Current Biology

Report

Wilderness areas under threat from global redistribution of agriculture

Highlights

- As climate warms, crop production will increasingly shift into wilderness areas
- 2.7 million km^2 of wilderness will become suitable for agriculture within 40 years
- High-latitude wilderness in the northern hemisphere is particularly threatened
- Agricultural expansion is a major emerging threat to wilderness areas

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In brief

Gardner et al. show a stark increase in land within wilderness that will become newly suitable for agriculture within the next 40 years. They draw attention to this major emerging threat to wilderness, highlighting that without protection, the vital integrity of these valuable areas could be irreversibly lost.

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Report

Wilderness areas under threat from global redistribution of agriculture

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SUMMARY

Agriculture expansion is already the primary cause of terrestrial biodiversity loss globally[1,2]; yet, to meet the demands of growing human populations, production is expected to have to double by 2050.[3] The challenge of achieving expansion without further detriment to the environment and biodiversity is huge and potentially compounded by climate change, which may necessitate shifting agriculture zones poleward to regions with more suitable climates,[4] threatening species or areas of conservation priority.[5-7] However, the possible future overlap between agricultural suitability and wilderness areas, increasingly recognized for significant biodiversity, cultural, and climate regulation values, has not yet been examined. Here, using high-resolution climate data, we model global present and future climate suitability for 1,708 crop varieties. We project, over the next 40 years, that 2.7 million km^2 of land within wilderness will become newly suitable for agriculture, equivalent to 7% of the total wilderness area outside Antarctica. The increase in potentially cultivable land in wilderness areas is particularly acute at higher latitudes in the northern hemisphere, where 76.3% of newly suitable land is currently wilderness, equivalent to 10.2% of the total wilderness area. Our results highlight an important and previously unidentified possible consequence of the disproportionate warming known to be occurring in high northern latitudes. Because we find that, globally, 72.0% of currently cultivable land is predicted to experience a net loss in total crop diversity, agricultural expansion is a major emerging threat to wilderness. Without protection, the vital integrity of these valuable areas could be irreversibly lost.

RESULTS AND DISCUSSION

Global patterns of change in crop suitability

Climate change has driven and is likely to continue to drive poleward agricultural expansion into areas that are currently unsuitable for crops[4,8]—so called "agricultural frontiers" (*sensu* Hannah et al.[5]). In this regard, determining emerging agricultural pressures on wilderness areas is particularly significant given that much of the "last of the wild" persists at high latitudes and is subject to disproportionate warming.[9,10] To examine the possible threat to current wilderness from climate-driven agriculture shifts, we used the Food and Agricultural Organization (FAO) Ecocrop model[11] to model climate suitability of 1,708 crop varieties using recent (2008–2019) and future (2050–2061) climate data for Representative Concentration Pathways (RCP) 4.5 (intermediate scenario) and 8.5 (high-emissions scenario). We define an agricultural frontier as land unsuitable for any crop in 2008–2019 that is predicted to become suitable for at least one crop in 2050–2061. We quantified the overlap between agricultural frontiers and current wilderness using an existing global map of terrestrial wilderness,[12] which identifies areas that are free from human pressure and that cover a contiguous area of $\geq$10,000 km^2. We show that 40.1% (RCP4.5) to 43.1% (RCP8.5) of frontiers are in wilderness areas (Tables S1 and 1), almost double that expected based on land area alone, given that wilderness only covers ~23% of the Earth's surface.[12,13]

In the current periods and under both future climate scenarios, tropical areas were predicted to be suitable for the greatest number of crops, whereas high latitude, high altitudes, and desert climates were predicted to be least suitable (Figures 1 and S1). These patterns of suitability reflect the current global distribution of cultivated land, which falls outside of extremely cold and dry climates.[14] As a result, absolute changes in diversity, both losses and gains, were usually highest in the tropics. However, agricultural frontiers were located predominantly at high northern latitudes, with some of the largest expanses of frontier located in Alaska, Canada, and Northern Russia (Figure 1C). Currently, cultivation is limited by low minimum temperatures, and as climate change drives an increase in minimum temperatures, these areas become suitable for a greater number of crops. This effect is further driven by the disproportionate warming occurring at high-northern latitudes.[15] Thus, the high proportion of frontier land in wilderness reflects a global climate-driven northward shift in cultivable land into higher northern latitudes. Under RCP4.5, 1.85 million km^2 of wilderness is expected to become newly suitable for agriculture, and under RCP8.5 this figure rises to 2.75 million km^2.

Table 1. Biogeographic and latitudinal patterns of changing crop suitability

Biogeographic realm / Latitude	Total agricultural frontier area (km^2)	Agricultural frontier area in wilderness (km^2)	Proportion of agricultural frontier in wilderness	Proportion of wilderness that is agricultural frontier	Proportion of suitable land in non-wilderness with net loss of crop diversity
Afrotropic	496,133	27,775	0.056	0.025	0.821
Australasia	45,747	33,765	0.738	0.011	0.847
Indomalayan	8,169	0	0.000	0.000	0.922
Nearctic	1,189,411	755,363	0.635	0.059	0.599
Neotropic	306,066	66,441	0.217	0.017	0.753
Oceania	0	0	–	–	0.814
Palearctic	4,231,560	1,813,526	0.429	0.106	0.564
60° to 30°S	125,147	10,957	0.088	0.050	0.532
30° to 0°S	88,743	28,421	0.320	0.009	0.808
0° to 30°N	422,868	4,060	0.010	0.001	0.634
30° to 60°N	1,984,482	340,262	0.171	0.052	0.483
60° to 90°N	1,653,046	1,262,034	0.763	0.102	0.034
Total	**6,370,213**	**2,745,340**	**0.431**	**0.070**	**0.719**

Biogeographic and latitudinal patterns of changing crop suitability, here shown for the RCP8.5 scenario using a suitability threshold of 0.6. For each major biogeographic realm excluding Antarctica[28] and latitudinal bands north of 60°S, the total area of land unsuitable for any of the modeled crops in 2008–2019 and suitable for at least one crop in 2050–2061 (agricultural frontier), the total area and proportion of the agricultural frontier that is in wilderness, the proportion of wilderness in that realm that is an agricultural frontier, and the proportion of suitable land in non-wilderness with a net loss of crop diversity between the periods 2008–2019 and 2050–2061. A map of the biogeographic realms is shown in the supporting information (Figure S2). The equivalent values for RCP4.5 using a suitability threshold of 0.6 and RCP 8.5 using suitability thresholds of 0.4 and 0.8 are shown in Table S1. In Table S2, the effects of uncertainty in climate projections are shown.

Wilderness is already under threat from agriculture, and while significant wilderness is protected, an estimated 3.3 million km^2 (0.6%) has been lost since the early 1990s, and despite a considerable expansion in protected area globally, the increase in protection of wilderness has lagged significantly behind losses.[13] Thus far, however, the erosion of wilderness has been most pronounced in tropical regions, and high-latitude wilderness has remained relatively intact.[16] Realizing opportunities to expand cropland into high-latitude wilderness areas could destroy these intact natural habitats irreversibly, with significant adverse consequences for global conservation goals. It would also exacerbate the current food-security divide between the developed countries of the northern hemisphere and the developing countries of the tropics.

Patterns of change in crop suitability within biogeographic realms

To explore further geographic variation in threats to wilderness, we calculated the area of land that was agricultural frontier in wilderness and non-wilderness areas for each major biogeographic realm (excluding Antarctica)[17] and at different latitudes. The Palearctic and the Nearctic realms had the first- and second-largest total frontier areas, respectively (Table 1). The threat to wilderness is particularly high in these two realms. In the Nearctic, 48.4% (RCP4.5) to 63.5% (RCP8.5) of newly suitable land was in wilderness, equivalent to 2.7%–5.9% of the total wilderness currently in this realm. In the Palearctic, 44.3% (RCP4.5) to 42.9% (RCP8.5) of newly suitable land was in wilderness, equivalent to 10.6%–11.5% of the total current wilderness in this realm. Encroachment of wilderness is also particularly acute at higher latitudes. Between 60° and 90°N, 76.3% (RCP8.5) to 78.6% (RCP4.5) was in wilderness, equivalent to 6.4%–10.2% of the total wilderness currently in this realm (Tables 1 and S1).

Crops are, in part, a globally traded commodity, and the risk to wilderness areas from agricultural expansion would potentially be amplified or buffered by changes in suitability elsewhere.[18] We therefore quantified changes in the diversity of crops outside wilderness areas within each biogeographic realm. With the exclusion of newly suitable crops in future crop-diversity calculations (i.e., crop diversity only considering crops suitable in both periods), 95% of land in non-wilderness with crops historically experienced a loss in diversity (both RCPs), and 6.0% (RCP4.5) to 6.2% (RCP8.5) of currently suitable land became totally unsuitable for any crop in 2050-2061. With the inclusion of newly suitable crops, we found that between 76.7% (RCP4.5) and 71.9% (RCP8.5) of non-wilderness land that was suitable for at least one crop in the current period had fewer total crops by 2050–2061, equivalent to 58.5–62.3 million km^2. In all realms, more than 50% of non-wilderness land experienced a reduction in crop diversity irrespective of the emissions scenario (Tables 1 and S1). The projected loss of crop diversity was particularly acute in the Indomalayan realm, where >90% of the land area was predicted to lose crop diversity.

The projected decline in crop diversity, particularly from tropical regions (Figure 1), has the potential to reduce agricultural pressures on biodiversity, given that biodiversity is also highest in these regions. However, human populations and per-capita demand for food are rising most rapidly in the tropics,[19] and it therefore seems unlikely that a reduction in crop diversity will equate to reduced agricultural pressure. Areas predicted to become unsuitable for any crop variety, and thus those for which climatically driven agricultural abandonment is a prospect in the future, are located predominantly in arid regions that are not noted for their exceptional diversity.[20] Moreover, although natural habitat sometimes regenerates quickly on abandoned

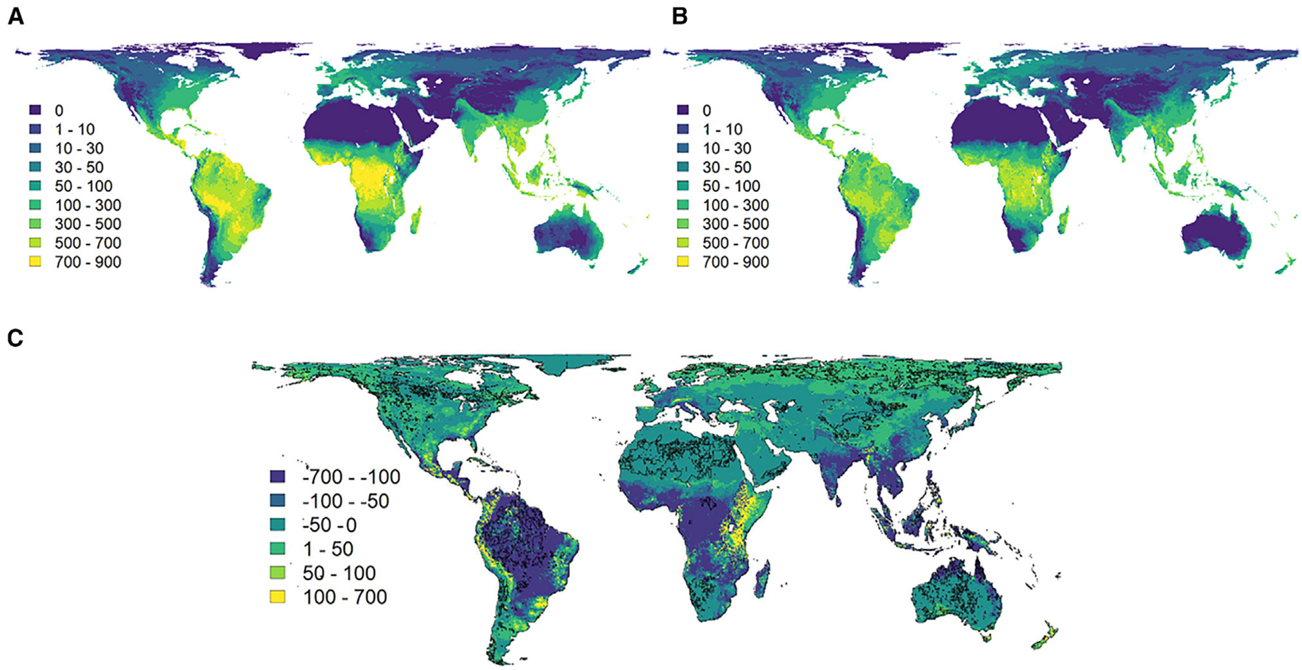


Figure 1. Changes in numbers of crops

Total number of crops with suitability score ≥ 0.6 (crop diversity) calculated as the mean over periods (A) 2008–2019 and (B) 2050–2061. In (C), net change in crop diversity between 2008–2019 and 2050–2061 is shown for RCP8.5. The black outline depicts wilderness areas (also provided as a separate figure in the supporting information). The equivalent figure for RCP4.5 is presented in the supporting information (Figure S1).

agricultural land, reductions in diversity often persist as species are hindered from reaching this habitat.[21] Thus, although localized reductions in agricultural pressure are likely, it seems somewhat unlikely that climatically driven reductions in agricultural suitability will offer a panacea for biodiversity loss.

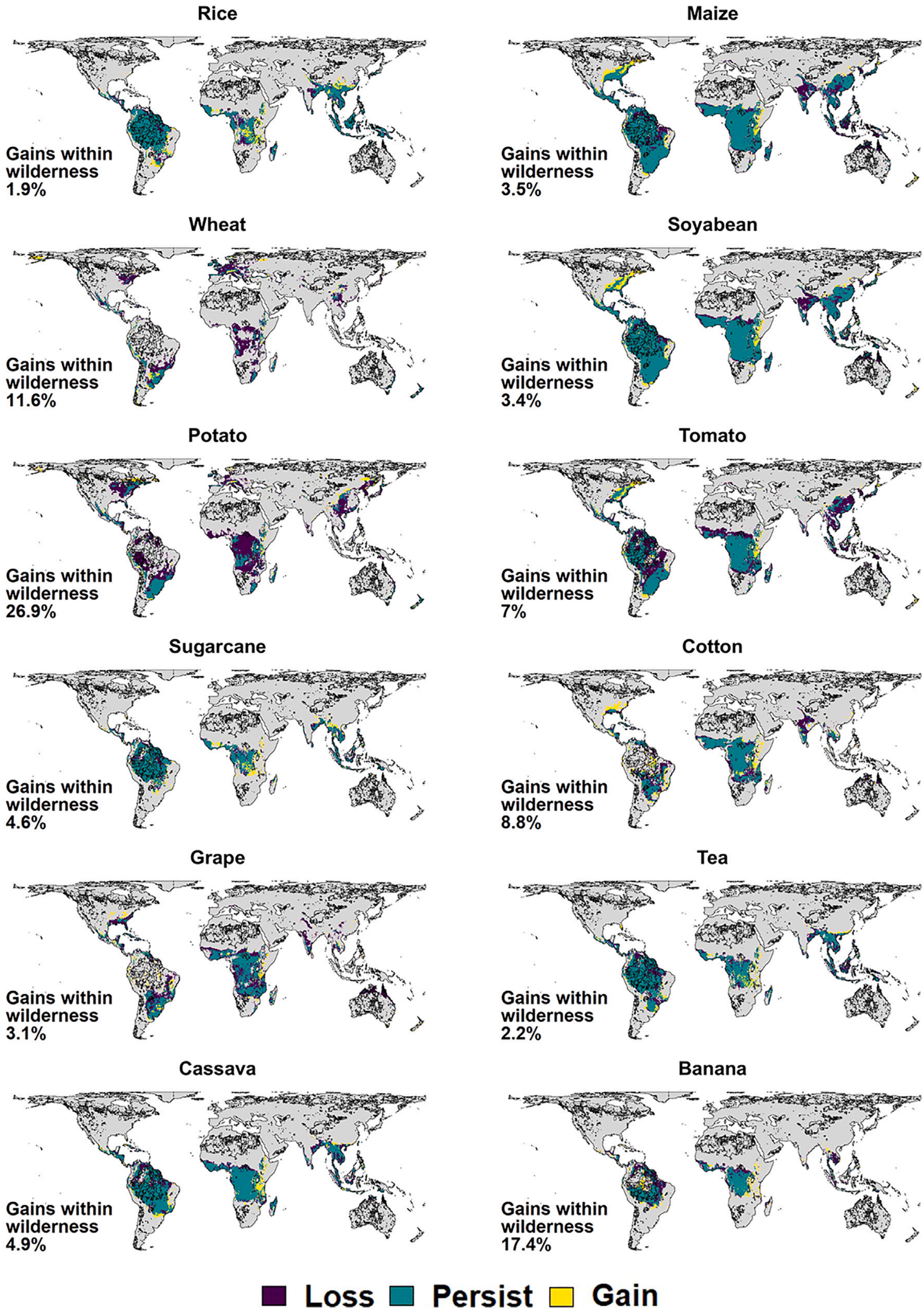
Uncertainty in projections

As with all assessments of future crop suitability, our results are contingent on model assumptions. The EcoCrop model and the Food and Agriculture Organization database of crop climatic requirements that underpins it seeks to evaluate whether climatic conditions are adequate within a growing season for a given crop variety. It uses temperature and precipitation to quantify the climate niche of a crop and, while parametrized for a large number of crop varieties, it is not a mechanistic dynamic model that explains crop yield on the basis of the underlying processes. Realized crop yields will depend on a range of technological, agricultural management, and socio-economic factors that were not included in our current modeling framework.[22] As such, our results should be viewed as a first-pass estimate of the effects of climate change on potential suitability for crop production and not as a quantitative estimate of future yields. Furthermore, our estimates of agricultural frontier expansion into wilderness areas and the overall diversity of crops in any given area are contingent on threshold-suitability values used to determine whether crop production is viable. Performing sensitivity analyses using a range of suitability thresholds yielded predictions of total area of wilderness that became suitable for cultivation, ranging from 1.78 to 3.76 million km^2, equivalent to 4.7%–9.6% of the total wilderness area (Tables S1 and S2). However, despite these uncertainties, we believe that the consistent overall conclusions across analyses establish that climate change-induced expansion poses a significant risk to wilderness areas.

Nevertheless, the degree of uncertainty in model outputs coupled with additional uncertainty in future climate changes means that our findings should not be interpreted as precise predictions. For each of the two RCPs, we used 12 probabilistic projections of future climates, and inevitably, each of the projections yielded slightly different estimates (Table S3). However, variations in the area of wilderness predicted to become newly suitable for crop production was relatively minor in comparison to differences predicted under the different concentration pathways. The more inevitable climate-change scenario (RCP4.5) for 2050–2061 produces about two-thirds of the agricultural expansion into wilderness area compared with that of the high-end projection (RCP8.5). These scenarios would diverge even more by 2100. Put another way, minimizing greenhouse gas emissions and sequestering carbon to minimize expected climate warming could substantially reduce the threat to wilderness areas.

Patterns of changing suitability for globally important crops

The pressure to convert newly suitable wilderness areas to cultivation is likely to be higher when losses of suitable land in non-wilderness areas concern globally important crops. We identified the 12 most-important crops in the world in terms of global production value according to the Food and Agricultural Organisation's (FAO) statistical database[23] and found that all crops



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were predicted to lose currently suitable land in non-wilderness areas and gain newly suitable land in wilderness areas (Table S3). On average, 7.9% of the newly suitable land for these crops in 2050–2061 was in wilderness, with values ranging from 1.9% for rice to 26.9% for potatoes (Figure 2).

To test how sensitive these findings were to the crops selected, we repeated the analysis selecting the 50 most-important crops in the world in terms of global production value. On average, 9.2% of the newly suitable land for these crops in 2050–2061 was in wilderness, with values ranging from 0% for peaches to 36.7% for onions (Table S3). Thus, while the immediate threat to wilderness may not be from globally important crops, many of which have a more tropical distribution, the potential threat from commercially important crops associated with cooler climates is nonetheless sizable, particularly given the predicted loss of currently suitable land in non-wilderness areas.

Conclusions

Our study shows that climate change will create opportunities to grow crops in new areas and suggests that agricultural expansion into wilderness may facilitate an increase in total crop production and mitigate climate-driven losses experienced elsewhere. This could provide a significant step towards reducing global poverty and food insecurity, especially as the demand for agricultural products increases alongside the growing human population and per-capita consumption. Nevertheless, we contend that wilderness must be protected. We are in the midst of a climate crisis, and wilderness areas are vital for the attainment of climate mitigation goals. They contain globally significant carbon stocks that contribute to stabilizing concentrations of atmospheric $C0_2$[13] and are therefore one of humanity's best defenses against climate change and its adverse effects, which will be felt most strongly in less-developed countries with the least adaptive capacity.[24] Wilderness areas are also fundamental to global efforts to conserve the world's biological and cultural diversity, which are both lost in more human-modified environments.[25]

Global agricultural production could be increased without the loss of wilderness. Indeed, future food production needs could be met by closing current yield gaps (the differences between observed and potential yields), increasing cropping efficiency, shifting diets away from excessive meat consumption, and reducing food waste.[26] Our analysis suggests that crop diversification could be an important part of these strategies. With declines in crop diversity, breeding or genetically modifying resistant crop strains or growing novel, newly suitable crops may be favored over the crops that are grown now and, indeed, may prove to be the only options in some places. Equally, farmers may shift cultivation to crop varieties that are suitable for the current (and future) climate, but which are not grown at present. In either case, to maximize productivity on current agricultural land, practices should be tailored to ensure that the crops grown, novel or not, are those best suited to the climate. However, as new agricultural systems emerge, so must conservation strategy and policy that safeguards wilderness. Wilderness needs to be conserved as an intact ecosystem and, indeed, this is intrinsic to its definition.[13] If protection is not pursued as the primary course of action, the entire existence and many values of wilderness areas will be lost, with largely irreversible outcomes for humans and nature.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2023.09.013.

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AUTHOR CONTRIBUTIONS

I.M.D.M. and K.J.G. led manuscript conception and design. A.S.G. gathered and analyzed the data and led writing of the manuscript. B.T., with help from M.D.S and I.M.D.M., led reanalyses of the analyses of the data following reviewer comments. All authors contributed significantly to drafts and gave final approval for publication of the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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Figure 2. Patterns of changing suitability of commercially important different crops
For the 12 most economically important crops, defined as those with the highest global production value in 2022,[33] areas predicted to become unsuitable (purple), remain suitable (green), and become newly suitable (yellow). Calculations are based on a 0.6 suitability threshold applied to mean suitability calculated over periods from 2008–2019 and 2050–2061, here shown for RCP8.5. The black outline depicts wilderness areas. The equivalent values of gains within wilderness for RCP4.5 and for the 50 most economically important crops are presented in the supporting information (Table S3).

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Data on global crop diversity and individual suitability maps for the twelve most important crops	This paper, Zenodo	https://doi.org/10.5281/zenodo.8407962
Software and algorithms		
R version 4.0.3	R Development Core Team	NA

RESOURCE AVAILABILITY

Lead contact
Further information and requests for resources should be directed to and will be fulfilled by the corresponding author, Ilya M. D. Maclean (i.m.d.maclean@exeter.ac.uk).

Materials availability
This study did not generate any new reagents.

Data and code availability

Data on global crop diversity and individual suitability maps for the twelve most important crops will be deposited on Zenodo upon acceptance and made publicly available as of the date of publication. DOIs will be listed in the key resources table.
All original code will be deposited on Zenodo upon acceptance and will be made publicly available as of the date of publication. DOIs will be listed in the key resources table.
Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

This study did not use experimental models.

Climate data
Historic 25 km gridded hourly 2m temperature and total daily precipitation for 2008-2019 were sourced from ERA5.[27] Climate projections for the period 2050–2061 were obtained from the Met Office Hadley Centre global UKCP18 programme.[28]

Data on climate requirements of crops
The climatic requirements of 1,708 crop varieties with important human uses were obtained from Food and Agriculture Organization (FAO) EcoCrop database[29] included as an inbuilt dataset in the ‘dismo’ R package.[11] Data on crop production values for 2022 were downloaded from the Food and Agricultural Organisation’s (FAO) statistical database.[23]

Data on wilderness extent and biogeographic realms
We sourced raster maps of (i) the global terrestrial wilderness sourced from Allan et al.[12] and (ii). biogeographic realms of the world from Olsen et al.[17]

METHOD DETAILS

Climate data processing
The UKCP18 climate projections comprised 12 probabilistic projections of future daily weather, encompassing the range of uncertainty in the HadGEM3GC3.05 model for the RCP8.5 scenario. The UKCP18 datasets are provided at a grid resolution of 60 km and are spatially coherent and retain physical consistency between the different climate variables. Under the RCP8.5 emissions scenario, greenhouse gas emissions are assumed to continue to rise throughout the 21st century, thus leading to a radiative forcing increase of 8.5 W/m^2 (~1370 ppm CO_2 equivalent) by 2100 relative to pre-industrial levels. RCP8.5 was used because it is the best match to the current trajectory in CO_2 emissions,[30] but as a lower-range scenario we also reconstructed climate data for RCP4.5. Because the

probabilistic daily projections were only available for the RCP8.5 scenario, we selected the 12-year period (2034-45) in which CO_2 equivalent in 2050-61 under RCP4.5[31] most closely matched the trajectory of CO_2 equivalent under RCP8.5 and used RCP8.5 climate data for this period in place of RCP4.5 data for 2050-61.

The UKCP18 data contain known biases, and to enable correction these data are also provided as historic datasets. We therefore downloaded mean daily temperature, the diurnal temperature range and daily precipitation data for the period 2010-2019, and re-sampled values to a grid resolution of 0.25° to match ERA5 data. Mean daily temperatures and diurnal temperature ranges were bias-corrected following Maclean.[32] UKCP18 and ERA5 data for the equivalent period were re-ordered by rank, and the relationship between the two fitted using a General Additive Model (GAM). The fitted GAM was then applied to the daily future climate, thereby applying a correction to future data based on differences in the range, mean and frequency distribution of values between historic UKCP and ERA5 data. Analyses were performed using the 'mgcv' package[33] for R.[34] Prior to doing so, known coastal biases in the ERA5 dataset were also corrected following Klinges et al.[35]

Future precipitation data were bias-corrected in two stages. First, for each grid cell, we compared the number of precipitation days in the historic UKCP18 and ERA5 data. If precipitation occurred on excess days in the historic UKCP18 dataset, we calculated the expected number of excess days in the future UKCP18 dataset and set the requisite number of days with lowest precipitation to zero. If precipitation occurred on too few days in the UKCP18 dataset, we generated a random dataset of precipitation with a statistical distribution consistent with ERA5 precipitation data, and replaced zero precipitation days in the future UKCP dataset with low-ranking precipitation amounts in the randomly generated dataset on days judged most likely to have precipitation based on total precipitation for periods either side. As a second stage, we calculated the ratio of ERA5 to historic UKCP18 total rainfall in each month and used this ratio as a fixed multiplier to the future UKCP18 data. Prior to calculating this ratio, the historic UKCP18 was subjected to the precipitation-day correction described above.

The bias-correction methods were applied separately for each grid cell and model projection, thereby ensuring that localized differences in climate between the 0.25° ERA5 and the coarser grid resolution UKCP18 data, were corrected for.

Crop suitability modeling

We calculated the global crop suitability of 1,708 crop varieties for 2008-2019 and 2050-2061 using the crop suitability model Ecocrop.[29] This model is based on the Food and Agriculture Organization (FAO) EcoCrop database[47], which contains information on the ecological requirements of crops with important human uses, for example as food, fodder, or for energy or industrial purposes. The crops selected were those for which FAO-derived ecological parameters were available in the 'dismo' R package.[11]

We used as inputs to the model monthly mean temperature, monthly minimum temperature (+5), and total monthly precipitation variables for each year in the periods 2008-2019 and 2050-2061. Monthly precipitation and mean, and minimum temperatures were derived from daily data. Daily minimum temperatures were derived by subtracting half the diurnal temperature range from the mean daily temperature. We added 5°C to the minimum temperature values as the model automatically adjusts the supplied minima by -5°C to account for possible underestimation of extremes in coarse temporal resolution data that are normally used to drive the model. To account for interannual and model-run variation in suitability, which can affect long-term average suitability scores,[36] we ran the model separately for each year and model projection. To account for permafrost, which would prevent agricultural use, and following Zabel et al.,[9] we assigned a suitability score of zero to any grid cell where the mean annual temperature was ≤ 0°C.

The Ecocrop model returns a climate suitability score ranging from 0 (unsuitable) to 1 (optimally suitable), which is in effect a relative measure of the extent to which climatic conditions are adequate within a growing season for given crop variety.[37] We calculated the mean suitability score for each crop across projections and the years 2008-2019 and 2050-2061 (separately for both climate scenarios), converted the outputs to binary (suitable / not suitable) using a threshold for suitability of ≥ 0.6,[38] and mapped changes in crop diversity. For each period, we then summed binary values to give the total number of crops with suitable climate in each grid cell location (crop diversity). We calculated the net change in crop diversity between periods as the total number of crops for which conditions were suitable in 2050-2061 minus the total number of crops for which they were suitable in 2008-2019. We also calculated future crop diversity without the addition of crops that became newly suitable in 2050-2061 (i.e., the total number of crops suitable in both periods). We defined an agricultural frontier as any grid cell unsuitable for any of the modeled crops in the 2008-2019 period and suitable for at least one modeled crop in the 2050-2061 period.

To test how sensitive our results were to the selected suitability threshold, we repeated the calculations with thresholds set at 0.4, and 0.8. To test how sensitive our results were to uncertainty in future climate, we conducted separate analyses for each projection and computed the standard deviations across projections.

To test the robustness of our conclusions to the inclusion of a wide range of crops, we repeated our analyses using the 50 most important grown crops in terms of global production value.[23] For the 12 crops with the highest global production values we mapped suitability for each crop individually.