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1 The environmental impacts of palm oil in 2 context

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44 **Abstract**

45 Delivering the Sustainable Development Goals (SDGs) requires balancing demands on land between
46 agriculture (SDG 2) and biodiversity (SDG 15). The production of vegetable oils, and in particular
47 palm oil, illustrates these competing demands and trade-offs. Palm oil accounts for 40%¹ of the
48 current global annual demand for vegetable oil as food, animal feed, and fuel (210 million tons²
49 (Mt)), but planted oil palm covers less than 5-5.5%³ of total global oil crop area (ca. 425 Mha)⁴, due
50 to oil palm's relatively high yields⁵. Recent oil palm expansion in forested regions of Borneo,
51 Sumatra, and the Malay Peninsula, where >90% of global palm oil is produced⁵, has led to substantial
52 concern around oil palm's role in deforestation. Oil palm expansion's direct contribution to regional
53 tropical deforestation varies widely, ranging from 3% in West Africa to 47% in Malaysia⁶. Oil palm is
54 also implicated in peatland draining and burning in Southeast Asia. Documented negative
55 environmental impacts from such expansion include biodiversity declines, greenhouse gas
56 emissions, and air pollution. However, oil palm generally produces more oil per area than other oil
57 crops⁷, is often economically viable in sites unsuitable for most other crops, and generates
58 considerable wealth for at least some actors⁸. Global demand for vegetable oils is projected to
59 increase by 46% by 2050⁹. Meeting this demand through additional expansion of oil palm versus
60 other vegetable oil crops will lead to substantial differential effects on biodiversity, food security,
61 climate change, land degradation, and livelihoods. Our review highlights that, although substantial
62 gaps remain in our understanding of the relationship between the environmental, socio-cultural and
63 economic impacts of oil palm, and the scope, stringency and effectiveness of initiatives to address
64 these, there has been little research into the impacts and trade-offs of other vegetable oil crops.
65 Greater research attention needs to be given to investigating the impacts of palm oil production
66 compared to alternatives for the trade-offs to be assessed at a global scale.

67 Over the past 25 years, global oil crops have expanded rapidly, with major impacts on land use⁹. The
68 land used for growing oil crops grew from 170 million ha (Mha) in 1961 to 425 Mha in 2017⁴ or ~30%
69 of all cropland world-wide¹⁰. Oil palm, soy, and rapeseed together account for >80% of all vegetable
70 oil production with cotton, groundnuts, sunflower, olive, and coconut comprising most of the
71 remainder (Table 1, Figure 1). These crops, including soy (125 Mha planted area⁴) and maize (197
72 Mha planted area⁴), are also used as animal feed and other products.

73 Oil palm is the most rapidly expanding oil crop. This palm originates from equatorial Africa where it
74 has been cultivated for millennia, but it is now widely grown in Southeast Asia. Between 2008 and
75 2017, oil palm expanded globally at an average rate of 0.7 Mha per year⁴, and palm oil is the leading
76 and cheapest edible oil in much of Asia and Africa. While it has been estimated that palm oil is an
77 ingredient in 43% of products found in British supermarkets¹¹, we lack comparable studies for the
78 prevalence of other oils.

79 As a wild plant, the oil palm is a colonising species that establishes in open areas. Cultivated palms
80 are commonly planted as monocultures, although the tree is also used in mixed, small-scale and
81 agroforestry settings. To maximize photosynthetic capacity and fruit yields, oil palm requires a warm
82 and wet climate, high solar radiation, and high humidity. It is thus most productive in the humid
83 tropics, while other oil crops, except coconut, grow primarily in subtropical and temperate regions
84 (Table 1). Moreover, because oil palm tolerates many soils including deep peat and sandy substrates,
85 it is often profitable in locations where few other commodity crops are viable. The highest yields
86 from planted oil palm have been reported in Southeast Asia⁵. Yields are generally lower in Africa¹²
87 and the Neotropics⁵, likely reflecting differences in climatic conditions including humidity and cloud
88 cover¹², as well as management, occurrence of pests and diseases, and planting stock¹³.

89 Palm oil is controversial due to its social and environmental impacts and opportunities. Loss of
90 natural habitats, reduction in woody biomass, and peatland drainage that occur during site

91 preparation are the main direct environmental impacts from oil palm development¹⁴. Such
92 conversion typically reduces biodiversity and water quality and increases greenhouse gas emissions,
93 and, when fire is used, smoke and haze^{5,15}. Industrial oil palm expansion by large multi-national and
94 national companies is also often associated with social problems, such as land grabbing and conflicts,
95 labour exploitation, social inequity¹⁶ and declines in village-level well-being¹⁷. In producer countries,
96 oil palm is a valued crop that brings economic development to regions with few alternative
97 agricultural development options⁸, and generates substantial average livelihood improvements
98 when smallholder farmers adopt oil palm¹⁸. Here we review the current understanding of the
99 environmental impacts from oil palm cultivation and assess what we know about other oil crops in
100 comparison. Our focus is on biodiversity implications and the environmental aspects of
101 sustainability, and we acknowledge the importance of considering these alongside socio-cultural,
102 political, and economic outcomes.

103 **DEFORESTATION AND OIL PALM EXPANSION**

104 A remote sensing assessment found that oil palm plantations covered at least 19.5 Mha globally in
105 2019 (Figure 2), of which an estimated 67.2% were industrial-scale plantings and the remainder
106 smallholders³. With 17.5 Mha, Southeast Asia has the largest area under production, followed by
107 South and Central America (1.31 Mha), Africa (0.58 Mha) and the Pacific (0.14 Mha). However, the
108 actual area under oil palm production could be 10–20% greater than the area detected from satellite
109 imagery, i.e. 21.5–23.4 Mha, because young plantations (< ca. 3 years), open-canopy plantations, or
110 mixed-species agroforests were omitted³. Estimates suggest that the proportion of oil palm area
111 under smallholder cultivation (typically less than 50 ha of land per family¹⁹) varies from 30–60% in
112 parts of Malaysia and Indonesia¹⁷ to 94% in Nigeria⁵.

113 The overall contribution of oil palm expansion to deforestation varies widely and depends in part on
114 assessment scope (temporal, spatial) and methods. We reviewed 23 studies that reported land use

115 or land cover change involving oil palm (Table S1 and S2). In Malaysian Borneo, oil palm was an
116 important contributor to overall deforestation²⁰. Here, new plantations accounted for 50% of
117 deforestation from 1972 to 2015 when using a 5-year cut-off to link deforestation and oil palm
118 development²¹ (Figure 3, Figure S2, Table S3). In contrast, one global sample-based study suggested
119 that between 2000 and 2013, just 0.2% of global deforestation in “Intact Forest Landscapes” was
120 caused by oil palm development²².

121 The degree to which oil palm expansion has replaced forests (defined as naturally regenerating
122 closed canopy forests) varies with context. From 1972 to 2015, around 46% of new plantations
123 expanded into forest, with the remainder replacing croplands, pasturelands, scrublands (including
124 secondary forest regrowth), and other land uses⁵. Individual studies reported forest clearance
125 ranging from 68% of tracked oil palm expansion in Malaysia and 44% in the Peruvian Amazon, to just
126 5–6% in West Africa, Central America, and South America excluding Peru (Figure 3). In general, oil
127 palm expansion in the Neotropics is characterized by the conversion of previously cleared lands
128 instead of forests^{23,24}, although the extent to which oil palm displaces other land uses into forests
129 remains uncertain. In Indonesia and Malaysian Borneo, industrial plantation expansion and
130 associated deforestation have declined since ca. 2011^{6,25}. However, smallholder plantings developed
131 to support demand by industrial palm oil mills may be increasing. To date, only two studies have
132 clearly differentiated between forest clearing by smallholders and industrial plantations (Table S2).
133 In Peru, 30% of smallholder plantings resulted in deforestation²⁶, while in Sumatra, Indonesia 39% of
134 smallholder expansion was into forest²⁷. While we still lack broader understanding of the
135 deforestation impacts of smallholders²⁷, recent studies from Indonesian Borneo show that like
136 industrial actors, smallholders sometimes convert fragile ecosystems such as tropical peatlands into
137 oil palm plantations²⁸. Other oil crops have not yet been mapped globally with similar levels of
138 accuracy, precluding detailed assessments and comparisons.

139 **OIL PALM’S DIRECT IMPACTS ON SPECIES**

140 The International Union for the Conservation of Nature (IUCN) Red List of Threatened Species²⁹
141 documents 321 species for which oil palm is a reported threat, significantly more than for other oil
142 crops (Figure 4, Table 1). Species threatened by oil palm made up 3.5% of the taxa threatened by
143 annual and perennial non-timber crops (9,088 species) and 1.2% of all globally threatened taxa
144 (27,159 species) in 2019 (Supplementary Materials, Table S4). These species include orangutans
145 *Pongo* spp., gibbons *Hylobates* spp. and the tiger *Panthera tigris*. Species threat lists, however, are
146 incomplete as most plant groups have not been comprehensively assessed, and the focus of threat
147 studies may be biased toward certain oil crops. For example, perennial crops (oil palm, coconut,
148 olive) might be more easily identified as a threat to a species than annual crops, because perennial
149 crops facilitate long-term studies that are more difficult with annual crops that may not be planted
150 every year. Also, the IUCN Red List focuses on threats in the recent past, and is thus biased toward
151 crops with recent rapid expansion. Better information is needed for all oil crops about where they
152 are grown, and how their expansion has affected and could affect natural and semi-natural
153 ecosystems and biodiversity. We note that because coconut is primarily grown in tropical island
154 nations it stands out as a particular threat for rare and endemic species with small ranges³⁰ (Table 1).

155 Oil palm plantations contain lower species diversity and abundance for most taxonomic groups
156 when compared to natural forest^{31,32}. Plant diversity in some plantations is less than 1% of that in
157 natural forests³¹, but because oil palm is perennial, associated plant diversity may exceed that of
158 annual oil crops (Table 1). One study found 298 plant species in the oil palm undergrowth³³, and
159 another found 16 species of fern on oil palm trunks³⁴, while a meta-analysis of plant diversity in a
160 range of annual crops, including oil crops, found between one and 15 associated plant species³⁵.

161 Plant diversity in any oil croplands also depends on management choices such as tillage, weeding
162 and the use of herbicides or other chemicals.

163 Recorded mammal diversity in oil palm is 47–90% lower than in natural forest^{36,37}, and strongly
164 depends on the proximity of natural forests. Oil palm plantations generally exclude forest specialist

165 species^{38,39}, which are often those species of greatest conservation importance. For example, forest-
166 dependent gibbons (Hylobatidae) cannot survive in stands of monocultural oil palm, but can make
167 use of interspersed forest fragments within an oil palm matrix³¹. Some species, although unable to
168 survive solely in oil palm, will utilise plantations. For instance, planted oil palm in Malaysian Borneo
169 supported 22 of the 63 mammal species found in forest habitats³⁶, and 31 of 130 bird species⁴⁰, most
170 of them relatively common species. Oil palm in Guatemala and Brazil supported 23 and 58 bird
171 species, respectively^{39,41}, while 12 species of snakes were found in a Nigerian oil palm plantation⁴².
172 Various species will enter plantations to feed on oil palm fruit, including Palm-nut Vultures
173 *Gypohierax angolensis*⁴³ and Chimpanzee *Pan troglodytes*⁴³ in Africa and porcupines (Hystricidae),
174 civets (Viverridae), macaques (Cercopithecidae), elephants (Elephantidae) and orangutans in
175 Southeast Asia⁴⁴. The highest diversity of animal species in oil palm areas, however, is generally
176 found in the wider landscape that includes remnant patches of native vegetation^{45,46}. Factors that
177 are likely to positively influence biodiversity values in both industrial-scale and smallholder
178 plantations include higher landscape heterogeneity, the presence of large forest patches and
179 connectivity among these⁴⁷, and the plant diversity and structure of undergrowth vegetation. For
180 example, in palm areas where there is systematic cattle grazing, bird and dung beetle abundance
181 and diversity increase^{48,49}.

182 Oil palm cultivation involves the introduction and spread of invasive species including the oil palm
183 itself (noted in Madagascar and Brazil's Atlantic Forests⁵⁰), as well as non-native cover crops and
184 nitrogen-fixing plants (e.g., *Mucuna bracteata* or *Calopogonium caeruleum*). Similarly, management
185 of oil palm plantations can increase the local abundance of species such as Barn Owls *Tyto alba*,
186 introduced into plantations to control rodents⁵¹. Oil palm plantations also support pests such as the
187 Black Rat *Rattus rattus*, pigs *Sus* spp., and beetles such as the Asiatic Rhinoceros Beetle *Oryctes*
188 *rhinoceros* and the Red Palm Weevil *Rhynchophorus ferrugineus*⁵². Such species can impact palm oil
189 production negatively, for example in reducing oil palm yields through damage to the palm or fruit

190 predation⁵³. They also have a range of local effects, both positive and negative for biodiversity,
191 including animals that prey on them, such as snakes, owls, monkeys and cats⁵⁴, while the extra food
192 provided by oil palm fruits can increase pig populations resulting in reduced seedling recruitment in
193 forests neighbouring oil palm⁵⁵.

194 Management within oil palm areas to retain riparian reserves and other set-asides containing
195 natural forest may contribute to pollination and pest control within the plantation, although they
196 may also harbour pests and disease⁵⁶. Studies to date suggest overall limited, or neutral, effects of
197 such set-asides on pest control services, spill over of pest species, or oil palm yield⁵⁷. There are also
198 plenty of unknowns, for example, the African beetle *Elaiodobius kamerunicus* has been introduced
199 as an effective oil palm pollinator and is now widely naturalised in Southeast Asia and America
200 where it also persists in native vegetation and visits the inflorescences of native palms but its
201 impacts, if any, are unexamined (DS pers. obs.). No systematic analysis has been conducted to assess
202 the impact of non-native and invasive species associated with other oil crops.

203 Smallholder plantations tend to be smaller and more heterogeneous than industrial developments,
204 which potentially benefits wildlife, but this remains poorly studied³². A handful of studies indicate
205 that smallholdings support a similar number of, or slightly more, bird and mammal species than
206 industrial plantations, e.g. ⁵⁸. However, species in smallholder plantations may be more exposed to
207 other pressures, such as hunting, when compared to industrial plantations⁵⁸.

208 **OTHER ENVIRONMENTAL IMPACTS**

209 Oil palm plantations have a predominantly negative net effect on ecosystem functions when
210 compared to primary, selectively logged or secondary forest¹⁵. The clearance of forests and drainage
211 of peatlands for oil palm emits substantial carbon dioxide⁵⁹. Oil palms can maintain high rates of
212 carbon uptake⁶⁰ and their oil can potentially be used to substitute fossil fuels, and thus contribute
213 towards sustainable energy (SDG 7) and climate change response (SDG 13). Yet, biofuel from oil

214 palm cannot compensate for the carbon released when forests are cleared and peatlands drained
215 over short or medium time-scales (<100 years)⁶¹. Moreover, the carbon opportunity cost of oil palm,
216 which reflects the land's opportunity to store carbon if it is not used for agriculture, is not very
217 different from annual vegetable oil crops⁶¹ (Table 1).

218 Oil palm plantations, and the production of palm oil, can also be sources of methane⁶² and nitrous
219 oxide⁶³, both potent greenhouse gases that contribute further to climate change, although the
220 former is sometimes used as biogas, reducing net greenhouse gas release⁶⁴. Other emissions
221 associated with oil palm development include elevated isoprene production by palm trees, which
222 influences atmospheric chemistry, cloud cover and rainfall, although how this affects the
223 environment remains unclear⁶⁵. In addition, there is some evidence that emissions of other organic
224 compounds, e.g., estragole and toluene⁶⁶, are also higher in oil palm plantations than in forest, but
225 these emissions appear minor compared to isoprene⁶⁷.

226 Forest loss and land use conversion to oil palm impact the local and regional climate, although the
227 extent of these impacts remains debated⁶⁸. For example, increased temperatures and reduced
228 rainfall recorded over Borneo since the mid-1970s are thought to relate to the island's declining
229 forest cover which is partly due to the expansion of oil palm, with climate changes being greater in
230 areas where forest losses were higher⁶⁹. Indeed, oil palm plantations tend to be hotter, drier and
231 less shaded than forests due to their less dense canopy, and often have higher evapotranspiration
232 rates than forests⁷⁰. A drier hotter climate increases the risk of fire and concomitant smoke
233 pollution, especially in peat ecosystems⁷¹. In addition to human health consequences (e.g.,
234 respiratory diseases, conjunctivitis), such fires can impact wildlife⁷² and atmospheric processes. For
235 example, aerosols from fires can scatter solar radiation, disrupt evaporation, and promote drought⁶⁸.
236 Few of these relationships are well-studied.

237 Conversion of natural forests to oil palm plantations increases run-off and sediment export due to
238 loss or reduction of riparian buffers, reduced ground cover, and dense road networks⁷³. Streams
239 flowing through plantations tend to be warmer, shallower, sandier, more turbid, and to have
240 reduced abundances of aquatic species such as dragonflies (Anisoptera) than streams in forested
241 areas⁷⁴. Fertilizers, pesticides, and other chemicals used on plantations also impact water quality and
242 aquatic habitats⁷⁵. The effluent from most modern mills is minimized, but release into local rivers
243 has caused negative impacts to people and to aquatic and marine ecosystems⁷⁶. Some hydrological
244 impacts may be viewed as positive: for example, construction of flood-control channels and
245 sedimentation ponds for palm oil effluent can benefit some water birds⁷⁷.

246 Drainage of peatlands and other wetlands to establish oil palm disrupts hydrological cycles,
247 potentially impacting neighbouring forests and other habitats⁷⁸. The protection and restoration of
248 riparian buffers and reserves within oil palm plantations is therefore key to preserving water quality,
249 with recent research also showing the importance of these landscape features for biodiversity and
250 ecosystem function⁷⁹. Riparian reserve widths required by law in many tropical countries (20–50 m
251 on each bank) can support substantial levels of biodiversity, maintain hydrological functioning, and
252 improve habitat connectivity and permeability for some species within oil palm⁷⁹. However, research
253 is urgently needed regarding minimum buffer width and size requirements under different contexts,
254 for different taxa, and for different oil crops.

255 **THE FUTURE OF OIL PALM**

256 Demand for agricultural commodities is growing. Some predict that palm oil production will
257 accelerate across tropical Africa⁸⁰. However, due to current socio-cultural, technical, political and
258 ecological constraints only around one-tenth of the potential 51 million ha in the five main
259 producing countries in tropical Africa is likely to be profitably developed in the near future¹³,
260 although this might change as technological, financial and governance conditions improve⁸¹. The

261 expansion of oil palm in the Neotropics is also uncertain because of greater challenges the sector
262 faces compared to Southeast Asia, including lower yields, high labour costs, volatile socio-political
263 contexts, and high investment costs⁵. Although the importance of these factors varies from country
264 to country, in general the expansion of the palm oil industry in the Americas depends heavily on
265 economic incentives and policies, and access to international markets.

266 Meeting the growing demand for palm oil, while adhering to new zero deforestation policies⁸², and
267 consumer pressure to be more sustainable, will likely require a combination of approaches, including
268 increasing yields in existing production areas especially those managed by smallholders⁹, and
269 planting in deforested areas and degraded open ecosystems such as man-made pastures⁶⁰. These
270 strategies span a land-sparing and land-sharing continuum, with higher-yielding oil palm cultivation
271 sparing land and perhaps reducing overall impacts on biodiversity³⁸, although intermediate
272 strategies on the sparing-sharing continuum may be better at meeting broader societal goals⁸³.
273 Irrespective of the optimal strategy, replanting with high-yielding palms or implementing land
274 sharing agroforestry techniques are challenging for smallholders, who often lack resources and
275 technical knowledge, and may not be able to access improved varieties required to increase yields⁸⁴.
276 In such situations, provision of technical support from government agencies, non-government
277 organisations or private companies may help smallholders choose intensification over clearing more
278 land to increase palm oil production¹².

279 The extent to which biofuel demand by international markets will drive oil palm expansion remains
280 unclear. There is resistance from environmental non-governmental organizations and governments,
281 including the European Union, the second-largest palm oil importer after India⁵, to the use of palm
282 oil as a biofuel to replace fossil fuels and meet climate change mitigation goals. Such resistance is
283 related to the high CO₂-emissions from oil palm-driven deforestation and associated peatland
284 development⁸⁵. Nonetheless, if oil palm is developed on low carbon stock lands, estimates suggest it
285 may have lower carbon emissions per unit of energy produced than other oil crops like European

286 rapeseed⁸⁶. Consistent and comparable information on the extent and consequences of other oil
287 crops is urgently required to encourage more efficient land use⁶¹.

288 **GOVERNANCE OPTIONS**

289 Efforts to address the impacts of oil palm cultivation and palm oil trade have been the focus of
290 several initiatives. For example, the two main producer countries have set up the Malaysian
291 Sustainable Palm Oil and Indonesian Sustainable Palm Oil certification schemes, which mandate that
292 oil palm producers comply with a set of practices meant to ensure social and environmentally
293 responsible production. International concerns related to deforestation have been addressed
294 through the High Carbon Stock and High Conservation Value approaches⁸⁷, which are methodologies
295 that guide identification and protection of lands with relatively intact forest or value for biodiversity,
296 ecosystem services, livelihoods and cultural identity. These frameworks are used by producers to
297 meet the requirements of palm oil sustainability initiatives including certification under the
298 Roundtable on Sustainable Palm Oil (RSPO) standard. This standard was recently expanded to
299 include protection, management, and restoration of riparian areas within certified plantations, a
300 prohibition on new planting on peat, and compliance with the standard is now being used to meet
301 corporate zero-deforestation commitments⁵. There is evidence for positive impacts of RSPO
302 certification achieved through improved management practices, including changes in agrochemical
303 use, improved forest protection, and reduced fires and biodiversity losses, although these effects
304 remain small^{88,89}.

305 Many producers and traders of palm oil have now committed to “zero deforestation”. A 2017 cross-
306 commodity survey⁹⁰ found that companies in the palm oil sector have the highest proportion of no-
307 deforestation commitments across four commodity supply chains (palm oil, soy, timber and cattle)
308 linked to global deforestation. Although most of these commitments have been made by retailers
309 and manufacturers⁹⁰, oil palm growers have also made such pledges. In 2018, 41 of the 50 palm oil

310 producers with the largest market capitalization and land areas had committed to address
311 deforestation, with 29 of them pledging to adhere to zero deforestation practices⁹¹. These
312 commitments have been identified as a factor in declining expansion of oil palm in Malaysia and
313 Indonesia^{6,25}, although low commodity prices have likely also contributed⁶. Such private supply chain
314 initiatives like certification and zero-deforestation commitments may be most effective in reducing
315 environmental impacts when leveraged with public and institutional support such as plantation
316 moratoria for certain areas and national low-carbon rural development strategies⁹², as has been
317 demonstrated, for example, in Brazilian soy production⁹³.

318 **LAND USE TRADE-OFFS AMONG VEGETABLE OILS**

319 While the environmental impacts of oil palm on natural ecosystems are overwhelmingly negative,
320 such impacts also need to be considered in relation to other land uses, including competing
321 vegetable oil commodities, all of which have their own implications for biodiversity, carbon
322 emissions and other environmental dynamics (Table 1). Global vegetable oil production is expected
323 to expand at around 1.5% per year between 2017 and 2027⁹⁴, while use is projected to expand at
324 1.7% per year globally between 2013 and 2050 from a baseline of 165 million tons (Mt), including for
325 use in food, feed and biofuel⁹. Unless demand for oil decelerates, this implies an additional
326 production of an average of 3.86 Mt of vegetable oil per year. If this production was delivered by oil
327 palm alone, yielding ca. 4 tons of crude palm oil per ha^{5,7}, 31.3 Mha of additional vegetable oil
328 production land would be needed between 2020 and 2050. If, the addition instead all came from
329 soy, yielding about 0.7 tons of oil per ha⁹, 179 Mha of extra land, or nearly six times as much, would
330 be required. This simple calculation glosses over nuances of substitutability⁹⁵ or differential yield
331 increases among crops, but illustrates the magnitude of differences between land needed by oil
332 palm and other oil crops⁹⁶.

333 Understanding impacts is, however, not just a matter of comparing current and projected
334 distributions and yields of different crops and thus land needs, but also requires clarifying how each
335 hectare of land converted to an oil crop impacts both the environment and people. For example, soy
336 is known to have a large negative impact on biodiversity, with few vertebrates occurring in this
337 annual monoculture crop⁹⁷, and is responsible for loss of high biodiversity savanna and forest
338 ecosystems in South America⁹⁸. Thus, sustainable development, including simultaneous delivery of
339 SDGs 2 on agriculture and 15 on biodiversity (alongside contributions to SDG 7 on energy and SDG
340 13 on climate), must consider the wider trade-offs posed by sourcing global vegetable oils⁹⁹. One key
341 uncertainty is the extent to which demand can be met by increasing yields within established
342 vegetable oil croplands. An additional uncertainty is whether other options, for example microalgal-
343 derived lipids¹⁰⁰, may soon offer viable alternatives to meet demand for biofuel.

344 **THE WAY FORWARD**

345 The expansion of oil palm has had large negative environmental impacts and continues to cause
346 deforestation in some regions. Nevertheless, oil palm contributes to economic development⁵, has
347 improved welfare for at least some people¹⁷, and can be consistent with at least some conservation
348 goals especially when compared to other oil crops⁸¹. There remain substantial gaps in our
349 understanding of oil palm and the interaction between environmental, socio-cultural and economic
350 impacts of the crop, and the scope, stringency and effectiveness of governance initiatives to address
351 these⁵. None of these concerns and trade-offs are unique to oil palm: they also apply to other
352 vegetable oil crops^{30,98}, as well as other agricultural products¹⁰¹. Indeed, all land uses and not just
353 those in the tropics have impacts on their environment⁸, that can either be prevented or restored¹⁰².
354 Pressure on the palm oil industry has, however, apparently resulted in more research on the impacts
355 of palm oil production compared to other oils resulting in an urgent need to better study these
356 alternatives.

357 In a world with finite land and growing demands, we must consider global demands for food, fuel
358 and industrial uses hand-in-hand with environmental conservation objectives. Oil palm's high yields
359 mean that it requires less land to meet global oil demand than other oil crops. However, minimising
360 overall vegetable oil crop impacts requires evaluation for their past, current and projected
361 distribution and impacts, and review of their yields and global trade and uses. This information is
362 needed to enable better planning and governance of land use for all oil crops, matching risks and
363 opportunities with local conditions and realities, and to optimize the simultaneous delivery of the
364 SDGs.

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654

655 **Author contributions**

656 EM, DS, and TB conceptualized this study and developed the initial manuscript, with KC, JGU, DG,
657 JSHL, DJB, SAW, MA, SW, LPK, JFA, ZS and AD assisting in the acquisition, analysis, and interpretation
658 of the data and further writing. ES, TS, JA, HP, CS, DM, PF, NM, RH, MP, and MS provided substantial
659 input into the text revisions, and NZ, JA, DJB, KC, DG, AD and JFA designed the graphics.

660

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667 and MP have done work paid by palm oil companies or the Roundtable on Sustainable Palm Oil.

668 **FIGURE LEGENDS**

669

670 **Figure 1. Main vegetable oil crops (see Table 1). (a) Harvested area from 1961 to 2017. (b)**

671 **Vegetable oil production from 1961 to 2014. Data from FAOSTAT⁴.**

672

673 **Figure 2. Maps of industrial and smallholder-scale oil palm from analysis of satellite imagery until**

674 **the second half of 2019³, and examples of species it affects negatively: (a) *Panthera onca* (Near**

675 **Threatened)¹⁰³ and *Ara macao* (Least Concern)³⁹; (b) *Pan troglodytes* (Endangered)⁸⁰; (c) *Panthera***

676 ***tigris* (Endangered)¹⁰⁴, *Helarctos malayanus* (Vulnerable)¹⁰⁴, *Pongo pygmaeus* (Critically**

677 **Endangered)¹⁰⁵, *Casuarius unappendiculatus* (Least Concern)¹⁰⁶, and *Dendrolagus goodfellowi***

678 **(Endangered)¹⁰⁷. The maps lack information on plantations < 3 years old and planted oil palm in**

679 **mixed agroforestry settings, but provide the most up-to-date estimates available. For each region**

680 **the percentages of intact (green) and non-intact forests (orange) are shown relative to the total**

681 **extent of forest ecosystems²².**

682

683 **Figure 3. Oil palm's estimated role in deforestation aggregated across studies, years, and regions.**

684 **Panel a depicts the contribution of oil palm to overall deforestation, while b shows the percentage**

685 **of all oil palm expansion that cleared forest (Supplementary Methods). There were no data for**

686 **Peru and South and Central America for panel a, and no global data for panel b. Southeast Asia (SE**

687 **Asia) excludes Indonesia and Malaysia, which are shown separately, while South America excludes**

688 **Peru. Each filled circle represents one time period from a single study, with individual studies**

689 **represented by distinct colours. The size of the circle corresponds to the relative number of area-**

690 **years represented in that time period (larger circles represent a larger study area and longer time**

691 **period of sampling). Boxplot middle bars correspond to the unweighted median across study-time**

692 periods; lower and upper hinges represent the 25th and 75th percentiles of study-time periods; and
693 whiskers extend from the upper (lower) hinge to the largest (smallest) value no further than 1.5
694 times the interquartile range from the hinge (Figure S2, Tables S2 and S3).

695

696 **Figure 4 - Species groups with more than 8 threatened species with the terms "palm oil" or "oil**
697 **palm" in the threats texts of the IUCN Red List of Threatened Species Assessments²⁹. In total 321**
698 **species assessments had oil palm plantations as one of the reported threats (301 when excluding**
699 **groups with < 8 threatened species), which constitutes 3.5% of threatened species threatened by**
700 **annual and perennial non-timber crops (9,088 species) and 1.2% of all globally threatened species**
701 **(27,159 species) in 2019 (Supplementary Material and Table S4). CR = Critically Endangered; EN =**
702 **Endangered; VU = Vulnerable.**

703

704

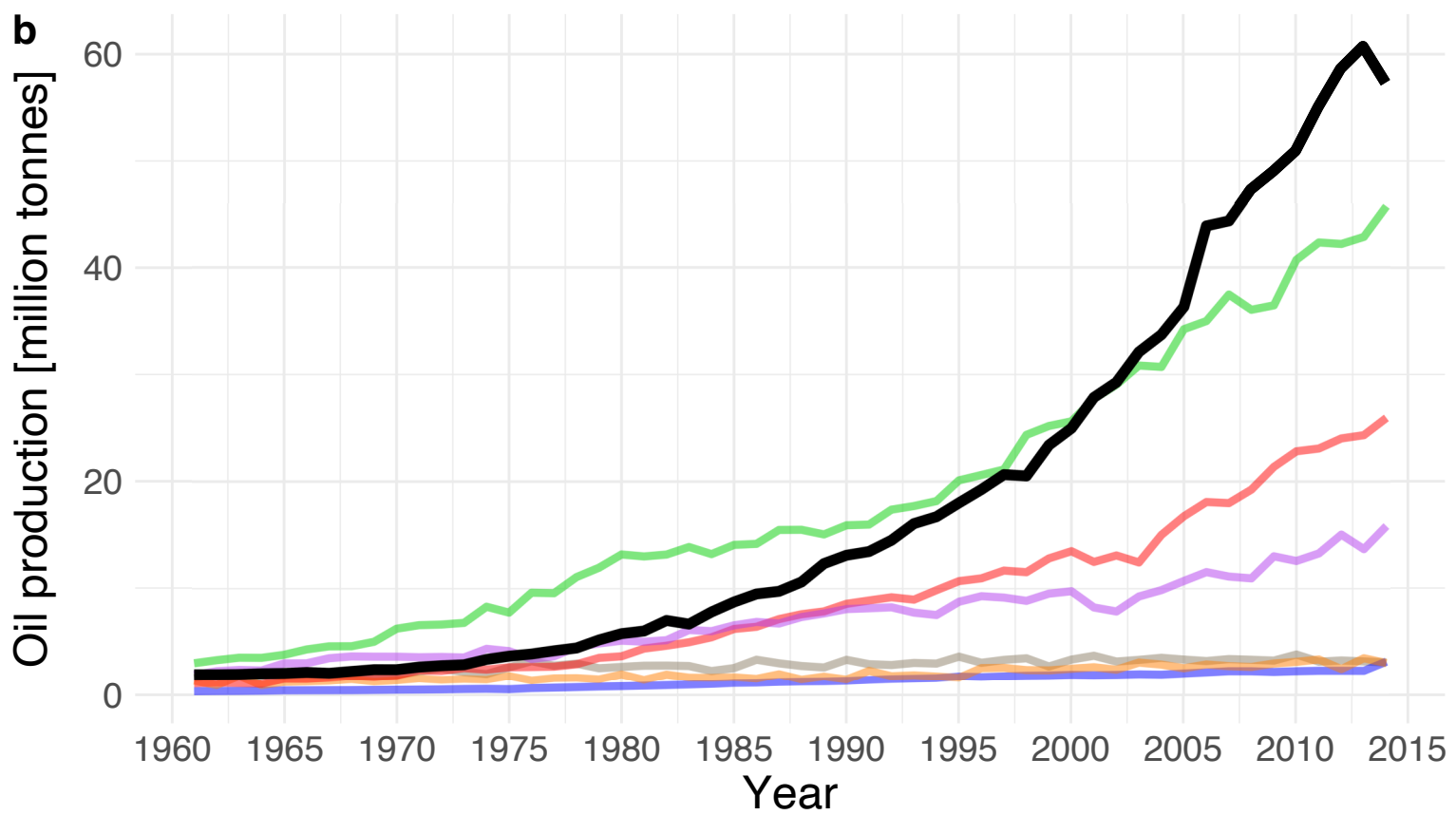
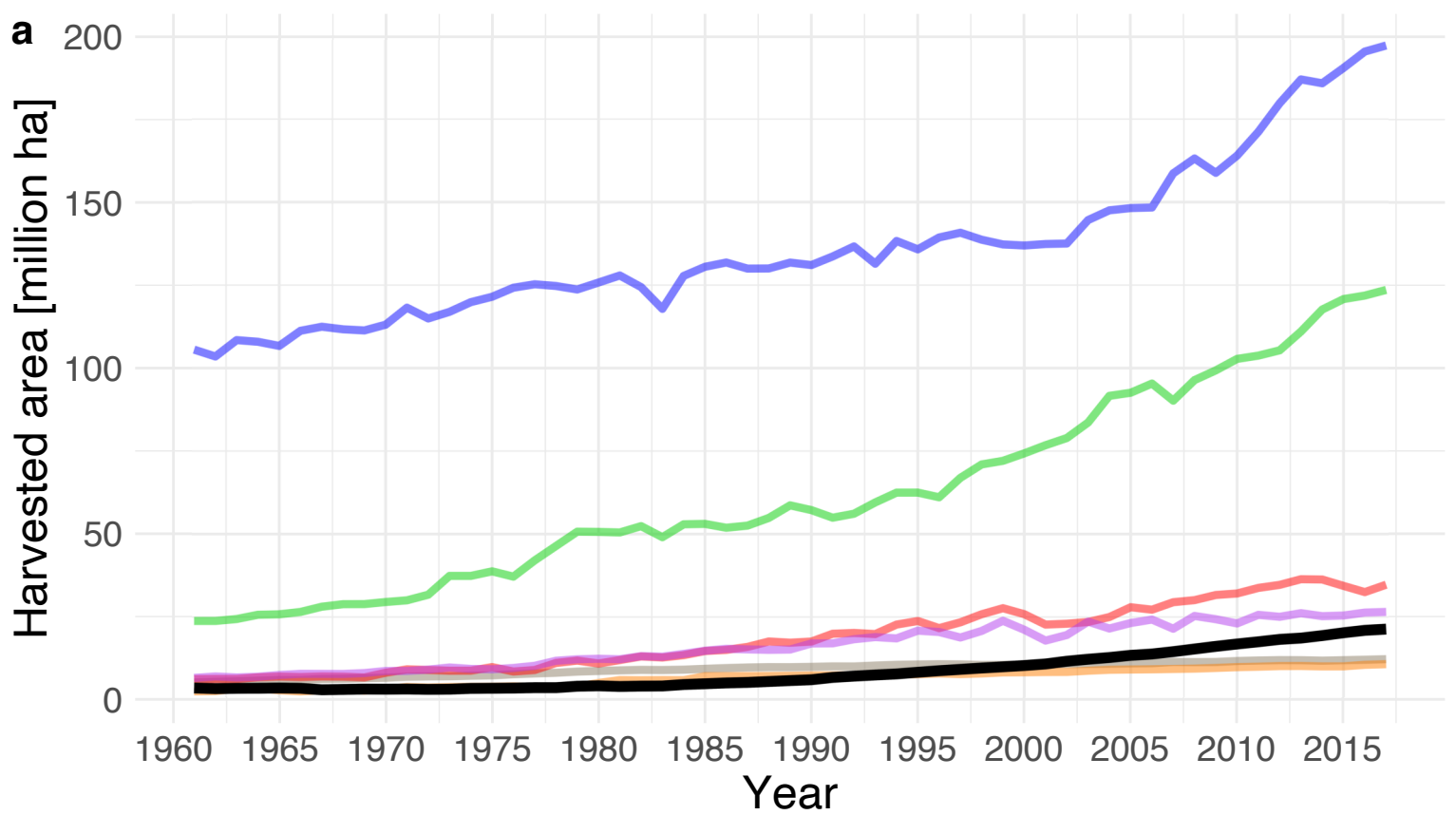
705

706 **Table 1. Overview of the major oil crops, typical production cycle, yields, main production**
707 **countries, biomes in which impacts primarily occur, carbon emissions, the number of threatened**
708 **species according to the IUCN Red List of Threatened Species²⁹ for which the specific crop is**
709 **mentioned as a threat, and the median species richness and median range-size rarity (amphibians,**
710 **birds and mammals) of species occurring within the footprint of each crop with first and third**
711 **quartile in brackets (IUCN Red List) (see Supporting Online Methods, Figure S1, Table S4). Carbon**
712 **emissions include carbon opportunity costs and production emissions⁶¹. “n/a” indicates that no**
713 **data are available.**

Oil crop	Type of crop	Oil yield (t ha ⁻¹) 108,109	Main oil production countries	Main biome impacted	Kg CO2e/MJ ⁶¹	# species threatened by crop ²⁹	Median Species Richness (number of species) ²⁹	Median range-size rarity (ha ha ⁻¹ 10e5) ²⁹
Oil palm <i>Elaeis guineensis</i>	Perennial (25 years cycle)	1.9–4.8	Indonesia, Malaysia, Thailand	Tropical rainforest	1.2	321	472 [443, 504]	36 [27, 57]
Soybean <i>Glycine max</i>	Annual (~6 months cycle), rotated with other crops	0.4–0.8	China, USA, Brazil, Argentina	Subtropical grass savanna, temperate steppe, and broadleaf forest	1.3	73	278 [251, 462]	10 [5, 14]
Rapeseed <i>Brassica napus</i> and <i>B. campestris</i>	Annual (~6 months cycle). Rotated with other crops	0.7–1.8	China, Germany, Canada	Temperate steppe and broadleaf forest and taiga	1.2	1	227 [187, 308]	4 [3, 10]
Cotton <i>Gossypium hirsutum</i>	Annual (~6 months cycle). Rotated with other crops	0.3–0.4	China, India	Subtropical monsoon, dry and humid forest and temperate areas	1.2	35	299 [234, 347]	10 [7, 12]
Groundnuts or peanuts <i>Arachis</i>	Annual (4-5 months crop cycle).	0.5–0.8	China, India	Subtropical monsoon, dry and humid forest and	1.5	6	351 [308, 426]	11 [7, 16]

<i>hypogaea</i>	Rotated with other crops			temperate areas				
Sunflower <i>Helianthus annuus</i>	Annual (3-4 months crop cycle). Rotated with other crops	0.5–0.9	Ukraine, Russia	Temperate steppe and broadleaf forest	1.0	1	189 [177, 222]	3 [2, 9]
Coconut <i>Cocos nucifera</i>	Perennial (30 – 50 y cycle)	0.4–2.4	Philippines, Indonesia, India	Tropical and subtropical forest	n/a	65	317 [264, 414]	73 [35, 113]
Maize <i>Zea mays</i>	Annual (5-6 months crop cycle). Rotated with other crops	0.1–0.2	USA, China,	Temperate steppe and broadleaf forest	0.7	131	273 [222, 427]	9 [5, 20]
Olive <i>Olea europaea</i>	Perennial, long lived. Sometimes inter-cropped	0.3–2.9	Spain, Italy, Greece	Mediterranean vegetation	n/a	14	n/a	n/a

714



Oil crop

- Coconut
- Olive
- Sunflower
- Maize
- Rapeseed
- Soybean
- Oil palm

