' inclusion of 5% OP mortality from fire damage. There is a requirement for further studies on CO_2 fertilization of OP [27].

In some regions and countries, the pSEQ was more than 100% in the current report which indicates that there was the potential for growing more OP, rather than existing OP being able to sequester more CO_2.

OP plantations could potentially be established on degraded soil or by replacing low CO_2 sequestering crops with OP, thereby avoiding the need to grow OP on deforested land or peat soils [1]. In general, deforestation to create new OP plantations has not occurred at the same rate in South America and Africa when compared to Southeast Asia. CO_2 sequestration by OP may be significantly reduced in many parts of South America and Africa because of the detrimental future climate. However, conventional forests will also be susceptible to the negative effects of climate change, and for example, Brazilian forests may revert to Savannah [13], although OP can grow on this type of land [36].

The ability to sequester CO_2 is highly related to climate for growing plants, which is likely to change significantly in the future due to climate change. Paterson et al. [9] presented scenarios in which the climate suitability in Malaysia and Indonesia generally decreased by 2100, although certain regions within each country were less affected than others. Notably, there was limited evidence of new areas materialising where there was only an unsuitable climate before. Areas with enhanced suitability are mentioned above. Paterson et al. [10] indicated a considerable decrease in suitable climate in Southeast Asia, South America, and Africa. In Africa, areas surrounding Uganda were considered to have an enhanced climate for OP by 2100, and so sequestration could increase. It is interesting that increased OP development is being considered in this country [37]. The Congo Basin, in general, maintained a high level of suitability with at least one model, although it was lower than in the CT. Hence, more OP could be planted with potential for greater sequestration.

An ongoing challenge in designing policies related to climate change is determining the appropriate degree of change to accommodate in a future policy [38]. The present results indicate that growing OP to increase CO_2 sequestration in South America and/or Africa cannot rely on growing more OP in the countries that already grow large amounts of OP. For example, the data for (a) Colombia and (b) the OP belt countries in western Africa show significant reductions in suitable climate by 2100. The results indicate a response in these regions at the transformational level, which would be variously described as long-term, strategic, and anticipatory [39], and applies to countries where palm oil production is currently at a low level. These countries include Paraguay and Uganda. In contrast is the adaptive response, which is variously described as short-term, incremental, reactive, and localised. Experimental planting in areas with newly suitable climate in the future could be undertaken without high risk in (a) the west coast of Sumatra, Indonesia, (b) the border between Sabah, Sarawak and northern Kalimantan, and (c) West Papua, Indonesia (see above) as these areas are already in proximity to large OP developments.

5. Conclusions

Decisions regarding moving plantations to new locations within countries and to different countries have risks which need balancing against the potential maladaptation [40] of doing nothing, and where short-term benefits from decisions outweigh long-term costs (social, economic, and environmental) of planting more OP. There is the possibility of simply hoping for the best [41]. Overall, the scenarios reported herein will enable decisions on how to adapt the palm oil industry to climate change by actors with the relevant knowledge. Decisions will also be required about the social and ecological contexts of the possible locations in which projects may be implemented [40]. Furthermore, plans made in the near future can be modified if necessary as real-life data becomes available. More models, in addition to those in Paterson et al. [9,10] and Beringer et al. [27], are required urgently to determine additional scenarios for the future of OP.

To address climate change more generally, there is a need to decrease emissions through large reductions in fossil fuel use, and to achieve this, the palm oil industry would benefit from being even more active in, for example, supporting further government initiatives in reducing greenhouse gases.

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Data Availability Statement

Supporting data can be obtained from the author.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Murphy, D.J., 2024. Carbon sequestration by tropical trees and crops: a case study of oil palm. Agriculture. 14, 1133. DOI: https://doi.org/10.3390/agriculture14071133

[2] Colozza, D., 2024. UNICEF. Climate Change and Nutrition in Indonesia. A Review of the Evidence for Policy and Programme Strengthening. United Nations Children's Fund: Jakarta, Indonesia.

[3] Hansen, J.E., Sato, M., Simons, L., et al., 2023.

Global warming in the pipeline. Oxford Open Climate Change. 3, 1–33. DOI: https://doi.org/10.1093/oxfclm/kgad008

[4] Anon., 2025. Copernicus Climate Change Service. Available from: https://climate.copernicus.eu (cited 1 January 2025).

[5] Grüter, R., Trachsel, T., Laube, P., et al., 2022. Expected global suitability of coffee, cashew and avocado due to climate change. PLoS ONE. 17, e0261976. DOI: https://doi.org/10.1371/journal.pone.0261976

[6] Cassamo, C.T., Draper, D., Romeiras, M.M., et al., 2023. Impact of climate changes in the suitable areas for *Coffea arabica* L. production in Mozambique: agroforestry as an alternative management system to strengthen crop sustainability. Agriculture, Ecosystems and Environment. 346, 108341.

[7] Ogunkanmi, L., MacCarthy, D.S., Adiku, S.G.K., 2022. Impact of extreme temperature and soil water stress on the growth and yield of soybean (*Glycine max* (L.) Merrill). Agriculture. 12, 43. DOI: https://doi.org/10.3390/agriculture12010043

[8] Paterson, R.R.M., 2023. Future climate effects on yield and mortality of conventional versus modified oil palm in SE Asia. Plants. 12, 2236. DOI: https://doi.org/10.3390/plants12122236

[9] Paterson, R.R.M., Kumar, L., Taylor, S., et al., 2015. Future climate effects on suitability for growth of oil palms in Malaysia and Indonesia. Scientific Reports. 5, 14457.

[10] Paterson, R.R.M., Kumar, L., Shabani, F., et al., 2017. World climate suitability projections to 2050 and 2100 for growing oil palms. Journal of Agricultural Science. 155, 659–702.

[11] Soares, J.R.S., Ramos, R.S., Siqueira da Silva, R., et al., 2021. Climate change impact assessment on worldwide rain fed soybean based on species distribution models. Tropical Ecology. 62, 612–625. DOI: https://doi.org/10.1007/s42965-021-00174-1

[12] Forzieri, G., Dakos, V., McDowell, N.G., et al., 2022. Emerging signals of declining forest resilience under climate change. Nature. 608, 534–539. DOI: https://doi.org/10.1038/s41586-022-04959-9

[13] Bottino, M.J., Nobre, P., Giarolla, E., et al., 2024. Amazon savannization and climate change are projected to increase dry season length and temperature extremes over Brazil. Scientific Reports. 14, 5131.

[14] Allen, M.R., Frame, D.J., Fridlingstein, P., et al., 2024. Geological net zero and the need for disaggregated accounting for carbon sinks. Nature. 638(8050), 343–350. DOI: https://doi.org/10.1038/s41586-024-08326-8

[15] Wang, N., Akimbo, K., Nemet, G., 2021. What went wrong? Learning from three decades of carbon capture, utilization and sequestration (CCUS) pilot and demonstration projects. Energy Policy. 158, 112546.

[16] Paterson, R.R.M., Lima, N., 2018. Climate change affecting oil palm agronomy, and oil palm cultivation increasing climate change, require amelioration. Ecology and Evolution. 8, 452–461. DOI: https://doi.org/10.1002/ece3.3610

[17] Lamade, E., Bouillet, J.P., 2005. Carbon storage and global change: the role of oil palm. OCL. 12, 154–160. DOI: https://doi.org/10.1051/ocl.2005.0154

[18] Murphy, D., 2024. The role of oil palm crops in global carbon sequestration. Proceedings of The Oil and Fats International Congress (OFIC) 2024; October 22–23, 2024; Kuala Lumpur, Malaysia. https://www.linkedin.com/posts/denis-murphy-3b144a26_our-latest-report-on-sustainable-palm-oil-activity-7297281055110189057-s-rE/ (accessed on 10 January 2025).

[19] Pulhin, F.B., Lasco, R.D., Urquiola, J.P., 2014. Carbon sequestration potential of OP in Bohol, Philippines. Ecosystem Development Journal. 4, 14–19.

[20] Kho, L.K., Jepsen, M.R., 2015. Carbon stock of oil palm plantations and tropical forests in Malaysia: a review. Singapore Journal of Tropical Geography. 36, 139–278. DOI: https://doi.org/10.1111/sjtg.12100

[21] Paterson, R.R.M., 2022. Longitudinal trends of future suitable climate for conserving oil palm indicates refuges in tropical south-east Asia with comparisons to Africa and South America. Pacific Conservation Biology. 28, 57–67. DOI: https://doi.org/10.1071/PC20067

[22] Jamaludin, N.F., Muis, Z.A., Hashim, H., et al., 2024. A holistic mitigation model for net zero emissions in the palm oil industry. Heliyon. 10, e27265. DOI: https://doi.org/10.1016/j.heliyon.2024.e27265

[23] Fleiss, S., Hill, J.K., McClean, C., et al., 2018. Potential impacts of climate change on oil palm cultivation. A science-for-policy paper by the SEnSOR programme. Available from: https://sensorproject.net/wp-content/uploads/2018/01/Climate-change-report-FINAL.pdf (cited 1 January 2025).

[24] White, A.C., Rogers, A., Rees, M., et al., 2016. How can we make plants grow faster? A source–sink perspective on growth rate. Journal of Experimental Botany. 67, 31–45. DOI: https://doi.org/10.1093/jxb/erv447

[25] Walker, A.P., De Kauwe, M.G., Bastos, A., et al., 2021. Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO_2. New Phytologist. 229, 2413–2445.

[26] Way, D.A., Cook, A., Rogers, A., 2021. The effects of rising CO_2 concentrations on terrestrial systems: scaling it up. New Phytologist. 229, 2383–2385. DOI: https://doi.org/10.1111/nph.17096

[27] Beringer, T., Müller, C., Chatterton, J., et al., 2023. CO_2 fertilization effect may balance climate change impacts on oil palm cultivation. Environmental Research Letters. 18, 054019. DOI: https://doi.

org/10.1088/1748-9326/accbd5

[28] Paterson, R.R.M., 2024. Comment on 'CO_2 fertilization effect may balance climate change impacts on oil palm cultivation'. Environmental Research Letters. 19, 018003. DOI: https://doi.org/10.1088/1748-9326/ad1345

[29] Murphy, D.J., Goggin, K., Paterson, R.R.M., 2021. Oil palm in the 2020s and beyond: Challenges and solutions. CABI Agriculture and Bioscience. 2, 39. DOI: https://doi.org/10.1186/s43170-021-00058-3

[30] Anon., 2024. Annual carbon dioxide (CO_2) emissions worldwide from 1940 to 2024. Statistica. Available from: https://www.statista.com/statistics/276629/global-co2-emissions/ (cited 1 January 2025).

[31] Paterson, R.R.M., 2020. OP survival under climate change in Kalimantan and alternative SE Asian palm oil countries with future basal stem rot assessments. Forest Pathology. 50, e12604.

[32] Paterson, R.R.M., 2020. Oil palm survival under climate change in Malaysia with future basal stem rot assessments. Forest Pathology. 11, 1–8. DOI: https://doi.org/10.1111/efp.12641

[33] Paterson, R.R.M., 2020. Depletion of Indonesian oil palm plantations implied from modeling OP mortality and Ganoderma boninense rot under future climate. AIMS Environmental Science. 7, 366–379.

[34] Paterson, R.R.M., 2022. Future scenarios for Fusarium wilt disease and mortality of oil palm in Nigeria, Ghana and Cameroon, extrapolated to Malaysia and Indonesia. European Journal of Plant Pathology. 162, 105–117.

[35] Paterson, R.R.M., 2020. Future scenarios for oil palm mortality and infection by Phytophthora palmivora in Colombia, Ecuador and Brazil, extrapolated to Malaysia and Indonesia. Phytoparasitica. 48, 513–523.

[36] Rüegg, J., 2017. Oil palm plantations in savannas: impact on biomass carbon stocks and soil organic carbon (SOC) dynamics [Master Thesis]. Zurich, Switzerland: Swiss Federal Institute of Technology. pp. 1–75.

[37] Ddamulira, G., Asiimwe, A., Masika, F., et al., 2024. Agronomic suitability for oil palm growing in Uganda. Journal of Agricultural Science. 16, 14–21.

[38] Nair, S., 2020. Designing policy pilots under climate uncertainty: a conceptual framework for comparative analysis. Journal of Comparative Policy Analysis: Research and Practice. 22, 344–359. DOI: https://doi.org/10.1080/13876988.2019.1695973

[39] Holzkämper, A., 2017. Adapting agricultural production systems to climate change—what's the use of models? Agriculture. 7, 86. DOI: https://doi.org/10.3390/agriculture7100086

[40] Schipper, E.L.F., 2020. Maladaptation: When adaptation to climate change goes very wrong. One Earth. 3, 409–414. DOI: https://doi.org/10.1016/j.oneear.2020.09.014

[41] Thompson, E., 2020. Escape From Model Land. Basic Books: London, UK. pp. 1–320.