1. Supplementary Information:

Item	Present?	Filename This should be the name the file is saved as when it is uploaded to our system, and should include the file extension. The extension must be .pdf	A brief, numerical description of file contents. i.e.: *Supplementary Figures 1-4, Supplementary Discussion, and Supplementary Tables 1-4.*
Supplementary Information	Yes	Meijaard et al. Oil palm and biodiversity (Supporting Information) – final.pdf	Supplementary materials. Figures S1-S2. Table S1-S3.
Reporting Summary	No		

A. Additional Supplementary Files

Type	Number If there are multiple files of the same type this should be the numerical indicator. i.e. "1" for Video 1, "2" for Video 2, etc.	Filename This should be the name the file is saved as when it is uploaded to our system, and should include the file extension. i.e.: *Smith_ Supplementary Video 1.mov*	Legend or Descriptive Caption Describe the contents of the file
Supplementary Table	1	Table S4.xlxs	List of species on the IUCN Red List of Threatened Species for which oil crops are one of the threats to the

			survival (1=impacted by the crop; 0=not impacted by the crop).

The environmental impacts of palm oil in context

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Abstract

Delivering the Sustainable Development Goals (SDGs) requires balancing demands on land between agriculture (SDG 2) and biodiversity (SDG 15). The production of vegetable oils, and in particular palm oil, illustrates these competing demands and trade-offs. Palm oil accounts for 40%[1] of the current global annual demand for vegetable oil as food, animal feed, and fuel (210 million tons[2] (Mt)), but planted oil palm covers less than 5-5.5%[3] of total global oil crop area (ca. 425 Mha)[4], due to oil palm's relatively high yields[5]. Recent oil palm expansion in forested regions of Borneo, Sumatra, and the Malay Peninsula, where >90% of global palm oil is produced[5], has led to substantial concern around oil palm's role in deforestation. Oil palm expansion's direct contribution to regional tropical deforestation varies widely, ranging from 3% in West Africa to 47% in Malaysia[6]. Oil palm is also implicated in peatland draining and burning in Southeast Asia. Documented negative environmental impacts from such expansion include biodiversity declines, greenhouse gas emissions, and air pollution. However, oil palm generally produces more oil per area than other oil crops[7], is often economically viable in sites unsuitable for most other crops, and generates considerable wealth for at least some actors[8]. Global demand for vegetable oils is projected to increase by 46% by 2050[9]. Meeting this demand through additional expansion of oil palm versus other vegetable oil crops will lead to substantial differential effects on biodiversity, food security, climate change, land degradation, and livelihoods. Our review highlights that, although substantial gaps remain in our understanding of the relationship between the environmental, socio-cultural and economic impacts of oil palm, and the scope, stringency and effectiveness of initiatives to address these, there has been little research into the impacts and trade-offs of other vegetable oil crops.

Greater research attention needs to be given to investigating the impacts of palm oil production compared to alternatives for the trade-offs to be assessed at a global scale.

Over the past 25 years, global oil crops have expanded rapidly, with major impacts on land use[9]. The land used for growing oil crops grew from 170 million ha (Mha) in 1961 to 425 Mha in 2017[4] or ~30% of all cropland world-wide[10]. Oil palm, soy, and rapeseed together account for >80% of all vegetable oil production with cotton, groundnuts, sunflower, olive, and coconut comprising most of the remainder (Table 1, Figure 1). These crops, including soy (125 Mha planted area[4]) and maize (197 Mha planted area[4]), are also used as animal feed and other products.

Oil palm is the most rapidly expanding oil crop. This palm originates from equatorial Africa where it has been cultivated for millennia, but it is now widely grown in Southeast Asia. Between 2008 and 2017, oil palm expanded globally at an average rate of 0.7 Mha per year[4], and palm oil is the leading and cheapest edible oil in much of Asia and Africa. While it has been estimated that palm oil is an ingredient in 43% of products found in British supermarkets[11], we lack comparable studies for the prevalence of other oils.

As a wild plant, the oil palm is a colonising species that establishes in open areas. Cultivated palms are commonly planted as monocultures, although the tree is also used in mixed, small-scale and agroforestry settings. To maximize photosynthetic capacity and fruit yields, oil palm requires a warm and wet climate, high solar radiation, and high humidity. It is thus most productive in the humid tropics, while other oil crops, except coconut, grow primarily in subtropical and temperate regions (Table 1). Moreover, because oil palm tolerates many soils including deep peat and sandy substrates, it is often profitable in locations where few other commodity crops are viable. The highest yields from planted oil palm have been reported in Southeast Asia[5]. Yields are generally lower in Africa[12] and the Neotropics[5], likely reflecting differences in climatic conditions including humidity and cloud cover[12], as well as management, occurrence of pests and diseases, and planting stock[13].

Palm oil is controversial due to its social and environmental impacts and opportunities. Loss of natural habitats, reduction in woody biomass, and peatland drainage that occur during site preparation are the main direct environmental impacts from oil palm development[14]. Such conversion typically reduces biodiversity and water quality and increases greenhouse gas emissions, and, when fire is used, smoke and haze[5,15]. Industrial oil palm expansion by large multi-national and national companies is also often associated with social problems, such as land grabbing and conflicts, labour exploitation, social inequity[16] and declines in village-level well-being[17]. In producer countries, oil palm is a valued crop that brings economic development to regions with few alternative agricultural development options[8], and generates substantial average livelihood improvements when smallholder farmers adopt oil palm[18]. Here we review the current understanding of the environmental impacts from oil palm cultivation and assess what we know about other oil crops in comparison. Our focus is on biodiversity implications and the environmental aspects of sustainability, and we acknowledge the importance of considering these alongside socio-cultural, political, and economic outcomes.

DEFORESTATION AND OIL PALM EXPANSION

A remote sensing assessment found that oil palm plantations covered at least 19.5 Mha globally in 2019 (Figure 2), of which an estimated 67.2% were industrial-scale plantings and the remainder smallholders[3]. With 17.5 Mha, Southeast Asia has the largest area under production, followed by South and Central America (1.31 Mha), Africa (0.58 Mha) and the Pacific (0.14 Mha). However, the actual area under oil palm production could be 10–20% greater than the area detected from satellite imagery, i.e. 21.5–23.4 Mha, because young plantations (< ca. 3 years), open-canopy plantations, or mixed-species agroforests were omitted[3]. Estimates suggest that the proportion of oil palm area under smallholder cultivation (typically less than 50 ha of land per family[19]) varies from 30–60% in parts of Malaysia and Indonesia[17] to 94% in Nigeria[5].

The overall contribution of oil palm expansion to deforestation varies widely and depends in part on assessment scope (temporal, spatial) and methods. We reviewed 23 studies that reported land use or land cover change involving oil palm (Table S1 and S2). In Malaysian Borneo, oil palm was an important contributor to overall deforestation[20]. Here, new plantations accounted for 50% of deforestation from 1972 to 2015 when using a 5-year cut-off to link deforestation and oil palm development[21] (Figure 3, Figure S2, Table S3). In contrast, one global sample-based study suggested that between 2000 and 2013, just 0.2% of global deforestation in “Intact Forest Landscapes” was caused by oil palm development[22].

The degree to which oil palm expansion has replaced forests (defined as naturally regenerating closed canopy forests) varies with context. From 1972 to 2015, around 46% of new plantations expanded into forest, with the remainder replacing croplands, pasturelands, scrublands (including secondary forest regrowth), and other land uses[5]. Individual studies reported forest clearance ranging from 68% of tracked oil palm expansion in Malaysia and 44% in the Peruvian Amazon, to just 5–6% in West Africa, Central America, and South America excluding Peru (Figure 3). In general, oil palm expansion in the Neotropics is characterized by the conversion of previously cleared lands instead of forests[23,24], although the extent to which oil palm displaces other land uses into forests remains uncertain. In Indonesia and Malaysian Borneo, industrial plantation expansion and associated deforestation have declined since ca. 2011[6,25]. However, smallholder plantings developed to support demand by industrial palm oil mills may be increasing. To date, only two studies have clearly differentiated between forest clearing by smallholders and industrial plantations (Table S2). In Peru, 30% of smallholder plantings resulted in deforestation[26], while in Sumatra, Indonesia 39% of smallholder expansion was into forest[27]. While we still lack broader understanding of the deforestation impacts of smallholders[27], recent studies from Indonesian Borneo show that like industrial actors, smallholders sometimes convert fragile ecosystems such as tropical peatlands into oil palm plantations[28]. Other oil crops have not yet been mapped globally with similar levels of accuracy, precluding detailed assessments and comparisons.

OIL PALM'S DIRECT IMPACTS ON SPECIES

The International Union for the Conservation of Nature (IUCN) Red List of Threatened Species[29] documents 321 species for which oil palm is a reported threat, significantly more than for other oil crops (Figure 4, Table 1). Species threatened by oil palm made up 3.5% of the taxa threatened by annual and perennial non-timber crops (9,088 species) and 1.2% of all globally threatened taxa (27,159 species) in 2019 (Supplementary Materials, Table S4). These species include orangutans *Pongo* spp., gibbons *Hylobates* spp. and the tiger *Panthera tigris*. Species threat lists, however, are incomplete as most plant groups have not been comprehensively assessed, and the focus of threat studies may be biased toward certain oil crops. For example, perennial crops (oil palm, coconut, olive) might be more easily identified as a threat to a species than annual crops, because perennial crops facilitate long-term studies that are more difficult with annual crops that may not be planted every year. Also, the IUCN Red List focuses on threats in the recent past, and is thus biased toward crops with recent rapid expansion. Better information is needed for all oil crops about where they are grown, and how their expansion has affected and could affect natural and semi-natural ecosystems and biodiversity. We note that because coconut is primarily grown in tropical island nations it stands out as a particular threat for rare and endemic species with small ranges[30] (Table 1).

Oil palm plantations contain lower species diversity and abundance for most taxonomic groups when compared to natural forest[31,32]. Plant diversity in some plantations is less than 1% of that in natural forests[31], but because oil palm is perennial, associated plant diversity may exceed that of annual oil crops (Table 1). One study found 298 plant species in the oil palm undergrowth[33], and another found 16 species of fern on oil palm trunks[34], while a meta-analysis of plant diversity in a range of annual crops, including oil crops, found between one and 15 associated plant species[35].

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

Recorded mammal diversity in oil palm is 47–90% lower than in natural forest[36,37], and strongly depends on the proximity of natural forests. Oil palm plantations generally exclude forest specialist species[38,39], which are often those species of greatest conservation importance. For example, forest-dependent gibbons (Hylobatidae) cannot survive in stands of monocultural oil palm, but can make use of interspersed forest fragments within an oil palm matrix[31]. Some species, although unable to survive solely in oil palm, will utilise plantations. For instance, planted oil palm in Malaysian Borneo supported 22 of the 63 mammal species found in forest habitats[36], and 31 of 130 bird species[40], most of them relatively common species. Oil palm in Guatemala and Brazil supported 23 and 58 bird species, respectively[39,41], while 12 species of snakes were found in a Nigerian oil palm plantation[42]. Various species will enter plantations to feed on oil palm fruit, including Palm-nut Vultures *Gypohierax angolensis*[43] and Chimpanzee *Pan troglodytes*[43] in Africa and porcupines (Hystricidae**)**, civets (Viverridae), macaques (Cercopithecidae), elephants (Elephantidae) and orangutans in Southeast Asia[44]. The highest diversity of animal species in oil palm areas, however, is generally found in the wider landscape that includes remnant patches of native vegetation[45,46]. Factors that are likely to positively influence biodiversity values in both industrial-scale and smallholder plantations include higher landscape heterogeneity, the presence of large forest patches and connectivity among these[47], and the plant diversity and structure of undergrowth vegetation. For example, in palm areas where there is systematic cattle grazing, bird and dung beetle abundance and diversity increase[48,49].

Oil palm cultivation involves the introduction and spread of invasive species including the oil palm itself (noted in Madagascar and Brazil's Atlantic Forests[50]), as well as non-native cover crops and nitrogen-fixing plants (e.g., *Mucuna bracteata* or *Calopogonium caeruleum*). Similarly, management of oil palm plantations can increase the local abundance of species such as Barn Owls *Tyto alba*, introduced into plantations to control rodents[51]. Oil palm plantations also support pests such as the Black Rat *Rattus rattus*, pigs *Sus* spp., and beetles such as the Asiatic Rhinoceros Beetle *Oryctes rhinoceros* and the Red Palm Weevil *Rhynchophorus ferrugineus*[52]. Such species can impact palm oil production negatively, for example in reducing oil palm yields through damage to the palm or fruit predation[53]. They also have a range of local effects, both positive and negative for biodiversity, including animals that prey on them, such as snakes, owls, monkeys and cats[54], while the extra food provided by oil palm fruits can increase pig populations resulting in reduced seedling recruitment in forests neighbouring oil palm[55].

Management within oil palm areas to retain riparian reserves and other set-asides containing natural forest may contribute to pollination and pest control within the plantation, although they may also harbour pests and disease[56]. Studies to date suggest overall limited, or neutral, effects of such set-asides on pest control services, spill over of pest species, or oil palm yield[57]. There are also plenty of unknowns, for example, the African beetle *Elaiedobius kamerunicus* has been introduced as an effective oil palm pollinator and is now widely naturalised in Southeast Asia and America where it also persists in native vegetation and visits the inflorescences of native palms but its impacts, if any, are unexamined (DS pers. obs.). No systematic analysis has been conducted to assess the impact of non-native and invasive species associated with other oil crops.

Smallholder plantations tend to be smaller and more heterogeneous than industrial developments, which potentially benefits wildlife, but this remains poorly studied[32]. A handful of studies indicate that smallholdings support a similar number of, or slightly more, bird and mammal species than industrial plantations, e.g. [58]. However, species in smallholder plantations may be more exposed to other pressures, such as hunting, when compared to industrial plantations[58].

OTHER ENVIRONMENTAL IMPACTS

Oil palm plantations have a predominantly negative net effect on ecosystem functions when compared to primary, selectively logged or secondary forest[15]. The clearance of forests and drainage of peatlands for oil palm emits substantial carbon dioxide[59]. Oil palms can maintain high rates of carbon uptake[60] and their oil can potentially be used to substitute fossil fuels, and thus contribute towards sustainable energy (SDG 7) and climate change response (SDG 13). Yet, biofuel from oil palm cannot compensate for the carbon released when forests are cleared and peatlands drained over short or medium time-scales (<100 years)[61]. Moreover, the carbon opportunity cost of oil palm, which reflects the land's opportunity to store carbon if it is not used for agriculture, is not very different from annual vegetable oil crops[61] (Table 1).

Oil palm plantations, and the production of palm oil, can also be sources of methane[62] and nitrous oxide[63], both potent greenhouse gases that contribute further to climate change, although the former is sometimes used as biogas, reducing net greenhouse gas release[64]. Other emissions associated with oil palm development include elevated isoprene production by palm trees, which influences atmospheric chemistry, cloud cover and rainfall, although how this affects the environment remains unclear[65]. In addition, there is some evidence that emissions of other organic compounds, e.g., estragole and toluene[66], are also higher in oil palm plantations than in forest, but these emissions appear minor compared to isoprene[67].

Forest loss and land use conversion to oil palm impact the local and regional climate, although the extent of these impacts remains debated[68]. For example, increased temperatures and reduced rainfall recorded over Borneo since the mid-1970s are thought to relate to the island's declining forest cover which is partly due to the expansion of oil palm, with climate changes being greater in areas where forest losses were higher[69]. Indeed, oil palm plantations tend to be hotter, drier and less shaded than forests due to their less dense canopy, and often have higher evapotranspiration rates than forests[70]. A drier hotter climate increases the risk of fire and concomitant smoke pollution, especially in peat ecosystems[71]. In addition to human health consequences (e.g., respiratory diseases, conjunctivitis), such fires can impact wildlife[72] and atmospheric processes. For example, aerosols from fires can scatter solar radiation, disrupt evaporation, and promote drought[68]. Few of these relationships are well-studied.

Conversion of natural forests to oil palm plantations increases run-off and sediment export due to loss or reduction of riparian buffers, reduced ground cover, and dense road networks[73]. Streams flowing through plantations tend to be warmer, shallower, sandier, more turbid, and to have reduced abundances of aquatic species such as dragonflies (Anisoptera) than streams in forested areas[74]. Fertilizers, pesticides, and other chemicals used on plantations also impact water quality and aquatic habitats[75]. The effluent from most modern mills is minimized, but release into local rivers has caused negative impacts to people and to aquatic and marine ecosystems[76]. Some hydrological impacts may be viewed as positive: for example, construction of flood-control channels and sedimentation ponds for palm oil effluent can benefit some water birds[77].

Drainage of peatlands and other wetlands to establish oil palm disrupts hydrological cycles, potentially impacting neighbouring forests and other habitats[78]. The protection and restoration of riparian buffers and reserves within oil palm plantations is therefore key to preserving water quality, with recent research also showing the importance of these landscape features for biodiversity and ecosystem function[79]. Riparian reserve widths required by law in many tropical countries (20–50 m on each bank) can support substantial levels of biodiversity, maintain hydrological functioning, and improve habitat connectivity and permeability for some species within oil palm[79]. However, research is urgently needed regarding minimum buffer width and size requirements under different contexts, for different taxa, and for different oil crops.

THE FUTURE OF OIL PALM

Demand for agricultural commodities is growing. Some predict that palm oil production will accelerate across tropical Africa[80]. However, due to current socio-cultural, technical, political and ecological constraints only around one-tenth of the potential 51 million ha in the five main producing countries in tropical Africa is likely to be profitably developed in the near future[13], although this might change as technological, financial and governance conditions improve[81]. The expansion of oil palm in the Neotropics is also uncertain because of greater challenges the sector faces compared to Southeast Asia, including lower yields, high labour costs, volatile socio-political contexts, and high investment costs[5]. Although the importance of these factors varies from country to country, in general the expansion of the palm oil industry in the Americas depends heavily on economic incentives and policies, and access to international markets.

Meeting the growing demand for palm oil, while adhering to new zero deforestation policies[82], and consumer pressure to be more sustainable, will likely require a combination of approaches, including increasing yields in existing production areas especially those managed by smallholders[9], and planting in deforested areas and degraded open ecosystems such as man-made pastures[60]. These strategies span a land-sparing and land-sharing continuum, with higher-yielding oil palm cultivation sparing land and perhaps reducing overall impacts on biodiversity[38], although intermediate strategies on the sparing-sharing continuum may be better at meeting broader societal goals[83]. Irrespective of the optimal strategy, replanting with high-yielding palms or implementing land sharing agroforestry techniques are challenging for smallholders, who often lack resources and technical knowledge, and may not be able to access improved varieties required to increase yields[84]. In such situations, provision of technical support from government agencies, non-government organisations or private companies may help smallholders choose intensification over clearing more land to increase palm oil production[12].

The extent to which biofuel demand by international markets will drive oil palm expansion remains unclear. There is resistance from environmental non-governmental organizations and governments, including the European Union, the second-largest palm oil importer after India[5], to the use of palm oil as a biofuel to replace fossil fuels and meet climate change mitigation goals. Such resistance is related to the high CO_2–emissions from oil palm-driven deforestation and associated peatland development[85]. Nonetheless, if oil palm is developed on low carbon stock lands, estimates suggest it may have lower carbon emissions per unit of energy produced than other oil crops like European rapeseed[86]. Consistent and comparable information on the extent and consequences of other oil crops is urgently required to encourage more efficient land use[61].

GOVERNANCE OPTIONS

Efforts to address the impacts of oil palm cultivation and palm oil trade have been the focus of several initiatives. For example, the two main producer countries have set up the Malaysian Sustainable Palm Oil and Indonesian Sustainable Palm Oil certification schemes, which mandate that oil palm producers comply with a set of practices meant to ensure social and environmentally responsible production. International concerns related to deforestation have been addressed through the High Carbon Stock and High Conservation Value approaches[87], which are methodologies that guide identification and protection of lands with relatively intact forest or value for biodiversity, ecosystem services, livelihoods and cultural identity. These frameworks are used by producers to meet the requirements of palm oil sustainability initiatives including certification under the Roundtable on Sustainable Palm Oil (RSPO) standard. This standard was recently expanded to include protection, management, and restoration of riparian areas within certified plantations, a prohibition on new planting on peat, and compliance with the standard is now being used to meet corporate zero-deforestation commitments[5]. There is evidence for positive impacts of RSPO certification achieved through improved management practices, including changes in agrochemical use, improved forest protection, and reduced fires and biodiversity losses, although these effects remain small[88,89].

Many producers and traders of palm oil have now committed to “zero deforestation”. A 2017 cross-commodity survey[90] found that companies in the palm oil sector have the highest proportion of no-deforestation commitments across four commodity supply chains (palm oil, soy, timber and cattle) linked to global deforestation. Although most of these commitments have been made by retailers and manufacturers[90], oil palm growers have also made such pledges. In 2018, 41 of the 50 palm oil producers with the largest market capitalization and land areas had committed to address deforestation, with 29 of them pledging to adhere to zero deforestation practices[91]. These commitments have been identified as a factor in declining expansion of oil palm in Malaysia and Indonesia[6,25], although low commodity prices have likely also contributed[6]. Such private supply chain initiatives like certification and zero-deforestation commitments may be most effective in reducing environmental impacts when leveraged with public and institutional support such as plantation moratoria for certain areas and national low-carbon rural development strategies[92], as has been demonstrated, for example, in Brazilian soy production[93].

LAND USE TRADE-OFFS AMONG VEGETABLE OILS

While the environmental impacts of oil palm on natural ecosystems are overwhelmingly negative, such impacts also need to be considered in relation to other land uses, including competing vegetable oil commodities, all of which have their own implications for biodiversity, carbon emissions and other environmental dynamics (Table 1). Global vegetable oil production is expected to expand at around 1.5% per year between 2017 and 2027[94], while use is projected to expand at 1.7% per year globally between 2013 and 2050 from a baseline of 165 million tons (Mt), including for use in food, feed and biofuel[9]. Unless demand for oil decelerates, this implies an additional production of an average of 3.86 Mt of vegetable oil per year. If this production was delivered by oil palm alone, yielding ca. 4 tons of crude palm oil per ha[5,7], 31.3 Mha of additional vegetable oil production land would be needed between 2020 and 2050. If, the addition instead all came from soy, yielding about 0.7 tons of oil per ha[9], 179 Mha of extra land, or nearly six times as much, would be required. This simple calculation glosses over nuances of substitutability[95] or differential yield increases among crops, but illustrates the magnitude of differences between land needed by oil palm and other oil crops[96].

Understanding impacts is, however, not just a matter of comparing current and projected distributions and yields of different crops and thus land needs, but also requires clarifying how each hectare of land converted to an oil crop impacts both the environment and people. For example, soy is known to have a large negative impact on biodiversity, with few vertebrates occurring in this annual monoculture crop[97], and is responsible for loss of high biodiversity savanna and forest ecosystems in South America[98]. Thus, sustainable development, including simultaneous delivery of SDGs 2 on agriculture and 15 on biodiversity (alongside contributions to SDG 7 on energy and SDG 13 on climate), must consider the wider trade-offs posed by sourcing global vegetable oils[99]. One key uncertainty is the extent to which demand can be met by increasing yields within established vegetable oil croplands. An additional uncertainty is whether other options, for example microalgal-derived lipids[100], may soon offer viable alternatives to meet demand for biofuel.

THE WAY FORWARD

The expansion of oil palm has had large negative environmental impacts and continues to cause deforestation in some regions. Nevertheless, oil palm contributes to economic development[5], has improved welfare for at least some people[17], and can be consistent with at least some conservation goals especially when compared to other oil crops[81]. There remain substantial gaps in our understanding of oil palm and the interaction between environmental, socio-cultural and economic impacts of the crop, and the scope, stringency and effectiveness of governance initiatives to address these[5]. None of these concerns and trade-offs are unique to oil palm: they also apply to other vegetable oil crops[30,98], as well as other agricultural products[101]. Indeed, all land uses and not just those in the tropics have impacts on their environment[8], that can either be prevented or restored[102]. Pressure on the palm oil industry has, however, apparently resulted in more research on the impacts of palm oil production compared to other oils resulting in an urgent need to better study these alternatives.

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

LITERATURE CITED

1 USDA. Oil Seeds: World Markets and Trade. November 2019. (Foreign Agricultural Service, United States Department of Agriculture, Washington, DC, 2019).

2 USDA-FAS. Oilseeds: World Markets and Trade. Circular Series FOP 8-10 August. (United States Department of Agriculture Foreign Agricultural Service, Washington, DC, 2010).

3 Descals, A. *et al.* High-resolution global map of smallholder and industrial closed-canopy oil palm plantations. Preprint at https://essd.copernicus.org/preprints/essd-2020-159/. doi:10.5194/essd-2020-159 (2020).

4 FAOSTAT. Food and Agriculture Data. http://www.fao.org/faostat/en/#home. (Food and Agriculture Organization of the United Nations, Rome, Italy, 2019).

5 Meijaard, E. *et al. Oil Palm and Biodiversity – A Situation Analysis. DOI: 10.2305/IUCN.CH.2018.11.en*. (IUCN Oil Palm Task Force, 2018).

6 Gaveau, D. L. A. *et al.* Rise and fall of forest loss and industrial plantations in Borneo (2000–2017). *Cons. Lett.* **0**, e12622, doi:10.1111/conl.12622 (2019).

7 Johnston, M., Foley, J. A., Holloway, T., Kucharik, C. & Monfreda, C. Resetting global expectations from agricultural biofuels. *Env. Res. Lett.* **4**, 014004, doi:10.1088/1748-9326/4/1/014004 (2009).

8 Meijaard, E. & Sheil, D. The Moral Minefield of Ethical Oil Palm and Sustainable Development. *Front. Forests Glob. Change* **2**, doi:10.3389/ffgc.2019.00022 (2019).

9 Byerlee, D., Falcon, W. P. & Naylor, R. L. *The Tropical Oil Crop Revolution: Food, Feed, Fuel, and Forests*. (Oxford University Press, 2017).

10 Ramankutty, N. *et al.* Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security. *Ann. Rev. Plant Biol.* **69**, 789-815, doi:10.1146/annurev-arplant-042817-040256 (2018).

11 Independent. The guilty secrets of palm oil: Are you unwittingly contributing to the devastation of the rain forests?. https://www.independent.co.uk/environment/the-guilty-

secrets-of-palm-oil-are-you-unwittingly-contributing-to-the-devastation-of-the-rain-1676218.html. (2009).

12 Woittiez, L. S., van Wijk, M. T., Slingerland, M., van Noordwijk, M. & Giller, K. E. Yield gaps in oil palm: A quantitative review of contributing factors. *Europ. J. Agron.* **83**, 57-77, doi:10.1016/j.eja.2016.11.002 (2017).

13 Feintrenie, L., Gazull, L., Goulaouic, R. & Miaro III, L. Spatialized production models for sustainable palm oil in Central Africa: Choices and potentials. Presented at Scaling Up Responsible Land Governance. Annual World Bank Conference on Land and Poverty, Washington DC, March 14-18, 2016. (2016).

14 Sheil, D. *et al.* The impacts and opportunities of oil palm in Southeast Asia. What do we know and what do we need to know? *CIFOR Occ. Paper*, no. 51 (2009).

15 Dislich, C. *et al.* A review of the ecosystem functions in oil palm plantations, using forests as a reference system. *Biol. Rev.* **92**, 1539-1569, doi:10.1111/brv.12295 (2017).

16 Li, T., M. *Evidence-based options for advancing social equity in Indonesian palm oil: Implications for research, policy and advocacy*. (Center for International Forestry Research (CIFOR), 2018).

17 Santika, T. *et al.* Does oil palm agriculture help alleviate poverty? A multidimensional counterfactual assessment of oil palm development in Indonesia. *World Dev.* **120**, 105-117, doi:10.1016/j.worlddev.2019.04.012 (2019).

18 Krishna, V., Euler, M., Siregar, H. & Qaim, M. Differential livelihood impacts of oil palm expansion in Indonesia. *Agric. Econ.* **48**, 639-653, doi:10.1111/agec.12363 (2017).

19 RSPO Smallholders Task Force. Smallholders. Retrieved from https://rspo.org/smallholders#definition. (2012).

20 Gaveau, D. L. A. *et al.* Four decades of forest persistence, loss and logging on Borneo. *PLOS ONE* **9**, e101654, doi:10.1371/journal.pone.0101654 (2014).

21 Gaveau, D. L. A. *et al.* Rapid conversions and avoided deforestation: examining four decades of industrial plantation expansion in Borneo. *Sci. Rep.* **6**, 32017, doi:10.1038/srep32017 (2016).

22 Potapov, P. *et al.* The last frontiers of wilderness: Tracking loss of intact forest landscapes from 2000 to 2013. *Sc. Adv.* **3**, e1600821, doi:10.1126/sciadv.1600821 (2017).

23 Vijay, V., Pimm, S. L., Jenkins, C. N. & Smith, S. J. The Impacts of Oil Palm on Recent Deforestation and Biodiversity Loss. *PLOS ONE* **11**, e0159668, doi:10.1371/journal.pone.0159668 (2016).

24 Furumo, P. R. & Aide, T. M. Characterizing commercial oil palm expansion in Latin America: land use change and trade. *Env. Res. Lett.* **12**, 024008, doi:10.1088/1748-9326/aa5892 (2017).

25 Austin, K. G., Schwantes, A., Gu, Y. & Kasibhatla, P. S. What causes deforestation in Indonesia? *Env. Res. Lett.* **14**, 024007, doi:10.1088/1748-9326/aaf6db (2019).

26 Gutiérrez-Vélez, V., H. *et al.* High-yield oil palm expansion spares land at the expense of forests in the Peruvian Amazon. *Env. Res. Lett.* **6**, 044029, doi:10.1088/1748-9326/6/4/044029 (2011).

27 Lee, J. S. H. *et al.* Environmental Impacts of Large-Scale Oil Palm Enterprises Exceed that of Smallholdings in Indonesia. *Cons. Lett.* **7**, 25-33, doi:10.1111/conl.12039 (2014).

28 Schoneveld, G. C., Ekowati, D., Andrianto, A. & van der Haar, S. Modeling peat- and forestland conversion by oil palm smallholders in Indonesian Borneo. *Env. Res. Lett.* **14**, 014006, doi:10.1088/1748-9326/aaf044 (2019).

29 IUCN. The IUCN Red List of Threatened Species. Version 2019-2. https://www.iucnredlist.org. (Gland, Switzerland, 2019).

30 Meijaard, E., Abrams, J. F., Juffe-Bignoli, D., Voigt, M. & Sheil, D. Coconut oil, conservation and the conscientious consumer. *Curr. Biol.* **30**, R757-R758, doi:10.1016/j.cub.2020.05.059 (2020).

31 Foster, W. A. *et al.* Establishing the evidence base for maintaining biodiversity and ecosystem function in the oil palm landscapes of South East Asia. *Phil. Trans Roy. Soc. B: Biol. Sc.* **366**, 3277, doi:10.1098/rstb.2011.0041 (2011).

32 Savilaakso, S. *et al.* Systematic review of effects on biodiversity from oil palm production. *Env. Evidence* **3**, 4, doi:10.1186/2047-2382-3-4 (2014).

33 Germer, J. U. *Spatial undergrowth species composition in oil palm (Elaeis guineensis Jacq.) in West Sumatra*, Kommunikations-, Informations- und Medienzentrum der Universität Hohenheim, (2003).

34 Sato, T., Itoh, H., Kudo, G., Kheong, Y. S. & Furukawa, A. Species Composition and Structure of Epiphytic Fern Community on Oil Palm Trunks in Malay Archipelago. *Tropics* **6**, 139-148, doi:10.3759/tropics.6.139 (1996).

35 Letourneau, D. K. *et al.* Does plant diversity benefit agroecosystems? A synthetic review. *Ecol. Appl.* **21**, 9-21, doi:10.1890/09-2026.1 (2011).

36 Wearn, O. R., Carbone, C., Rowcliffe, J. M., Bernard, H. & Ewers, R. M. Grain-dependent responses of mammalian diversity to land use and the implications for conservation set-aside. *Ecol. Appl.* **26**, 1409-1420, doi:10.1890/15-1363 (2016).

37 Pardo, L. E. *et al.* Land management strategies can increase oil palm plantation use by some terrestrial mammals in Colombia. *Scient. Rep.* **9**, 7812, doi:10.1038/s41598-019-44288-y (2019).

38 Phalan, B., Onial, M., Balmford, A. & Green, R. E. Reconciling Food Production and Biodiversity Conservation: Land Sharing and Land Sparing Compared. *Science* **333**, 1289-1291, doi:10.1126/science.1208742 (2011).

39 Almeida, S. M. *et al.* The effects of oil palm plantations on the functional diversity of Amazonian birds. *J. Trop. Ecol.* **32**, 510-525, doi:10.1017/S0266467416000377 (2016).

40 Edwards, D. P. *et al.* Selective-logging and oil palm: multitaxon impacts, biodiversity indicators, and trade-offs for conservation planning. *Ecol. Applic.* **24**, 2029-2049, doi:10.1890/14-0010.1 (2014).

41 Nájera, A. & Simonetti, J. A. Can oil palm plantations become bird friendly? *Agrofor. Syst.* **80**, 203-209, doi:10.1007/s10457-010-9278-y (2010).

42 Akani, G. C., Ebere, N., Luiselli, L. & Eniang, E. A. Community structure and ecology of snakes in fields of oil palm trees (*Elaeis guineensis*) in the Niger Delta, southern Nigeria. *Afr. J. Ecol.* **46**, 500-506, doi:10.1111/j.1365-2028.2007.00885.x (2008).

43 Humle, T. & Matsuzawa, T. Oil palm use by adjacent communities of chimpanzees at Bossou and Nimba Mountains, West Africa. *Int. J. Primatol.* **25**, 551-581, doi:10.1023/B:IJOP.0000023575.93644.f4 (2004).

44 Ancrenaz, M. *et al.* Of pongo, palms, and perceptions – A multidisciplinary assessment of orangutans in an oil palm context. *Oryx* **49**, 465–472, doi:10.1017/S0030605313001270 (2015).

45 Mitchell, S. L. *et al.* Riparian reserves help protect forest bird communities in oil palm dominated landscapes. *J. Appl. Ecol.* **55**, 2744-2755, doi:10.1111/1365-2664.13233 (2018).

46 Deere, N. J. *et al.* Implications of zero-deforestation commitments: Forest quality and hunting pressure limit mammal persistence in fragmented tropical landscapes. *Cons. Lett.* **13**, e12701, doi:10.1111/conl.12701 (2020).

47 Knowlton, J. L. *et al.* Oil palm plantations affect movement behavior of a key member of mixed-species flocks of forest birds in Amazonia, Brazil. *Trop. Cons. Sc.* **10**, 1940082917692800, doi:10.1177/1940082917692800 (2017).

48 Tohiran, K. A. *et al.* Targeted cattle grazing as an alternative to herbicides for controlling weeds in bird-friendly oil palm plantations. *Agron. Sust. Dev.* **37**, 62, doi:10.1007/s13593-017-0471-5 (2017).

49 Slade, E. M. *et al.* Can cattle grazing in mature oil palm increase biodiversity and ecosystem service provision? . *The Planter* **90**, 655-665 (2014).

50 IUCN. Global Invasive Species Database (GISD). Species profile *Elaeis guineensis*. Available from: http://www.iucngisd.org/gisd/species. [Accessed 27 February 2018]. (2015).

51 Wan, H. The introduction of barn owl (*Tyto alba*) to Sabah for rat control in oil palm plantations. *Planter* **76**, 215-222 (2000).

52 Bessou, C. *et al. Sustainable Palm Oil Production project synthesis: Understanding and anticipating global challenges*. (Center for International Forestry Research (CIFOR), 2017).

53 Puan, C. L., Goldizen, A. W., Zakaria, M., Hafidzi, M. N. & Baxter, G. S. Relationships among rat numbers, abundance of oil palm fruit and damage levels to fruit in an oil palm plantation. *Intergr. Zool.* **6**, 130-139, doi:10.1111/j.1749-4877.2010.00231.x (2011).

54 Holzner, A. *et al.* Macaques can contribute to greener practices in oil palm plantations when used as biological pest control. *Curr. Biol.* **29**, R1066-R1067, doi:10.1016/j.cub.2019.09.011 (2019).

55 Luskin, M. S. *et al.* Cross-boundary subsidy cascades from oil palm degrade distant tropical forests. *Nature Comms.* **8**, 2231, doi:10.1038/s41467-017-01920-7 (2017).

56 Mayfield, M. M. The importance of nearby forest to known and potential pollinators of oil palm (*Elaeis guineensis* Jacq.; Areceaceae) in southern Costa Rica. *Econ. Botany* **59**, 190, doi:10.1663/0013-0001(2005)059[0190:TIONFT]2 (2005).

57 Woodham, C. R. *et al.* Effects of replanting and retention of mature oil palm riparian buffers on ecosystem functioning in oil palm plantations. *Front. Forests Glob. Change*, doi:10.3389/ffgc.2019.00029 (2019).

58 Azhar, B. *et al.* The influence of agricultural system, stand structural complexity and landscape context on foraging birds in oil palm landscapes. *Ibis* **155**, 297-312, doi:10.1111/ibi.12025 (2013).

59 Wijedasa, L. S. *et al.* Denial of long-term issues with agriculture on tropical peatlands will have devastating consequences. *Glob. Change Biol.* **23**, 977-982, doi:10.1111/gcb.13516 (2016).

60 Quezada, J. C., Etter, A., Ghazoul, J., Buttler, A. & Guillaume, T. Carbon neutral expansion of oil palm plantations in the Neotropics. *Sc. Advan.* **5**, eaaw4418, doi:10.1126/sciadv.aaw4418 (2019).

61 Searchinger, T. D., Wirsenius, S., Beringer, T. & Dumas, P. Assessing the efficiency of changes in land use for mitigating climate change. *Nature* **564**, 249-253, doi:10.1038/s41586-018-0757-z (2018).

62 Reijnders, L. & Huijbregts, M. A. J. Palm oil and the emission of carbon-based greenhouse gases. *J. Cleaner Prod.* **16**, 477-482, doi:10.1016/j.jclepro.2006.07.054 (2006).

63 Murdiyarso, D., Van Noordwijk, M., Wasrin, U. R., Tomich, T. P. & Gillison, A. N. Environmental benefits and sustainable land-use options in the Jambi transect, Sumatra. *J. Veget. Sc.* **13**, 429-438, doi:10.1111/j.1654-1103.2002.tb02067.x (2002).

64 Harsono, S. S., Grundmann, P. & Soebronto, S. Anaerobic treatment of palm oil mill effluents: potential contribution to net energy yield and reduction of greenhouse gas emissions from biodiesel production. *J. Cleaner Prod.* **64**, 619-627, doi:10.1016/j.jclepro.2013.07.056 (2014).

65 Hewitt, C. N. *et al.* Nitrogen management is essential to prevent tropical oil palm plantations from causing ground-level ozone pollution. *Proc. Natl. Acad. Sc. USA* **106**, 18447, doi:10.1073/pnas.0907541106 (2009).

66 Misztal, P. K. *et al.* Direct ecosystem fluxes of volatile organic compounds from oil palms in South-East Asia. *Atmos. Chem. Phys.* **11**, 8995-9017, doi:10.5194/acp-11-8995-2011 (2011).

67 Guenther, A. *et al.* The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2. 1): an extended and updated framework for modeling biogenic emissions. (2012).

68 Ellison, D. *et al.* Trees, forests and water: Cool insights for a hot world. *Glob. Env. Change* **43**, 51-61, doi:10.1016/j.gloenvcha.2017.01.002 (2017).

69 McAlpine, C. A. *et al.* Forest loss and Borneo's climate. *Env. Res. Lett.* **13**, 044009, doi:10.1088/1748-9326/aaa4ff (2018).

70 Fan, Y. *et al.* Reconciling canopy interception parameterization and rainfall forcing frequency in the community land model for simulating evapotranspiration of rainforests and oil palm plantations in Indonesia. *J. Advan. Model. Earth Syst.* **11**, 732-751, doi:10.1029/2018MS001490 (2019).

71 Crippa, P. *et al.* Population exposure to hazardous air quality due to the 2015 fires in Equatorial Asia. *Sci. Rep.* **6**, 37074, doi:10.1038/srep37074 (2016).

72 Nichol, J. Bioclimatic impacts of the 1994 smoke haze event in Southeast Asia. *Atmosph. Env.* **31**, 1209-1219, doi:10.1016/S1352-2310(96)00260-9 (1997).

73 Carlson, K. M. *et al.* Consistent results in stream hydrology across multiple watersheds: A reply to Chew and Goh. *J. Geophys. Res. Biogeosci.* **120**, 812-817, doi:10.1002/2014JG002834 (2015).

74 Luke, S. H. *et al.* The effects of catchment and riparian forest quality on stream environmental conditions across a tropical rainforest and oil palm landscape in Malaysian Borneo. *Ecohydrol.* **10**, e1827, doi:10.1002/eco.1827 (2017).

75 Mayer, P. M., Reynolds, S. K., McCutchen, M. D. & Canfield, T. J. Meta-Analysis of Nitrogen Removal in Riparian Buffers. *J. Env. Qual.* **36**, 1172-1180, doi:10.2134/jeq2006.0462 (2007).

76 Chellaiah, D. & Yule, C. M. Effect of riparian management on stream morphometry and water quality in oil palm plantations in Borneo. *Limnologica* **69**, 72-80, doi:10.1016/j.limno.2017.11.007 (2018).

77 Sulai, P. *et al.* Effects of water quality in oil palm production landscapes on tropical waterbirds in Peninsular Malaysia. *Ecol. Res.* **30**, 941-949, doi:10.1007/s11284-015-1297-8 (2015).

78 Anda, M., Siswanto, A. B. & Subandiono, R. E. Properties of organic and acid sulfate soils and water of a ‘reclaimed’ tidal backswamp in Central Kalimantan, Indonesia. *Geoderma* **149**, 54-65, doi:10.1016/j.geoderma.2008.11.021 (2009).

79 Luke, S. H. *et al.* Riparian buffers in tropical agriculture: Scientific support, effectiveness and directions for policy. *J. Appl. Ecol.* **56**, 85-92, doi:10.1111/1365-2664.13280 (2019).

80 Wich, Serge A. *et al.* Will Oil Palm’s Homecoming Spell Doom for Africa’s Great Apes? *Curr. Biol.* **24**, 1659-1663, doi:10.1016/j.cub.2014.05.077 (2014).

81 Sayer, J., Ghazoul, J., Nelson, P. & Boedhihartono, A. K. Oil palm expansion transforms tropical landscapes and livelihoods. *Glob. Food Secur.* **1**, 114–119, doi:10.1016/j.gfs.2012.10.003 (2012).

82 RSPO. RSPO and HCSA Collaborate to Implement No Deforestation in High Forest Cover Landscapes. https://rspo.org/news-and-events/news/rspo-and-hcsa-collaborate-to-implement-no-deforestation-in-high-forest-cover-landscapes. (2018).

83 Law, E. A. *et al.* Mixed policies give more options in multifunctional tropical forest landscapes. *J. Appl. Ecol.* **54**, 51-60, doi:10.1111/1365-2664.12666 (2017).

84 Budiadi *et al.* Oil palm agroforestry: an alternative to enhance farmers’ livelihood resilience. *IOP Conf. Ser.: Earth Env. Sc.* **336**, 012001, doi:10.1088/1755-1315/336/1/012001 (2019).

85 Valin, H. *et al.* The land use change impact of biofuels consumed in the EU. Quantification of area and greenhouse gas impacts. (ECOFYS Netherlands B.V., Utrecht, the Netherlands, 2015).

86 Thamsiriroj, T. & Murphy, J. D. Is it better to import palm oil from Thailand to produce biodiesel in Ireland than to produce biodiesel from indigenous Irish rape seed? *Appl. Energy* **86**, 595-604, doi:10.1016/j.apenergy.2008.07.010 (2009).

87 Rosoman, G., Sheun, S. S., Opal, C., Anderson, P. & Trapshah, R. The HCS Approach Toolkit. (HCS Approach Steering Group, Singapore, 2017).

88 Carlson, K. M. *et al.* Effect of oil palm sustainability certification on deforestation and fire in Indonesia. *Proc. Natl. Acad. Sci. USA* **115**, 121-126, doi:10.1073/pnas.1704728114 (2018).

89 Furumo, P. R., Rueda, X., Rodríguez, J. S. & Parés Ramos, I. K. Field evidence for positive certification outcomes on oil palm smallholder management practices in Colombia. *J. Cleaner Prod.* **245**, 118891, doi:https://doi.org/10.1016/j.jclepro.2019.118891 (2020).

90 Donofrio, S., Rothrock, P. & Leonard, J. Tracking Corporate Commitments to Deforestation-free Supply Chains, 2017. (Forest Trends, Washington, DC, 2017).

91 SPOTT. Palm oil: ESG policy transparency assessments. https://www.spott.org/palm-oil/. (2018).

92 Furumo, P. R. & Lambin, E. F. Scaling up zero-deforestation initiatives through public-private partnerships: A look inside post-conflict Colombia. **62**, 102055, doi:https://doi.org/10.1016/j.gloenvcha.2020.102055 (2020).

93 Gibbs, H. K. *et al.* Brazil's Soy Moratorium. *Science* **347**, 377, doi:10.1126/science.aaa0181 (2015).

94 OECD and FAO. OECD□FAO Agricultural Outlook 2018□2027. (2017).

95 Parsons, S., Raikova, S. & Chuck, C. J. The viability and desirability of replacing palm oil. *Nat. Sust.* **3**, 412-418, doi:10.1038/s41893-020-0487-8 (2020).

96 Qaim, M., Sibhatu, K. T., Siregar, H. & Grass, I. Environmental, Economic, and Social Consequences of the Oil Palm Boom. *Ann. Rev.* **12**, 321-344, doi:10.1146/annurev-resource-110119-024922 (2020).

97 VanBeek, K. R., Brawn, J. D. & Ward, M. P. Does no-till soybean farming provide any benefits for birds? *Agricult. Ecosyst. Env.* **185**, 59-64, doi:https://doi.org/10.1016/j.agee.2013.12.007 (2014).

98 Green, J. M. H. *et al.* Linking global drivers of agricultural trade to on-the-ground impacts on biodiversity. *Proc. Natl. Acad. Sci. USA* **116**, 23202, doi:10.1073/pnas.1905618116 (2019).

99 Strona, G. *et al.* Small room for compromise between oil palm cultivation and primate conservation in Africa. *Proc. Natl. Acad. Sci. USA* **115**, 8811, doi:10.1073/pnas.1804775115 (2018).

100 Ajjawi, I. *et al.* Lipid production in *Nannochloropsis gaditana* is doubled by decreasing expression of a single transcriptional regulator. *Nature Biotech.* **35**, 647, doi:10.1038/nbt.3865 (2017).

101 De Beenhouwer, M., Aerts, R. & Honnay, O. A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry. *Agric. Ecosyst. Env.* **175**, 1-7, doi:10.1016/j.agee.2013.05.003 (2013).

102 Strassburg, B. B. N. *et al.* Global priority areas for ecosystem restoration. *Nature*, doi:10.1038/s41586-020-2784-9 (2020).

103 Payán, E. & Boron, V. The Future of Wild Mammals in Oil Palm Landscapes in the Neotropics. *Front. Forests Glob. Change* **2**, doi:10.3389/ffgc.2019.00061 (2019).

104 Maddox, T., Priatna, D., Gemita, E. & Salampessy, A. The conservation of tigers and other wildlife in oil palm plantations Jambi Province, Sumatra, Indonesia. ZSL Conservation Report No.7. (The Zoological Society of London, London, UK, 2007).

105 Ancrenaz, M. *et al. Pongo pygmaeus*. *IUCN Red List Threat. Sp.*, e.T17975A17966347 (2016).

106 Pangau-Adam, M., Mühlenberg, M. & Waltert, M. Rainforest disturbance affects population density of the northern cassowary *Casuarius unappendiculatus* in Papua, Indonesia. *Oryx* **49**, 735-742, doi:10.1017/S0030605313001464 (2014).

107 Alamgir, M. *et al.* Infrastructure expansion challenges sustainable development in Papua New Guinea. *PLOS ONE* **14**, e0219408, doi:10.1371/journal.pone.0219408 (2019).

108 Katiyar, R. *et al.* Microalgae: An emerging source of energy based bio-products and a solution for environmental issues. *Renew. Sust. Energy Rev.* **72**, 1083-1093, doi:10.1016/j.rser.2016.10.028 (2017).

109 Nomanbhay, S., Salman, B., Hussain, R. & Ong, M. Y. Microwave pyrolysis of lignocellulosic biomass—a contribution to power Africa. *Energy Sust. Soc.* **7**, 23, doi:10.1186/s13705-017-0126-z (2017).

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Author contributions

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

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FIGURE LEGENDS

Figure 1. Main vegetable oil crops (see Table 1). (a) Harvested area from 1961 to 2017. (b) Vegetable oil production from 1961 to 2014. Data from FAOSTAT[4].

Figure 2. Maps of industrial and smallholder-scale oil palm from analysis of satellite imagery until the second half of 2019[3], and examples of species it affects negatively: (a) *Panthera onca* (Near Threatened)[103] and *Ara macao* (Least Concern)[39]; (b) *Pan troglodytes* (Endangered)[80]; (c) *Panthera tigris* (Endangered)[104], *Helarctos malayanus* (Vulnerable)[104], *Pongo pygmaeus* (Critically Endangered)[105], *Casuarius unappendiculatus* (Least Concern)[106], and *Dendrolagus goodfellowi* (Endangered)[107]. The maps lack information on plantations < 3 years old and planted oil palm in mixed agroforestry settings, but provide the most up-to-date estimates available. For each region the percentages of intact (green) and non-intact forests (orange) are shown relative to the total extent of forest ecosystems[22].

Figure 3. Oil palm's estimated role in deforestation aggregated across studies, years, and regions. Panel a depicts the contribution of oil palm to overall deforestation, while b shows the percentage of all oil palm expansion that cleared forest (Supplementary Methods). There were no data for Peru and South and Central America for panel a, and no global data for panel b. Southeast Asia (SE Asia) excludes Indonesia and Malaysia, which are shown separately, while South America excludes Peru. Each filled circle represents one time period from a single study, with individual studies represented by distinct colours. The size of the circle corresponds to the relative number of area-years represented in that time period (larger circles represent a larger study area and longer time period of sampling). Boxplot middle bars correspond to the unweighted median across study-time

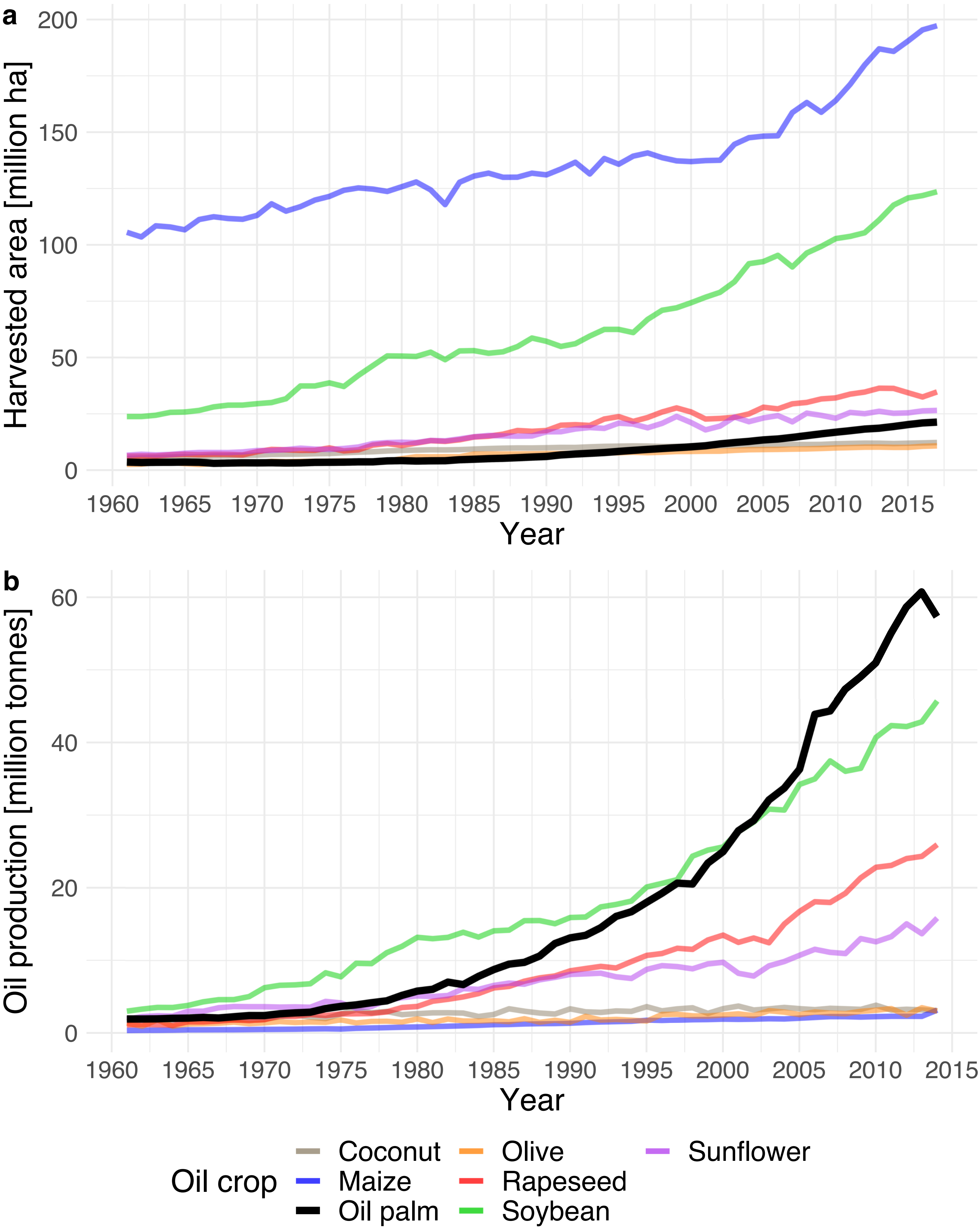
periods; lower and upper hinges represent the 25th and 75th percentiles of study-time periods; and whiskers extend from the upper (lower) hinge to the largest (smallest) value no further than 1.5 times the interquartile range from the hinge (Figure S2, Tables S2 and S3).

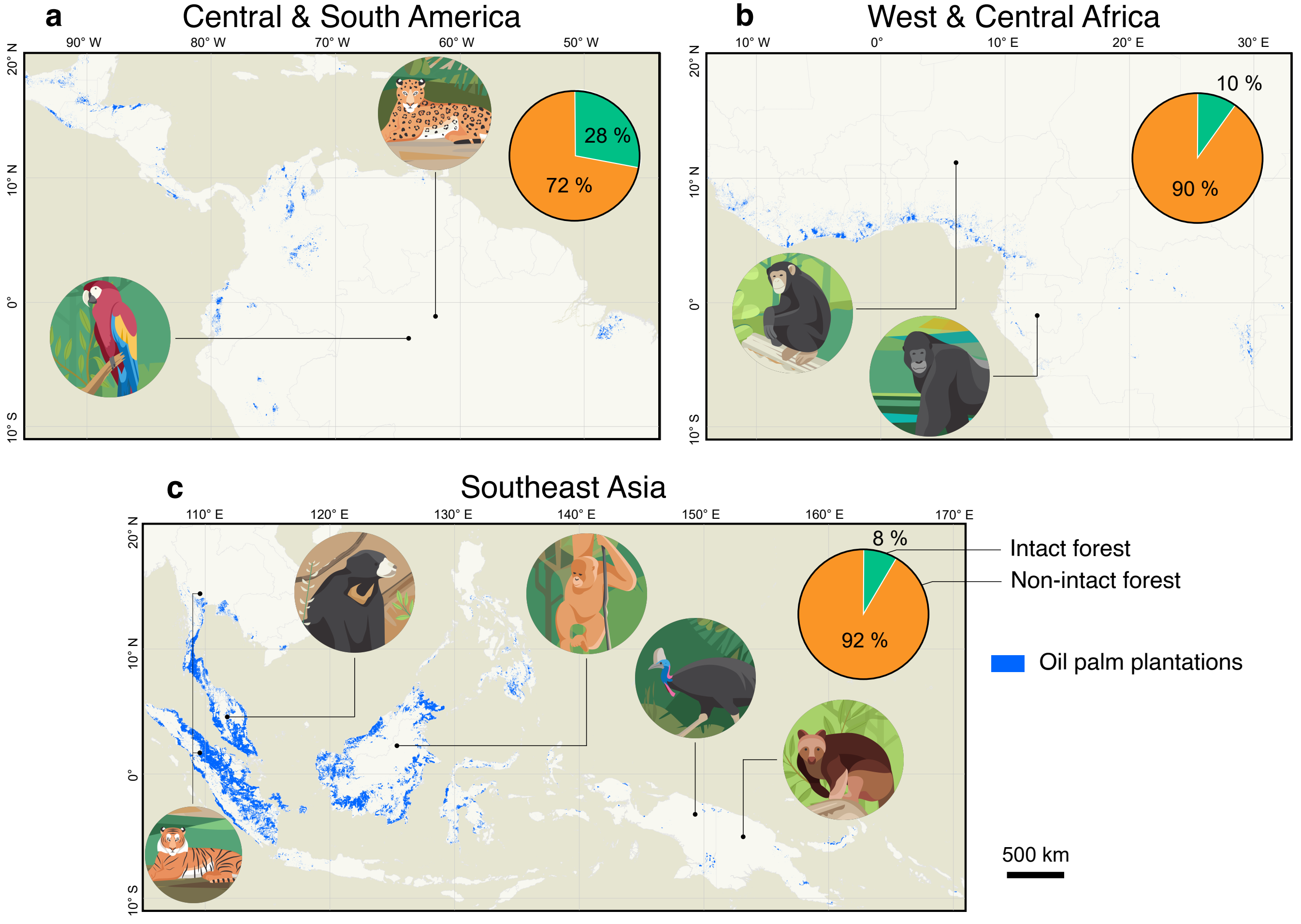
Figure 4 - Species groups with more than 8 threatened species with the terms "palm oil" or "oil palm" in the threats texts of the IUCN Red List of Threatened Species Assessments[29]. In total 321 species assessments had oil palm plantations as one of the reported threats (301 when excluding groups with < 8 threatened species), which constitutes 3.5% of threatened species threatened by annual and perennial non-timber crops (9,088 species) and 1.2% of all globally threatened species (27,159 species) in 2019 (Supplementary Material and Table S4). CR = Critically Endangered; EN = Endangered; VU = Vulnerable.

Table 1. Overview of the major oil crops, typical production cycle, yields, main production countries, biomes in which impacts primarily occur, carbon emissions, the number of threatened species according to the IUCN Red List of Threatened Species[29] for which the specific crop is mentioned as a threat, and the median species richness and median range-size rarity (amphibians, birds and mammals) of species occurring within the footprint of each crop with first and third quartile in brackets (IUCN Red List) (see Supporting Online Methods, Figure S1, Table S4). Carbon emissions include carbon opportunity costs and production emissions[61]. "n/a" indicates that no data are available.

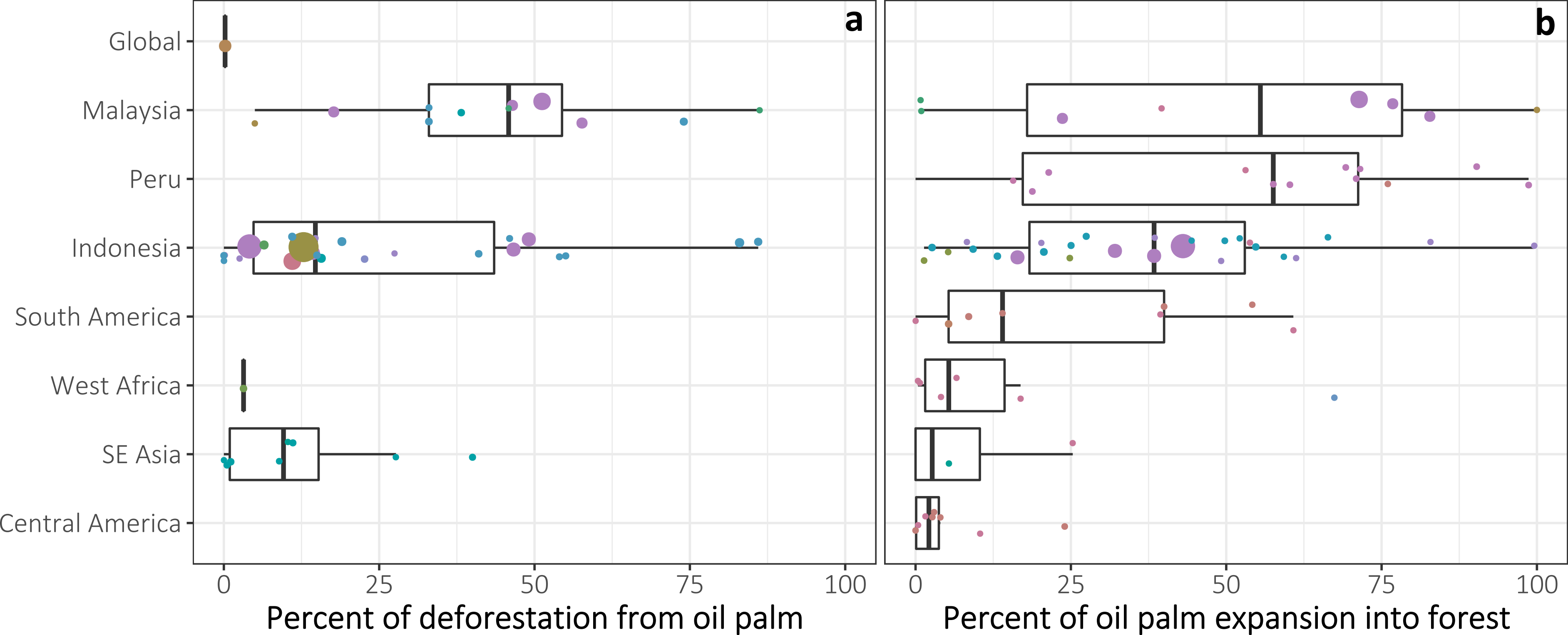
Oil crop	**Type of crop**	**Oil yield (t ha-1)** [108,109]	**Main oil production countries**	**Main biome impacted**	**Kg CO2e/MJ** [61]	**# species threatened by crop**[29]	**Median Species Richness (number of species)**[29]	**Median range-size rarity (ha ha^{-1} 10e5)**[29]
Oil palm *Elaeis guineensis*	Perennial (25 years cycle)	1.9–4.8	Indonesia, Malaysia, Thailand	Tropical rainforest	1.2	321	472 [443, 504]	36 [27, 57]
Soybean *Glycine max*	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 *Brassica napus* and *B. campestris*	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 *Gossypium hirsutum*	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 *Arachis*	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]

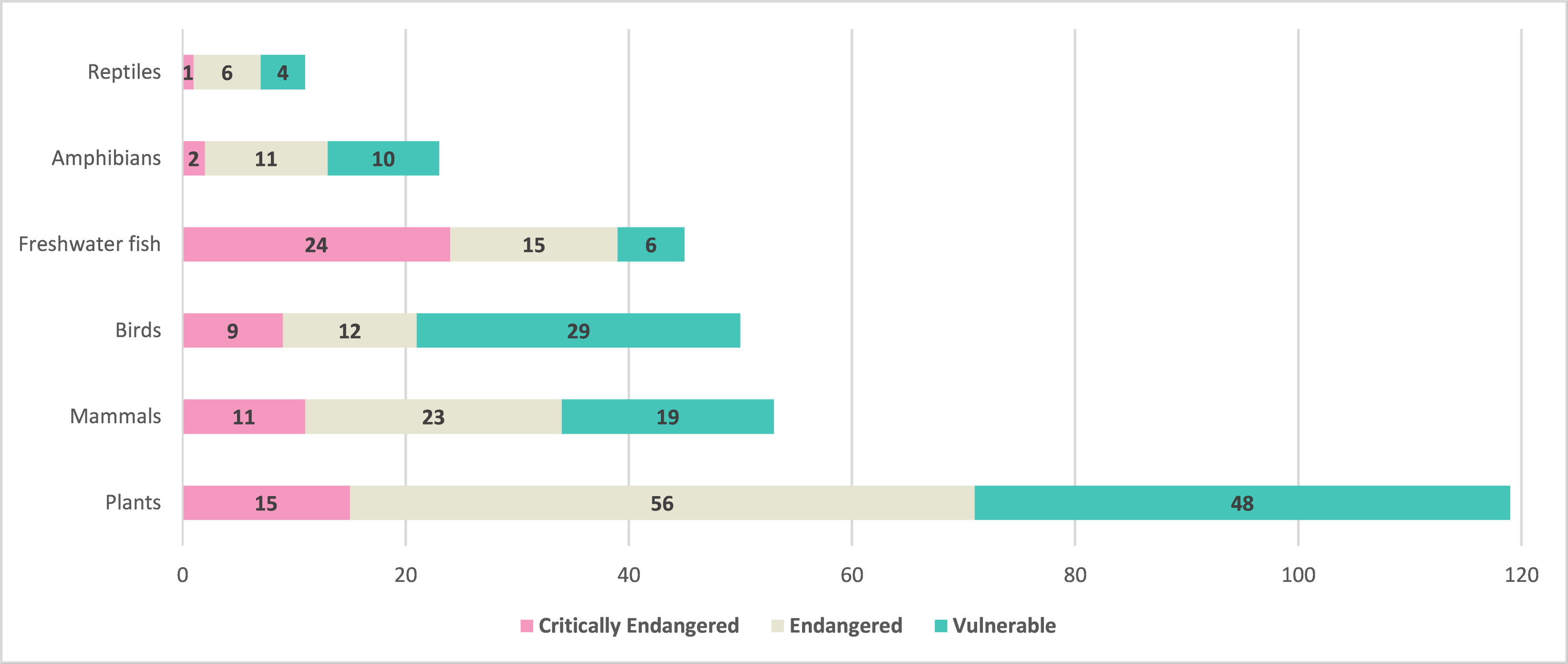
hypogaea	Rotated with other crops			temperate areas				
Sunflower *Helianthus annuus*	Annual (3-4 months crop cycle). Rotated with other crops	0.5–0.9	Ukraine, Russia	Temperate steppe and broadleaf forest	1.0	1	189 [177, 222]	3 [2, 9]
Coconut *Cocos nucifera*	Perennial (30 – 50 y cycle)	0.4–2.4	Philippines,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


a
Harvested area [million ha]
200
150
100
50
0
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year
b
Oil production [million tonnes]
60
40
20
0
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year
Oil crop
Coconut
Maize
Oil palm
Olive
Rapeseed
Soybean
Sunflower



a
Central & South America
90° W
80° W
70° W
60° W
50° W
20° N
10° N
0°
10° S
28 %
72 %
b
West & Central Africa
10° W
0°
10° E
20° E
30° E
20° N
10° N
0°
10° S
10 %
90 %
c
Southeast Asia
110° E
120° E
130° E
140° E
150° E
160° E
170° E
20° N
10° N
0°
10° S
8 %
92 %
Intact forest
Non-intact forest
Oil palm plantations
500 km


a
b
Global
Malaysia
Peru
Indonesia
South America
West Africa
SE Asia
Central America
0
25
50
75
100
Percent of deforestation from oil palm
Percent of oil palm expansion into forest



Reptiles
Amphibians
Freshwater fish
Birds
Mammals
Plants
1
6
4
2
11
10
24
15
6
9
12
29
11
23
19
15
56
48
0
20
40
60
80
100
120
Critically Endangered
Endangered
Vulnerable