

Implications of zero-deforestation palm oil for tropical grassy and dry forest biodiversity: Supplementary Information

Overview

This document provides the Supplementary Information for the Methods, Results and Discussion presented in the Main Article 'Implications of zero-deforestation palm oil for tropical grassy and dry forest biodiversity'. In Supplementary Information 1, we present an overview of current guidance for implementing zero-deforestation commitments (ZDCs) for oil palm in relation to grassy biomes and dry forests, and a review of recent High Conservation Value-High Carbon Stock Approach (HCV-HCSA) assessments conducted in these biomes. In Supplementary Information 2, we present sensitivity analyses of our key Results to the inclusion of intensively-managed pasture as a land-use type. In Supplementary Information 3 and 4, we present sensitivity analyses of our rainfed and irrigated oil palm suitability projections respectively, to the choice of oil palm suitability threshold, and to the choice of thresholds of woody vegetation structure determining protection under zero-deforestation commitments. We also present results using an existing agro-ecological model of rainfed oil palm suitability in Supplementary Information 3. In Supplementary Information 5, we present sensitivity analyses of the results of the potential impacts of zero-deforestation oil palm expansion on vertebrates (richness loss and range reduction of threatened species) presented in the Main Article, in line with the oil palm suitability model permutations presented in Supplementary Information 3 and 4. These sections thus quantify uncertainties around our results of suitable areas for oil palm expansion under ZDCs that are presented in the Main Article. In Supplementary Information 6, we present an extended Discussion of the limitations of our Methods and Results. In Supplementary Information 7, we present methodological details of modelling oil palm suitability (selection of predictors, model evaluation, selection and thresholding of oil palm suitability models, and deriving estimates of oil palm yield from model outputs), to support the Main Article Methods (it is expected that the Main Article Methods would be read prior to this document).

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Supplementary Information 1: HCV and HCS guidance for tropical grassy biomes and dry forests, and recent application

Implementation of zero-deforestation commitments through the RSPO

Globally, two-thirds of palm oil production volume is covered by some form of zero-deforestation commitment¹; and recent estimates suggest that almost 80% of the total palm oil production in Indonesia and Malaysia is covered by commitments for No Deforestation, Peat and Exploitation (NDPE), through commitments of palm oil refineries (refineries represent a bottleneck in palm oil supply chains, as there are relatively few across the whole sector)^{2,3}. Most implementation of ZDCs for oil palm is through the Roundtable on Sustainable Palm Oil (RSPO) certification scheme¹, whereby companies only include certified palm oil and/or its derivatives from certified producers in their supply chains¹. The RSPO was established in 2004, in response to extensive deforestation driven by oil palm expansion in Indonesia and Malaysia⁴⁻⁶, and its Principles and Criteria have been revised a number of times since its inception, to improve their rigour and address issues that come to light following initial implementation of new Principles and Criteria^{6,7}. The most recent revision was in 2018, when the RSPO adopted a zero-deforestation policy ('No Deforestation, No Peat, No Exploitation', or NDPE), in line with the large number of corporate supply chain ZDCs¹, implemented through the combined High Conservation Value-High Carbon Stock Approach (HCV-HCSA)⁸. Prior to developing a new RSPO-certified oil palm plantation, a combined HCV-HCSA assessment is conducted by a team with a range of expertise (e.g. biodiversity, remote sensing, social science), which undergoes external peer review prior to approval⁸⁻¹⁰. Potential HCVs and HCS areas are mapped separately and combined to delimit areas for conservation of natural habitat. Although intact, high-biodiversity or other high conservation value habitat in tropical grassy and dry forest biomes should, in theory, be identified as HCVs, in practise, the HCV-HCSA guidance is not yet comprehensive for biomes other than tropical moist forest, as we outline below.

High Carbon Stock (HCS)

The High Carbon Stock Approach (HCSA) was designed to conserve all forest except the most highly degraded areas, in response to ongoing conversion of logged-over forests in Southeast Asia following the adoption of the HCV approach by the RSPO in 2013¹¹. The HCSA uses a decision-tree process to designate

forest habitat for protection, based on the vegetation structure of rainforest in Southeast Asia⁹. Although the approach was designed with the aim of being transferable to any habitat type or region, it has not been developed for other habitat types or regions to date⁹. Forest conservation status is determined by its approximate carbon stocks and likely biodiversity value, based on vegetation structure and degree of habitat fragmentation, using forest structure in Southeast Asia as a reference for determining degradation⁹. Vegetation structure is assessed with data from remote sensing and tree inventories collected in the field (see Methods in the Main Article for details on how we estimated areas that would be protected under the HCSA globally). Following the HCSA assessment, habitat available for conversion to agriculture has low aboveground carbon stocks and canopy cover, which risks conversion of valuable habitat within dry forest and grassy biome ecoregions, especially while their HCVs may not be identified consistently (see below).

High Conservation Values (HCVs)

The HCV approach was originally developed to reduce biodiversity loss in the forestry sector, but is now frequently applied to agriculture¹¹, and was first included in the RSPO Principles and Criteria in 2007¹². HCVs comprise six categories of environmental and social conservation value: species diversity, landscape-level ecosystems and mosaics, ecosystems and habitats, critical ecosystem services, community needs, and cultural values¹³. Individual countries can create national-level interpretations of HCVs, but many of these were developed in relation to forestry alone and therefore do not include different biome types (see below; Supplementary Table 1). HCV assessments are generally conducted by a desk-based study to investigate the local habitat and rare, threatened and endangered species that may be present, followed by on-site field data collection of flora (generally trees only; Supplementary Table 2) and fauna, and interviews with local stakeholders (e.g. local community members, as part of the Free, Prior and Informed Consent process, and experts in local conservation). The generic HCV guidance includes a section on identifying HCVs in grasslands (“Annex 2. Grasslands in HCVs” in ¹³), but this focuses on identifying HCVs within grassland, rather than identifying which grassy biomes are HCV habitats themselves, and does not recognise some fundamental aspects of grassy biome ecology.

Without rigorous assessments of local biodiversity and land-use history appropriate to the biome, it is possible that ancient or biodiverse grassy biomes may not be recognised as a valuable habitat under

current guidance. Ancient, intact grassy biomes (and degrees of degradation of these habitats), which support high biodiversity, can appear superficially similar to degraded pasture or areas of arrested succession in rainforest ecoregions, although these latter habitats generally support low biodiversity^{14,15}. The current guidance omits discussion of the importance of disturbances (e.g. flooding, fire, grazing) for the functioning of grassy biomes, and the consequent dynamism of these habitats through space and time. There is no discussion of how survey methodology would differ between tropical moist forest and grassy biomes in the HCV guidance (e.g. incorporating an understanding of disturbance regimes and using floral indicators of habitat intactness specific to individual grassy biomes)¹⁶. Thus, field surveys may omit to capture variability in species (e.g. plants that occur seasonally, or only fire disturbance) and habitat (grassy biomes are often a mosaic of woodland and open, grassy areas), and may fail to accurately assess the degradation status of grassy biomes, because this requires field surveys at multiple time points¹⁶. The focus of HCV vegetation survey methodology on trees, generally >10cm diameter at breast height (Supplementary Table 2), may prevent identification of remaining areas of both tropical dry forest and grassy biome as HCV habitat, because some dry forests are so highly fragmented and exploited that only highly degraded patches remain^{17,18}, and herbaceous plants are an essential component of grassy biome ecosystems¹⁶. We examined both national-level HCV interpretations and recent HCV-HCSA assessments in tropical grassy and dry forest biomes, and found that current guidance is not sufficient to ensure consistent rigour in assessments, and the rigour and potential for omission of HCVs varies substantially among assessments (Supplementary Table 1, Supplementary Table 2).

National-level HCV interpretations

We examined whether national-level interpretations of HCV guidance include grassy biomes and dry forests, and detailed guidance to identify HCVs in these biomes (Supplementary Table 1). All of the national interpretation documents we examined were produced prior to the requirement that RSPO-certified palm oil should follow a combined HCV-HCSA, and were generally conceived prior to many ZDCs. Thus, they do not attempt to provide guidance for High Carbon Stock vegetation stratification. None of the documents discuss identification of biodiverse, ancient grassy or dry forest biomes, nor provide survey methodology, risking that the values of these habitats may not be identified correctly, as we outlined in the previous section.

Supplementary Table 1. Summary of inclusion of grassy biomes and dry forests in national-level interpretations of HCV guidance (tropical countries only). The biomes present are listed as those analysed in this article: tropical moist forest, grassy biome and dry forest. All documents were obtained from the HCV Resource Network website (<https://hcvnetwork.org/libraries/>).

Country	Biomes present in country	Year of guidance document	Includes specific guidance for grassy biomes and/or dry forests?	Document name
Bolivia	Moist forest, grassy biome, dry forest	2004	Guidance addresses all biomes and ecoregions (e.g. remaining habitat areas, overview of endemic and threatened species, overview of local community uses), without specifying survey methodology for any particular habitat type.	Guía de identificación de atributos para definir Bosques de Alto Valor de Conservación en Bolivia
Ecuador	Moist forest, dry forest	2005	Dry and semi-deciduous forests are included alongside moist forests, without specifying survey methodology. Dry/semi-deciduous forests of the Tumbesian region are listed as an important area for bird endemism, and coastal lowland semi-deciduous forest is listed as an endangered habitat type.	Guía para la Identificación y Manejo de Bosques de Alto Valor de Conservación en Ecuador
Liberia	Moist forest, small area of grassy biome	2012	None: guidance addresses moist forests.	HCV National Interpretation for Liberia
Ghana	Moist forest, grassy biome	2006	Focus on forests, with consideration given to gallery forest within savannas rather than the entire grassy biome habitat. Coastal savannas are recommended for conservation but no guidance on identification and management of grassy biomes is provided.	A National Interpretation of the HCV Forest Toolkit for Ghana
Gabon	Moist forest, grassy biome	2008	None: guidance addresses moist forests. Forest–savanna edges are listed as important for conservation.	Une interprétation nationale des forêts à Haute Valeur pour la Conservation pour le Gabon
Democratic Republic of Congo	Moist forest, grassy biome	2012	No specific guidance for different biome types. Some grassy biomes are listed as priority habitats for conservation, alongside forest habitats.	Forêts de Haute Valeur pour la Conservation en RDC
Cameroon	Moist forest, grassy biome	2008	No specific guidance for different biome types, although savannas are listed in the habitat types considered, alongside forests.	Toolkit of HCV process for small and low-intensity managed forests in Cameroon: Case of community forests
Malaysia	Moist forest	2018	N/A	Malaysian National Interpretation for the Identification of High Conservation Values
Indonesia	Moist forest, grassy biome, dry forest	2018	None: guidance addresses moist forests.	Panduan Identifikasi Kawasan Bernilai Konservasi Tinggi di Indonesia

Recent HCV-HCSA assessments conducted in grassy biomes and dry forests

We also examined recent HCV-HCSA assessments that have been conducted in areas of grassy biome and dry forest (Supplementary Table 2). We found that most assessments did not discuss the implications of the local biome and/or ecoregion for biodiversity surveys and levels of carbon stocks expected, leading to inconsistency in the extent of grassy biomes and dry forests that were designated for conservation. We found that grassy habitat is consistently prioritised for conversion to oil palm, in comparison to habitat with greater tree coverage, and that forest (including highly degraded areas) is consistently prioritised for conservation. Similarly, woody savanna areas are prioritised over those with fewer trees, without acknowledging that these habitat types could form part of an overall habitat mosaic in grassy biomes. Some assessments (e.g. (a, b, c) in Supplementary Table 2) explicitly stated that the concession area had been selected by the company because it contained extensive area of grassland or savanna, and would therefore avoid deforestation. None of the assessments conducted a comprehensive survey of flora within grassy biomes; and both the detail of surveys and extent of protection was inconsistent among reports. While the lack of information on savanna flora was acknowledged for Mouila Lot 3 Extension in Gabon ((b) in Supplementary Table 2), and the assessors adopted a precautionary approach by conserving 50% of savanna habitat within the concession, such decisions currently depend on the knowledge of individual assessors, and are not covered by the existing guidance for identifying HCVs (see above). Although the assessments examined in Supplementary Table 2 did not necessarily lead to poor decisions of land-use change, the information available in the summary reports assessed is not consistently sufficient to ascertain that the converted grassy areas were of low biodiversity value.

All reports that included an estimation of greenhouse gas emissions from conversion ((a, b, c, d, e, g) in Supplementary Table 2) found that the proposed planting of oil palm would result in net carbon sequestration, owing to the low estimated carbon stocks of grassy areas. However, none of the assessments included soil carbon stocks in their calculations, but estimations of these could be included alongside local soil type mapping (which is included in each assessment).

The assessments did not consistently address potential social impacts that are more likely to occur in grassy biomes and dry forest regions than moist forest (e.g. impacts on grazing, hunting, fire regimes and water

supply). Two of the assessments (g and h) discussed potential threats to the local water supply from the oil palm plantation (e.g. overuse, pollution), but this was not raised in the other reports. The assessments conducted in Africa ((a, b and i) refer to bushmeat hunting by local people but do not address the potential for loss of savanna/grassy habitat to reduce the locally available protein. Similarly, these assessments refer to fire regimes through burning conducted by local people, but fire management plans are not included in the reports.

Supplementary Table 2. Summary of recent HCV-HCSA (or standalone HCV) assessments conducted in potential grassy biome and dry forest areas. We obtained the information from public summary reports of HCV-HCSA assessments following the RSPO New Planting Procedure, through the RSPO website and the HCV Resource Network website (see URLs at end of table). We did not examine reports released prior to 2013, when the RSPO first included HCV assessments as part of its certification criteria for new plantings. We did not attempt to examine documentation for all potentially relevant assessments, but to provide an overview of recent assessments.

	Name and location	Year	Biomes encompassed	Habitat types and existing land-use of proposed planting area	Assessment of potential intact/high-value grassy biomes and/or dry forests (e.g. historic land-use analyses, floristic and habitat surveys etc.)	Carbon stock assessment of grassy areas	Proportion of proposed planting area on grassy habitat
a	Mouila Lot 3, Olam Palm Gabon	2015	Moist forest and grassy biome (Congolian coastal forests and Western Congolian forest savanna), according to ¹⁹ and report	Savanna grassland (~75%), forest patches (~25%), some small-scale agriculture and a cattle ranch	Both forest and savanna vegetation surveyed (in forest, trees ≥10 cm dbh (diameter at breast height); in savanna, all vegetation in 5x5m plots). Surveys of fauna focused on forest. Forest assessed for potential areas of primary habitat, but no equivalent conducted for savanna. Connectivity of savanna habitat not considered. There is written recognition that (i) savannas could contain rare/threatened herbaceous species that are overlooked, because they are only visible seasonally or difficult to identify; and (ii) that as savanna habitats in the region are increasingly targeted for development, they will become rare.	Savanna assigned aboveground carbon stocks value of 5t/ha (estimated as 7.1t/ha including belowground carbon, based on conversion ratio of 0.42)	100%
b	Mouila Lot 3 Extension, Olam Palm Gabon	2017	Moist forest and grassy biome (Congolian coastal forests and Western Congolian forest savanna), according to ¹⁹ and report	Savanna (78%; mostly grassland with some wet and woody savanna habitats) and gallery forest (22%)	Vegetation data from Mouila Lot 3 surveys used (see (a)), alongside a desk-based botanical risk assessment. Seven plant species of conservation concern deemed very likely to occur in the savanna habitat, and a nationally protected savanna antelope was sighted in the concession area. Local conservation groups raised the issue of extensive loss and fragmentation of the savanna habitat (the largest undeveloped section of the northern Ngounié savanna, one of two areas of savanna in Gabon). As a precautionary approach owing to data deficiency, 50% of the savanna habitat in the concession was designated as HCV, in a layout to maximise connectivity within and among habitat types.	Savanna assigned carbon stock of <10t/ha	100% (but 50% of all savanna in concession designated as HCV)

c	Guadalcanal Plain, New Britain Palm Oil, Solomon Islands	2018	Moist forest according to ¹⁹ , but grassy biome vegetation type appears to be historic ²⁰	Mostly grassland (the area was specifically chosen in order to plant on this habitat), with some forest and scrub and existing coconut plantation	Vegetation and HCV assessments focussed on the quality of remaining forest areas, with no biodiversity surveys in grassland. Grassland not identified as being regionally unique, in contrast to information in ²⁰ ; it was identified as being potentially historic (also grassy in 1976) but not therefore considered to be potentially valuable habitat.	Trees ≥5cm dbh measured for carbon stock estimation, none in grassland; grassland assumed to have value of 5t/ha.	68% Also some planting on scrub, coconut plantation, other cultivated land, and 'low density forest'.
d,e	Goodhope Asia Holdings Ltd, Plantations Nabire Baru and Sariwana Adi Perkasa, Papua Province, Indonesia	2020	Moist forest according to ¹⁹ , but ecosystems mapped within report included 'lowland grassland on plains', as well as lowland forest types and swamp forest	Largely secondary forest and existing oil palm, with small areas of scrub, open areas and shifting cultivation	No surveys of grassland flora or fauna. 'Lowland grassland on plains' designated as rare ecosystem and HCV, because it was deemed rare locally and had always been grassy according to locals.	'Open land', without trees ≥5cm dbh, assumed to have carbon stocks of 0 t/ha.	None. Planting was largely on 'scrub'.
f	Kalyan AgroVet Investments Ltd, Region des Plateaux, Togo	2015	Grassy biome, according to ¹⁹ and report	Largely abandoned plantations, with some small-scale agriculture, fallow and savanna (mainly grassy with some woodland and secondary forest)	Botanical surveys in all habitat types recorded trees ≥10cm dbh only. Savanna is described as degraded, unless highly wooded, but the evidence for this is unclear.	N/A (GHG assessment report not available).	Not quantified. Majority of planting in previous plantation areas.
g	Agroaceite, S.A., Quetzaltenango, Guatemala	2017	Coastal Pacific savanna biome, according to report; Central American dry forests, according to ¹⁹	Mostly pasture, plantations (rubber, banana) and cropland; small patches of secondary and gallery forest	No details of floristic surveys given. Remaining forest patches were deemed highly degraded and fragmented; there is no discussion of their potential regional significance in spite of this, given extensive habitat loss in this ecoregion ¹⁹ .	Trees ≥5cm dbh included in biomass surveys; grassy areas (no trees) assigned carbon stock of 5t/ha	Majority (pasture) but not quantified.

h	Agroindustrias de Mapastepec, Palmicultores San Nicolás, Campeche and Tabasco states, Mexico	2017	Dry forest according to report; moist forest (Petén-Veracruz and Pantanos de Centla) according to ¹⁹	Existing agriculture, grassy areas with and without shrubs, including pasture, and secondary forests	Floristic surveys included all vegetation strata (herbaceous plants, shrubs and trees) but were heavily focused on forest, also prioritising grassy areas with shrubs over those without (which are likely to support more biodiversity in this ecoregion). Grassy areas categorised with lowest possible environmental impact of conversion, alongside existing agricultural areas.	Grassy areas assigned carbon stock of 5t/ha	100%
i	Oil palm Buvuma Ltd, Central Region of Uganda	2019	Moist forest according to report; grassy biome (Victoria Basin forest-savanna) according to ¹⁹	Largely grassy areas, existing agricultural land, and scrub and shrubland, with some swamp and forest	Botanical surveys included trees ≥5cm dbh only; many survey plots in grassy areas had no botanical records. A stakeholder raised concern that loss of grassland would reduce grazing habitat for hippos, but this was not addressed as they had not been confirmed present in the area during faunal surveys.	Carbon stocks estimated based on ≥5cm dbh only; 'open land' (including grassland) estimated to have carbon stocks of 3.4 t/ha.	Not quantified. Majority of planting in existing agricultural land, open land (grassland) and scrub and shrubland.

URLs of source documents:

a.

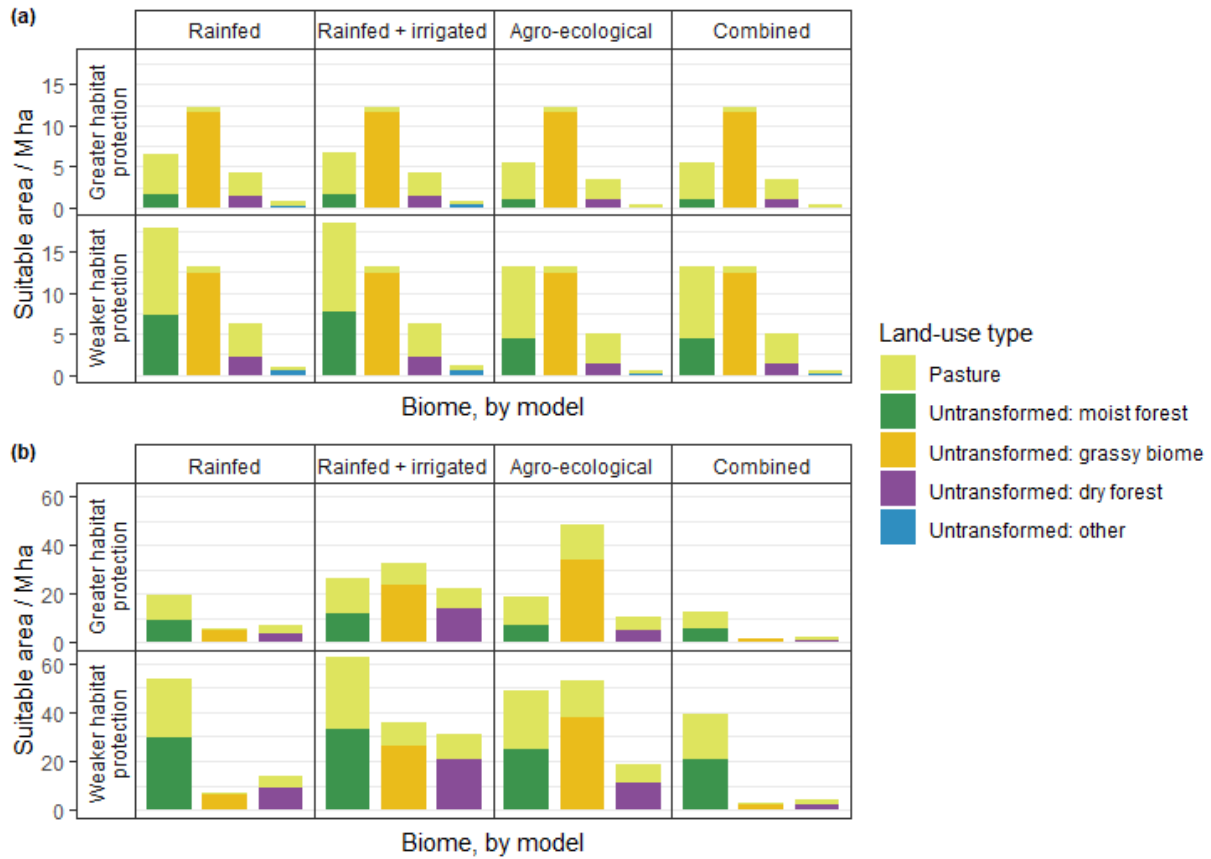
- i. <https://www.rspo.org/certification/new-planting-procedure/public-consultations/olam-international-limited-olam-palm-gabon-mouila-lot-3>
- ii. <https://www.rspo.org/acop/2015/olam-international-limited/RSPO%20GHG%20Emissions%20Mouila%203%20Gabon.pdf>
- b. <https://www.rspo.org/certification/new-planting-procedure/public-consultations/olam-international-limited-olam-palm-gabon-mouila-lot-3-extension>
- c. <https://www.rspo.org/certification/new-planting-procedure/public-consultations/new-britain-palm-oil-a-subsidiary-of-sime-darby-plantation-bhd-guadalcanal-plain-palm-oil-ltd>
- d. <https://www.rspo.org/certification/new-planting-procedure/public-consultations/goodhope-asia-holdings-ltd-pt-nabire-baru-pt-nb>
- e. <https://www.rspo.org/certification/new-planting-procedure/public-consultations/goodhope-asia-holdings-ltd-pt-sariwana-adi-perkasa-pt-sap>
- f. <https://www.rspo.org/certification/new-planting-procedure/public-consultations/kalyan-agrovet-investments-limited>
- g. <https://www.rspo.org/certification/new-planting-procedure/public-consultations/agroaceite-sa>
- h. <https://www.rspo.org/certification/new-planting-procedure/public-consultations/agroindustrias-de-mapastepec-sa-de-cv-palmicultores-san-nicolas>
- i. <https://hcvnetwork.org/reports/hcv-hcs-oil-palm-buvuma-limiteds-proposed-oil-palm-project-central-region-of-uganda/>

Supplementary Information 2: sensitivity analyses including intensively-managed pasture as a land-use type

In order to conduct sensitivity analyses of our main findings to the inclusion of intensively-managed (improved) pasture as a land-use type, we re-ran our main analyses for Colombia and tropical Brazil (i.e. North of -23.5°), incorporating intensively-managed pasture from IDEAM 2018 landcover for Colombia²¹, and MapBiomas 2020 landcover for Brazil^{22,23}. Both of these datasets were developed using multiple sources, including manual classification of satellite images, incorporation of local land-use statistics and biome type, and attempt to specifically distinguish natural grassy biomes from intensively-managed pasture. Brazil and Colombia have some of the highest cattle stocks globally²⁴, so we expect most other countries that we estimate as suitable for oil palm to have smaller areas of intensively-managed pasture. We discuss the limitations of this sensitivity analysis in Supplementary Information 6.

For rainfed oil palm expansion modelled using Maxent, thresholded at Minimal Predicted Area₉₉ (MPA₉₉), assuming greater habitat protection under the HCSA (i.e. the suitability model presented throughout the Main Article Results; see Supplementary Information 7), exclusion of pasture areas leads to 14.8 Mha estimated as suitable for rainfed oil palm expansion under zero-deforestation commitments in Colombia, and 17.9 Mha in Brazil in total (compared to previous estimates of 23.9 Mha and 32.0 Mha respectively: reductions of ~40%). We found that pasture occupied a greater proportion of the locations that we predicted as suitable for oil palm expansion in compliance with zero-deforestation commitments in forested biomes (moist forest and dry forest) than grassy biomes, for both Brazil and Colombia, for all suitability models examined (Supplementary Figure 1). 76% of the suitable moist forest in Colombia is pasture, leaving 1.6 Mha as potentially available for expansion, compared to only 6% of the suitable grassy biome, leaving 11.6 Mha potentially available for expansion. This is similar for Brazil: 53% of the moist forest suitable for expansion is pasture, leaving 9.1 Mha potentially available for expansion, in comparison to only 5% of grassy biome, leaving 5 Mha potentially available for expansion (Supplementary Figure 1). Thus, if we assume that intensively-managed pasture is unavailable for oil palm expansion, 87% of the potentially available areas in Colombia and 49% in Brazil would be within tropical grassy and dry forest biomes (compared to previous estimates of 69% and 39% respectively, without accounting for pasture).

Substantial percentages of suitable areas for zero-deforestation expansion within some ecoregions are pasture (e.g. nearly 80% of suitable areas for rainfed expansion in Magdalena-Urabá moist forests and Sinú Valley dry forests in Colombia; over 70% of suitable areas in Xingu-Tocantins-Araguaia moist forests and Mato Grosso tropical dry forests in Brazil; Supplementary Table 3). Nevertheless, if we assume that pasture is unavailable for expansion, and outside the area of remaining natural habitat (like cropland and existing tree plantations), our previous estimates of the percentage of non-cultivated land within individual ecoregions that is suitable for zero-deforestation oil palm expansion are generally similar to those accounting for pasture (Supplementary Figure 2). Similarly, incorporating pasture in our estimates of potential vertebrate richness loss upon conversion to oil palm reduces the expected richness loss from conversion, but assuming that pasture is unavailable for expansion results in minimal change to our previous estimates (Supplementary Figure 3).



Supplementary Figure 1. Total areas potentially available for zero-deforestation oil palm expansion in (a) Colombia, and (b) Brazil, including areas of improved/intensively managed pasture. Only areas outside locations protected under ZDCs are shown (i.e. equivalent to coloured areas in Fig. 1 of the Main Article, in which the ‘Rainfed’ model with ‘Greater habitat protection’ was presented). The models are (left to right): rainfed oil palm expansion, as developed in this article, with threshold MPA₉₉ for determining suitability; both irrigated (assuming up to 100% of surplus available water could be applied as irrigation) and rainfed expansion; an existing agro-ecological model of rainfed suitability²⁵, and a combined model of areas of overlap between the rainfed MPA₉₉ model and the agro-ecological model. Note that suitable areas of grassy biome in (a) are identical for all models because the entire Colombian Llanos was consistently modelled as climatically-suitable for oil palm. For weaker habitat protection, locations with aboveground carbon stocks of $\geq 75 \text{ Mg ha}^{-1}$ and $\geq 50\%$ canopy closure, and/or peat soil are protected; for greater habitat protection (where in practice, protection of low-carbon areas can depend on additional conservation values), locations with aboveground carbon stocks of $\geq 35 \text{ Mg ha}^{-1}$ and $\geq 30\%$ canopy closure, and/or peat soil are protected. Locations of cropland, urban areas and tree plantations are excluded, as are all IUCN class I/II protected areas.

Supplementary Table 3. Sensitivity of total areas suitable for zero-deforestation oil palm expansion to the incorporation of intensively-managed pasture in the analysis, per ecoregion, for (a, b) Colombia and (c, d) Brazil.

Suitability is for species distribution models thresholded at MPA₉₉: for rainfed cultivation (a, c) and both irrigated and rainfed cultivation (b, d). Only ecoregions with non-zero suitability are included. The ‘% of total untransformed habitat’ in the final column is the percentage of total remaining untransformed habitat (areas outside cropland, urban areas, tree plantations, and intensively-managed pasture) of the ecoregion that is suitable for expansion, assuming that pasture is not available, as opposed to the equivalent value without accounting for pasture (first numeric column, and in Table 1 of the Main Article, where areas of pasture are included within ‘non-cultivated land’). See Supplementary Figure 2 for scatterplots comparing these values. Note that areas assessed within each ecoregion are those within the relevant country alone, whereas those presented in Table 1 of the Main Article are for all locations within the tropics. Zero-deforestation commitments are assumed to protect all locations that fall under the ‘greater habitat protection’ threshold (see Supplementary Figure 6 for maps).

(a) Colombia; rainfed cultivation				
Ecoregion	Biome	Suitable area for expansion under ZDCs: 1000 km² (% of total non-cultivated land; pasture not accounted for in analysis)	% of suitable area that is pasture	Suitable area for expansion under ZDCs, excluding pasture: 1000 km² (% of total untransformed habitat)
Llanos	Grassy biome	123.1 (86.8%)	6.0%	115.8 (86.8%)
Magdalena-Urabá moist forests	Moist forest	45.5 (64.2%)	78.3%	9.9 (39.6%)
Sinú Valley dry forests	Dry forest	16.5 (75.1%)	79.6%	3.4 (42.1%)
Magdalena Valley dry forests	Dry forest	12.0 (64.1%)	51.8%	5.8 (61.3%)
Apure-Villavicencio dry forests	Dry forest	11.2 (53.0%)	75.0%	2.8 (50.7%)
Guajira-Barranquilla xeric scrub	Other	8.1 (35.3%)	65.7%	2.8 (16.2%)
Napo moist forests	Moist forest	5.2 (13.0%)	100.0%	0.0 (0.0%)
Magdalena Valley montane forests	Moist forest	4.7 (4.7%)	56.4%	2.0 (3.2%)
Cordillera Oriental montane forests	Moist forest	2.5 (4.3%)	96.6%	0.1 (0.2%)
Cauca Valley montane forests	Moist forest	2.2 (6.9%)	69.2%	0.7 (3.1%)
Patía valley dry forests	Dry forest	1.8 (67.7%)	28.6%	1.3 (71.4%)
Caquetá moist forests	Moist forest	1.8 (1.1%)	42.9%	1.0 (0.7%)
Northwest Andean montane forests	Moist forest	1.5 (3.2%)	33.3%	1.0 (2.4%)
Negro-Branco moist forests	Moist forest	1.2 (1.2%)	35.7%	0.8 (0.8%)
Cauca Valley dry forests	Dry forest	0.9 (25.0%)	80.0%	0.2 (18.2%)
Chocó-Darién moist forests	Moist forest	0.7 (1.2%)	100.0%	0.0 (0.0%)
Catatumbo moist forests	Moist forest	0.6 (10.6%)	14.3%	0.5 (10.9%)

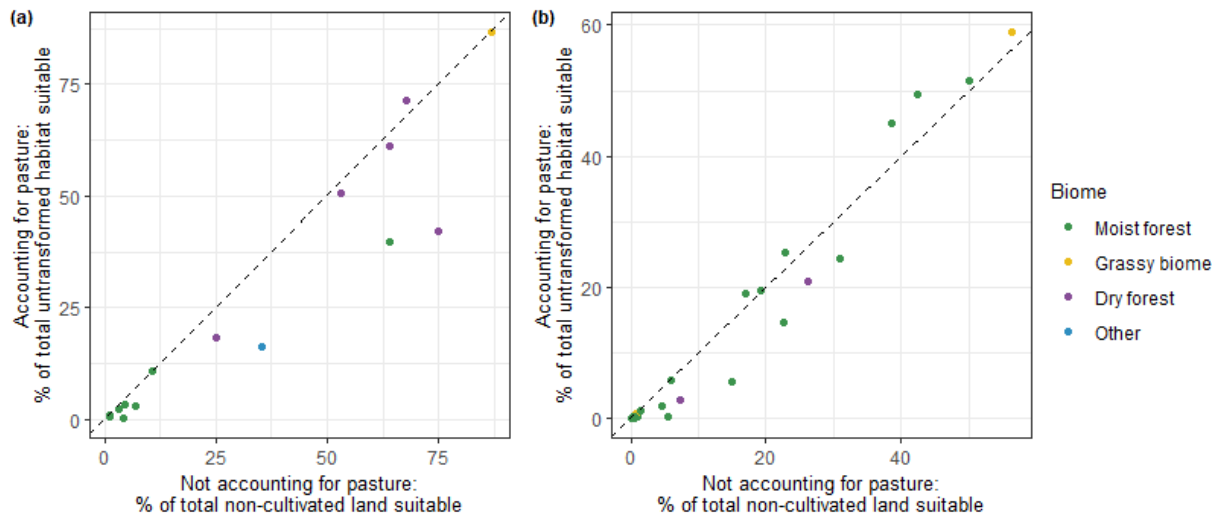
(b) Colombia; rainfed and irrigated cultivation				
Ecoregion	Biome	Suitable area for expansion under ZDCs: 1000 km2 (% of total non-cultivated land; pasture not accounted for in analysis)	% of suitable area that is pasture	Suitable area for expansion under ZDCs, excluding pasture: 1000 km2 (% of total untransformed habitat)
Llanos	Grassy biome	123.1 (86.8%)	6.0%	115.8 (86.8%)
Magdalena-Urabá moist forests	Moist forest	45.5 (64.2%)	78.3%	9.9 (39.6%)
Sinú Valley dry forests	Dry forest	16.5 (75.1%)	79.6%	3.4 (42.1%)
Magdalena Valley dry forests	Dry forest	12.0 (64.1%)	51.8%	5.8 (61.3%)
Apure-Villavicencio dry forests	Dry forest	11.2 (53.0%)	75.0%	2.8 (50.7%)
Guajira-Barranquilla xeric scrub	Other	8.3 (36.4%)	63.7%	3.0 (17.7%)
Napo moist forests	Moist forest	5.2 (13.0%)	100.0%	0.0 (0.0%)
Magdalena Valley montane forests	Moist forest	5.2 (5.2%)	52.5%	2.5 (3.9%)
Cordillera Oriental montane forests	Moist forest	2.6 (4.6%)	90.4%	0.3 (0.6%)
Cauca Valley montane forests	Moist forest	2.2 (6.9%)	69.2%	0.7 (3.1%)
Patía valley dry forests	Dry forest	1.8 (67.7%)	28.6%	1.3 (71.4%)
Caquetá moist forests	Moist forest	1.8 (1.1%)	42.9%	1.0 (0.7%)
Northwest Andean montane forests	Moist forest	1.7 (3.6%)	30.0%	1.2 (2.8%)
Negro-Branco moist forests	Moist forest	1.2 (1.2%)	35.7%	0.8 (0.8%)
Cauca Valley dry forests	Dry forest	0.9 (25.0%)	80.0%	0.2 (18.2%)
Chocó-Darién moist forests	Moist forest	0.7 (1.2%)	100.0%	0.0 (0.0%)
Catatumbo moist forests	Moist forest	0.6 (10.6%)	14.3%	0.5 (10.9%)

(c) Brazil; rainfed cultivation				
Ecoregion	Biome	Suitable area for expansion under ZDCs: 1000 km2 (% of total non-cultivated land; pasture not accounted for in analysis)	% of suitable area that is pasture	Suitable area for expansion under ZDCs, excluding pasture: 1000 km2 (% of total untransformed habitat)
Guianan savanna	Grassy biome	44.9 (56.5%)	1.7%	44.1 (59.1%)
Tocantins/Pindaré moist forests	Moist forest	41.3 (22.5%)	60.3%	16.4 (14.6%)
Xingu-Tocantins-	Moist	40.9	74.9%	10.3

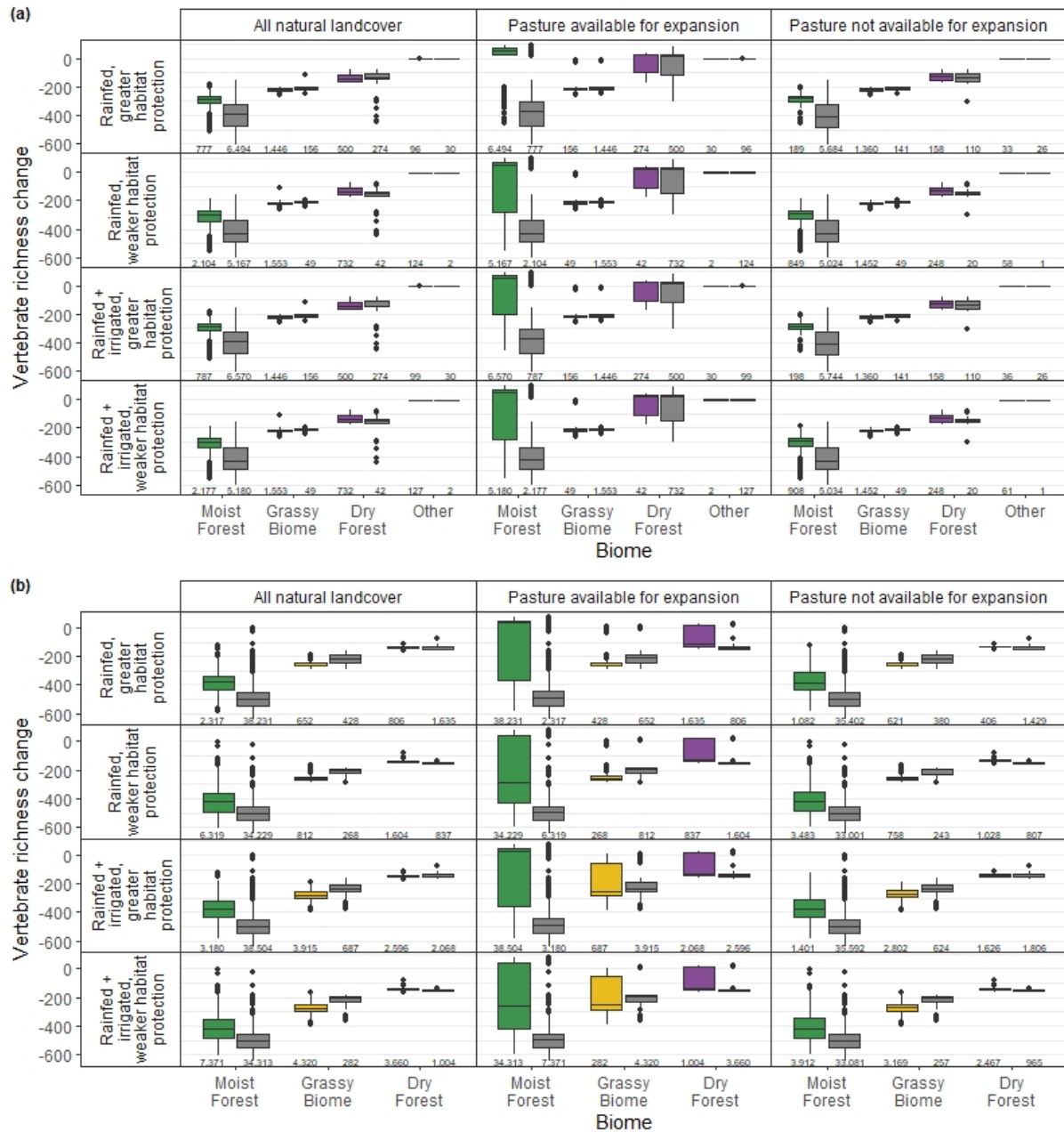
Araguaia moist forests	forest	(14.9%)		(5.5%)
Maranhão Babaçu forests	Dry forest	36.2 (26.3%)	36.9%	22.9 (20.9%)
Bahia coastal forests	Moist forest	30.4 (30.9%)	55.8%	13.4 (24.3%)
Madeira-Tapajós moist forests	Moist forest	30.1 (4.6%)	67.8%	9.7 (1.9%)
Mato Grosso tropical dry forests	Dry forest	27.6 (7.3%)	71.5%	7.9 (2.8%)
Marajó várzea	Moist forest	15.3 (19.2%)	0.6%	15.2 (19.5%)
Cerrado	Grassy biome	10.6 (0.7%)	17.5%	8.8 (0.8%)
Pernambuco coastal forests	Moist forest	6.4 (38.6%)	11.8%	5.7 (44.9%)
Caatinga	Dry forest	4.7 (0.7%)	18.0%	3.8 (0.7%)
Northeast Brazil restingas	Moist forest	4.4 (50.0%)	2.0%	4.3 (51.5%)
Pernambuco interior forests	Moist forest	3.5 (17.0%)	38.0%	2.2 (19.2%)
Bahia interior forests	Moist forest	3.4 (1.5%)	56.1%	1.5 (1.2%)
Uatumã-Trombetas moist forests	Moist forest	3.2 (0.7%)	5.3%	3.1 (0.7%)
Monte Alegre várzea	Moist forest	3.2 (5.9%)	7.8%	3.0 (5.8%)
Tapajós-Xingu moist forests	Moist forest	3.0 (0.9%)	60.0%	1.2 (0.4%)
Purus-Madeira moist forests	Moist forest	1.8 (1.0%)	71.3%	0.5 (0.3%)
Southwest Amazon moist forests	Moist forest	1.8 (0.6%)	81.0%	0.3 (0.1%)
Gurupa várzea	Moist forest	1.6 (22.9%)	0.0%	1.6 (25.3%)
Iquitos várzea	Moist forest	1.5 (5.6%)	94.4%	0.1 (0.4%)
Atlantic Coast restingas	Moist forest	1.2 (42.4%)	13.7%	1.0 (49.4%)
Japurá-Solimões-Negro moist forests	Moist forest	0.5 (0.2%)	0.0%	0.5 (0.2%)
Purus várzea	Moist forest	0.5 (0.4%)	16.5%	0.4 (0.3%)
Guianan piedmont moist forests	Moist forest	0.4 (0.5%)	0.0%	0.4 (0.5%)
Rio Negro campinarana	Moist forest	0.3 (0.5%)	0.0%	0.3 (0.5%)
Guianan lowland moist forests	Moist forest	0.3 (0.4%)	33.3%	0.2 (0.2%)
Serra do Mar coastal forests	Moist forest	0.2 (0.6%)	66.7%	0.1 (0.3%)
Juruá-Purus moist forests	Moist forest	0.1 (0.0%)	0.0%	0.1 (0.0%)
Alto Paraná Atlantic forests	Moist forest	0.1 (0.1%)	100.0%	0.0 (0.0%)

(d) Brazil; rainfed and irrigated cultivation				
Ecoregion	Biome	Suitable area for expansion under ZDCs: 1000 km2 (% of total non-cultivated land; pasture not accounted for in analysis)	% of suitable area that is pasture	Suitable area for expansion under ZDCs, excluding pasture: 1000 km2 (% of total untransformed habitat)
Guianan savanna	Grassy biome	44.9 (56.5%)	1.7%	44.1 (59.1%)
Tocantins/Pindaré moist forests	Moist forest	43.4 (23.7%)	60.7%	17.1 (15.2%)
Xingu-Tocantins-Araguaia moist forests	Moist forest	49.9 (18.2%)	73.0%	13.5 (7.3%)
Maranhão Babaçu forests	Dry forest	42.4 (30.7%)	34.4%	27.8 (25.4%)
Bahia coastal forests	Moist forest	38.6 (39.3%)	54.4%	17.6 (31.9%)
Madeira-Tapajós moist forests	Moist forest	48.9 (7.5%)	70.6%	14.4 (2.8%)
Mato Grosso tropical dry forests	Dry forest	76.2 (20.2%)	52.1%	36.5 (12.8%)
Marajó várzea	Moist forest	15.3 (19.2%)	0.6%	15.2 (19.5%)
Cerrado	Grassy biome	243.1 (16.1%)	33.9%	160.7 (14.9%)
Pernambuco coastal forests	Moist forest	10.3 (61.9%)	24.6%	7.8 (61.7%)
Caatinga	Dry forest	82.3 (11.6%)	28.2%	59.0 (10.8%)
Northeast Brazil restingas	Moist forest	4.7 (53.9%)	1.8%	4.6 (55.7%)
Pernambuco interior forests	Moist forest	6.8 (32.7%)	51.8%	3.3 (28.8%)
Bahia interior forests	Moist forest	16.9 (7.6%)	63.8%	6.1 (5.1%)
Uatumã-Trombetas moist forests	Moist forest	3.2 (0.7%)	5.3%	3.1 (0.7%)
Monte Alegre várzea	Moist forest	3.2 (5.9%)	7.8%	3.0 (5.8%)
Tapajós-Xingu moist forests	Moist forest	3.6 (1.1%)	61.9%	1.4 (0.5%)
Purus-Madeira moist forests	Moist forest	1.8 (1.0%)	71.3%	0.5 (0.3%)
Southwest Amazon moist forests	Moist forest	1.8 (0.6%)	81.0%	0.3 (0.1%)
Gurupa várzea	Moist forest	1.6 (22.9%)	0.0%	1.6 (25.3%)
Iquitos várzea	Moist forest	1.5 (5.6%)	94.4%	0.1 (0.4%)
Atlantic Coast restingas	Moist forest	1.2 (42.4%)	13.7%	1.0 (49.4%)
Japurá-Solimões-Negro moist forests	Moist forest	0.5 (0.2%)	0.0%	0.5 (0.2%)
Purus várzea	Moist forest	0.5 (0.4%)	16.5%	0.4 (0.3%)
Guianan piedmont moist forests	Moist forest	0.4 (0.5%)	0.0%	0.4 (0.5%)

Rio Negro campinarana	Moist forest	0.3 (0.5%)	0.0%	0.3 (0.5%)
Guianan lowland moist forests	Moist forest	0.3 (0.4%)	33.3%	0.2 (0.2%)
Serra do Mar coastal forests	Moist forest	1.7 (4.5%)	36.4%	1.1 (4.3%)
Juruá-Purus moist forests	Moist forest	0.1 (0.0%)	0.0%	0.1 (0.0%)
Alto Paraná Atlantic forests	Moist forest	9.7 (8.1%)	61.9%	3.7 (5.6%)
Pantanal	Grassy biome	31.7 (23.4%)	15.6%	26.7 (23.0%)
Brazilian Atlantic dry forests	Dry forest	18.4 (16.0%)	23.9%	14.0 (15.7%)
Chiquitano dry forests	Grassy biome	4.6 (7.4%)	62.6%	1.7 (5.0%)
Humid Chaco	Grassy biome	0.6 (53.4%)	50.0%	0.3 (50.0%)
Caatinga Enclaves moist forests	Moist forest	0.4 (10.0%)	0.0%	0.4 (10.0%)



Supplementary Figure 2. Scatterplots of the total remaining non-cultivated land suitable for rainfed zero-deforestation oil palm expansion per ecoregion, compared with the same value estimated when accounting for pasture, for (a) Colombia and (b) Brazil. ‘% of total untransformed habitat’ is the percentage of total remaining untransformed habitat (areas outside cropland, urban areas, tree plantations, and intensively-managed pasture) of the ecoregion that is suitable for expansion, assuming that pasture is not available, whereas the ‘% of total non-cultivated land suitable’ is the percentage of total remaining habitat outside cropland, urban areas and tree plantations that is suitable for expansion (not accounting for pasture as a land-use type: this is equivalent to the estimates presented in the Main Article). Note that areas assessed within each ecoregion are those within the relevant country alone. All suitability is for rainfed cultivation according to the model thresholded at MPA₉₉; zero-deforestation commitments are assumed to protect all locations that fall under the ‘greater habitat protection’ threshold. Dashed lines represent $y = x$.



Supplementary Figure 3. Sensitivity test to the inclusion of intensively-managed pasture in estimated vertebrate species richness loss from oil palm expansion in (a) Colombia, and (b) Brazil. Richness change is estimated as the difference between existing richness and plantation richness; negative values denote number of species lost. Datapoints are ~10-km grid-cells that we estimated as climatically-suitable for expansion (rainfed suitability thresholded at MPA₉₉ and both rainfed and irrigated suitability, assuming up to 100% of surplus available water could be applied for irrigation: see horizontal panels), and sample sizes are provided beneath each boxplot. Existing cropland, urban areas, tree plantations and IUCN class I/II protected areas are excluded as unavailable. Left-hand panel: assuming all areas climatically-suitable for oil palm have natural landcover (as for analyses presented in Main Article Fig. 4); central panel: incorporating pasture into estimates of existing richness by assuming that only species that can persist in pasture are present in grid-cells classified as pasture, yet assuming that areas of pasture could be available for expansion; right-hand panel: assuming that areas of intensively-managed pasture are unavailable for expansion (i.e. excluding all areas of pasture from the boxplots). As for Main Article Fig. 4, coloured boxplots denote locations potentially available for zero-deforestation expansion, and grey boxplots denote locations protected under the HCS approach (two levels of protection: see horizontal panels). Boxplot centre lines show the median, lower and upper hinges show the first and third quartiles respectively, whiskers extend to the maximum and minimum values within 1.5*inter-quartile range, and outliers are plotted individually.

Supplementary Information 3: sensitivity analyses of suitability for rainfed oil

palm cultivation

Comparison of thresholds for oil palm suitability and habitat protection under ZDCs

Threshold determining suitable area for oil palm

We found that our species distribution model estimates of total suitable area for rainfed oil palm cultivation, and hence total suitable area potentially available for expansion under ZDCs, are highly sensitive to the model threshold (MPA₉₅, MPA₉₉, MPA₁₀₀) for determining suitability (Supplementary Table 4; Supplementary Figure 4; Supplementary Figure 5; Supplementary Figure 6). For each thresholded model, we also found that applying the threshold for ‘weaker’ (i.e. less) habitat protection under zero-deforestation (following the High Carbon Stock Approach, where all non-cultivated habitat of $\geq 75 \text{ Mg ha}^{-1}$ and $\geq 50\%$ canopy closure is protected) increases our estimates of total suitable area for oil palm potentially available for expansion under zero-deforestation commitments, in comparison to applying the threshold for ‘greater’ protection (where all non-cultivated habitat of $\geq 35 \text{ Mg ha}^{-1}$ and $\geq 30\%$ canopy closure is protected, as presented in the Main Article) (Supplementary Table 4). Nevertheless, the relative area of habitat potentially suitable for zero-deforestation oil palm expansion remains similar between biomes and biogeographic realms under the different thresholds of suitability for oil palm and habitat protection (Supplementary Figure 4; Supplementary Figure 5; Supplementary Figure 6). The majority of the variation in total suitable area is within areas of low expected productivity, which comprise 87.4% - 97.4% of the total suitable area (non-cultivated habitat outside existing protected areas) in all models (Supplementary Figure 7).

Thresholds determining habitat protection under ZDCs

We found that the absolute difference in the area of moist forest potentially suitable for zero-deforestation oil palm expansion (i.e. not protected by zero-deforestation commitments) between habitat protection thresholds (greater and weaker protection) is greater than that for other biomes, when comparing protection thresholds within a given threshold of model suitability (Supplementary Figure 4; Supplementary Figure 5; Supplementary Figure 6). Thus, the area of degraded tropical moist forest available for zero-deforestation oil palm expansion appears highly sensitive to the choice of threshold for protection under

zero-deforestation, which in turn depends on local identification of additional conservation values (High Conservation Values and/or community lands, identified during HCV assessments and community consultations), because areas designated following our scenario of 'greater habitat protection' under the High Carbon Stock Approach are protected depending on identification of additional conservation values in practice.

Comparison of species distribution models with an existing agro-ecological model

Suitable area

To test the sensitivity of our results to reliance on a single species distribution model of oil palm suitability, we also conducted analyses using an existing agro-ecological model of oil palm suitability²⁵; and for the areas of overlap between this agro-ecological model and our final species distribution model (as selected in Supplementary Information 7, thresholded for suitability at MPA₉₉), representing a conservative, 'high-confidence' suitability model (see Extended Data Fig. 2). We found that the total suitable area for oil palm estimated by our final model and the agro-ecological model are similar (1,368 Mha and 1,380 Mha respectively), but for the agro-ecological model, estimates of areas potentially available for zero-deforestation oil palm expansion are slightly greater (i.e. more of the total suitable area falls outside locations protected under ZDCs than for our model; Supplementary Table 4). This difference arises largely from differences in the estimated area of tropical grassy biome potentially available for zero-deforestation expansion: estimates of the agro-ecological model (145-210 Mha, depending on the HCS threshold for habitat protection) are roughly double estimates of our final model (78-111 Mha), with large differences for both Africa and Latin America (Supplementary Figure 5; Supplementary Figure 6). The estimated suitable area for expansion in other biomes is similar for the agro-ecological model and our final model (Supplementary Figure 5; Supplementary Figure 6). As expected, the total suitable area for oil palm across the tropics is lower for the combined model of suitable areas based on overlap of these two models (1,158 Mha), as are the suitable areas which are potentially available under zero-deforestation commitments (110 – 254 Mha; Supplementary Table 4). Nevertheless, the relative areas of suitability among realms and biomes are similar to those estimated by our final species distribution model, thresholded at MPA₉₉ (Supplementary Figure 5).

Expected yield

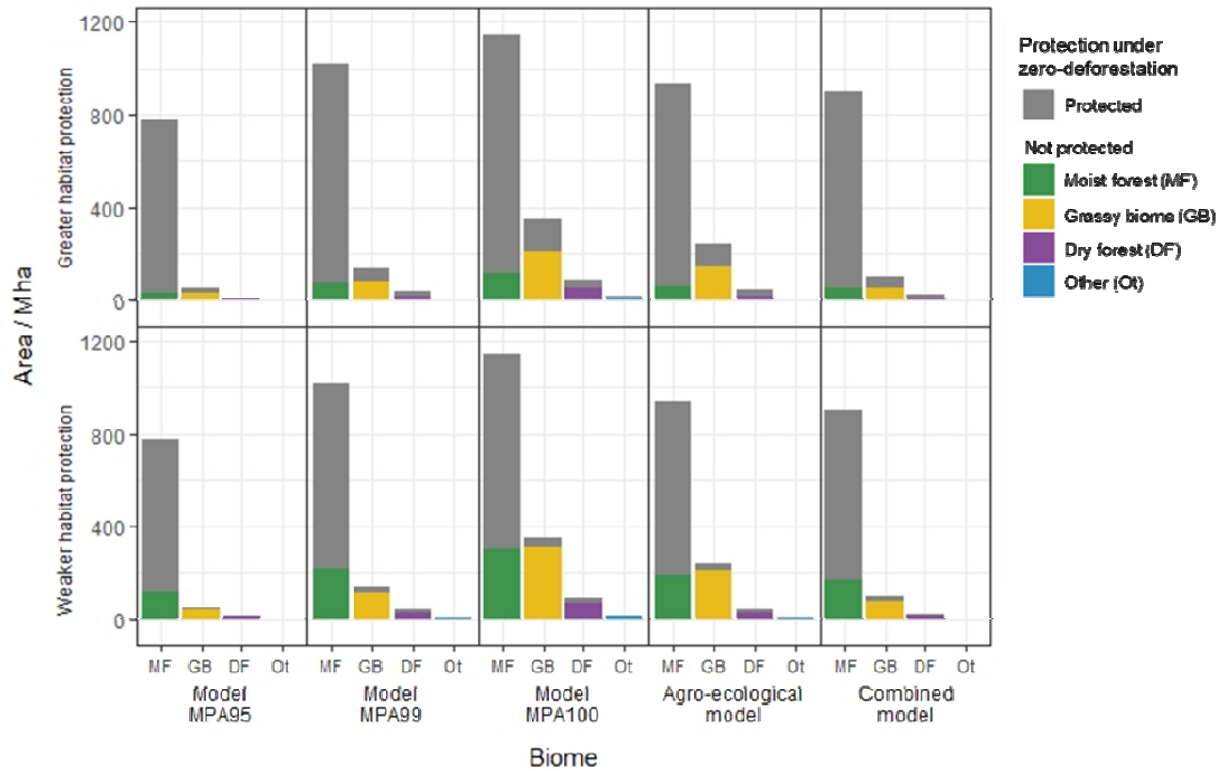
Although the agro-ecological model has five classes of relative suitability, the distribution of expected yield values (see Supplementary Figure 25) is very similar to that of the MPA₉₉ model presented in the Main Article Results (Supplementary Figure 7; Supplementary Figure 8). According to the agro-ecological model, 96% of locations suitable for zero-deforestation expansion have an expected annual fresh fruit bunch yield of $< \sim 11 \text{ tha}^{-1}$, compared to 97% expected to yield $\sim 10 \text{ tha}^{-1}$ for our final model (species distribution model thresholded at MPA₉₉), assuming the ‘greater habitat protection’ scenario for application of the HCSA. As for the species distribution model (see Main Article), this low expected yield applies particularly to the suitable locations in grassy biomes (98.8%) and dry forests (98.6%), but also moist forests (87.33%), and the only areas in the highest suitability class (with expected yield of 20 tha^{-1} for the agro-ecological model) are in moist forest (Supplementary Figure 8).

Ecoregion-level suitability

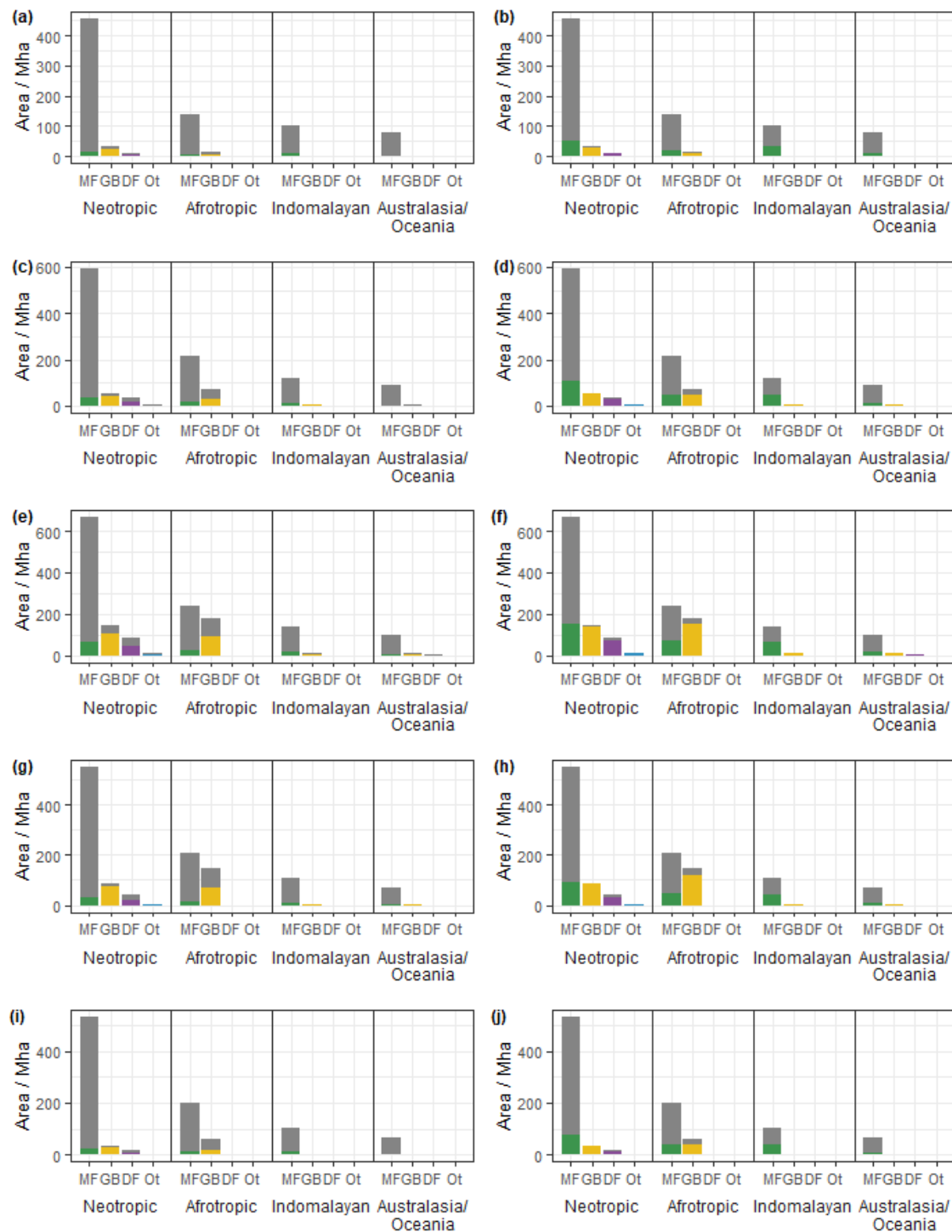
Many of the 20 ecoregions with the largest-ranking predicted suitable areas for zero-deforestation oil palm expansion were shared between the existing agro-ecological model of oil palm suitability and the final species distribution model (thresholded at MPA₉₉; Supplementary Table 5), although the agro-ecological model predicted extensive suitable areas in some ecoregions that the rainfed species distribution model did not (e.g. Cerrado). Of moist forest, grassy biome and dry forest biomes, the percentage of remaining non-cultivated habitat of individual ecoregions suitable for zero-deforestation oil palm expansion is highest for dry forest ecoregions in all permutations (choice of suitability model, habitat protection under zero-deforestation commitments, and rainfed-only expansion or also including locations requiring irrigation: see Supplementary Information 4) (Supplementary Figure 14). Reducing protection under zero-deforestation commitments from greater habitat protection to weaker habitat protection increases the percentage of tropical moist and dry forest ecoregions suitable for oil palm expansion more than for the other biomes, highlighting the sensitivity of potential biodiversity impacts of expansion in these biomes to the precise habitat protection applied in the field (Supplementary Figure 14).

Supplementary Table 4. Estimates of total climatically-suitable area for rainfed oil palm cultivation, across the three thresholds for suitability, and for the existing agro-ecological model of suitability for oil palm²⁵. Results for MPA₉₉ are presented in the Main Article. Non-cultivated habitat includes primary vegetation, secondary vegetation and pasture, and excludes cropland, urban areas and tree plantations. We estimated protection under zero-deforestation commitments following HCSA (High Carbon Stocks Approach) thresholds: for weaker habitat protection, locations with aboveground carbon stocks of $\geq 75 \text{ Mg ha}^{-1}$ and $\geq 50\%$ canopy closure, and/or peat soil are protected; for greater habitat protection (where in practice, protection of low-carbon areas can depend on additional conservation values), locations with aboveground carbon stocks of $\geq 35 \text{ Mg ha}^{-1}$ and $\geq 30\%$ canopy closure, and/or peat soil are protected.

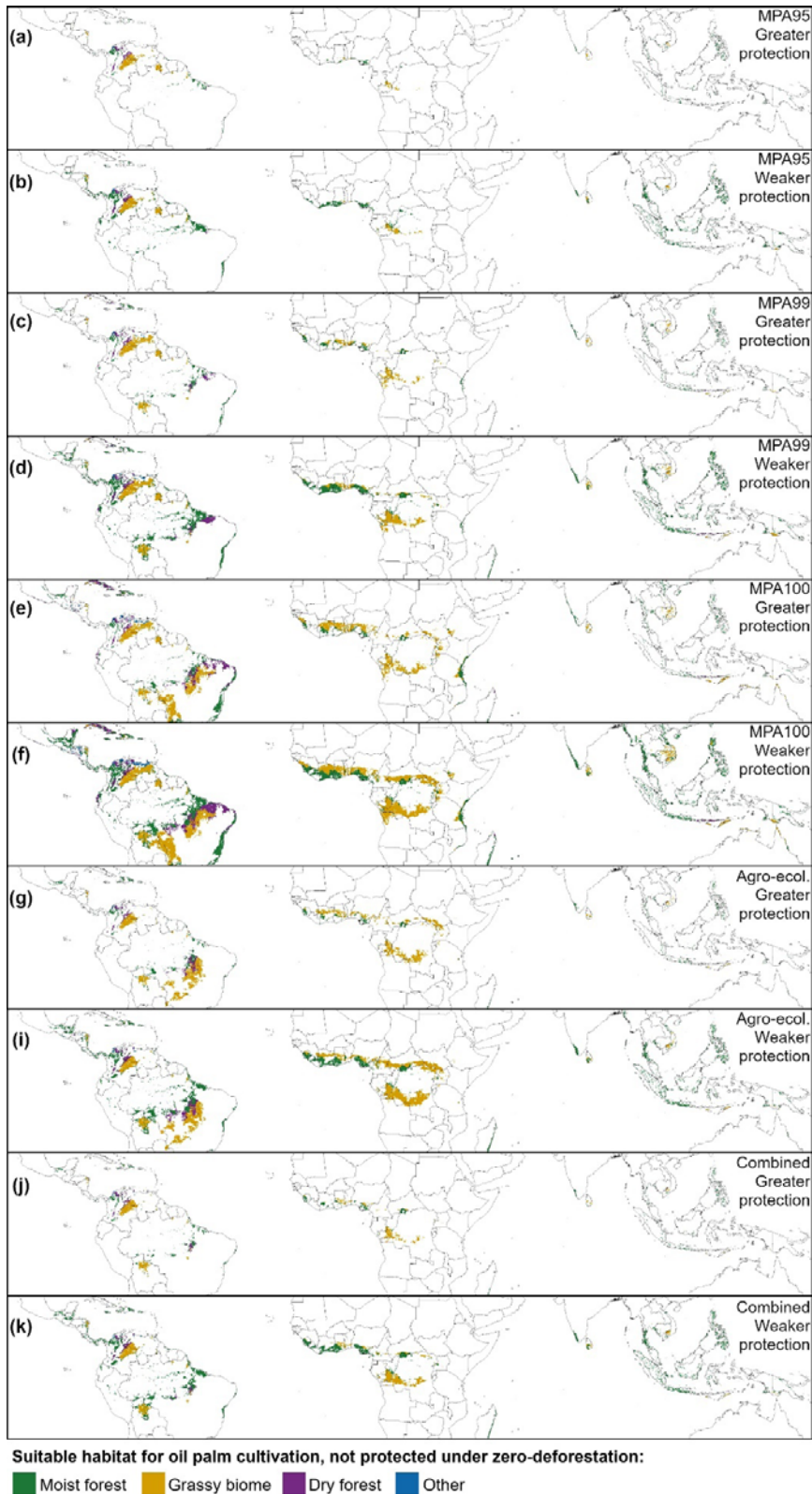
Species distribution model threshold for suitability	Areal estimate (Mha)				
	Total suitable area	Total suitable non-cultivated habitat	Total suitable non-cultivated habitat outside IUCN class I/II protected areas	Total suitable non-cultivated habitat not protected by zero-deforestation (weaker habitat protection)	Total suitable non-cultivated habitat not protected by zero-deforestation (greater habitat protection)
MPA ₉₅	960	889	840	169	69.8
MPA ₉₉	1,368	1,264	1,198	358	167
MPA ₁₀₀	1,860	1,674	1,594	694	375
Comparison of species distribution models with existing agro-ecological model					
Existing agro-ecological model ²⁵	1,380	1,279	1,219	429	223
Combined model (overlapping areas of MPA ₉₉ and ²⁵)	1,158	1,078	1,023	254	110



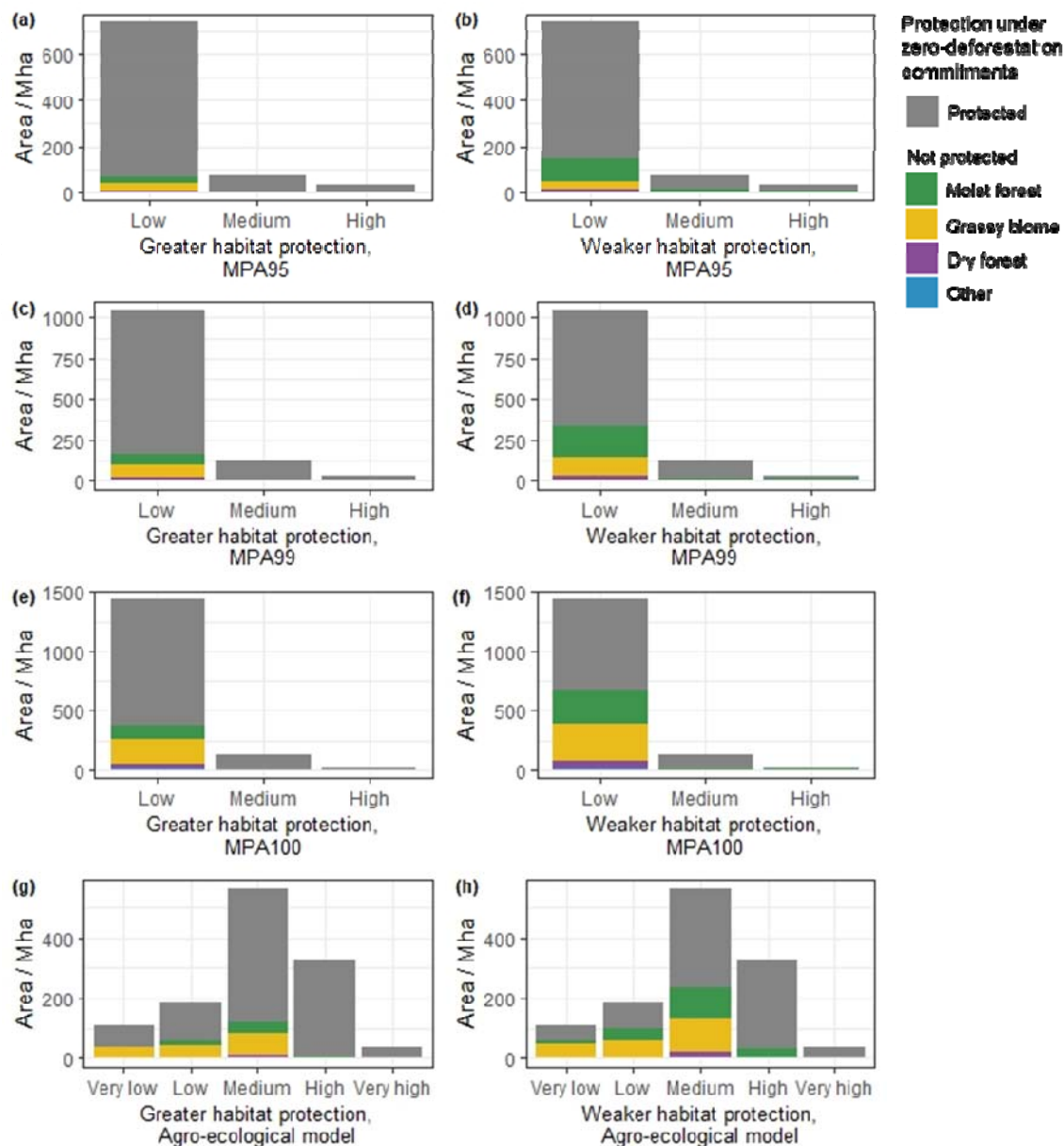
Supplementary Figure 4. Global area of non-cultivated habitat climatically-suitable for rainfed oil palm cultivation, compared among models of oil palm suitability and thresholds of habitat protection under zero-deforestation commitments. For weaker habitat protection, locations with aboveground carbon stocks of $\geq 75 \text{ Mg ha}^{-1}$ and $\geq 50\%$ canopy closure, and/or peat soil are protected; for greater habitat protection (where in practice, protection of low-carbon areas can depend on additional conservation values), locations with aboveground carbon stocks of $\geq 35 \text{ Mg ha}^{-1}$ and $\geq 30\%$ canopy closure, and/or peat soil are protected. Locations of cropland, urban areas and tree plantations are excluded; as are all IUCN class I/II protected areas. Note that results for MPA₉₉ under greater habitat protection are presented in the Main Article.



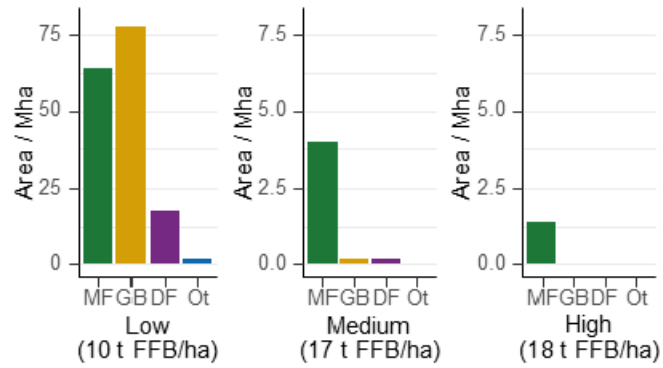
Supplementary Figure 5. Area of non-cultivated habitat climatically-suitable for rainfed oil palm cultivation, by biogeographic realm, compared among models of oil palm suitability and thresholds of habitat protection under zero-deforestation commitments. For greater habitat protection under zero-deforestation commitments (a,c,e,g,i), and for weaker habitat protection under zero-deforestation commitments (b,d,f,h,j); for suitability threshold MPA₉₅ (a,b), MPA₉₉ (c,d) and MPA₁₀₀ (e,f); the existing agro-ecological model of suitability for oil palm²⁵ (g,h); and the overlapping area of MPA₉₉ and the agro-ecological models (i,j). Locations potentially available for expansion under ZDCs (not protected) are shown in colours and locations protected under ZDCs are shown in grey (also see Supplementary Figure 4 for global totals).



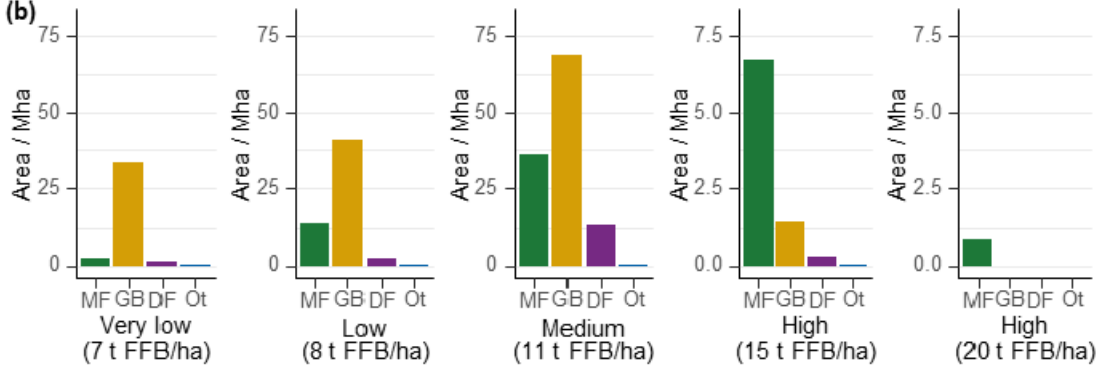
Supplementary Figure 6. Maps of non-cultivated habitat climatically-suitable for rainfed oil palm cultivation under zero-deforestation commitments, compared for thresholds for oil palm suitability for models developed in this article (MPA₉₅, MPA₉₉, MPA₁₀₀), an existing agro-ecological model, and a ‘combined model’ of the agro-ecological and MPA₉₉ models), for two thresholds of habitat protection under zero-deforestation commitments (greater habitat protection, weaker habitat protection). These maps correspond to coloured areas in Supplementary Figure 4 and Supplementary Figure 5. Note that results for MPA₉₉ under greater habitat protection are presented in the Main Article.



(a)



(b)



Supplementary Figure 8. Total areas of non-cultivated habitat climatically-suitable for rainfed oil palm expansion under zero-deforestation commitments, classified according to suitability (and expected yield), by biome.

Compared for (a) Species distribution model thresholded for suitability at MPA₉₉ (b) existing agro-ecological suitability model²⁵. Data presented in (a) is also presented in Figure 3 of the Main Article. Note differences in y axes. We have arranged the plots so that the three suitability classes of our suitability model are aligned with three of the five suitability classes of the agro-ecological model that correspond to the most similar yields and estimated suitable areas; note that these were developed independently, by contrasting methods. Biomes are moist forest ('MF'), grassy biome ('GB'), dry forest ('DF') and other ('Ot'). See Supplementary Figure 25 for obtaining yield estimates. We assume that all habitat protected under the 'Greater habitat protection' scenario (≥ 35 Mg ha⁻¹ and $\geq 30\%$ canopy closure, and/or peat soil are protected) is unavailable for expansion under ZDCs. Locations of cropland, urban areas and tree plantations are excluded; as are all IUCN class I/II protected areas.

Supplementary Table 5. Areas of individual ecoregions suitable for oil palm expansion under ZDCs for the 20 ecoregions with the largest area suitable, according to suitability estimates derived from (a) the agro-ecological model by Pirker *et al.*²⁵, and (b) the combined agro-ecological and species distribution model (areas of overlap of the agro-ecological model and the species distribution model thresholded at MPA₉₉ developed in this article. Note that these estimates both correspond to rainfed cultivation alone, and assume that all habitat protected under the ‘Greater habitat protection’ scenario (locations ≥ 35 Mg ha⁻¹ and $\geq 30\%$ canopy closure, and/or peat soil are protected) is unavailable for expansion under ZDCs. Ecoregion names in **bold are also present in Table 1a in the Main Article, i.e. rank in the top 20 ecoregions with the largest suitable are according to both the estimated suitability for the MPA₉₉ rainfed model and the estimates presented below. Realms are coded as N: Neotropic; A: Afrotropic.**

	(a) Agro-ecological model				(b) Combined model			
	Ecoregion	Biome	Realm	Suitable area for expansion under ZDCs: 1000 km ² (% of total non-cultivated land)	Ecoregion	Biome	Realm	Suitable area for expansion under ZDCs: 1000 km ² (% of total non-cultivated land)
1	Cerrado	Grassy	N	447 (29.5%)	Llanos	Grassy	N	168 (48.7%)
2	Southern Congolian forest-savanna	Grassy	A	191 (33.9%)	Western Congolian forest-savanna	Grassy	A	83.5 (22.5%)
3	Llanos	Grassy	N	168 (48.7%)	Beni savanna	Grassy	N	73.3 (66.8%)
4	Guinean forest-savanna	Grassy	A	152 (29.0%)	Southern Congolian forest-savanna	Grassy	A	58.5 (10.4%)
5	Northern Congolian Forest-Savanna	Grassy	A	136 (19.4%)	Guinean forest-savanna	Grassy	A	48.4 (9.3%)
6	Mato Grosso tropical dry forests	Dry forest	N	107 (28.4%)	Magdalena-Urabá moist forests	Moist forest	N	39.1 (55.0%)
7	Western Congolian forest-savanna	Grassy	A	104 (28.0%)	Xingu-Tocantins-Araguaia moist forests	Moist forest	N	37.1 (13.5%)
8	Beni savanna	Grassy	N	73.3 (66.8%)	Madeira-Tapajós moist forests	Moist forest	N	30.3 (4.3%)
9	Xingu-Tocantins-Araguaia moist forests	Moist forest	N	59.7 (21.8%)	Apure-Villavicencio dry forests	Dry forest	N	30.1 (53.7%)
10	Madeira-Tapajós moist forests	Moist forest	N	57.8 (8.1%)	Eastern Guinean forests	Moist forest	A	29.5 (16.5%)
11	Magdalena-Urabá moist forests	Moist forest	N	39.1 (55.0%)	Northeast Congolian lowland forests	Moist forest	A	26.3 (5.2%)
12	Eastern Guinean forests	Moist forest	A	34.5 (19.3%)	Mato Grosso tropical dry forests	Dry forest	N	25.3 (6.7%)
13	Apure-Villavicencio dry forests	Dry forest	N	30.1 (53.7%)	Tocantins/Pindare moist forests	Moist forest	N	23.7 (12.9%)
14	Northeast Congolian lowland forests	Moist forest	A	27.3 (5.4%)	Western Guinean lowland forests	Moist forest	A	22.2 (11.0%)
15	East Sudanian savanna	Grassy	A	27.1 (3.0%)	Hispaniolan moist forests	Moist forest	N	17.6 (41.7%)
16	Western Guinean lowland forests	Moist forest	A	26.0 (12.9%)	Cross-Niger transition forests	Moist forest	A	15.2 (84.0%)
17	West Sudanian savanna	Grassy	A	23.8 (2.4%)	Sinú Valley dry forests	Dry forest	N	14.9 (67.9%)
18	Tocantins/Pindare moist forests	Moist forest	N	23.7 (12.9%)	Southwest Amazon moist forests	Moist forest	N	14.6 (1.9%)
19	Hispaniolan moist forests	Moist forest	N	19.9 (47.0%)	Marajó várzea	Moist forest	N	14.2 (17.8%)
20	Central Zambesian wet miombo woodlands	Grassy	A	19.6 (2.2%)	Nigerian lowland forests	Moist forest	A	12.8 (20.6%)

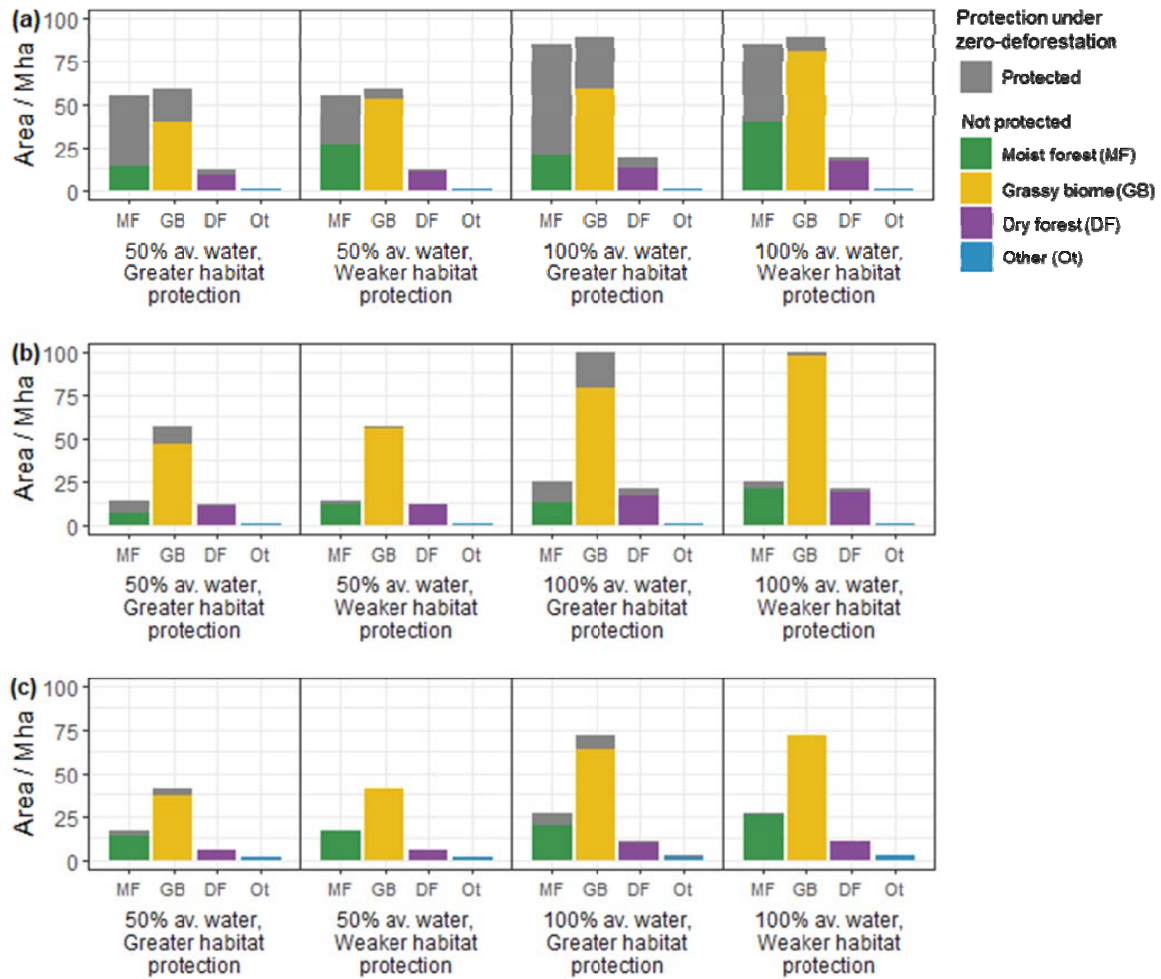
Supplementary Information 4: sensitivity analyses of suitability for irrigated oil

palm cultivation

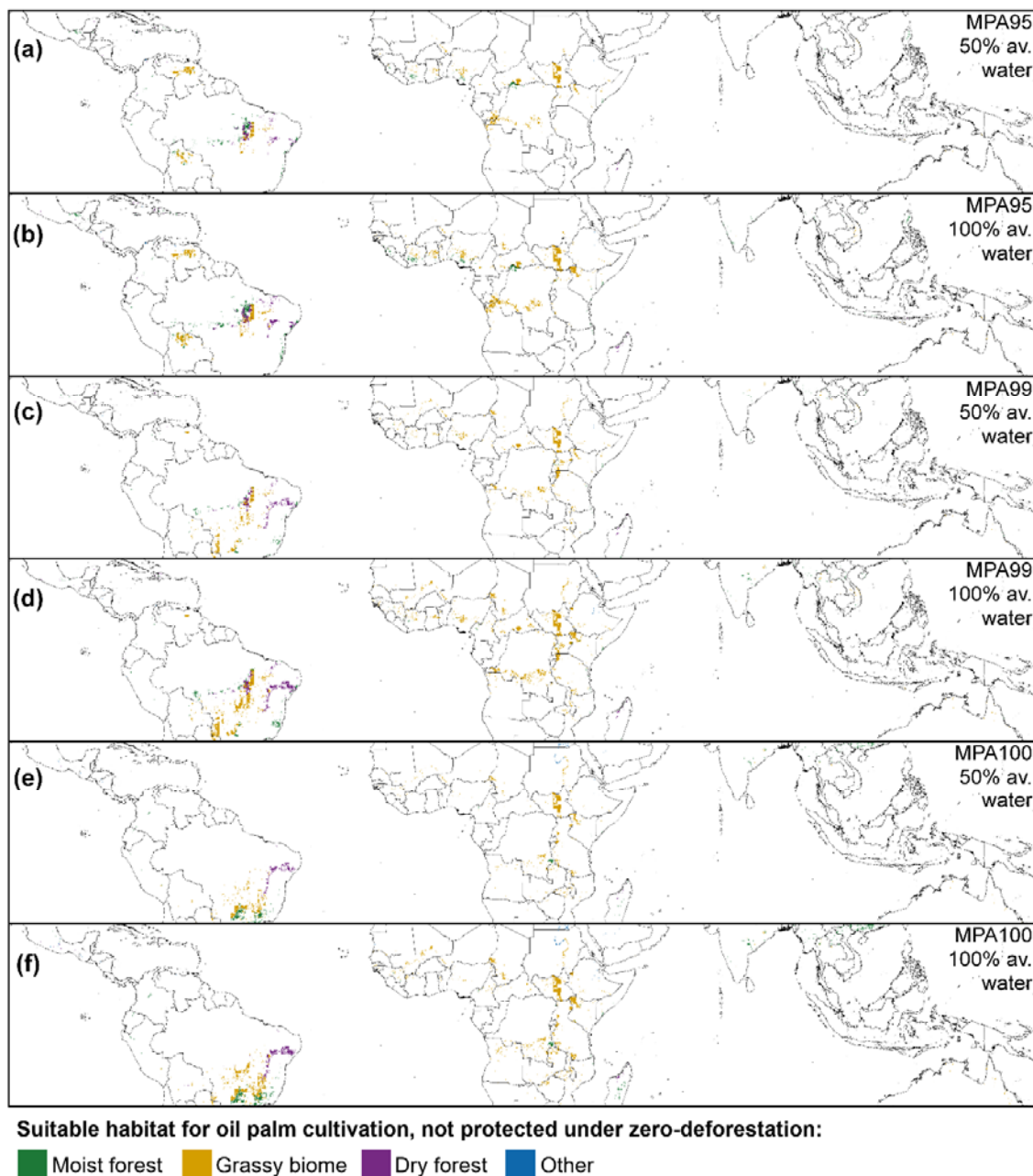
Excluding locations suitable for rainfed oil palm cultivation, we estimate that irrigation could allow an additional 63-138 Mha of land to be climatically suitable for cultivation (Supplementary Table 6). We found that these estimates of total additional suitable area (i.e. area requiring irrigation) are sensitive to water availability, as using up to 100% of surplus available water consistently renders a greater area suitable than using only 50% surplus available water (Supplementary Table 6, Supplementary Figure 9). These total areal estimates are somewhat sensitive to thresholds of model suitability (MPA_{95} , MPA_{99} , MPA_{100}) and habitat protection under zero-deforestation commitments (weaker habitat protection, greater habitat protection), but less so than the sensitivity of areas suitable for rainfed cultivation overall (Supplementary Table 6, Supplementary Figure 9; see Supplementary Table 4 for estimates of rainfed suitability). Because we excluded locations suitable for rainfed cultivation from our estimates of locations suitable for irrigation-only, we found that the locations predicted as suitable alter with model suitability threshold, although the areal estimates are broadly similar (Supplementary Table 6, Supplementary Figure 10, Supplementary Figure 11). Moreover, the majority of locations suitable for irrigated-only cultivation are not in areas which fall under protection by zero-deforestation commitments (Supplementary Figure 9). Thus, as for rainfed cultivation, the distribution of areas suitable for oil palm under irrigation-only remains similar between biomes for different model permutations (Supplementary Figure 9). As for rainfed suitability, the majority of the variation in suitable areas requiring irrigation is within areas of low expected productivity, which comprise 91.8% - 98.3% of the total suitable non-cultivated habitat requiring irrigation for all model permutations (Supplementary Figure 12; Supplementary Figure 13). Including locations suitable for irrigated cultivation has little impact on the pattern of the percentages of remaining non-cultivated land in individual ecoregions that is suitable for zero-deforestation oil palm expansion (Supplementary Figure 14).

Supplementary Table 6. Estimates of total climatically-suitable area for irrigated-only oil palm cultivation, across the three thresholds for suitability, and two levels of water use for irrigation. We have excluded locations suitable for rainfed oil palm cultivation for each model, so that some models with greater total rainfed extent (e.g. MPA₁₀₀) have smaller additional suitable areas under irrigation than other models. Results for MPA₉₉ are presented in the Main Article. We simulated irrigation in locations where annual cumulative water deficit >100mm, by using either 50% or 100% of surplus available water to supplement rainfall. As above (see Supplementary Table 4 for results for rainfed cultivation only), non-cultivated habitat includes primary vegetation, secondary vegetation and pasture, and excludes cropland, urban areas and tree plantations. We estimated protection under zero-deforestation commitments following HCSA (High Carbon Stocks Approach) thresholds: for weaker habitat protection, locations with aboveground carbon stocks of $\geq 75 \text{ Mg ha}^{-1}$ and $\geq 50\%$ canopy closure, and/or peat soil are protected; for greater habitat protection (where in practice, protection of low-carbon areas depends on additional conservation values), locations with aboveground carbon stocks of $\geq 35 \text{ Mg ha}^{-1}$ and $\geq 30\%$ canopy closure, and/or peat soil are protected.

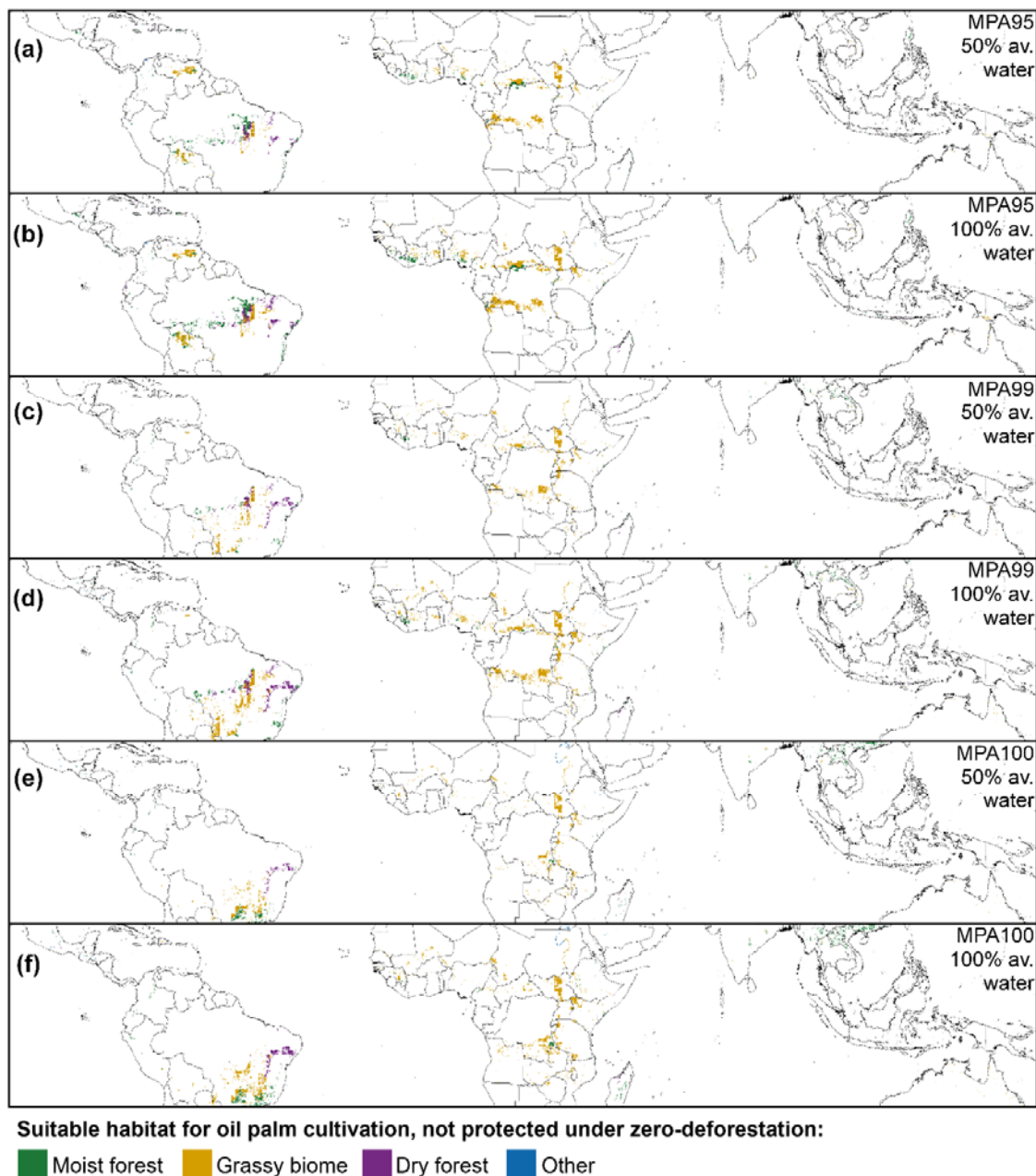
Surplus available water used for irrigation	Threshold for suitability	Areal estimate (Mha)				
		Total suitable area	Total suitable non-cultivated habitat	Total suitable non-cultivated habitat outside IUCN class I/II protected areas	Total suitable non-cultivated habitat not protected by zero-deforestation (weaker habitat protection)	Total suitable non-cultivated habitat not protected by zero-deforestation (greater habitat protection)
50%	MPA ₉₅	147	128	125	90.7	63.0
	MPA ₉₉	123	84.4	83.0	80.0	64.4
	MPA ₁₀₀	110	66.4	65.3	64.8	57.6
100%	MPA ₉₅	228	197	193	137	92.5
	MPA ₉₉	206	148	145	138	108
	MPA ₁₀₀	179	114	112	111	95.7



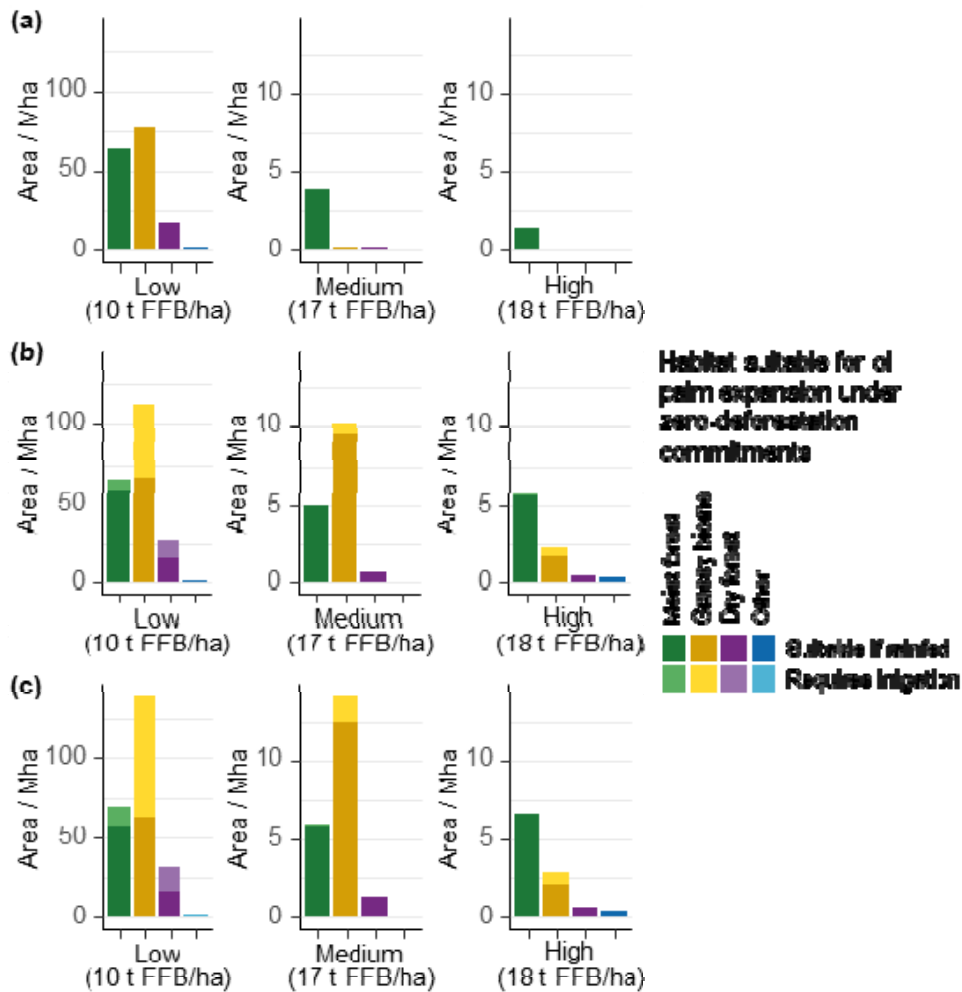
Supplementary Figure 9. Area of non-cultivated habitat climatically-suitable for irrigated-only oil palm cultivation, compared for the two levels of water use for irrigation (50% and 100% of surplus available water), the two thresholds for protection under zero-deforestation (greater habitat protection, weaker habitat protection), and the three thresholds of suitability: (a) MPA₉₅ threshold for suitability; (b) MPA₉₉ threshold for suitability; (c) MPA₁₀₀ threshold for suitability. We simulated irrigation for in locations where annual cumulative water deficit >100mm, by using either 50% or 100% of surplus available water ('av. water') to supplement rainfall. For weaker habitat protection, locations with aboveground carbon stocks of $\geq 75 \text{ Mg ha}^{-1}$ and $\geq 50\%$ canopy closure, and/or peat soil are protected; for greater habitat protection (where in practice, protection of low-carbon areas can depend on additional conservation values), locations with aboveground carbon stocks of $\geq 35 \text{ Mg ha}^{-1}$ and $\geq 30\%$ canopy closure, and/or peat soil are protected. Locations of cropland, urban areas and tree plantations are excluded; as are all IUCN class I/II protected areas. We have excluded locations suitable for rainfed oil palm cultivation for each model, so that some models with greater total rainfed extent (e.g. MPA₁₀₀) have smaller additional suitable areas under irrigation than other models. Results for MPA₉₉ under greater habitat protection and using 100% of surplus available water are presented in the Main Article.



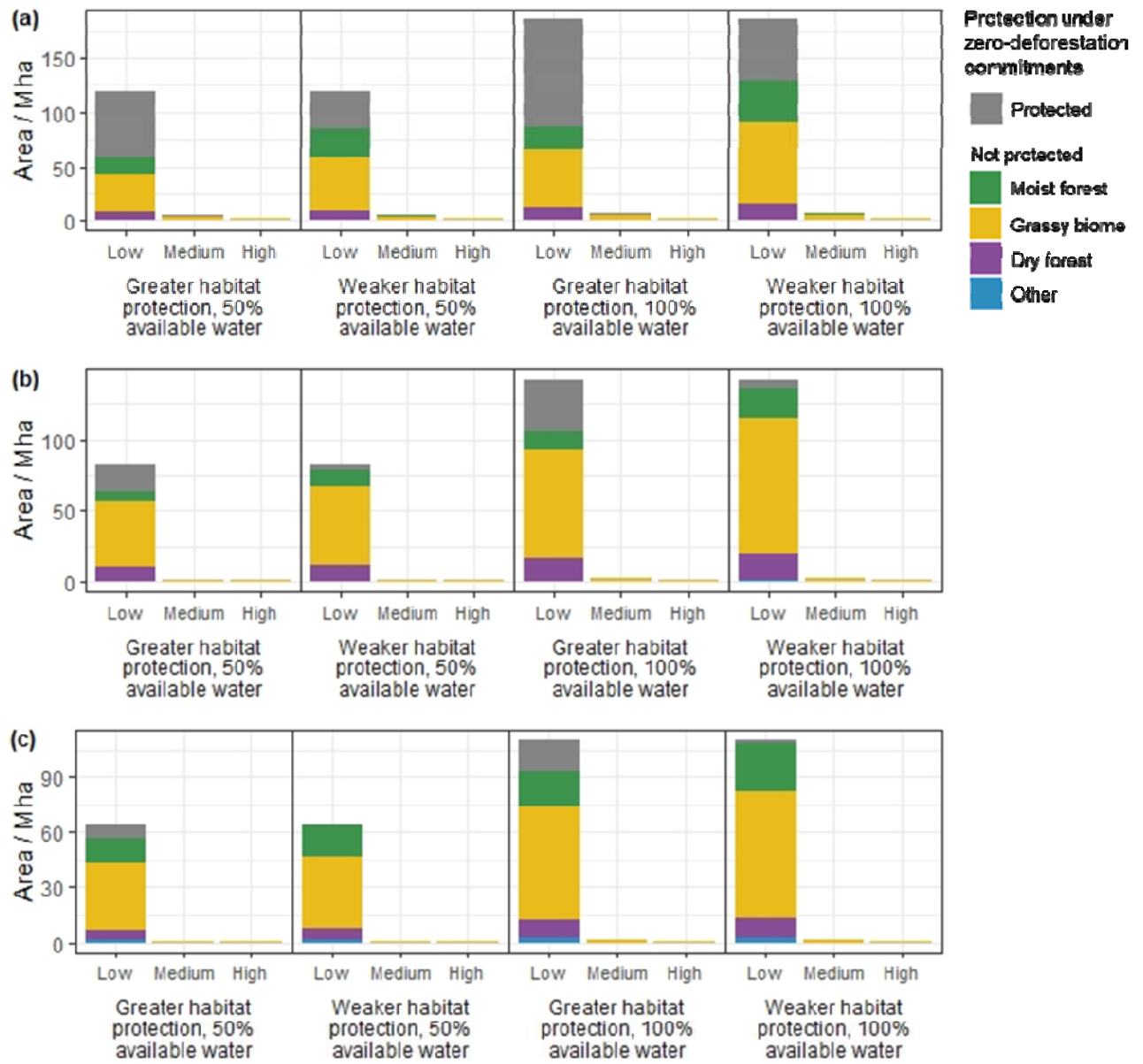
Supplementary Figure 10. Maps of climatically-suitable habitat for irrigated-only oil palm cultivation that is potentially available for zero-deforestation expansion, for the scenario of greater habitat protection under zero-deforestation commitments. Maps are compared among model thresholds for suitability (MPA₉₅, MPA₉₉, MPA₁₀₀; see Supplementary Information 7) and percentage of surplus available water ('av. water') applied as irrigation (in locations where annual cumulative water deficit > 100mm; up to either 50% or 100% surplus available water used for irrigation). For greater habitat protection under zero-deforestation commitments, locations with aboveground carbon stocks of $\geq 35 \text{ Mg ha}^{-1}$ and $\geq 30\%$ canopy closure, and/or peat soil are protected from expansion. Locations of cropland, urban areas and tree plantations are excluded; as are all IUCN class I/II protected areas. Locations suitable for rainfed cultivation are not shown (see Supplementary Figure 6); note that some locations estimated as suitable under irrigation in models with low suitability thresholds are estimated as suitable for rainfed cultivation in models with higher suitability thresholds. See Extended Data Figs. 3, 4 for larger versions of (c, d) alongside suitability for rainfed cultivation. Areas of (d) are presented in the Main Article Fig. 3.



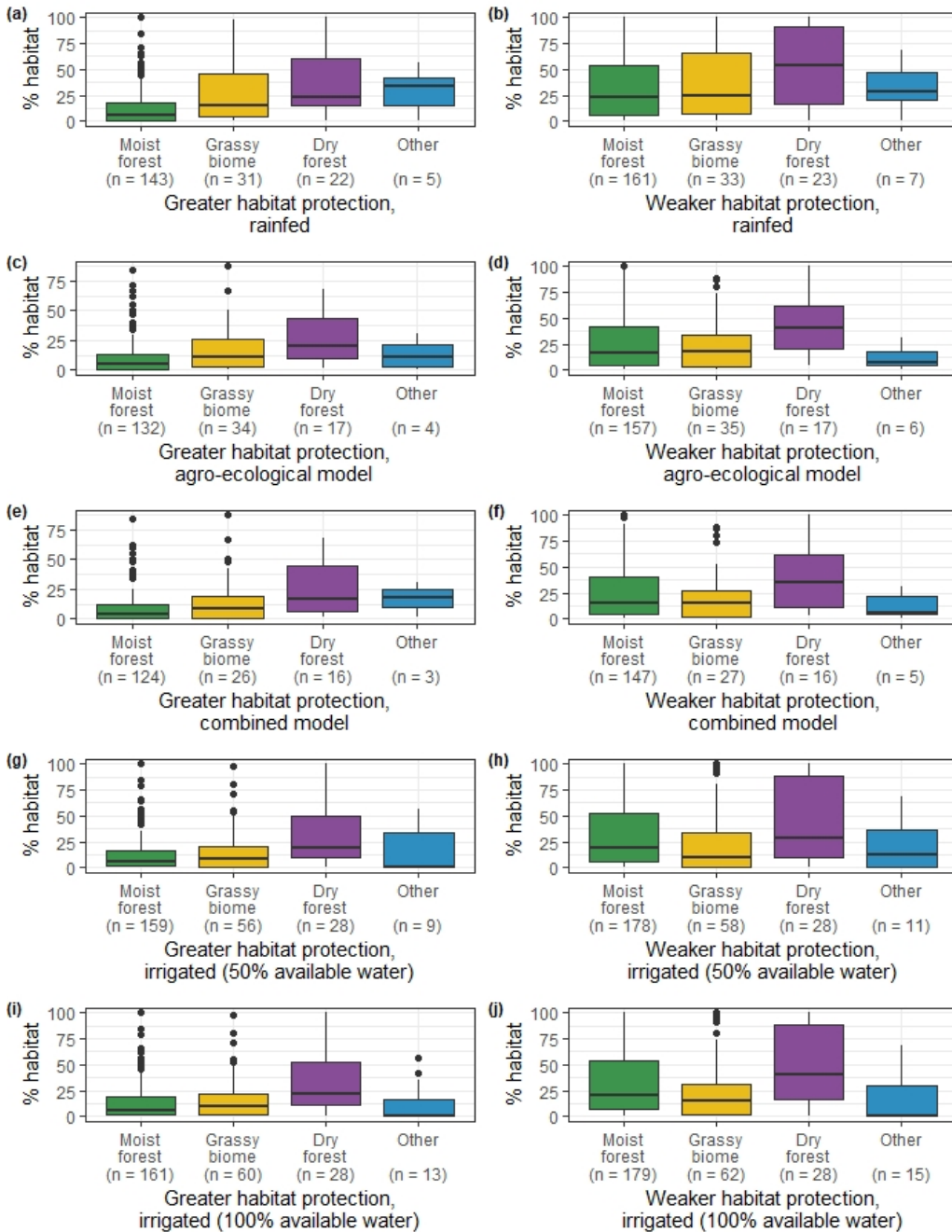
Supplementary Figure 11. Maps of climatically-suitable habitat for irrigated-only oil palm cultivation that is potentially available for zero-deforestation expansion, for the scenario of weaker habitat protection under zero-deforestation commitments. Maps are compared among model thresholds for suitability (MPA₉₅, MPA₉₉, MPA₁₀₀; see Supplementary Information 7) and percentage of surplus available water ('av. water') applied as irrigation (in locations of annual cumulative water deficit >100mm; up to either 50% or 100% surplus available water used for irrigation). For weaker habitat protection under zero-deforestation commitments, locations with aboveground carbon stocks of ≥ 75 Mg ha⁻¹ and $\geq 50\%$ canopy closure, and/or peat soil are protected. Locations of cropland, urban areas and tree plantations are excluded; as are all IUCN class I/II protected areas.



Supplementary Figure 12. Total areas of non-cultivated habitat climatically-suitable for oil palm expansion under zero-deforestation commitments, classified according to suitability (and expected yield), by biome. (a) Under rainfed cultivation, (b) under irrigation, using 50% available water, (c) under irrigation, using 100% available water. The suitability and classes are for MPA₉₉: this is a replicate of Main Article Fig. 3 but also includes irrigation estimated using 50% water availability (only (a) and (c) are shown in the Main Article). Note differences in y axes. For the (b) and (c), dark colours represent the expected yield of locations which are also suitable if rainfed (i.e. those shown in (a)), but under irrigation; and pale colours represent locations only suitable under irrigation. The difference between the distribution of expected yield values for dark colours in (a) with those in (b) and (c) thus represents the effect of applying irrigation to the locations suitable for rainfed cultivation. We assume that all habitat protected under the 'Greater habitat protection' scenario ($\geq 35 \text{ Mg ha}^{-1}$ and $\geq 30\%$ canopy closure, and/or peat soil are protected) is unavailable for expansion under ZDCs.



Supplementary Figure 13. Area of non-cultivated habitat climatically-suitable for rainfed oil palm cultivation, for each of the three classes of suitability classes (low, medium, high), compared among three model thresholds for suitability (a) MPA₉₅, (b) MPA₉₉, (c) MPA₁₀₀ (see Supplementary Information 7); two thresholds of habitat protection under zero-deforestation commitments (weaker habitat protection, greater habitat protection); and two thresholds of percentage of surplus available water applied as irrigation (in locations where annual cumulative water deficit > 100mm; up to either 50% or 100% surplus available water used for irrigation). We have excluded locations suitable for rainfed oil palm cultivation for each model, so that some models with greater total rainfed extent (e.g. MPA₁₀₀) have smaller additional suitable areas under irrigation than other models. For weaker habitat protection, locations with aboveground carbon stocks of $\geq 75 \text{ Mg ha}^{-1}$ and $\geq 50\%$ canopy closure, and/or peat soil are protected; for greater habitat protection (where in practice, protection of low-carbon areas can depend on additional conservation values), locations with aboveground carbon stocks of $\geq 35 \text{ Mg ha}^{-1}$ and $\geq 30\%$ canopy closure, and/or peat soil are protected. Locations of cropland, urban areas and tree plantations are excluded; as are all IUCN class I/II protected areas. Note differences in y axes. Values in (b) under greater habitat protection and up to 100% available water use correspond to those presented in Main Article Fig. 3.



Supplementary Figure 14. Percentages of remaining non-cultivated habitat per-ecoregion, suitable for oil palm expansion under zero-deforestation commitments, by biome, compared for rainfed (a, b, c, d, e, f) and both rainfed and irrigated expansion (g, h, using up to 50% of surplus available water for irrigation; and i, j, using up to 100% of surplus available water for irrigation), and for different thresholds of protection under zero-deforestation commitments (greater habitat protection, weaker habitat protection). Results for the species distribution model thresholded at MPA₉₉ are shown in (a, b, g, h, i, j); results for the existing agro-ecological suitability model²⁵ are shown in (c, d) and those for the areas of overlap between the rainfed species distribution model and agro-ecological model in (e, f). For weaker habitat protection, locations with aboveground carbon stocks of $\geq 75 \text{ Mg ha}^{-1}$ and $\geq 50\%$ canopy closure, and/or peat soil are protected; for greater habitat protection (where in practice, protection of low-carbon areas can depend on additional conservation values), locations with aboveground carbon stocks of $\geq 35 \text{ Mg ha}^{-1}$ and $\geq 30\%$ canopy closure, and/or peat soil are protected. Locations of cropland, urban areas and tree plantations are excluded; as are all IUCN class I/II protected areas. Results for (a) are shown in the Main Article Fig. 2. Note that panels for 'irrigation' also include suitability for rainfed oil palm. Boxplot centre lines show the median, lower and upper hinges show the first and third quartiles respectively, whiskers extend to the maximum and minimum values within 1.5*inter-quartile range, and outliers are plotted individually.

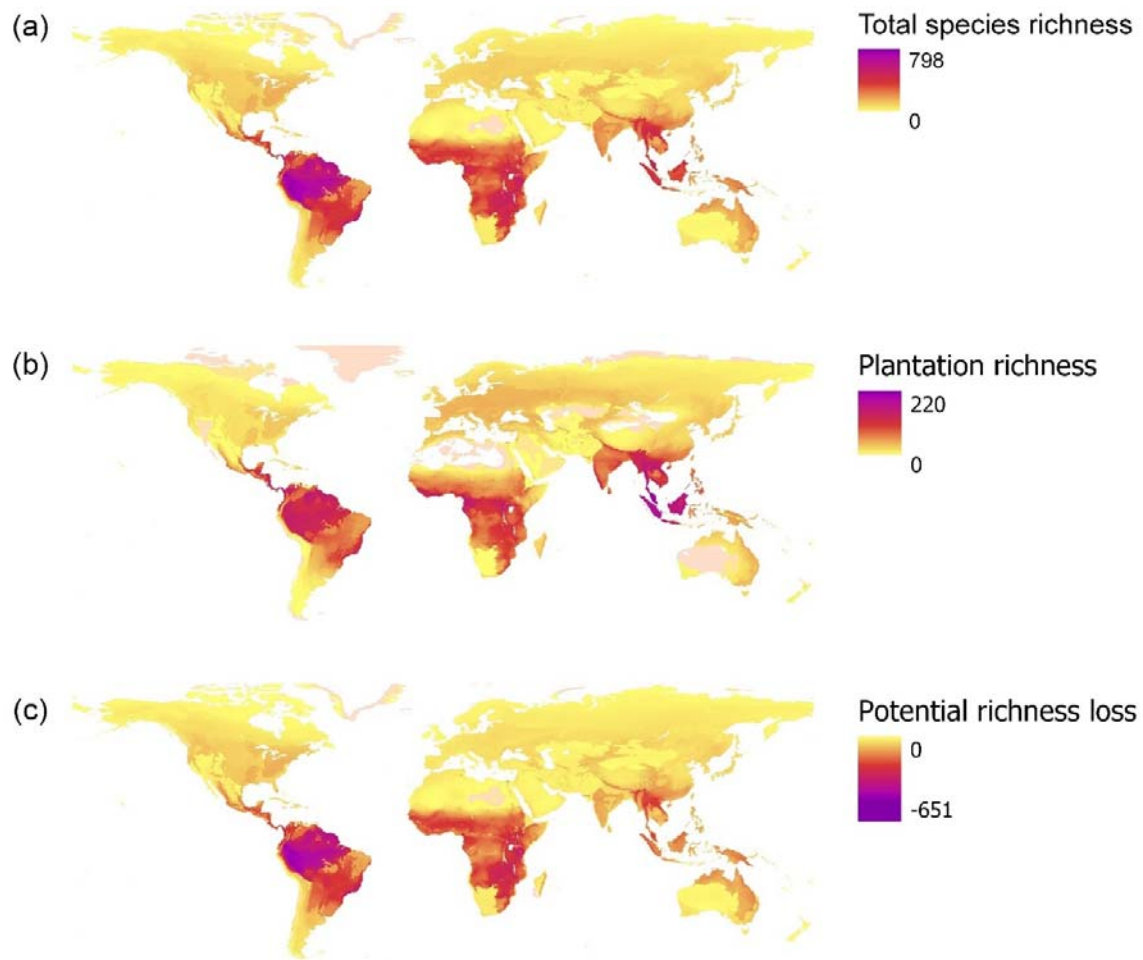
Supplementary Information 5: sensitivity analyses of potential impacts of oil palm expansion on vertebrates

We refined range maps of terrestrial vertebrates according to natural and transformed habitat types in which each species could persist (see Main Article Methods) according to the matching in Supplementary Table 7, and estimated potential vertebrate species richness loss from conversion of non-cultivated habitat to oil palm plantation (Supplementary Figure 15). Our results that zero-deforestation commitments could exacerbate richness loss from oil palm expansion in certain grassy and dry forest biomes, by prioritising locations of greater potential richness loss for conversion, held true across all model permutations that we tested (including locations suitable for both irrigated and rainfed expansion, compared to rainfed expansion alone; using the existing agro-ecological model²⁵ of rainfed suitability, and areas of overlap between this model and our final rainfed species distribution model thresholded at MPA₉₉; and classifying protection under zero-deforestation commitments according to ‘greater habitat protection’ or ‘weaker habitat protection’ thresholds; Supplementary Figure 16, Supplementary Figure 17). We found that the number of threatened vertebrate species that could undergo range loss from zero-deforestation oil palm expansion was considerably greater for the scenario of weaker habitat protection under zero-deforestation commitments (protection of locations with aboveground carbon stocks of ≥ 75 Mg ha⁻¹ and $\geq 50\%$ canopy closure; 1273 threatened species could undergo range loss in total, for rainfed expansion) than for greater habitat protection (protection of locations with aboveground carbon stocks of ≥ 35 Mg ha⁻¹ and $\geq 30\%$ canopy closure; 879 threatened species could undergo range loss in total, for rainfed expansion) (Supplementary Figure 18). Numbers of threatened species that could undergo range loss for the existing agro-ecological model²⁵ were similar (1165 threatened species could undergo range loss from zero-deforestation oil palm expansion for the scenario of ‘weaker habitat protection’, and 809 species for the scenario of ‘greater habitat protection’; Supplementary Figure 18). Including locations suitable for irrigated oil palm expansion increased the number of threatened vertebrates that could undergo range loss (1071 species for ‘greater habitat protection’) compared to rainfed expansion alone (879 species), although the impact of this was less than that of the thresholds for habitat protection under zero-deforestation commitments (Supplementary Figure 18). Weaker habitat protection under zero-deforestation

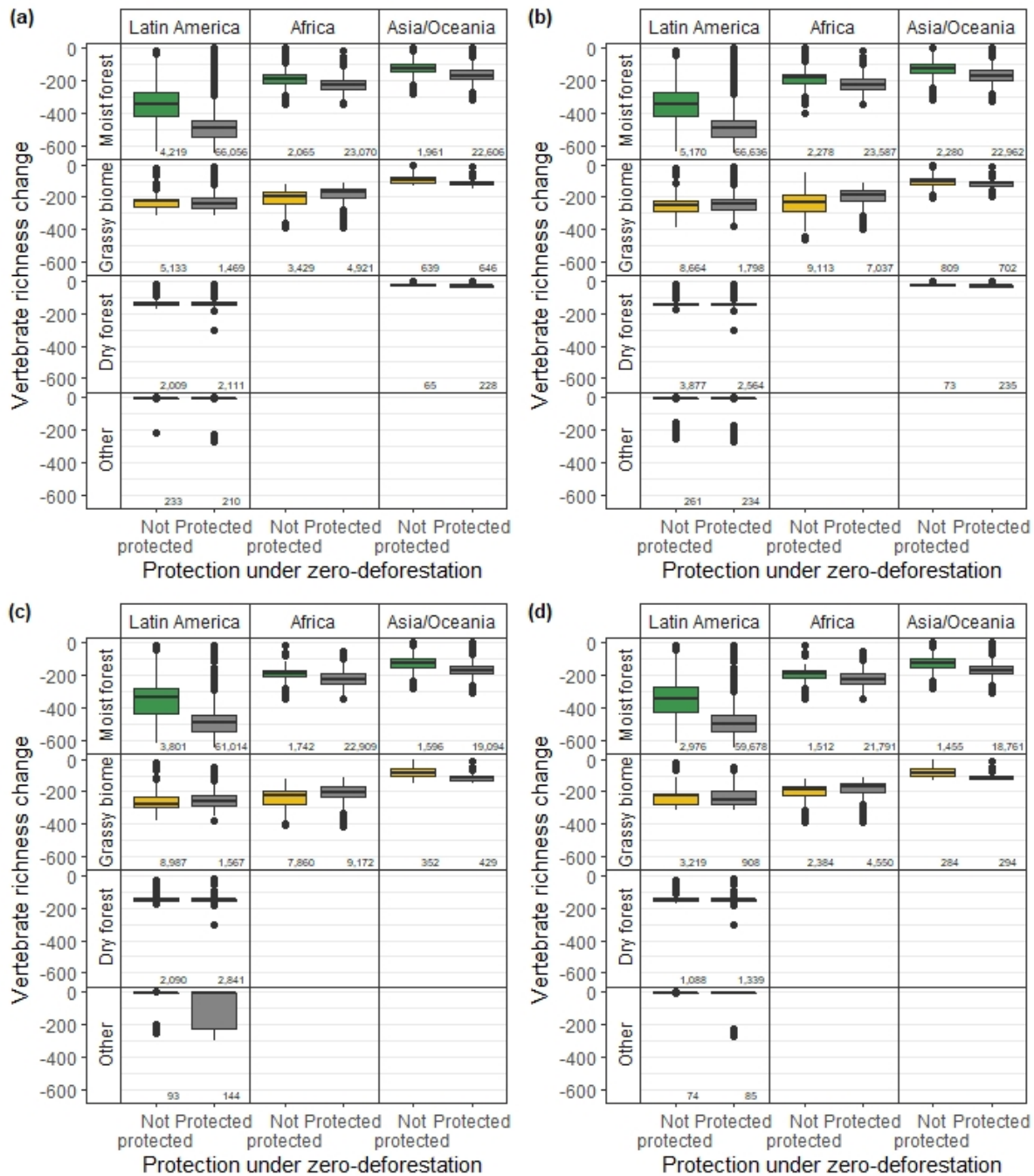
commitments allowed considerably greater range loss for these species than greater habitat protection, although this largely impacted the tropical moist forest biome; whereas including irrigated oil palm expansion had little impact on the percentage of range that could be lost (Supplementary Figure 18). The proportion of threatened species' ranges that overlaps with areas suitable for zero-deforestation oil palm expansion is small for all permutations of suitability, for 'greater habitat protection' under ZDCs (median <5% for all threatened species with ranges overlapping suitable areas for oil palm; Supplementary Figure 19). The scenario of 'weaker habitat protection' results in comparatively larger areas of threatened species' ranges overlapping with areas suitable for zero-deforestation oil palm expansion, largely from increased suitability in the moist forest biome (overall median 12-18% of range overlapping depending on suitability model; Supplementary Figure 19). However, the impacts of the difference in habitat protection for threatened species in moist forest is unclear in practice, because we expect that we have overestimated the biodiversity impacts of expansion for the moist forest biome in particular, where habitat is likely to be highly degraded (Supplementary Information 6).

Supplementary Table 7. Matching IUCN Red List habitat classifications^{26,27} with habitat classes of Terrestrial Ecoregions of the World¹⁹ and global spatial data on locations of cropland, urban areas^{28,29} and tree plantations³⁰. We considered a species as present in a given grid-cell (5 arc-minute resolution) if its range contained the grid-cell centre, and if the habitat type (non-cultivated habitat according to Terrestrial Ecoregions of the World, masked by cropland, urban areas and tree plantations) was listed as a suitable habitat, according to this matching table.

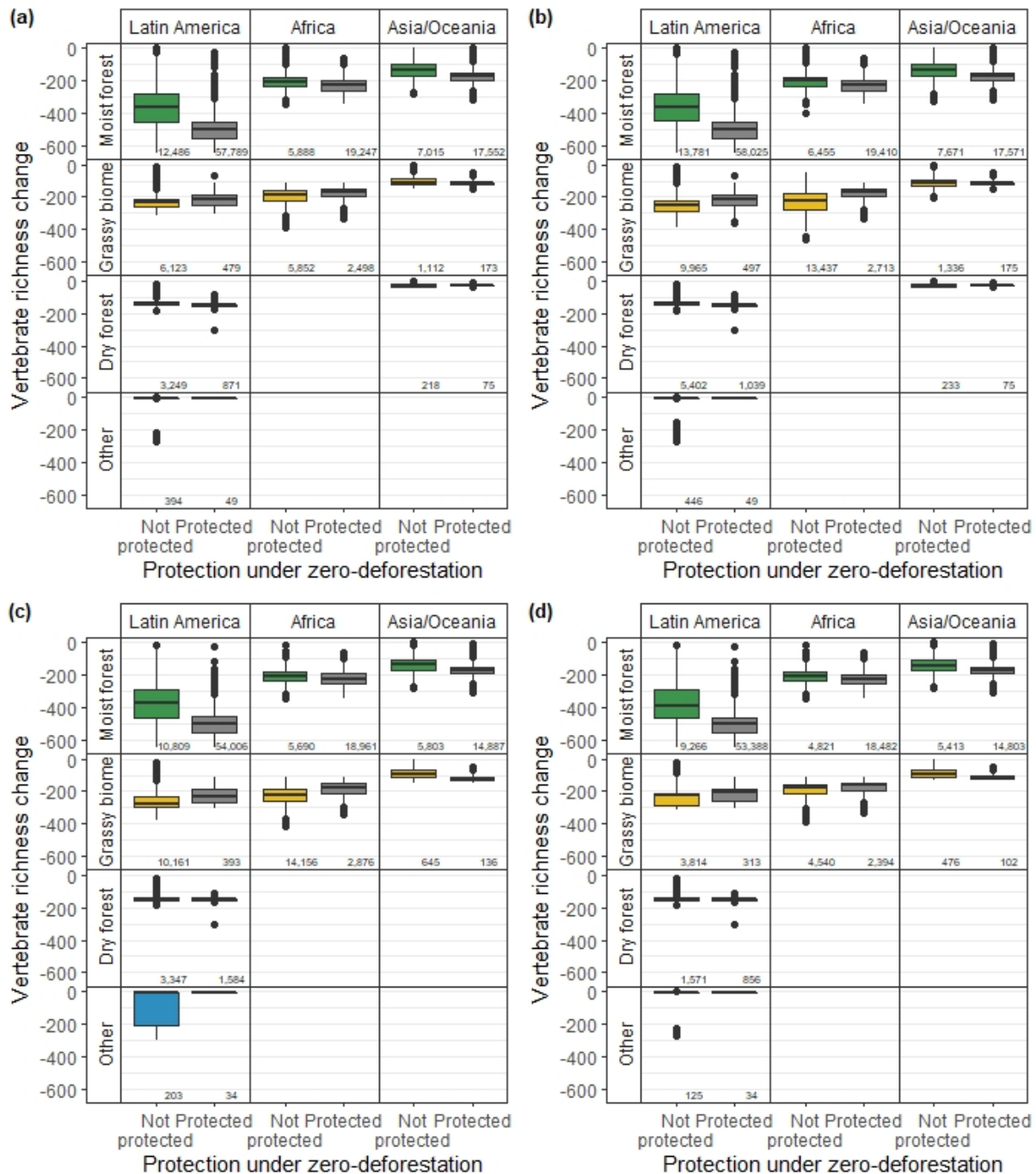
IUCN^{26,27}	Terrestrial ecoregions 2017¹⁹
Boreal forest	Boreal forests/taiga
Subarctic forest; Subantarctic forest	Boreal forests/taiga; Tundra
Temperate forest	Temperate broadleaf and mixed forests; temperate conifer forests
Subtropical/tropical dry forest	Tropical and subtropical dry broadleaf forests; tropical and subtropical coniferous forests
Subtropical/tropical moist lowland forest; subtropical/tropical swamp forest; subtropical/tropical moist montane forest	Tropical and subtropical moist broadleaf forests; tropical and subtropical coniferous forests
Subtropical/tropical mangrove forest vegetation	Mangroves
Dry savanna	Tropical and subtropical grasslands, savannas and shrublands; temperate grasslands, savannas and shrublands; montane grasslands and shrublands
Moist savanna	Tropical and subtropical grasslands, savannas and shrublands; temperate grasslands, savannas and shrublands; flooded grasslands and shrublands; montane grasslands and shrublands
Subarctic shrubland; subantarctic shrubland; boreal shrubland; tundra; subarctic grassland; subantarctic grassland	Tundra
Temperate shrubland; temperate grassland	Temperate grasslands, savannas and shrublands; montane grasslands and shrublands
Subtropical/tropical dry shrubland; subtropical/tropical moist shrubland	Tropical and subtropical grasslands, savannas and shrublands; montane grasslands and shrublands; flooded grasslands and savannas
Subtropical/tropical high altitude shrubland	Montane grasslands and shrublands
Mediterranean-type shrubby vegetation	Mediterranean forests, woodland and scrub
Subtropical/tropical dry lowland grassland	Tropical and subtropical grasslands, savannas and shrublands
Subtropical/tropical wet/flooded lowland grassland	Tropical and subtropical grasslands, savannas and shrublands; flooded grasslands and savannas
Subtropical/tropical high altitude grassland	Tropical and subtropical grasslands, savannas and shrublands; Montane grasslands and shrublands
Wetlands (inland)	Flooded grasslands and savannas
Inland rocky areas	
Caves & subterranean habitats	
Desert (hot desert, temperate desert, cold desert)	Deserts and xeric shrublands; tundra
	Copernicus landcover map^{28,29}
Arable land	Cropland
Urban areas	Urban
	Spatial Database of Planted Trees³⁰
Plantations	Tree plantations (including oil palm)
	IDEAM Corine Landcover²¹ (Colombia only) or MapBiomass^{22,23} (tropical Brazil only)
Pasture	Open pasture ('Pastos limpios' in Colombia); pasture (in Brazil)



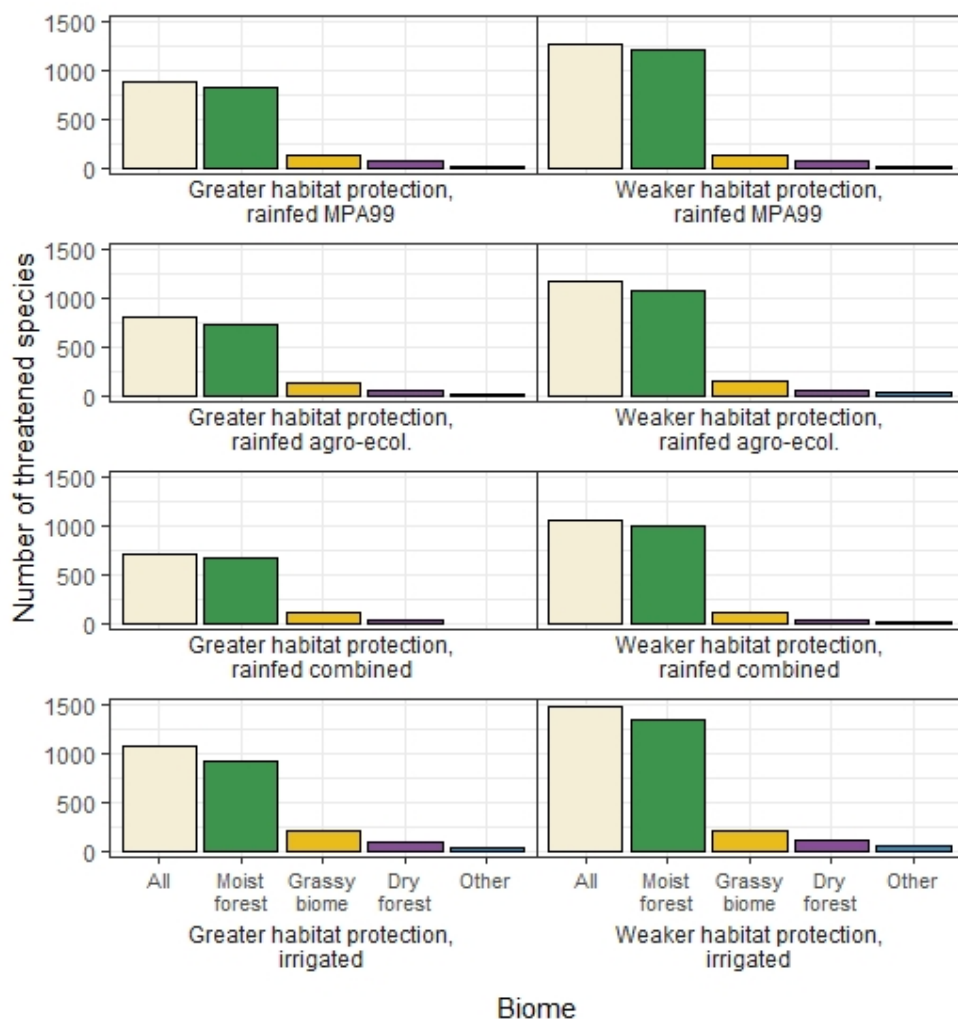
Supplementary Figure 15. Global maps of estimated vertebrate species richness, from refined range maps. (a) Total richness in natural landcover; (b) potential richness of tree plantations (including oil palm plantations); (c) potential richness loss from conversion of non-cultivated habitat to tree/palm plantation (i.e. the difference between (b) and (a)).



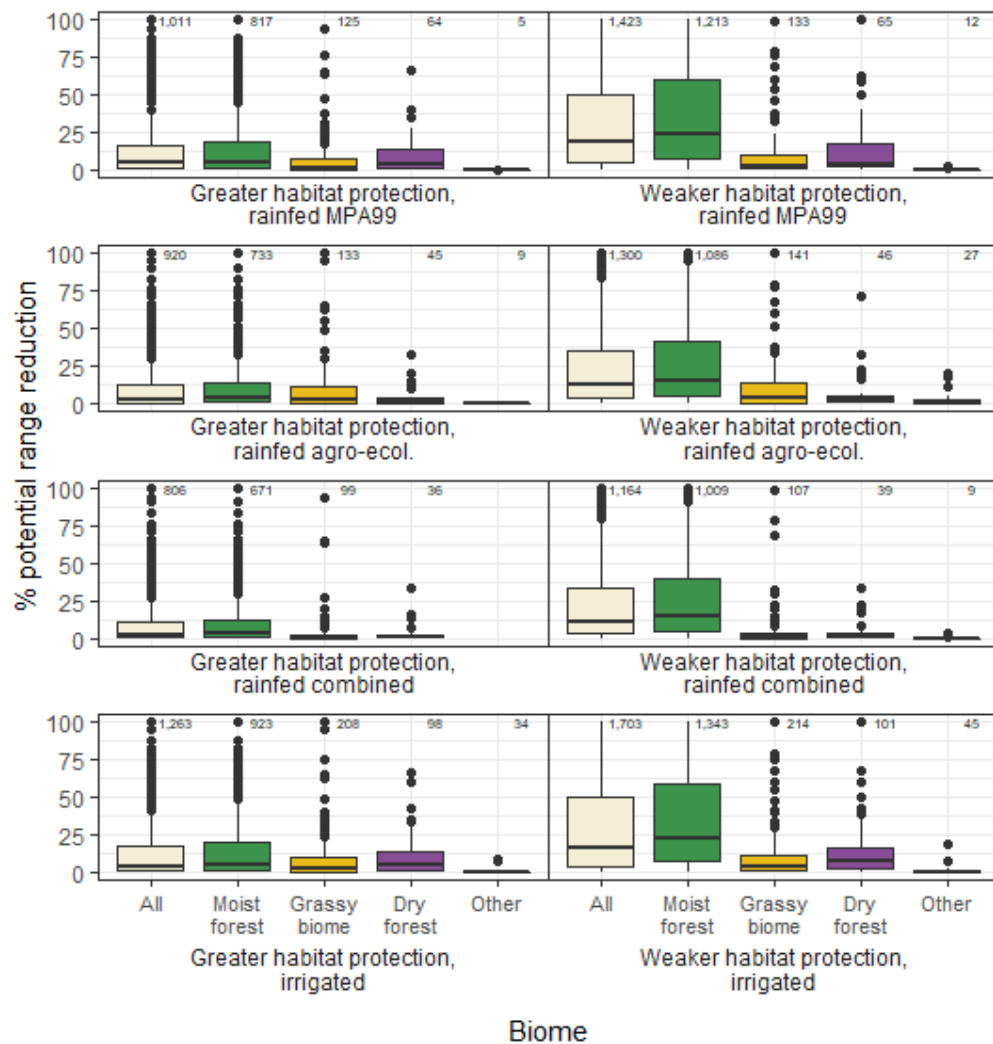
supplementary Figure 16. Potential impacts of zero-deforestation oil palm expansion on vertebrate richness, under the scenario of 'greater habitat protection', compared for: (a) Rainfed oil palm expansion, according to the final species distribution model (MPA₉₉); (b) both rainfed and irrigated oil palm expansion, according to the final species distribution model (MPA₉₉); (c) rainfed oil palm expansion, according to the existing agro-ecological model²⁵; (d) rainfed oil palm expansion, according to areas of overlap of the final species distribution model and existing agro-ecological model²⁵. For greater habitat protection (where in practice, protection of low-carbon areas can depend on additional conservation values), locations with aboveground carbon stocks of $\geq 35 \text{ Mg ha}^{-1}$ and $\geq 30\%$ canopy closure, and/or peat soil are protected. Locations of cropland, urban areas and tree plantations are excluded; as are all IUCN class I/II protected areas. All estimates of irrigated expansion assume up to 100% of surplus available water could be applied for irrigation. Boxplots show potential richness loss for all grid-cells; central bars show the median, lower and upper hinges show the first and third quartiles respectively, whiskers extend to the maximum and minimum values within 1.5*inter-quartile range, and outliers are plotted individually. Sample sizes (numbers of ~10-km grid cells) are given to the lower right of each boxplot; we excluded panels with individual boxplots of insufficient sample size ($n < 30$) from the plots.



Supplementary Figure 17. Potential impacts of zero-deforestation oil palm expansion on vertebrate richness, under the scenario of ‘weaker habitat protection’, compared for: (a) Rainfed oil palm expansion, according to the final species distribution model (MPA₉₉); (b) both rainfed and irrigated oil palm expansion, according to the final species distribution model (MPA₉₉); (c) rainfed oil palm expansion, according to the existing agro-ecological model²⁵; (d) rainfed oil palm expansion, according to areas of overlap of the final species distribution model and existing agro-ecological model²⁵. For weaker habitat protection, locations with aboveground carbon stocks of $\geq 75 \text{ Mg ha}^{-1}$ and $\geq 50\%$ canopy closure, and/or peat soil are protected. Locations of cropland, urban areas and tree plantations are excluded; as are all IUCN class I/II protected areas. All estimates of irrigated expansion assume up to 100% of surplus available water could be applied for irrigation. Boxplots show potential richness loss for all grid-cells; central bars show the median, lower and upper hinges show the first and third quartiles respectively, whiskers extend to the maximum and minimum values within $1.5 \times$ inter-quartile range, and outliers are plotted individually. Sample sizes (numbers of $\sim 10\text{-km}$ grid cells) are given to the lower right of each boxplot; we excluded panels with individual boxplots of insufficient sample size ($n < 30$) from the plots.



Supplementary Figure 18. Comparison of number of threatened vertebrate species that have ranges overlapping with areas suitable for zero-deforestation oil palm expansion. Results are compared for rainfed suitability (rows: species distribution model thresholded at MPA₉₉, agro-ecological model, and combined model of areas of overlap) and both rainfed and irrigated suitability (final row, assuming that up to 100% of surplus available water is used for irrigation); and for habitat protection threshold under zero-deforestation commitments (columns). Number of threatened vertebrate species (of a global total of $N = 3,155$ that we estimated with some terrestrial range following refinement by landcover type at 5' resolution) with overlapping ranges with locations climatically-suitable for zero-deforestation oil palm expansion. For weaker habitat protection, locations with aboveground carbon stocks of $\geq 75 \text{ Mg ha}^{-1}$ and $\geq 50\%$ canopy closure, and/or peat soil are protected; for greater habitat protection (where in practice, protection of low-carbon areas can depend on additional conservation values), locations with aboveground carbon stocks of $\geq 35 \text{ Mg ha}^{-1}$ and $\geq 30\%$ canopy closure, and/or peat soil are protected. Locations of cropland, urban areas and tree plantations are excluded; as are all IUCN class I/II protected areas.



Supplementary Figure 19. Comparison of percentage of threatened species' ranges which overlap with locations climatically-suitable for zero-deforestation oil palm expansion. Results are compared for rainfed suitability (rows: species distribution model thresholded at MPA₉₉, agro-ecological model and combined model of areas of overlap) and both rainfed and irrigated suitability (final row, assuming that up to 100% of surplus available water is used for irrigation); and for habitat protection threshold under zero-deforestation commitments (columns). Zero values are excluded (i.e. only species that occur in climatically-suitable, unprotected locations in a given biome are included). For weaker habitat protection, locations with aboveground carbon stocks of $\geq 75 \text{ Mg ha}^{-1}$ and $\geq 50\%$ canopy closure, and/or peat soil are protected; for greater habitat protection (where in practice, protection of low-carbon areas can depend on additional conservation values), locations with aboveground carbon stocks of $\geq 35 \text{ Mg ha}^{-1}$ and $\geq 30\%$ canopy closure, and/or peat soil are protected. Locations of cropland, urban areas and tree plantations are excluded; as are all IUCN class I/II protected areas. Results for rainfed cultivation and greater habitat protection under zero-deforestation commitments are shown in Figure 4 of the Main Article. Boxplot centre lines show the median, lower and upper hinges show the first and third quartiles respectively, whiskers extend to the maximum and minimum values within $1.5 \times$ inter-quartile range, and outliers are plotted individually. Sample sizes (number of threatened species' ranges overlapping with locations suitable for zero-deforestation oil palm expansion) are shown to the upper right of each boxplot, and displayed as a barchart in Supplementary Figure 18.

Supplementary Information 6: limitations in analyses and interpretations

General uncertainties

As with any analysis that combines a number of different datasets, there are various potential sources of error in our results, particularly because data for the Tropics tend to have greater uncertainty than in temperate regions. We decided to conduct all analyses at 5' grid-cell resolution, the finest possible from the component datasets. As the grid-cells are ~10km at the Equator, in practice individual grid-cells contain substantial variation in all variables included in our analyses, inevitably leading to some inaccuracies in our results. Marginal errors will also have arisen through our resampling of the component data that originally had a higher resolution, and analysing spatial polygons (e.g. ecoregions, species range maps) per grid-cell. Our results are therefore appropriate for identifying large-scale spatial patterns in suitability for oil palm, vegetation structure or vertebrate diversity, but on-the-ground assessments are required for understanding local suitability for expansion and its potential impacts.

We have assessed where oil palm could expand in compliance with ZDCs, and found that the majority of locations are in dry forests and grassy biomes, rather than moist forest. However, our analysis has not incorporated any economics or elements of governance, and therefore cannot disentangle the potential for leakage of expansion from moist forest to other biomes due to ZDCs³¹ from the potential for ongoing demand increases for palm oil to drive expansion in any biome³². Moreover, any implementation of ZDCs will necessarily interact with national and regional policies, such as the targeted expansion of oil palm in the Llanos to increase Colombian biofuel production³³. Thus, further research that incorporates economic and governance dimensions of land-use change relating to oil palm, and alternative land-uses (e.g. oil crops and food crops, pasture etc.) is essential for better understanding the likely dynamics of expansion under ZDCs.

Limitations and uncertainties in modelling climatic suitability for oil palm

Although we outline a number of limitations of our approach in this section, we are confident in our conclusions presented in the Main Article, because they appear robust to our sensitivity analyses (Supplementary Information 3-5).

Climate data

The global gridded climate data, on which our oil palm suitability models were based, were interpolated from a number of on-the-ground measurements, but the Tropics are poorly sampled relative to temperate regions, and uncertainties in precipitation are high in parts of Latin America and Southeast Asia³⁴. The component datasets for the species distribution models of suitability for oil palm had some temporal discrepancies (e.g. climate data were averaged for 1970-2000³⁴, hydrological data were averaged for 2005-2009³⁵, oil palm mills used to train the models were collated in 2018³⁶). Therefore, it is possible that the relationships between oil palm and climate contained systematic inaccuracies relating to the temporal difference in these component datasets. However, any systematic inaccuracies in the climate-suitability relationships are unlikely to have manifested in the final suitability predictions, because we used the same climate data for both training and projecting suitability, and because many of the oil palm mills would have been established in the decades preceding 2018, which reduces the temporal difference with the climate data.

Moreover, we recognise that our suitability projections were for the average climate of ~1985³⁴, but some changes in precipitation and temperature have occurred since the 1980s³⁷. Most substantially, the increase in temperature³⁷ will have increased suitability in some regions (e.g. high-elevation areas) relative to our model projections, provided that they have sufficient rainfall. Precipitation has not changed substantially in most tropical locations over this timeframe³⁷, but both increases and decreases in precipitation in some areas could have altered their suitability relative to our model outputs.

Training the suitability models using oil palm mill locations

Our choice to use locations of industrial oil palm mills³⁶ to train the models may have some impacts on our suitability projections. These industrial mills are adjacent to industrial oil palm plantations³⁰, and therefore represent locations of high-input, high-yield oil palm production (see Main Article Methods). Smallholder production that feeds into the global supply chains covered by ZDCs (as opposed to palm oil production for local markets) is generally associated with industrial oil palm mills (e.g. in Southeast Asia, where smallholders either sell fresh fruit bunches to the oil palm mills for processing³⁸, or are directly associated with industrial plantations through 'plasma schemes')³⁸. However, our models do not account for

smallholder oil palm cultivation that supplies local markets (e.g. 'artisanal' cultivation and milling), as is widespread in much of Africa (where oil palm is native)^{38,39}. Thus, our models are not suitable for assessing the potential for smallholder/artisanal oil palm expansion supplying local markets, which has driven substantial land-use change in Sub-Saharan Africa in recent years⁴⁰. Nevertheless, this local smallholder production is highly unlikely to be covered by ZDCs, as these are implemented across globalised supply chains (Supplementary Information 1), so we expect our estimates of potential locations for zero-deforestation oil palm expansion to be robust. However, if oil palm varieties that maintain high yields in more marginal locations (e.g. in colder or drier locations) are developed and adopted by industrial plantations^{41–43}, bioclimatic suitability for industrial expansion may appear more similar to bioclimatic suitability for artisanal/smallholder production, encompassing a greater total area that includes current marginal locations, particularly in grassy biome regions that are currently too dry^{42,44}. Thus, current models of bioclimatic suitability for oil palm (including the models developed in this article) will require updating if and when the climatic tolerances of industrial oil palm cultivation are broadened.

Omitted drivers of suitability for oil palm expansion

We omitted to include soil properties (such as texture, drainage, and content and availability of nutrients) in our oil palm suitability models, because the majority of tropical soils are suitable for oil palm cultivation, particularly when managed by industrial plantations^{25,39}. We did, however, exclude mangrove ecoregions from our analyses as these are not strictly terrestrial, are liable to encroachment by rising sea levels^{45,46}, and have saline soils that are highly limiting to oil palm yield³⁹. The existing agro-ecological suitability model for oil palm cultivation identified very few locations across the tropics as limited by soil properties, which management could not mitigate: generally sandy soils of fast drainage (e.g. an area of arenosol in the Republic of Congo, Western Congolian forest-savanna ecoregion)²⁵. Thus, soil properties may render certain locations less suitable for oil palm than we have predicted, but these are a minority of our estimated suitable areas for expansion.

Additionally, we have not attempted to account for socio-economic factors that affect the likelihood of oil palm expansion. We have not accounted for the availability of infrastructure that could reduce the costs of oil palm plantation development (e.g. proximity to roads, ports, and factories processing crude palm oil). In

general, presence of road networks substantially increases deforestation and biodiversity loss^{47,48}. The availability of existing infrastructure may be particularly relevant to the potential for irrigated oil palm expansion, because irrigation would require additional infrastructure and increase the costs of plantation development. However, plantations have frequently expanded in remote locations in recent years^{4,49}, and developed necessary infrastructure for operation as part of plantation development (e.g. oil palm mills, minor roads, housing and reservoirs)^{50–52}. Given that proximity to existing settlements and infrastructure could exacerbate the likelihood of conflicts between the plantation and existing local stakeholders, the relationship between existing infrastructure and likelihood for zero-deforestation oil palm expansion is unclear. In addition, it was beyond the scope of our analysis to account for national and regional policies to instigate or prevent oil palm expansion. Many tropical countries have mandates to increase domestic biofuel production and consumption⁵³, which could stimulate oil palm expansion^{54,55} (e.g. in the Colombian Llanos³³). Similarly, many locations outside IUCN class I and II protected areas could be protected from expansion through local policies, if implemented effectively (e.g. as community lands or through restriction of foreign purchasing of land for agriculture). Thus, the actual likelihood of expansion will vary depending on a number of socio-economic factors that we have not accounted for, across the areas that we predict as climatically-suitable for oil palm expansion.

Estimated suitability for irrigated oil palm

Accuracy of our modelled suitability for irrigated-only oil palm is likely to vary across space, because of variation in accuracy of the hydrological data for surplus available water³⁵. The hydrological data predict river discharge less successfully in West Africa than other regions³⁵, and the authors, Sutanudjaja *et al.*, note that their estimates of seasonality in total water storage correlate negatively with previous estimates for the Amazon, Niger, and Nile river basins, which could arise from errors in the previous model or insufficient representation of changes in groundwater and effects of wetlands in the PCRaster GLOBal Water Balance v.2 (PCR-GLOBWB 2) model (which generated the surplus available water data used in our analyses)³⁵. The estimates of water withdrawal generally have high accuracy, but withdrawal by small-scale agriculture, and for domestic and industrial use, tends to be slightly underestimated³⁵, suggesting that actual water availability for irrigation, and thus suitability for irrigated oil palm, may be lower than we

predicted overall in some areas. Moreover, Sutanudjaja *et al.* pooled the availability of desalinated and surface water within $\sim 1^\circ$ zones, and groundwater within $\sim 0.5^\circ$ zones, in order to account for local redistribution of water through space (for which detailed global data are not available)³⁵. This has given rise to visible $\sim 1^\circ$ zones within our maps of suitability for irrigated oil palm cultivation (Extended Data Figs. 3, 4), and suggests minor inaccuracies in the availability of water within and around these zones, because actual water redistribution is likely to vary spatially within these zones, and could be redistributed a greater distance than the zone area in some cases.

In addition, we have estimated potential for irrigation using static (averaged) monthly estimates of surplus available water, but actual water availability is dynamic and would change if irrigation were implemented. The PCR-GLOBWB 2 model includes a two-way interaction between water demand, withdrawal, consumption, and availability, particularly in locations where both demand (e.g. for irrigation) and the return flow of utilised water are high^{35,56}. If irrigation of a new oil palm plantation were implemented, water withdrawal for irrigation would reduce downstream water availability, although some of the water used for irrigation would return and contribute to the downstream supply. It was beyond the scope of our modelling to incorporate any dynamics in hydrology, as we were modelling suitability for oil palm expansion at a single timepoint (representing the current climate). This emphasises the need for local hydrological impact assessments prior to implementing irrigation.

Landcover classification: locations available for oil palm expansion

Accuracy of the landcover data is generally higher than for alternative datasets⁵⁷, and both user's and producer's accuracies for permanent water bodies are high (95% and 87% respectively). However, accuracy is lower for croplands (user's accuracy of 70% and producer's accuracy of 84%) and urban areas (user's accuracy of 77% and producer's accuracy of 76%). There were substantial errors of omission of cropland in Africa (producer's accuracy 65%), and of urban areas in South America (producer's accuracy 61%). Thus, we have likely somewhat overestimated the total area potentially available for oil palm expansion in some locations, particularly in grassy biome areas of Africa where smallholder cropland is common, but also underestimated the available area in other locations.

Estimated oil palm yield

The Spatial Production Allocation Model (SPAM) yield data that we used for estimating oil palm yield in new locations were derived from national production and yield statistics, spatially-disaggregated across the areas deemed suitable for oil palm production according to the Global Agro-Ecological Zones (GAEZ) suitability maps^{44,58}. Any biases shared between the suitability models developed in this article and the GAEZ models (e.g. preference for certain climate types) would therefore have been amplified during the matching of yield values to suitability classes (see Supplementary Figure 25). Additionally, oil palm yield varies substantially depending on a number of factors that we did not account for in our suitability models (e.g. fertiliser input, harvesting frequency, oil palm variety, costs and access to labour and markets), and is also likely to vary within 5' grid-cells³⁹. Thus, our oil palm yield estimates may have some inaccuracies but are likely to reveal overall patterns in expected yield.

Effects of climate change on suitability

Our models of climatic suitability for oil palm are for current (~1985) climate, and we have not addressed how climate change will affect future suitability. An existing estimate suggests that the area of land that is highly suitable for oil palm cultivation will decrease by 22% globally by 2050, owing to increasing drought and temperatures⁵⁹, with the most substantial predicted suitability reductions in Brazil and Colombia⁵⁹. Climate change will also affect oil palm cultivation through rising sea levels⁶⁰, changes to oil palm pests and diseases⁶¹, and a wide range of socio-economic impacts (among other factors)⁶². However, overall impacts of climate change on oil palm are highly uncertain: there is substantial variation and uncertainty in projected changes to precipitation across the Tropics⁶², and the degree to which carbon dioxide fertilisation may enhance plant water-use efficiency and reduce the impacts of drought is unclear^{63,64}. Thus, it is likely that some of the locations we predict as suitable for expansion will not have long-term viability under climate change, but the extent and intensity of impacts is highly uncertain.

Determination of areas suitable for zero-deforestation expansion by biome

Biome and ecoregion classification

Some ecoregion boundaries for areas with which we are familiar appear erroneous (e.g. Northeast Congolian lowland forests extend into an area of savanna; a ‘finger’ of savanna in southern Gabon is mispositioned and classified as moist forest in our analyses), in line with frequent mis-classification of tropical grassy biomes and dry forests^{14,15,18,65}. This has reduced our estimate of the total area of tropical grassy and dry forest habitat suitable for expansion under ZDCs, and inflated our estimate of moist forest habitat suitable for zero-deforestation oil palm expansion. We did not attempt to manually correct any ecoregion boundaries, because systematic error correction would have required consultation with experts for every tropical region. The Terrestrial Ecoregions of the World map¹⁹ was developed by a consortium of scientists, and is, to our knowledge, the most up-to-date map of grassy and dry forest biome locations globally.

Estimation of locations protected under ZDCs

We estimated locations likely to be protected under ZDCs, according to the HCV-HCSA, by applying generic thresholds for vegetation structure globally, although in practice, habitat protection varies case-by-case, with the presence of HCVs considered alongside woody vegetation structure (see Main Article Methods and Supplementary Information 1 for details). The vegetation datasets that we used to estimate protection under ZDCs (above-ground biomass^{66,67} and canopy closure⁶⁸) are for 2010, so subsequent deforestation will have taken place in some locations, leading to overestimation of areas that would be designated as protected under ZDCs (mostly in moist forest, where estimated protection was most extensive). We noticed that some areas that we estimated as protected under HCS were classified as intensively-managed pasture in Colombia and Brazil (pasture data for 2018 and 2020 respectively: see Supplementary Information 2), suggesting that these locations were deforested since 2010, or suggesting inaccuracies in the data. Locations that were deforested since 2010, and consequently misclassified as ‘protected’ under ZDCs in our analysis, would not necessarily be available for oil palm expansion, as they are likely to be under use as cropland or pasture (additionally, any deforestation since 2018 would not comply with the RSPO Principles

and Criteria⁸: Supplementary Information 1). Thus, deforestation that we have not captured in our analyses is unlikely to affect our conclusion that grassy biomes and dry forests are likely to undergo oil palm expansion in compliance with zero-deforestation commitments.

We were unable to map HCVs, as identification of local biodiversity and socio-cultural values would require on-the-ground surveys and assessments. For areas of tropical moist forest, we expect that our estimates of protection based on vegetation structure have also captured the vast majority of biodiversity HCVs, because biodiversity HCVs are likely to occur in the intact or less-degraded forest that we estimate as protected by ZDCs^{69–72}. Moreover, the uncertainty for the above-ground biomass data, which we used to determine habitat protection under ZDCs, tends to be low for areas of moist forest, but higher in moist savanna areas in Africa and dry forests in Latin America⁷³. Thus, we expect that actual protection under ZDCs is likely to vary more substantially around our estimates for grassy and dry forest biomes than for moist forest; indeed, our review of recent assessments in these biomes highlighted variation in the extent of habitat protected owing to the current lack of detailed guidance (Supplementary Information 1).

We were also unable to account for land ownership and community use of land, which could result in protection or classification of land as HCV, depending on the outcome of HCV assessments and community consultations conducted as part of the Free, Prior and Informed Consent process (see Supplementary Information 1). It is possible that more extensive areas would be classified as protected for socio-cultural HCVs or other aspects of community land use in dry forests and grassy biomes, because of the extensive links between human use and these habitats^{14,65,74,75}, than in moist forest. Thus, there are uncertainties in our total estimation of habitat protected under ZDCs in tropical grassy biomes and dry forests in particular. Nevertheless, oil palm companies are beginning to target grassy habitats in order to reduce the likely extent of protected (HCV/HCS) habitat within plantations (Supplementary Information 1), highlighting the need for improved guidance to identify valuable biodiversity for protection in these biomes, and for improvements to the current practise of Free, Prior and Informed Consent^{76,77}.

Sensitivity analyses including intensively-managed pasture

It is possible that there are higher errors of omission in the intensively-managed pasture maps for Colombia and Brazil in grassy biomes than forested biomes, because the greater contrast between natural forest

vegetation and pasture may render higher accuracy of pasture classification in forest biomes. The data for Colombia (IDEAM landcover) were classified from satellite imagery, followed by further manual classification using a combination of sources, including consideration of the biome type²¹. It is therefore possible that the classification applied a precautionary approach and classified some pastures as natural grassy vegetation in the Llanos. The MapBiomas data for Brazil^{22,23} have high errors of omission of pasture (~70% producer's accuracy). It is therefore likely that our sensitivity analysis in Supplementary Information 2 did not account for the full extent of pasture in the suitable areas for oil palm in these countries. However, we do note that the majority of mapped pasture in the Cerrado is in the southern part of the biome, which is not suitable for oil palm. Additionally, even if our sensitivity analysis underestimated the full extent of intensively-managed pasture overlapping with areas climatically-suitable for oil palm, most other countries are likely to have smaller areas of intensively-managed pasture than Brazil and Colombia²⁴, so any underestimation of pasture in our sensitivity analysis would be less relevant at a global scale. Recent deforestation for pasture has predominantly occurred in Latin America⁷⁸, and extensive grazing of natural (or semi-natural) vegetation, as opposed to planted, improved pasture, is widespread across Africa^{14,74}. Thus, the (hypothetical) incorporation of intensively-managed pasture into our global results would likely have little impact outside Latin America, and the most extensive areas of pasture are likely to be in Colombia and Brazil⁷⁸, which we have accounted for in Supplementary Information 2.

Vertebrate richness loss

We estimated vertebrate richness loss from expansion by calculating the sum of refined vertebrate range maps that overlapped with a given grid-cell centre, at the resolution of 5' (~10 km at the Equator), which we used for all analyses. However, grid-cell resolutions <2° can overestimate richness calculated from species range polygons⁷⁹, although our refinements of the range polygons by habitat type are likely to reduce this. Nevertheless, we expect the broad patterns of richness loss across space, and thus among biomes and continents, to be robust^{79,80}, because our richness estimates follow established patterns of species richness and potential loss on conversion to agriculture across the Tropics^{80,81}.

Additionally, the areas potentially suitable for expansion in moist forest are likely to be highly degraded, given their low aboveground carbon (and are more frequently intensively-managed pasture in comparison

to suitable areas in grassy and dry forest biomes: Supplementary Information 2). However, the areas we identify as suitable for expansion under ZDCs in tropical grassy and dry forest biomes include both unique, ancient habitats that support considerably greater diversity than highly-degraded tropical moist forest⁸², and degraded habitats, where expansion could occur with low carbon emissions and biodiversity loss^{83,84}. We estimated vertebrate occurrence by assuming that habitat was intact, so we likely systematically overestimated the vertebrate richness loss and range reduction from expansion in moist forest, where no locations suitable for expansion under ZDCs are intact, in comparison to grassy biomes and dry forests, where some suitable locations are highly likely to be intact.

Supplementary Information 7: additional methodological details for oil palm

suitability models

Selection of climatic predictors of oil palm suitability

We selected five climatic predictors known to correlate with oil palm growth and yield³⁹: mean annual temperature (MAT, °C), minimum temperature of the coldest month (Tmin, °C), mean annual precipitation (MAP, mm), an annual moisture index (AMI), and maximum water deficit (MWD, mm). We downloaded three of these (MAT, Tmin and MAP) from WorldClim, calculated AMI as the ratio of mean annual precipitation to mean annual potential evapotranspiration (PET, calculated according to the Hargreaves Equation⁸⁵)^{86,87}, and we calculated MWD as the greatest cumulative deficit in mean monthly rainfall, where a deficit is a month with rainfall < monthly PET, representing the length and severity of dry season⁸⁸. Some of these predictors were inter-correlated (Supplementary Table 8), so we ran models with two uncorrelated predictors, Tmin and MWD, which represent the most strongly limiting climatic factors for oil palm growth and yield³⁹.

Supplementary Table 8. Inter-correlation of the five climatic predictors, calculated using Spearman's Rho, with $r > 0.7$ (shown in bold) indicating high inter-correlation. The inter-correlation values shown are for the dataset used in the final model (see below), but were similar across all datasets used in model calibration.

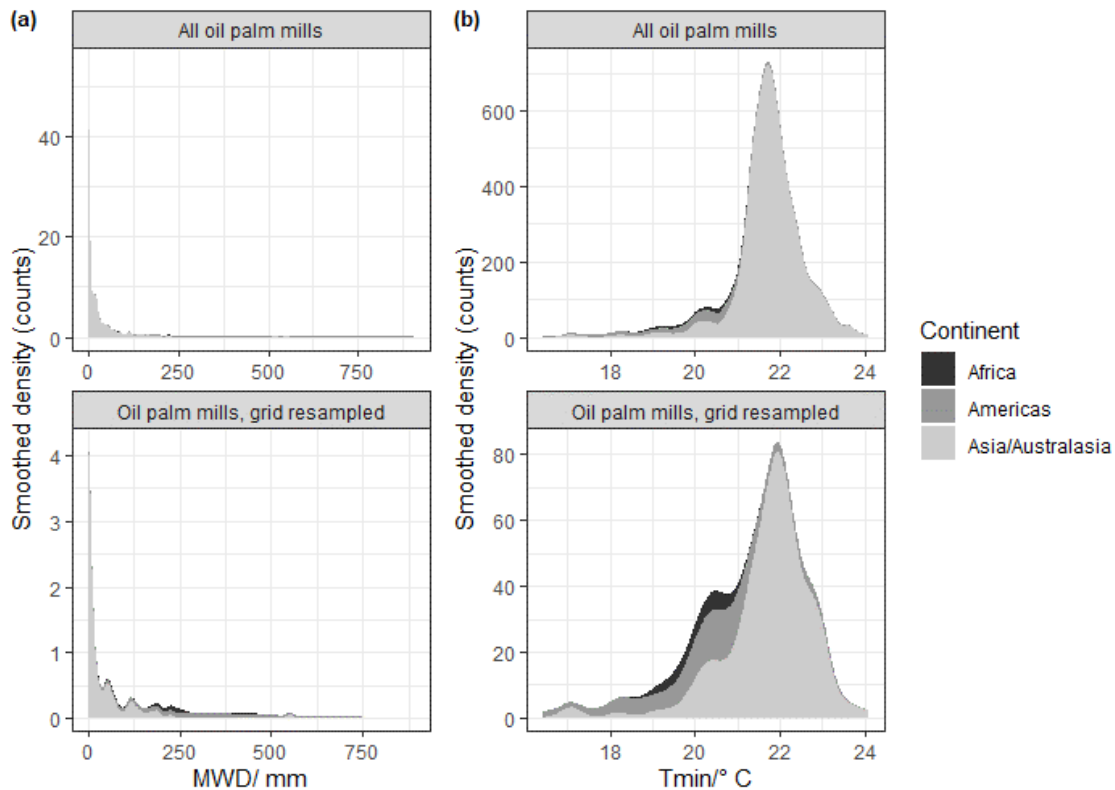
	MAT	Tmin	MAP	MWD	AMI
MAT	1				
Tmin	0.862	1			
MAP	0.164	0.394	1		
MWD	0.038	-0.230	-0.811	1	
AMI	0.0857	0.352	0.972	-0.812	1

Evaluation of oil palm suitability models

To obtain a measure of model transferability, indicating model accuracy during spatial prediction, we calculated the moving-window Continuous Boyce Index⁸⁹ for cross-validation, using the function “*ecospat.boyce*” in the R package *ecospat* version 3, by training each model on two out of three spatially distinct portions of the data (Americas, Africa and Asia/Australasia), and testing it on the remaining portion. As rainfall and temperature distributions differ between these continents (see Supplementary Figure 20 for the distribution of climate values at oil palm mills in each continent), this provides a test of model performance when predicted to novel climatic environments from the training data.

For evaluation of the full models, we compared our model projections to a largely-independent dataset of oil palm plantations in 23 countries³⁰. We rasterised these polygons of oil palm plantations to the resolution of our model outputs (5') before converting them to points, and removed potentially irrigated locations using the same methods as for the training data of oil palm mills (we excluded all locations within 10 km of non-zero water withdrawal for irrigation³⁵ and in regions with widespread irrigation of oil palm⁹⁰; see Methods for oil palm presence locations in Main Article). To assess unclassified (i.e. continuous model outputs) full model performance, we calculated the moving window Continuous Boyce Index⁸⁹ as for the cross-validation, testing our continuous suitability predictions against these oil palm plantations³⁰ and 50,000 randomly selected background points. The Continuous Boyce Index represents the correlation between the ratio of predicted to expected presence points (for a given suitability value or bin, the ratio of presences predicted by the model to the number of points expected to have the suitability value given chance alone, i.e. based on the relative area of habitat that has the suitability value of interest) and the

projected suitability values⁸⁹. For low projected suitability values, a good model has a low ratio of predicted to expected presence points; and for high projected suitability values, a good model has a high ratio of predicted to expected presence points; thus the relationship between these provides a measure of model performance. The Continuous Boyce Index can have values ranging from -1 to 1 (where negative values indicate an incorrect model, that tends to predict absences in locations of testing presence data; 0 indicates a model similar to chance alone; and positive values indicate a good model, that predicts presences in locations of testing presence data), and is highly correlated with metrics for evaluating species distribution models that incorporate both presence and absence data, such as Area Under the Curve (AUC) of false-positive to true-positive ratios⁸⁹.



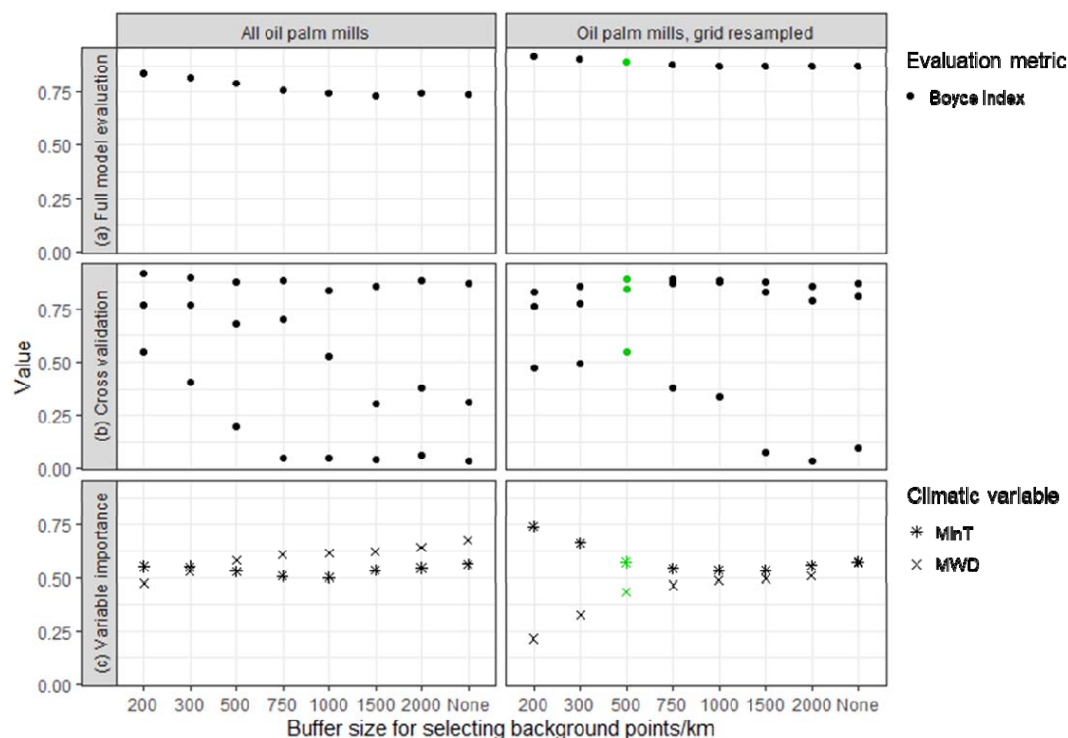
Supplementary Figure 20. Distribution of temperature and rainfall values for (a) full oil palm mill dataset and (b) systematically resampled oil palm mill dataset (reducing spatial autocorrelation by resampling at a coarse grid-cell resolution of 1°, or ~111 km at the Equator). Climate values at oil palm mill locations in Asia/Australasia dominate the overall distribution, owing to the high number of mills in Indonesia and Malaysia. Grid resampling reduces this, which leads to improved model predictive power for (see below).

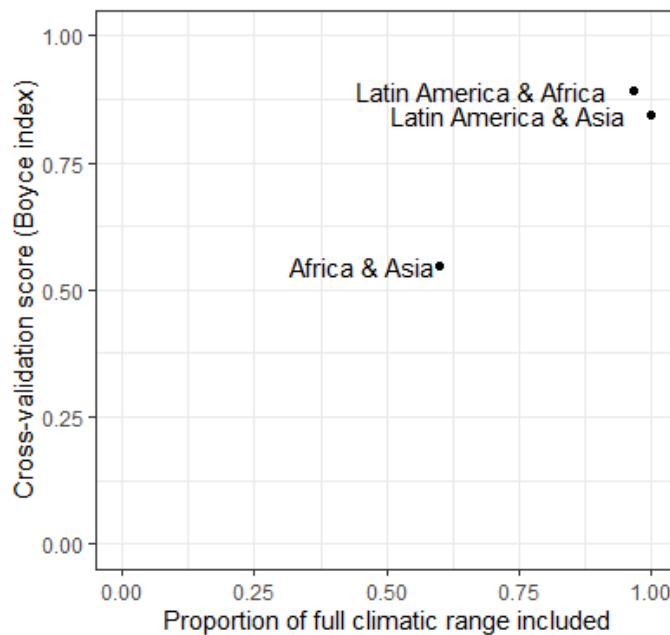
Selection of best model

We selected the top model using the following criteria: high full model performance (high continuous Boyce Index score); high transferability to new environments (consistently high continuous Boyce Index scores when trained and tested on spatially distinct portions of the data); and relatively high importance of both climatic predictors (to avoid domination of the model by a single predictor)⁹¹.

We found that all models accurately predicted suitability for oil palm (full-model continuous Boyce Index 0.729-0.918 when tested with largely-independent oil palm plantation locations³⁰), but that models tended to vary in their transferability (cross-validation Boyce Index 0.004-0.919) and relative variable importance (Supplementary Figure 21). Models with correction for spatial autocorrelation (by grid resampling the training data) had higher transferability (cross-validation continuous Boyce Index) than models without the correction, and higher full model accuracy (full model continuous Boyce Index). Of the models with correction for spatial autocorrelation, smaller background buffer sizes conferred greater transferability, with the highest transferability for the model with 500 km background buffer size, and smaller background buffer sizes also conferred greater full model performance (Supplementary Figure 21). We therefore selected the model with a 500 km background buffer size and correction for spatial autocorrelation as the best model, which has the highest transferability (continuous Boyce Index 0.546-0.892 for cross-validation), as well as a high full-model score (continuous Boyce Index, 0.890), and is not dominated by a single climatic predictor (Supplementary Figure 21).

Whilst the lowest cross-validation continuous Boyce Index score for our selected best model is relatively low (0.546), we expect this score to represent a conservative estimate of full model transferability, because the most highly-scoring cross-validations for this model were trained on data which spanned a range of climate space close to that of the full model (Supplementary Figure 22; also see Supplementary Figure 20 for differences in distributions of climate values at mill locations in each continent). We therefore expect the full model to have transferability similar to its higher cross-validation scores (0.846, 0.892).





Supplementary Figure 22. Cross-validation continuous Boyce index scores, in comparison to the proportion of the full climatic range of training data encompassed by each subset, for each cross-validation run of the best model. Labels correspond to the continents which were used to train each run (Latin America, Africa and Asia/Australasia); the remaining continent was used for testing. The cross-validation runs which most accurately predicted suitability for oil palm (continuous Boyce index) are those which were trained on data spanning a high proportion of the climatic range occupied by the full training data, suggesting that the full model (trained on the full climatic range) has high transferability. We calculated climatic range as the minimum convex polygon for scaled climatic variables (Tmin and MWD).

Thresholding of oil palm suitability models

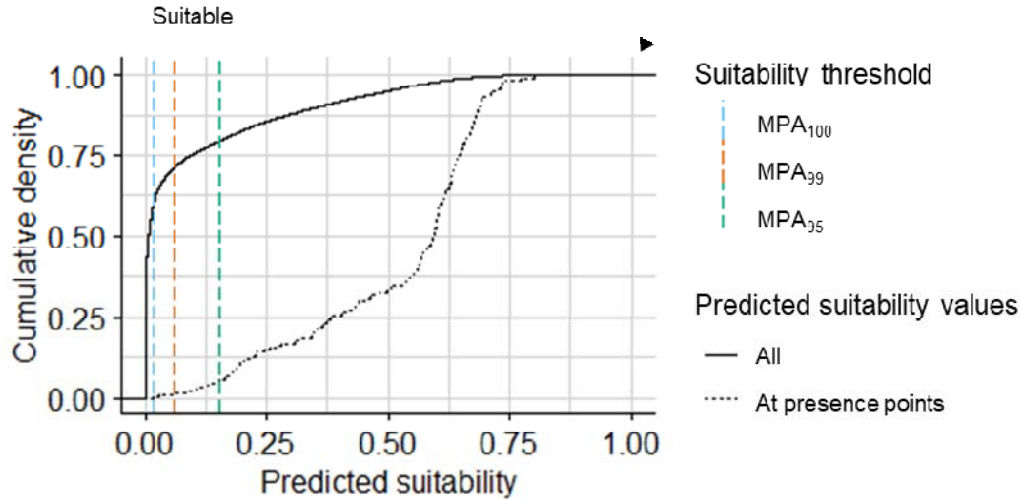
We used Minimal Predicted Area thresholding^{89,92} to classify the continuous suitability projections of our best model (0-1), based on the distribution of continuous projected suitability values at oil palm mill (i.e. 'presence') locations used to train the model (Supplementary Table 9, Supplementary Figure 23). To test the sensitivity of our projected climatically suitable area to the threshold used to determine suitability, we used three Minimal Predicted Area thresholds to classify our best model. We classified locations as 'suitable' where the predicted suitability value was greater than the minimum predicted suitability for a given percentile of the oil palm mills used to train the model (thresholds for suitability ranged 0.018 – 0.152; Supplementary Figure 23), and we classified all other locations as 'unsuitable'. Additionally, we classified the suitable locations into three classes of expected productivity, with equal percentiles of predicted values at the oil palm mill locations used to train the models (Supplementary Table 9). We later relate these expected productivity classes to oil palm yield values (Supplementary Figure 25).

We compared the performance of the three different classifications of our best model using the True Skill Statistic (TSS)⁹³ and the Jaccard coefficient, to compare our predicted suitable area to that of an agro-ecological model of suitability for oil palm²⁵. We calculated TSS using oil palm plantations that are largely-independent of the oil palm mills dataset used to train the models (a map of global tree plantations compiled from mixed sources, largely from remote sensing, with a small subset of oil palm plantations verified against the oil palm mills dataset used to train the models)³⁰ as testing presence locations, and randomly sampled points outside these plantations as testing pseudo-absence points, in equal number to the testing presence locations. We calculated the Jaccard coefficient for comparison of our classified model with an agro-ecological model of suitability for oil palm cultivation, in which suitability for oil palm cultivation was determined by expert knowledge of suitable ranges of a large number of biophysical variables for cultivation²⁵. This model incorporated many more biophysical variables for oil palm suitability than we could examine (because intercorrelation of variables did not present issues for the methodology), so thus provided a suitability model for comparison with our results that was based on contrasting methods.

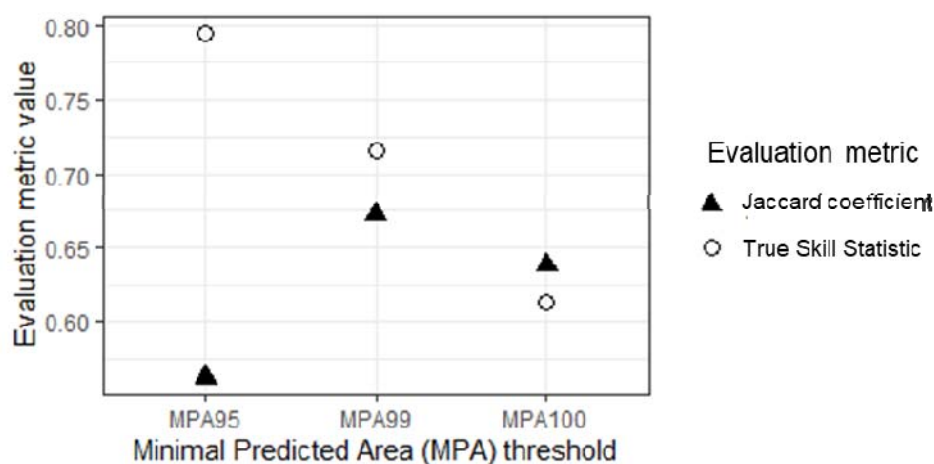
We found that TSS is highest for the model classified using MPA₉₅ (i.e. with the smallest total predicted area), whereas the Jaccard coefficient is highest for the model classified using MPA₉₉ (i.e. with an intermediate predicted area) (Supplementary Figure 24, Extended Data Fig. 2). TSS incorporates both sensitivity and specificity, and all three of our final model classifications have high sensitivity (0.996-1.00), the TSS scores of our final model classifications are penalized by their specificity (0.613-0.798). However, our randomly sampled pseudo-absence points used to test the model could be suitable for oil palm cultivation in practise, but not planted with oil palm for a variety of reasons. Our TSS scores are therefore likely to underestimate the performance of our models. We therefore present figures in the Main Article using the model thresholded at MPA₉₉, at which the two validation measures (TSS and Jaccard coefficient) are most closely equalised, and at which the Jaccard coefficient is highest, and present uncertainty of results from model thresholding in Supplementary Information 3 and 4. As a sensitivity test to our reliance on a single suitability model, we also perform analyses using the agro-ecological model²⁵, which we present in Supplementary Information 3-5.

Supplementary Table 9. Percentiles of predicted values at presence locations used to classify the continuous best model outputs (0-1) into suitable and unsuitable locations, with three classes of expected productivity, according to Minimal Predicted Area thresholding.

Minimal Predicted Area threshold for suitability	Relative area predicted as suitable	Unsuitable	Suitable: expected productivity		
			Low	Medium	High
MPA ₉₅	Smallest	$\leq P_{95}$	$>P_{95}$ and $\leq P_{63.3}$	$>P_{63.3}$ and $\leq P_{31.7}$	$>P_{31.7}$
MPA ₉₉	Medium	$\leq P_{99}$	$>P_{99}$ and $\leq P_{66}$	$>P_{66}$ and $\leq P_{33}$	$>P_{33}$
MPA ₁₀₀	Largest	$\leq P_{100}$ (minimum)	$>P_{100}$ and $\leq P_{66.7}$	$>P_{66.7}$ and $\leq P_{33.3}$	$>P_{33.3}$



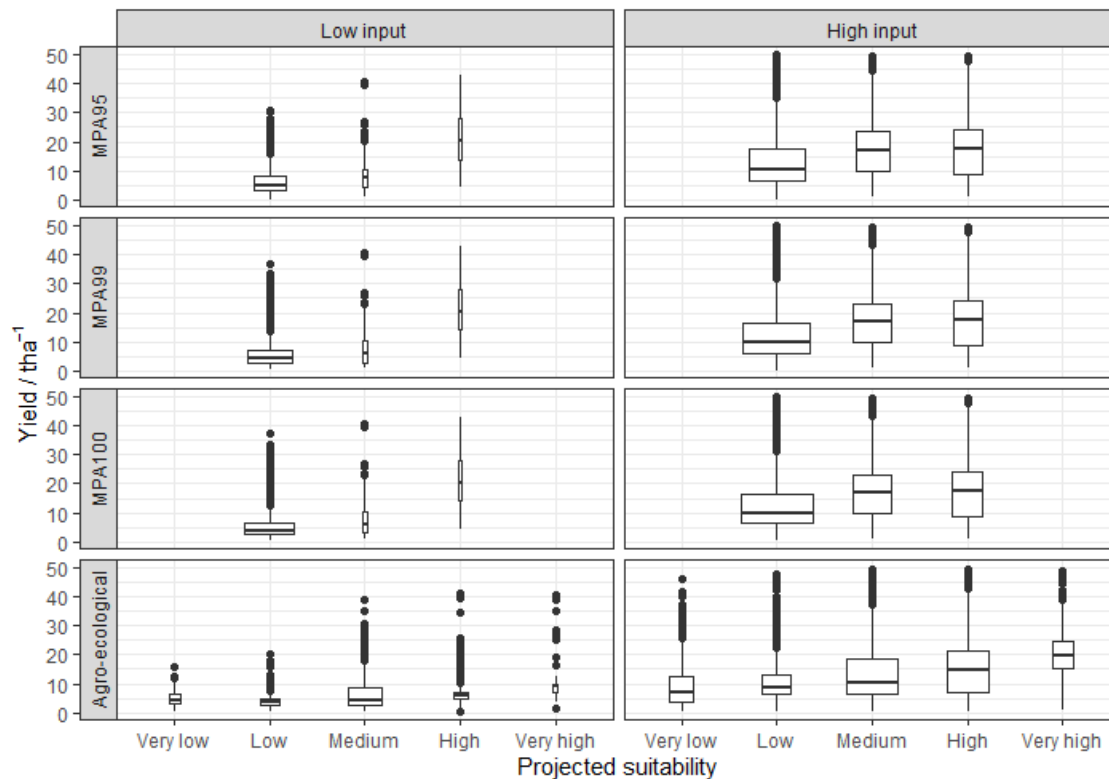
Supplementary Figure 23. Cumulative density of continuous predicted suitability values of the best model, at presence points (oil palm mills) used to train the model (dotted line), and for all grid-cells in the tropics (solid line); with the three MPA thresholds used to classify the output into suitable/unsuitable. Cumulative density refers to number of oil palm mills for the presence points used to train the model; and to number of grid-cells (in WGS 1984 unprojected coordinate system) for all predicted values.



Supplementary Figure 24. Evaluation metrics to compare three Minimal Predicted Area thresholds for classifying the continuous suitability predictions of the best model into suitable and unsuitable locations for oil palm cultivation. We calculated TSS using largely-independent oil palm plantations³⁰ as testing presence locations, and random pseudo-absence points. We calculated the Jaccard coefficient for comparison of our classified model with an agro-ecological model²⁵.

Estimating oil palm yield from projected suitability values

Our oil palm suitability projections represented expected suitability for oil palm cultivation, from which we were able to derive values of expected oil palm yield for each of the three suitable classes for oil palm cultivation (low, medium and high; see Supplementary Table 9). We overlaid our maps of the three suitability classes with maps of estimated oil palm yield for the year 2010⁹⁴, which were produced by spatial allocation of reported crop production statistics from global administrative units. We compared our species distribution model outputs with all grid-cells of oil palm yield, where actual yield $>0 \text{ tha}^{-1}$ (i.e. production was occurring; Supplementary Figure 25).



Supplementary Figure 25. Oil palm yield values for each projected suitability class, shown for low and high fertiliser input cultivation, for each of the three thresholds used to classify the best model (MPA₉₅, MPA₉₉, MPA₁₀₀; see Supplementary Table 9), and for the agro-ecological suitability model²⁵. The rainfed oil palm yield data are derived from national crop production statistics, spatially disaggregated globally, for the two production systems of low and high fertiliser input⁹⁴. We have re-named the five suitability classes from ²⁵ to correspond with those in our models for plotting purposes; note that these were developed by contrasting methods. Central bars show the median, lower and upper hinges show the first and third quartiles respectively, whiskers extend to the maximum and minimum values within 1.5*inter-quartile range, outliers are plotted individually, and boxplot width relates to sample size within each group (proportional to the square-root of the within-group sample size). N = 138,107 5-arc minute grid-cells for all groups; smallest n = 71 for low input, high expected productivity, all species distribution models; largest n = 21,429 for high input, low expected productivity, MPA₁₀₀. We excluded all grid-cells with outlying yield >50 tha⁻¹ (n = 727 across all plots) as these appear to be erroneous overestimates³⁹. Note that results for MPA₉₉ are reported in the Main Article.

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