

1 **The global cropland sparing potential of high-yield farming**

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14 The global expansion of cropland exerts substantial pressure on natural ecosystems and is expected to
15 continue with population growth and affluent demand. Yet, earlier studies indicated that crop
16 production could be more than doubled if attainable crop yields were achieved on present cropland.
17 Here we show based on crop modelling that closing current yield gaps by spatially optimizing fertilizer
18 inputs and allocation of 16 major crops across global cropland would allow to reduce the cropland area
19 required to maintain present production volumes by nearly 50% of its current extent. Enforcing a
20 scenario abandoning cropland in biodiversity hotspots and uniformly releasing 20% of cropland area for
21 other landscape elements, still enabled reducing the cropland requirement by almost 40%. As a co-
22 benefit, greenhouse gas emissions from fertilizer and paddy rice, as well as irrigation water
23 requirements are likely to decrease with reduced area of cultivated land, while global fertilizer input
24 requirements remain unchanged. Spared cropland would provide space for substantial carbon
25 sequestration in restored natural vegetation. Only targeted sparing of biodiversity hotspots supports
26 species with small-range habitats, while biodiversity would hardly profit from a maximum land sparing
27 approach.

28 Globally, agricultural activity and the continuous expansion of croplands impose wide-ranging
29 environmental burdens on natural ecosystems. Intensively managed cropland is characterized by
30 excessive and imbalanced applications of N and P, whereas low-input agricultural systems result in
31 nutrient-poor soils and low yields^{1,2}. Globally, freshwater use in agricultural irrigation consumes about
32 70% of total water withdrawals³, and cropland farming contributes about 5% of global anthropogenic
33 GHG emissions, mainly through emissions of paddy rice methane (CH₄) and soil nitrous oxide (N₂O) from
34 added mineral N fertilizer and manure⁴. Biodiversity loss is challenging to quantify, but estimated to
35 exceed safe boundaries, primarily due to habitat loss⁵. Most recently, the land sparing debate⁶⁻⁹ has
36 gained new momentum from the Half Earth project¹⁰ that aims to return half the area of land under
37 anthropogenic management to natural land cover to restrict biodiversity losses and abate other
38 externalities of anthropogenic land use⁶. The need for this type of strategy is even more urgent, given

39 the increasing global demand for agricultural products^{11,12}. Yet, biophysical benchmarks for ambitious
40 land sparing targets and associated externalities remain virtually unknown.

41 Earlier studies have suggested that cropland will likely further expand in the future due to population
42 growth and climate change¹³, while effective cropland sparing would need to involve measures such as
43 dietary change to reduce crop demand^{14–16}. In contrast, global nutrient input intensification, crop
44 switching, and expansion of irrigated land may increase global crop production volumes by up to 150%
45 for major crops^{17–21} depending on whether and how these strategies are combined. Intensification has
46 also been identified in conceptual and semi-quantitative studies as a promising strategy for the
47 abatement of land conversion, expansion of natural land cover^{7,8,22}, and reduction of environmental
48 impacts, depending on management specifics²³. However, while average yields for major crops have
49 been increasing globally during the past decades, they have stagnated or decreased in various parts of
50 the world and the present pace in yield gains is considered insufficient to meet future crop demand²⁴.
51 Persisting global yield gaps in major crops have been attributed foremost to nutrient deficits and to a
52 lesser extent to insufficient water supply¹⁹.

53 **Estimation of global cropland requirement**

54 In this study, we quantified the potential of land sparing through intensification of nutrient inputs to
55 meet plant requirements and optimal spatial allocation of 16 major crops to estimate a lower boundary
56 of cropland requirement for meeting present crop demands (Figure 1). We used the established global
57 gridded crop model EPIC-IIASA¹⁷ to estimate non-nutrient limited crop yields, with and without sufficient
58 irrigation water supply, depending on land use information to avoid expansion of irrigated land. EPIC-
59 IIASA combines the process-based agronomic model Environmental Policy Integrated Climate^{25,26} (EPIC)
60 with a global data infrastructure gridded at 5' x 5' resolution. The 5 arcmin grid cells with identical soil
61 texture and topography classes and located within the same 30' x 30' climate grid and administrative
62 region were aggregated to simulation units. The resulting 120000 simulation units thus vary in size from
63 5' x 5' to 30' x 30' or total corresponding surface areas from 69 to 2500 km² near the equator depending
64 on input data heterogeneity (Supplementary Figure 19; Supplementary Text 2). Maps of present
65 cropland were aggregated from 5' x 5' source data to the same spatial scale of simulation units to
66 provide consistent input data on area and crop yields for the cropland allocation model.

67 Crop distributions were spatially allocated using a linear optimization algorithm under three simple
68 criteria that comprised minimizing the extent of current global cropland; maintaining 2011-2015 global
69 production volumes for each crop; and avoiding novel expansion of cropland locally. This was done (I)
70 allowing the full use of the current cropland in each simulation unit to create a global “maximum land
71 sparing” (MLS) scenario or (II) with a complete release of annual cropland in biodiversity hotspots and a
72 forced release of at least 20% of cropland area in each simulation unit to create a “targeted land
73 sparing” (TLS) scenario. The first serves for providing a benchmark of what extent of land sparing is
74 technically feasible given present agricultural technologies. The latter provides a benchmark for a global
75 scenario focused on habitat restoration for threatened species in hotspots combined with the
76 establishment of uniformly distributed landscape compartments as wildlife habitats²⁷ or buffers for
77 adverse impacts of high-input agriculture²⁸. Two supplementary scenarios serve for assessing how
78 constraining crop distributions to their present growing regions (scenario MLS_{ncs}) or allowing crops to
79 cover a maximum of 34% cropland in a simulation unit – indirectly increasing crop diversity locally -
80 (scenario MLS_{wcd}) affect results in the MLS scenario. As such, these scenarios are hypothetical, leaving

81 aside policy- and socio-economic implications, but they can nonetheless inform decision-makers about
82 the biophysical feasibility of ambitious land sparing targets. While the focus of our analysis is on
83 cropland sparing potential, we also quantified, based on model results directly or auxiliary datasets,
84 changes in requirements for N and P fertilizer and irrigation water; selected GHG emissions; carbon (C)
85 storage in resultant, expanded areas of natural vegetation; and potential increase in natural habitats for
86 wildlife. Further details are provided in the Methods section.

87 **Global cropland sparing potential and spatial patterns**

88 Intensification and optimal crop reallocation under the MLS scenario decreased the cropland
89 requirement to nearly 50% of the baseline for all crops and to 46% for the 16 selected crops (Figure 2).
90 The greatest sparing potential was for typical smallholder crops, such as sorghum and pulses, with >80%
91 of land released (Supplementary Table 1). Lower land gains (<50%) were estimated on the other hand
92 for crops for which production tends to be highly intensified, such as maize, rice, soybean, wheat, and
93 sugar crops. The TLS scenario also reduced cropland area to remaining 62% of the baseline, indicating
94 that radical reductions in cropland area are not restricted to a narrow set of solutions, and high yields
95 may be sustained across large regions for most crops. Results were highly comparable for a wider range
96 of land use and attainable crop yield datasets, showing that our estimates are robust within the limits of
97 available data (Supplementary Text 1 and Supplementary Text 2).

98 Contiguous regions of cropland release in the MLS scenario are primarily located in agro-climatically
99 unfavourable regions, such as the Western USA, Central Asia, and Sahel, but also in productive regions
100 such as large parts of South Asia and in southern Russia (Figure 3b). Despite local concentrations of
101 cropland in most productive areas, patterns of total fresh matter production volumes per continent
102 remained comparable to the baseline with substantial and moderate gains in Africa and Asia at the cost
103 of Europe and especially America (Supplementary Figure 4). The TLS scenario resulted in a wider
104 distribution of cropland (Figure 3c), which is mostly driven by implicit cropland release in this scenario
105 (Supplementary Figure 5). About 20% global annual cropland were released in biodiversity hotspots and
106 globally uniform a minimum of 20% in the remainder of the cropland area (corresponding to 17% of
107 global annual cropland). This left only a minor fraction of areas released subject to land use efficiency
108 gains. These were again mostly located in agro-climatically adverse regions such as desert borders.

109 **Drawbacks of and barriers to cropland sparing and concentration**

110 The release of cropland over large contiguous regions in both scenarios may entail substantial socio-
111 economic implications with respect to livelihoods, as shown also in recent research on global
112 conservation targets²⁹, and may affect regional food self-sufficiency. Yet, the fact that patterns of
113 cropland release are largely contrasting among the two scenarios indicates that a mixed approach,
114 including the sparing of cropland in biodiversity hotspots only to the degree necessary for maintaining
115 wildlife habitats, could be implemented to balance socio-economic trade-offs with land sparing benefits
116 among regions. Comprehensive global research on social acceptance for land sparing is lacking and
117 certainly context-dependent. Conceptual studies suggest a range of policy measures from financial
118 compensation for abandoned cropland to payments for restored vegetation management and further
119 knowledge transfer and infrastructure for improved crop management to steer policy implementations
120 of intensification for cropland sparing⁸. Notwithstanding, the reconciliation of global targets with local
121 and regional stakeholder demands will require holistic approaches bridging these scales, which likely

122 poses the greatest challenge in achieving effective global land sparing^{30,31}. And any further
123 concentration of crop production will increase the already extensive reliance of large parts of the world
124 on food imports, amplifying the requirement for resilient global trade systems³².

125 Spatial shifts in crop cultivation areas are a constant process³³ and have been subject to disruptive
126 regime shifts for specific crops and regions in the past³⁴. Both do not necessarily follow patterns of
127 domestic demand but serve often for income generation and diversification³⁵. However, the adoption of
128 new crops or farming practices in general requires more information and policy interventions in regions
129 in which they are not practiced so far. Analysing the spatial occurrence of crops in both scenarios herein
130 reveals that <20% of resulting cropland area are occupied by crops in simulation units in which they are
131 presently not grown, and <1% in major Koeppen-Geiger climate regions and countries in which the
132 respective crops are presently not cultivated (not shown). Constraining the cropland allocation model to
133 only assign crops in the MLS scenario to simulation units in which they are presently cultivated while
134 allowing their local acreage to change (supplementary scenario MLS_{ncs}) results in 1% lower land sparing
135 potential (Supplementary Figure 6). This indicates that the free shifting of crops is not a key mechanism
136 behind our findings and that crops are already cultivated in regions in which they are or can be most
137 productive. Yet, areas of crops presently cultivated for cultural and historic reasons may be given up in
138 the model. In this context, it needs to be stressed that our study aims to provide information on the
139 cropland that is essentially required to meet present demand and should not suggest to abandon
140 agriculture in places in which it provides important local cultural and social services.

141 Furthermore, optimizing cropland distribution based on land use efficiency may result in wide-spread
142 monocropping systems with higher vulnerability to biotic and abiotic stressors, high requirement for
143 pest control agents, and little provision of on-farm biodiversity. To address the impact of enforcing crop
144 diversity on cropland sparing potential, we evaluated a supplementary scenario allowing only up to 34%
145 of each simulation unit to be covered by a specific crop in the MLS scenario (supplementary scenario
146 MLS_{wcd}). This reduces the cropland sparing potential by 5% relative to the present extent
147 (Supplementary Figure 6) while resulting in the co-occurrence of 2-3 crops in most simulation units
148 (Supplementary Figure 8). The concurrence of several crops translates into the feasibility of inter-annual
149 crop rotations, which are a key measure for integrated crop protection³⁶. Due to the capped area share
150 of single crops, simulation units with only one or two crops attributed can similarly implement rotating
151 inter-annual fallows. This supplementary scenario also results in higher crop diversity at the continental
152 scale, especially in Europe, compared to the other land sparing scenarios (c.f. Supplementary Figure 7
153 and Supplementary Figure 4).

154 **Associated changes in externalities**

155 Reductions in cropland area, combined with optimal N and P fertilization, may reduce or at least not
156 exacerbate major agricultural input requirements and externalities globally (Figure 4). We found that
157 total N and P application would increase by only 6% in the MLS scenario, and decrease by 1-4% in the
158 TLS scenario. This includes the presently inevitable prevalence of substantial nutrient losses such as
159 leaching and erosion. Our results confirm that current excessive and imbalanced nutrient supply
160 outweigh soil nutrient mining² and that the reduction in area of nutrient-mined soils, which can be
161 expected to increase the exogenous nutrient demands for closing yield gaps in our scenarios, can be
162 compensated by reduced applications of N and P tailored to meet crop demands in areas of presently
163 excessive fertilization (Supplementary Text 3). Yet, locally, foremost N and partly P surpluses may well

164 exceed those reported for around the year 2000, depending on which input sources are considered
165 (Supplementary Figure 11). Especially the MLS scenario results in a shift towards higher local N surpluses
166 per area whereas the TLS scenario closely resembles past patterns of conservative estimates neglecting
167 inputs from manure, deposition, and biological fixation. For the TLS scenario, low P surpluses occur
168 more frequently, in part due to the larger extent of remaining cropland compared to the MLS scenario,
169 which again exhibits a more frequent occurrence of moderate to high surpluses. Notably, the latter is
170 also caused by a larger fraction of cropland remaining in tropic regions in which weathered soils with
171 high P fixation occur more frequently³⁷.

172 Crop water requirement from irrigation decreased under the MLS scenario by 380 km³ to 65% of the
173 baseline (approx. 1100 km³), and under the TLS scenario by 218 km³ to 78% of the baseline, precluding
174 losses within the irrigation system that exceed the actual global crop water requirement³⁸. Water
175 requirements vary with crop³, climate, and land surface extent³⁹; hence the reduction in cropland area is
176 a main driver of reduced irrigation volume. Thus, cropland sparing does not necessarily entail expansion
177 of irrigation infrastructures if yields in rainfed regions are maximized by optimal fertilization and crop
178 choice. This is consistent with earlier global and regional studies finding nutrient limitations to be a
179 substantially more important driver for current yield gaps than irrigation^{19,40}.

180 Greenhouse gas emissions from paddy rice and fertilized soils decreased to 87% and 82% (-0.15 and -
181 0.21 Pg CO₂ equiv.) of the baseline in the MLS and TLS scenario, respectively. As N application remains
182 fairly constant, this is mostly caused by the decrease of CH₄ emissions from the reduced cultivation area
183 for rice. Carbon (C) lost from potential natural vegetation is used as a proxy for C sequestration
184 potential, if natural vegetation on spared cropland fully recovers. The largest C storage capacity occurs
185 in tropical ecosystems, the lowest in arid climates⁴¹. Accordingly, the proportion of cropland remaining
186 in the tropics under the MLS scenario (Figure 3b) resulted with 29% avoided loss of C from natural
187 vegetation on present cropland in a proportionally low sequestration potential. However, this
188 sequestration potential is equivalent to 20.5 Pg C, underpinning that land sparing for vegetation
189 restoration may halt further deforestation that is a major contributor to global CO₂ emissions. The
190 amount of C sequestration potential is higher in the TLS scenario, as major biodiversity hotspots are
191 located in the tropics (Supplementary Figure 16). This increases the C sequestration potential to 24.2 Pg
192 C.

193 The habitat suited mammal species with restricted ranges and intolerant to cropland (n=716) in
194 presently cultivated regions increases substantially in the TLS scenario (+12.8%) but only marginally in
195 the MLS scenario (+2.6%). When considering all species of terrestrial mammals occurring in present
196 cropland regions (n=3922), the average gains decrease to 7.6% under the TLS scenario and increase to
197 4.9% in the MLS scenario (see Supplementary Figure 17 for results on various species groups). The effect
198 in the TLS scenario is partly attributable to the sparing of cropland specifically for small-range species.
199 The modest gain in average habitat for all terrestrial mammals in the MLS scenario in turn reflects that
200 cropland presently covers about 10% of the global ice-free land surface and therefore only a comparably
201 small fraction of actual and potential natural vegetation. Thus, our results underpin that land sparing is
202 most effective if pursued in a targeted way and focused on species strongly affected by conversion of
203 natural vegetation to cropland.

204 Our assessment of potential biodiversity impacts quantifies changes in suitable habitat area for species
205 intolerant to cropland, a time-independent indicator free of assumptions on population dynamics and

206 applicable for a wide range of species^{42,43}. Yet, this neglects potential impacts of intensification on
207 biodiversity *in situ* on cropland. The bulk of empirical studies on species density-crop yield relationships
208 found that these follow a negatively convex functional form for species sensitive to cropland with
209 rapidly decreasing species density already at low yields⁴⁴. This favours land sparing as a conservation
210 strategy opposed to land sharing or wildlife-friendly farming. The abundance of species tolerant to
211 cropland in turn may depend on multiple factors such as crop diversity and field configuration, nutrient
212 inputs, pesticide applications, small-scale landscape configuration, and species' sensitivities to these
213 aspects⁴⁵. Due to lack of data and granular spatial resolutions, these aspects cannot be addressed herein
214 and hardly in global studies at present. Indications that substantial land sparing can be achieved with
215 sustainable intensification in some regions but less so in others is provided in the evaluation of crop
216 diversity and nutrient budgets above. Yet, local assessments employing detailed species- and
217 ecosystem-specific knowledge will be required to explicitly quantify such effects.

218 In summary, both land sparing scenarios entail various co-benefits along agro-environmental
219 dimensions. Thereby, the targeted land sparing approach not only allows for the implicitly higher habitat
220 restoration potential, but also lower nutrient requirements and higher C sequestration potential,
221 although differences between scenarios are often marginal. As all modelling studies, our findings are
222 subject to a range of uncertainties and limitations, which we consider to render our results conservative
223 rather than overly optimistic (Supplementary Text 3 and Supplementary Text 4).

224 **Conclusions and wider implications of extensive land sparing**

225 The potential for cropland sparing quantified herein contrasts with earlier agro-economic studies
226 indicating that further cropland expansion is likely to occur in future decades^{13,46,47}. Noteworthy, these
227 forward-looking studies account for changes in climate and atmospheric CO₂ concentration as well as
228 socio-economic drivers and constraints, including diffusion rates for improved agricultural technologies,
229 national agricultural policies, international trade relations, and future increases in demands, which limit
230 their comparability to ours. Earlier studies exploring combinations of biophysical and socio-economic
231 options for abating increasing land pressure of agricultural production already identified agro-
232 technologic change as an important element^{15,16} but presented compound scenarios that do not allow
233 for quantifying the land sparing potential of optimal crop production and associated externalities
234 directly. Quantifications of production potentials¹⁷⁻²¹ in turn do not consider actual crop demands and
235 none of the mentioned studies covered targeted land sparing for wildlife habitats and other landscape
236 elements. In this context, our results provide a benchmark of the present potential for cropland sparing
237 if high land use efficiency was realized and if specific targets are defined for restoring wildlife habitats.

238 The gap between the present extent of global cropland and the actual cropland requirement quantified
239 herein indicates that at the global scale land management and associated policies, rather than
240 biophysical limitations, are the major production-side drivers of adverse environmental change
241 mediated by the expansion of cropland⁴⁶. Thus, achieving ambitious land sparing targets in the near
242 term will require radical acceleration in the dissemination of available agro-technologies as well as
243 integration across society³⁰ to avoid cropland expansion often caused by sole incentives for
244 intensification⁷ while maintaining livelihoods of populations potentially affected by agricultural change.
245 Globally coordinated efforts⁴⁸ will be required to balance national interests concerning food security and
246 agricultural revenues with global environmental targets.

247 **Methods and Data**

248 The study investigated global cropland sparing potential based on crop modelling of attainable yields for
249 16 major crops, crop-specific land use datasets, and spatial optimization of cropland allocation (Figure 1)
250 to minimize global cropland extent via maximizing land use efficiency, i.e. assigning the most productive
251 crops to cropland locally. The considered crops represent 85% of global cropland cultivated with annual
252 crops and sum up to more than 75% of total cropland area, vegetal calorie supply, and fertilizer
253 consumption⁴⁹. With the exceptions of cassava and sugarcane, we excluded perennial crops from our
254 analyses, due to their low flexibility for crop switching and specific trajectories of yield improvement.
255 Within the optimization algorithm, current crop-specific area may expand or shrink with the goal of
256 minimizing global cropland extent, while maintaining defined crop-specific production volumes reported
257 by FAO for 2011-2015⁴⁹ and without expanding total cropland extent locally. We opted for the most
258 recent period for which data are available to account for contemporary increases in crop production.
259 The five-year mean is a compromise between avoiding bias from selecting a single year and
260 underestimating present production volumes when using a longer historical period. The study design is
261 further detailed in Supplementary Methods 1 and visualized in Figure 1.

262 **Land sparing scenarios**

263 We evaluated cropland sparing potential for two distinct main scenarios: (i) the “maximum land sparing”
264 (MLS) potential allowing the entire present cropland in each simulation unit or pixel to remain occupied
265 after crop reallocation if it is a solution of the optimization, and (ii) a “targeted land sparing” (TLS)
266 scenario. The latter forces the release of all cropland covered by the considered crops in biodiversity
267 hotspots and a uniform release of at least 20% of present cropland cover by 16 major crops in each
268 simulation unit or pixel. The latter fraction is considered to spare a compartment of the landscape for
269 other, i.e. regenerative, uses. Herein, it is assumed to be covered by natural vegetation in the
270 quantification of externalities (carbon sequestration and area of habitat), but may in principle also serve
271 for buffer strips, windbreaks, or other landscape elements.

272 Two supplementary scenarios based on the MLS scenario (Figure 1E) provide additional information (I)
273 whether the cultivation of crops in regions in which their cultivation is presently not recorded plays a
274 major role in the land sparing potential found herein, which is termed “MLS without crop switching”
275 (MLS_{nccs}); and (II) if substantial cropland sparing is still feasible if single crops are allowed to only cover
276 ≤34% of cropland in each simulation unit, indirectly enforcing the occurrence of several crops in most
277 simulation units and hence fostering crop diversity, which also enables crop rotations. This scenario is
278 termed “MLS with crop diversity” (MLS_{wcd}).

279 Land use optimization approaches similar to the main scenarios have been studied earlier, but
280 addressed global production potentials employing input intensification only¹⁹, crop switching only^{20,21}, or
281 both¹⁸, or investigated production potentials for single crops under climate change¹⁷. Land sparing
282 potential of optimized cropland allocation has been addressed by Müller et al.⁵⁰ among other aspects of
283 crop production and consumption. Yet, constraints on available land for cropping per pixel were not
284 considered below the physical pixel area, crop demands were partly computed, and intensification was
285 not accounted for.

286 **Crop modelling framework**

287 Crop simulations were performed for 16 major crops (Figure 2) with the well-established global gridded
288 crop model (GGCM) EPIC-IIASA¹⁷, which is based on the field-scale process-based agronomic
289 Environmental Policy Integrated Climate (EPIC) model^{25,26} (formerly known as Erosion Productivity
290 Impact Calculator). EPIC-IIASA has been applied extensively in global impact studies and across regions,
291 and has been evaluated positively for reproducing both historic absolute yields under business-as-usual
292 management and inter-annual yield variability⁵¹⁻⁵³. Simulated attainable crop yields were capped at the
293 95th percentile globally to avoid bias towards extremely high yields in the crop-to-cropland allocation.
294 Key processes of the core model EPIC are summarized in Folberth et al.⁵⁴ and briefly described in
295 Supplementary Methods 3.

296 EPIC-IIASA is based on a 5 x 5' grid (equivalent to about 8.3 km x 8.3 km near the equator) for soil
297 characteristics⁵⁵ and topography⁵⁶ that are aggregated, based on classification of key characteristics, to
298 homogenous response units. These are further intersected using a 30 x 30' climate grid (about 50 km x
299 50 km near the equator) and national administrative boundaries to define final simulation units⁵⁷.
300 Accordingly, simulation units vary in size from 5' x 5' to 30' x 30' depending on local heterogeneity.
301 More detail on the definition of simulation units is provided in Supplementary Methods 2. The EPIC
302 model was run for each simulation unit, crop, and water management system (rainfed or with sufficient
303 irrigation) separately, treating it as a representative homogenous field. Climate data were based on the
304 daily climate database AgMERRA⁵⁸, specifically developed for agricultural applications, at a spatial
305 resolution of 30' x 30'. Crop-specific growing seasons were derived from Sacks et al.⁵⁹. Supplementary
306 Methods 2 provide further details on the EPIC-IIASA model.

307 Data on multi-cropping are lacking at the global scale and are only reflected in reported harvest areas
308 that partly exceed the physical area of cropland. As our focus was on physical cropland sparing, we
309 focused our optimization on single cropping of physical cropland, disregarding potential multi-cropping
310 and rotations. The exception was for rice cultivation: according to SPAM 2005 v3.2⁶⁰, total cropping
311 intensity is about 115% for the considered crops, with single cropping dominant in most crops, but an
312 intensity of 150% for rice. Therefore, rice was simulated for two seasons where suggested by calendar
313 data, to minimize underestimation of rice double cropping. Yields for the two seasons were summed to
314 treat double-cropped rice as a single crop in the estimation of physical area requirements. For the land
315 use datasets referring to harvested area (see below), separate rice simulations were performed for a
316 single season. A brief discussion of the potential impacts of multi-cropping is provided in Supplementary
317 Text 4.

318 **Evaluation of attainable crop yields**

319 We evaluated simulated attainable yields against two widely used spatially explicit datasets, based on
320 reported yields and extrapolation of (a) high-input rainfed and irrigated crop yields from SPAM 2005
321 v3.2⁶⁰ and (b) attainable yields¹⁹ based on the M3 dataset¹⁹. Evaluations are presented in Supplementary
322 Text 2 and Supplementary Figures 12 and 14. All three datasets (including the estimates from
323 biophysical crop modelling) were derived using different methodologies; this limits comparability of
324 yield distributions. It may be assumed, however, that our comparison allows for the evaluation of crop
325 model overestimation of yield potentials. It should be noted that the yield category closest to attainable
326 yields in SPAM reports rainfed, high-input yields, based on moderate to sufficient levels of nutrient
327 input. Irrigated yields are a single category that may typically be assumed to receive high (unknown)
328 levels of nutrient inputs. The attainable yields from M3 are based on spatially explicit reported yields c.

329 2000 from administrative level censuses and climate bins based on temperature and precipitation. For
330 each of these climate bins, the upper 95th percentile of reported yields is assumed to represent the
331 attainable yield.

332 **Cropland allocation model**

333 Spatially explicit cropland optimization was performed at the level of simulation units with the objective
334 of minimizing global cropland requirement, but maintaining 2011-2015 production volumes for each
335 crop⁴⁹ (Figure 1). Reported production as a target accounts for any dietary and other use preferences as
336 opposed to more aggregated approaches based on recommended supply levels or requirements.

337 The main cropland dataset selected for the analysis was SPAM 2005 v3.2, because it provides crop-
338 specific physical areas. In contrast to other datasets that typically report either crop-specific harvested
339 areas or total physical cropland, this dataset allows for the assessment of physical cropland sparing
340 potential only for cropland cultivated with the crops included in this analysis. Robustness of our results
341 was evaluated from the optimization of two additional crop-specific harvested area datasets (see
342 below).

343 The land use optimization model was programmed in GAMS software (<https://gams.com/>), where input
344 data are yield potentials from either the EPIC crop model or inventory data (see below) and current
345 crop-specific areas at the simulation unit level. Thresholds for uniform cropland release in the TLS
346 scenario were defined by finding a minimal feasible solution in steps of 85%, 80%, 67%, and 50% for
347 each attainable crop yield x cropland dataset combination. For the SPAM 2005 physical area dataset,
348 this threshold was found to be 80% (or 20% of uniformly released land).

349 The optimization problem is formulated as:

$$350 \quad \underset{s_{ijk}}{\text{minimize}} \sum_{i, j, k} a_{ij} s_{ijk} \quad (\text{Eq. 1})$$

$$351 \quad \text{s. t.} \quad \sum_{i, j} a_{ij} s_{ijk} y_{ijk} \geq p_k, \quad (\text{Eq. 2})$$

$$352 \quad \sum_k s_{ijk} \leq \alpha, \quad s_{ijk} \geq 0. \quad (\text{Eq. 3})$$

353

354 where a_{ij} is current area of cropland [ha] occupied by the considered crops in simulation unit i under
355 water supply type j ; s_{ijk} is the respective share allocated to crop k to be optimized; y_{ijk} is the simulation
356 unit-, irrigation type-, and crop-specific yield [t ha^{-1}]; p_k is current production²³ of crop k [t]; α is the
357 maximum allowed optimized cropland share within the considered simulation unit area, $\alpha = 1$ for the
358 maximum land sparing scenario, and in the targeted land sparing scenario $\alpha = 0.8$ for SPAM 2005
359 physical area, $\alpha = 0.85$ for SPAM 2005 harvested area, MIRCA2000, and the M3 dataset.

360 We performed optimizations for additional datasets and combinations thereof to account for
361 uncertainties in cropland distribution⁶¹ and attainable yields. Crop model estimated attainable yields
362 were combined with cropland distributions from SPAM 2005 v3.2⁶⁰ or MIRCA2000⁶² that provide
363 spatially explicit harvested areas for the considered crops, for rainfed and irrigated cultivation systems
364 separately. We performed the same complementary optimization using a set of statistically derived
365 attainable yields and corresponding areas from M3^{19,63}; this dataset does not distinguish between

366 rainfed and irrigated systems, so yields were not combined with the other land use datasets. As none of
367 the spatial datasets provides the same crop-specific areas as FAOSTAT for the reference period 2011-
368 2015²³, crop areas from FAOSTAT were used as a basis from which to derive relative cropland area
369 reduction, after an absolute number of cropland requirement had been obtained in the optimization
370 routine. Accordingly, cropland areas in all spatial datasets underestimate present cropland, which
371 increased for the considered crops by about 14% since 2000 (M3 and MIRCA2000 reference), and by 7%
372 since 2005 (SPAM 2005 reference). Further limitations and uncertainties of the land sparing modelling
373 and estimation of attainable yields are addressed in Supplementary Text 4.

374 **Definition of biodiversity hotspots**

375 Biodiversity hotspots were defined based on rarity-weighted richness as the sum of number of species
376 present in a grid cell weighted by their range size (1/Area of Habitat (AOH))⁶⁴. Higher values occur in grid
377 cells rich in species with small ranges. These cells have a large global responsibility for species
378 conservation. Rarity-weighted richness was quantified in absolute terms and in addition normalized per
379 WWF ecoregion⁶⁵ and continent to account for regions of (a) high absolute importance for biodiversity,
380 which are typically concentrated in the tropics, and (b) regional importance for biodiversity within
381 specific ecoregions⁴². From both resulting datasets, the 90th percentile was selected to be abandoned for
382 targeted land sparing in the TLS scenario (Supplementary Figure 16).

383 **Quantification of agricultural externalities**

384 Crop nutrient requirements

385 N, P, and irrigation water were applied by the EPIC model based on deficits compared with optimal
386 supply and relative crop stress thresholds (see Supplementary Methods 2). The model considered losses
387 (leaching, runoff, erosion, immobilization, and gaseous emissions) and limited the number of crop
388 management operations to a level common to current management practices (annual application of P,
389 and restricted number of applications for N and water within a given time period) to represent an
390 optimal management strategy that balances realistic overheads for plant nutrient inputs. Fertilizer
391 requirements for crops that were not considered in the optimization were derived from the proportions
392 of crop-specific fertilizer application rates around 2000¹⁹ to total fertilizer application volumes during
393 the 2011-2015 reference period, as reported in FAOSTAT⁴⁹.

394 Besides exogenous inputs, nutrients used by crop plants are also sourced from soil stocks and
395 mineralization of organic matter as well in the field as in the crop model. While these represent a
396 substantial short-term source of nutrients, depletion occurs over time that may lead to the
397 underestimation of fertilizer requirement. Amounts of N and P required for sustainable nutrient
398 replenishment in such cases were estimated from a fertilizer requirement of 120% of crop uptake. For
399 soils with high or very high P immobilization potential⁶⁶, we ensured the fertilizer requirement was twice
400 the crop uptake³⁷. For leguminous crops (groundnuts, pulses, and soybean), we assumed that at yields
401 >2.5 t ha⁻¹, only 80% of N demand is met through fixation⁶⁷, and added 20% of crop uptake as
402 supplementary fertilizer. More details on the *ex-post* accounting for potentially higher nutrient
403 requirements than estimated by the crop model are provided in Supplementary Methods 3.

404 Nutrients in plant residues and manure

405 N and P embodied in removed crop residues (straw, stalks, stover) or burning of crop residues in the
406 field were not modelled explicitly. To account for removal of N and P from the field as post-harvest
407 residues in supplementary evaluations, we estimated crop residue dry matter from reference period
408 crop production volumes²³ and crop harvest indices in the EPIC model, and then calculated volumes of N
409 and P based on the USDA crop nutrient tool⁶⁸. National crop-specific residue removal and burning rates
410 were obtained from a recent global report⁶⁹ that covers all crops included in this study, with the
411 exception of sugar beet, groundnut, pulses, millet, and rice. For the first four of these crops, we
412 approximated values using coefficients of potato for sugar beet, soybean for groundnuts and pulses, and
413 sorghum for millet. For countries lacking data, we applied a mean based on major UN regions. Data for
414 rice were obtained from a recent literature review⁴. For burned residue, we assumed that 80% of N and
415 40% of P are lost as emissions. Total removal from the field amounted to 19.6 Tg N and 2.2 Tg P,
416 respectively. Fertilizer requirements were scaled according to a fertilizer:uptake ratio in crop yield, to
417 account for additional losses due to increased fertilizer application. Present amounts of N and P
418 contributed by manure cycling to cropland were estimated from the literature as 17.3 Tg and 4.2 Tg,
419 respectively^{70,71}. The additional or reduced requirements for N and P replenishment with present rates
420 of residue removal and manure application, as well as uncertainties in the nutrient budgets, are
421 discussed in Supplementary Text 3.

422 Irrigation water requirement

423 Irrigation water requirements estimated by the EPIC model to meet plant water demand do not
424 consider inefficiencies due to losses during the extraction to field application process. These may be
425 more than twice the actual plant demand, depending on the irrigation system in place³⁸. For the relative
426 change in irrigation water requirement for the crops considered, we compare the irrigation requirement
427 on the total cropland to that in each land sparing scenario. To account for the crops not considered in
428 the simulations, we scaled crop-specific irrigation water requirements from a study based on the Global
429 Crop Water Model (GCWM) model that considers all major crops or crop groups³.

430 Expansion of irrigated land would also provide a means for increasing crop yields⁷² and accordingly
431 decreasing land requirement. We do not consider this option here due to its lower flexibility compared
432 to nutrient input intensification as (a) it requires upfront investment in infrastructure, (b) it is subject to
433 policy and governance decisions on water resources, (c) it is subject to competition among sectors, and
434 (d) inter-annual variations in water availability for irrigation affect crops differently *in-situ* based on
435 economic considerations among others⁷³.

436 Greenhouse gas emissions

437 Greenhouse gas emissions in CO₂ equivalents were calculated following the tier 1 methodology of FAO⁷⁴
438 for the major cropland emission contributors of paddy rice fields (CH₄) and nitrogen fertilizer (N₂O),
439 based on fixed N₂O emissions per unit of applied fertilizer and national coefficients of CH₄ emissions ha⁻¹
440 of harvested paddy rice. Other emissions, for example from manure and crop residues, were assumed to
441 remain constant. Estimates of emissions of N₂O for crops not considered in the optimization were based
442 on N fertilizer requirements, as calculated above.

443 Carbon in potential natural vegetation

444 The potential loss of C from natural vegetation expected to develop on spared cropland has been
445 investigated by West et al.⁴¹ to quantify C losses in food production. Using the publically available
446 dataset of C stored in potential natural vegetation [t ha⁻¹], we quantified reductions in C loss following
447 minimization of cropland area compared with the baseline cropland area in the SPAM 2005 v3.2
448 database for crops considered in the optimization and for other crops, separately. The exact calculation
449 is provided in Supplementary Methods 4.

450 Area of habitat

451 We modeled the Area of Habitat (AOH) for each terrestrial mammal species with range data and habitat
452 preferences available from the IUCN Red List database (accessed April 2018). The AOH is defined as the
453 area characterized by abiotic and biotic properties that is habitable by a particular species. Specifically,
454 we modelled the AOH as the areas that (i) fall within the mapped range and (ii) map to the known
455 habitat preferences of the species. The species ranges of terrestrial mammals were downloaded from
456 the IUCN database. We considered only habitat types coded as 'suitable' by taxonomic experts within
457 the IUCN database. In absence of a map of IUCN habitat classes, and similarly to all previous work
458 modelling of AOH^{42,43}, we cross-walked the IUCN habitat classes into an existing land-use product to
459 translate habitat preferences into land-cover and land-use preferences. Accordingly, our assessment
460 only accounts for biogeographic distributions of species habitats but not for impacts of land use
461 intensification on wild species on cropland *in situ*.

462 As land-cover base layer we used the European Space Agency CCI (ESA-CCI) land-cover map for the year
463 2015⁷⁵ and re-allocated cropland areas as calculated from the SPAM2005 baseline or the land sparing
464 scenarios, including annual and perennial crops not considered in the land use model to account for all
465 cropland. When cropland area was higher than estimated in the ESA-CCI map, the additional area was
466 allocated to all natural land-cover types (except water and ice) in proportion to their extent in the grid
467 cell. Similarly, when cropland area was lower than estimated in the ESA-CCI map, the excess cropland
468 was allocated to all natural land-cover types (except water and ice) in proportion to their extent in the
469 grid cell. We then summarized the results as distribution of AOH changes in optimized versus baseline
470 scenarios across all species, species sensitive to cropland areas (those for which cropland is considered
471 unsuitable according to IUCN habitat preferences), species in the lower quartile of range-size
472 distribution, and species in the lower quartile of range-size distribution sensitive to cropland areas. The
473 latter was selected as the main results, outcomes for the other species sub-selections are presented in
474 Supplementary Figure 17.

475 **Data processing and visualization**

476 Evaluations were performed in R⁷⁶, and plots were produced using ggplot2⁷⁷ and rasterVis⁷⁸. The
477 visualization of simulation units in Supplementary Figure 19 was produced with ESRI ArcGIS 10.7.

478

479 **Correspondence and requests for materials** should be addressed to CF

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485 Cover project.

486 **Author contributions**

487 CF, NK, and MO designed the study; CF and NK performed central analyses; JB, RS, and PV contributed
488 models and data; CF wrote an initial draft; CF, NK, JB, RS, PV, PC, IAJ, JP, and MO contributed
489 substantially to the interpretation of the results and revisions of the manuscript.

490 **Competing interests**

491 The authors declare no competing interests.

492 **Data availability**

493 Datasets required for reproducing key results of the cropland allocation model are available via
494 <http://dare.iiasa.ac.at/74/>

495 **Code availability**

496 The code required for reproducing key results of the cropland allocation model is available from the
497 same repository as the data (see above).

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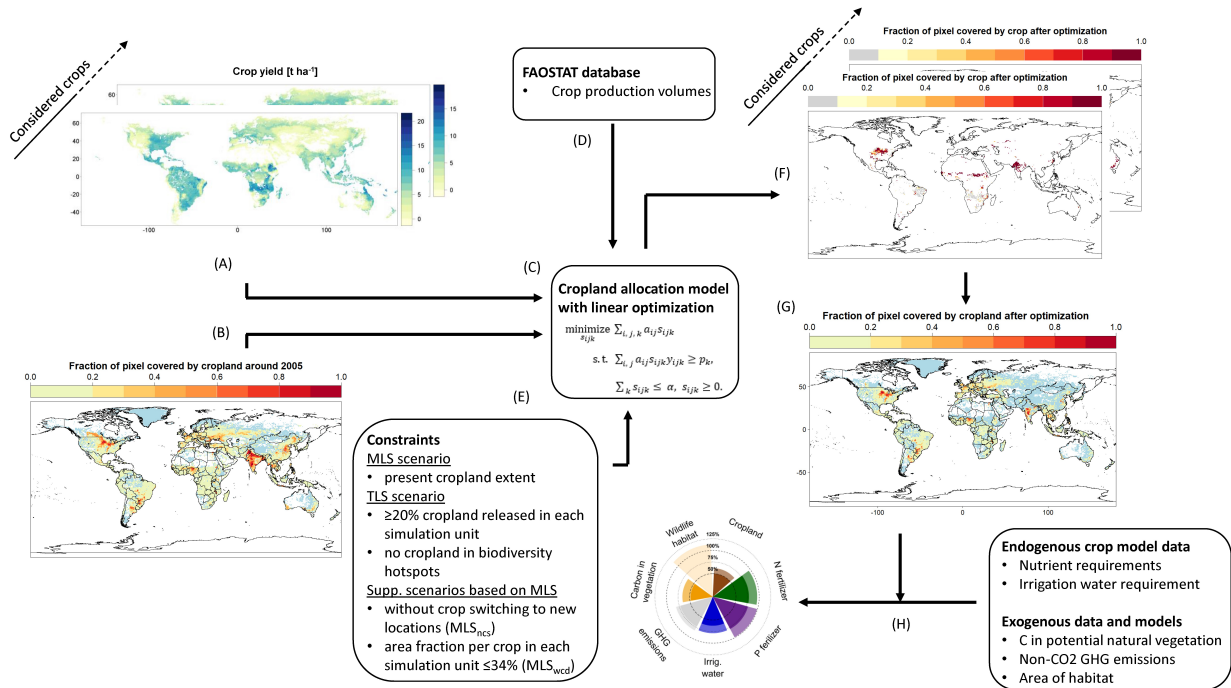
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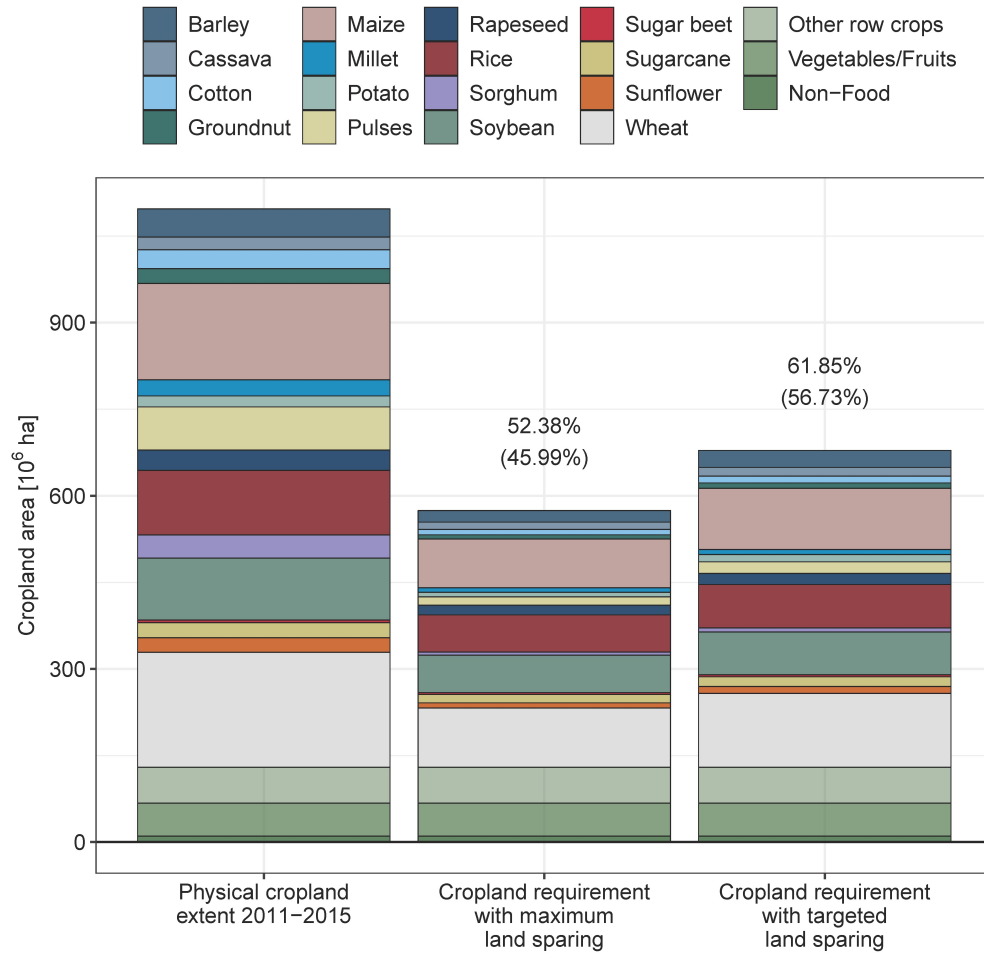
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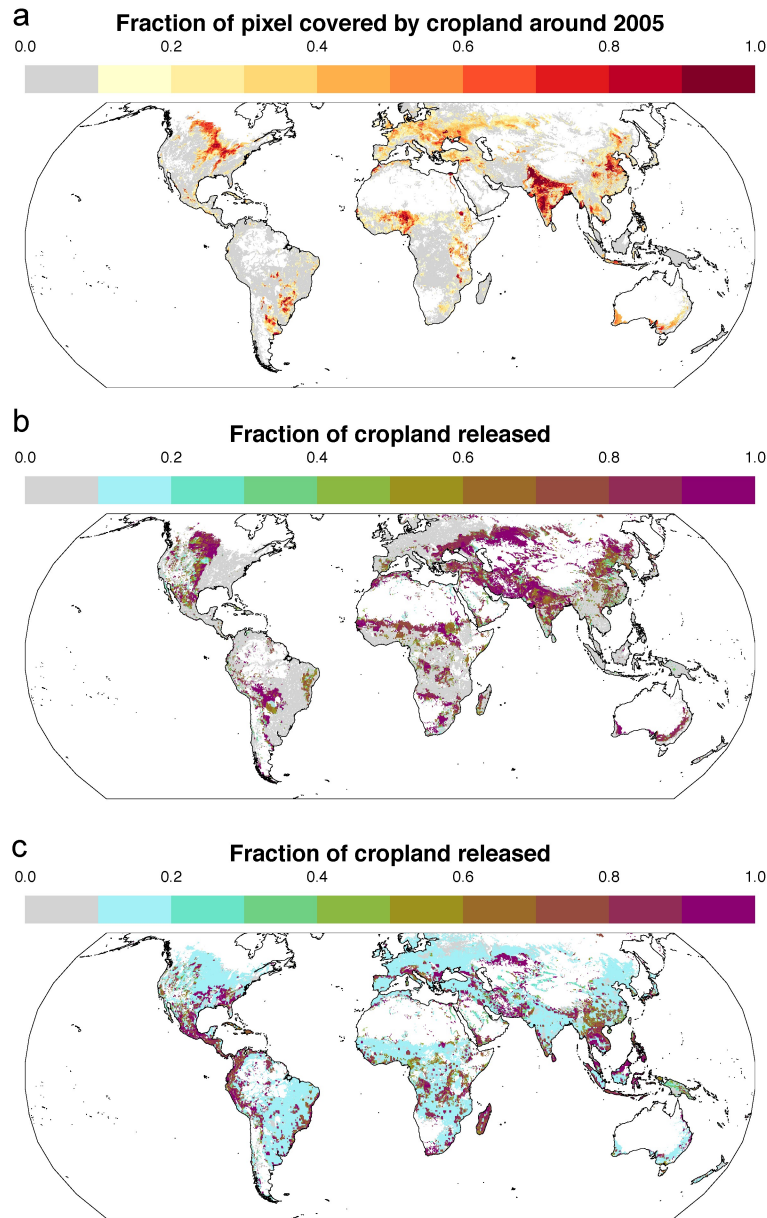
659 **Figure 1: Schematic of the study design.** Attainable crop yields (A) from the EPIC-IIASA global gridded crop model (or
 660 statistically derived yield datasets) are combined with present cropland data for these crops (B) from SPAM2005⁶⁰ (or other
 661 suitable land use datasets) into a linear optimization model (C). This model has the objective to minimize cropland extent via
 662 cropland allocation based on land use efficiency while maintaining present production volumes (D) for two main scenarios (I)
 663 with the only constraint of presently available cropland (MLS scenario) or (II) with imposing a release of cropland in biodiversity
 664 hotspots and a uniform global release of 20% cropland (TLS scenario). Further constraints (E) are introduced for two
 665 supplementary scenarios (see Methods). The optimization results in crop-specific land use datasets (F), which are aggregated to
 666 total remaining cropland including the crops not considered in the optimization (G). Externalities (H) are quantified based on
 667 outputs of the crop model itself (nutrient input and irrigation water requirement) or based on external data and models (carbon
 668 sequestration potential, change in area of habitat, and greenhouse gas emissions). Crop model simulations and cropland
 669 allocation were performed at the level of globally 120000 simulation units aggregated from 5' x 5' pixels (about 8.3 km x 8.3 km
 670 near the equator) to a maximum size of 30' x 30' (about 50 km x 50 km near the equator) based on physical heterogeneity and
 671 administrative borders. The cropland area in each 5' x 5' pixel was subsequently scaled according to the relative change in
 672 cropland extent in the overlying simulation unit (see Supplementary Figure 19) for the estimation of externalities and
 673 visualization. The central cropland allocation scheme is shown for exemplary simulation units in Supplementary Figure 18.

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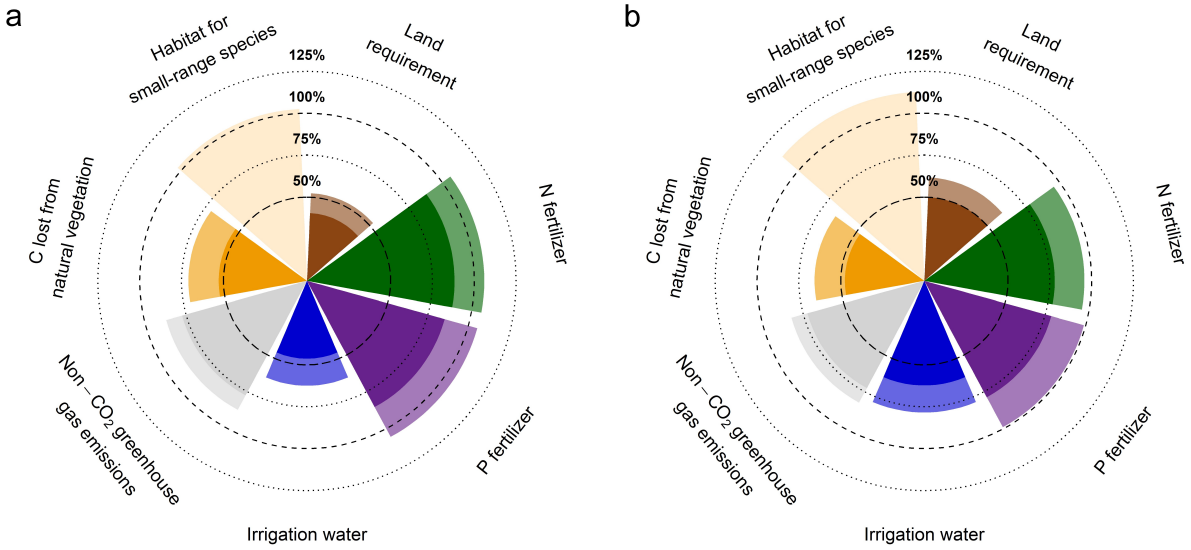
676 **Figure 2: Global extent of annual cropland in the reference period and the two land sparing scenarios.** Bars show cropland of
 677 16 major crops considered in the study and three crop groups not considered in the period 2011-2015 (column one), estimated
 678 area of cropland optimized for maximum land sparing potential (column two), and optimized cropland extent with sparing of at
 679 least 20% of cropland in each simulation unit and completely abandoning biodiversity hotspots (column three). Crops not
 680 considered in the optimization are aggregated into three groups at the base of each bar. Percent values refer to area of total
 681 annual cropland (upper) and simulated crops (lower, in parentheses). Globally, annual crops plus sugarcane extended to about
 682 1100 Mha of cropland during the reference period, of which about 950 Mha were planted with the crops considered in the
 683 optimization (major cereals, grains, pulses, and sugar). The remaining 150 Mha encompassed “Other row crops”, “Fruits and
 684 Vegetables”, and “Non-food/feed crops” shown at the base of each bar (Supplementary Table 1). The baseline physical extent of
 685 cropland for each crop was calculated based on harvested areas reported in FAOSTAT⁴⁹ for the reference period and cropping
 686 intensity according to the SPAM2005 v3.2 database⁶⁰.



687

688 **Figure 3: Proportion of each 5' x 5' pixel covered by cropland cultivated and cropland fractions released in the two land**
 689 **sparing scenarios.** Cropland proportion in each pixel c. 2005 according to the SPAM2005 v3.2 database⁶⁰ (a), fraction released
 690 after optimization of cropland requirement for maximum land sparing (b), and fraction released after optimization for targeted
 691 land sparing with complete release of cropland in biodiversity hotspots and uniformly $\geq 20\%$ of cropland (see Supplementary
 692 Figure 16) (c). Data in (b) and (c) correspond to bars two and three in Figure 2.

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695 **Figure 4: Relative changes in key agricultural externalities following optimization of area of cropland for the two scenarios.**
 696 Panels show (a) maximum land sparing (bar 2 in Figure 2) and (b) targeted land sparing (bar 3 in Figure 2) compared with the
 697 baseline scenario (100% circle; see bar 1 in Figure 2; status in 2011-2015) for 16 major crops (dark colors) and the remaining
 698 annual crops (light colors; not estimated for biodiversity potential). Proportions of nitrogen (N) and phosphorus (P) fertilizer, and
 699 irrigation water applied to crops during the reference period were extrapolated linearly from crops in c. 2000 reported by
 700 Mueller et al.¹⁹, or for irrigation water from Siebert and Doell³. Greenhouse gas emissions comprise methane from rice and
 701 nitrous oxide from fertilizer and assume the other major sources (manure and crop residue) remain unchanged. Carbon (C) lost
 702 from potential natural vegetation is the amount of C stored in potential natural vegetation after cropland sparing relative to
 703 that during the baseline (100% of C in natural vegetation lost in cropland), using data from West et al.⁴¹. Habitat for small-range
 704 species is the average change in habitat area for terrestrial mammals intolerant to cropland in the lower quartile of range size
 705 distributions of terrestrial mammals in the IUCN Red List of Threatened Species⁷⁹ after recovery of natural vegetation on
 706 abandoned cropland. Details on the quantification of each externality are provided in the Methods.

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