High energy and fertilizer prices are more damaging than food export curtailment from Ukraine and Russia for food prices, health and the environment

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Higher food prices arising from restrictions on exports from Russia or Ukraine have been exacerbated by energy price rises, leading to higher costs for agricultural inputs such as fertilizer. Here, using a scenario modelling approach, we quantify the potential outcomes of increasing agricultural input costs and the curtailment of exports from Russia and Ukraine on human health and the environment. We show that, combined, agricultural inputs costs and food export restrictions could increase food costs by 60–100% in 2023 from 2021 levels, potentially leading to undernourishment of 61–107 million people in 2023 and annual additional deaths of 416,000 to 1.01 million people if the associated dietary patterns are maintained. Furthermore, reduced land use intensification arising from higher input costs would lead to agricultural land expansion and associated carbon and biodiversity loss. The impact of agricultural input costs on food prices is larger than that from curtailment of Russian and Ukrainian exports. Restoring food trade from Ukraine and Russia alone is therefore insufficient to avoid food insecurity problem from higher energy and fertilizer prices. We contend that the immediacy of the food export problems associated with the war diverted attention away from the principal causes of current global food insecurity.

The Ukraine–Russia war has created widespread suffering and deaths in Ukraine but is also leading to damaging consequences in other parts of the world through sudden and unanticipated events (that is, shocks) to global markets, especially food commodity markets. These impacts, which are mediated through the global food system[1,2], have the potential to result in large environmental and human health harms. The implications for food security were frequently discussed from the start of the war by the media, policymakers and academics. The emphasis has frequently been on the role of curtailment of food exports from the region, either due to blockages of Ukrainian Black Sea ports or difficulties exporting from Russia, and the potential impact of this on higher prices and food shortages[3,4]. Food price rises

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are likely to have a disproportionate effect on the world's poorest, including though nutritional health, as a higher proportion of income is spent on food[5,6].

International wheat prices increased by 12% (20% for cereals) in the 3 months from the start of the Ukraine–Russia war[7]. However, even before the war started, global food prices were increasing in response to energy price rises, as the world emerged from its post-COVID economic downturn, with food prices having increased by 23% (30% for cereals) in the year to May 2022 (ref. [7]). While, prices dropped from mid-May, supported by the signing on 27 July 2022 of agreement to facilitate grain exports from Ukraine via the Black Sea, by end of September 2022 wheat prices were still 27% higher than 12 months before[8]. Energy prices affect food prices directly by increasing agricultural input costs, such as fertilizers, since nitrogen fertilizer production is highly energy demanding and uses natural gas (methane) as a feedstock. The food system also has high energy needs including for agricultural machinery, irrigation, heating, food processing, storage (refrigeration and drying), packaging and transport. It has been estimated that natural gas accounts for 70–80% of the total costs of fertilizer production[9]. The price of natural gas increased by 139% from April 2021 to April 2022 (ref. [10]), with an increase in price of 182% for urea (a commonly used nitrogen fertilizer), over the same period[11] ('Supplementary Fig. 1). As well as impacting energy markets, the conflict has affected fertilizer markets, as Russia is a major fertilizer exporter (13% of global nitrogen and 17% of potassium fertilizers exports in 2020 (ref. [12])), with shortages expected[13], and prices are expected to remain high[14]. Farmers may respond to rising fertilizer costs by reducing their use, which leads to smaller crop yields and overall production declines, further pushing up food prices[15]. Higher food prices may also lead to the expansion of agricultural areas as farmers bring new land into production in response to market signals[16–18]. Environmentally important parts of the world, such as the tropics, are especially sensitive to agricultural expansion[19], such that disruptions to the global food system may lead to severe impacts on biodiversity and carbon stocks arising from deforestation[20,21].

Ukraine, sometimes described as the breadbasket of Europe, and Russia are both major exporters of agricultural commodities, particularly wheat and vegetable oils. Russia was the largest exporter of wheat in 2020/2021, exporting 38.3 million tonnes (Mt), while Ukraine exported 16.8 Mt, which together accounts for 29% of global exports[22] (Fig. 1). For cereals, 19% of global exports come from either Russia (49.2 Mt, 10%) or Ukraine (44.4 Mt, 9%). Some countries are highly dependent on these exports, for example, Egypt receives 84% of their wheat imports (19.5 Mt) from these countries[12]. Although smaller in absolute terms, 62% (7.1 Mt) of global sunflower oil exports come from the region[12], and 6.8% (28.5 Mt) of oilseed crops. While sanctions against Russia, for example, by the European Union and United States, do not include food or fertilizer, Russia has claimed that 'vessels that carry Russian grain have fallen under sanctions'[23], as well as alleged difficulties due to removal from the SWIFT payment system and higher shipping insurance costs[13]. Potential for problems with Russian exports and problems exporting from Ukraine[24] have raised serious and widespread concerns about global food shortages and price rises, although these concerns have reduced with the Black Sea grain corridor agreement[25].

The relative impact of these two different mechanisms (that is, energy and fertilizer price rises and food export restrictions) on future global food price inflation is not well understood, although the emphasis in current debates has tended to focus on the role of the disruption to exports. Furthermore, there is a lack of assessment of the scale of the potential harms from food price increases for human nutritional health or the environmental consequences. In this Article, we apply a scenario modelling approach (Fig. 2) to better understand and quantify these consequences, including exploring how the current situation differs from a counterfactual scenario with no energy price or export restriction shock.

Results

A food system model, LandSyMM (https://landsymm.earth), was used to explore four stylized scenarios to better understand the role of different current drivers of global food price increases and their consequences. LandSyMM has a detailed representation of land use and the food system, including trade and consumption dynamics, and has previously been used to explore nutritional health and environmental outcomes[26–29]. The reference or 'no shocks' scenario was a counterfactual where energy and fertilizer prices were maintained at 2020/2021 levels (Supplementary Fig. 1) and there was no imposition of restrictions on food exports. The other three scenarios differed by either (1) imposing a shock on energy and fertilizer prices, the 'energy price shock' scenario; (2) restricting food exports from Russia and Ukraine, the 'export restriction shock'; or (3) a combination of both energy price and food export restriction shocks, the 'energy and export shocks' scenario (Fig. 3), with all food commodity groups included in the analysis. All shocks were imposed in 2022 and remain in place until the end of the simulations in 2040, with human nutritional health outcomes presented in 2023 and environmental consequences in 2030. Simulating the outcomes until 2040 is a stylized and parsimonious approach that provides insight into the relative impact of energy and fertilizer price rises versus food export restrictions from Russia and Ukraine in the short term, as well as a better understanding of how the global food system could be reconfigured over a longer time period, if these conditions are maintained. A Monte Carlo approach was used to explore outcome uncertainty by sampling parameter probability distributions, with 30 ensemble members for each scenario.

Higher energy prices and export restrictions increase food costs

Global market prices were higher in the three shock scenarios than the scenario with no shocks (Fig. 4), with prices tending to increase to 2024 and then stabilizing at a new elevated level. The increases were greatest in the combined energy and export restrictions shocks scenario. The largest increase in the median ensemble price occurred in this scenario with an initial increase of 149% for oil crops in 2024 and remaining at 91% in 2030. Wheat had the next-highest increases in the initial years, with a maximum increase of 122% in 2024 and 95% in 2030. Increases in the energy shock scenario were moderately lower; for example, the maximum increase in wheat prices in 2024 was 95% and 81% in 2030. The export restriction shock was substantially less, with a maximum increase of 8.1% in 2023 and 4.1% in 2030. Most other food commodities followed a similar pattern, except for ruminants where a lower price response occurred (20% increase by 2030 for the combined shock scenario). Starchy roots, sugar, and fruit and vegetables were also less impacted, with increases of 40–50%.

Food spending is affected differentially by global market prices owing to variations in consumption patterns (both between countries and through time), levels of self-sufficiency and levels of trade tariffs. The change in cost of purchasing a regionally representative basket of food, assuming constant 2021 levels of consumption, indicate increases in all regions and shock scenarios (Table 1). In aggregate, food costs increase globally by 2.6% in the export restriction scenario in 2023. However, this increase is modest in comparison with the 74% and 81% for the energy prices and combined scenarios, respectively.

Higher food prices damage human health

Food consumption patterns in each country are altered by the shock scenarios with consequences for human health due to diet- and weight-related risk factors from the number of portions of red meat, fruit and vegetables consumed, total calorie intake and the population distribution of body mass index (BMI). While health risks from undernourishment can occur rapidly, the risks associated with consumption of fruit, vegetables or red meat require long-term patterns of dietary changes to be fully expressed. Globally, in 2023, total number
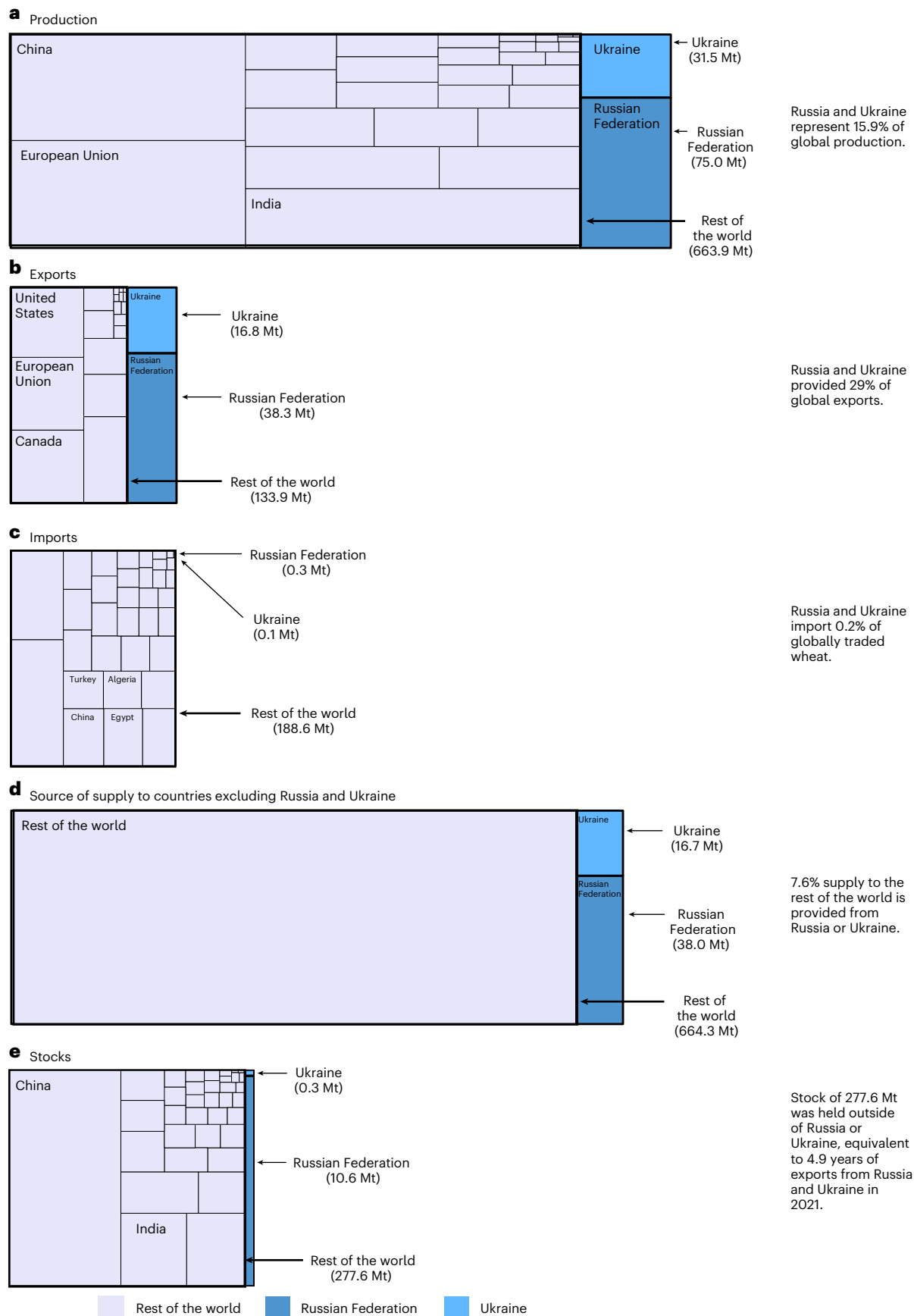
Fig. 1 | The role of Russia and Ukraine in the global wheat market. a, Global production in 2021. **b,c**, Global international exports (**b**) and imports (**c**) in 2020/2021. **d**, The source of supply to all countries globally excluding Russia and Ukraine in 2021. **e**, Global stocks ending in 2021. In **a**–**e**, values are in millions of tonnes (Mt). The source of supply (**d**) shows whether supply to countries outside of Russia and Ukraine is from production within those countries or was provided, in 2021, by imports from Russia and Ukraine. All areas shown are drawn in proportion to the mass of wheat using a common scale. Values from FAO[22].
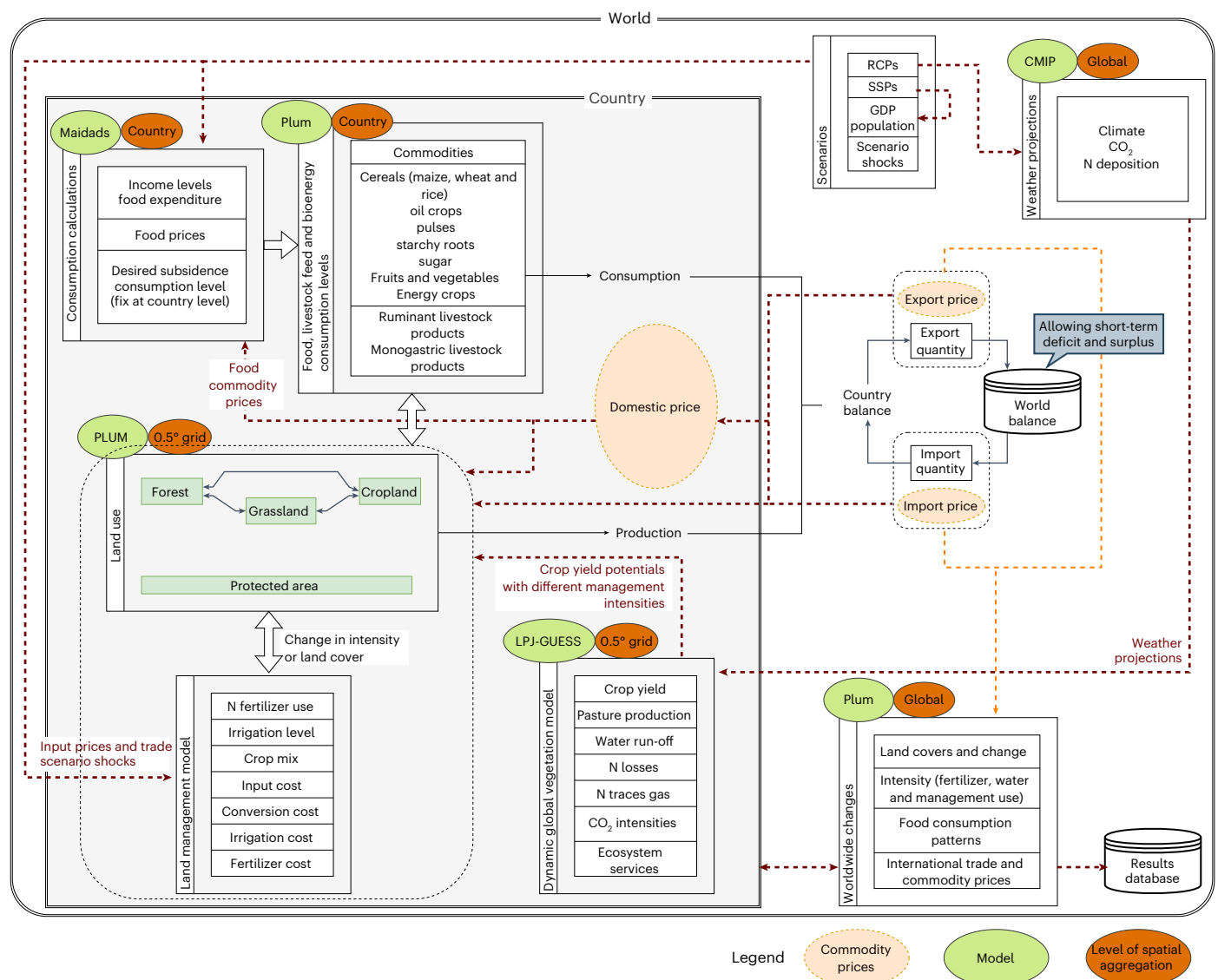
Fig. 2 | Diagram of LandSyMM structure. The cross-scale interactions between submodels (PLUMv2, LPJ-GUESS and MAIDADS) and the climate input data from the Coupled Model Intercomparison Project (CMIP) are shown. These interactions and those between spatial gridded data and country- and world-level calculations occur at each annual time step of the model.

of deaths due to undernourishment is a median of 252,000 (90% quantile range of 193,000–341,000) in the energy and export restriction scenario, 238,000 (177,000–314,000) in the energy shock scenario, and 7,000 (0–17,000) in the export restriction scenario. Including all the diet-related health risk factors 732,000 (416,000–1,010,000) total net annual additional deaths are projected to occur from the diets projected to be consumed in 2023 in the energy and export restriction scenario (Fig. 5), with 711,000 (296,000–991,000) and 6,000 (−54,000 to 76,000) deaths in the energy price shock and export restriction shock scenarios, respectively (Supplementary Figs. 2 and 3). These changes in death rates including all dietary risks assume that consumption of that diet persists for an extended period. The increase of food prices are less in 2030 than 2023 (Table 1 and Fig. 4), which reduces the annual additional deaths associated with the diets projected for these years. Long-term consumption of the diet 2030 was found to reduce the additional total deaths by 31–34% in comparison with the 2023 diets (Supplementary Figs. 4 and 5), for example, with 507,000 (303,000–675,000) net additional deaths including all dietary factors in the combined shock scenario. The uncertainty for the export restrictions scenario is high compared with the median change, as the

parameter variation from the Monte Carlo sampling has a greater effect than the losses of exports applied (Fig. 5 and Supplementary Fig. 2).

The net death rates are a balance between additional deaths from consuming less fruit and vegetables as well as more underweight people, and reductions in deaths from fewer obese and overweight people as well lower red meat consumption. The higher food prices in the shock scenarios lowers food intake and reduces obesity and overweight rates while increasing the proportion of the underweight population. The diets projected for 2023 are associated with 117 million (89–139 million, 90% quantile range) fewer obese or overweight people in the energy and export restriction scenario, but 83 million (61–107 million) more underweight. In the energy price shock scenario, there are 112 million (92–132 million) fewer obese or overweight people and 78 million (57–99 million) more who are underweight, while for the export restriction scenario there are 3 million (0–8 million) fewer obese or overweight people and 2 million (0–5 million) more who are underweight. Globally, 342 additional deaths per million people are projected for the combined scenario annually from long-term consumption of the projected 2023 diet, which is partially offset by an annual 77 avoided deaths per million people, giving 265 net deaths per million. Sub-Saharan
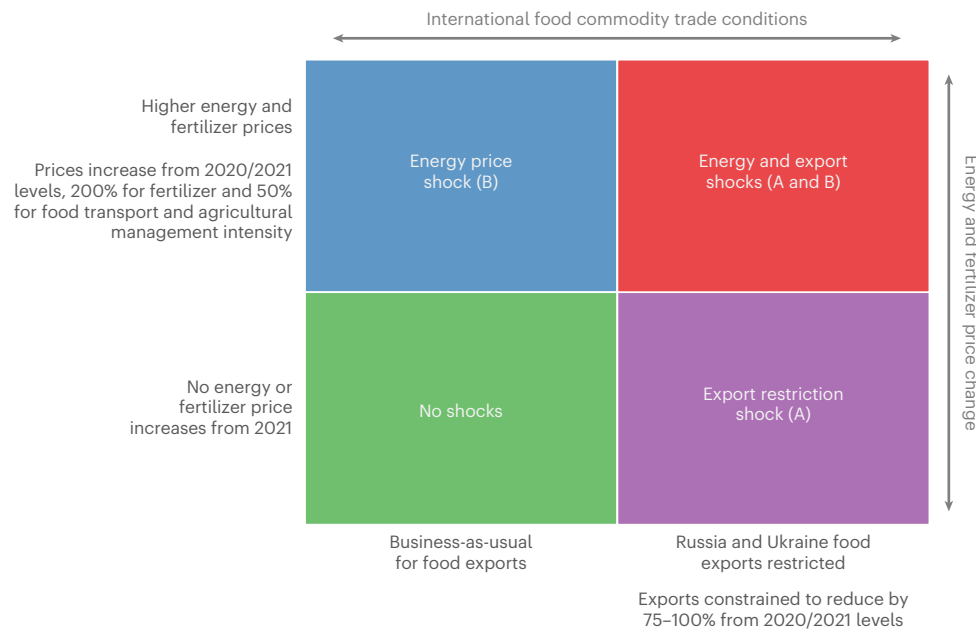
Fig. 3 | Diagram of the four scenarios modelled in the study. Two-dimensions of export restrictions (*x* axis) and energy price shocks (*y* axis). The scenario specific shocks are imposed in 2022, with all other parameterizations being consistent between the scenarios.
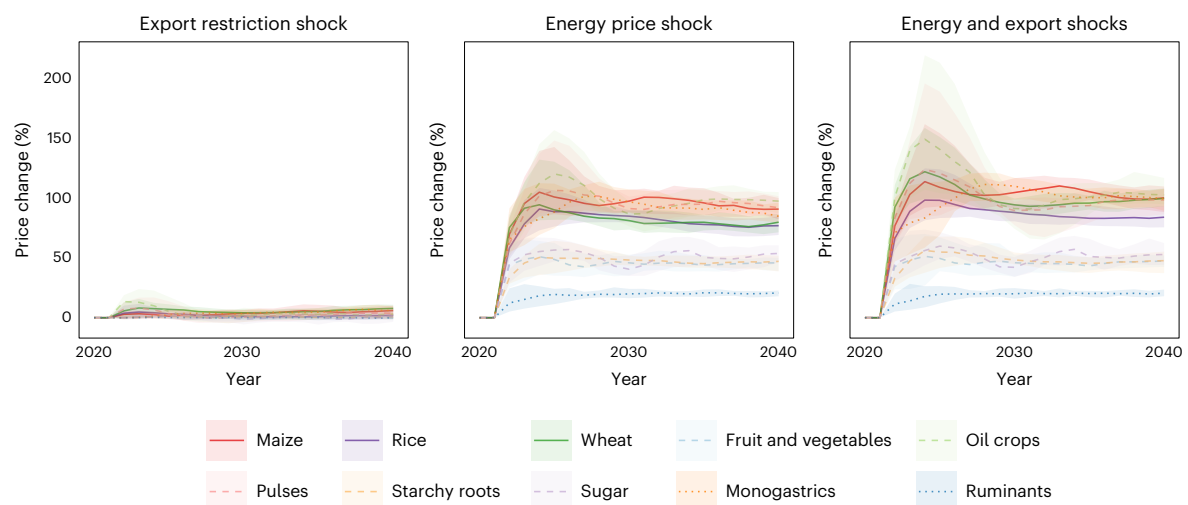

Fig. 4 | Percentage change in global commodity market prices between the no shock scenario and the three other scenarios. All food commodity groups modelled are shown. Lines show median value for scenario ensemble (*n* = 30 members) and ribbon 90% quantile range.

Africa had the highest change in rate of annual net deaths with 307 (204–425) net deaths per million population, which is dominated by deaths due to the relative risks of being underweight (67% of the increase). This is followed by the Middle East and North Africa with 140 (30–205) additional deaths per million per year. Conversely, North America is less impacted with an annual 46 (18–46) additional deaths per million.

Land use changes threaten climate and biodiversity

The agricultural and land use systems also respond to each of the simulated shocks. Higher fertilizer prices in the energy price and combined scenarios both lead to a rapid drop in fertilizer use, with the total global quantity of inorganic nitrogen applied approximately halving (Fig. 6 and Supplementary Table 2). The use of other inputs to crop production increase, with expansion of cropland area (for food and feed) and more irrigation water applied. The additional agricultural land is partially converted from forest and partially from natural land, although there is uncertainty over the proportions of this allocation. At the level of the global values (Fig. 6), there are no clear differences between the no shock and the export restriction scenarios. However, the aggregate values hide changes in the distribution of land use (Supplementary Fig. 8), with a reduction in intensity of production in Russia and Ukraine and increases in other areas, including China, India, Brazil and the United States in the export restriction scenario. Land use patterns in the energy price shock scenario (Supplementary Fig. 9) show the widespread decrease in fertilizer use, with the expansion of agriculture predominantly in the tropics and Russia. In the combined scenario, this expansion of agricultural area in Russia is reversed to become a contraction (Fig. 7, Supplementary Fig. 10 and Supplementary Tables 3 and 4), with expansion of agricultural land instead occurring in

Table 1 | Percentage change in 2023 and 2030 in food commodities consumed in each region from 2021 prices and based on constant 2021 consumption quantities (that is, Laspeyres index[26]); regional values are calculated as weighted average by country populations

Region	Year	Scenario		
		Export restriction shock	Energy price shock	Energy and export shocks
East Asia and Pacific	2023	2.4 (1.1–5.4)	77.5 (62.6–97.7)	83.8 (62.5–108.2)
	2030	1.7 (0.4–2.6)	75.5 (70.3–84.0)	80.9 (75.6–89.3)
Europe and Central Asia	2023	2.5 (1.4–5.5)	69.4 (57.9–87.7)	77.3 (58.1–100.5)
	2030	1.7 (0.6–2.5)	68.0 (63.3–74.8)	73.9 (68.7–81.1)
Latin America and Caribbean	2023	1.8 (0.8–4.3)	66.8 (53.8–83.8)	71.6 (52.4–92.0)
	2030	1.5 (0.1–2.3)	64.1 (59.4–70.2)	68.4 (64.2–74.6)
Middle East and North Africa	2023	3.2 (0.9–7.1)	72.6 (58.7–87.4)	82.1 (63.2–101.3)
	2030	1.7 (0.6–2.4)	69.5 (64.1–75.3)	74.5 (69.7–81.3)
North America	2023	2.8 (1.4–6.1)	72.4 (60.2–87.9)	81.0 (61.6–100.9)
	2030	1.8 (0.9–2.8)	70.0 (66.1–75.7)	76.5 (71.5–82.8)
South Asia	2023	3.3 (0.5–6.7)	75.4 (61.2–91.0)	84.7 (65.4–101.4)
	2030	1.4 (0.4–1.9)	72.1 (66.7–78.2)	76.3 (71.1–82.6)
Sub-Saharan Africa	2023	2.6 (0.5–5.0)	72.2 (57.1–85.0)	79.1 (60.6–96.3)
	2030	1.4 (0.5–2.0)	69.2 (64.2–74.7)	72.5 (68.8–78.2)
World	2023	2.6 (0.8–5.9)	74.1 (59.2–89.8)	81.2 (61.5–100.4)
	2030	1.6 (0.6–2.2)	71.1 (66.0–77.9)	76.2 (71.5–82.8)

Each cell shows the median of the scenario ensemble (*n*=30) and the 90% quantile range in parentheses.

other locations. The land use expansion for this scenario in 2030 compared with the no shock scenario is a median of 227 Mha (130–349 Mha, 90% quantile range), an area approximately equal to the combined area of Belgium, France, Germany, Ireland, Italy, the Netherlands, Portugal, Spain and the UK or the area of Democratic Republic of the Congo, the 11th largest country in the world[30]. This is an annual rate of expansion of agricultural land nearly double that of 1970–2000 (ref. 16).

Discussion

The results suggest a lower importance of the restrictions on food exports from Russia than has been widely reported. 'Russia and Ukraine produce 30% of the global wheat exports' is a typical framing (for example, ref. 31), and sometimes misreported as a similar percentage of global supply or production (for example, ref. 32). Even when correctly described, this common narrative alone is not sufficient to support the view that the consequence of stopping these exports will be global food shortages. There are three reasons why this framing provides only a partial view that may imply an overstatement of the impacts from reducing food exports from Russia and Ukrainian for the rest

of the world. These are (1) domestic consumption, (2) stocks and (3) substitution. (1) The majority of cereals (83%, and 76% for wheat) are not traded internationally, but are grown and consumed in the same country[22]. Expressing exports from Russia and Ukraine as a percentage of the rest of the world supply gives a better representation of their importance. In these terms, 7.6% of wheat and 3.6% of all cereals used by the rest of the world came from either Russia or Ukraine. For oil crops, a concentration of export of sunflower oil from the region (62% in 2020) looks less substantial when considered within the context of the market for vegetable oil crops more broadly (6.8%) (ref. 12). (2) There are substantial stocks held for staple commodities, such as wheat. There were 268.3 Mt of wheat stocks outside of Russia and Ukraine in 2021, which made up part of the 802.9 Mt of cereal stocks (Fig. 1). Therefore, wheat stocks represent an equivalent of nearly 5 years of total annual Russian and Ukrainian wheat exports. The buffering of these stocks provides time for production changes to replace the loss of exports, if they could be made accessible where required. (3) There is scope for substitutions between agricultural commodities that act to spread the shock of the loss of these exports over more commodities. In response to price signals that indicate relative scarcity of impacted foods, consumers can partially shift consumption to other cereals and foods. However, such shifts in consumption are not straightforward or without consequences as consumers have cultural and behavioural aspects that frame preference and choices. Furthermore, cereals are not only used as food for human consumption with around a third (31%, 236.0 Mt of 761.9 Mt in 2020/2021) of wheat and a half of cereals (54%, 1,500.9 Mt of 2763.4 Mt) used for animal feed or other uses, such as bioenergy[22]. This provides further scope to either reduce or substitute to alternatives, for example, with other sources of animal feed. Relative changes in commodity prices creates incentives to substitute between the crops used for feeding animal, and higher feed costs encourages more intensive pasture management to reducing the need to use crops for ruminant feed.

Our modelling attempts to include the impact of these factors and produces a relatively modest increase in global food prices due to a loss of exports from Russia and Ukraine. Although this framing suggests that the issue is not shortages of food on a global scale, it does not mean there would not be substantial and damaging consequences for the poorest who are least able to afford higher food prices, as demonstrated and quantified by the results presented here. There is still a threat of serious harm if healthy and sufficient food is not affordable to everyone.

Environmental sustainability effects

The food system is already operating outside of environmentally sustainable limits, with agriculture being a major driver for transgressing planetary boundaries[33]. Energy and thus nitrogen fertilizer price increases in the scenarios modelled were found to lead to an expansion of agricultural area (both to produce food for human consumption and for animal feed), which has important impacts on the environment because of potential deforestation, forest degradation and concurrent losses in carbon stocks and biodiversity[20,27]. Much of the modelled expansion (Fig. 7) occurs in the tropics, a part of the world that is especially sensitive to deforestation and environmental degradation[19,34]. Efforts to protect biodiversity and carbon stocks through protected areas may achieve these aims within the areas protected but could create other trade-offs, including increasing food prices and stimulating environmental impacts outside of protected areas, that is, indirect land use change[35,36]. Set against the negative environmental impacts from the projected expansion of agricultural land, higher nitrogen fertilizer costs would lead to reductions in use that could have environmental benefits for air and water quality (for example, reducing eutrophication). However, the increases in management intensity and irrigation rates would have environmental harms. Higher management intensity could lead to, for example, greater pesticide use with potential to harm
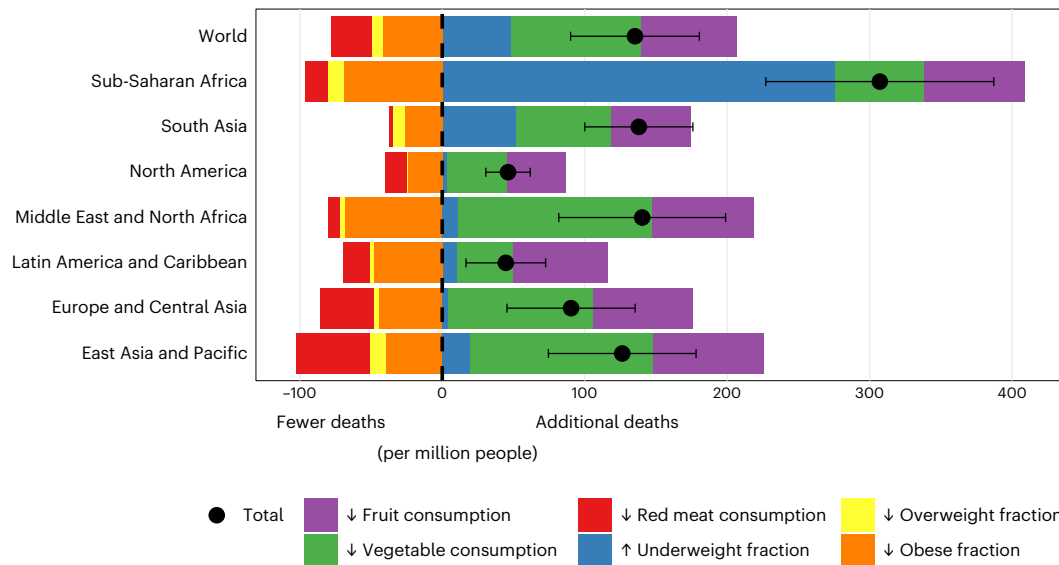
Fig. 5 | Change in annual deaths between the no shock scenario and combined energy and export restriction scenario. Results assume that 2023 projected dietary patterns are maintained long term. Colours represent the different risk factors related to nutritional health. Reductions in red meat consumption and lower rates of overweight- and obesity-related deaths reduce mortality, while lower fruit and vegetable consumption and higher rates of underweight people increase mortality. The median net impact on total change in deaths is plotted as a black circle, with error bars showing 90% quantile range for the simulation ensemble ($n = 30$ members).
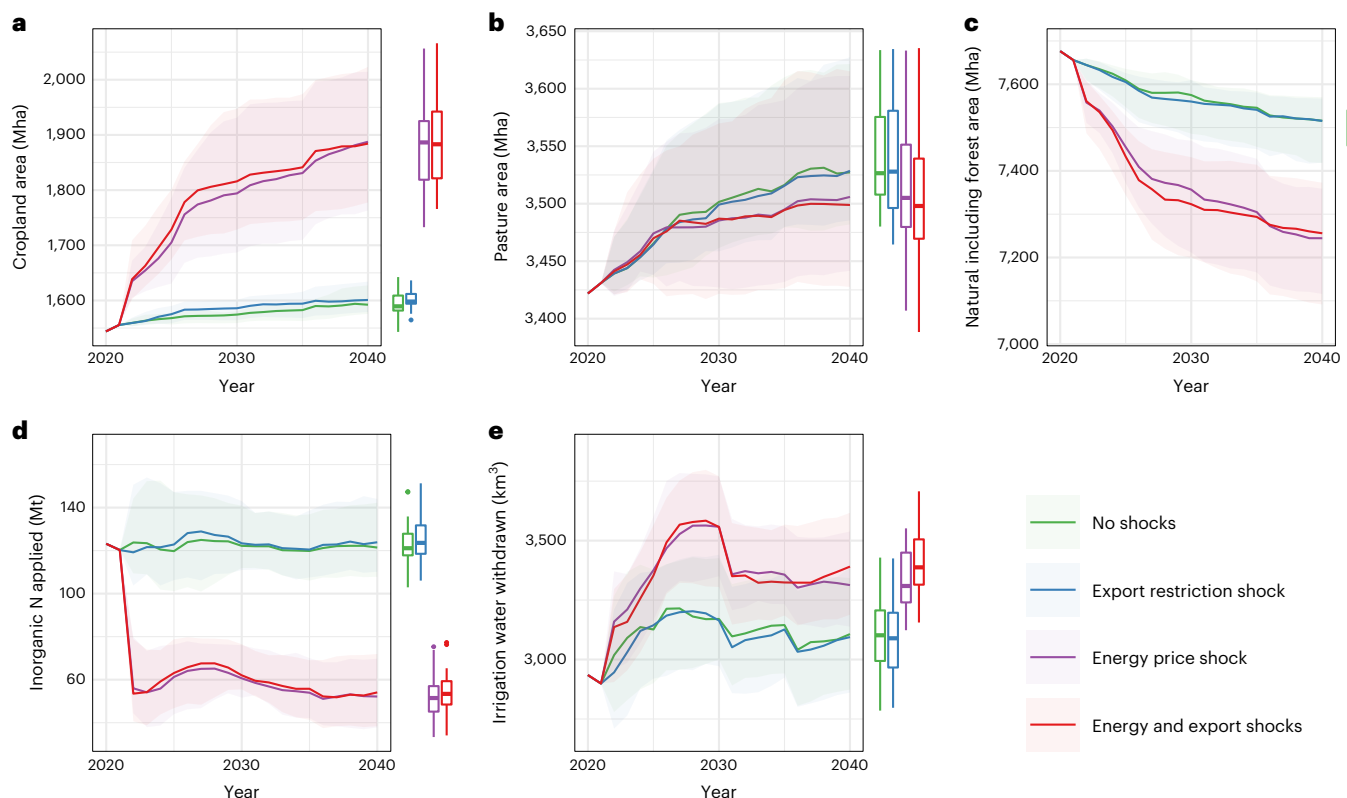

Fig. 6 | Global agricultural land use from 2020 to 2040. Four scenarios with and without input price shocks and export restriction for Russia and Ukraine are shown. Other scenario parameters were identical in all simulations, with socioeconomic values from SSP2 and climate from RCP4.5. Uncertainty ranges for each scenario were determined using a stochastic sampling method of model parameters ($n = 30$ ensemble members). Lines shows median value and ribbon 90% quantile range. Box plots are for the modelled values in 2040, showing median, interquartile range, up to 1.5 interquartile range whiskers, and outliers. **a**, Global cropland area. **b**, Global pasture area. **c**, Area of natural land including for forest. **d**, Quantity of inorganic nitrogen fertiliser applied. **e**, Water withdrawn for irrigation.
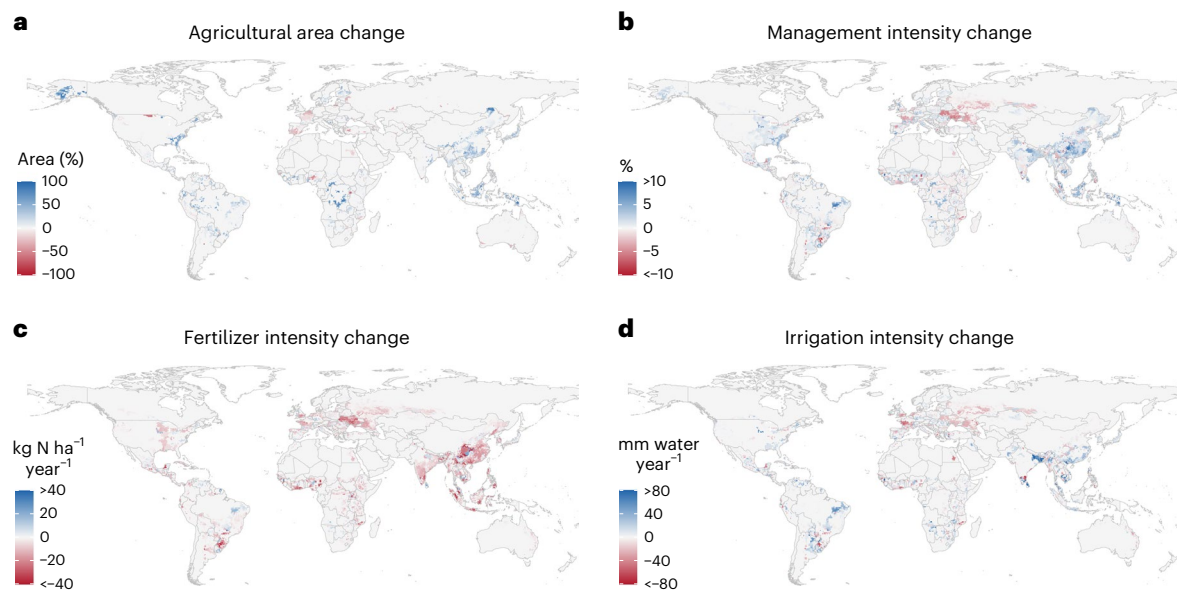
Fig. 7 | Difference in land use in 2030 between the combined energy and export shocks scenario and the no shock scenario. a, Changes in agricultural area as a percentage of the land area in each grid cell. **b**, Index of management intensity in agricultural production. **c**, Fertilizer application rate. **d**, Rate of irrigation water applied.

biodiversity[37], while increasing irrigation would place further pressures on scarce water resources in arid and semi-arid regions[38].

Policy and societal responses

Imposition of further trade restrictions would be detrimental to the food system's capacity to adapt to the loss of these food exports or other shocks, as was seen in the 2007/2008 prices[6,39,40]. Coordinated actions are important to keep global markets functioning as frictionlessly as possible[41], and thereby avoid limit damaging health and environmental outcomes. Lessons from the food price spikes of 2007/2008 and 2011/2012, that avoiding protectionist responses due to the magnification effect on the global food markets, appear to have been learnt given the statements from the World Bank, International Monetary Fund, World Food Programme and World Trade Organization regarding the need for coordinated international actions[42]. Whether these organizations have the capacity to sufficiently influence the decision making of individual states in this regard remains to be seen. However, the rise in the number of protectionist measures[43], including in India and Malaysia[44], is a concerning sign.

If farmers hold off from using fertilizers in the hope of lower prices, they may reduce productivity by more than modelled here. Earlier purchase of fertilizers applied in 2022 is likely to have buffered some of the fertilizer price rises more than accounted for here, which suggests that the increases simulated to occur in 2022 may be deferred until the 2023 harvest[45,46]. Additionally, climate change, including more frequent extreme climate events, will increasingly damage agricultural productivity in many regions[2,47]. A lack of effective climate change mitigation responses would exacerbate such effects over longer time periods where targets to limit warming levels are breached. Food prices can increase because of conflict, civil unrest and migration[48,49], with suggestions that unrest may double in 2022 owing in part to food price inflation[50]. Such social unrest has implications in turn for food production, trade and security[48,51]. Overall, there are multiple actions that are not represented in the analysis presented here that could move the situation for food affordability to a yet more serious situation with widespread food shortages and lack of availability.

Recessions and other aspects

The modelling conducted here represents only the land use sector of the economy, with income (and population) levels prescribed on the basis of the 'Middle of the road' shared socioeconomic pathway scenario (that is, SSP2) (ref. 52). However, the broader economy will also be impacted by, for example, higher energy prices, tending to result in lower incomes or recession[53]. Inflation in energy and non-food commodities will also further restrict spending on food. Therefore, these results potentially understate the health outcomes; if these effects were incorporated, the result would be higher rates of malnourishment and death. This would be associated with slightly lower price rises and land use change as food demand would decrease.

There are other aspects not considered by the analysis presented here that could increase the magnitude of the consequences explored (for example, export bans aimed at protecting local food prices[43]), or reduce them (for example, increases in welfare payments or food subsidies). Energy and fertilizer markets were exogenous in the model presented, with price for these commodities prescribed in each scenario. Higher prices in these markets have been driven, in part, by the war in Ukraine, with the conflict constraining Russian fertilizer exports[14,54]; in 2020, Russia provided 14% of global fertilizer exports[12]. The food export restriction scenario modelled here includes only curtailment of food exports, and restrictions on energy and fertilizer markets is explicitly not included, that is, fertilizer prices remain at 2020/2021 levels. Conversely, the energy and export shocks scenario combines both elements, by increasing energy and fertilizer prices consistent with current observed market conditions. Variations in prices between locations for the energy and fertilizer markets, or lack of availability of fertilizer in some locations, were not included. While inclusion of such factors may lead to some adjustment in distribution of land use responses, we believe these would be small and offsetting, and the overall results would not be materially impacted. The presented results are stylized scenario experiments that should not be seen as predictions, but they nonetheless provide insights with relevance to policy and global responses to the unfolding situation.

Limiting the worst outcomes

This may be the end of an era of cheap food. The implications are damaging to those in global society who are least able to afford to feed themselves a sufficient and healthy diet. However, the previous food system was also creating many undesirable outcomes, for example, an obesity epidemic, a major contributor to climate change, and the

dominant factor in the loss of biodiversity[55]. More expensive food is not necessarily bad for these outcomes. Lower fertilizer usage reduces the greenhouse gas emissions associated with fertilizer production and application and reduces eutrophication in the environment. Higher energy and fertilizer prices would encourage agricultural practices with lower and more efficient use of fossil fuels and fertilizers, while higher food prices could encourage increased innovation and higher agricultural productivity. It may also play a role in changing consumer behaviours to more sustainable practices, for example, helping to reduce food waste and reducing consumption of animal products. Higher food prices means discretionary food spending, for example, on ruminant meat, is reduced[56]; this is partially responsible for the lower ruminant price increases found (Fig. 4). Therefore, policies that try to return the food system to the situation in 2021, such as subsidizing fertilizers, may miss the opportunity to instead achieve better sustainability outcomes[57].

While the consequences of higher food prices are not all 'bad', the outcomes associated with increased rates of malnourishment and land use change are extremely concerning. It is the poorest who are most harmed and are disproportionately so in regions such as Sub-Saharan Africa, with outcomes exacerbating existing inequalities within and between countries[58] and increase malnourishment and associated morbidity and mortality. Interventions that seek to address these negative outcomes while retaining the more positive ones and reducing these inequalities would be necessary. These could include targeted actions to ensure healthy and nutritious food is affordable for everyone, without subsidizing food for the wealthier in society. Increased protection of land can help to stop uncontrolled agricultural land expansion and the associated environmental harms[26]. Although this could further increase food prices, coupled with other measures to ensure affordability as well as availability, the outcomes need not be negative.

Persistence of the current situation

The scenario models do not explore a reversion of the shocks, where market restrictions are removed, and energy and fertilizer prices decrease, perhaps towards early 2021 levels. The Black Sea grain agreement in July 2022 has allowed some resumption of exports, with more than 5.3 Mt of grain having been exported to September 2022 (ref. 25), but energy and fertilizer prices remain high. Although fertilizer prices have fallen from the peaks of May 2022, in August 2022 prices have more than doubled since the start of 2021 (ref. 11). Natural gas price index is 3.5 times higher than 12 months earlier and more than 6 times higher than the start of 2021, leading to cuts in nitrogen fertilizer production as plants become uneconomic and expectations of future fertilizer price rises[59]. A reduction in fertilizer prices would help to alleviate the pressure on food prices and reduce nutritional harms, although the land use change that has occurred may be permanent, including the loss of primary ecosystems. However, there is no certainty about how long the Russia–Ukraine war will continue. There have been warnings that the conflict may last for years, and the reconfiguration of political and economic relationships may remain longer still[5,60]. High energy and fertilizer prices may also persist in part owing to the need to decarbonize the energy system, which both limits fossil fuel production and encourages governments to implement or expand carbon pricing policies that would increase energy prices[61]. It is therefore highly uncertain how long high energy and fertilizer prices will continue.

Conclusion

There is sufficient food worldwide; the issue is primarily affordability. While food prices are already rising (11.4% in the year to August 2022 (ref. 7)), the results presented here suggest that further price rises will occur through 2023 if energy and fertilizer prices remain at historically high levels, causing substantial harm to human health and the environment. More needs to be done to break the link between higher food prices and these outcomes. Longer term, shifts in food production,

trade and consumption are also needed to achieve a food system that is more resilient, equitable and sustainable. Although desirable, restarting food supplies from Ukraine may be insufficient to avoid the dire consequences from the current situation for the nutrition of the poorest in society. The emphasis on the direct curtailment of food exports from the region (for example, refs. 3,4), and the importance of restarting them, may be misplaced, as factors such as fertilizer prices may be more important drivers of higher food prices. Urgent targeted action regardless of whether these supplies are restarted or not is needed to ensure that sufficient nutritious food is affordable to everyone.

Methods

LandSyMM

LandSyMM is a state-of-the-art global land-use model that couples a dynamic global vegetation model (LPJ-GUESS)[62] with a food demand system (MAIDADS)[56], and an international trade and land system model (PLUM)[27,28]. LandSyMM combines spatially explicit, biophysically derived yield responses with socioeconomic scenario data to project future demand, land-use and management inputs (Fig. 2). We use climate input data from the fifth Coupled Model Intercomparison Project (CMIP5) (ref. 63) for the IPSL-CM5A-MR climate model[64]. LandSyMM improves upon existing global land use models by having a more detailed spatial representation of crop yields and the responses of crops to intensity of production. Agricultural intensity is represented by three factors: nitrogen fertilizer application rate, irrigation water use and a management intensity index (representing, for example, pesticide use, phosphorous and potassium fertilizer, control of soil pH and increased use of machinery or labour). Furthermore, LandSyMM calculates commodity demand endogenously, and, unlike most land-use models, demand for commodities responds dynamically to changing commodity prices. Consumption of staple foods (cereals, oil crops and pulses) shifts to greater consumption of meat and fruit and vegetables as incomes rise[65]. Conversely, as prices increase, the model represents a consumption shift away from 'luxury' goods such as meat, fruit and vegetables back towards staple crops, as well as lower consumption overall.

Increase in demand for commodities is met by in-country expansion or intensification of crop production or by imports from the global market. Commodity production in excess of a country's domestic demand is exported to the global market. The global market is not constrained to be in equilibrium, instead allowing over- or under-supply of commodities buffered through global stocks. The global market prices are updated for the following year in proportion to the net out-of-equilibrium quantity as a fraction of the stock level. For example, oversupply of a commodity on the global market decreases the price as stocks rise; this reduces the benefits from its export and reduces the cost of importing it, as well as shifting consumer demands for that commodity, creating a tendency to correct for the oversupply. The restrictions to exports from Russia and Ukraine were applied exogenously as a constraint on the maximum level of exports for each commodity, calculated from the supply in 2021 and a percentage reduction in exports.

The method from Henry et al.[26], which develops the approach of Springmann et al.[66,67], was used to calculate the number of additional and avoided deaths. This approach uses population impact fractions as a means of determining the proportions of mortality that would be avoided if the risk exposure were changed from the no shock scenario to the export and energy scenarios, while the distribution of other risk factors in the population remain unchanged. As such, the effects of changes in dietary- and weight-related risk factors for 2023 and 2030 are compared for the three shock scenarios against the no shock reference scenario, using a 2021 baseline in all cases. Deaths caused by coronary heart disease, stroke, colorectal cancer, all cancers, type-II diabetes and other causes from diet and weight related risk factors by age group are considered. We included three dietary

risk factors (reduced fruit, reduced vegetable and increased red-meat consumption) and four levels of weight-related risks (underweight, normal weight, overweight and obese). For the dietary risk factors, we calculated the number of servings of red meat, fruit and vegetables consumed on average per person per day in a country, while for the weight-related risk factors we calculated mean annual BMI per country and subsequent changes in the proportion of the population that is underweight (BMI <18.5 kg m^{-2}), normal weight (BMI 18.5–25 kg m^{-2}), overweight (BMI 25–30 kg m^{-2}) or obese (BMI 30+ kg m^{-2}).

Scenarios

The four scenarios (Fig. 3) explore the inclusion or not of food export restrictions from Ukraine and Russia and the higher agricultural input costs associated with higher energy prices, but in all other regards the scenarios were identical. All scenarios used country gross domestic product (GDP) and populations projections for the 'Middle of the Road' Shared Socioeconomic Pathway (that is, SSP2) (ref. 52) and climate change projections based on Representative Concentration Pathway (RCP) 4.5 (ref. 68). While there are interactions between the scenario narratives and GDP, these were not considered, and each scenario ensemble used equal GDP projections. Parameter and scenario uncertainties were explored using a Monte Carlo approach with 30 ensemble members for each scenario. Supplementary Table 1 gives the parameter probability distributions sampled for the four scenarios.

The Russia and Ukraine food export restrictions assume that between 75% and 100% of the export levels from 2021 are unable to continue from 2022, and this remains in place for the rest of the simulation. This would represent the imposition of strong sanctions against Russian exports, for example, including secondary sanctions[69], and the inability of Ukraine to maintain exports, for example, through lack of access to ports on the Black Sea[70]. This is perhaps towards the more extreme (pessimistic) end of the likely outcomes for exports from the region. The range is sampled as a uniform distribution for the ensemble members of two scenarios where export restrictions are imposed (Supplementary Table 1).

The energy price shock in the relevant scenarios are implemented by three parameter changes, relating to fertilizer costs, management intensity costs and food transport costs. The fertilizer prices are constant in all scenarios until 2022, and remain at this level in scenarios with no energy shock. In scenarios with an energy shock, fertilizer prices are increased by 200% (Supplementary Fig. 1). This corresponds to a similar increase in observed urea prices[11]. The higher cost for fuel for farm machinery and transport is represented by an increase in management intensity (that is, inputs other than fertilizer and irrigation) and transport costs by 50%. These price increases are implemented as a scaling of the parameter probability distributions (Supplementary Table 1). All price increases were maintained until the end of the simulations in 2040.

Reporting summary

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

Data availability

Input data sources from the Food and Agriculture Organization (FAO; https://www.fao.org/faostat), World Bank (https://databank.world-bank.org) and the IIASA SSP database (https://tntcat.iiasa.ac.at/SspDb) are publicly available. The crop and pasture yield potential data from LPJ-GUESS are available on request from the corresponding authors. Source data are provided with this paper.

Code availability

The model code used is publicly available at https://git.ecdf.ed.ac.uk/lul/plumv2/tags/RussiaUkrainePaper. Full results files can be provided on request to the authors.

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Acknowledgements

Author contributions

P.A. conceived of the idea, and all authors contributed to scenario design. P.A. developed the model and analysed the data. J.M. developed Fig. 1. All authors reviewed the results and developed the main conclusions, as well as drafting and approval of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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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	Only secondary data was used as inputs to the model simulations. No software was used for data collection.
Data analysis	The model code used can be found at https://git.ecdf.ed.ac.uk/lul/plumv2/tags/RussiaUkrainePaper

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Input data sources from FAO (https://www.fao.org/faostat), World Bank (https://databank.worldbank.org) and the IIASA SSP database (https://tntcat.iiasa.ac.at/SspDb) are publicly available. The crop and pasture yield potential data from LPJ-GUESS are available on request from the corresponding authors, due to large data size. The model code used is publicly available at https://git.ecdf.ed.ac.uk/lul/plumv2/tags/RussiaUkrainePaper.

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All studies must disclose on these points even when the disclosure is negative.

Study description	Model simulation study of events on global food system of higher energy prices and export restrictions from Russia and Ukraine.
Research sample	Monte Carlo sampling approach on model parameter probability distributions.
Sampling strategy	Sample size of 30 ensemble members for each scenario
Data collection	Only secondary data was used as inputs to the model simulations.
Timing and spatial scale	Model simulation run until 2040 with global spatial scale at 0.5 degree grid resolution.
Data exclusions	None
Reproducibility	Model runs are reproducible giving same scenario setup.
Randomization	Parameters spaces was sampled randomly using a Monte Carlo approach
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