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Effects of profit-driven cropland expansion and conservation policies

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Biodiversity protection and climate change mitigation require understanding of the potential trade-offs from possible future cropland expansion. Here we apply an interdisciplinary coupled modelling approach to identify areas under the globally highest expansion pressure of 1% to 30% future cropland expansion by 2030. On the basis of recent projections, we analyse the potential impacts on agricultural markets, biodiversity and CO_2 land-use emissions of a 3.6% global cropland expansion scenario by 2030. We assess how global conservation policies could shift expansion pressure and alter the ensuing impacts. Our results confirm that the areas under pressure are located mainly in the tropics. A cropland expansion of 3.6% increases global agricultural production by 2%. The associated land-use change generates 17.1 Gt CO_2 emissions and leads to a further decline in biodiversity intactness of 26% in the expanded areas. Conservation policies prohibiting the expansion into forests, wetlands and existing protected areas could substantially reduce emissions from land-use change, maintaining global agricultural productivity, but might have contrary effects on biodiversity. Strategic land-use planning could help reconcile agricultural production with environmental protection. The map of areas under expansion pressure presented here could contribute to improving the spatial planning of conservation measures.

Despite large potential to close current yield gaps[1–3] and even to reduce the globally cultivated area[4,5], cropland is still expanded in many regions[6], most notably in Africa and South America. Future projections indicate that this expansion is likely to continue[7–9] despite a range of associated negative effects[10,11]: the loss and fragmentation of natural habitat[12] threatens biodiversity[13,14], with the tropics being a hotspot of this development[15,16]. In the past decades, more than half of new cropland and pasture area was created at the expense of intact forests[16] and natural vegetation[6], with cropland encroaching even in already protected areas[17]. Carbon emissions induced by deforestation largely contribute to climate change[18–23], and cropland expansion could undermine natural climate solutions for mitigation[24,25]. Cropland expansion thus conflicts with important goals of the twenty-first century, such as protecting climate and biodiversity[26–28]. Identifying areas that are under the highest pressure of being converted into cropland in the future is essential to identify hotspots where resulting trade-offs might be strongest.

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While past dynamics of cropland expansion and relevant drivers are well investigated[6,7,29], there is uncertainty about future dynamics[30,31]. Besides environmental conditions determining crop growth potential, socio-economic factors strongly affect expansion dynamics[32]. Population growth and consumption preferences, for instance, are among the most influential determinants of future cropland extent[31], and deforestation in the first decades of the twenty-first century was found to be mainly commodity driven[33,34]. Moreover, international trade can spatially shift the effects of socio-economic drivers over large distances[35]. Accordingly, integrated research frameworks are required that capture this cross-scale interplay of environmental and economic factors that determine the profitability of land to be agriculturally used. At the same time, spatially explicit approaches are needed to assess the environmental impacts of cropland expansion and potentially arising trade-offs[36]. Yet, while various studies on future expansion exist[7,9,14], only a few capture the interdisciplinary context of the drivers and trade-offs in a global, spatially explicit research framework that links global and local dynamics[10,11,37,38]. Spatial data on potential future expansion areas are rarely provided[14] and mostly refer to one specific expansion scenario investigated, thus also limiting impact assessments to the provided data for specific expansion scenarios. Quantitative and spatial data on expansion pressure would enable impact assessments with individual and varying assumptions on future cropland extents, thereby making them less dependent on the few existing future cropland projections.

To combine these different requirements, we developed an integrative, spatially explicit and quantitative approach to simulate future profit-driven cropland expansion. It assesses the relative profitability of expansion across different crops on a 0.5° grid to identify the globally most profitable expansion areas, which we assume to be under the highest pressure to be converted into cropland. Thus, the aim of this study is not to investigate to which extent cropland might expand under a certain socio-economic scenario in the future, but to investigate which areas are under the globally highest expansion pressure considering future socio-economic and environmental conditions. The quantitative profitability ranking approach enables the exploration of areas under expansion pressure in various future scenarios of cropland expansion.

In this study, we use this integrative approach to identify land under the globally highest expansion pressure until 2030, thereby considering socio-economic business-as-usual conditions carrying forward current trends. As a first step, we map the spatial location and regional distribution of up to 4.27 million km^2 under expansion pressure, which is equivalent to an increase in global current cropland by up to 30%. The results form the basis for analysis of expansion scenarios from 1% up to 30% cropland expansion as upper boundary. As a second step, referring to expansion projections from the most recent (2023) agricultural outlook of the UN Food and Agriculture Organization (FAO) and the Organization for Economic Cooperation and Development (OECD)[39], we then investigate a global cropland expansion scenario of 3.6%, corresponding to an expanded area of 515,000 km^2 (EXP scenario; Extended Data Fig. 1). For this scenario, we identify the areas under expansion pressure and evaluate the resulting effects of converting them into cropland on agricultural markets, biodiversity and CO_2 emissions to investigate the environmental and socio-economic effects compared to a reference future without expansion (REF scenario). In the context of current political targets to stop deforestation[40,41], mitigate climate change[27] and protect biodiversity[26,28], we moreover analyse the impact of global conservation policies on expansion dynamics and resulting trade-offs. Therefore, we implement a second expansion scenario in which we prohibit the conversion of forests[29], wetlands[42] and protected areas[43] into cropland (CON scenario) under otherwise identical scenario conditions (for details on scenario design, see Methods). We again analyse the spatial distribution of expansion pressure for an area of 4.27 million km^2 to generally map how expansion pressure might be spatially shifted by conservation policies, and then analyse the 3.6% expansion scenario to assess how socio-economic and environmental impacts might be affected.

Within our integrative land-use change model iLANCE (integrative land-allocation sequencer), profit-driven cropland expansion is modelled by combining environmental conditions and simulated crop yields with socio-economic drivers of land-use change and regional economic conditions. Therefore, the biophysical crop model PROMET is coupled with the economic computable general equilibrium model DART-BIO (Extended Data Fig. 2). PROMET is applied to simulate crop growth globally for a future time period around 2030 (2016 to 2045, Shared Socioeconomic Pathways (SSP)585), providing crop yields under current crop management. Socio-economic dynamics driving agri-food demand and supply serve as input for DART-BIO to model future changes in crop prices, production and trade patterns until 2030. On the basis of the interplay between the simulated crop yields from PROMET and the relative marginal profitability of crop cultivation derived from DART-BIO, the iLANCE expansion module evaluates the relative profitability of cropland expansion at each pixel. The globally most profitable areas for cropland expansion are identified, thereby taking data on potentially cultivable land[44] and current cropland areas[45] into account. Due to this quantitative profitability ranking, the output data on areas under expansion pressure can be used to investigate various scenarios of an increase in future cropland extent by extracting the assumed top share of the globally most profitable areas, for example, for the 3.6% expansion scenarios. The effects of cropland expansion on agricultural markets are explored by feeding back the changes in cropland extent and agricultural productivity resulting from iLANCE as exogenous changes into DART-BIO. To assess the effects on biodiversity, we calculate the Biodiversity Intactness Index (BII)[46], thereby referring to data on current land-use[29,47] and cropping intensity[45,48], and evaluate its changes under expansion. In addition, we analyse how the world's most threatened biodiversity hotspots[49] are quantitatively affected by expansion pressure as well as their biodiversity intactness. On the basis of carbon storage data[50,51] and spatial land-use/-cover data[29,47,52], we estimate the land-use change induced CO_2 emissions. The results are analysed at 0.5° spatial resolution or at aggregated regional level (Extended Data Fig. 3). The methods are described in detail in Methods and in Supplementary Note 1. Gridded data on areas under expansion pressure and their profitability ranking are provided for download at 0.5° spatial resolution and aggregated at country level for a global cropland expansion from 1% up to 30% (see Data availability statement).

Results

Unrestricted cropland expansion

We find more than one-third of the globally investigated 4.27 million km^2 most profitable areas for cropland expansion in Africa (36%), followed by Asia and Russia (24%) and South America (15%). Particularly large areas under expansion pressure are located in Central African countries, with the globally largest area in Angola (585,000 km^2), and large areas in Cameroon and Gabon (Fig. 1 and Extended Data Fig. 4). In South America, the area under expansion pressure is particularly large in Brazil and Argentina, while areas under expansion pressure in Asia and Russia are mainly located in India, China, countries in the Middle East and Russia. Australia shows globally the fourth largest area of profitable land for expansion (313,000 km^2) after Angola, the USA and Brazil (Supplementary Note 2.1).

In Asia and Europe, the areas under expansion pressure are mainly located at the frontiers of current cropland on pixels that are, to a large extent, already agriculturally used, while in Africa, South America and Russia they are located on pixels currently not or barely used for crop cultivation. Globally, around 70% of the most profitable expansion areas are located on pixels with 10% or less cropland cover, with 8% even on pixels considered as not or barely used for crop cultivation (0.1% or less cropland cover) (Supplementary Note 2.2).

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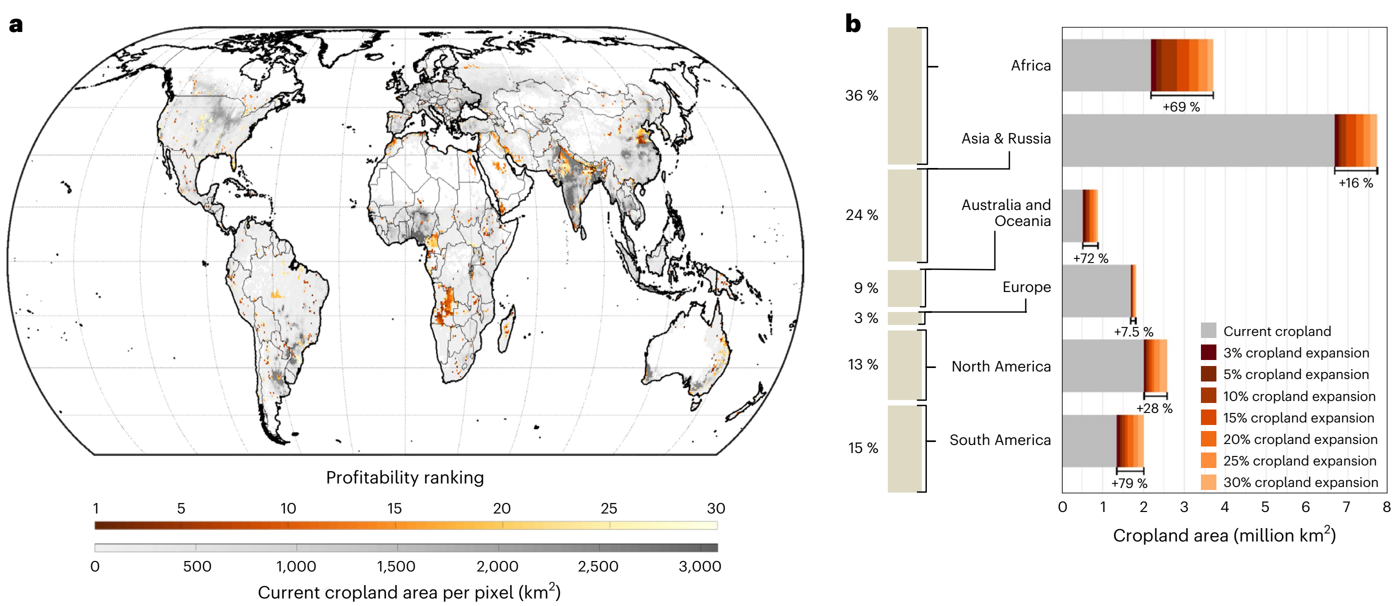

Fig. 1 | Areas under expansion pressure up to a potential increase in current cropland of 30% without conservation policies. a, Pixel-based profitability ranking of expansion areas, indicating under which global cropland expansion (1% to 30%) a pixel is among the globally most profitable ones to be transformed into cropland. Grey areas display current cropland. **b**, Regional distribution of the most profitable expansion areas displaying the regional area shares and the potential relative expansion of up to 30% of current cropland within each region.

Scenario of 3.6% unrestricted global cropland expansion

Extracting the globally most profitable expansion areas for the projected 3.6% cropland increase[39] in the EXP scenario, we find the 515,000 km^2 under globally highest expansion pressure to be similarly distributed across the continents as the 4.27 million km^2 (Fig. 2a). As visible in Fig. 1a, the most profitable areas for cropland expansion (displayed in dark red) are mainly located in Australia, Brazil, China and India, and various African countries such as Angola, Ethiopia, South Africa and the Democratic Republic of Congo. Globally, around 34% of the areas are located on pixels not or barely used for crop cultivation (0.1% or less cropland cover) (Fig. 2b). The share of areas under expansion pressure at already cultivated locations is particularly high in Asia, for example, Eastern Asia (100%) and India (91%). In Brazil, the areas under highest expansion pressure are mainly (75%) located at the frontiers of current cropland in pixels already cultivated, while more than half of the most profitable land for expansion in Paraguay, Argentina, Chile and Uruguay (56%), and in sub-Saharan Africa (59%) is located in currently not or barely cultivated pixels (Extended Data Fig. 5).

Impacts on agricultural markets

Implementing the 3.6% EXP scenario in the economic model raises global agricultural production until 2030 by +2% compared with a reference future without cropland expansion (REF scenario). Particularly the production of cash crops such as sugar cane/ sugar beet and soy increases (+2.8% and +2.7%, respectively), these crops being mainly cultivated in regions highly profitable for cropland conversion. On average, crop prices are −7% lower than in the REF scenario, leading to generally higher consumption levels and lower producer income due to falling prices in all regions. The global volume of imports and exports increases by 4%. Especially regions with high relative cropland expansion, such as Australia and Oceania, South America or Africa, exhibit strong production increases (Fig. 3a) that are often accompanied by higher net exports; for example, wheat in Australia and Oceania (+32% production increase, +53% net exports). In Brazil, mainly the production of maize (+3%) and cash crops such as soy (+2%) and sugar cane (+2%) increases, contributing to an increase in overall regional export of +3%. In sub-Saharan Africa, in particular the production of food crops such as grains (wheat +11%, maize +3%, other grains +3%) increases. Three-quarters of this production increase is used to satisfy domestic consumption, while the rest is exported, leading to an increase in exports of +7%. In Asia and Russia, overall production increases only slightly by +1%, with regions such as India and China increasing their net imports by +10% and +6.6%, respectively, rather than their production (+0.7% and +1%, respectively).

Looking at the Gross Domestic Product (GDP) as a welfare indicator, the possibility to increase domestic production with cropland expansion and to import at lower prices generally increases the GDP especially in net-importing regions in Asia, such as India (+1.2%), Malaysia and Indonesia (+0.8%), and China (+0.7%) (Fig. 3b). For most net exporters, on the other hand, the EXP scenario leads, despite increased production, to a decline in GDP due to lower world market prices. In South America, the GDP drops, for example, by −0.4% in Brazil and by −0.3% in Paraguay, Argentina, Chile and Uruguay. In a few exporting regions, the lower prices can be compensated, for example, by an increased export quantity in Australia, New Zealand and Oceania, and by additional increases in total consumption resulting from lower domestic food prices due to a rise in cultivation of food crops in sub-Saharan Africa and the rest of Latin America.

Land-use-change emissions and biodiversity impacts

Expanding current cropland by around 3.6% in the EXP scenario would generate 17.1 Gt CO_2 emissions and reduce the BII across these areas by −26%.

The areas under expansion pressure in the EXP scenario are currently mainly covered with secondary vegetation (53%) or used as pasture (39%) (Fig. 4a). Since a major part (71%) of the areas is located in the tropics, almost half (42%) of the associated global emissions is generated by the conversion of land with tropical moist and seasonal forest as potential natural vegetation (PNV), of which 88% and 61% are primary or secondary forests, respectively. In addition, more than 75% of the temperate and boreal forest PNV under expansion pressure is considered as primary or secondary vegetation. Overall, the regions with the largest areas under expansion pressure show the highest CO_2 emissions potentially generated by cropland conversion (Fig. 4b). In Africa, those emissions are generated almost equally by the conversion of areas with grass- and shrubland PNV (52%) and forest PNV (48%),

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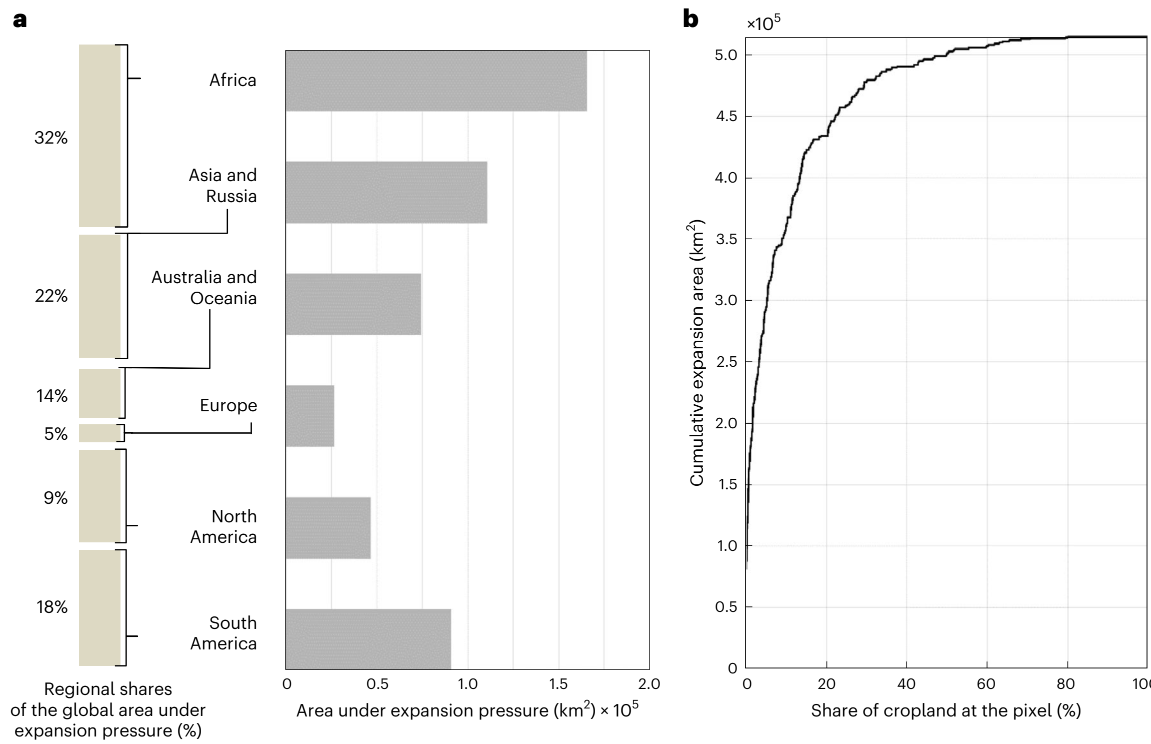

Fig. 2 | Areas under expansion pressure in the 3.6% EXP scenario. a, Regional distribution of areas under expansion pressure and their global shares in the total area under pressure. **b**, Global cumulative distribution of area under expansion pressure (%) at pixels with shares from 0% to 100% currently covered with cropland.

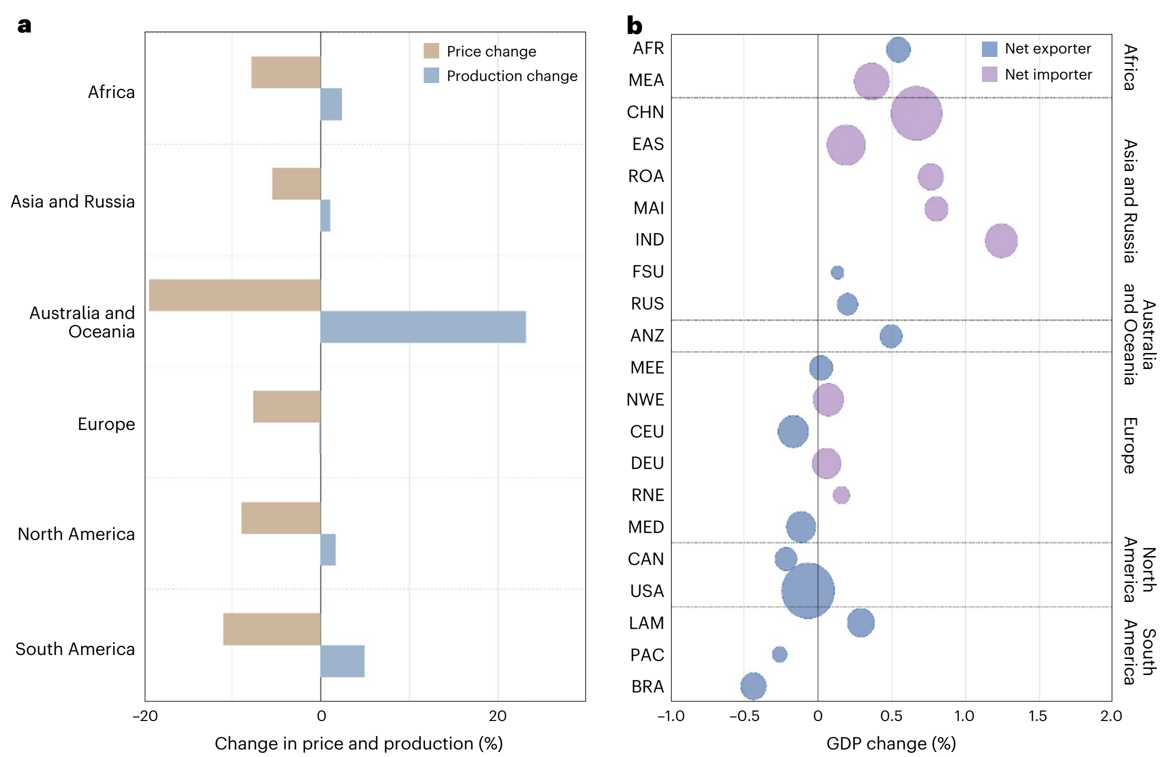

Fig. 3 | Economic impacts of converting the areas under expansion pressure into cropland until 2030 in the 3.6% EXP scenario vs the REF scenario. a, Relative changes in producer prices and production (%) per region. **b**, Relative changes in the GDP (%) for the 21 economic regions, distinguishing between net exporters and net importers. The size of the dots represents the absolute GDP of the regions under the EXP scenario in 2030. The region mapping and abbreviations of the economic regions can be found in Extended Data Fig. 3.

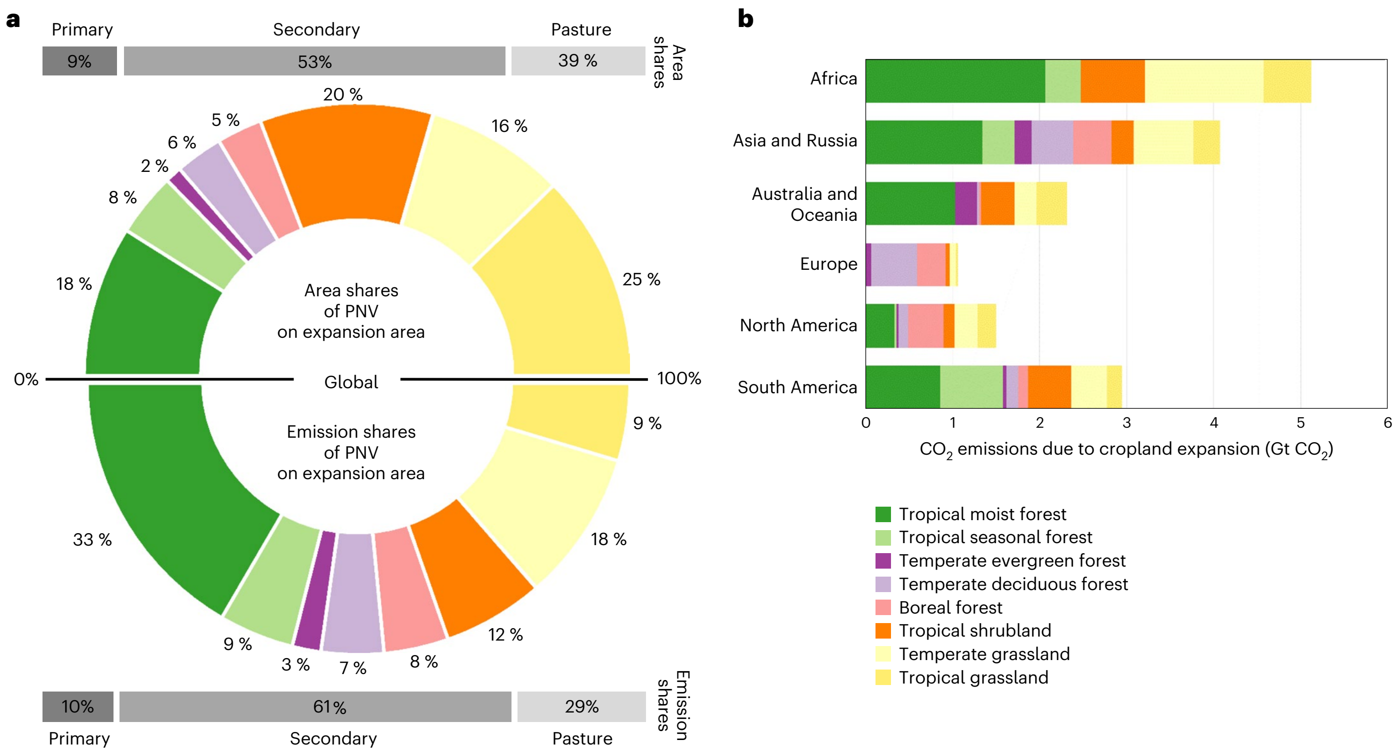

Fig. 4 | CO_2 emissions generated by converting the areas under expansion pressure into cropland in the 3.6% EXP scenario. a, Shares of the different cover types (primary, secondary, pasture) and PNV types on the global area under expansion pressure (top) and the generated CO_2 emissions (bottom). **b**, Regional distribution of the generated CO_2 emissions in absolute terms (Gt CO_2).

while in Asia and Russia, and South America, around two-thirds of the emissions comes from a conversion of forest PNV (69% and 63%, respectively). Globally, the highest share of emissions generated from conversion of tropical forests can be found in South America (54%), followed by Africa (48%), while emissions in Europe and North America are mainly generated by converting areas with temperate and boreal forest PNV (87% of the regionally generated CO_2 emissions in Europe and 36% in North America).

The reduction in biodiversity intactness across the areas under expansion pressure is strongest (−39%) in Australia and Oceania (Fig. 5a), where around 25% of the areas is currently covered with primary vegetation. The second strongest BII decrease can be found in South America (−34%), where biodiversity intactness would be particularly reduced across the areas under expansion pressure in Brazil (−35%) and Paraguay, Argentina, Chile and Uruguay (−32%) (Supplementary Note 3). The BII decline in North America (−28%) is especially strong in Canada (−44%), where almost one-third of the identified areas is currently still covered with primary vegetation, of which 10% is even classified as being under minimal human influence. In Africa, and Asia and Russia, the BII drops by around −24% across the areas under expansion pressure. In Russia (−38%), areas under pressure are largely currently covered with secondary vegetation (49%) or used as pastureland (41%), and only 18% of the areas is located on pixels currently already under cultivation (>5% cropland at the pixel). In other countries in Asia and Russia, such as in China or India, on the other hand, large parts (47% and 91%, respectively) are located at the frontiers of current cropland, and correspondingly less primary and also secondary vegetation is potentially converted into cropland in these regions. The BII decrease across these areas is −21% and −18%, respectively, among the lowest globally. Globally, areas under expansion pressure are particularly located in the world's most threatened biodiversity hotspots of the Eastern Afromontane (42,000 km²), Indo-Burma (23,000 km²), the tropical Andes and the Cerrado (both 17,000 km² each), and the Horn of Africa (15,000 km²) (Fig. 5b).

Effects of global conservation policies

Introducing conservation policy puts 47% of the 4.27 million km² globally most profitable areas for expansion under protection, of which 17% are currently already classified as protected[43]. Identifying the next most profitable areas not protected by conservation policies (until again 4.27 million km² under expansion pressure are identified) displays the potential spatial shift of expansion pressure induced by conservation policies (Fig. 6a). Even though the expansion pressure does not strongly shift between the large world regions (Extended Data Fig. 6), there are strong spatial shifts within those regions. In South America, for instance, the total area under expansion pressure decreases in Brazil (−14%) and shifts from the central part in the Amazon to the south, southwest and the Cerrado region (Fig. 6a). On the other hand, more land is under expansion pressure in the southern part of the continent in Paraguay, Argentina, Chile and Uruguay (+36%), mainly in the Gran Chaco region. Globally, the share of areas under expansion pressure being located on pixels with less than 10% cropland cover is reduced from 70% to 55%, and less area currently not or barely used for crop cultivation is under expansion pressure (Supplementary Note 2.2).

The introduction of conservation policies within a 3.6% expansion scenario in the CON scenario particularly reduces the area under expansion pressure in Europe (−42%, −11,300 km²), and Asia and Russia (−9%, −10,200 km²). In Africa and South America, on the other hand, the total area under expansion pressure increases by +10% and +11%, respectively (Extended Data Fig. 7). In South America, expansion pressure shifts mainly from Paraguay, Argentina, Chile and Uruguay (−14%) to the rest of Latin America (+48%), but also to Brazil (+2%) (Fig. 6b). Overall, however, the countries with the globally largest area under expansion pressure remain similar to the EXP scenario: Australia, Brazil,

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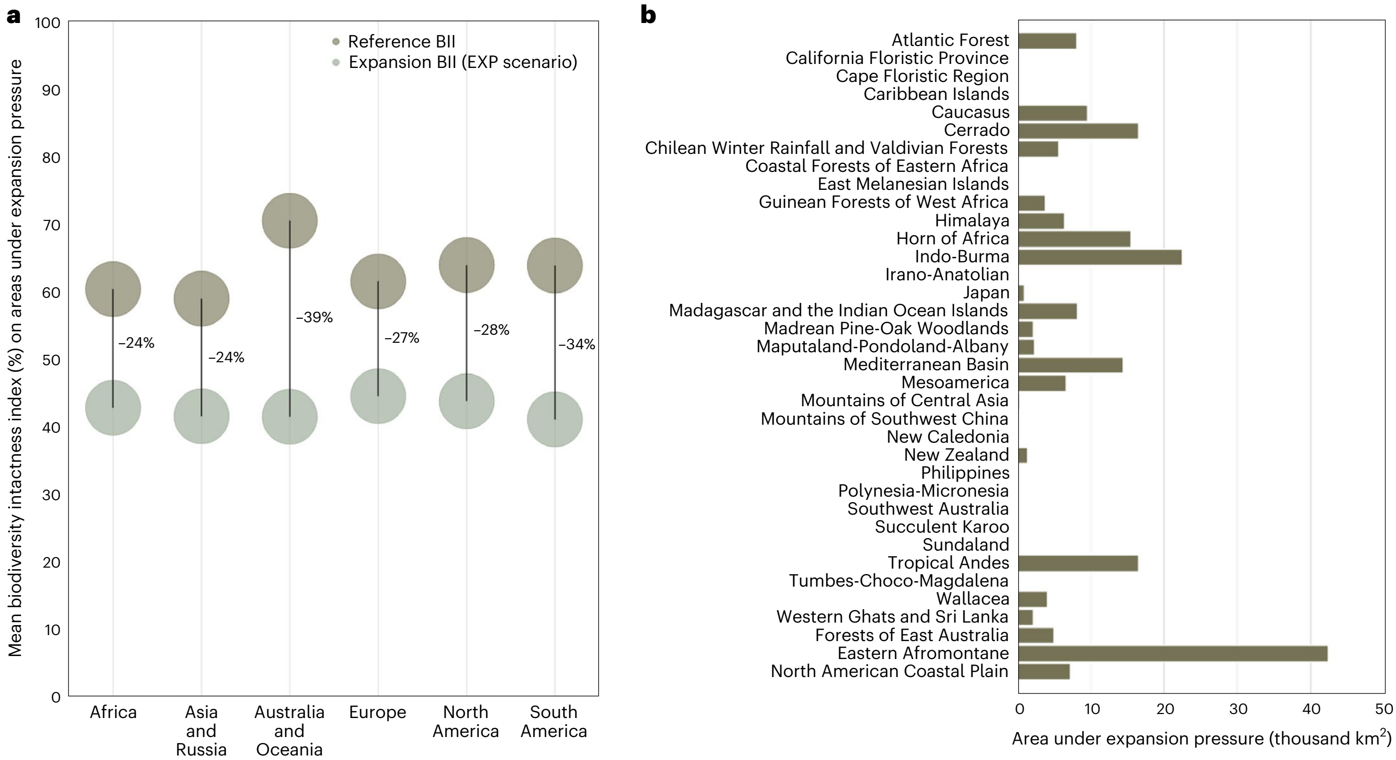

Fig. 5 | Regional impacts of the transformation of the areas under expansion pressure into cropland on biodiversity in the 3.6% EXP scenario. a, Regional biodiversity intactness and its changes due to cropland expansion. The shaded circles display the BII across the areas under expansion pressure under current land use (Reference BII) and under their use as cropland (Expansion BII). Moreover, the regional change in BII (%) from the reference to the respective scenario is displayed as a percentage. **b**, Area (thousand km^2) identified to be under expansion pressure in the world's most threatened biodiversity hotspots[49] under the 3.6% EXP scenario.

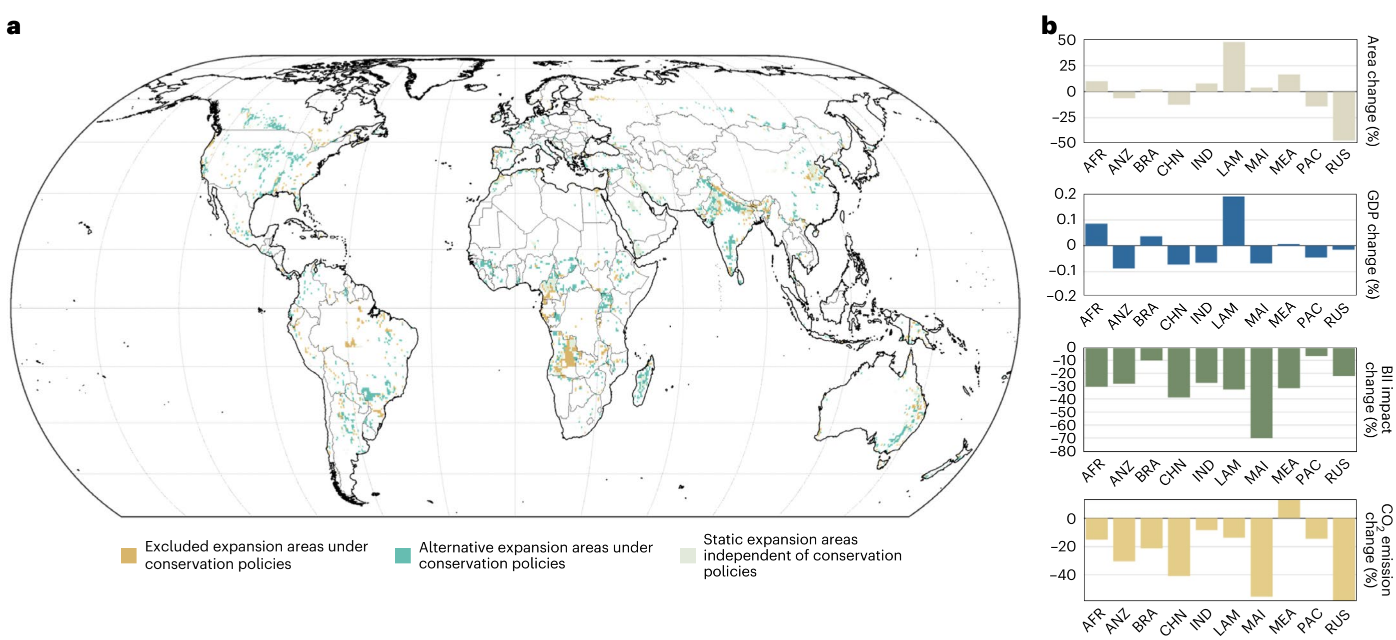

Fig. 6 | Changes in the spatial patterns of expansion pressure and the socio-economic and environmental impacts under the implementation of conservation policies. a, Spatial shift in areas under expansion pressure for the identified areas up to an increase of current cropland by 30% (4.27 million km^2) as a defined upper boundary. Brown areas have been identified to be under expansion pressure without the consideration of conservation policies, but are protected by the assumed conservation policy; green areas are the areas into which expansion pressure shifts under conservation policies; grey areas are under expansion pressure with and without conservation policies. **b**, Relative changes in area under expansion pressure (%), GDP (%), BII impact (%) and CO_2 land-use emissions (%) between the expansion scenarios with (CON scenario) and without (EXP scenario) conservation policies under a global expansion of 3.6%, for selected economic regions (see Extended Data Fig. 3 for region mapping).

Angola, Ethiopia, South Africa and Madagascar, China and India. Particularly in Malaysia and Indonesia, and sub-Saharan Africa, expansion pressure is strongly shifted to locations already cultivated, with the share of area under expansion pressure on pixels currently cultivated rising from 29% to 57% in Malaysia and Indonesia, and from 41% to 55% in sub-Saharan Africa. On the other hand, a higher share of area under expansion pressure is located in not or barely cultivated pixels in South America in Brazil (from 25% to 32%) and also Paraguay, Argentina, Chile and Uruguay (from 56% to 80%).

Agricultural production is only marginally reduced by −0.1% and regionally shifts according to the changes in potentially expanded area. It is mainly reduced in Australia, New Zealand and Oceania (−3%), Paraguay, Argentina, Chile and Uruguay (−1%), and the USA (−1%), and shifted in particular to the rest of Latin America (+3%), sub-Saharan Africa (+0.5%), and the Middle East and Northern Africa (+0.5%). The impacts on the GDP, however, are marginal (<±0.1%) in most regions (Fig. 6b), indicating that the introduction of conservation policies may cause only marginal economic costs in a 3.6% expansion scenario.

The spatial shift in expansion pressure away from forests, wetlands and protected areas in the CON scenario reduces the global CO_2 emissions associated with converting these areas into cropland by almost −25% to 13 Gt CO_2. Areas with tropical grass- and shrubland PNV account for more than half (54%) of the global area under expansion pressure. Compared with the EXP scenario, the pressure on primary and secondary vegetation decreases by −4 and −21 percentage points, respectively. Yet, more pastureland is under expansion pressure, with almost two-thirds (63%) of the areas under expansion pressure being currently used as pasture. Regionally, the decline in area under expansion pressure more than halves the potential CO_2 emissions in Europe (−58%) and reduces them by −30% in Asia and Russia, and Australia and Oceania, but particularly in Russia (−59%), Malaysia and Indonesia (−55%) and China (−41%) (Fig. 6b). CO_2 emissions increase in Eastern Asia (+15%), where also the area under expansion pressure increases in the CON scenario (+8%). Despite the increased area under expansion pressure in Africa and South America, the potentially generated CO_2 emissions drop by −20% in South America and by −15% in Africa, resulting mainly from a shift in expansion pressure from tropical forests into tropical and temperate grass- and shrublands.

In both regions, Africa and South America, the introduction of conservation policies moreover leads to a reduced decline in biodiversity intactness across the areas under expansion pressure (−17% and −27% instead of −24% and −34%, respectively) (Supplementary Fig. 23). The impact on biodiversity intactness is most strongly reduced in Australia and Oceania (by 11 percentage points to −28%), mainly resulting from a shift in expansion pressure away from primary vegetation into managed pastureland. The BII across the areas under expansion pressure in Asia and Russia drops by −16% in the CON scenario (instead of −24% in the EXP scenario). Strongest effects can be observed in Malaysia and Indonesia (Fig. 6b), where the expansion pressure shifts away from primary and secondary vegetation into pastureland, while rather moderate changes can be observed in the rest of Asia and Russia, for example, in China (−13% instead of −21%), India (−13% instead of −18%) and Russia (−29% instead of −38%). Globally, the BII decline across the identified areas under pressure is −18% instead of −26%, around two-thirds of the decline in the EXP scenario. Regarding the world's most threatened biodiversity hotspots, introducing conservation policies shifts expansion pressure away from hotspots such as the Indo-Burma hotspot, the Chilean Winter Rainfall and Valdivian Forests, Mesoamerica or the Atlantic Forest to the biodiversity hotspot of Madagascar and the Indian Ocean Islands (+200%), the New Zealand hotspot (+100%) and the hotspot of the Horn of Africa (+46%) (Supplementary Fig. 23).

Discussion

The location of regions we find under expansion pressure in the future tie in with the spatial patterns of recent and past expansion dynamics[6], and are in line with projections that locate future expansion mainly in the tropics in sub-Saharan Africa, and Central and South America[10,53], in the Middle East and Northern Africa[38,53], and Australia[10]. Particularly Angola, Brazil and Ethiopia already show a rapid cropland increase in the recent past (Angola, Brazil[6]) or are identified as future expansion hotspots in other studies (Brazil, Ethiopia[37,38]).

Economic and environmental impacts

The higher production of globally traded cash crops such as sugar cane/sugar beet and soy under the 3.6% EXP scenario and the resulting reduction in global agricultural prices could change the relative wealth of regions differently, depending also on their exports and imports: net-importing regions in Asia and the Middle East and Northern Africa economically benefit from falling world market prices and higher gross domestic output, while the GDP of net-exporting regions whose agricultural sector is strongly dependent on cash crop exports, especially Brazil and the southern part of South America, are negatively affected. These findings corroborate the strong impact of global market interactions on the regional economic implications of expansion, thus highlighting the importance of global approaches to investigate such effects.

Our results on the potential pressure of expansion on biodiversity intactness agree with previous global studies[37,38] that identify South America and the tropics in general as hotspots (Supplementary Note 2.4). Yet, we find biodiversity intactness to be also particularly threatened in areas under expansion pressure in Canada and Russia. Here, the underrepresentation of observational data in northern latitudes in the underlying database used to assess the BII[54,55] can even lead to an underestimation of expansion effects on the BII (see Methods).

Comparing the areas under the highest expansion pressure identified in the 3.6% EXP scenario with the location of all 4.27 million km^2 under expansion pressure, we find the most profitable areas to be more often located on pixels currently not or barely used for crop cultivation (35% in the 3.6% EXP scenario, and 8% under a 30% expansion without conservation policies; see Supplementary Note 2.2). The emissions induced by converting the areas under expansion pressure into cropland in the 3.6% EXP scenario are proportionally reduced and around 10% of the emissions generated when converting all 4.27 million km^2 of a 30% cropland increase (Supplementary Note 2.3). The relative reduction of the BII across the potentially expanded areas, however, is very similar (see Supplementary Notes 2.4 and 3). Thus, we see that even comparatively small increases in cropland affect land where biodiversity intactness is reduced in the same relative magnitude as in more severe expansion scenarios. Further analysis of different global expansion targets and the resulting socio-economic and environmental impacts could provide further information about the correlations, the sensitivity of the impacts, and also reveal potential nonlinearities.

Effects of conservation policies

The reduction in environmental impacts under conservation policies, even in regions where the area under expansion pressure is stable or increases compared with the EXP scenario, suggests that the assumed policies could substantially contribute to reconcile agricultural production with environmental protection without compromising global agricultural productivity. This underlines the potential of existing political agreements for reducing deforestation and protecting forests[40,41], as well as the importance of informed, strategic land-use planning. Yet, particularly in the context of biodiversity conservation, globally uniform conservation policies protecting certain ecosystems, such as forests or wetlands, might lead to trade-offs threatening other highly biodiverse ecosystems such as grasslands. This points to the importance of considering regional particularities in global conservation policies and to the need for integrative research frameworks that link the global and local scale. The developed iLANCE framework can serve as an example of how this can be achieved.

By providing data on areas under high expansion pressure at 0.5° spatial resolution and aggregated at country level for future global cropland expansion from 1% up to 30%, we can distinguish between areas under pressure in low and in more severe expansion scenarios. For further impact assessments based on the output data, flexible assumptions can be made on the extent of expansion up to an increase of 30%. The results of this study could improve the effectiveness of conservation strategies and political efforts on global nature and biodiversity conservation, such as the Kunming–Montreal Global Biodiversity Framework[56], by ensuring that alongside areas with high conservation value, areas under high expansion pressure or where biodiversity might be threatened most by cropland expansion are also taken into account. Further research on the drivers of cropland expansion, their quantitative impact and spatial and temporal distribution is needed to improve simulations of land-use change dynamics in integrative models. An in-depth understanding of potential future dynamics is necessary to identify not only potentially arising trade-offs, but also possibilities to create co-benefits between agricultural production, global climate protection and biodiversity conservation goals.

Methods

Analysis framework and scenario design

The globally most profitable lands for cropland expansion were identified by applying the integrative land-allocation sequencer iLANCE. iLANCE is a newly developed land-use model based on an established approach coupling the biophysical crop growth model PROMET and the Computable General Equilibrium (CGE) model DART-BIO, which has previously been used in other interdisciplinary studies[2,44]. It allows for integratively simulating crop allocation and land-use change on current cropland on the basis of biophysical and socio-economic drivers globally at 0.5° spatial resolution. For this study, we extended the iLANCE model using an expansion module to investigate the spatial allocation of profit-driven cropland expansion. The models are described in the sections below.

In this study, we investigated the spatial patterns of expansion pressure with and without conservation policies up to a hypothetical increase in current cropland of 30% until 2030 to take into account the high uncertainty of future cropland projections[57]. The assessments serve as an upper threshold, based on which a relative profitability ranking was created that allowed extraction of the most profitable pixels for any predefined global expansion rate up to 30%. It is important to note that we did not assess the absolute profitability for global cropland expansion, but instead investigated the areas that could be assumed to be under the highest expansion pressure due to their relatively highest profitability for cropland expansion within an exogenously defined global expansion scenario (Supplementary Note 1.1).

The areas of a potential cropland expansion of 3.6% were investigated for both scenarios: cropland expansion with conservation policies (CON scenario) and without conservation policies (EXP scenario). The potential environmental and socio-economic effects were analysed and compared to a future reference scenario (REF scenario) without expansion (Extended Data Fig. 1).

All three scenarios (REF, EXP and CON scenarios) assumed a socio-economic business-as-usual development until 2030, but differed in their assumption on future expansion dynamics and land-use regulations:

In the REF scenario, we assumed that the sum of managed land area (cropland, pastureland, managed forests) is constant until 2030 (no expansion into unmanaged land).

For the assessment of expansion pressure without conservation policies (EXP scenario), the profitability of land for expansion was assessed without any land-use regulations to investigate areas under expansion pressure independently of current or future potential conservation or protection policies. This took into account that (1) established protected areas can change as well as conservation interests and (2) cropland already encroaches into protected areas[17].

To investigate how conservation policies impact profit-driven cropland expansion, we introduced the conservation policy scenario (CON scenario), in which global policies prohibit expansion into forests[29], wetlands[42] and strictly protected areas[43] by referring to the potentially available cropland dataset[44] (2010–2039; Representative Concentration Pathway (RCP)8.5) (see Supplementary Note 1.1). For the socio-economic development (business-as-usual) and the cropland expansion magnitude (3.6%), the assumptions were identical to those of the EXP scenario.

Spatial analysis level and region mapping

iLANCE bridges the scale between the PROMET simulations at 0.5° spatial resolution and the 187 Agro-Ecological Subregions (AES) into which DART-BIO is structured. The resulting land-use maps of iLANCE are available at 0.5° spatial resolution.

In this study, the results were analysed (1) at gridcell level with 0.5° spatial resolution, (2) at the level of the 21 economic regions defined in DART-BIO, or (3) aggregated to 6 world regions to provide a more aggregated perspective on the results (Extended Data Fig. 3). When aggregating the economic data to the 6 world regions, two economic regions—rest of Latin America (LAM) and Middle East and Northern Africa (MEA)—span across the borders of two world regions (North and South America, and Africa and Asia and Russia, respectively). We allocated LAM to South America and MEA to Africa.

Crop modelling

The crop yields were simulated with the biophysical land surface process model PROMET[58]. It simulates crop growth on around 170,000 representative samples at an hourly time step for each year of the 30-year time period around the economic target year 2030, considering climate change under SSP585. Potential yields were simulated for 18 agricultural crops (Extended Data Table 1), assuming optimized crop management and current irrigation patterns[59], and aggregated to 30-year averages to (1) avoid bias from selecting a single-year yield, caused by annual variabilities and (2) refer to yields that represent a timespan in which land-use decisions are made. To focus on agricultural expansion without additional agricultural intensification, we applied a bias adjustment based on statistical yields at AES level[48] to adjust the simulated potential yields to the current statistical intensification level while conserving yield changes induced by climate change. In a final step, the yields of the 18 crops simulated with PROMET were aggregated to the 10 crop categories considered in DART-BIO (Extended Data Table 1) to be consistent with the representation of crops in the economic model, which is necessary for the coupling within iLANCE. For details on the crop modelling, see Supplementary Note 1.2.

Economic modelling and marginal profit functions

To assess the impacts of cropland expansion on prices, production and trade patterns, we employed the CGE model DART-BIO, a multiregional and multisectoral model of the world economy. In its current version, it is calibrated to the GTAP 9 database[48], aggregated to 21 economically homogeneous regions (Extended Data Fig. 3) and 53 sectors. The agricultural sector is represented by 10 crop categories (Extended Data Table 1), two livestock sectors, and 20 sectors including processed food and biofuels. To assess the sectoral competition for land in a more differentiated way, the production factor land is disaggregated[60] within the 21 regions into Agro-Ecological Zones[60,61] defined by parameters relevant for agricultural productivity[62]. This results in 187 AES globally (see Supplementary Note 1.3 for more details).

DART-BIO provides subregional and crop-specific marginal profit functions, with respect to land, that are derived from the market equilibrium and depend inter alia on the productivity of land in relation to other factor inputs (capital, labour, energy). The marginal profit determines the achievable profit for allocating a certain crop category on an additional unit of land as a function of the already allocated area to this crop category within an AES, and is thus a key input into iLANCE. Let Θ_{Lc} be defined as the factor income share of land for each crop category and each AES, Θ_{KLEc} the factor income share of capital, labour and energy, ρ the elasticity of substitution and A and B the AES within an economic region; the marginal profit (MP) (US$ per hectare (ha)) attainable by allocating a cropland area L was calculated as follows:

$$\mathrm{MP}\left[\frac{\$}{\mathrm{ha}}\right] = \left[\Theta_{KLEc} + \sum_{B\neq A}\Theta_{Lc} + \Theta_{Lc}^{1-\rho}\times L_{Lc}^{\rho}\right]^{\frac{1-\rho}{\rho}} \times \Theta_{Lc}{}^{1-\rho} \times L_{Lc}^{\rho-1} - 1 \quad (1)$$

The marginal profits to land depend on market interactions, which in the model may dynamically change depending on scenario assumptions. Therefore, the relative profitability of different crop categories not only varied between different AES, but might also shift depending on the scenario. Generally, the attainable marginal profit was highest for the first cultivated hectare of a crop category and decreased the more cropland was allocated, until we assumed that it approached zero, when the area to be allocated within an AES was reached. For details on how marginal profit functions are determined, see ref. 2. We used the marginal profit function in the iLANCE model to globally rank all crop categories in all AES according to their profitability when allocating an additional unit of cropland within the AES (see below).

Integrative assessment of profit-driven cropland expansion

The globally most profitable pixels for cropland expansion were assessed with iLANCE by combining the simulated crop yields from PROMET and the marginal profit functions for each crop category and each AES from DART-BIO, describing the relative marginal profits to land under the expansion scenarios (Extended Data Fig. 2). For the allocation of cropland, iLANCE considered current land-use constraints, referring to data on areas that are potentially cultivable and potentially available for cropland use[44], and information on the current cropland extent. For the latter, we spatialized the GTAP 9 data to be consistent with the cropland areas in the economic model by referring to spatial data from ref. 45 and the MIRCA2000 dataset[63] (Supplementary Note 1.4).

Integrating these data, iLANCE simulated profit-driven cropland expansion by calculating the potentially attainable profit for cropland allocation and expansion per unit area at each pixel and relatively compared them. Thereon based, the globally relatively most profitable pixels were successively selected until the defined upper boundary of global cropland expansion, here 30%, was reached.

Impact assessment on biodiversity

To assess the impact of cropland expansion on biodiversity, we calculated the Biodiversity Intactness Index, which describes the change in species richness and species abundance compared to a pristine natural ecosystem state in response to land use[46]. Therefore, we adapted and extended the PREDICTS modelling approach[64] used in ref. 65 and methods described in refs. 54,66. The BII was calculated as a result of community composition and species abundance in a pristine ecosystem compared to the impact of land-use and additional pressure variables we included, such as human population density[67], distance to the nearest road[68] and environmental similarity[54,65]. The biodiversity input was based on the PREDICTS database[55] and its extension[69].

The assessment of the biodiversity intactness and its change under cropland expansion required spatial information on land-use/-cover and intensity, distinguishing between 8 land-use intensity classes: primary vegetation under minimal use intensity, primary vegetation, secondary vegetation, cropland with three different use intensities (minimal use, light use, intense use), pasture and urban areas. The created spatial dataset with the required land-use intensity classes was used to link the PREDICTS dataset to the expansion output of iLANCE. Primary vegetation with minimal use intensity represented the reference—a pristine ecosystem state with minimal human influence (for details, see Supplementary Note 1.5).

To simulate the impact of land use on biodiversity, two linear mixed-effects models were constructed, simulating species abundance on local sites (abundance model) and compositional similarity among local sites (compositional similarity model). The resulting predictions of abundance and compositional similarity for each land-use intensity class were multiplied by the fractional land-use raster data for each land-use intensity class and then divided by the primary vegetation with minimal use intensity representing a pristine ecosystem state. On the basis of this, the BII was calculated by multiplying the resulting abundance by the compositional similarity raster data (Supplementary Note 1.5, equation (3))[54].

To add an additional perspective to the assessment of biodiversity impacts of cropland expansion, we took into account whether biodiversity is currently already particularly threatened by also quantifying the area under expansion pressure within the 3.6% EXP and CON scenarios for areas located in the world's most threatened biodiversity hotspots. These biodiversity hotspots are defined as areas that have already lost 70% of primary vegetation while hosting at least 1,500 vascular plant species[49]. Moreover, we assessed how biodiversity intactness changed across these biodiversity hotspots when the identified areas were converted from their current land use into cropland.

Evaluation of generated land-use-change CO_2 emissions

To estimate the CO_2 emissions induced by converting the identified areas under expansion pressure into cropland, we assessed the change in carbon stocks on the basis of the potential natural vegetation cover and the current land-use state compared to use as cropland. For our calculations, we used data on the average carbon stocks in biomass and soil of 11 different types of potential natural vegetation depending on their land-use states as primary land, secondary land, pastureland or cropland, based on ref. 50.

While the spatial distribution of the different PNV types is provided in refs. 52,70, the spatial distribution of primary land, secondary land and pastureland was assessed in the same way as for the biodiversity impact assessment on a 1 km spatial resolution, referring to HILDA+ land-use data[29] and the integrative global dataset on human influence[47]. Primary land was defined as forests, unmanaged grass-/shrubland or land with sparse vegetation (HILDA+ classes 44, 55, 66) under low or very low human influence, which distinguishes it from secondary land as well as from pastureland.

Due to a lack of data on PNV-specific land-use states, we assumed that within a 0.5° pixel, each PNV type is used as primary land, secondary land and pastureland according to the area ratio between the three land-use states at the pixel. Accordingly, similar to other studies[50], we assumed expansion in all specified PNV and land-use types proportionally to their area share on the pixel in the unrestricted expansion scenario. Within the conservation policy scenario, on the other hand, expansion into forests is prohibited, which is why we assumed cropland to be expanded primarily into non-forest PNV types and forest PNV types currently used as pasture.

On this basis, we assessed the carbon stocks on the expansion areas for all existing PNV types under the current land-use states as well as under potential use as cropland. The difference between the two carbon storage potentials describes the carbon emissions caused by land-use change through cropland expansion. They were transformed to CO_2 emissions by multiplying the emissions by the ratio of the molecular weight of carbon dioxide to that of carbon. This approach does not take temporal dynamics into account but attributes all (instantaneous and delayed) emissions related to the cropland expansion to the time when the transformation into cropland occurs, assuming that carbon stocks before and after the land-use and land-cover change (LULCC) event are at equilibrium[50]. We found this method to be sufficient for the purpose of our study, since no temporal attribution of carbon fluxes is required.

Potentials and limitations

While the expansion module in iLANCE takes biophysical growing conditions, agricultural management, socio-economic drivers and the resulting economic conditions into account, further factors can impact expansion dynamics. Regarding past expansion, for instance, studies show that it disproportionately occurred near areas with historic expansion[30,71,72], and natural environments are most intensively modified in areas with high market influence[73]. Moreover, extreme poverty[15] and the building of infrastructure, such as roads[34], can spatially be associated with agricultural expansion and could thus be considered as drivers of cropland expansion. For this study, we decided to focus solely on profit-driven expansion and thus did not include these further factors into our expansion module for various reasons: a main issue is that there is still a lack of knowledge on the relevance and the magnitude of impact of these drivers and also on how both vary across space and time[30,31]. Market density, for example, has less impact on cropland expansion dynamics in South Asia and Africa, where large parts of agriculture are focused on subsistence[73]. A high profitability of land use often provides an economic impetus, for example, for road construction[15]; in some cases, large-scale actors might even be able to impact the conditions for cropland expansion, such as accessibility, infrastructure or even policies[74]. Moreover, a recent study shows that the distance to markets explains current cropland extent but not current expansion dynamics[30]. Thus, including those factors would be associated with large uncertainties. Further limiting factors are the availability of such data at a sufficient spatial resolution on a global scale[30] and the lack of knowledge on how the factor quantitatively impacts the economic profitability of a pixel for cropland expansion. The latter is necessary to maintain the quantitative approach in the iLANCE model that allows for the profitability assessment of cropland use. To our knowledge, such data are not yet available on a global scale, which would make further assumptions necessary, for example, on the monetary effect of the spatial proximity of an area to roads on the attainable marginal profit on this land when transformed into cropland. Due to the spatial explicitness of our approach, however, further factors and constraints of expansion can individually be applied in the post processing by masking specific pixels that do not meet defined criteria for expansion according to the research question. Yet, the need remains for an improved global but spatially differentiated understanding of drivers and predictors of future agricultural expansion[30,75] and their quantitative impact. This holds particularly for expansion at the frontiers of current cropland, which is relatively poorly explained by existing data on drivers[30], and thus might be insufficiently captured in our profit-driven approach.

To focus on the potential dynamics of future agricultural expansion, we assumed the potentially expanded areas to be cultivated with the same intensity as the current cropland in the corresponding Agro-ecological Zone[60] of the economic study region. Accordingly, potential additional impacts of future agricultural intensification on expansion dynamics[76–79] were not considered in this study. Yet, contrasting and comparing the effects of expansion with potential socio-economic and environmental effects of intensification is an important aspect, particularly in the context of biodiversity conservation[77,80–88], which can be addressed in future studies using the presented modelling framework. A sensitivity analysis of the identified areas under expansion pressure to different assumptions on agricultural intensification can be found in Supplementary Note 4. Moreover, the regional implementation of conservation policies and investigation of potential leakage effects[89] could be an interesting potential application area of the presented approach.

The assessment of potential future expansion areas is based on a global profitability ranking and the assumption that the globally most profitable areas for cropland expansion are under the highest pressure of being converted into cropland. The approach thus does not capture other national or regional conditions that, for instance, could additionally cause cropland expansion in the respective region on areas with a lower profitability relative to the global ranking. It is moreover important to note that, as the profitability ranking is, inter alia, based on static economic trends, the economic outcomes are also highly dependent on the assumed continuation of these trends with regard to land expansion. Accordingly, the economic results are also likely to change under changing political or socio-economic conditions as well as relative to exogenous shocks, for example, geopolitical developments.

Applying the BII allows for assessing the potential reduction in biodiversity intactness if currently uncultivated land is transformed into cropland. While the index takes species abundance and compositional similarity into account (see Supplementary Note 1.5), it does not provide information on whether endangered species might be affected. In addition, the BII does not capture lagged responses of biodiversity to pressure over time (so called extinction debt), as the database refers to the current point in time, assuming the full impact on biodiversity has already been achieved for the land-use intensity classes[65,66]. As a relative measure describing the biodiversity intactness compared to a pristine ecosystem state of the area, the BII moreover does not reflect the biodiversity in absolute terms. The focus on pristine ecosystems and the BII being a relative measure might also lead to an underestimation of the impacts on biodiversity in areas with other habitat types and of substantial biodiversity importance, such as global biodiversity hotspots that have already lost 70% of primary vegetation while hosting at least 1,500 vascular plant species[49]. Moreover, threatened species located in areas already degraded or with lower biodiversity intactness might be overlooked. Combining the BII with other diversity metrics and data, such as the included analysis focusing on the world's most threatened biodiversity hotspots[49], provides additional information regarding, for example, impacts on threatened species or species loss, the biodiversity impacts in endangered ecosystems or in areas with a particularly high biodiversity. Overall, the BII is a suitable index for this analysis of biodiversity impacts resulting from cropland expansion, as it is, to our knowledge, the only global biodiversity indicator that is able to connect land-use intensity to its impact on biodiversity at pixel level on a global scale. It builds on the vast PREDICTS database, the largest database containing information on land use and its intensity across a wide range of taxa[55].

In the design of the CON scenario, we excluded forests, wetlands and protected areas from cropland expansion. We have chosen this scenario design (1) due to the high relevance of forests and wetlands for biodiversity protection and carbon sequestration[18,21,52,90,91], (2) to take into account that those land covers were highly affected by past and recent cropland expansion[12,16,17,92] and (3) to reflect current global political conservation efforts, such as the Glasgow Leaders' Declaration on Forests and Land Use[40] or the EU Regulation on deforestation-free supply chains[41]. Yet, it is important to mention that other land covers, for example, native grassland, are important ecosystems[93,94] of relevance for biodiversity conservation and carbon sequestration[95]. As shown in the analysis, globally uniform protection of certain ecosystems, such as forests, might cause environmental trade-offs in certain regions by shifting expansion pressure to other highly biodiverse ecosystems. Grasslands, for instance, are well known to make an important contribution to biodiversity[96–98], with the Cerrado being the world's most biodiverse tropical savannah[99] that, however, is already highly threatened by land-use conversion and resulting habitat loss[100–102]. Its protection and restoration could play an important role in conserving threatened species[100,103,104]. Thus, further research on which areas should be prioritized for conservation measures is needed for more strategic conservation planning[36,94–96].

Reporting summary

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

Data availability

The created data on the areas under expansion pressure and the profitability ranking of these areas for both scenarios, EXP scenario and CON scenario, at 0.5° spatial resolution and aggregated at country level are available via Zenodo at https://doi.org/10.5281/zenodo.12505548 (ref. 105).
The data were analysed using MATLAB and R.

Code availability

The codes to assess the areas under the highest pressure for cropland expansion, to evaluate the land-use change induced CO_2 emissions and to investigate the impacts on biodiversity intactness are available upon request.

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Author contributions
J.M.S., R.D. and F.Z. conceived the study. J.M.S., F.Z., R.D., T.H., C.N. and R.S. conceptualized the research design. J.M.S. and F.Z. conducted the PROMET simulations, the CO_2 emission analysis and prepared the land-use input data for the biodiversity intactness analysis. R.D., T.H., F.S. and M.S. prepared the database for the DART-BIO simulations. R.D. and T.H. conducted the DART-BIO simulations. C.N. and R.S. conducted the biodiversity intactness analysis. J.M.S., R.D., T.H. and F.Z. conducted the model coupling between DART-BIO and PROMET with the iLANCE model. J.M.S. prepared the first draft of the manuscript. J.M.S., R.D., F.Z., T.H., F.S., M.S., C.N., R.S. and W.M. discussed the results and contributed to the paper and its revision.

Competing interests
The authors declare no competing interests.

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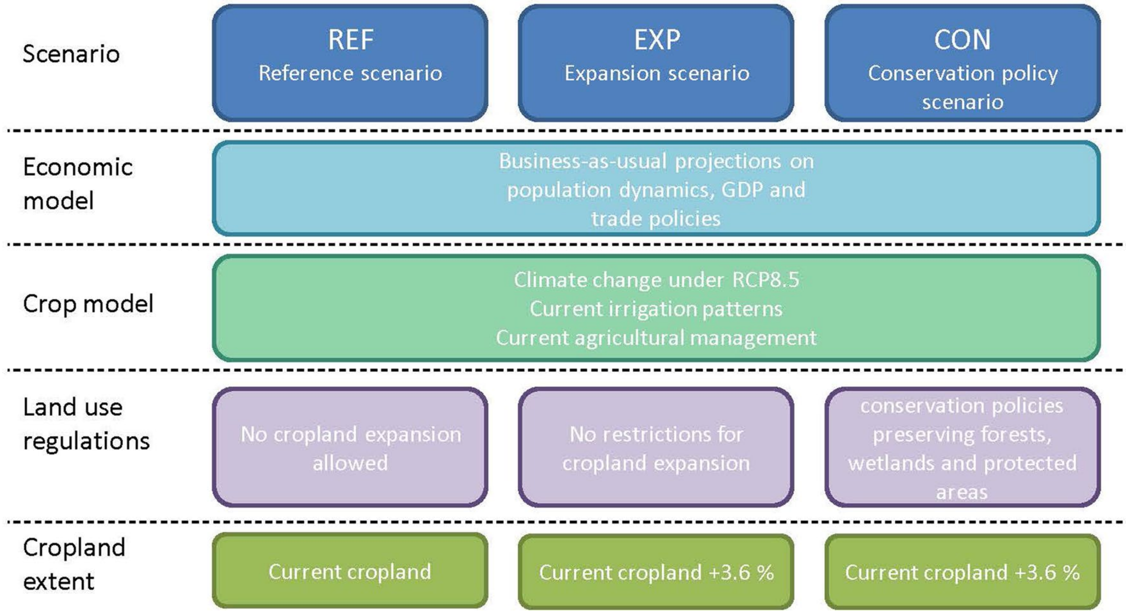
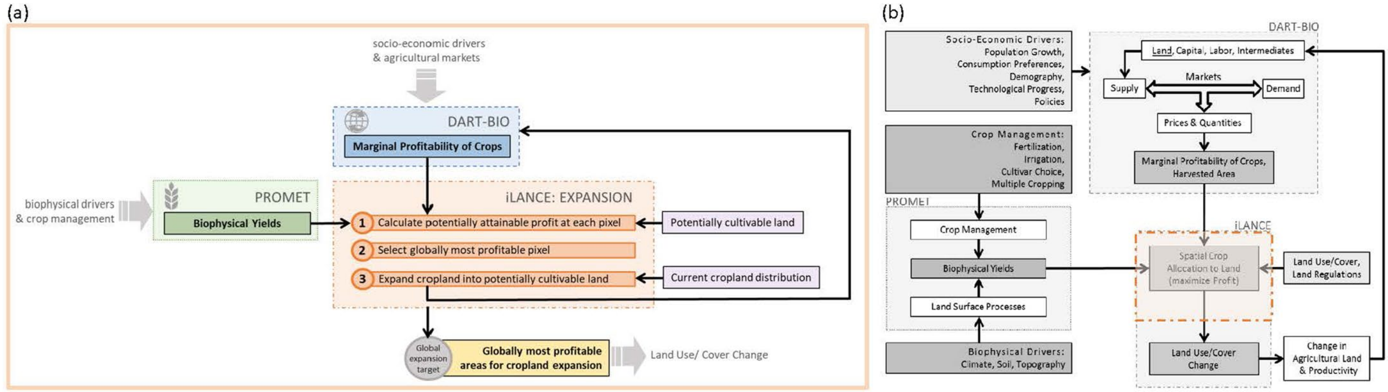


Extended Data Fig. 1 | Overview of the scenario design. To evaluate the economic impact of cropland expansion on prices, production and trade patterns, the expansion scenario (EXP) is compared to a reference scenario without cropland expansion (REF) until 2030. The impacts of conservation policies are assessed by comparing two identical future expansion scenarios that only differ in the presence (CON scenario) or absence (EXP scenario) of conservation policies protecting forests, wetlands and already protected areas from a conversion into cropland. A detailed description on the scenario design is provided in the Methods section.

 https://doi.org/10.1038/s41893-024-01410-x



Extended Data Fig. 2 | Overview of the applied research framework. a) displays the developed expansion module in iLANCE and the various inputs from the biophysical and economic model as well as land-use information. (**b**) locates the expansion module in the integrative coupling framework of the land-use model iLANCE and provides a wider context of the model structure.

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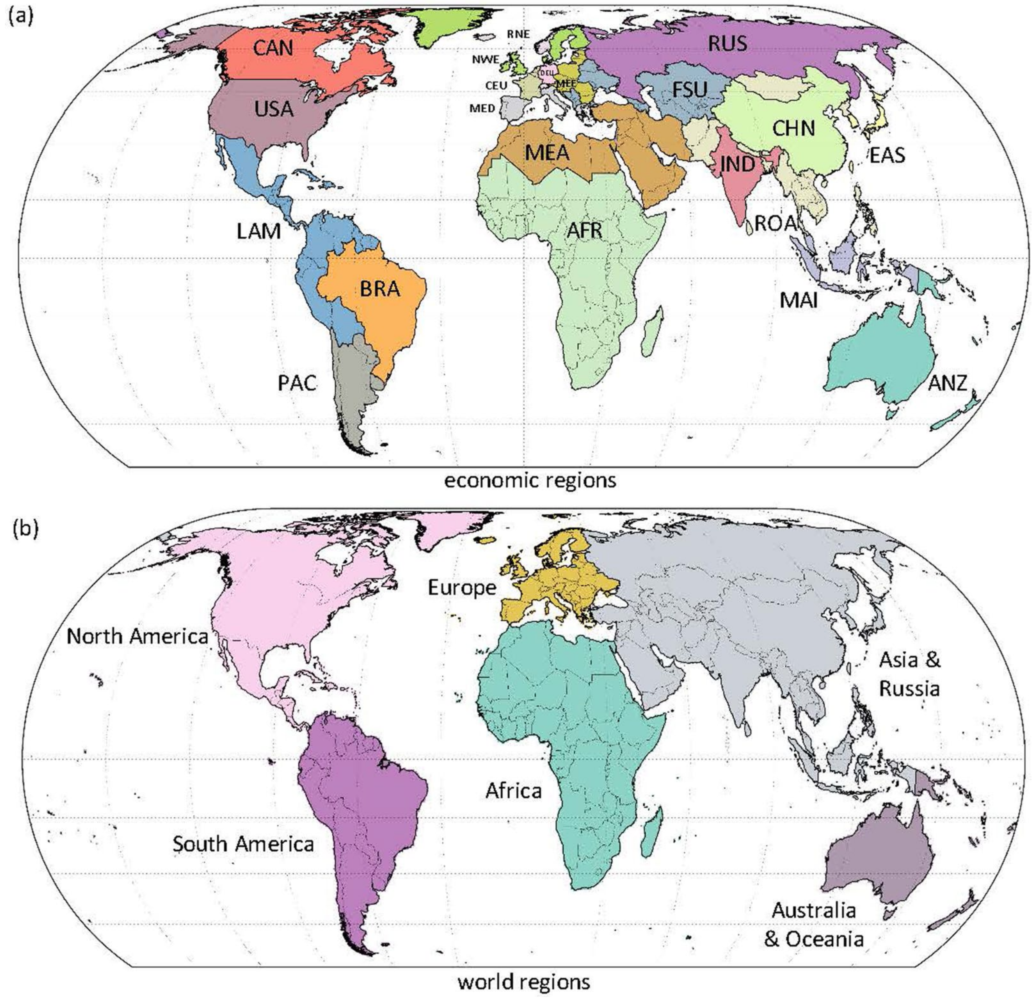

Extended Data Fig. 3 | Region mapping for the analysis of the results.
a) Region mapping of the 21 economic study regions: AFR (Sub-Saharan Africa), ANZ (Australia, New Zealand and Oceania), BRA (Brazil), CAN (Canada), CEU (Central Europe), CHN (China), DEU (Germany), EAS (Eastern Asia), FSU (Rest of Former Soviet Union), IND (India), LAM (Rest of Latin America), MAI (Malaysia and Indonesia), MEA (Middle East and Northern Africa), MED (Mediterranean), MEE (Middle Eastern Europe), NWE (North Western Europe), PAC (Paraguay, Argentina, Chile, Uruguay), RNE (Rest of Northern Europe), ROA (Rest of Asia), RUS (Russia), USA (United States of America). (**b**) Region mapping of the 6 aggregated ‚world regions': Africa, Australia & Oceania, Asia & Russia, Europe, North America and South America. The region borders of both maps show the aggregated country borders according to the global administrative areas of GADM version 3.6. (https://gadm.org/).

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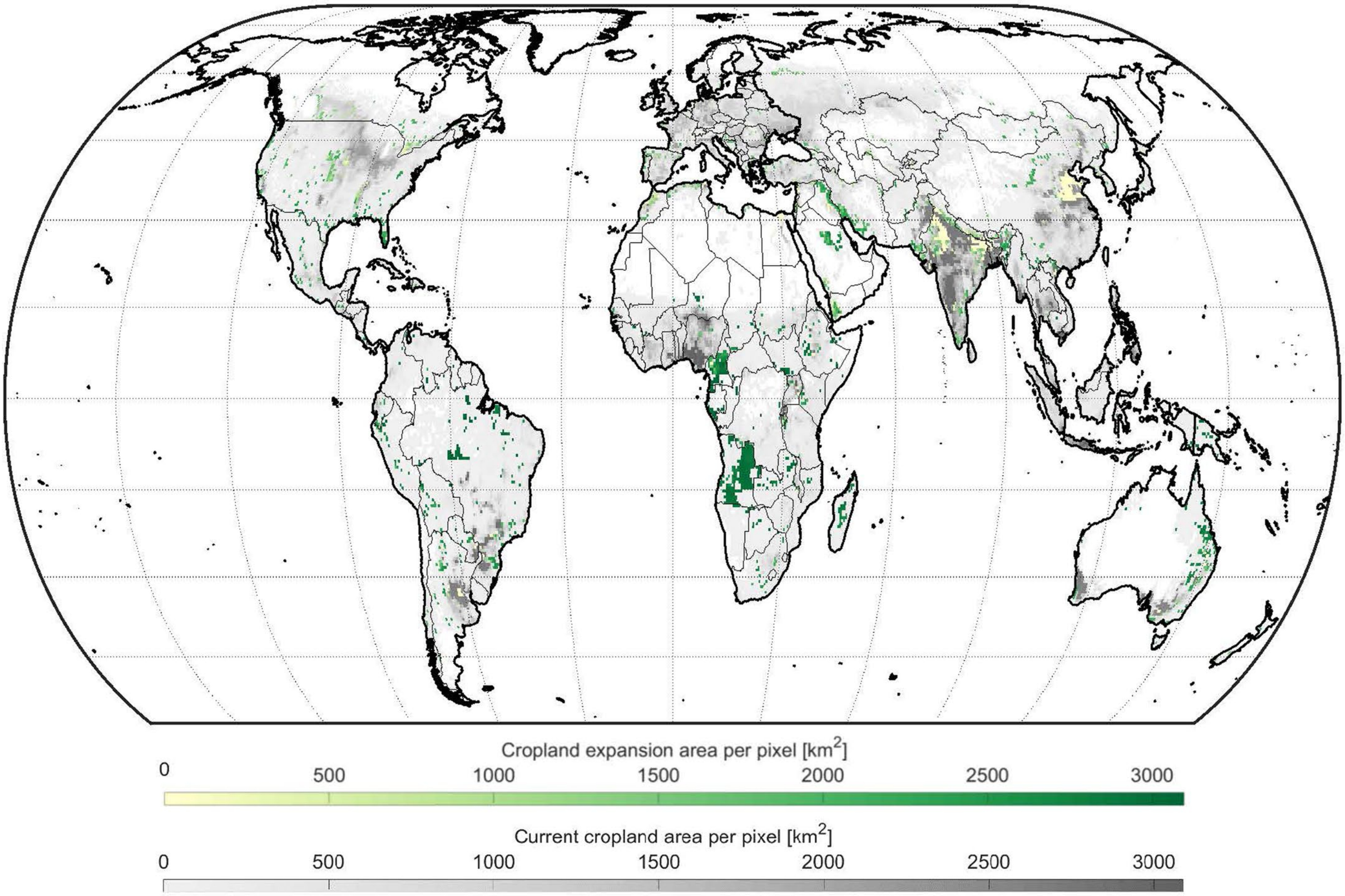
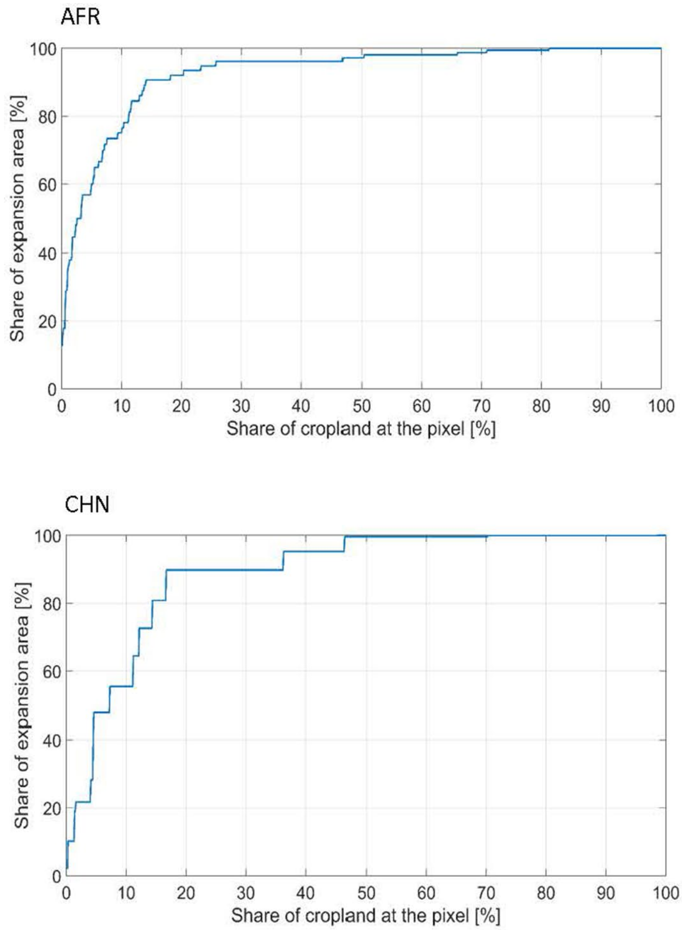
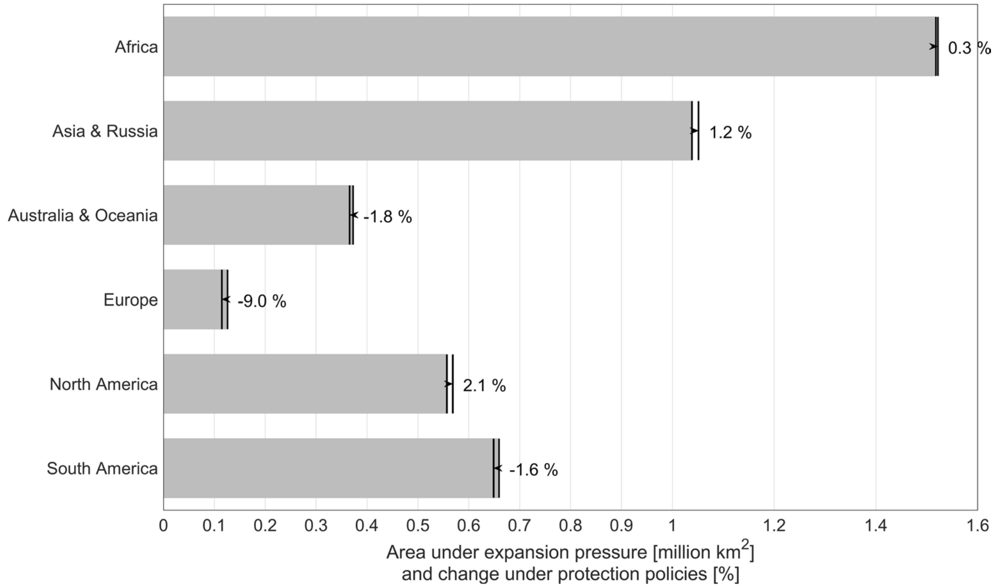


Extended Data Fig. 4 | Area under expansion pressure. Area under expansion pressure per pixel [km^2] under a global cropland expansion of 30%. The grey areas display the current cropland distribution [km^2].



Extended Data Fig. 5 | Expansion pressure at the frontiers of current cropland. Cumulative share of the regionally most profitable expansion area [%] under the 3.6% EXP scenario located at pixels with shares from 0% to 100% currently covered with cropland exemplarily for the four regions Sub-Saharan Africa (AFR), Brazil (BRA), China (CHN) and Paraguay, Argentina, Chile & Uruguay (PAC).

https://doi.org/10.1038/s41893-024-01410-x



Extended Data Fig. 6 | Regional expansion pressure under 30% cropland increase. Regional distribution of the identified profitable area for cropland expansion [million km^2] under an increase in current cropland by 30% without conservation policies, and the relative changes [%] under the introduction of conservation policies for each world region.

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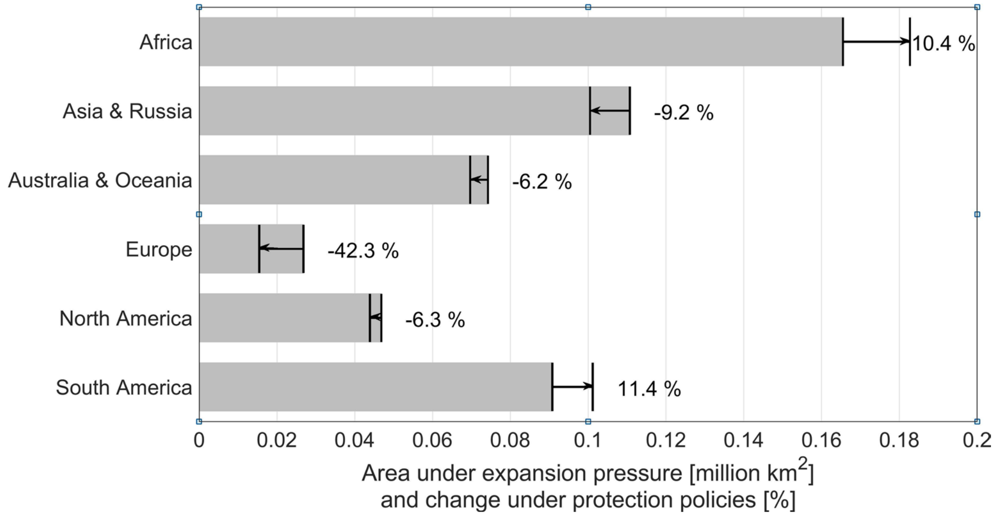

Extended Data Fig. 7 | Regional expansion pressure under 3.6% cropland increase. Regional distribution of the identified profitable area for cropland expansion [million km^2] under an increase in current cropland by 3.6% without conservation policies, and the relative changes [%] under the introduction of conservation policies for each world region.

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Extended Data Table 1 | Overview of the considered crops and crop categories

PROMET Crops	DART-BIO Crop Categories	
Sugar cane Sugar beet	cb	Sugar cane & sugar beet
Maize	mze	Maize
Paddy rice	pdr	Paddy rice
Oil palm	plm	Oil palm fruit
Rapeseed	rsd	Rapeseed
Soy	soy	Soybean
Summer wheat, Winter wheat	wht	Wheat
Barley, Millet, Rye, Sorghum	gron	Other cereal grains
Groundnut, Sunflower	osdn	Other oil seeds
Potato, Cassava, Maize silage	agr	Rest of crops

Crops simulated with PROMET (left column) and the according Crop Categories the crops are representing in the DART-BIO model, including their abbreviations (right columns).

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	no software was used for data collection
Data analysis	Economic analysis: GAMS software, code of DART model not pubished but can be provided upon request. Biodiversity Analysis: The following R packages were used: Gower package version 1.0.1, geosphere package version 1.5-18, car package, sjPlot package version 2.8.14, bayestestR package, version 0.13.2 and lme4 package, version 1.1.32. Details are described in the supplement. The code for the biodiversity analysis is available upon request. Carbon Emissions and Land use change: MATLAB R2020b, code available upon request, methods are described in the cited published literature. PROMET is described in published literature cited in the paper. PROMET code is not publically available because of both scientific and commercial use. It may be opened to editor and reviewers under specific NDA agreements.

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

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Data on the areas under expansion pressure and the profitability ranking of these areas is available for both scenarios, EXP scenario and CON scenario, at 0.5° spatial resolution and aggregated at countrylevel: << Link to the Zenodo Dataset will be provided here. >>

For this study, the following datasets have been used:

Aguiar, A., Narayanan, B., McDougall, R. An Overview of the GTAP 9 Data Base. GTAP Data Bases: GTAP Data Base Archives (purdue.edu) (2016).

Hudson, L., Newbold, T., Contu, S., Hill, S. L. L. et al. The 2016 release of the PREDICTS database. Natural History Museum. https://doi.org/10.5519/0066354 (2016).

Monfreda, C., Ramankutty, N., Foley, J.A. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Earthstat. http://www.earthstat.org/harvested-area-yield-175-crops/ (2008).

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Riggio, J. et al. Global human influence maps reveal clear opportunities in conserving Earth's remaining intact terrestrial ecosystems. Dryad. https://doi.org/10.25338/B80G7Z (2020).

Schneider, J., Zabel, F., Mauser, W. Global inventory of potentially cultivable land and potentially available cropland under different scenarios and policies. Zenodo. https://doi.org/10.5281/zenodo.5993934 (2022).

Winkler, K., Fuchs, R., Rounsevell, M. D. A., Herold, M. HILDA+ Global Land Use Change between 1960 and 2019. PANGAEA. https://doi.org/10.1594/PANGAEA.921846 (2020).

Research involving human participants, their data, or biological material

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Reporting on sex and gender	n/a
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Behavioural & social sciences study design

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Study description	n/a
Research sample	n/a
Sampling strategy	n/a
Data collection	n/a
Timing	n/a
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Non-participation	n/a
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Ecological, evolutionary & environmental sciences study design

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Research sample	n/a
Sampling strategy	n/a
Data collection	n/a
Timing and spatial scale	n/a
Data exclusions	n/a
Reproducibility	n/a
Randomization	n/a
Blinding	n/a

Did the study involve field work? ☐ Yes ☒ No

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☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks	n/a
Novel plant genotypes	n/a
Authentication	n/a