nature sustainability

Article

https://doi.org/10.1038/s41893-024-01292-z

Telecoupled impacts of the Russia–Ukraine war on global cropland expansion and biodiversity

Received: 5 June 2023

Accepted: 25 January 2024

Published online: 01 March 2024

Check for updates

Li Chai[1,2,3] ✉, Ao Liu[2], Xuecao Li[4], Zhenshan Guo[5], Wanru He[4], Jianxi Huang[4], Tiecheng Bai[6] & Jianguo Liu[7] ✉

The Russia–Ukraine War is impacting global food systems, which may trigger global cropland expansion and consequently lead to biodiversity loss far from war zones. To quantify such impacts on biodiversity, we simulated the global cropland expansion provoked by the reshaping of international virtual cropland flows under different war scenarios and conducted a biodiversity impact assessment. The results indicate that, in the baseline situation (33.57% reduction in Ukraine's exports), the war would result in an additional 8.48 Mha of cropland expansion compared with the 'no war' scenario. This cropland expansion would impact biodiversity most in countries such as the United States, Spain, France, India and Brazil. The cessation of Russia's participation in the Black Sea Grain Initiative would lead to a doubling of cropland expansion and biodiversity loss compared with the baseline situation. If the conflict deteriorates further, that is, no exports from Russia and Ukraine, cropland expansion and biodiversity loss would increase by up to 2.9 and ~4.5 times, respectively. These findings highlight the need for proactive measures to mitigate the impact of this war on biodiversity and suggest that actions to implement the post-2020 Global Biodiversity Framework should take into account the potential impacts of conflicts on biodiversity.

Since the onset of the full-scale Russian invasion of Ukraine in February 2022, the Russia–Ukraine war has relentlessly disrupted agricultural production in Ukraine[1], a major exporter of oilseeds and cereals. At the same time, most Ukrainian ports have been affected by armed conflict, including its largest port, Odesa. These factors have resulted in a sharp reduction in Ukraine's agricultural exports[2]. Russia's agricultural system has also been disrupted due to international sanctions imposed on seeds. For national food security reasons, Russia has also imposed a partial ban on its agricultural exports. The export reduction by Ukraine and Russia, the world's major exporters of grain and oilseed crops, has substantially impacted the international agricultural market[3,4]. In addition, as panic has increased, a number of nations have restricted their agricultural exports, exacerbating reverse globalization[2]. The imbalance between supply and demand has led to soaring prices of agricultural products[4]. To stabilize domestic food prices, many countries may expand agricultural land to narrow gaps between domestic supply and demand[5].

Cropland, expanding globally by 5 Mha yr^{-1} (ref. 6), drives habitat conversion and degradation, contributing to worldwide biodiversity declines. Agricultural expansion accounts for a 30% drop

[1]International College Beijing, China Agricultural University, Beijing, China. [2]College of Economics and Management, China Agricultural University, Beijing, China. [3]National Innovation Center for Digital Fishery, China Agricultural University, Beijing, China. [4]College of Land Science and Technology, China Agricultural University, Beijing, China. [5]The School of Languages, Cultures and Societies, University of Leeds, Leeds, UK. [6]School of Information Engineering, Tarim University, Alaer, China. [7]Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI, USA. ✉e-mail: chaili@cau.edu.cn; liuji@msu.edu

 https://doi.org/10.1038/s41893-024-01292-z

in biodiversity within the Amazon and Afrotropics[7]. Rapidly rising prices for agricultural products may increase the incentive for farmers to expand agricultural land by blindly encroaching on ecological land[8,9]. During the high maize prices of 2007–2012, the United States experienced an accelerated cropland expansion at high costs to wildlife[10]. Such large-scale global land transformation could lead to severe biodiversity loss even in biodiversity hotspots[11–13]. The Russia–Ukraine war has resulted in a rapid increase in food price[14,15] and thereby may accelerate cropland expansion, posing an added threat to global biodiversity[16]. For instance, Europe has set out to convert fallow land with biodiversity restoration functions for agricultural production[16,17]. Rushed changes to land-use policy made in Europe in response to the Russia–Ukraine war have been argued to threaten European biodiversity[17]. According to the modelling in ref. 18, the Russia–Ukraine war would boost agricultural production in many countries worldwide, including the United States, Brazil, China and India. Alarmingly, much of the modelled agricultural expansion is centred in the tropics[18], where biodiversity is notably vulnerable to land conversion. However, it remains uncertain how severely global biodiversity would be threatened under different scenarios and which countries would potentially suffer heightened risks of biodiversity loss.

Here, to provide a context for the impact of the war, we first analysed virtual cropland flows (that is, land used to produce crops that were exported) before the war. We also applied the widely used Global Trade Analysis Project (GTAP) model[19,20] to simulate the impact of the Russia–Ukraine war on global cropland use. The GTAP model, as a comparative static analysis approach, allowed us to isolate the effect of the war. We then simulated the spatial expansion of cropland induced by the war and assessed the associated biodiversity loss, including regional species loss and global species extinction. Four scenarios were designed in this study to examine the impacts under different war situations, including $S_{baseline}$ (the baseline situation with 33.75% export reduction from Ukraine), $S_{BlackSea}$ (81.75% export reduction from Ukraine if the Black Sea is blockaded), $S_{NoExport}$ (no exports from Ukraine) and S_{worst} (the worst situation with no exports from Ukraine and Russia). Our study provides presumably the first quantitative assessment of the severity of potential biodiversity loss at the country level under different scenarios of the Russia–Ukraine war. The results from this study can help expand and advance the post-2020 Global Biodiversity Framework by incorporating the biodiversity impacts of war into relevant plans and actions.

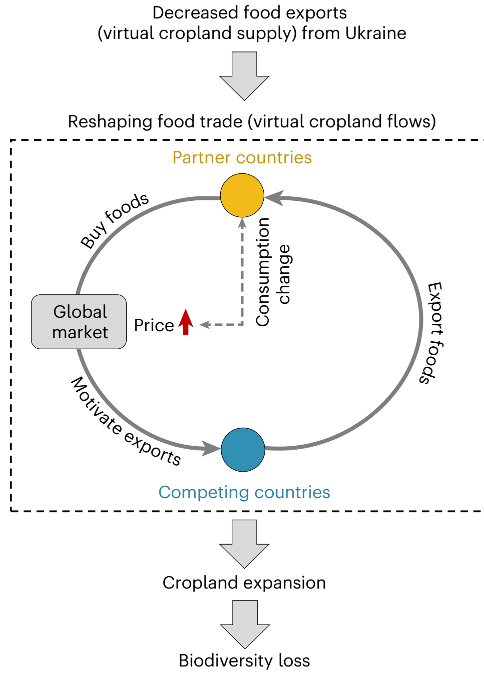

Fig. 1 | Mechanism diagram. Cascading mechanisms by which war affects cropland expansion and global biodiversity.

Food trade and virtual cropland flows reshaped by the war

Figure 1 shows the cascading mechanisms by which the war could influence cropland expansion and biodiversity in the regions distant from the conflict zones, a type of telecoupled impacts[21,22]. Receiving war shocks (that is, reduced export from Ukraine), Ukraine's trading partners (partner countries in Fig. 1) would suffer a direct hit from the declined supply of foods (and virtual land) from Ukraine. To combat the shocks, in addition to expanding domestic agricultural production, these countries would need to increase their share of imports from other countries to fill the gap caused by the reduced supply from Ukraine. As a result, global agricultural prices will rise in line with the increased demand for imports from partner countries (Supplementary Data). Global wheat prices have skyrocketed by 60% since Russia's invasion of Ukraine[14,15]. The elevated prices would reduce food consumption, exacerbating hunger in partner countries. Moreover, high prices could also motivate exports from Ukraine's agricultural competitors (competing countries in Fig. 1) such as the United States and Brazil, resulting in potential risks to cropland expansion and biodiversity loss. The reshaped food trade and virtual cropland land flows would cause global cropland expansion and biodiversity loss.

We investigated Ukraine's foods and virtual cropland exports before the war, that is, in a 'no war' scenario, on the basis of data from the Food and Agriculture Organization (FAO)[23] and Multi-Regional Input-Output (MRIO) tables[24]. In 2018–2020 (the latest 3 years for which data are available[23]), Ukraine exported 64.26 million tonnes of crops and products annually (Fig. 2a), including wheat (29%), oilseeds and oils (19%), other cereals (50%) and other crops (2%). There was 20.41 Mha of virtual cropland embodied in these agricultural exports (Fig. 2a). Oilseeds and oils exports contributed the most virtual cropland (7.90 Mha), followed by other cereals (6.20 Mha), wheat (5.73 Mha) and other crops (0.58 Mha). Countries in West Asia and Europe, such as Israel and Spain, were the major importers of Ukraine's virtual cropland before the war (Supplementary Figs. 1 and 2).

Russia's invasion has greatly disturbed Ukraine's agricultural production and exports. According to estimates from the Ministry of Agrarian Policy and Food of Ukraine (MAPFU), the country's 2022 agricultural exports fell by 33.57% compared with the 'no war' scenario (2018–2020) due to the Russian invasion[25]. The impact of the decrease can largely reshape global food trade over time and change the associated patterns of international virtual cropland flows. We employed the GTAP model to simulate how international virtual cropland flows would change compared with the 'no war' scenario.

Among Ukraine's trading partners, Israel would enlarge its imports (0.58 Mha) from other countries the most, followed by Lebanon (0.28 Mha), South Korea (0.27 Mha), Georgia (0.20 Mha) and Turkmenistan (0.14 Mha), as shown in Fig. 2b. These countries are either short of water and arable land (for example, Israel) or low in crop productivity (for example, Lebanon), resulting in a heavy reliance on cereals imports. After the outbreak of the Russia–Ukraine war, their choice to purchase cereals from other countries at high prices rather than expand domestic production can be explained by the theory of comparative advantage.

Among the competitors of Ukraine's agriculture, Russia would increase exports the most (1.33 Mha), followed by the United States (0.67 Mha), Australia (0.60 Mha), Canada (0.46 Mha), Brazil (0.44 Mha) and Argentina (0.30 Mha), as shown in Fig. 2b. These countries were the top net exporters of virtual cropland embodied in oilseeds and cereals (Supplementary Fig. 3). Driven by high prices of agricultural products, these countries are prone to cropland expansion[9,10].

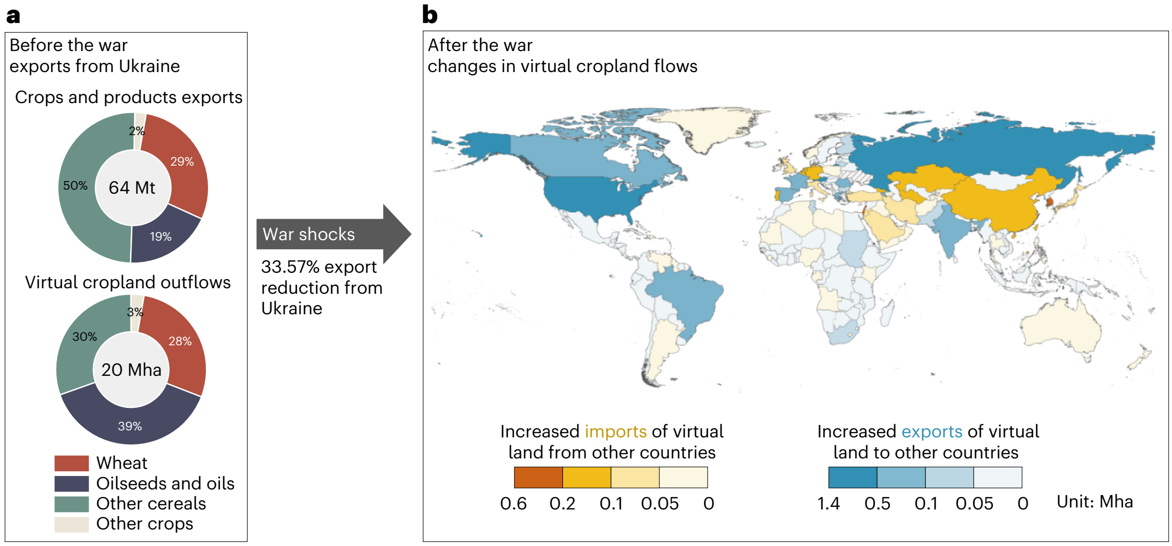

Fig. 2 | Impacts of the war on international virtual cropland flows. a, Food exports and virtual cropland outflows from Ukraine before the war (the average of 2018–2020). **b**, Increased imports or exports of virtual cropland among the countries outside the war zones.

Global cropland expansion

Changes in the international flows of food (and virtual cropland) would lead to a global cropland expansion. According to our simulations, in the baseline situation (33.57% reduction in Ukrainian exports), the Russia–Ukraine war would cause a global cropland expansion of 8.48 Mha.

We conducted a spatial simulation of global cropland expansion at 1 km resolution (Fig. 3a) and aggregated the results into ecoregion level (Fig. 3b). The expansion would occur mainly in the producing regions of cereals and oilseeds, including North America (the North American Prairie), South America (the Pampas and the Cerrado), Europe (the Mediterranean Basin, the Danubian Plains, the Massif Central and the East European Plain), Asia (the West Siberian Plain, the Northeast China Plain, the Malwa Plateau and Java Island) and Oceania (the Murray–Darling Basin). These areas are susceptible to profit-driven cropland expansion when the prices of cereals and oilseeds increase as a result of reduced exports from Ukraine. Some of these areas are biodiversity hotspots, such as the Cerrado, the Mediterranean Basin and Java Island. These hotspots all face a conflict between biodiversity and agricultural expansion[11,26,27], a conflict that will be exacerbated by the Russia–Ukraine war.

Globally, cropland expansion would mainly occur on grassland (82.60%) and forest (17.07%), with limited expansion on wetland (0.20%) and bareland (0.13%), as shown in Fig. 3c. Most cropland expansion (65.45%) would occur in the top 10 countries (Fig. 3d), including Russia (1.40 Mha), the United States (0.94 Mha), Australia (0.62 Mha), Canada (0.49 Mha), Brazil (0.45 Mha), Spain (0.43 Mha), France (0.41 Mha), Argentina (0.30 Mha), India (0.30 Mha) and Romania (0.21 Mha). Cropland in the United States has been reported to be expanding rapidly at an average rate of ~1 Mha annually[10], posing a serious threat to wildlife. Our simulation shows that the United States would expand its cropland by at least a further 0.94 Mha owing to the Russia–Ukraine war, which will in turn be more threatening to biodiversity. If the circumstances of the war worsen, for example, if the Black Sea Grain Initiative (BSGI) does not proceed, or if Russian exports are also curbed, the expansion of cropland in the United States would be even more severe.

Global biodiversity loss

Land transformation, that is, converting from natural habitats to cropland, would result in a potential risk of biodiversity loss. Once natural land is converted to cropland, it would take a long period for ecosystem quality[28] and biodiversity[29] to recover. Thus, the biodiversity loss assessed in this study is an aggregated impact spanning the regeneration period[30], with units of species*year, similar to previous relevant studies[29,31]. This study assesses biodiversity loss at two scales, namely, regional species loss and global species extinction. Regional species loss is defined as the regional extinction of non-endemic species and is therefore potentially reversible if individuals of the species from other regions move into the region of interest[29,31,32]. If a species is endemic to the region, its regional loss will be permanent, that is, global extinction[29,31,32]. Globally, it is projected that there will be a regional species loss of up to 31,396 species*years and a global species extinction of 486 species*years attributable to cropland expansion due to the Russia–Ukraine war (Fig. 4).

As shown in Fig. 4a, the loss of regional biodiversity is projected to occur predominantly among birds at 62.97%, while mammals, reptiles and amphibians would account for 21.42%, 9.83% and 5.78%, respectively, at the global level. In contrast to the regional species losses, the four taxa would be more evenly affected in terms of global species extinction (Fig. 4b), with 22.31%, 25.63%, 21.15% and 30.91% of the extinctions occurring in birds, mammals, reptiles and amphibians, respectively.

Figure 4c illustrates the geographical distribution of regional species losses. Overall, the distribution would be concentrated, with the top 10 countries that would suffer the largest losses accounting for 61.17% of the total global losses. The red part of Fig. 4c shows the top three countries in terms of regional species losses, namely, the United States (4,794 species*years or 15.27% globally), Spain (2,899 species*years) and France (2,037 species*years).

Figure 4d shows the geographical distribution of species extinctions globally, with the top 10 countries that would suffer the largest extinctions accounting for 59.42% of total global extinctions. The three most affected countries are shown in red in Fig. 4d. The United States would still be most affected with an extinction impact of 64 species*years or 13.26% of the world, followed by Spain (44 species*years) and India (43 species*years). Notably, due to the high-endemism richness of Mesoamerica, South America and Southeast Asia[12,33], species extinctions in these regions are projected to be more pronounced than regional species losses in these countries. For example, our results show a remarkable shift in rankings when comparing regional species loss to global species extinction. Mexico, originally 19th in regional species loss, jumps to 11th in global species extinction.

 https://doi.org/10.1038/s41893-024-01292-z

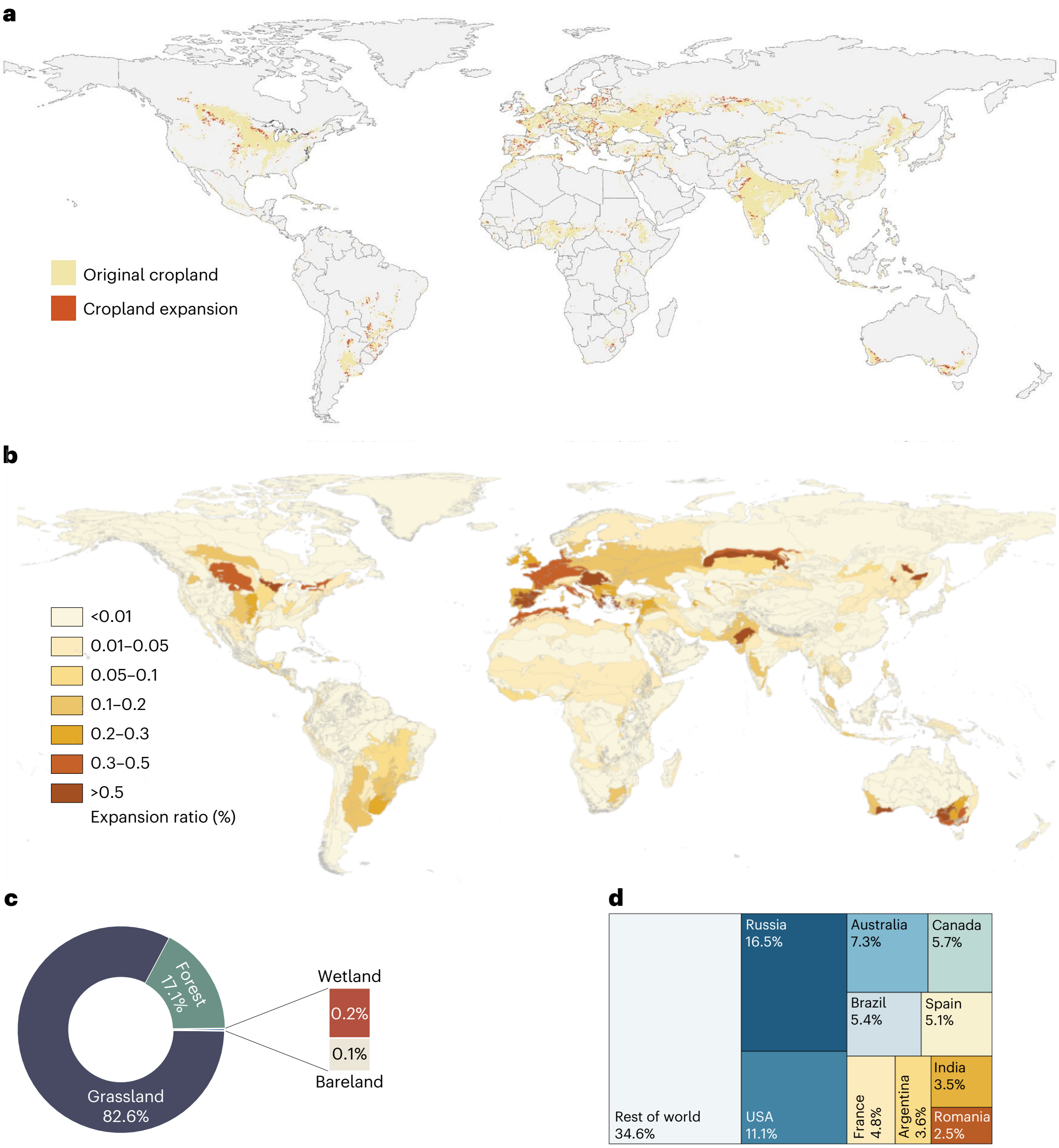

Fig. 3 | Global cropland expansion triggered by the Russia–Ukraine war. a, Spatial distribution. **b**, Ratio of expanded cropland to the total area in each ecoregion. **c**, Share of occupied land cover[51]. **d**, Share of countries.

Similarly, Argentina jumps from 18th to 9th, Brazil from 12th to 4th, the Philippines from 35th to 14th and Malaysia from 24th to 15th.

It is important to note that biodiversity loss is determined by cropland expansion, characterization factors (Supplementary Fig. 4) and species richness. Some countries, such as Russia and Canada, are ranked 8th and 24th in global species extinction despite their large cropland expansion (ranked 1st and 4th, respectively), by virtue of their low species richness. Despite the Cerrado (Brazil) and the Pampas (Argentina) boasting higher species densities than the North American Prairie (the United States), the biodiversity losses of Brazil and Argentina are less than those of the United States due to two primary factors: (1) With increased conversion of natural habitat, the marginal loss of biodiversity would be more substantial[29,31]. In contrast to the Cerrado and the Pampas, the North American Prairie has undergone a greater degree of habitat conversion for cropland use, resulting in a larger marginal characterization factor for biodiversity loss (Supplementary Fig. 4). (2) The characterization factor for biodiversity loss resulting from land transformation is contingent upon species recovery time. According to previous studies[29,34], the recovery time in the North American Prairie is approximately fourfold of that in the Cerrado and the Pampas.

Scenario analysis

We performed scenario analysis to examine the impacts of conflict escalation on global cropland expansion and biodiversity loss, as shown in Table 1. The spatial simulation results of global cropland expansion under different scenarios are shown in Supplementary Fig. 5. With the help of the United Nations and Turkey, Russia and Ukraine signed the BSGI[35] to allow Ukraine to ship its agricultural exports through the ports on the Black Sea in July 2022. Grain prices are highly sensitive to the BSGI. The signing of BSGI led to a drop of more than 50% from the historically high wheat prices in March 2022.

In the baseline situation ($S_{baseline}$), exports from Ukraine are reduced by 33.57% as consequences of disturbed agricultural production in

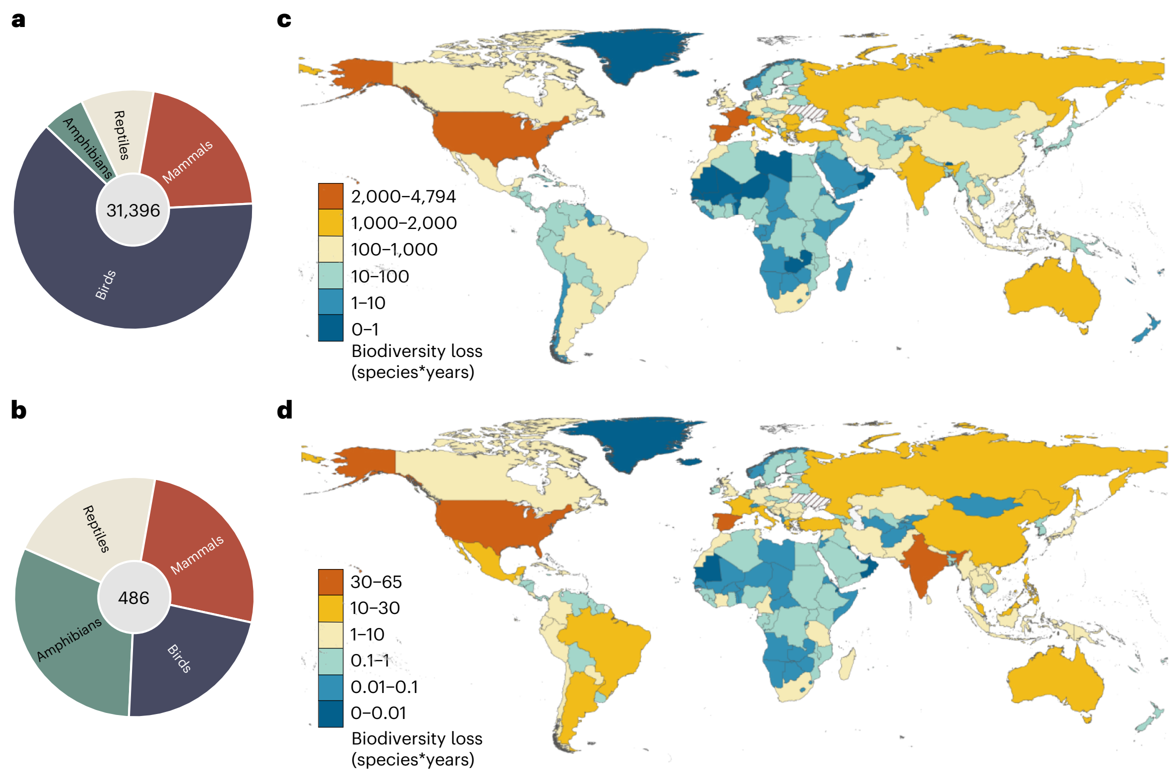

Fig. 4 | Global biodiversity loss induced by Russia's invasion of Ukraine. a, Taxa distribution of total regional species loss. **b**, Taxa distribution of global species extinction. **c**, Spatial distribution of regional species loss. **d**, Spatial distribution of global species extinction. Four taxa are considered: mammals, birds, amphibians and reptiles. Unit is species*years.

Table 1 | Cropland expansion and biodiversity loss

	$S_{baseline}$	$S_{BlackSea}$	$S_{NoExport}$	S_{worst}
Cropland expansion (Mha)	8.48	17.10	19.99	32.92
Grassland	7.01	13.91	16.20	26.03
Forest	1.45	3.13	3.72	6.65
Bareland	0.01	0.03	0.04	0.15
Wetland	0.02	0.03	0.04	0.08
Regional species loss (species*years)	31,396	63,482	74,270	139,098
Birds	19,771	39,964	46,750	86,166
Mammals	6,725	13,602	15,913	30,217
Reptiles	3,087	6,246	7,310	14,889
Amphibians	1,813	3,670	4,296	7,826
Global species extinction (species*years)	486	989	1,158	2,272
Birds	108	221	259	464
Mammals	125	252	296	583
Reptiles	103	208	243	523
Amphibians	150	307	360	702

Cropland expansion and biodiversity loss under the following scenarios: 33.75% export reduction from Ukraine in the baseline situation ($S_{baseline}$), 81.75% export reduction from Ukraine if Black Sea is blockaded ($S_{BlackSea}$), no exports from Ukraine ($S_{NoExport}$) and no exports from Ukraine and Russia (S_{worst}).

Ukraine but with Russia's participation in BSGI. This would result in a cropland expansion of 8.48 Mha, a regional species loss of 31,396 species*years and a global species extinction of 486 species*years.

As the war worsened, Russia announced its withdrawal from the BSGI in July 2023, leading to a 9% surge in wheat prices. The renewal and consistent implementation of the BSGI remain shrouded in uncertainty. Thus, in Scenario 2 ($S_{BlackSea}$), we simulated a scenario where Russia halts the BSGI if the conflict intensifies. Under this situation, exports from Ukraine are estimated to decline by 81.75% due to the Black Sea blockade. This would lead to a doubling of cropland expansion and loss of biodiversity as compared with the $S_{baseline}$. If the war continues to deteriorate, agricultural production in Ukraine will be further disrupted and rail and road transport may be cut off, leading to zero exports from Ukraine. This is why in Scenario 3 ($S_{NoExport}$) we simulated a circumstance where Ukraine would export nothing. Cropland expansion and biodiversity losses under $S_{NoExport}$ would rise by a further 17% on top of the losses under $S_{BlackSea}$, with cropland expansion reaching 19.99 Mha, regional species loss reaching 74,270 species*years and global species extinction reaching 1,158 species*years.

Scenario 4 (S_{worst}) simulates one of the worst scenarios of the war, in which Russia and Ukraine would stop exporting agricultural products entirely. Compared with $S_{baseline}$, global cropland expansion under S_{worst} would be 288% higher, reaching 32.92 Mha; regional species loss would be 343% higher, reaching 139,098 species*years; and global species extinction would rise by 367% to 2,272 species*years. In S_{worst}, some of Russia's trading partners, such as Turkey, would be substantially impacted by the cessation of agricultural exports from Russia. From $S_{NoExport}$ to S_{worst}, Turkey would suffer a 472% increase in biodiversity loss and a rise in the global ranking from 9th to 2nd. Further simulations with various export reductions from Russia (between $S_{NoExport}$ and S_{worst}) are shown in Supplementary Fig. 9.

Our results show that global cropland expansion induced by the Russia–Ukraine war would increase from 8.48 Mha ($S_{baseline}$) to 32.92 Mha (S_{worst}), as shown in Table 1. For comparison, ref. 36 estimated that the USA–China trade war could cause an additional 13.9 Mha of global

https://doi.org/10.1038/s41893-024-01292-z

land use for soybean production. Reference [6] estimated that the global cropland area has increased by 101.9 ± 45.1 Mha since the twenty-first century, equal to ~5 Mha yr^{-1} on average. This means that the Russia–Ukraine war would advance the global cropland expansion process by 1.7 yr ($S_{baseline}$) to 6.6 yr (S_{worst}). For biodiversity impacts, ref. 37 estimated that the global species extinction (mammals, birds, reptiles and amphibians) due to land transformation was 173 species*years in the year 2000, while in our study, global species extinction induced by the Russia–Ukraine war would be 486 ($S_{baseline}$) to 2,272 (S_{worst}) species*years, as shown in Table 1.

Policy implications

This study shows that the Russia–Ukraine war impacts international food trade and inflicts damage on global biodiversity. While current attention predominantly centres on the impact of the war on food supply and price, we urge that the damage to the natural world should also be brought to the forefront as this damage is often irreversible with short timespans. Once natural land is converted to cropland, it would take decades, if not centuries, for ecosystem quality recovery[28] and ~350 yr for biodiversity recovery[29]. To sidestep such irreversible ecological degradation, we put forth the following recommendations.

First, the BSGI, which serves as a pivotal mechanism for ensuring the export of Ukrainian grain via the Black Sea, needs to be consistently upheld. Our results indicate that, in a scenario where Russia suspends its commitment to the BSGI, global grain prices would rise, and both agricultural expansion and biodiversity loss would double. The current reality is that Russia's stance on the BSGI remains inconsistent, and the BSGI is being leveraged as a tool in the geopolitical tussle between Russia and the North Atlantic Treaty Organization. Consequently, there is a pressing need for the United Nations to exert greater efforts in mediating and ensuring the steadfast implementation of the BSGI.

Second, the vicious trade wars induced by the game of international relations should be avoided, given that international food trade benefits biodiversity in most cases[38]. At present, regions such as Europe and the United States have imposed various sanctions on Russia. Although current sanctions on Russia do not directly target food trade, measures such as those imposed on the SWIFT payment system and shipping insurance have visibly hindered Russia's agricultural exports. Russia, being a more significant agricultural exporter than Ukraine (Supplementary Figs. 2 and 3), plays a crucial role in global food systems. According to our findings, in a hypothetical situation where Russian agricultural exports cease, there would be a sharp increase in global biodiversity loss. Even more concerning is that sanctions on Russia might result in higher prices for fertilizers and energy. As highlighted in ref. 18, the increased prices of fertilizers and energy could lead to cropland expansion more severe than that caused by food export restrictions.

Third, sustainable and effective interventions should be taken to avert farmers in biodiversity hotspots such as Brazil's Cerrado[39], Mesoamerica and Southeast Asia from blindly and rapidly expanding their agricultural land, driven by inflated prices for short-term agricultural products. The United States has experienced a rapid cropland expansion in the period of high maize prices[10]. However, the rapid expansion of cropland could be avoided by effective policy implementation, for example, the reduced deforestation in Brazil brought about by the implementation of the Amazon Soy Moratorium[40].

Fourth, sufficient post-war assistance must be provided to Ukraine to facilitate the rapid revival of its agricultural sector. At present, challenges such as loss of labour, damaged agricultural machines, destroyed irrigation facilities, unexploded ordnance in cultivated fields and radioactive soil contamination have severely affected Ukraine's agricultural output. Even with cessation of the war, it is improbable for Ukraine to quickly return to its pre-war productivity levels. A recent report suggests that it might take nearly 30 years for Ukrainian agriculture to regain its pre-war status[41].

Fifth, dietary transition in Europe could help mitigate the war's impacts. As a major importer of grains from Russia and Ukraine (Supplementary Figs. 1 and 2), Europe predominantly used these grains to feed livestock[23]. Reference [42] demonstrated that a transition towards the planetary health diet (that is, eating more plants and less meats) in the European Union and the United Kingdom would conserve a substantial volume of crops for livestock. This conservation can nearly offset the crop production deficits from Russia and Ukraine. Thus, more efforts are needed to promote sustainable healthy diets, especially in Europe.

Lastly, any policy designed for food systems must prioritize food security. The ongoing Russia–Ukraine war presents significant challenges, not only in terms of halting biodiversity loss (as outlined in Sustainable Development Goal (SDG) 15) but also in achieving zero hunger (as mentioned in SDG 2). Due to Ukraine's curtailed agricultural exports, global grain prices have surged, particularly affecting many of the low-income countries in Africa. These elevated prices exacerbate food security concerns, contributing to an upsurge in global hunger figures. It is imperative that our strategies to curb cropland expansion incorporate these food security concerns[18]. A promising approach is to further enhance agricultural productivity, which could increase crop yields and promote intensification of land use, especially in countries greatly impacted by the war.

In conclusion, given the already urgent biodiversity crisis, the international community should take bold steps to address the challenges induced by the Russia–Ukraine war. It is important to incorporate telecoupled impacts of war on biodiversity into actions in implementing the post-2020 Global Biodiversity Framework.

Limitations of the study

This study only focuses on the cascading impacts of food export restrictions. If other cascading mechanisms are considered, such as higher prices of fertilizers and energy[18], the Russia–Ukraine war may result in more severe cropland expansion and biodiversity loss. To isolate the effect of the war, we adopted a comparative static analysis approach, that is, the GTAP model, to perform the simulations. The static model is unable to provide the time when equilibriums are achieved and to simulate dynamic processes such as price fluctuations and the process of annual expansion of cropland. Further studies may incorporate these factors for a more complete understanding of the consequences of the Russia–Ukraine war.

The potential impact of climate change on crop yields and subsequent implications for future cropland expansion have not been addressed in this study. Previous research[43] indicates that end-of-century maize productivity may experience a shift ranging from a 24% decrease to a 5% increase, while wheat stands to gain between 9% and 18%. Reduced maize yields resulting from projected climate change could exacerbate cropland expansion and biodiversity loss, particularly in countries such as Mexico and Brazil. To comprehensively assess the impacts of climate change on cropland expansion, future research should focus on providing datasets that offer lower uncertainty, higher spatial resolution and specific crop considerations, such as sunflower cultivation.

It should also be noted that the biodiversity impact assessment in this study only indicates potential loss rather than real species loss. Biodiversity loss, in reality, is subject to many factors, such as climate and conservation. Despite this, our projection of biodiversity loss is necessary as it allows us to make a quantitative comparison among different scenarios and identify the countries that would suffer the severest impacts.

Methods

MRIO analysis

We employed an MRIO model[24] to assess the virtual cropland flows from Ukraine and Russia to the rest of the world. The most commonly used MRIO datasets suffer from the issue of low levels of spatial detail (no separated data for Ukraine in EXIOBASE[44]) or sectoral detail (coarse-grained categorization of agriculture in Euro26). Reference [24] compiled a high-resolution MRIO table (189 countries × 163 sectors) on the basis of the datasets from EXIOBASE, Eora26 and FAO, as well as constructed a corresponding satellite table containing land use. We adopted the data for 2015, the latest year with such a high-resolution table, to perform the MRIO analysis.

Life-cycle land use was calculated using the equation:

$$\mathbf{Land} = \mathbf{D}(\mathbf{I} - \mathbf{A})^{-1} \tag{1}$$

where **Land** is the life-cycle land use coefficient matrix composed of land_i^r (unit is km^2 per EUR), that is, the life-cycle land use by sector i in region r; **D** is the direct land-use coefficient matrix composed of d_i^r; **A** is the direct consumption coefficient matrix consisting of $a_{i,j}^{r,s}$, that is, the direct consumption of sector j in region s by sector i in region r; and **I** refers to an identify matrix.

Virtual land flows were assessed using the equation:

$$\mathrm{flow}^{r,s} = \sum_i \mathrm{land}_i^r \times y_i^{r,s} \tag{2}$$

where $\mathrm{flow}^{r,s}$ is the virtual agricultural land flow from region r to s with an area unit of km^2 and $y_i^{r,s}$ is the final use of commodity i that is produced in region r and finally used by region s with a monetary unit of EUR.

GTAP model

We employed the GTAP model[19,20] to examine the cascading effects induced by the war. GTAP is a multiregional and multisectoral model built on computable general equilibrium theory. The model assumes a perfectly competitive market with constant returns to the scale of production while maximizing producer profits and consumer utility. The GTAP model follows Armington's assumption that there will be differentiation of imported crops with respect to their origin, while substitution in consumption is possible for the same crop, whether imported or domestically produced. Product prices are affected by relevant transportation costs and tariffs. Consumers, including households, governments and businesses, are affected by price when making purchases. GTAP captures market-mediated responses under different policy scenarios through changes in the supply–demand relationship and participant behaviour. Through global trade, GTAP also transmits the effects of shocks worldwide while connecting countries and regions.

The GTAP 10 database[19,20], which is the most current version, was employed in this study. It covers 141 countries and regions worldwide and includes 65 sectors and 5 primary production factors. We followed the default setting of 141 countries and regions in GTAP and divided the sectors into 10 refined agricultural sectors and 1 other sector (all non-agricultural sectors). The agricultural sectors include rice, wheat, other cereals, vegetables, fruits and nuts, oilseeds, sugarcane, other crops, bovine and goat, milk and other foods. In this study, maize was not separated from the 'other cereals' sector due to lack of relevant data. This might affect the accuracy of simulation results to some extent. However, our categorization is acceptable because according to the 2020 data provided by the United Nations[23], the sector of other cereals is dominated by maize (79%) and barley (11%) in terms of global crop production; ~58% of maize and barley is used as feed for animals globally[23], indicating that they are partially substitutes for each other. Thus, it is acceptable to follow the GTAP default setting where maize is categorized into the sector of other cereals[45,46]. Adhering to the GTAP default settings also includes land mobility, where we considered that the total amount of land is constant in an economy, but that land can be transformed within the economy.

In the simulations, we called a reduction or halt to the agricultural exports from Ukraine and Russia. However, we cannot implement the export restrictions directly in the GTAP model because the trade flows are endogenous variables. Thus, we adopted the same approach as that used in a previous study[47] by swapping the export variable with the exogenous variable 'imported product technology'. Thus, we used imported product technology as a proxy to reduce exports. The reduction in imported product technology reduces exports to the point where it matches the restrictions we desire in our scenarios. Although non-agricultural sectors may have some spillover effects from the shock received through the supply chain, they are beyond the scope of this study. The GTAP output was then fed into the MRIO model to investigate the changing virtual cropland flows.

Spatial modelling of future cropland expansion

We modelled the future spatial expansion of cropland using the logistic-CA model consisting of three main components: suitability, neighbourhood and land constraints.

We first extracted the cropland dynamics from the MODIS Land Cover Type (MCD12Q1) v.6.1 database, which provides global coverage of land cover types. The original land cover types consist of 17 specific classes from the Type 1 product (Supplementary Table 2). We then combined these specific classes into eight primary categories (that is, forest, grassland, wetland, cropland, urban, glacier, bareland and water). The two phases (2010 and 2020) of cropland data were used to calibrate the cropland growth model, serving as a proxy to forecast future cropland expansion. Here we aggregated the cropland data into 1 km resolution for the global expansion simulation because this is the commonly used resolution at the global scale and can also match with other ancillary spatial proxies, such as population, in our study.

We employed some spatial factors to derive the suitability surface in the cropland modelling. Biophysical, climate and socioeconomic factors play crucial roles in cropland expansion by determining the potential locations of new cropland pixels. The adopted spatial factors in this process include locations (that is, the distances to country centres), traffic (that is, the minimum distances to primary roads and highways), terrain (that is, digital elevation model and slope), socioeconomics (that is, population) and climate (that is, annual mean temperature and precipitation) (Supplementary Table 3). These spatial factors were derived from the Database of Global Administrative Area (https://gadm.org/), the OpenStreetMap (http://www.openstreetmap.org/), the US Geological Survey (http://earthexplorer.usgs.gov/), the Gridded Population of the World v.4.11 and the TerraClimate database (https://www.climatologylab.org/terraclimate.html). All these spatial factors were normalized to a spatial resolution of 1 km.

We calibrated the cropland growth model using two phases of cropland dynamics (2010 and 2015) and evaluated the model performance from 2015 to 2020. We identified the changed and unchanged regions regarding the crop from 2010 to 2020. By using the prepared spatial proxies, we can calibrate the model to make it reflect the actual change in crop dynamics. For example, our model indicated that population has a larger weight than climate in China, whereas its weight is probably smaller than that of climate in Brazil. We identified the changed pixels with cropland transitions and randomly generated 20% of samples in these changed (10%) and persistent (10%) regions. We evaluated the derived suitability surface using the receiver operating characteristic (ROC) curve approach (Supplementary Fig. 7). The derived results can be compared with the reference map by dividing the continuous suitability surface into binary maps using different thresholds, forming the ROC curve. The area under the curve (AUC) can be measured from the ROC curve and serves as a quantitative indicator to evaluate the derived suitability. We applied the derived suitability layer to model the expected crop expansion from 2015 to

2020. We then evaluated the model performance by calculating the overall accuracy and kappa coefficient (a measure widely used for interrater reliability) between the modelled and referenced crop maps in 2020 (Supplementary Fig. 8).

We modelled the spatial expansion of cropland using the logistic-CA model consisting of three main components: suitability, neighbourhood and land constraints. We implemented a logistic regression model[48–50] for transition rule extraction considering various cropland-related spatial factors. Assuming that there are n spatial factors ($x_1, x_2, \ldots, x_n$), the logistic regression model can be expressed as equations (3) and (4). The neighbourhood configuration closely relates to its size, shape and surrounding land cover types. It is a fundamental and crucial component in the CA model as a driving force in modelling cropland expansion. In this procedure, the non-cropland grids are more likely to transform into cropland grids if many developed cropland grids surround them (equation (5)). We also included land constraints in the developed logistic-CA model. For instance, restricted lands, such as water, glacier, and urban and protected areas, were not allowed for converting to cropland in the spatial modelling. They were represented as a land constraint term $L = 0$.

$$z = b_0 + b_1 x_1 + \ldots + b_n x_n \tag{3}$$

$$p_{\text{suit}} = \frac{\exp(z)}{1 + \exp(z)} \tag{4}$$

where P_{suit} is the obtained suitability of development from the biophysical, climate and socioeconomic conditions, z is the directly regressed value, and b_n and x_n are the nth coefficient and spatial proxy, respectively. Parameters in equation (3) were derived from randomly collected samples in changed (that is, from other land cover types to cropland) and persistent regions during 2010–2020.

$$\Omega_{ij}^{t} = \frac{\sum_{m^2} \text{con}(L_{ij} = \text{Cropland})}{m * m - 1} \tag{5}$$

where Ω represents the influence of neighbourhood. m is the window size and con() is a conditional function, which returns 1 when the status of the cell L_{ij} is cropland.

We then calculated the overall cropland development probability on the basis of suitability, neighbourhood and land constraints. We determined the development probabilities P_{dev} for future cropland expansion using equation (6) on the basis of the cropland extent in 2020. In general, pixels with higher combined development probability are preferentially considered for cropland development. We iteratively processed these pixels according to their development probabilities at an annual step until the total cropland increments derived from the estimation had been allocated in a spatially explicit manner during the modelling process.

$$P_{\text{dev}_{i,j}} = P_{\text{suit}_{i,j}} \times \Omega_{i,j}^{t} \times L \tag{6}$$

where P_{dev} is the development probability, and P_{suit}, Ω and L represent the suitability surface, neighbourhood and land constraints, respectively.

Biodiversity impacts assessment

The transformation from natural lands to cropland results in a sudden decline of land quality and threatens biodiversity[30]. The transformed land will gradually recover to its initial quality with the forces of nature, known as regeneration. The regeneration time is long and could take hundreds of years to completely recover to the initial quality. Biodiversity is severely threatened during the regeneration period due to low land quality. In life-cycle impact assessment (LCIA), the land transformation-related biodiversity loss is assessed by integrating the impacts spanning the regeneration period[30], so its unit is species*years, where 'years' refers to the regeneration time. In other words, the land transformation-related biodiversity loss in LCIA is defined to be an aggregated impact for a long period.

If a species is endemic to the ecoregion, its loss will be permanent and irreversible, that is, global extinction. Therefore, we considered two types of biodiversity impact, namely, regional species loss and global species extinction.

On the basis of an adapted species–area relationship (SAR) model, ref. 29 quantified the ecoregion-level characterization factors for species loss caused by land use and land transformation. Reference [31] further improved the impact assessment and calculated the characterization factors for biodiversity impacts for 804 terrestrial ecoregions of the world. We obtained the global map of terrestrial ecoregions from ref. 51. We used the datasets of ref. 31 for integration with our simulation results of cropland expansion to assess global biodiversity loss. Four taxa were considered in this study: birds, mammals, reptiles and amphibians. The datasets of ref. 31 provide the factors for either marginal impacts or average impacts. The marginal impact is defined as the first derivative of the respective average impacts, indicating the biodiversity loss when an additional area of ecoregion is damaged. The marginal values were used in this study as biodiversity would suffer from marginal effects of land transformation induced by the Russia–Ukraine war.

Scenario design

We designed four scenarios in this study to project the consequences of the Russia–Ukraine war. The MAPFU reported Ukraine's agricultural exports in a year of Russian invasion (March 2022 to March 2023)[25]. Compared with the 3 yr average (2019–2021)[23] reported by FAO, the annual agricultural exports of Ukraine were estimated to be reduced by 33.57% in the baseline situation (S_{baseline}). In Scenario 2 (S_{BlackSea}), we simulated a scenario where Russia halts the BSGI. Russia signed the BSGI on 22 July 2022 to temporarily allow Ukraine to export its agricultural products via the ports in the Black Sea. According to the estimates of the MAPFU[25], 72.52% of the exports were delivered via ports in the Black Sea during the BSGI (August 2022 to March 2023). On the basis of such an estimation, the exports from Ukraine were projected to be reduced by 81.75% compared with the previous years (2019–2021) in a scenario of Black Sea blockade (S_{BlackSea}). In Scenario 3 (S_{NoExport}), we simulated a scenario where all transportation of Ukraine's exports, including via ports, ferry, railway and vehicle, are blockaded and thus there are no exports from Ukraine. The lingering effects of the war may further escalate. Russian agricultural exports may also be restricted due to possible trade and other conflicts. Such a phenomenon is already in place, with international sanctions imposed on Russian seed imports. Thus, in Scenario 4 (S_{worst}), we simulated the worst scenario of the war in which there are no exports from Russia and Ukraine. To investigate the effects of Russia's export reduction, we conducted additional simulations between S_{NoExport} and S_{worst}, assuming no exports from Ukraine and varying levels of export reductions (20%, 40%, 60% and 80%) from Russia.

Reporting summary

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

Data availability

The GTAP Database is available at https://www.gtap.agecon.purdue.edu/databases/. The Multi-Regional Input-Output database adopted to investigate virtual agricultural land flows can be found at https://doi.org/10.5281/zenodo.3993659. The datasets of characterization factors adopted to calculate the biodiversity loss due to land transformation are available free of charge in the supporting information of the previous study at https://doi.org/10.1021/acs.est.5b02507.

Code availability

All data processing and analysis were conducted in ArcGIS (v.10.7), MATLAB (v.2021), GTAP (v.10) and Microsoft Excel (v.2016). The code and model output files are available at https://doi.org/10.5281/zenodo.10546479.

References

1. Behnassi, M. & El Haiba, M. Implications of the Russia–Ukraine war for global food security. *Nat. Hum. Behav.* **6**, 754–755 (2022).
2. The war in Ukraine is exposing gaps in the world's food-systems research. *Nature* **604**, 217–218 (2022).
3. Tollefson, J. What the war in Ukraine means for energy, climate and food. *Nature* **604**, 232–233 (2022).
4. Bentley, A. Broken bread—avert global wheat crisis caused by invasion of Ukraine. *Nature* **603**, 551 (2022).
5. Carriquiry, M., Dumortier, J. & Elobeid, A. Trade scenarios compensating for halted wheat and maize exports from Russia and Ukraine increase carbon emissions without easing food insecurity. *Nat. Food* **3**, 847–850 (2022).
6. Potapov, P. et al. Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. *Nat. Food* **3**, 19–28 (2022).
7. Kehoe, L. et al. Biodiversity at risk under future cropland expansion and intensification. *Nat. Ecol. Evol.* **1**, 1129–1135 (2017).
8. Jouf, C. & Lawson, L. European farmers' responses to higher commodity prices: cropland expansion or forestlands preservation? *Ecol. Econ.* **191**, 107243 (2022).
9. Wimberly, M. C. et al. Cropland expansion and grassland loss in the eastern Dakotas: new insights from a farm-level survey. *Land Use Policy* **63**, 160–173 (2017).
10. Lark, T. J., Spawn, S. A., Bougie, M. & Gibbs, H. K. Cropland expansion in the United States produces marginal yields at high costs to wildlife. *Nat. Commun.* **11**, 4295 (2020).
11. Molotoks, A. et al. Global projections of future cropland expansion to 2050 and direct impacts on biodiversity and carbon storage. *Glob. Change Biol.* **24**, 5895–5908 (2018).
12. Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. & Kent, J. Biodiversity hotspots for conservation priorities. *Nature* **403**, 853–858 (2000).
13. Outhwaite, C. L., McCann, P. & Newbold, T. Agriculture and climate change are reshaping insect biodiversity worldwide. *Nature* **605**, 97–102 (2022).
14. Clark, D. Wheat prices have surged over 60% this year, driven by the war in Ukraine. *Investopedia* https://www.investopedia.com/wheat-price-spike-fuels-inflation-5272396 (2022).
15. *June 2022 Food Price Monitoring and Analysis (FPMA) Bulletin* (FAO, 2022).
16. Liu, J., Balmford, A. & Bawa, K. S. Fuel, food and fertilizer shortage will hit biodiversity and climate. *Nature* **604**, 425 (2022).
17. Strange, N., Geldmann, J., Burgess, N. D. & Bull, J. W. Policy responses to the Ukraine crisis threaten European biodiversity. *Nat. Ecol. Evol.* **6**, 1048–1049 (2022).
18. Alexander, P. et al. High energy and fertilizer prices are more damaging than food export curtailment from Ukraine and Russia for food prices, health and the environment. *Nat. Food* **4**, 84–95 (2023).
19. *GTAP v.10 Data Base* (Purdue University, 2019); https://www.gtap.agecon.purdue.edu/about/project.asp
20. McDougall, R. A., Walmsley, T. L., Golub, A., Ianchovichina, E. I. & Itakura, K. in *Dynamic Modeling and Applications for Global Economic Analysis* (eds Ianchovichina, E. & Walmsley, T. L.) 120–135 (Cambridge Univ. Press, 2012).
21. Hull, V. & Liu, J. Telecoupling: a new frontier for global sustainability. *Ecol. Soc.* **23**, 41 (2018).
22. Liu, J. Leveraging the metacoupling framework for sustainability science and global sustainable development. *Natl Sci. Rev.* **10**, nwad090 (2023).
23. *FAOSTAT* (FAO, accessed March 2023); https://www.fao.org/faostat/en/#data
24. Cabernard, L. & Pfister, S. A highly resolved MRIO database for analyzing environmental footprints and Green Economy Progress. *Sci. Total Environ.* **755**, 142587 (2021).
25. *ENG Export of Agriproducts* (Ministry of Agrarian Policy and Food of Ukraine, accessed March 2023); https://public.tableau.com/app/profile/fsuw/viz/ENGExportofAgriproducts/Dashboard1
26. Zabel, F. et al. Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity. *Nat. Commun.* **10**, 2844 (2019).
27. Song, X. P. et al. Massive soybean expansion in South America since 2000 and implications for conservation. *Nat. Sustain.* **4**, 784–792 (2021).
28. Koellner, T. et al. UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA. *Int. J. Life Cycle Assess.* **18**, 1188–1202 (2013).
29. de Baan, L., Mutel, C. L., Curran, M., Hellweg, S. & Koellner, T. Land use in life cycle assessment: global characterization factors based on regional and global potential species extinction. *Environ. Sci. Technol.* **47**, 9281–9290 (2013).
30. Canals, L. M. I. et al. Key elements in a framework for land use impact assessment within LCA. *Int. J. Life Cycle Assess.* **12**, 5–15 (2007).
31. Chaudhary, A., Verones, F., de Baan, L. & Hellweg, S. Quantifying land use impacts on biodiversity: combining species-area models and vulnerability indicators. *Environ. Sci. Technol.* **49**, 9987–9995 (2015).
32. Chaudhary, A. & Kastner, T. Land use biodiversity impacts embodied in international food trade. *Glob. Environ. Change* **38**, 195–204 (2016).
33. Kier, G. et al. A global assessment of endemism and species richness across island and mainland regions. *Proc. Natl Acad. Sci. USA* **106**, 9322–9327 (2009).
34. Curran, M., Hellweg, S. & Beck, J. Is there any empirical support for biodiversity offset policy? *Ecol. Appl.* **24**, 617–632 (2014).
35. Ukraine, Russia agree to export grain, ending a standoff that threatened food supply. *Associated Press* (22 July 2022).
36. Fuchs, R. et al. Why the US–China trade war spells disaster for the Amazon. *Nature* **567**, 451–454 (2019).
37. Chaudhary, A., Pfister, S. & Hellweg, S. Spatially explicit analysis of biodiversity loss due to global agriculture, pasture and forest land use from a producer and consumer perspective. *Environ. Sci. Technol.* **50**, 3928–3936 (2016).
38. Chung, M. G. & Liu, J. International food trade benefits biodiversity and food security in low-income countries. *Nat. Food* **3**, 349–355 (2022).
39. Strassburg, B. B. et al. Moment of truth for the Cerrado hotspot. *Nat. Ecol. Evol.* **1**, 0099 (2017).
40. Heilmayr, R., Rausch, L. L., Munger, J. & Gibbs, H. K. Brazil's Amazon Soy Moratorium reduced deforestation. *Nat. Food* **1**, 801–810 (2020).
41. Bogonos, M. *Agricultural Outlook Ukraine – 2050 Projections for Crops* (Kyiv School of Economics, 2023).
42. Sun, Z., Scherer, L., Zhang, Q. & Behrens, P. Adoption of plant-based diets across Europe can improve food resilience against the Russia–Ukraine conflict. *Nat. Food* **3**, 905–910 (2022).
43. Jägermeyr, J. et al. Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nat. Food* **2**, 873–885 (2021).
44. Stadler, K. et al. EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input-output tables. *J. Ind. Ecol.* **22**, 502–515 (2018).

45. Qin, Y. et al. Snowmelt risk telecouplings for irrigated agriculture. *Nat. Clim. Change* **12**, 1007 (2022).
46. Qian, X. Y., Liang, Q. M., Liu, L. J., Zhang, K. & Liu, Y. Key points for green management of water-energy-food in the Belt and Road Initiative: resource utilization efficiency, final demand behaviors and trade inequalities. *J. Clean. Prod.* **362**, 132386 (2022).
47. Zhai, L., Yuan, S. & Feng, Y. The economic effects of export restrictions imposed by major grain producers. *Agric. Econ.* **68**, 11–19 (2022).
48. Li, X. et al. A cellular automata downscaling based 1 km global land use datasets (2010–2100). *Sci. Bull.* **61**, 1651–1661 (2016).
49. Cao, B. et al. A 1 km global cropland dataset from 10 000 BCE to 2100 CE. *Earth Syst. Sci. Data* **13**, 5403–5421 (2021).
50. Li, X. et al. A new global land-use and land-cover change product at a 1-km resolution for 2010 to 2100 based on human–environment interactions. *Ann. Am. Assoc. Geogr.* **107**, 1040–1059 (2017).
51. Olson, D. M. et al. Terrestrial Ecoregions of the World: A New Map of Life on Earth: a new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. *BioScience* **51**, 933–938 (2001).

Acknowledgements
L.C. acknowledges support from the National Key R&D Program of China (2022YFD1500205). J.L. acknowledges support from the US National Science Foundation (1924111 and 2118329), the USDA NIFA (2023-68012-39076) and Michigan AgBioResearch. We thank S. Nichols for helpful comments on an earlier version of this paper.

Author contributions
L.C. and J.L. conceptualized the project; L.C., X.L. and A.L. designed the methodology; L.C. and A.L. undertook formal analyses; L.C., X.L., A.L. and W.H. performed the investigations; L.C. and J.L. supervised the work; J.H. and T.B. validated the results; L.C., A.L., X.L. and W.H. visualized the data; L.C. wrote the first draft; J.L. and Z.G. contributed to the review and editing of the paper.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41893-024-01292-z.

Correspondence and requests for materials should be addressed to Li Chai or Jianguo Liu.

Peer review information *Nature Sustainability* thanks Damià Barceló, Peter Alexander, Nathalie J. Lambrecht and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.