**Environmental Costs vs. Nutritional Benefits of Rapeseed Oil and African Palm Oil Production for Human Consumption: A Case Study from Canada and Malaysia**

Mauricio R. Bellon[[1]](#footnote-1)

Swette Center for Sustainable Food Systems, Arizona State University

Executive Summary

This study presents a comparative assessment of the negative environmental impacts and associated external costs generated by the production of rapeseed oil and African palm oil, as well as a comparison of key nutrients available in these oils relevant to human health. A Life Cycle Assessment (LCA) was carried out focusing on the farm production of the raw materials needed to produce one kg of canola crude oil and of palm crude oil. Pressing/extraction of the oils, their refinement, and disposal of waste were not included in the analysis. Most environmental impacts take place during the production phase for both oils. Environmental impacts resulting from the LCA were monetized. Two regions were selected for the analysis of each oil: (1) the province of Saskatchewan in Canada for rapeseed production, and (2) the provinces of Sabah and Sarawak in Malaysia for palm production. For palm oil, two production systems were examined: (1) production under deforestation, and (2) under no deforestation. Results show that external environmental costs of producing rapeseed oil and palm oil at farm gate are substantial compared to their market price. Rapeseed oil has the highest cost ($2.62 vs. $0.80/kg), followed by palm oil produced under deforestation ($2.27 vs. 0.68/kg), with palm oil produced under no deforestation having the lowest cost by a substantial margin is ($0.55 vs. 0.68/kg). External costs from land use change and biodiversity loss were calculated separately, but follow the same pattern, rapeseed oil with the highest cost ($2.34/kg), followed by palm oil produced under deforestation ($0.82/kg), and, lastly under no deforestation ($0.34/kg). Aside from production costs, there are significant differences in their nutritional profiles. Palm oil has a substantially higher content of saturated fatty acids, while rapeseed oil has higher levels of Vitamin K, a high level of unsaturated fatty acids, and high quantities of phytosterols. Given the amounts and types of fatty acid content, rapeseed oil can be considered superior to palm oil. Regardless of production circumstances, and even though palm oil produced without deforestation generates the smallest environmental and biodiversity loss costs, the nutritional profile of this oil is inferior to that of rapeseed oil. The choice of rapeseed versus palm oil depends on how the environmental external costs are weighted against the nutritional properties of both oils. For palm oil, sourcing it from plantations established without deforestation is crucial to minimize its external costs. Our conclusions were based on a partial assessment of elements of natural capital and a complete application of True Cost Accounting would provide fuller information.

1. Introduction

Edible Plant Oils (EPO) consists of a wide variety of plant-derived oils, with sources ranging from olive, sesame, rice bran, coconut, palm, and corn, just to name a few. Global demand for EPO’s from all sources continues to rise to meet both consumer demands for cooking oils and manufacturing demands for raw ingredients (Zhou et al., 2020). Plant-based milk alternatives and meat alternatives have also contributed to this rising demand, as manufacturers use EPOs like palm oil to replicate the smoothness and creamy texture of animal fats, while also enhancing the taste of the product (Ahmad et al., 2022; Good Food Institute, 2022). Along with rising demand, there has also been an increase of concerns from consumers, scientists, and dieticians around human health impacts and the overall environmental sustainability associated with different EPOs and their production processes (Liao, 2022; MacWilliam et al., 2016; Parsons et al., 2020, Zhou et al., 2020). African palm, canola, and soybean oil are the top three leaders in global seed oil production and as such have received the most scrutiny (Fine et al., 2015; Zhou et al., 2020).

This report is a partnership between the Swette Center for Sustainable Food Systems and the KAITEKI Institute (TKI) to explore the application of True Cost Accounting (TCA) of food systems to real world situations in order to inform business decision making. TCA is an emerging economic assessment that looks beyond traditional financial metrics and aims to integrate the broader human, social, and ecological impacts of our food systems activities on four types of capital: natural, produced, social and human (Baker et al., 2021). Given the interest of TKI on edible oils, it was agreed to focus on selected edible oils. Due to short-term business needs, it was decided that a full fledge TCA was not feasible in the time available, therefore there was an agreement to focus on a comparative assessment of the negative environmental impacts and associated external costs[[2]](#footnote-2) generated by rapeseed oil and African palm oil, as well as a comparison of key nutrients available in these oils relevant to human health. Environmental costs are an important component of natural capital in the TCA approach. The other three capitals were not addressed in this study. To assess the environmental impacts of the production of these oils a Life Cycle Assessment (LCA) was carried out. A LCA is a framework that is used to understand the full impacts of the production of a good or service by breaking down material flows into smaller systems where it is easier to quantify environmental impacts (Ling-Chin et al., 2016). The LCA focused on the farm production of rapeseed grain and fresh fruit bunches (FFB)[[3]](#footnote-3) from African palm, from planting to harvesting. Pressing/extraction of the oil, its refinement, and disposal of waste generated were not included in the analysis. Most environmental impacts take place during the production phase (MacWilliams et al., 2016; Reynaud et al., 2016; Schmidt, 2007). The environmental impacts resulting from LCA were then monetized with monetization factors taken from the document *Monetisation Factors for True Pricing Version 2.0.3* (True Price, 2021). Comparisons are done based on the amount of rapeseed grain and FFB of palm necessary to produce one kg of canola crude oil and of palm crude oil (details explained in the Methods section). To contextualize the study, two regions were selected for each oil: (1) the province of Saskatchewan in Canada for rapeseed production, and (2) the provinces of Sabah and Sarawak in Malaysia for palm production. These provinces are globally important areas of production of the respective oils. For palm oil, two production systems were examined: (1) production under deforestation, and (2) under no deforestation. Based on the LCA and the monetization of the resulting impacts, external costs in US$ per kg of oil were calculated and compared with market prices. A comparison of key nutrients available in these oils relevant for human health was also carried out as well. The implications of the external costs of the production of these oils vis-à-vis their nutritional composition are discussed.

1.1 Overview of Rapeseed Oil

To first clarify our terminology, this report refers to particular type of rapeseed oil, known as “canola oil,” although both terms are used indistinctively throughout this report. Canola refers to a modified cultivar of rapeseed developed in Canada and introduced to commercial production there in the last century. Canola is the product of selective breeding to produce a low-erucic[[4]](#footnote-4) and low-glucosinolate[[5]](#footnote-5) rapeseed that was both healthier and usable as animal feed (Daun, 2011). Oil extracted from canola has superior stability against oxidation and rancidity, while the plant has cold hardiness, and a comparative ease of harvest and oil extraction relative to other seed crops (Daun, 2011; Nykter at al., 2008). Canada is the world largest producer of rapeseed/canola accounting for about 15% of global production (FAOSTAT, 2023a). This report utilizes data sets from Saskatchewan, Canada’s leading province for canola production, accounting for 54% of the total area harvested and of production (Statistics Canada, 2023).

1.2 Overview of Palm Oil

Palm oil is widely used and traded worldwide and has the highest global yield of any seed oil (Parsons et al., 2020), with 84% of production coming from Malaysia and Indonesia (FAOSTAT, 2023b). The provinces of Sabah and Sarawak located in the island of Borneo, account for 45.5% of Malaysian palm oil production and 53.9% of the area planted in Malaysia (Parveez et al., 2022). The widespread use of palm oil is due to several factors: a neutral flavor, high-smoke point, lower cost in comparison to canola or soybean oil, as well as its unique molecular makeup being nearly evenly split between saturated and unsaturated fatty acids (Parsons et al., 2020). To briefly explain this last point, palm oil can be fractionated into two separate products—the solid and liquid fatty acids—allowing the oil to be used for a wider range of culinary purposes, depending on if a firm solid or free-flowing liquid is desired (Mba et al., 2015). While other EPOs can be modified to remain solid or liquid, unlike palm oil this state change can produce trans-fatty acids, which have been shown to negatively impact human health (Parsons et al., 2020). Finally, it is important to note that while the FFB are the raw material for crude palm oil (CPO) used in human foods, the seed kernels of oil palms can also be used as a source of oil production, but since this oil is primarily used in cosmetics and is processed at a different step of production in the supply chain, it is not included in this report’s analysis of edible palm oil (Murphy et al., 2021).

2. Methods

2.1 Environmental impacts

As indicated in the introduction, to assess the environmental impacts of the production of rapeseed (canola) oil and African palm oil a Life Cycle Assessment (LCA) was carried out with the *openLCA* software and the *Agribalys*e 3.1 database. O*penLCA* is an open-source free program for performing LCA (<https://www.openlca.org/>). Agribalyse 3.1 is a French Life Cycle Inventory (LCI) database (<https://agribalyse.ademe.fr/>). It incorporates data from the *World Food LCA Database (WFLDB)* (<https://quantis.com/who-we-guide/our-impact/sustainability-initiatives/wfldb-food/>) and the *ecoinvent* Database (<https://ecoinvent.org/the-ecoinvent-database>) for non-French products. The ReCiPe 2016 Life Cycle Assessment Impact (LCIA) method was used to translate the emissions and resources used calculated with the LCA into a limited number of environmental impact scores that characterize the product analyzed (Huijbregts et al., 2017). The impact scores are determined through “…characterisation factors, which indicates the environmental impact per unit of stressor (e.g., per kg of resource extracted or emission released)” (Huijbregts et al., 2017, 139). These factors can be derived at midpoint or endpoint levels. Midpoint factors usually are located at the point after which the environmental mechanism is similar for all environmental flows, while endpoint characterization factors correspond to three areas of protection in terms of damages to human health, the ecosystem, and resource availability. Midpoint and endpoint characterization factors are complementary (Huijbregts et al., 2017). Given that there are different values and degrees of uncertainty, the ReCiPe method provides three different perspectives for the characterization factors. Here, the so-called “hierarchist” perspective was used. This perspective is based on scientific consensus and often considered the default (Huijbregts et al., 2017).

The focus of the analysis is on the farm production of rapeseed grain and fresh fruit bunches (FFB) from oil palm, from planting to harvesting. Pressing/extraction of the oil and its refinement were not included in the analysis. Most environmental impacts take place during the production phase (MacWilliams et al., 2016; Reynaud et al., 2016; Schmidt, 2007). However, to be able to compare both rapeseed and palm oil, the respective environmental impacts were calculated for the average amount of seed and FFB necessary to produce 1 kg of crude rapeseed oil and crude palm oil (CPO) respectively. To contextualize the analysis in terms of production, yields, area planted and prices, data from the provinces of Saskatchewan in Canada, and Sabah Sarawak in Malaysia were used for rapeseed and palm, respectively. Canada and Malaysia are important producers and exporters of these oils worldwide. Within these countries, the selected provinces are important producers of these oils.

Three product systems[[6]](#footnote-6) were used for the assessment:

**Rapeseed, at farm (WFLDB 3.1), location Canada**. For this system, the inventory includes representative production practices for non-irrigated rapeseed grain production in western Canada. Practices include sowing, pesticide application, fertilization, harvest, grain drying, machine infrastructure, fuel use and transport on farm.

**Palm fruit bunch production, on recently transformed land, location Malaysia**. For this system, the inventory includes all inputs, machine operations and infrastructure, used to produce 1 kg of FFB. Operations include fertilizer and pesticide application, irrigation, weed, pest and pathogen control, transport of harvested fruit to farm and clearing of the plantation. It assumes that arable land for the plantation is provided by the recent clear-cutting of rainforest and a lifetime of 20 years for the plantation. Production costs are averaged across the whole lifetime of the plantation. It is assumed that most operations are done by hand. This activity ends after harvest and transport to the farm at the farm gate.

**Palm fruit bunch, without deforestation, at farm gate, location Malaysia**. This product system is similar to the previous one, except that no recent clear-cutting of rainforest took place for its establishment. Therefore, except for that aspect, operations, inputs, and assumptions are similar.

Since 1 kg of rapeseed seed and palm FBB are not comparable, as explained above, the respective environmental impacts were calculated for the average amount of seed and FFB necessary to produce 1 kg of crude rapeseed oil and crude palm oil (CPO) respectively. For rapeseed, the conversion rate of crushed seed to crude oil is 0.4387 and it was calculated based on data from Statistics Canada, “Crushing statistics of major oilseeds” ([Table 32-10-0352-01 Crushing statistics of major oilseeds](https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210035201), <https://doi.org/10.25318/3210035201-eng>). This means that 1 kg of crushed seed yields approximately 438.7 grams of oil. Therefore, 2.2794 kg of crushed canola seed are necessary to produce 1 kg of oil. For FFB, according to Hashim et al. (2012) the typical crude extraction rate during the milling process is between 18-23% by weight of FFB. Parveez et al. (2022) report an extraction rate for Malaysia of 19.92% for 2020. This is the ratio used here. This means that 1 kg of FFB yields approximately 199.2 grams of CPO. Therefore, 5.0201 kg of FFB are needed to produce 1 kg of CPO.

The environmental impacts were calculated per kg of oil, but also per hectare. To accomplish this, the average yields of rapeseed for Saskatchewan, Canada and for FFB from Sabah and Sarawak, Malaysia for 2020 were used. The key parameters used in this assessment are presented in Table 1.

Table 1. Parameters used in assessment (year 2020)

|  |  |  |
| --- | --- | --- |
|  | Rapeseed1 | African palm2 |
| Location | Saskatchewan, Canada | Sabah & Sarawak, Malaysia |
| Oil content | 0.4387 | 0.1992 |
| Kg of seed/FFB needed to produce 1 kg of oil | 2.2794 | 5.0201 |
| Average yield, seed/FFB (ton/ha) | 2.395 | 15.915 |
| Average oil yield (ton/ha) | 1.051 | 3.170 |
| Area needed to produce 1 kg of oil (inverse of yield expressed in m2/kg) | 9.515 | 3.155 |
| Area planted (ha) | 4,588,800 | 3,127,574 |
| Mature area planted (only for palm) (ha) | NA | 2,776,208 |
| Total production (ton seed/FFB) | 10,967,900 | 43,683,303 |
| Total production (ton of oil) | 4,811,618 | 8,701,714 |
| Price per ton of oil local currency | CAD$ 532.953 | R 2,685.504 |
| Price per ton of oil US$ (2021) | 0.805 | 0.685 |

1 Statistics Canada. Estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units. <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210035901>

2Parveez et al. (2022).

3 Statistics Canada, Canadian International Merchandise Trade Database. Canadian canola seed average export values. <https://www.canolacouncil.org/markets-stats/exports/#export-values>.

4CPO (local delivered). Parveez et al. (2022).

5See footnotes bottom of Table 3 below for explanation on conversion rates and adjustments.

An LCA was run for each of the product systems per kg of oil and per hectare. The LCIA for each of these combinations provided impact results at midpoint for 17 categories in different units according to the category. Figure 1 presents an overview of the impact categories covered in the ReCiPe2016 LCIA method to the damage pathway and endpoints in terms of damages to human health, the ecosystem, and resource availability (Huijbregts et al., 2017)



Figure 1. Overview of impact categories, damage pathways, and endpoints in terms of damages. Reproduced from Huijbregts et al., (2017).

2.2 Monetization

To monetize the 17 impact results estimated by the LCIA at midpoint, each impact was multiplied by a monetization factor taken from the document *Monetisation Factors for True Pricing Version 2.0.3* (True Price, 2021). These monetization factors have been developed by True Price and Wageningen Economic Research within the Public Private Partnership True and Fair Price for Sustainable Products. The methodology used is presented in Galgani et al. (2023). According to the authors, “[M]onetisation factors are estimates of the remediation cost of the social and environmental impacts that must be included to estimate the true price of a product. These impacts are measured by a set of footprint indicators and every footprint indicator can be converted to a monetary unit using the corresponding monetisation factor. When all footprint indicators are measured and monetised for a product, the true price can be calculated.” (True Price, 2021, p. 5)

The monetization factors are provided in Euro and International US $ of 2021 per unit of impact. The categories and units are compatible with the ReCiPe2016 method; therefore, they can be applied directly to the impact estimates calculated here. However, there is an exception. In the case of land use/transformation, the units provided are not the same and it is not clear how to convert the units of the midpoint result to make them compatible with the monetization factor provided by True Price. For this reason, land use impacts are reported, but not monetized. To compensate partly for this problem, a separate calculation was done for impacts on biodiversity, which are closely in line with land use/transformation (see next section).

Once the impact results were monetized, they were added to give a total external cost, i.e., the monetary value of the environmental externalities generated by the production of rapeseed and palm oil at the farm level. These costs are compared with the market price of each of the oils. To have an idea of the externalities at the landscape level, not just per unit of product, the monetary value of the externalities per ha was multiplied by the area planted and compared to the total value of the production from the area for each type of oil. For palm oil, it cannot simply be assumed that all the area planted has been either the result of deforestation or not at all. Therefore, five scenarios are calculated: 100%, 75%, 50%, 25% and 0% of the area from deforestation.

2.3 Biodiversity

The status and dynamic of biodiversity are closely related to land use and land use change (transformation). It is assumed that the amount of biodiversity in a particular area depends on the degree of intactness of the land area, i.e., the degree that land has the undisturbed composition and abundance of species and ecosystem processes that have naturally evolved there through time. However, human use of the land changes the degree of intactness, reducing the undisturbed biodiversity present there. This process is captured by the concept of *Mean Species Abundance* (MSA) defined as “an indicator of biodiversity intactness as the mean abundance of original species relative to their abundance in undisturbed ecosystems.” (CISL, 2020). MSA is a fraction between 0 and 1, i.e., no difference between the productive area and the pristine state vs. all original biodiversity has been lost. GLOBIOweb (<https://www.globio.info/globioweb>) is a web-based tool that provides access to indicators of local terrestrial biodiversity intactness in MSA values in a spatially explicit way, considering different types of land uses for user defined areas (i.e., a province). It provides summary information on:

* Mean MSA and mean MSA loss
* Natural land cover
* Forest cover
* Protected area coverage
* Areas with MSA values of 0.8 and higher, as a proxy of remaining wilderness areas.

Data on those parameters were obtained from GLOBIOweb for the provinces of Saskatchewan, Canada and Salah and Sarawak in Malaysia. The MSA obtained were used to monetize the value of biodiversity loss in those provinces.

Monetization factors are based on the opportunity cost of biodiversity losses due to human activities such as agriculture, that require the land. The monetary valuation of land use is done by calculating the monetary value of the ecosystem services lost. While that of land use change is done by calculating the restoration costs that will be required to restore the land to its original biodiversity state (Galgani et al., 2021). The document *Monetisation Factors for True Pricing Version 2.0.3* (True Price, 2021) provides monetization factors in MSA\*ha\* year for land occupation and in MSA\*ha for land use change, both by biome[[7]](#footnote-7). The relevant biomes are Grassland/savannah for Canada and Tropical Forest for Malaysia. However, the calculation is done in 1 minus MSA (1-MSA), since that is the fraction of biodiversity lost due to land use/change.

Obviously, not all biodiversity loss can be attributed to the production of rapeseed or palm oil, therefore the area needed to produce 1 ton of those oils, based on their yields, is calculated (the inverse of the yield) and this is amount is multiplied by the relevant 1-MSA. In turn, this number is multiplied by the relevant monetization factor. In the case of land use change, the monetization is done on land use and land use change, since there are simultaneous opportunity costs for using and for transforming the land (this is the same approach used in ReCiPe2016). So, the resulting monetary value refers to the value of the biodiversity loss associated with the land used or transformed to produced 1 ton of the relevant oil. The total cost can be estimated by multiplying the cost per kg by the total amount of oil ton produced.

2.4 Nutrition and health

Although nutrition and its relationship with health are not part of traditional environmental impact assessments, they can be part of True Cost Accounting. Furthermore, given the interest of TKI on these issues, a very simple analysis was carried out comparing the composition of both types of oils for key components that have been recognized as important for a healthy diet in the literature (Zhou et al., 2020).

3. Results

3.1 Midpoint impact results

Results show that the environmental impacts of producing the amount of rapeseed and palm FFB at the farm level required to produce 1 kg of the respective oils are higher for rapeseed than for palm oil either involving deforestation or not for the production of the latter. The only exception is for global warming, where palm oil under deforestation generates impacts several times higher than rapeseed oil. However, palm oil under no deforestation generates substantially lower global warming impacts than rapeseed oil. An interesting result is that impact of rapeseed oil in human non-carcinogenic toxicity is many times higher than palm oil and that palm actually shown “negative” numbers, that in this context means a positive effect involving the absorption of zinc by the plant (results not shown). In terms of land use, the impacts are reported by two subcomponents: occupation and transformation (i.e., land use change). The impacts of rapeseed are higher as well, even though palm oil under deforestation involves impacts due to direct occupation of the land as well as its transformation from primary forest. These differences reflect the higher productivity of palm per unit area, and that it is a plantation with an occupation of 10 years, versus rapeseed that is an annual crop.

Table 2. Results of midpoint impact results

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Impact category | Reference unit | Rapeseed | Palm Oil Deforestation | Palm Oil No deforestation |
| Fine particulate matter formation | kg PM2.5 eq | 0.0105 | 0.0040 | 0.0012 |
| Fossil resource scarcity | kg oil eq | 0.2851 | 0.0604 | 0.0664 |
| Freshwater ecotoxicity | kg 1,4-DCB | 0.0311 | 0.0135 | 0.0153 |
| Freshwater eutrophication | kg P eq | 0.0006 | 0.0001 | 0.0001 |
| Global warming | kg CO2 eq | 1.8825 | 7.7672 | 0.4927 |
| Human carcinogenic toxicity | kg 1,4-DCB | 0.0304 | 0.0140 | 0.0119 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 8.1527 | -0.4385 | -0.2943 |
| Ionizing radiation | kBq Co-60 eq | 0.0595 | 0.0070 | 0.0079 |
| Land use | m2a crop eq | 12.1804 | 2.9139 | 1.4145 |
| Occupation, annual crop | m2a crop eq | 12.0629 | NA | NA |
| Occupation, permanent crop | m2a crop eq | NA | 1.4069 | 1.4069 |
| Transformation, from forest, primary (non-use) | m2a crop eq | NA | 1.5017 | NA |
| Marine ecotoxicity | kg 1,4-DCB | 0.0448 | 0.0126 | 0.0149 |
| Marine eutrophication | kg N eq | 0.0132 | 0.0019 | 0.0078 |
| Mineral resource scarcity | kg Cu eq | 0.0077 | 0.0537 | 0.0541 |
| Ozone formation, Human health | kg NOx eq | 0.0098 | 0.0019 | 0.0009 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 0.0099 | 0.0022 | 0.0010 |
| Stratospheric ozone depletion | kg CFC11 eq | 0.0000 | 0.0000 | 0.0000 |
| Terrestrial acidification | kg SO2 eq | 0.0719 | 0.0070 | 0.0071 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 3.9096 | 1.0348 | 1.0435 |
| Water consumption | m3 | 0.0196 | 0.0335 | 0.0336 |

Note: NA-not applicable

In order to have a more intuitive view of these results, the impacts of palm oil produced with and without deforestation are presented as a percentage with respect to the impacts of rapeseed (Fig. 1). This figure provides a better way to compare impacts that are in different units. The line at 100% indicates that impacts are equal to those of rapeseed. These results show that palm generates higher impacts than rapeseed for water consumption, mineral resource scarcity, and global warming. There are a few impacts where palm under no deforestation generates higher impacts that palm under deforestation, including marine eutrophication, marine ecotoxicity, and freshwater ecotoxicity.

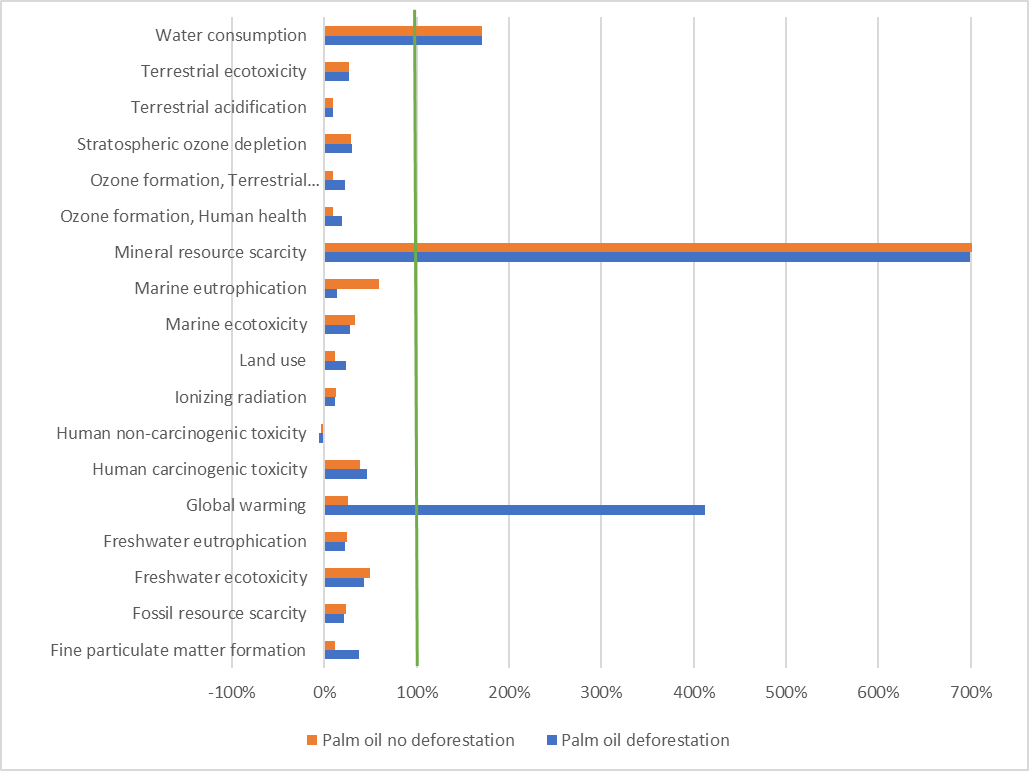


Figure 2. Relative impacts of palm oil produced with and without deforestation compared to rapeseed oil production.

3.2 Monetization of midpoint impact results

Results from monetizing these impacts (Table 3) show that the largest total environmental cost is associated with rapeseed oil ($2.62/kg), followed by palm oil under deforestation ($2.27/kg) and the lowest is palm oil under no deforestation ($0.557kg). These estimates ignore the impacts of land use because, as explained in the methodology section, it was not clear how to convert the units provided by the LCA to the monetization factors available. Land use and biodiversity costs were estimated through a different method and are presented below. Results show however that external costs are substantially higher than the market value of the oil produced in all cases.

Results from monetization of the impacts are also presented by hectare (Table 4) and show that palm oil produced under deforestation generates large external costs ($7,197.67/ha), many times that of rapeseed oil (2,755.15/ha) or palm oil produced under no deforestation ($1,745.90). These differences are related mostly to global warming impacts of producing palm oil under deforestation.

Table 3. Monetization of impact results per kg of oil

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Impact category | Monetization Factor ($/unit) | Rapeseed oil | Palm oil deforestation | Palm oil no deforestation |
| Fine particulate matter formation | 75 | 0.790 | 0.300 | 0.090 |
| Fossil resource scarcity | 0.516 | 0.147 | 0.031 | 0.034 |
| Freshwater ecotoxicity | 0.0579 | 0.002 | 0.001 | 0.001 |
| Freshwater eutrophication | 290 | 0.164 | 0.037 | 0.041 |
| Global warming | 0.224 | 0.422 | 1.740 | 0.110 |
| Human carcinogenic toxicity | 0.395 | 0.012 | 0.006 | 0.005 |
| Human non-carcinogenic toxicity | 0.027 | 0.220 | -0.012 | -0.008 |
| Ionizing radiation | 0.001 | 0.00006 | 0.000007 | 0.000008 |
| Land use-Occupation, annual crop | 3,470 | na | na | na |
| Land use-Occupation, permanent crop, Tropical Forest | 3,030 | na | na | na |
| Land use- clear cutting primary forest to arable land perennial crop, Tropical Forest | 4,160 | na | na | na |
| Marine ecotoxicity | 0.0026 | 0.0001164 | 0.0000327 | 0.0000387 |
| Marine eutrophication | 20.1 | 0.266 | 0.038 | 0.157 |
| Mineral resource scarcity | 0.26 | 0.002 | 0.014 | 0.014 |
| Ozone formation, Human health | 4.19 | 0.041 | 0.008 | 0.004 |
| Ozone formation, Terrestrial ecosystems | 4.19 | 0.042 | 0.009 | 0.004 |
| Stratospheric ozone depletion | 65.4 | 0.002 | 0.001 | 0.001 |
| Terrestrial acidification | 6.7 | 0.482 | 0.047 | 0.047 |
| Terrestrial ecotoxicity | 0.0004 | 0.00156 | 0.00041 | 0.00042 |
| Water consumption | 1.49 | 0.029 | 0.050 | 0.050 |
| **Total external cost ($/kg of oil)** |  | **2.62** | **2.27** | **0.55** |
| **Market price ($/kg of oil)** |  | **0.801** | **0.682** | **0.682** |

Note: na-not available.

1Source: Statistics Canada, Canadian International Merchandise Trade Database. Average canola crude oil export value 2020, 1 ton canola crude oil in Canadian dollars of 2020. The price has been transformed to US$ with an exchange rate of CAD 1.341/1 US$ and adjusted to 2021 prices using the Word Bank GDP Deflator between 2020 and 2021 (<https://data.worldbank.org/indicator/NY.GDP.DEFL.ZS?end=2021&start=2012>). Market prices were adjusted to 2021 to make them comparable with the monetization factors used.

2Source: Parveez et al. (2022) Table 6. Malaysian price of 1 ton of CPO, local delivered in Malaysian Ringgit of 2020. The price has been transformed to US$ with an exchange rate of CAD 4.201/1 US$ and adjusted to 2021 prices by using the Word Bank GDP Deflator between 2020 and 2021 (<https://data.worldbank.org/indicator/NY.GDP.DEFL.ZS?end=2021&start=2012>). Market prices were adjusted to 2021 to make them comparable with the monetization factors used.

Note: the prices of rapeseed and palm oil are not completely equivalent since the former is export price and the latter is local delivered. Unfortunately, Canadian data on prices was only available for export.

Table 4. Monetization of impact results per hectare

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Impact category | Monetization Factor ($/unit) | Rapeseed | Palm oil deforestation | Palm oil no deforestation |
| Fine particulate matter formation | 75 | 829.99 | 951.88 | 285.26 |
| Fossil resource scarcity | 0.516 | 154.59 | 98.80 | 108.58 |
| Freshwater ecotoxicity | 0.0579 | 1.89 | 2.48 | 2.81 |
| Freshwater eutrophication | 290 | 171.87 | 118.70 | 129.72 |
| Global warming | 0.224 | 443.08 | 5515.79 | 349.91 |
| Human carcinogenic toxicity | 0.395 | 12.63 | 17.57 | 14.95 |
| Human non-carcinogenic toxicity | 0.027 | 231.29 | -37.54 | -25.19 |
| Ionizing radiation | 0.001 | 0.06 | 0.02 | 0.03 |
| Land use-Occupation, annual crop | 3,470 | na | na | na |
| Land use-Occupation, permanent crop, Tropical Forest | 3,030 | na | na | na |
| Land use- clear cutting primary forest to arable land perennial crop, Tropical Forest | 4,160 | na | na | na |
| Marine ecotoxicity | 0.0026 | 0.12 | 0.10 | 0.12 |
| Marine eutrophication | 20.1 | 279.62 | 120.15 | 497.64 |
| Mineral resource scarcity | 0.26 | 2.10 | 44.41 | 44.75 |
| Ozone formation, Human health | 4.19 | 43.34 | 25.07 | 12.51 |
| Ozone formation, Terrestrial ecosystems | 4.19 | 43.77 | 29.56 | 12.78 |
| Stratospheric ozone depletion | 65.4 | 2.44 | 2.26 | 2.12 |
| Terrestrial acidification | 6.7 | 506.01 | 149.04 | 149.90 |
| Terrestrial ecotoxicity | 0.0004 | 1.64 | 1.31 | 1.32 |
| Water consumption | 1.49 | 30.70 | 158.06 | 158.69 |
| **Total external cost ($/ha)** |  | **2,755.15** | **7,197.67** | **1,745.90** |

Note: Not available.

3.3 Midpoint impact results at the landscape level

To appreciate the environmental costs of these products at the landscape level, the total external costs per total area planted were estimated (Table 5). In the case of palm oil, it was assumed that all area was either planted under deforestation or no deforestation, which clearly is not realistic, but it was done to provide a range for these costs. The external cost per ton was also calculated as a check. In the case of rapeseed, the estimate is realistic since land use is relatively homogenous in Saskatchewan. The landscape costs there more than $12.6 billion per year, a substantial sum. Assuming all planted area was done under deforestation, the external cost for palm oil will be more than $22.5 billion. However, if all production were done under no deforestation, the cost would be about $5.4 billion. The value of the externalities is much higher than the market value of oil production.

Table 5. Estimates of external cost at landscape level

|  |  |  |  |
| --- | --- | --- | --- |
|  | Rapeseed | Palm oil deforestation | Palm oil no deforestation |
| Cost/ha Int US$ 2021 | 2,755 | 7,198 | 1,746 |
| Area planted | 4,588,800 | 3,127,574 | 3,127,574 |
| External cost (US$ 2021) | 12,642,849,647 | 22,511,232,160 | 5,460,442,034 |
| Production seed/FFB (ton) | 10,967,900 | 43,683,303 | 43,683,303 |
| Production oil (ton) | 4,811,618 | 8,701,714 | 8,701,714 |
| Cost/ton US $1 | 2.63 | 2.59 | 0.63 |
| Price/ton of oil (2020) (local currency) | CAD 995.94 | RM 2,685.50 | RM 2,685.50 |
| Price/ton of oil (2021) (US$) | 802.15 | 675.64 | 675.64 |
| Cost/ton US$ | 2.63 | 2.59 | 0.63 |
| Value of production (US$) | 3,859,661,752 | 5,879,249,086 | 5,879,249,086 |

1This cost is slightly different from the one in Table 3 because it was calculated by dividing the total production by the area planted. In Table 3 is calculated based on the yield calculated by dividing the total production by area harvested. In addition, total area planted in the case of palm oil includes immature plantations that may not have produced at all.

As indicated, it is unlikely that all area planted to palm is done in either extreme scenario, therefore external costs were estimated for combinations of both types of production conditions (Fig. 3). The larger the area deforested, the larger the external costs and vice versa. It should be pointed out that with 50% deforestation, the total external costs of producing palm oil are roughly similar to those of producing rapeseed oil ($12.6 vs. 14 billion). Therefore, the comparison of the external costs of producing rapeseed oil vs. palm oil depends on the proportion of area deforested vs. not deforested associated with the production of the latter.

Figure 3. Scenarios of external costs of palm oil production depending on the degree of deforestation involved.

3.5 Land use and biodiversity

Land use and biodiversity conditions are very different between Canada and Malaysia (Table 6). In Saskatchewan most of the land has been converted to agriculture, with some remnants of grassland and forest. Natural land cover only accounts for 11% of the area. According to the mean MSA, only 29% of the original species remains, and 71% have been lost. In Sabah and Sarawak, the situation is dramatically different. Most of the land cover is natural, predominantly forest. Agriculture only accounts for about a fourth of the area. Therefore, there is still a high degree of intactness, with a mean MSA of between 63 and 65% of the original species remaining. Species loss, however, is not trivial since about a third of them have been lost.

Table 6. Summary statistics of biodiversity, land use, and land cover from the GLOBIOweb tool for 2020

|  |  |  |  |
| --- | --- | --- | --- |
| Location | Canada | Malaysia | |
|  | Saskatchewan | Sabah | Sarawak |
| **Biodiversity** |  |  |  |
| Mean MSA | 0.29 | 0.63 | 0.65 |
| Mean MSA loss | 0.71 | 0.37 | 0.35 |
| Natural land cover (%) | 11 | 74 | 74 |
| Natural forest cover (%) | 5 | 74 | 74 |
| Area with MSA >= 0.8 (%) | 3 | 4 | 0 |
| Protected area cover (%) | 10 | 25 | 5 |
| **Land cover and use** |  |  |  |
| Settlement | 0.202 | 0.47 | 0.27 |
| Agriculture | 76.23 | 24.76 | 25.38 |
| Forest | 5.23 | 73.68 | 72.60 |
| Grassland | 15.8 | 0.18 | 0.31 |
| Wetland | 0.05 | 0 | 0 |
| Shrub/sparse veg. | 0.09 | 0.003 | 0 |
| Bare | 0.55 | 0 | 0 |
| Water | 1.86 | 0.91 | 1.44 |

Monetization of the biodiversity impacts associated with land use shows that the value is much higher for rapeseed oil in Saskatchewan ($2.24/kg) than in Sabah and Sarawak for palm oil. In the latter, the monetary value depends on whether palm oil production entails only occupation or occupation plus transformation of tropical forest. It may seem surprising that the value is so much higher in Saskatchewan, but this is related to the higher loss and therefore opportunity cost of the species there, compared with the species loss in Sabah and Sarawak, since most of the area is still under natural land cover. In addition, the tropical forests of Malaysia are more diverse than the temperate grasslands and boreal forests of Canada. However, the monetization factor used is higher for land use occupation of a grassland than for a tropical forest. The monetization factor for land transformation is substantially higher than for land use occupation for a tropical forest. It should be noted that the monetization factor for land use transformation for a grassland is only $313/(MSA\*ha). Most of the land in Saskatchewan has already been transformed and there is very little than is converted from natural vegetation to arable land. In any case, the monetary value of species loss associated with rapeseed production is substantially higher than with palm oil production, whether it includes land occupation or land occupation and transformation. Rapeseed larger monetary value also reflect that about three times as much land is necessary to produce the same amount of oil compared to palm oil.

Table 7. Monetization of biodiversity impacts associated with land use

|  |  |  |  |
| --- | --- | --- | --- |
|  |  | Canada  Saskatchewan | Malaysia  Sabah & Sarawak1 |
| Mean MSA loss (MSA-1) |  | 0.71 | 0.37 |
| Area to produce 1 kg of oil (ha/ton) |  | 0.00095 | 0.00032 |
| Impact | Monetization factor ($/MSA) | $/kg | $/kg |
| Land occupation grassland | 3,4702 | 2.34 | NA |
| Land occupation, Tropical Forest | 3,0302 | NA | 0.34 |
| Land transformation, Tropical Forest | 4,1603 | NA | 0.47 |
| Sum of land occupation and clearing |  | 2.24 | 0.82 |

1 Based on the average MSA of both provinces,

2 $/(MSA\*ha\*year)

3$/(MSA\*ha)

NA-not applicable

3.6 Nutrition and health

A comparison of nutrient contents per 100 g of oil from the USDA FoodData database (SR Legacy Foods, (<https://fdc.nal.usda.gov/fdc-app.html#/>) for rapeseed and palm oils show that these oils have different nutritional profiles (Table 8). Table 8 also presents the percentage of nutritional content of one oil versus the other. Note that since for some nutrients, one oil did not have any content the percentage cannot be calculated (grey in the table).

Palm and rapeseed oils have similar levels of alpha-tocopherol, the most common form of Vitamin E, a fat-soluble antioxidant that is involved in immune responses. Unlike palm oil, rapeseed oil contains gamma-tocopherol. This from of Vitamin E may possess unique features that are different from alpha-tocopherol. There is some evidence that that plasma concentrations of gamma-tocopherol are inversely associated with the incidence of cardiovascular disease and prostate cancer (Jiang et al., 2001).

Rapeseed oil has a substantial higher content of Vitamin K than palm oil. This vitamin is important for blood coagulation and bone structure.

Palm oil has a substantially higher content of saturated fatty acids (SFAs) than rapeseed oil, about seven times as much. This is especially true for palmitic acid, which is the major component of the fruit of oil palms. High consumption of SFAs has been associated with raising total cholesterol and Low-density cholesterol (LDL), as well as chronic diseases (Calder, 2015; Chow, 2008).

Rapeseed oil has a high level of unsaturated fatty acids (UFAs) compared to palm oil. UFAs play important roles in the human body and their consumption is considered to be healthy (Zhou et al., 2020). There are two types of UFAs, monounsaturated (MUFUs) and polyunsaturated (PUFAs). The former can be synthesized by the human body, while the latter has to be obtained from the diet. For both types, rapeseed oil has a higher content than palm oil, particularly for oleic acid (MUFA 18:1), linoleic acid (PUFA 18:2), and linolenic acid (PUFA 18:3). Since the consumption of these UFAs is considered healthy (Zhou et al., 2020), in terms of amounts and types of fatty acid content, rapeseed oil can be considered superior to palm oil.

Rapeseed oil has high quantities of phytosterols, such campesterol and Beta-sitosterol, absent in palm oil. Phytosterols can inhibit the absorption of cholesterol and have significant preventive and therapeutic effects on cardiovascular diseases and cervical cancers. They have strong anti-inflammatory effects (Zhou et al., 2020).

Given the differences in nutrient composition of palm and rapeseed oils, the latter seems to be superior to the former in terms of contributing to a healthy diet. Obviously, if these oils are used as ingredients in other products, their nutritional properties, and their implications for human diets and health may be different. Direct consumption of palm oil is limited in Western countries, and much more common in Sub-Saharan and Asian countries. Consumption of rapeseed oil is common in Western countries. For these reasons, a direct comparison of the nutritional implications of consuming these oils should be done with caution.

Table 8. Comparison of nutrient content of palm and canola oils (nutrient/100 g of oil)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Name** | **Unit** | **Rapeseed**  **oil2** | **Palm oil1** | **Rapeseed/**  **palm** | **Palm/**  **rapeseed** |
| Iron, Fe | mg | 0 | 0.01 |  |  |
| Choline, total | mg | 0.2 | 0.3 | 66.7 | 150.0 |
| Vitamin E (alpha-tocopherol) | mg | 17.5 | 15.9 | 110.1 | 90.9 |
| Tocopherol, beta | mg | 0.01 | 0 |  |  |
| Tocopherol, gamma | mg | 27.3 | 0 |  |  |
| Tocopherol, delta | mg | 0.99 | 0 |  |  |
| Tocotrienol, alpha | mg | 0.03 | 0 |  |  |
| Tocotrienol, delta | mg | 0.01 | 0 |  |  |
| Vitamin K (phylloquinone) | µg | 71.3 | 8 | 891.3 | 11.2 |
| *Fatty acids, total saturated* | *g* | *7.36* | *49.3* | *14.9* | *669.8* |
| SFA 12:0 | g | 0 | 0.1 |  |  |
| SFA 14:0 | g | 0 | 1 |  |  |
| SFA 16:0 (palmitic acid) | g | 4.3 | 43.5 | 9.9 | 1,011.6 |
| SFA 18:0 | g | 2.09 | 4.3 | 48.6 | 205.7 |
| SFA 20:0 | g | 0.65 | 0 |  |  |
| SFA 22:0 | g | 0.33 | 0 |  |  |
| *Fatty acids, total monounsaturated* | *g* | *63.3* | *37* | *171.1* | *58.5* |
| MUFA 16:1 | g | 0.214 | 0.3 | 71.3 | 140.2 |
| MUFA 18:1 (oleic acid) | g | 61.7 | 36.6 | 168.6 | 59.3 |
| MUFA 18:1 c | g | 61.7 | 0 |  |  |
| MUFA 20:1 | g | 1.32 | 0.1 | 1,320.0 | 7.6 |
| *Fatty acids, total polyunsaturated* | *g* | *28.1* | *9.3* | *302.2* | *33.1* |
| PUFA 18:2 (linoleic acid) | g | 19 | 9.1 | 208.8 | 47.9 |
| PUFA 18:2 n-6 c, c | g | 18.6 | 0 |  |  |
| PUFA 18:3 (linolenic acid) | g | 9.14 | 0.2 | 4,570.0 | 2.2 |
| PUFA 18:3 n-3 c,c,c (ALA) | g | 9.14 | 0 |  |  |
| *Fatty acids, total trans* | *g* | *0.395* | *0* |  |  |
| *Fatty acids, total trans-monoenoic* | *g* | *0.03* | *0* |  |  |
| TFA 18:1 t | g | 0.03 | 0 |  |  |
| TFA 18:2 t, t | g | 0.365 | 0 |  |  |
| *Fatty acids, total trans-polyenoic* | *g* | *0.365* | *0* |  |  |
| Stigmasterol | mg | 3 | 0 |  |  |
| Campesterol | mg | 241 | 0 |  |  |
| Beta-sitosterol | mg | 413 | 0 |  |  |

1 <https://fdc.nal.usda.gov/fdc-app.html#/food-details/171015/nutrients>

2 <https://fdc.nal.usda.gov/fdc-app.html#/food-details/748278/nutrients>

5. Discussion

The external environmental costs of producing rapeseed oil and palm oil at farm gate are substantial compared to their market price. Rapeseed oil has the highest cost, followed closely by palm oil produced under deforestation, while the lowest cost by a substantial margin is palm oil produced under no deforestation. Regardless of production circumstances, and even though palm oil produced without deforestation generates the smallest environmental cost, the nutritional profile of this oil is inferior to that of rapeseed oil. However, as pointed out earlier, if these oils are used as ingredients in other products, their nutritional properties, and their implications for human diets and health may be different.

The main driver of external costs is the carbon emissions associated with the production of these oils. These emissions in turn are related to land use and land use change (transformation), particularly in the case of palm oil, which also has implications for biodiversity loss. The external costs associated with biodiversity loss estimated here also show that rapeseed oil production generates the largest costs while palm oil production under no deforestation, the lowest. These estimates depend on the monetization factors used, which in turn depend on the valuation of the opportunity costs associated with the biodiversity of the temperate grassland biome for rapeseed oil and of the tropical forest biome for palm oil.

These monetization factors are based on the meta-analysis from de Groot et al. (2012) and reported in The Ecosystem Service Valuation Database (ESVD) (<https://www.esvd.info/>). This database contains 52 valuation studies of temperate grasslands, none from North America which is the biome where rapeseed is produced in Saskatchewan. However, it contains 194 valuation studies of tropical rainforest specifically from Malaysia, the biome where palm oil is produced in Sabah and Sarawak. It is likely that the monetization factor for the biome where rapeseed oil is produced is less accurate than the one for tropical forests, where palm is produced. Furthermore, the monetary external costs estimated in this study do not consider the uniqueness of the biodiversity lost. Not only might the level of biodiversity in a tropical rainforest be larger than the one of a temperate grassland, but also the species composition and their uniqueness should be different. For example, the land where rapeseed is produced in Saskatchewan has already been transformed for a long time and basically additional area comes from the replacement of crops, e.g., wheat by rapeseed (MacWilliams et al., 2016). However, the expansion of palm oil at the expense of tropical forested areas may lead to the reduction of habitats for unique species such as the orangutan. Therefore, the external costs of biodiversity loss estimated here should be taken with a note of caution.

Another issue worth mentioning are the concerns that have been raised about the widespread adoption of genetically modified (GM) canola and its impacts on the environment and health (MacWilliams et al., 2016). This is a controversial and politically charged issue. There are benefits of GM canola adoption. For example, GM adoption has been found to be a driver of increased carbon sequestration due to its association with reduced or no tillage (Sutherland et al., 2021). There is evidence of a reduction in the amount of active ingredient of herbicides applied per hectare and decreases in the environmental impact of the top five canola herbicides used (Smyth et al., 2011). However, at the landscape level, the environmental and human health effects level of the widespread herbicide use associated with the extensive adoption of GM varieties, 95% of the area in Canada is planted to GM canola, have not been assessed. Examples of this might be the effects on ecosystems services, evolutionary changes in non-target species, and health of human populations. These are issues that have to be explored further to have a better assessment of the net environmental costs of rapeseed oil production in North America (GM varieties have also been widely adopted in the USA).

Although not directly addressed in this study, in terms of human capital, palm oil production is still mostly done by human labor, particularly migratory labor in Malaysia (Reynaud et al., 2016). There are issues of underpayment of casual workers (Reynaud et al., 2016). Migratory labor is so important in Malaysia that oil production decreased significantly during the COVID-19 pandemic due to travel and immigration restrictions (Parveez et al., 2022). In contrast, rapeseed production in Canada is heavily mechanized, therefore it is unlikely that there will be major external costs associated with human labor.

It is important to emphasize that this study is not a full fledge True Cost Accounting exercise and it only took into consideration the environmental negative externalities, i.e., costs up to the farm gate, ignoring the full supply chain of these oils, as well as the positive externalities, as well as human and social capital that may be involved. With its limitations this study shows that in the end the choice of rapeseed versus palm oil depends on how the environmental external costs are weighted against the nutritional properties of both oils. It is clear that for palm oil, sourcing it from plantations established without deforestation is crucial to minimize its external costs. It is not clear however, how to account for past deforestation in this assessment. Further analysis and a complete application of the TCA methodology is warranted given our conclusions.

References

Ahmad, M., Qureshi, S., Akbar, M. H., Siddiqui, S. A., Gani, A., Mushtaq, M., Hassan, I., & Dhull, S. B. (2022). Plant-based meat alternatives: Compositional analysis, current development and challenges. *Applied Food Research*, 2, 100154. <https://doi.org/10.1016/j.afres.2022.100154>

Baker, L. E., Daniels, P. A., & Gemmill-Herren, B. (Eds.). (2021). *True cost accounting for food: Balancing the scale*. Routledge.

Calder, P. C. (2015) Functional roles of fatty acids and their effects on human health. *Journal of Parenteral and Enteral Nutrition*, 39(suppl 1), 18S–32S. <https://doi.org/10.1177/0148607115595980>

CISL - University of Cambridge Institute for Sustainability Leadership (CISL). (2020). Measuring business impacts on nature: A framework to support better stewardship of biodiversity in global supply chains. Cambridge, UK, University of Cambridge Institute for Sustainability Leadership.

Chow CK. (2008). *Fatty Acids in Foods and Their Health Implications*. 3rd ed. Boca Raton, CRC Press.

Daun, J. K. (2011). Origin, Distribution, and Production. In Canola (pp. 1–27). Elsevier. <https://doi.org/10.1016/B978-0-9818936-5-5.50005-X>

de Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L. C., ten Brink, P., van Beukering, P. (2012). Global estimates of the value of ecosystems and their services in monetary units. *Ecosystem Services*, 1, 50–61. <https://doi.org/10.1016/J.ECOSER.2012.07.005>

FAOSTAT (2023a). Data on average production of rapeseed oil for the world 2016-2021 retrieved from <https://www.fao.org/faostat/en/#data/QCL/visualize> (March 3, 2023).

FAOSTAT (2023b). Data on average production of palm oil for the world 2016-2021 retrieved from <https://www.fao.org/faostat/en/#data/QCL/visualize> (March 3, 023.

Fine, F., Lucas, J.-L., Chardigny, J.-M., Redlingshöfer, B., & Renard, M. (2015). Food losses and waste in the French oilcrops sector. *OCL*, 22(3), A302. https://doi.org/10.1051/ocl/2015012

Galgani, P., van Veen, B., Kanidou, D, de Adelhart Toorop, R, Woltjer, G. (2023). *True price assessment method for agri-food products*. True Price, Wageningen Economic Research.

Galgani, P., Woltjer, G, D, de Adelhart Toorop, R, de Groot Ruiz, A., Varoucha, E. (2021). *Land use, Land use change, Biodiversity and Ecosystem Services*. True Price, Wageningen Economic Research.

Good Food Institute. (2022). U.S. retail market data for the plant-based industry. Retail Sales Data: Plant Based Meat, Eggs, Dairy | GFI Gfi.Org. <https://gfi.org/marketresearch/>

Hashim, K., Tahiruddin, S., Asis, A. J. (2012). Palm and Palm Kernel oil production and processing in Malaysia and Indonesia. In Lai, O. M., Tan, C. P., Akoh, C.C. (eds). *Palm Oil. Production, Processing, Characterization, and Uses*, pp. 235-250. AOCS Press.

Huijbregts, M. A. K., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M. Zijp, M., Hollander, A., van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *International Journal of Life Cycle Assessment*, 22, 138-147.

ISO (2006). *Environmental management—life cycle assessment—requirements*

*and guidelines* (ISO 14044:2006). <https://www.iso.org/standard/38498.html>

Jiang, Q., Christen, S., Shigenaga, M. K., Ames, B. N. (2001). γ-Tocopherol, the major form of vitamin E in the US diet, deserves more attention. *American Journal of Clinical Nutrition*, 74, 714-722. <https://doi.org/10.1093/ajcn/74.6.714>

Liao, S. (2022, May 31). Do Seed Oils Make You Sick? Consumer Reports. <https://www.consumerreports.org/healthy-eating/do-seed-oils-make-you-sick-a1363483895/>

Ling-Chin, J., Heidrich, O., & Roskilly, A. P. (2016). Life cycle assessment (LCA) – from analysing methodology development to introducing an LCA framework for marine photovoltaic (PV) systems. *Renewable and Sustainable Energy Reviews*, 59, 352–378. <https://doi.org/10.1016/j.rser.2015.12.058>

MacWilliam, S., Sanscartier, D., Lemke, R., Wismer, M., & Baron, V. (2016). Environmental benefits of canola production in 2010 compared to 1990: A life cycle perspective. *Agricultural Systems*, 145, 106–115. <https://doi.org/10.1016/j.agsy.2016.03.006>

Mba, O. I., Dumont, M.-J., & Ngadi, M. (2015). Palm oil: Processing, characterization and utilization in the food industry – A review. Food Bioscience, 10, 26–41. <https://doi.org/10.1016/j.fbio.2015.01.003>

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(1), 39. <https://doi.org/10.1186/s43170-021-00058-3>

Nykter, M., Kymäläinen, H.-R., & Gates, F. (2008). Quality characteristics of edible linseed oil. *Agricultural and Food Science*, 15, 402. <https://doi.org/10.2137/145960606780061443>

Parsons, S., Raikova, S., & Chuck, C. J. (2020). The viability and desirability of replacing palm oil. *Nature Sustainability*, 3, 412–418. <https://doi.org/10.1038/s41893-020-0487-8>

Parveez, G. K. A., Kamil, N. N., Zawawi, N. Z., Ong-Abdullah, M., Rasuddin, R., Loh, S. K., Selvaduray, K. R. Hoong, S. S., Idris, Z. (2022). Oil palm economic performance in Malaysia and R&D progress in 2021. *Journal of Oil Palm Research*, 34, 185-218. DOI: <https://doi.org/10.21894/jopr.2022.0036>

Raynaud, J., Fobelets, V., Georgieva, A., Joshi, S., Kristanto, L., de Groot Ruiz, A., Bullock, S., Hardwicke, R., (2016). Improving Business Decision Making: Valuing the Hidden Costs of Production in the Palm Oil Sector. A study for The Economics of Ecosystems and Biodiversity for Agriculture and Food (TEEBAgriFood) Program.

Schmidt, J. H. (2010). Comparative life cycle assessment of rapeseed oil and palm oil. The International *Journal of Life Cycle Assessment*, 15, 183–197. <https://doi.org/10.1007/s11367-009-0142-0>

Smyth, S. J., Gusta, M., Belcher, K., Phillips, P. W. B., Castle, D. (2011). Changes in herbicide use after adoption of HR canola in Western Canada. *Weed Technology*, 25, 492-500. <https://doi.org/10.1614/WT-D-10-00164.1>

Statistics Canada. (2023, February 7). Estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units. Statistics Canada. <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210035901>

Sutherland, C., Gleim, S., Smyth, S. J. (2021). Correlating genetically modified crops, glyphosate use and increased carbon sequestration. *Sustainability*, 13, 11679. <https://doi.org/10.3390/su132111679>

True Price (2021*). Monetisation Factors for True Pricing Version* 2.0.3. Amsterdam, True Price.

University of Cambridge Institute for Sustainability Leadership (CISL). (2020). *Measuring business impacts on nature: A framework to support better stewardship of biodiversity in global supply chains*. Cambridge, UK: University of Cambridge Institute for Sustainability Leadership.

Zhou, Y., Zhao, W., Lal, Y., Zhang, B., Zhang, D. (2020). Edible plant oil: Global status, health issues, and perspectives. Frontiers in Plant Science, 11, 1315. <https://www.frontiersin.org/articles/10.3389/fpls.2020.01315/full>

1. Nicholas Benard and Elora Bevacqua provided valuable help for the development of this report. [↑](#footnote-ref-1)
2. In this context, an external cost is a cost that has not been incorporated into the market price of the production, consumption, or disposal of a good or service. [↑](#footnote-ref-2)
3. The fruit of the African palm grows in dense bunches known as FFB. These are the raw material for palm oil mills. [↑](#footnote-ref-3)
4. Erucic acid is a monounsaturated omega-9 fatty acid present in oil-rich seeds of the *Brassicaceae* family of plants, particularly rapeseed and mustard. It is considered a food contaminant of vegetable oils. It has been linked to cardiovascular disease (<https://www.efsa.europa.eu/en/press/news/161109>). [↑](#footnote-ref-4)
5. Glucosinolates are secondary plant metabolites common in rapeseed, they can have negative effects on higher concentrations if consumed as animal feed (<https://en.wikipedia.org/wiki/Glucosinolate>). [↑](#footnote-ref-5)
6. A product system is “[the] collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product.” (ISO 14044, 2006) [↑](#footnote-ref-6)
7. Biomes are the largest unit of ecological classification that is convenient to recognize below the entire globe. Terrestrial biomes are typically based on dominant vegetation structure (Galgani et al., 2021). Monetization factors are provided for six biomes. [↑](#footnote-ref-7)