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Oil palm cultivation can be expanded while sparing biodiversity in India

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India is the world's largest consumer and importer of palm oil. In an aggressive push towards self-sufficiency in vegetable oils, the Indian government is prioritizing the rapid expansion of domestic oil palm plantations to meet an expected doubling in palm oil consumption in the next 15 years. Yet the current expansion of oil palm in India is occurring at the expense of biodiversity-rich landscapes. Using a spatially explicit model, we show that at the national scale India appears to have viable options to satisfy its projected national demand for palm oil without compromising either its biodiversity or its food security. At finer spatial scales, India's oil palm expansion needs to incorporate region-specific contingencies and account for trade-offs between biodiversity conservation, climate change, agricultural inputs and economic and social security. The policy decisions that India takes with respect to oil palm can substantially reduce future pressures to convert forests to oil palm plantations in the tropics globally.

In Southeast Asia, and increasingly in tropical Africa and South America[1–4], the global demand for palm oil is causing widespread replacement of forests that are critical for biodiversity with species-depauperate oil palm monocultures. India is the largest global consumer of palm oil (8.9 Mt in 2019–2020, ~20% of global consumption)[5]. However, India produces only ~1% of its domestic requirement[6], importing ~99% from Indonesia and Malaysia (that is, until a recent boycott of Malaysian palm oil)[7]. India's palm oil consumption is strongly linked to its population size (linear correlation, 2001–2020; $R = 0.95$; $P < 0.01$; Supplementary Fig. 1)[5]. India's palm oil demand already outstrips consumption by both China and the United States combined[5], and projected population growth in India is likely to drive domestic palm oil consumption further upwards. With this burgeoning demand, India's future production and import policies with respect to palm oil are expected to have immense ramifications for tropical biodiversity worldwide.

In anticipation of this rapid rise in future demand, India has been pushing towards self-sufficiency in vegetable oils under its Atmanirbhar Bharat (Self-Reliant India) programme. The government of India has been prioritizing the expansion of domestic oil palm plantations through heavy subsidies for seedlings, irrigation and other agricultural inputs[8]. Since 1991, land area under oil palm in India has increased over 30-fold, reaching 114,350 ha in March 2015[9]. The expansion of oil palm plantations continues apace, especially in India's biodiversity-rich northeast[10,11] where oil palm plantations are replacing lands with globally important biodiversity value.

For instance, the New Land Use Policy of the northeast Indian hill state of Mizoram officially describes shifting cultivation as wasteful and has earmarked this land-use type for replacement with monoculture oil palm plantations[12]. Until 2018, Mizoram had planted 28,295 ha of oil palm[13], largely at the expense of highly biodiverse forest-crop mosaics[14]. Other northeast Indian states are following suit, rapidly converting supposedly degraded landscapes into oil palm. A total of 2,881 ha of the crop has already been planted in the northeastern states of Assam, Arunachal Pradesh, Nagaland and Tripura[15], which are part of two Global Biodiversity Hotspots[16]. The forests and swidden landscapes targeted for conversion to oil palm are rich in biodiversity and support vulnerable, forest-dependent species. There is a danger that oil palm expansion in northeast India could imperil highly biodiverse landscapes and globally threatened species, as has occurred elsewhere in the tropics[1], while also compromising livelihoods and social security[8,12,14].

A key question is whether India can meet its future palm oil demand while sparing landscapes of high conservation value (HCV), or whether it will be forced to continue importing palm oil from ever-expanding plantations at the cost of tropical biodiversity, both domestically and globally[1,4]. We investigated India's potential for the development of suitable oil palm cultivation by examining spatial overlaps between (1) potential areas bioclimatically suitable for oil palm under differing scenarios of irrigation, agricultural inputs and climate change under the Special Report on Emissions Scenarios (SRES) A2 scenario, (2) HCV ecosystems and (3) existing cropland (in particular, rice). In doing so, we identify land where India may increase palm oil production while sparing natural ecosystems, and still safeguard the livelihoods and food security of local communities.

Results and discussion

The area biophysically suitable for oil palm cultivation in India varies from 7.86 to 73.26 Mha depending on both future climate and water supply (Table 1 and Fig. 1). Both climate change (under the A2 scenario) and artificial irrigation are likely to substantially increase the potential area in which oil palm can be grown (Fig. 1 and Supplementary Table 1). However, roughly 45–60% of these areas are currently occupied by HCV land cover, with the remainder under other land uses (Figs. 2 and 3 and Supplementary Table 1). Should India spare these biodiverse habitats, there is still 7.86–38.8 Mha of land suitable for oil palm cultivation (Table 1 and Figs. 2 and 3).

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Table 1 | Extent of land suitable for oil palm in India under different scenarios of climate change, water source and agricultural inputs

Climate scenario	Water source	Agricultural inputs	Oil palm cultivable area (Mha)	Land use/land cover (percentage)					Percentage area under HCV habitats
				Forest	Grassland	Cropland	Built-up	Other	
No climate change	Irrigated	High	57.21	36.47	4.99	53.29	3.19	2.07	45.62
		Medium	57.21	36.47	4.99	53.29	3.19	2.07	45.62
		Low	57.21	36.47	4.99	53.29	3.19	2.07	45.62
	Rain-fed	High	7.86	55.26	1.37	37.81	3.95	1.61	59.72
		Medium	8.21	54.44	1.42	38.57	4.01	1.56	59.09
		Low	8.36	53.67	1.45	39.38	3.95	1.55	58.32
SRES A2 climate scenario[a]	Irrigated	High	73.26	34.97	7.08	53.01	2.87	2.07	46.87
		Medium	73.26	34.97	7.08	53.01	2.87	2.07	46.87
		Low	73.26	34.97	7.08	53.01	2.87	2.07	46.87
	Rain-fed	High	7.53	56.98	1.61	34.98	3.57	2.86	61.22
		Medium	7.62	57.08	1.60	34.75	3.63	2.95	61.55
		Low	7.04	58.33	1.42	34.05	3.69	2.51	62.07

Land use and land cover under the different scenarios are provided as percentages of land suitable for oil palm cultivation. The last column shows the percentage area cultivable under oil palm that is currently a region of HCV. HCV areas consist of biodiversity hotpots, remnant natural habitat and legally protected areas. [a]CO_2 concentration in 2100 projected at 870 ppm by the Intergovernmental Panel on Climate Change.[28]

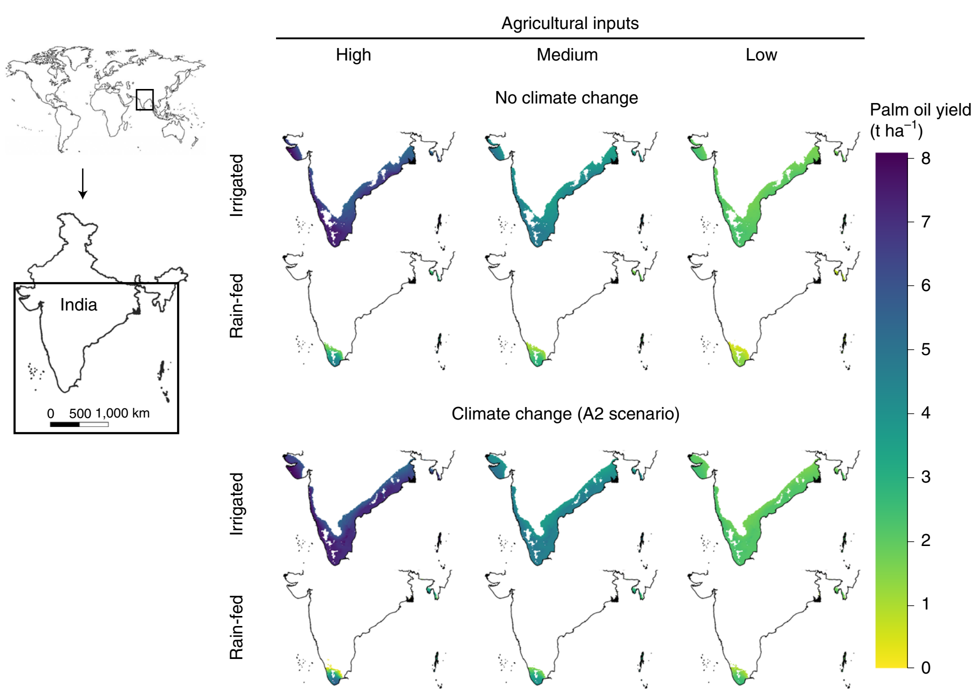

Fig. 1 | Suitability of land for oil palm cultivation in India. Areas biophysically suited to the cultivation of oil palm in India under differing scenarios of climate, irrigation and agricultural inputs, with corresponding yields. White regions represent areas unsuitable for the cultivation of oil palm.

However, a large proportion (~40–50%) of the non-biodiverse land suitable for oil palm is currently cultivated, largely for rice (Fig. 2a and Table 1), and one of the many options for oil palm expansion could involve trade-offs between palm oil gains and rice production losses. One way to approach such a trade-off is to identify lands suitable for oil palm that are 'marginal' in terms of rice production, and to focus oil palm expansion onto these lands. Up to 16.08 Mha of marginal rice lands are suitable for oil palm cultivation (Supplementary Fig. 2). By completely replacing marginal rice with oil palm under optimal inputs (Supplementary Table 1), India can potentially produce 108.92 Mt of palm oil at the expense of 18.94 Mt of rice (~7% of India's food grain production; Supplementary Table 1)[17]. This is ~1.5 times the projected global demand for palm oil in 2030[18]. Replacing all of India's marginal rice (arbitrarily defined as <2 t ha^{-1}) areas with oil palm is both infeasible and undesirable, and we certainly do not advocate that India's oil palm policy should focus solely on replacing marginal rice. Nonetheless, the hypothetical analysis we present provides an example of the many possible spatially explicit planning exercises that India can—and should—undertake before replacing natural or semi-natural vegetation types of high biodiversity value with oil palm (see Future directions).

The key point is that India does not need to alter its biodiversity-rich ecosystems to greatly boost its domestic oil palm production. In this respect, India is in a globally unique position.

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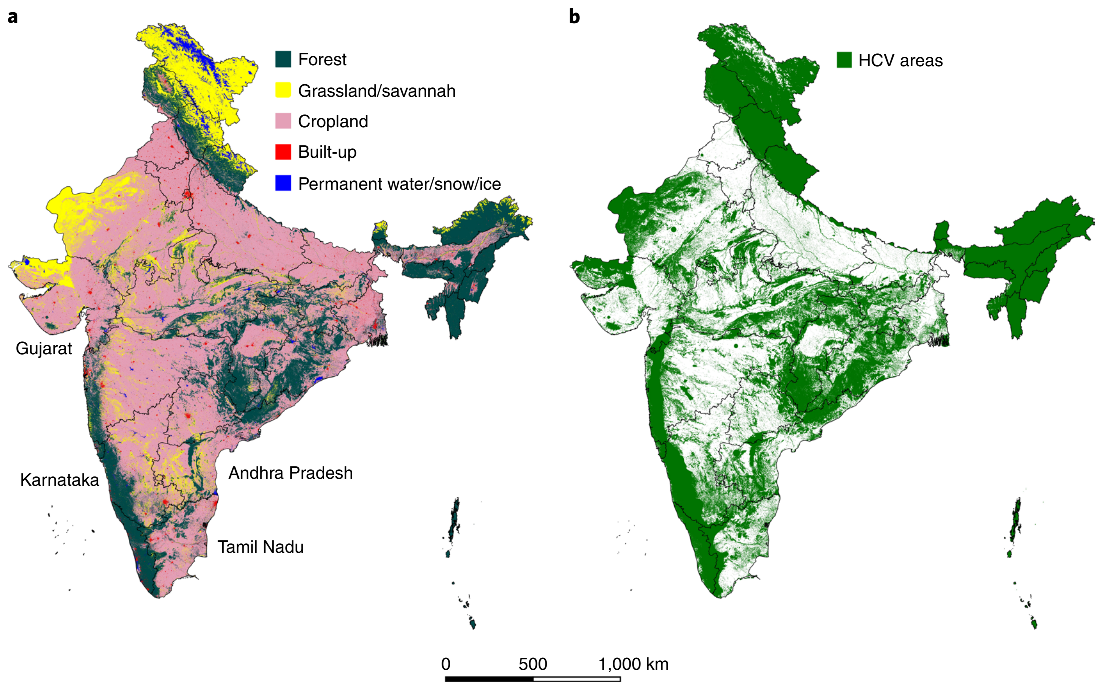

Fig. 2 | Land use, land cover and HCV areas in India. a, Types of land use/land cover. **b**, HCV areas. State boundaries are shown by solid black lines.

Whereas 38% and 68% of oil palm plantations in Indonesia and Malaysia, respectively, have been developed at the expense of forests[19], India's oil palm expansion can be planned from the very start to minimize biodiversity losses and negative impacts to livelihoods. Furthermore, the future expansion of oil palm plantations in Southeast Asia, Africa and the Neotropics—much of which will produce palm oil for export to India if India does not increase its own domestic production—is highly likely to occur at the cost of the remaining forests, which harbour high concentrations of rare mammal and bird species[1]. For tropical biodiversity worldwide, therefore, India's impending land-use decisions will be critical. As the largest market for palm oil globally, and one that is poised to grow rapidly, India can reduce future pressure on forest lands across the global tropics—especially in emerging production landscapes such as tropical Africa and America—by meeting most of its future domestic demand in areas vital for neither biodiversity nor food production.

Substantially increasing palm oil yields in India will depend not only on replacing an acceptable fraction of existing crops with oil palm, but also on investing in mechanization, high-yielding cultivars, fertilizers and pesticides[17], which, we recognize, can generate other environmental problems, and should be studied carefully before indiscriminate oil palm expansion. It should be noted, however, that oil palm, although requiring more potassium per hectare than rice, is less demanding in terms of nitrogen and phosphorus[20].

With respect to irrigation, however, growing oil palm in India will be much more water-intensive than growing rice, and will probably require practices such as drip irrigation and soil mulching to reduce overall water demand (Supplementary Information and Supplementary Table 2). In monsoonal, semi-arid, peninsular India—where a vast majority of the area is bioclimatically suitable for oil palm (Fig. 1)—maximizing oil palm yield would require roughly 19.16 megalitres of water per hectare annually, compared with 8.23 megalitres for marginal rice (Supplementary Information and Supplementary Tables 2 and 3). Of this requirement, a large fraction (~13.25 megalitres) will need to be sourced from surface and groundwater irrigation during the non-monsoonal dry months, because rainfall can provide only ~30% of the water required to cultivate oil palm (Supplementary Table 2). Water will be the key concern of the future, given India's high reliance on groundwater for agricultural irrigation, and declines in groundwater levels in arid parts of the country.

In regions suitable for oil palm, groundwater tables are deep[21], and withdrawals range from 40–80% of annual aquifer recharge from precipitation; however, only 5–10% of total rainfall contributes to groundwater recharge, with high water losses from runoff and evaporation[22]. Therefore, while irrigating oil palm under current patterns of groundwater use will be challenging, there may be opportunities to enhance year-round groundwater availability through managed aquifer recharges, especially given the low costs associated with such techniques[22]. For instance, using injection wells and percolation tanks to recharge groundwater aquifers costs only US$2–5 per megalitre of water, and the overall costs of these improvements are likely to be defrayed by planned investment in oil palm plantations. India must officially encourage rainwater harvesting and aquifer recharge techniques hand-in-hand with, or ideally before, expanding oil palm plantations. Critically, with higher projected temporal variability in rainfall, forested and semiforested tropical landscapes will become even more important as watersheds and for mitigating the severity of floods and droughts; replacing forests with oil palm is therefore likely to compound the impact of extreme rainfall events on agricultural productivity.

Of special concern is India's push to expand oil palm plantations in its northeast at the cost of some of the world's most important ecosystems for biodiversity (notably, the East Himalayan and Indo-Myanmar biodiversity hotspots)[16]. From a purely agricultural perspective, most of these regions appear to be bioclimatically unsuitable for oil palm (Fig. 1). Therefore, oil palm expansion in these areas would occur at the cost of many globally threatened species, while providing questionable agricultural gains. Equally important is the need for a regulatory policy to ensure that new plantations in parts of the states of Andhra Pradesh (currently producing most of India's palm oil), Gujarat, Karnataka and Tamil Nadu do not replace semi-arid savannah grasslands and grassland-crop mosaics

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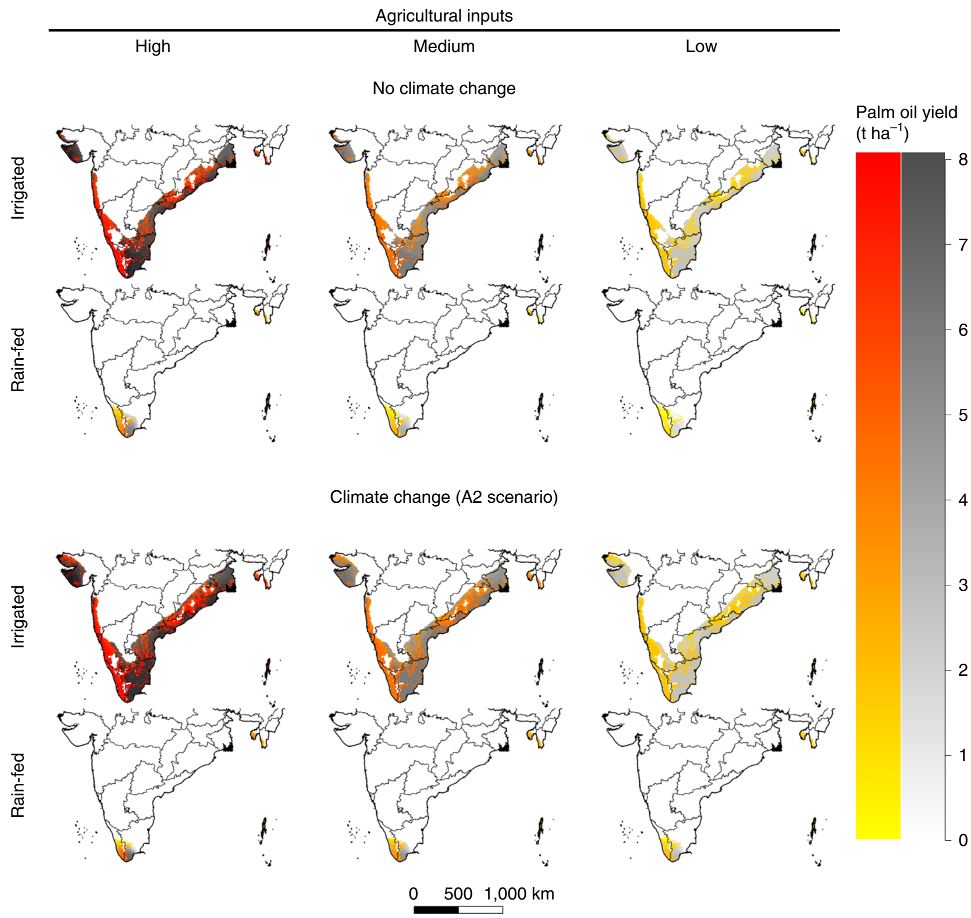

Fig. 3 | Overlaps between HCV areas and potential oil palm growing areas. Regions marked in colour (yellow to red) are those where potential oil palm growing areas overlap with HCV areas, and therefore represent areas where oil palm cultivation should not be expanded. Regions marked in grey (light to dark grey) are areas suitable for the cultivation of oil palm that lie outside HCV regions. Higher yields are represented by darker red (in areas where oil palm and conservation value overlap) or darker grey (non-overlapping areas). Areas in white are not suitable for the cultivation of oil palm.

(Table 1 and Figs. 2a and 3) that are vital for a suite of endangered fauna, including the Indian wolf (*Canis lupus pallipes*), lesser florican (*Sypheotides indica*) and the great Indian bustard (*Ardeotis nigriceps*). These areas include—but are not limited to—Kutch in Gujarat and the Rollapadu area in Andhra Pradesh (Fig. 2).

At the national scale, India can be self-sufficient in palm oil production without having to compromise the integrity of HCV habitats. Realizing this, however, will require substantial political will, economic inflow and, most importantly, socioeconomic and environmental safeguards. Planting oil palm typically results in a three-year hiatus before plantations begin yielding crop, which necessitates offering farmers interim incentives to switch to oil palm, a measure already recognized and monetarily supported by the government of India[9]. Further, the government must also ensure that farmers, especially smallholder agriculturists, switch to economically and socially just, sustainable oil palm cultivation, perhaps by adopting and expanding on the guidelines proposed by the Roundtable on Sustainable Oil Palm. The Roundtable has yielded environmental and social benefits, although trade-offs in these outcomes do occur based on the context under which oil palm is cultivated[23]. A win–win for India, and for the global tropics, would be for India to simultaneously spare its own biodiversity and substantially increase palm oil production to meet a substantial fraction of its domestic consumption. Given the high stakes for tropical biodiversity, a strong domestic framework with appropriate safeguards[6], combined with international oversight and support, will be crucial to ensure that India expands its oil palm plantations responsibly and sustainably.

Future directions. Our study offers a preliminary, spatially explicit (albeit coarse-grained) analysis to guide the expansion of oil palm plantations in India while preserving the country's imperilled and globally important biodiversity. Economic, social, political and nutritional factors will require attention at finer spatial scales, with further analyses that incorporate these site-specific nuances. For instance, in many arid parts of the country, areas suitable for oil palm occur on lands that are not cultivated for rice but instead are devoted to the production of crops such as cashew and mango. In such regions, oil palm will have to replace other crops, and farmers who switched to oil palm with drip irrigation systems are making higher profits than in the past[24]. Land tenure regimes will also require more attention. In northeast India, for example, a large proportion of forest land is community-owned and managed. Replacing these forests with oil palm will probably result in 'land grabs' and the transfer of land ownership to a few influential individuals, exacerbating socioeconomic inequalities and threatening livelihood security, as has occurred in the past in similar sociocultural situations[25,26]. Infrastructure to support the entire supply chain of palm oil (for example, processing facilities and transport networks) will need to be set up in parallel with the establishment of new plantations because of the short shelf life of the oil palm fruit. Finally, we recognize that alternative socioclimatic scenarios are

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possible. For example, the A2 climate scenario we followed is one of many climate projections, and predictions of actual future climate remain uncertain. Nonetheless, we find clear evidence that India can expand its oil palm plantations without incurring major losses of biodiversity, and we have developed a spatially explicit approach to identify suitable areas for oil palm expansion in the world's largest consumer nation. This approach can be used as a starting point to inform and expand India's land-use plans for achieving vegetable oil self-sufficiency while reducing its impact on biodiversity.

Methods

Calculating potential area under oil palm and oil palm yields. We obtained data on areas suitable for oil palm cultivation in India (based on temperature, precipitation and agroclimatic constraints) from the Global Agro-Ecological Zones database (GAEZ) of the Food and Agriculture Organization[17]. We used spatially explicit oil palm yield data (resolution, 0.083°)[17] for 12 combinations of different scenarios of (1) climate change (no climate change or climate change under the A2 scenario)[27], (2) irrigation (rain-fed or artificially irrigated) and (3) agricultural input (low, medium or high)[16]. The GAEZ[17] database models land area potentially suitable for crop cultivation under different expectations of climate change (following the climate models within the SRES of the Intergovernmental Panel on Climate Change)[28]. Of the various SRES scenarios (A1, B1, A2 and B2) for which GAEZ[17] projects areas biophysically suitable for oil palm cultivation, we chose to analyse data for the A2 because it is most similar to RCP8.5; the latter is considered to be the most appropriate future climate scenario under current conditions[29]. In addition to oil palm yield, we also obtained spatially explicit data on rice yields[17].

We used land-use/land-cover data from the Copernicus Programme of the European Union (resolution, 100 m)[30] to identify areas of forest, savannah/grasslands, cropland and other land-cover types. We also obtained maps of areas contained within Global Biodiversity Hotspots[16] (shapefile from ref. [31]) and all Protected Areas (shapefile from ref. [32]).

We used the programs QGIS[33] and R[34] for our spatially explicit analyses. R code and vector and raster files used in the analyses are provided in the Supplementary Information. First, we identified the regions within India that are suitable for the cultivation of oil palm under the 12 different scenarios. These data were in the form of rasters, each pixel of which also included information on oil palm yield. While retaining these 12 rasters to calculate oil palm yields under different scenarios (see below), we also converted the rasters to vector polygons to obtain simple outlines within which areas suitable for oil palm were contained.

Next, we used the land-cover raster data[30] to reclassify land cover into forest, savannah/grassland, cropland, built-up areas and other land-cover classes. We combined the various forest types identified by Schwalm et al.[29] into a single 'forest' land-cover class. Copernicus data[30] do not explicitly identify savannahs and grasslands. Instead, we collectively reclassified the land-cover classes identified as 'shrubland', 'herbaceous vegetation' and 'bare and spare vegetation' into a single 'savannah/grassland' land-cover class. We then merged the forest and savannah/grassland layers, and further combined the resulting layer with the protected area and biodiversity hotspot vectors to obtain a single 'HCV areas' layer for India.

For each of the 12 scenarios, we then calculated the land area covered by (1) forest, (2) savannah/grassland, (3) existing crops, (4) built-up and (5) other land-cover classes within regions that could also support oil palm. Following this, we excluded HCV areas from oil palm growing regions ('spared oil palm areas'). Because most land in the spared oil palm areas is under cropland (predominantly rice cultivation), we also identified the spatial overlap between spared oil palm areas and areas currently 'marginal' for rice production (arbitrarily defined as yielding $<2\,\mathrm{t\,ha^{-1}}$)[17]. Finally, for each of the 12 scenarios, we calculated palm oil yields that could potentially be obtained by replacing all marginal rice-growing areas with oil palm plantations.

Because the availability of water for irrigating crops is likely to be of great concern under future climate conditions, we also calculated the water footprints of oil palm and rice, and the amount of water (separately from rainfall and irrigation) currently used for rice cultivation in potential oil palm growing regions (Supplementary Information, Supplementary Table 2 and Supplementary Fig. 3).

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

Source data on spatially explicit oil palm yields under various scenarios are freely available at https://gaez.fao.org/pages/data-viewer. Source data on land use and land cover are freely downloadable at https://land.copernicus.eu/global/products/lc. Vector and raster data files used in the analyses in this manuscript are available at https://doi.org/10.5061/dryad.fj6q573v3.

Code availability

The R script used in the analyses in this manuscript is available at https://doi.org/10.5061/dryad.fj6q573v3.

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Author contributions
U.S., N.V. and D.S.W. co-conceived the paper. U.S., N.V., J.S.H.L., D.D.C. and K.F.D. extracted the data from online sources and performed the analysis. U.S. wrote the first draft of the manuscript and all authors contributed substantially to revisions.

Competing interests
The authors declare no competing interests.

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Software and code

Policy information about availability of computer code

Data collection	Data were downloaded from freely available repositories of (a) the Global Agro-Ecological Zones database of the Food and Agriculture Organization, and (b) the United States Department of Agriculture. All analysis was done in QGIS v3.16 and in R.
Data analysis	All analysis was performed in QGIS v3.16 and R. The R script used for the analysis is available at doi:10.5061/dryad.fj6q573v3.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

Data used in this study are freely available at: http://www.fao.org/nr/gaez/en/ and: https://land.copernicus.eu/global/products/lc. All vector and raster raw data files used in the analysis have been uploaded at doi:10.5061/dryad.fj6q573v3.

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Field-specific reporting

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☐ Life sciences ☒ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This study is based on remotely sensed data and on projected crop yield based on specific climate scenarios. The data are quantitative and explore overlaps between projected crop-suitable regions and existing land cover.
Research sample	Research samples are not applicable to this work. Data can be accessed from the links provided in the data accessibility statement.
Sampling strategy	This is not applicable to the study. Data are from remote sensing.
Data collection	Data are from remote sensing. Blinding and other considerations do not apply to this study.
Timing	Not applicable.
Data exclusions	Not applicable
Non-participation	Not applicable
Randomization	Not applicable

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Materials & experimental systems

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☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

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