Diversified global vegetable oil production can mitigate climate change and increase other environmental and socioeconomic benefits

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Abstract:

Global vegetable oil production is a crucial ingredient for food and household products but also a major source of greenhouse gas (GHG) emissions and other environmental externalities. A diversified supply may improve sustainability and resilience of profitable vegetable oil production globally. Here, we provide the first spatial assessment of the environmental and economic effects of major vegetable oil crops soybean, palm, rapeseed, sunflower, groundnut, and olive globally, based on new data from a meta-analysis and life cycle assessment. We show that diversified vegetable oil production through a highly productive oil tree crop *Camellia oleifera* can reduce GHG emissions, water use, land use, and pesticide use by 14.0%, 4.9%, 7.3%, 9.3%, respectively and increase farmer income by 82.6%. When considering enabling conditions for technology and policy support, these benefits increase 1.3, 2.1, 1.8, 1.7, and 3.2 folds, respectively. Our results provide practical guidance where and how diversified oil crop production can advance a sustainable food system transformation and help to mitigate climate change.

1. Introduction

The global food system faces the dual challenge of meeting the demands for food, fiber, and energy from a growing population while addressing exacerbating environmental issues (1). More than 30% of the total agricultural land is currently used for vegetable oil crop production (2), 80% of which is occupied by the six major oil crops oil palm, soybean, rapeseed, groundnut, sunflower, and olive (3,4). These oils are used for example in cooking oil, cosmetics, and biofuel production, and with global demand increasing steadily (5). However, production supplies are strongly impacted by a tense geopolitical situation and climate change both of which affect global trade and prices (6). Moreover, vegetable oil production is a major driver of cropland expansion, associated with up to 1.9 $GtCO_2$ - eq (23%) of global food carbon emissions (7) and heavily relying on pesticides and fertilizers, which exert pressure on soil and water resources (8,9). Palm oil and soybean oil, two of the most widely used oil crops, have been linked with biodiversity decline, deforestation, and negative impacts on human livelihoods (8,10,11). Despite decades of research efforts, a spatially explicit synthesis of environmental and economic effects of all major vegetable oil crops is currently missing (12,13).

Efforts to mitigate environmental impacts while maintaining or even increasing vegetable oil yields have focused on improving supply chain transparency through effective policy (e.g. the EU deforestation free supply chain law including oil palm and soybean; 14,15), enhancing farmer income through sustainability standards (16), and various agricultural diversification practices (e.g., crop rotations or agroforestry; 17). Diversified supply of vegetable oil ideally contributes to a triple win-win-win solution whereby the outcomes are healthier oils with a lower environmental footprint and high revenue (18). Identifying such new opportunities usually requires breeding or gene editing existing crops for preferable traits (19), improved management for instance through agroforestry (20,21), exploring alternative exotic oils such as microbial single-cell oils (22,23) or bioprospecting new species (24). Woody oil crops such as *Camellia oleifera* (hereafter Camellia) are potential candidates for a triple win solution but are largely underutilized options (20,25).

Camellia has the second highest oil yield potential of 2.8 t/ha just after palm oil (26,27) with high nutritional value (see Table S1) (25,28,29), can protect farmer livelihoods, prevent soil erosion, and increase biodiversity through agroforestry or intercropping (24,30,31,32). Currently, however, Camellia is cultivated almost exclusively in China (25) and a lack of data on the environmental and social parameters (33) has prevented an integrated assessment of the environmental and social effects of diversified vegetable oil production (8,12).

Here, we provide the first quantitative global and spatially explicit assessment of GHG emissions, water use, land use, fertilizer use, and farmer income for six major vegetable oil crops based on a meta-analysis and life cycle assessments. We then quantify Camellia production globally as a potential long-term crop substitute without land expansion and oil yield loss to reduce environmental impacts and increasing farmer income with a healthier vegetable oil (see Fig. S1). Our Camellia analysis used machine learning for the land suitability assessments and global agro-ecological zones modelling to derive three yield scenarios.

2. Results

2.1 Global environmental impact of six main vegetable oil crops

We conducted a global meta-analysis (13) based on 837 unique records in 285 studies to parametrize a life cycle assessment and then map the environmental impacts of groundnut, soybean, oil palm, sunflower, rapeseed, and olive (for details see Methods Section and Extended Section 1.2.3). In 2015, all vegetable oil crops accounted for 298.3 Mha of harvested areas, of which 40.5% was occupied by soybean, 11.6% by rapeseed, 8.9% by groundnut, 8.2% by sunflower, 7.6% by palm, and 3.4% by olive (3, 4).

The total annual GHG emissions of the six vegetable oils are 1.2 Gt CO_2eq/year, with 44.5%, 34.9%, 8.9%, 6.1%, 4.3%, and 1.3% coming from soybean, palm, groundnut, rapeseed, sunflower, and olive oil, respectively (Fig.1a). The total global emissions from soybean are 547.1 Mt CO_2eq/year, originating in South America (466.4 Mt CO_2eq/year),

North America (45.5 Mt CO_2eq/year), Asia and Oceania (20.6 Mt CO_2eq/year), Africa (9.8 Mt CO_2eq/year), and Europe (4.7 Mt CO_2eq/year). At a country level, soybean oil production in Brazil generated the highest GHG emissions of 59.2%, followed by Argentina (13.1%), the Republic of Paraguay (7.73%), and the United States (7.66%). For palm oil, the total amount is 429.2 Mt CO_2eq/year emitted in Asia and Oceania (360.2 Mt CO_2eq/year), Africa (48.5 Mt CO_2eq/year), North America (8.9 Mt CO_2eq/year) and South America (8.4 Mt CO_2eq/year). The highest total emissions (64.4%) come from Indonesia, the world's largest palm oil producer, followed by Malaysia (17.9%), and Nigeria (9.2%). These emissions likely come from N_2O, and CO_2 through fertilizer application and land use change (see Methods). The amount of GHG emitted per 1 liter oil are highest in palm oil (9.7 kg CO_2 eq/L) due mainly to deforestation, followed by olive oil (8.5 kg CO_2 eq/L), groundnut oil (8.4 kg CO_2 eq/L), soybean oil (8.4 kg CO_2 eq/L), rapeseed oil (4.0 kg CO_2 eq/L) and sunflower oil (3.5 kg CO_2 eq/L) (Fig. S15). For more details on all oil crops see Fig. S14 and Fig. S29.

The total annual water use (i.e., the aggregation of green, blue, and grey water use) is 876.0 km^3/year, with the descending order of soybean (364.2 km^3/year), followed by palm (160.8 km^3/year), rapeseed (145.7 km^3/year), groundnut (109.9 km^3/year), sunflower (65.2 km^3/year), and Olive (30.1 km^3/year) (Fig. S14b). Water use in Asia and Oceania is highest at 360.0 km^3/year, followed by South America (184.3 km^3/year), North America (126.6 km^3/year), Africa (99.4 km^3/year), and Europe (98.7 km^3/year). The water-use intensity for producing 1-liter oil also varied across regions (Fig. S16), which is affected by the length of the crop growing period (especially for tree crops like palm and olive), evapotranspiration, crop-specific factors, and climate variables. The mean water-use intensity ranged from 14.5 m^3/L for olive oil, 13.9 m^3/L for soybean oil, 9.7 m^3/L for groundnut oil, 6.8 m^3/L for rapeseed oil, 5.7 m^3/L for sunflower oil, to 5.3 m^3/L for palm oil.

The total annual land use of all six vegetable oil crops is 168.3 Mha/year when taking multi-cropping, inter-cropping, or fallow into account (see Methods). Total land use is highest for soybean (79.1 Mha/year), palm (35.2 Mha/year), rapeseed (19.6 Mha/year), groundnut (12.4 Mha/year), followed by olive (11.7 Mha/year), and sunflower (10.2

Mha/year). Regionally, land use is highest in Asia and Oceania (59.7 Mha/year), South America (36.9 Mha/year), North America (31.9 Mha/year), then Africa (20.6 Mha/year), and Europe (19.1 Mha/year) (Fig.1c). The regional variation in land-use intensity per liter oil was low in rapeseed and sunflower but relatively high for palm, groundnut, soybean and olive (Fig. S17). The mean value of land-use intensity differs for producing 1-liter vegetable oil among crops, ranging from 8.4 m^2 for sunflower, 10.4 m^2 for rapeseed, 11.0 m^2 for palm, 11.9 m^2 for groundnut, 31.9 m^2 for soybean, and 51.6 m^2 for olive, respectively.

The total annual pesticide use of the six vegetable oil crops is 953.6 kt/year, with 37.1%, 30.2%, 14.2%, 10.9%, and 7.6% coming from Asia and Oceania, South America, North America, Africa, and Europe, respectively (Fig.1d). Pesticide use in South America from soybean production is 274.8 kt/year, which accounts for 60.9% of total pesticide use for soybean production globally and is higher than the total amount used for all other vegetable oil crops; palm, rapeseed, groundnut, olive, and sunflower are 229.5 kt/year, 95.5 kt/year, 92.2 kt/year, 43.5 kt/year and 38.8 kt/year, respectively.

We found the total farmer income from the six vegetable oils to be 66.5 billion USD/year, with 31.9%, 23.7%, 19.7%, 16.7%, and 8.0% coming from Asia and Oceania, South America, North America, Europe, and Africa, respectively (Fig.1e). The farmer income differs between regions and is highest in Asia and Oceania for groundnut (7.3 billion USD/year), palm (5.2 billion USD/year), and rapeseed (3.8 billion USD/year), followed by South America for soybean (13.9 billion USD/year) and then Europe for both sunflower (5.5 billion USD/year) and olive (2.6 billion USD/year). For all details see Fig. S18.

2.2 Camellia can reduce environmental impacts of vegetable oil production

Our land suitability mapping (Methods) shows that 52.2 Mha within the current vegetable oil production areas are suitable for production without land expansion for vegetable oil crop cultivation (Fig. S11b and Table S16). Brazil, which is the major producer of soybean oil, may replace almost one quarter (24.4%) of its vegetable oil crop planting

areas with Camellia. With a cumulative potential of over 50%, Argentina, the United States, Indonesia, and India could replace 19.8%, 11.1%, 8.4%, and 5.4% within the current vegetable oil production areas, respectively. China is the biggest producer and consumer of Camellia oil globally with the potential of 4.9% of Camellia planting in the current vegetable oil crop planting areas (Fig. S12).

Our yield modelling for Camellia cultivation predicted a mean potential yield of 14.4 t/ha and the highest yield to be 32.0 t/ha for fresh fruit (Fig. S13d). Advanced biotechnology and management techniques such as genome editing for seed oil domestication and sprout anvil grafting technology could increase Camellia yields up to 22.5 t/ha with a further 7-10 times increase in the future (24,25). Our three yield scenarios, therefore, were a conservative scenario (or 50% of potential yield, S1), strategic improvement scenario (or 75% of potential yield, S2), and a technology-policy-enabling scenario (or 100% of potential yield, S3) to simulate the environmental impacts of Camellia oil in a life cycle assessment (Methods).

Camellia oil produces substantially lower GHG emission of 4.4 kgCO_2 eq/L, 3.0 kgCO_2 eq/L, and 2.3 kgCO_2 eq/L in S1 and all crops in S2 and S3, respectively, compared to the six main vegetable oil crops for most crops (3.5 kgCO_2 eq/L for sunflower oil; 4.0 kgCO_2 eq/L for rapeseed oil; 8.4 kgCO_2 eq/L for groundnut oil and soybean oil, 8.5 kgCO_2 eq/L for olive oil; 9.7 kgCO_2 eq/L for palm oil; Fig. S15). For water use, Camellia oil has an advantage starting from Scenario 2 with a much lower mean value (9.7 m^3/L) than soybean oil (13.9 m^3/L) and olive oil (14.5 m^3/L) and compared to all vegetable oil crops in Scenario 3 (Fig. S16 and Fig. S20b). Land use of Camellia oil for all three scenarios (6.3, 4.2, and 3.1 m^2/L for S1, S2, and S3, respectively; Fig. S21) is much lower than all other vegetable oils (7.9 m^2/L, 8.4 m^2/L, 9.2 m^2/L, 10.4 m^2/L, and 18.6 m^2/L for groundnut, sunflower, soybean, rapeseed, and olive oil, respectively; Fig. S17) except for palm oil (2.9 m^2/L).

2.3 Priority areas for crop replacement with Camellia cultivation

When considering all six vegetable oil crops together for individual optimization for GHG emission, water use, and land use reduction as well as farmer income increase, the replacing priority areas ranking as soybean followed by groundnut, rapeseed, sunflower, palm, and then olive were consistent across the three Camellia yield scenarios (Table S22) (Fig. S22). Maximizing farmer income per hectare and for each of the three Camellia yield scenarios resulted in the largest area replacements with 42.4 Mha (18.1%), 44.3 Mha (18.9%), and 45.1 Mha (19.2%). In contrast, optimization for all five objectives leads to the lowest area replacement with 26.3 Mha (11.2%), 37.1 Mha (15.8%), and 42.0 Mha (17.9%), corresponding to Camellia yield scenarios 1-3, respectively. When optimizing GHG emission reduction, the total replacing areas across the three yield scenarios are 34.0 Mha (14.5%), 38.9 Mha (16.6%), and 42.7 Mha (18.2%), for the water use reduction objective 33.4 Mha (14.2%), 42.2 Mha (18.0%), and 44.2 Mha (18.8%), for the land use reduction objective 42.2 Mha (18.0%), 44.1 Mha (18.8%), and 44.9 Mha (19.1%), and for pesticide use reduction objective 39.9 Mha (17.0%), 42.1 Mha (17.9%), and 43.3 Mha (18.4%). When considering the spatial distribution, the main benefits for Camellia replacement in Africa are for groundnut, palm, and sunflower, in South America for soybean, in Asia and Oceania for rapeseed, and in Europe for olive (Fig. 2).

When only considering the conservative Camellia yield scenario 1 and optimization of all five objectives together, the replacing area for individual oils production areas are accounting for 20.7 Mha (17.3%), 2.6 Mha (10.0%), 1.5 Mha (4.5%), 0.7 Mha (3.7%), 0.4 Mha (4.4%), and 0.3 Mha (1.3%), of soybean, groundnut, rapeseed, palm, olive, and sunflower, respectively (Fig. 2), which are accounting for 8.8%, 1.1%, 0.7%, 0.3%, 0.2%, and 0.1% of all vegetable oil crops harvested areas. The soybean area replacement then results in the highest benefits of all five objectives, with 26.8% (146.5 Mt CO_2eq), 7.7% (28.2 km^3), 11.9% (9.4 Mha), 15.6% (70.8 kt), and 156.3% (45.5 billion USD) of decreasing GHG emission, water use, land use, pesticide use, and increasing farmer income, respectively. Replacing olive production areas have the lowest effect on decreasing GHG emissions (0.5 Mt CO_2eq) and increasing farmer income (0.6 billion USD), while replacing

sunflower production areas has the lowest effect on water use (0.7 km^3), land use (0.1 Mha), and pesticide use (0.3 kt). These area replacements and resulting benefits increase for Camellia yield scenario 2 and 3 respective, such as for the comprehensive consideration of all five objectives, 1.2 and 1.3 folds of GHG emission, 1.7 and 2.1 folds of water use, 1.5 and 1.8 folds of land use, 1.4 and 1.7 folds of pesticide use, and 2.1 and 3.2 folds of farmer income (for details see Fig. S22, Fig. 3A, Fig. 3B, and Fig. 3C).

2.4 Diversified vegetable oil production without land expansion and yield loss

For tangible solutions, we consider only solutions without land expansion and at least maintaining global vegetable oil yield. In a first step, we focused on replacing global vegetable oil crop production area with Camellia and optimizing all five objectives simultaneously. We found that replacing 26.3 Mha (11.2%) under the conservative Camellia yield scenario 1 resulted in reduction of GHG emissions, water, land, and pesticide use by 14.0% (172.1 Mt CO_2 eq/year), 4.9% (43.4 km^3/year), 7.3% (12.3 Mha/year), 9.3% (88.8 kt/year), respectively, and an increase of farmer income by 82.6% (55.1 billion USD/year) (Fig. 3A). When we replaced 37.1 Mha (15.8%) of global vegetable oil production with Camellia assuming strategic yield improvements (S2; 75% potential yield), GHG emissions, land use, water use, and pesticide use, was reduced by 16.8% (206.9 Mt CO_2 eq/year), 8.2% (71.7 km^3/year), 11.2% (18.8 Mha/year), 13.0% (124.1 kt/year), respectively and farmer income increases by 173.6% (115.7 billion USD/year) (Fig. 3B). When replacing 42.0 Mha (17.9%) of vegetable oil production area under the technology and policy enabled Camellia yield scenario (S3; 100% potential yield), GHG emissions, land use, water use, and pesticide use are reduced by 18.2% (223.6 Mt CO_2 eq/year), 10.5% (92.0 km^3/year), 13.4% (22.6 Mha/year), 15.4% (146.7 kt/year), respectively and farmer income is increased by 261.4% (174.2 billion USD/year) (Fig. 3C). For single-objective results under the three Camellia yield scenarios, refer to Fig. S23, S24, and S25.

In a second step, we ranked replacement areas according to the crops and areas that can achieve the highest benefits of all objectives simultaneously (Fig. 3D). For Camellia

yield scenario 1, the identified 26.3 Mha (11.2%; see above) replacement area provides most benefits when separated amongst soybean (20.7 Mha), groundnut (2.6 Mha), rapeseed (1.5 Mha), palm (0.7 Mha), olive (0.4 Mha), and sunflower (0.3 Mha) (Fig. 3A). For details on all Camellia yield scenarios please see Extended Section 3 and Fig S13. Southern Brazil, Argentina, Paraguay, southern Nigeria, and Tanzania, central India, and southern China were among the top-ranked 10% areas for reducing global GHG emission (Fig. S26a, S27a, and S28a), and also for optimizing all five objectives together (Fig. S26e, S27e, and S28e). The eastern United States, southern China, Brazil, central India, and Guinea had the highest potential to reduce water use (Fig. S26b, S27b, and S28b), land use (Fig. S26c, S27c, and S28c), pesticide use (Fig. S26d, S27d, and S28d), and to increase farmer income (Fig. S26e, S27e, and S28e).

3. Discussion

Our spatially explicit results on the environmental and socioeconomic impacts of global vegetable oil production allow for targeted spatial planning and close critically important knowledge gaps (12). The total GHG emissions of six main vegetable oil crops, for soybean and for palm oil are 1.2 Gt CO_2eq/year, 0.5 Gt CO_2eq/year and 0.4 Gt CO_2eq/year, respectively, which corresponds well with non-spatial values of 1.9 Gt CO_2eq/year, 0.6 Gt CO_2eq/year and 0.9 Gt CO_2eq/year, respectively (7). There is some variation in the total water uses for each oil crop, because other studies only considered the green and blue water use (34). However, irrigation and fertilization in traditional vegetable oil crops production results in a significant grey water footprint (35), and, hence, must be considered in the evaluations.

Our results also highlight the importance to use spatially explicit analysis to identify differences in regional patterns. The total land use of six vegetable oil crops is 168.3 Mha and, hence, lower compared to the harvested area of 222.1 Mha, because we consider spatially explicit land occupation by multiple cropping, intercropping, or fallow (see Methods) (4). Our land use estimates for each vegetable oil are much higher than those reported in Poore and Nemecek (2018) (13), because we report the global average land

use intensity based on our detailed regional results. For instance, producing 1 liter oil requires up to 233.3 m^2/year of land in Portugal for olive oil and 135.1 m^2/year in South Africa for soybean oil (36,37). We found this regional variation in land-use intensity to be low in rapeseed and sunflower but high for the other four vegetable oil crops (Fig. S17). Our systematic literature review and meta-analysis is covering 10,500 regional or farm-level input information in 43 countries (Fig. S3) and considered scenario analysis for potential yield developments when assessing the impact of Camellia cultivation within all suitable areas. We, therefore, trust that our work provides the most robust systematic mapping of vegetable oil crops' environmental impacts and exploration of global priority areas for long-term potential crop substitution to date. Understanding the geographic variation is critical for decision makers to optimize global vegetable oil crop distribution for the least environmental impact but the greatest benefits without land expansion and oil yield loss.

The substitution of vegetable oil crops with Camellia may bring opportunities for farmer livelihoods, nutrition security and biodiversity conservation. First, Camellia production will likely contribute to livelihood security, because Camellia replacement leads to vegetable oil production increase in all our scenarios. In China, (www.ce.cn) (2024) the annual income generated from the Camellia oil supply chain exceeded 8.3 billion USD in 2023 and promoted rural development by increasing employment by 24.0% (4 million people) in Jiangxi Province (40). Farmer income is diversified through Camellia cultivation and, hence, may be less likely to be affected by external shocks from climate change depending on specific crop combinations. Second, Camellia oil is also of high nutritional value and may contribute to nutrition security if supplies increase. For instance, Camellia oil has highest monounsaturated fatty acid composition compared to all other vegetable oils (Fig. S30a) and is rich in antioxidants. The oil has also proven medicinal benefits such as regulating blood lipids, alleviating liver damage, and preventing Alzheimer disease (41) (Fig. S30b). Lastly, several studies have also shown biodiversity benefits related to Camellia cultivation in agricultural landscapes through promoting soil aggregate formation and improving soil fertility (24,31,32). Camellia production is suitable for agroforestry production, which by itself is known to enhance agrobiodiversity providing essential ecosystem services (42,43). Camellia agroforestry has been reported with soybean, groundnut, and rapeseed (44). In

China, changes in the national policy to promote Camellia cultivation has facilitated restoration of degraded lands and promoting the 'ecological civilization' concept in China (45,46,47).

Overall, we have quantified the environmental footprint and socioeconomic value of global vegetable oil production and the benefits of diversified production with the tree oil crop Camellia. Our results provide important guidelines for farmers other decision makers, as to which vegetable oil crop substitution may maximize reduction of GHG emissions, water use, land use, pesticide use and the increase of farmer incomes. Implementation, however, depends on various aspects of an enabling environment. First, infrastructure and financial subsidies are required to support Camellia cultivation with high labor input and profitability during the first 5 years of planting (48). Suitable pathways may follow government schemes as seen for instance for cocoa agroforestry production in Ghana, West Africa or impact investments into sustainable agricultural landscapes (49,50). Second, lock-ins from cultural values, palatability, perceived health benefits, and social norms (51,52) are of critical consideration. For instance, olive oil production in Italy is a cultural heritage and likely much more difficult to substitute compared to soy production in Brazil, which is driven by large corporations rather than culture (53,54). Lastly, technology innovations for instance in breeding will help to close Camellia yield gaps. When Camellia yields are even closer to palm oil yields, crop substitutions will be more attractive to all stakeholders (Fig. S30c; 26,27) with sizable environmental, nutritional, and social benefits (55).

Diversifying global vegetable oil production with crop replacement can contribute to targets of the Global Biodiversity Framework (56) and the Sustainable Development Goals. For instance, when planted as an agroforestry system, Camellia can contribute to biodiversity benefits in degraded landscapes. Camellia agroforestry with corn and Purple Sweet Potato in China have been shown to regulate plantation air and soil temperature, and soil relative humidity, which in turn can enhance shoot growth of Camellia and understory plant diversity (57,58). Land sharing strategies, whereby Camellia cultivation is integrated into abandoned forest fragments to produce vegetable oil, have been shown to increase

plant diversity and release pressure on cropland (59,60,61). Of all concomitant benefits of diversified vegetable oil production, a 14.0% reduction in greenhouse gas emissions in the most conservative yield scenario suggests a strong climate change mitigation potential in an agricultural sector that contributes almost a quarter of all emissions. While Camellia farms can certainly not be regarded as a universal solution for sustainable vegetable oil production, it is crucial to recognize the potential benefits and develop strategies to harness them (12). Our approach to identify priority areas for crop substitution with a limited proportion of the replacing areas can chart a realistic pathway for enhanced diversified vegetable oil production with ramifications for multiple agriculture related sustainable development goals.

4. Methods

We first performed a comprehensive life cycle assessment (LCA) of six major vegetable oil crops - groundnut, soybean, palm, rapeseed, sunflower, and olive for a spatially explicit assessment of environmental and economic effects. We then combined global vegetable oil crop distribution datasets with a Camellia global habitat suitability assessment, and production capacity modelling to enhance global vegetable oil production efficiency through optimized vegetable oil crops land allocation. We did not allow for increasing the overall land area and oil yield loss from the replacement by Camellia *cultivation* locally. We visualize our methods in Fig. S1 and provide details below.

4.1 Mapping global vegetable oil environmental and economic impacts

The environmental impact results are calculated through an LCA according to ISO norms (ISO14040, 2006; ISO14044, 2006) (62,63). For each crop's vegetable oil system, we include the following life-cycle processes: the production of inputs (such as fertilizers and electricity), transport of the inputs to the plantation, and crop harvest in the agricultural stage and vegetable oil production in the industrial stage to calculate the GHG emission for producing 1-liter oil. For water and land use, we mainly consider the stage of crop production, since insignificant amounts of water and land are consumed outside the production phase (64). Limited data availability prevented us from extending our analysis to all production stages along the value chain. Furthermore, we also calculated the quantity of pesticide use for producing 1-liter oil and farmer income for per hectare land of Camellia production and all other vegetable oil crops considered here (i.e., groundnut, palm, rapeseed, soybean, sunflower, and olive). All the agricultural input data were collected by conducting a meta-analysis of 285 studies with 837 observations categorized as sub-national and national studies, covering 10,500 regional or farm-level inventories globally (Extended Section 1.2).

GHG emission. For the GHG emissions from land use change, we mainly consider the above and below-ground C stock change, forest burning, and organic soil burning, but excluding the leaching, runoff, and induced non-CO_2 emissions (65). Specifically, we excluded the CO_2 emissions from land use change of groundnut, olives, rapeseed, and

363 sunflower crops, as the total percentage of current crop area transformed from forest are
364 less than 1% globally (66) (Table S9). We also used the FAO statistical database to estimate
365 CH_4 and N_2O emissions from forest burning, and CO_2, CH_4, and N_2O emissions from
366 organic soil burning at the country level for all six vegetable oil crops (Table S11, Table
367 S12). As Camellia trees are not currently grown on a large scale globally, we used a global-
368 scale Terrestrial Ecosystem Model (67) to quantify the potential impact of growing Camellia
369 on carbon emissions. The agricultural inputs for the seven types of vegetable oil crops
370 mainly include planting seeds or nurseries, fertilizers, agricultural film, pesticides, diesel,
371 and electric energy consumed by agricultural machinery or water irrigation. For the oil
372 processing stage, we collected the carbon emission from the published papers by referring
373 to the flow of 1 liter of (refined) oil (Table S14). We estimate their GHG emissions through
374 emission factors and results are expressed in kg CO_2e kg^{-1} for crop fruit and kg CO_2e $liter^{-}$
375 ^{1} for vegetable oil, with the global warming potential (GWP) of CH_4 and N_2O being 34 and
376 298 kg CO_2 e kg^{-1}, respectively.

377 **Water use.** We use the CROPWAT 8.0 model and the FAO Penman-Monteith equation
378 to calculate green water and blue water footprints (68,69), with considering the crop
379 coefficient and potential evapotranspiration (Equation 1). The grey water footprint also was
380 calculated to represent the water consumption to dilute pollutant concentrations from
381 fertilizer applications to reach natural background concentrations or to meet ambient water
382 quality standards.

383 $$ET_0 = \frac{0.408\Delta\times(R_n-G)+900\gamma/(T_{mean}+273)\times U_2\times(e_s-e_a)}{\Delta+\gamma(1+0.34U_2)} \quad \text{Eq. (1)}$$

384 where ET_0 is the potential evapotranspiration; Δ is saturated water pressure curve slope
385 (kPa/℃); R_n is ground surface radiation of crop canopy surface (MJ/(m*d)); G Soil heat flux
386 (MJ/(m2·d)); γ is the wet and dry constant (KPa/℃); T_{mean} is the daily average temperature
387 at 2 meters (℃); U_2 is the wind speed at 2 meters (m/s); e_s is the saturated water pressure
388 (Kpa); e_a is the actual water pressure (Kpa). The calculation process of Δ, R_n, γ, T_{mean}, and
389 U_2 are referred to from "FAO Irrigation and Drainage Paper, No. 56, Crop
390 Evapotranspiration" (69) and the details are explained in Extended Section 3.2.3.

391 **Land use.** By taking the difference between temporary and permanent crops into

consideration, we divided the vegetable oil crops into two main types namely temporary crops (groundnut, rapeseed, soybean, and sunflower) and permanent crops or orchard crops (Camellia, palm, and olive). Land use for each vegetable oil crop was calculated from occupation time and inverse crop yields in each region, with actual yield for the current six types of vegetable oil crops and three scenarios of potential yield for Camellia.

Pesticide use. Unlike the life cycle assessment required to estimate the processed-based GHG emission, crop water use, and land use, pesticide use is assessed directly based on meta-analysis and official statistical data, with studies being weighted in three ways: 1) within-region country weights; 2) between-region country weights; and 3) between-country weights to enable one geography reflecting another, where data was unavailable. For more details see Extended Section 1.2.3. Here, the pesticide use excludes minerals used for pest management, such as Sulphur or Copper, to make the amount of substance and the amount of active ingredients comparable.

Farmer income. The crop-specific total production was calculated based on specific rainfed or irrigated yield and harvested areas. For the price of the six vegetable oil crops considered here, we used the average value from 2017 to 2021 obtained from FAOSTAT to get the producer prices in each country (USD $Tonne^{-1}$) (Table S23) (3). As currently Camellia is mainly planted in China, the farmer incomes coefficient information was taken from the National Development and Reform Commission (70) and producer prices of Camellia seed were set as 19.74 RMB/Kg (100 USD=660 RMB) (71). The farmer's net profit varies based on the agricultural and labor inputs, such as the pesticide and fertilizer use intensity. Hence, for each agricultural commodity selected, we assumed a 20% margin of profit to obtain the opportunity cost for each vegetable oil crop's fruits, as a likely conservative (that is, high) estimate based on profit margins in the USA (non-small farms) (72), some EU countries (73) and Canada (74). This simplified assumption results from limited data availability and variable profit margins, in particular with farm sizes (75).

4.2 The potential distribution and yield supply of Camellia cultivation

4.2.1 Land suitability assessment.

To identify the potential of land distribution for planting Camellia, we selected 11

421 indicators based on a comprehensive literature review from 3 aspects of climatic,
422 topographic, and soil factors from multiple databases to model the spatially explicit
423 distribution of suitable areas. For a full description of indicator selection, modelling details,
424 and data sources, please see Extended Section 2. As the weight of each indicator varies in
425 published papers, we used a "random forest" machine learning algorithm to identify the
426 weight for each indicator of current Camellia plating observations. Random forests are
427 robust to overfitting and variable importance when modelling crop distributions and
428 predicting the yields (76, 77). The decision to use a random-forest approach was supported
429 by its superior performance metrics compared to other machine learning approaches (Fig.
430 S9).

431 Beyond the natural environmental viability that we considered from the land suitability
432 assessment, we further identified five additional constraint factors (land use type, terrestrial
433 and inland protected areas, world roads areas, intact forest landscapes, and global key
434 biodiversity areas) that are likely to limit the suitable areas for large-scale Camellia
435 cultivation development due to ecological protection or social constraints. For the land use
436 constraints, we ultimately considered excluding the land cover with rainfed, irrigated, or
437 post-flooding cropland, urban areas, water bodies, and permanent snow or ice. After
438 obtaining these spatially explicit data layers of five constraint factors, we resampled each
439 at a 0.083° resolution to match with the 11 graphic data layers. We first processed the 11
440 indicators layer as described in Table S16 to classify each grid into four classes, not suitable,
441 moderately suitable, suitable, or very suitable. For the five additional constraint factors, we
442 assume that some areas (for example, the areas within the protected areas, the key
443 biodiversity areas, or the intact forest) will be completely unsuitable for planting Camellia.
444 These five layers were further processed to assign double-valued with 0 and 1, where 0
445 represents not suitable and 1 represents suitable. These layers were then multiplied
446 together to create the overall global map of land suitability shown in Fig. S11. Field
447 verification in Extended Section 2.4 with an 88.20% cross-validation ratio shows the high
448 reliability of our land suitability assessment result.
449

4.2.2 iGAEZ modelling on potential yield.

To simulate crop yields globally for land suitable areas of Camellia, we developed a new approach called iGAEZ (improved Global Agro-Ecological Zones model) based on the GAEZ model (78). While GAEZ does provide evaluation of the biophysical limitations and production potentials of land, iGAEZ provides realistic crop yield combinations considering the whole spectrum of climatic and agricultural conditions. iGAEZ model generates the optimal crop parameter of the whole growth cycle to provide the best realistic crop yield combinations. Doing this, the improved model takes regionally differentiated climatic – social - economic status and crop condition into account. The details of each procedure in the iGAEZ model are detailed in Extended Section 3 with the results of the photosynthetic potential yield, light and temperature potential yield, climatic potential yield, and natural comprehensive potential yield, respectively (Fig. S13).

5.2.3 Scenario design.

We develop three scenarios in this study, namely, a conservative scenario (S1), where the Camellia yield potential stays close to business-as-usual and reflects actual yield. In the strategic improvement scenario (S2), we assume implementation of advanced cultivation techniques and optimized input use to achieve a 25% increase in Camellia yield over current levels. In a technology-policy-enabling scenario (S3), both technology advances and policy improve to promote woody and environmental oilseed yield. Every scenario is contingent upon the one before. Specifically, in S1, estimates of yield growth were set as 50% of the final natural comprehensive potential yield at any spatial scale for best indicating near the actual yield. The actual yields for Camellia *seeds* are mainly collected from China Agriculture Outlook (79) and the 2019 China Forestry and Grassland Statistic yearbook (80). The current actual yield records of Camellia seed in China for Anhui, Hunan, and Guangxi Province are 6.7, 7.8 and 6.5 t/ha, respectively (81,82), which are still much lower than their yield potentials (that is, 14.4 t/ha) but close to half of the yield potential. In S2, we made 75% of the potential yield as an attainable or exploitable yield ceiling of Camellia. Due to diminishing profits from investing in additional production inputs and labor as yields

approach the potential yield ceiling, present farm yields tend to plateau when they reach 75–80% of potential yield, also known as the exploitable yield ceiling (83,84). In S3, we assume a 100% potential yield of Camellia. This assumes that technology-oriented policies are implemented and yield improvement through technologies make 100% potential yield attainable.

4.3 Spatial prioritization of Camellia crop-replacing model

We applied a multicriteria optimization framework (75,85) to identify global priority areas for replacement from current vegetable oil crops to Camellia plantations and to quantify trade-offs and synergies across five objectives, including GHG emission, water use, land use, pesticide use, and farmer income. To do so, we: (i) estimated the current six main types of vegetable oil crops planted worldwide and their producing environmental impacts and farmer income; (ii) estimated potential long-term replacing benefits by Camellia plantation across five objectives; (iii) implemented a multicriteria optimization algorithm based on linear programming to show the spatial prioritization ranking for Camellia planting areas; and (vi) simulated different global replacement scenarios based on each objective or comprehensive consideration under different Camellia yield potential. Our study is global with a focus on all terrestrial regions suitable for production of the six main types of vegetable oil crop from −80° to 80° latitude and from −180° to 180° degrees longitude.

Trade-offs among five objectives for sustainable vegetable oil production. To estimate the potential benefits of replacement from current vegetable oil crops to Camellia plantation, we set our five objectives when implementing the crop replacement to achieve a sustainable vegetable oil production system, that is, (1) maximize GHG emission reductions, (2) maximize water use reductions, (3) maximize land use reductions, (4) maximize pesticide use reductions, and (5) maximize farmer income increasing.

We first used the total oil production or the total harvested areas for each oil crop to calculate the current total environmental and economic impacts based on the previous results per liter of oil or hectare area in Section 1.3. For each grid, the current (2015) vegetable oil production from each crop z of rainfed ($OilPro_{Cur,Rai,i,z}$) and irrigated

($OilPro_{Cur,Irr,i,z}$) were calculated as Equation 2.

$$OilPro_{Cur,Rai/Irr,i,z} = \alpha_z \times HarA_{Rai/Irr,i,z} \times OY_{Rai/Irr,i,z} \quad \text{Eq. (2)}$$

$$OY_{Rai/Irr,i,z} = \alpha_z \times Y_{Rai/Irr,i,z} \quad \text{Eq. (3)}$$

$$EN_{Cur,Rai/Irr,i,z,j} = PL_{EN,i,z,j} \times OilPro_{Cur,Rai/Irr,i,z} \quad \text{Eq. (4)}$$

$$EC_{Cur,Rai/Irr,i,z} = PH_{EC,i,z} \times HarA_{Rai/Irr,i,z} \quad \text{Eq. (5)}$$

where $HarA$ is the harvested area (ha) for each vegetable oil crop in grid i; z is the six types of vegetable oil crops with the value from 1, 2, 3, ..., 6 referring to groundnut, soybean, palm, rapeseed, sunflower, and olive, respectively; α_z is the oil extraction ratio for different crops to produce 1 liter (refined) oil (Table S6). OY is the oil yield (kg/ha) by considering the crop fruits yield Y and oil extraction ratio α_z; the subscripts Rai and Irr represent two cropping systems in rainfed and irrigated, respectively; $PL_{EN,i,z,j}$ is the environmental impact of producing per liter oil and j is the value of 1,2,3, and 4, representing the environmental indicators with GHG emission, water use, land use, and pesticide use, respectively. $PH_{EC,i,z}$ is the economic impact with the indicator of net farmer income per hectare. $EN_{Cur,Rai/Irr,i,z,j}$ and $EC_{Cur,Rai/Irr,i,z}$ are the total environmental and economic impact in grid i. Then, we estimated the benefits of Camellia planting replacement, which can be expressed as:

$$\mathrm{BEN_{i,j}} = \sum_{Z=1}^{6} \Delta PL_{EN,i,\mathrm{j}} \times HarA_{Replaced,Rai/Irr,i,z} \times OY_{Rai/Irr,i,z} \quad \text{Eq. (6)}$$

$$\mathrm{BEC_i} = \sum_{Z=1}^{6} \Delta PH_{EC,i,j} \times HarA_{Replaced,Rai/Irr,i,z} \quad \text{Eq. (7)}$$

$$\Delta PL_{EN,i,\mathrm{j}} = PL_{EN,i,z,j} - PL'_{EN,i,CA,j} \quad \text{Eq. (8)}$$

$$\Delta PH_{EC,i,j} = PH_{EC,i,z} - PH'_{EC,i,CA} \quad \text{Eq. (9)}$$

where $\mathrm{BEN_{i,j}}$ is the total replacing benefit of environmental indicator of j and $\mathrm{BEC_i}$ is the total replacement economic benefit. Especially, after crop replacement, it will possibly require additional transportation and transaction costs, which farmers do not bear. We acknowledge that our model has the limitations of not considering the additional costs and assumption of the constant harvested area under crop replacement. Thus, we made a very conservative estimation of replacing benefits by using the oil yield of original crops instead of Camellia in Eq. (6) to offset partial impacts as the crop-replacing constraint of higher oil yield compared to original crops. $PL'_{EN,i,CA,j}$ is the environmental impact of producing per liter Camellia oil under three potential yield scenarios; $PH'_{EC,i,CA}$ is the net farmer income per hectare of Camellia plantation. $\Delta PL_{EN,i,\mathrm{j}}$ and $\Delta PH_{EC,i,j}$ are the differences between the

current crop and Camellia per unit of the environmental and economic impact. $HarA_{Replaced,Rai/Irr,i,z}$ is the current harvested area (ha) of replaced locations.

Crop-replacing constraints. There is a need to determine the crop replacement constraints to ensure successful implementation of crop replacement. The first constraint in Equation 10 limits the location of the vegetable oil crop to be replaced, which depends on the oil yield of Camellia ($\mathrm{OY_{i,CA}}$). The requirement of higher or equal to the current vegetable oil yield is to ensure no oil yield loss. In the second constraint for scale, A_i is the total percentage of the current six types of vegetable oil crops harvested areas to be replaced by Camellia. Based on recommendations from the literature (85), the proportion of the areas replaced or fallowed is usually limited to a maximum value of $\Delta\mathrm{CL}$ = 20% to ensure global food market stability. In the study, the maximum value of $\Delta\mathrm{CL}$ = 23.5%, which is our estimated proportion of all suitable areas for planting Camellia within the current vegetable oil production areas to the total six main vegetable oil harvested areas. Here, we assumed that the replaced harvested areas would remain the same with the current crops once identifying replacement, which is for maintaining defined crop-specific production and vegetable oil volumes (78). Furthermore, the current crop-specific producing area will not expand to minimize the global vegetable oil-producing land extent and directly avoid global burden-shifting, especially for the land use pressure. The third constraint was implemented based on pursuing different objectives. If we consider maximizing additional environmental impact reductions, it requires $\Delta PL_{EN,i,\mathrm{j}} \geq 0$ meaning the environmental impact of producing per liter Camellia oil is lower than current vegetable oil. If under the comprehensive consideration of all five objectives, it requires both $\Delta PL_{EN,i,\mathrm{j}} \geq 0$ per liter oil and $\Delta PH_{EC,i,j} \geq 0$ per planting hactare area.

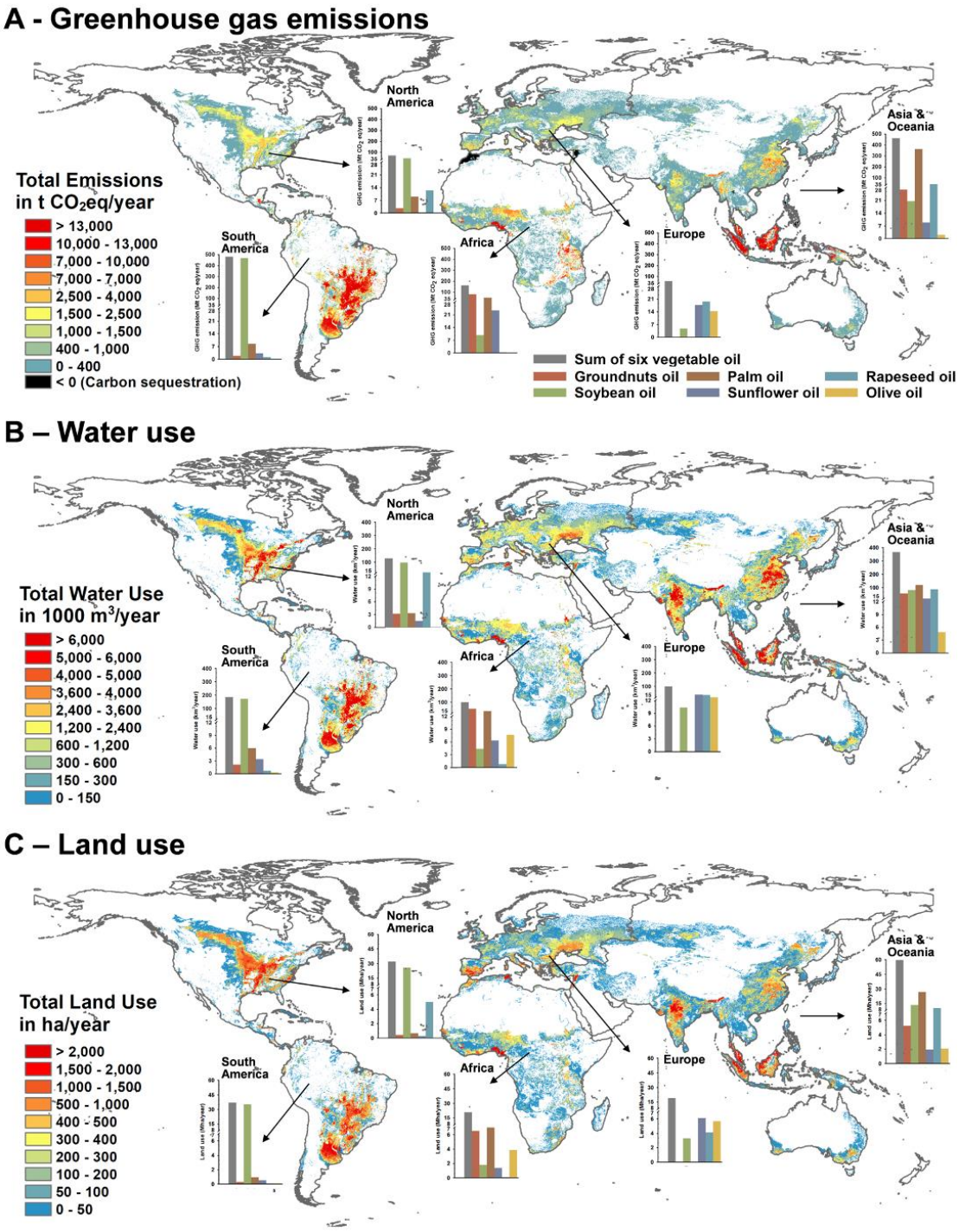
$$\text{subject 1 to } OY_{i,CA} \geq OY_{Rai/Irr,i,z} \qquad \text{Eq. (10)}$$

$$\text{subject 2 to } \frac{\sum_{Z=1}^{6} HarA_{Replaced,Rai/Irr,i}}{\sum_{Z=1}^{6} HarA_{\mathrm{total}}} = \mathrm{A_i} \leq \Delta\mathrm{CL} \qquad \text{Eq. (11)}$$

$$\text{subject 3 to } \Delta PL_{EN,i,\mathrm{j}} \geq 0 \text{ and/or } \Delta PH_{EC,i,j} \geq 0 \qquad \text{Eq. (12)}$$

Spatial prioritization ranking and scenarios setting. To identify the priority areas for

Camellia replacement to the current vegetable oil crops, we ran a multicriteria optimization algorithm based on an objective function that defines the amount of area to be replaced in each planning unit to maximize benefits. By modelling 108 scenarios of replacement prioritization (3 potential yield levels of Camellia × 6 types of main vegetable oil crops of groundnut, soybean, palm, rapeseed, sunflower, and olive × 6 targets by trade-offs among each five objective and/or the comprehensive consideration of all), we aim to interplay with land potentially spared from low vegetable oil production efficiency to achieve different replacing targets on environmental and/or economic benefits. There are 100 priority levels in each scenario divided as the equal grid number with the spatial layout of targeted replacing areas and then ranked as the high benefits of each five objectives and/or the comprehensive. All spatial prioritization ranking maps, unless otherwise noted, were the result of aggregating the nested sets of priorities for total benefit formulations by replacing six vegetable oil crops. For the comprehensive consideration of all five objectives, an equal weighting was chosen to understand how the five components trade off and to focus on the layout and replacing scale of priority on a macro scale.


A - Greenhouse gas emissions
Total Emissions in t CO_2eq/year
> 13,000
10,000 - 13,000
7,000 - 10,000
7,000 - 7,000
2,500 - 4,000
1,500 - 2,500
1,000 - 1,500
400 - 1,000
0 - 400
< 0 (Carbon sequestration)
North America
South America
Africa
Europe
Asia & Oceania
Sum of six vegetable oil
Groundnuts oil
Palm oil
Rapeseed oil
Soybean oil
Sunflower oil
Olive oil
B – Water use
Total Water Use in 1000 m^3/year
> 6,000
5,000 - 6,000
4,000 - 5,000
3,600 - 4,000
2,400 - 3,600
1,200 - 2,400
600 - 1,200
300 - 600
150 - 300
0 - 150
C – Land use
Total Land Use in ha/year
> 2,000
1,500 - 2,000
1,000 - 1,500
500 - 1,000
400 - 500
300 - 400
200 - 300
100 - 200
50 - 100
0 - 50

583

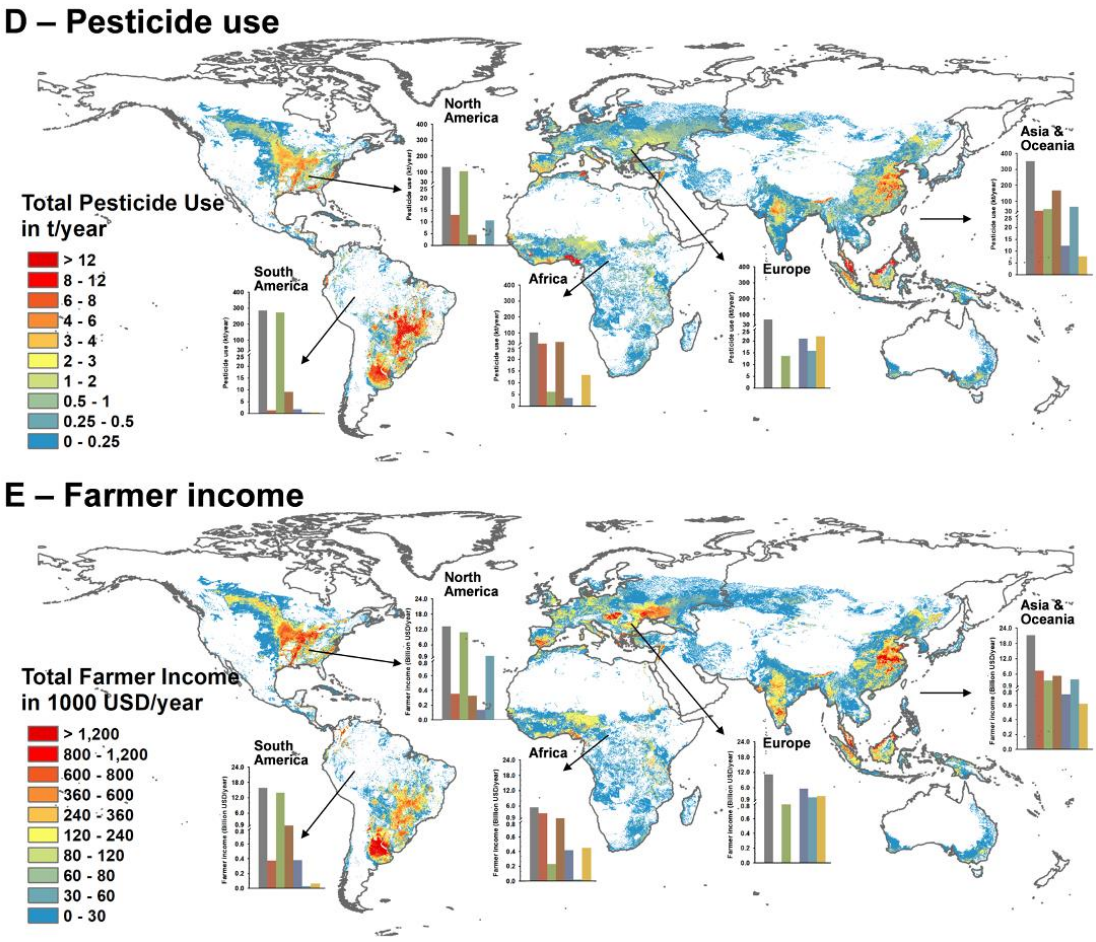
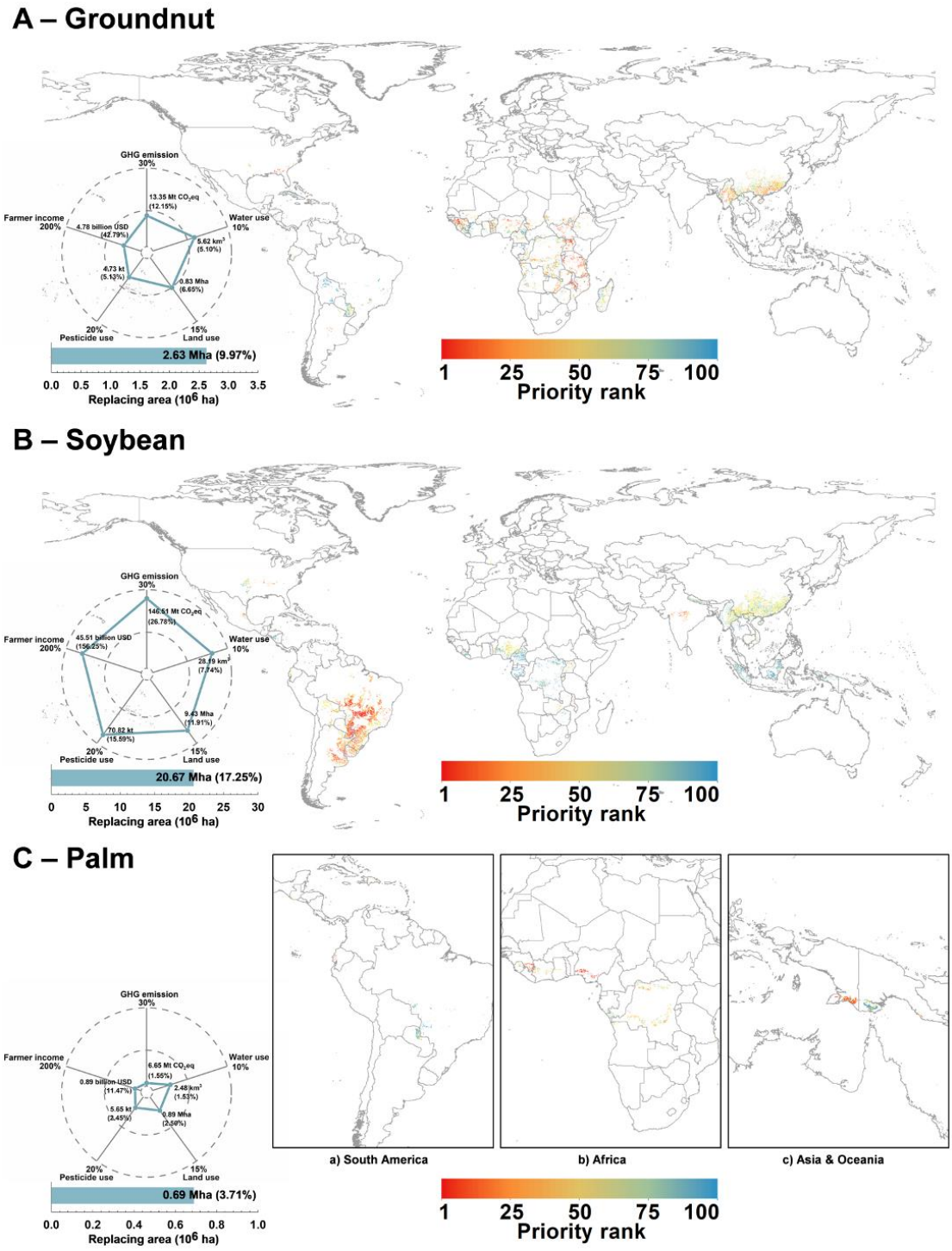


Fig. 1: Global environmental and socioeconomic effect of the six main vegetable oil crops. Shown are the effects of groundnut, soybean, palm, rapeseed, sunflower, and olive on GHG emissions (A), water use (B), land use (C), pesticide use (D), and farmer income (E).


A – Groundnut
GHG emission 30%
13.35 Mt CO2eq (12.15%)
Water use 10%
5.62 km3 (5.10%)
0.83 Mha (6.65%)
Land use 15%
Pesticide use 20%
4.73 kt (5.13%)
Farmer income 200%
4.78 billion USD (42.79%)
2.63 Mha (9.97%)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
Replacing area (10^6 ha)
1 25 50 75 100
Priority rank
B – Soybean
GHG emission 30%
140.51 Mt CO2eq (26.78%)
Water use 10%
28.19 km3 (7.74%)
9.43 Mha (11.91%)
Land use 15%
Pesticide use 20%
70.82 kt (15.59%)
Farmer income 200%
45.51 billion USD (156.25%)
20.67 Mha (17.25%)
0 5 10 15 20 25 30
Replacing area (10^6 ha)
1 25 50 75 100
Priority rank
C – Palm
GHG emission 30%
6.65 Mt CO2eq (1.55%)
Water use 10%
2.48 km3 (1.53%)
0.89 Mha (2.50%)
Land use 15%
Pesticide use 20%
5.65 kt (3.45%)
Farmer income 200%
0.89 billion USD (11.47%)
0.69 Mha (3.71%)
0.0 0.2 0.4 0.6 0.8 1.0
Replacing area (10^6 ha)
a) South America
b) Africa
c) Asia & Oceania
1 25 50 75 100
Priority rank

589

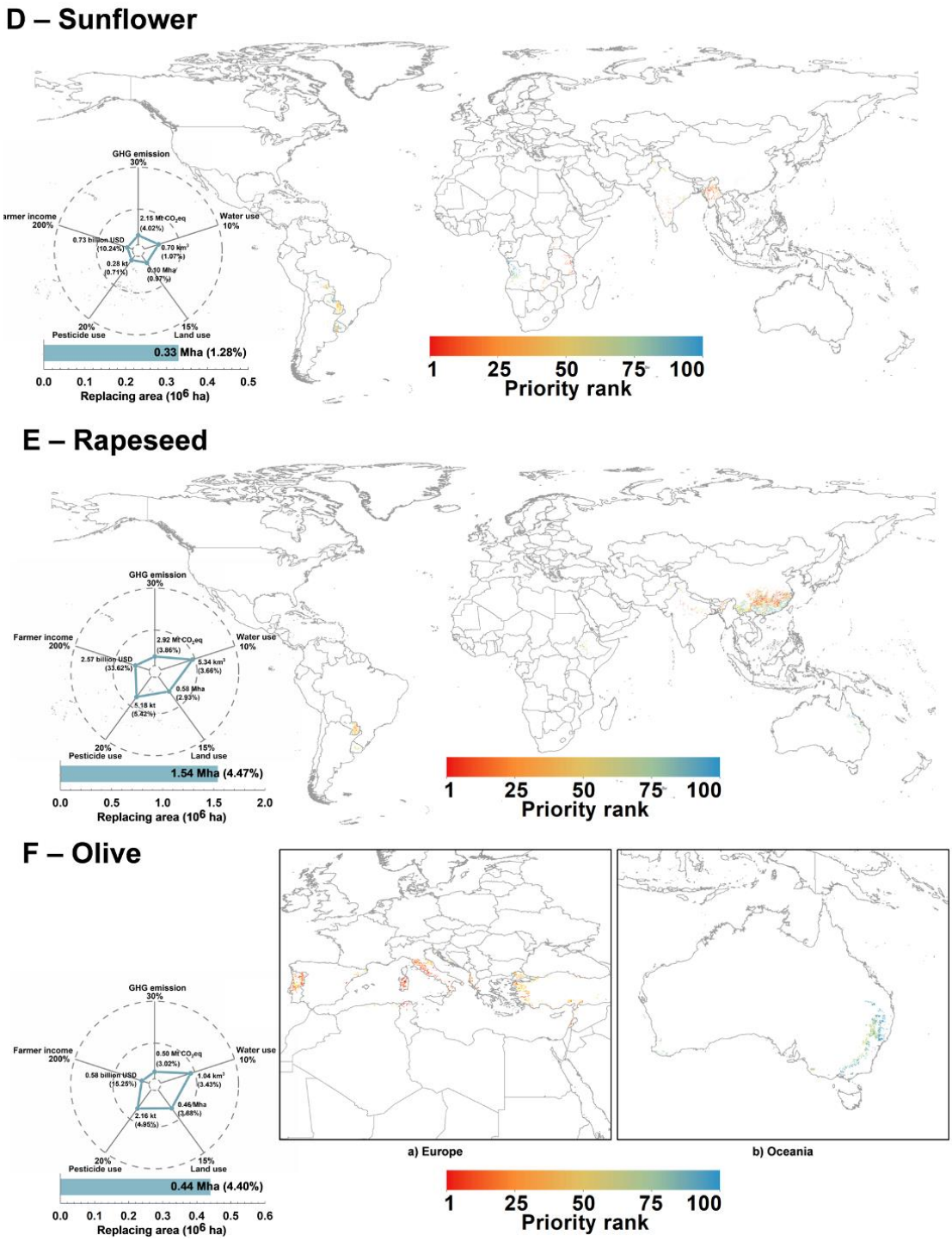


Fig. 2: Priority areas for crop replacement with Camellia cultivation. Panels show the replacement areas for six vegetable oil crops under a conservative Camellia yield scenario (S1) and optimizing reduction of GHG emissions, water use, land use, pesticide use per liter oil, and increase of farmer income per hectare land simultaneously: groundnut (A), soybean (B), palm (C), sunflower (D), rapeseed (E), and olive (F). Note that for palm (C) and olive (F), we zoom in to continent level as replacing areas would be difficult to see otherwise. Priorities refer to the

highest (red: 1–10) to lowest (blue: 90–100) valuable areas for Camellia replacement to achieve simultaneous objective optimization.

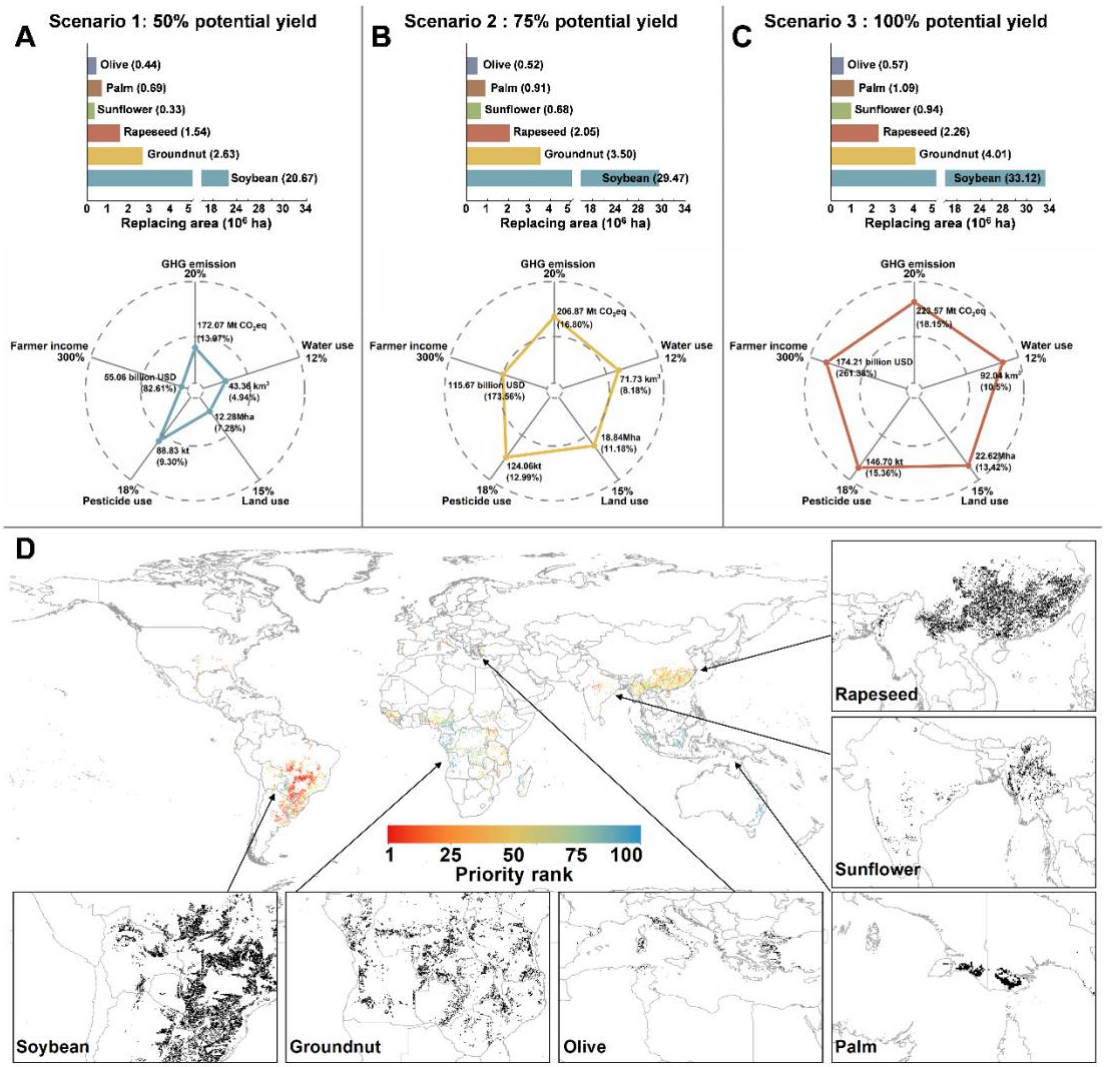


Fig. 3: Global spatial priority areas for Camellia replacement to reduce GHG emission, water use, land use, and pesticide use per liter oil, and increase farmer income per hectare land. For a conservative (A), strategic (B), and technology-policy-enabling Camellia yield improvement scenario (C) when all five objectives are optimized simultaneously. The histograms and radar plots show the total replacing areas for each vegetable oil crop and quantified benefits for each objective, respectively. Spatial benefits of vegetable oil crop replacement differ between continents and crops as shown for the conservative Camellia yield scenario (S1) (D). For details see main text.

CRediT authorship contribution statement

Conceptualization – SZ, TCW; Formal Analysis – SZ; Investigation – SZ; Writing – SZ, TCW Supervision – TCW; Funding acquisition – TCW.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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