






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The Russia-Ukraine war decreases food affordability but could reduce global greenhouse gas emissions

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The Russian invasion of Ukraine has the potential to exacerbate food insecurity around the world, as both countries are major exporters of grains and other agricultural products. In this model-based scenario study, medium-term effects of the war are quantified on agricultural production, trade flows, market prices, food security, land use, and greenhouse gas emissions. The scenarios assess the possible consequences of macro-economic and agricultural production impacts in Ukraine, trade sanctions against Russia, and conflict-related energy price developments for global trade, food security, and greenhouse gas emissions. From a food security perspective, we conclude that there is enough food on the global level, but higher food and energy prices cause problems for low-income populations, spending a large part of their income on staple foods. Agricultural production and area expansion in parts of the world other than Ukraine and Russia could pose a risk to biodiversity and lead to higher greenhouse gas emissions related to land. However, total greenhouse gas emissions might decrease as lower emissions from less use of fossil energy due to higher energy and fertilizer prices in the whole economy dominate additional emissions resulting from land use change.

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The Russian invasion of Ukraine on February 24, 2022, led to rapid and substantial price increases in international grain and oilseed markets and has increased acute food security concerns in many parts of the world^{1–3}. Ukraine and Russia—which together exported 28% of wheat, 16% of maize, 65% of sunflower oil, 23% of sunflower seed and 13% of rapeseed of the world volumes in 2020—mainly supply low-income countries in the Middle East and Africa with these essential food commodities. Bread prices already rose sharply in the months after the start of the conflict in these import-dependent countries^{2,3}. Energy and fertilizer prices, already rising before the start of the war, were further pushed up by the conflict, leading to higher agricultural production costs with possible consequences for harvests in the coming years. While many analyses of the impact of the conflict for food markets focus on short-term and net-import country specific effects^{4–7}, on global effects of one commodity⁸, on various agricultural product⁹ or on longer term agricultural products¹⁰, none of the studies until now provides global longer-term economy-wide perspective of the Russian invasion into Ukraine. This becomes highly relevant as evidently the conflict still continues, and insights are needed into what extent this war will affect global food security and related climate and environmental consequences for years to come.

This study addresses these issues by simulating medium-term impact of the conflict – i.e. two years after Russia's invasion into Ukraine on the 24th of February in 2022. The contribution of this study is that it incorporates circular flows of income and expenditures which are important from a food access perspective. Most model-based studies on food security impacts report only food availability¹¹, but food security is a much more complicated issue, and understanding its future requires insights into income distribution, purchasing power, political processes, and institutional change^{12,13}. In this study we include food access, which is highly relevant to the expected price increases due to supply constraints due to the war. For access to food both income and expenditures of various labour types are important, and especially the income side is ignored in studies evaluating the impacts of the conflict on food markets to date.

In addition, we add an integrated land-food-fertilizer-energy perspective which is important to cover relations between agricultural and energy sectors. The consequences of negative production shocks in Ukraine and Russia are transmitted through trade relations around the world and are central to our analyses. Fertilizers are energy intensive and a key input for agriculture. Given that Russia is an important exporter of Nitrogen (N), Phosphorus (P) and Potassium (K) fertilizers¹⁴, fertilizers play a pivotal role in channeling the impacts of the war across the world. By capturing the land-food-fertilizer-energy nexus, this study provides an economy-wide perspective on greenhouse gas (GHG) emissions coming from land use expansion and other sources, such as energy savings and substituting fossil-based by renewable energy sources. Agricultural land use expansion is also a key driver of biodiversity¹⁵. It is thus possible to evaluate potential trade-offs between food security and environment provoked by the Ukraine-Russia conflict and obtain a holistic picture of its impacts.

Where most previous studies are based on expert judgments, sector-specific or country models, this study uses a computable general equilibrium (CGE) model, that allows us to consider economic and environmental impacts of the conflict in an economy-wide analysis framework. The application of CGE models to analyse to medium-term economic shocks has also been used in case of the Covid-19 pandemics^{16–21}. In this study, we use the agricultural and bioeconomy focused Modular Applied GeNeral Equilibrium Tool (MAGNET) model that integrates the food, fertilizer and energy markets on a global scale, embeds

bilateral trade-flows and includes circular flows of income and expenditures for various labour types^{22–24}. The model explicitly represents N, P and K next to detailed agricultural and energy markets²⁵ and it is characterised by segmented labour markets between agricultural and non-agricultural markets acknowledging that workers in agriculture cannot easily move to find a job outside agriculture. Food availability, which includes all domestically produced and imported food available for consumption at household level, is measured in kcal per capita per day^{26–28}. Food access relates to people's food purchasing power and therefore to food prices, dietary patterns, and income developments²⁸. This study uses the 'food purchasing power' indicator, by relating price developments of a specific food consumption basket to income developments of a particular income group.

Furthermore, we determine environmental impacts by looking at agricultural land use and GHG emissions. Agricultural land use is an important environmental indicator as land use expansion for agriculture may lead to deforestation, forest degradation and concurrent losses in carbon stock and biodiversity¹⁵. GHG emissions are influenced by the war in various ways as on the one hand land use expansion in other parts of the world might lead to higher emissions as carbon is released into the air and on the other side higher energy and fertiliser prices lead to energy savings and substitution away from fossils fuels to renewable energy sources, and therefore to lower GHG emissions. While agricultural focused studies^{9,10} include the agricultural land use related emissions, such studies ignore the potential saved GHG emissions in the rest of the economy due to higher energy prices.

Based on a scenario-analysis this study estimates the possible medium-term effects (i.e., effects for the next two years) of the war on agricultural production, trade flows, market prices, food security, land use and GHG emissions at national levels, presenting impacts on different regions of the world and in some low-income countries that are heavily dependent on wheat, other grain and oilseed imports.

Ukraine conflict's contribution to food security. In this study we formulate seven scenarios to estimate the impact of the war between Russia and Ukraine on international food markets. Each of these scenarios consists of assumptions, some of which reflect consequences of trade sanctions against Russia already announced by Western countries in the first months after the start of the war. Note that our assumptions about expected impacts on the economy and agricultural production in Ukraine and Russia are based on sources available up to June 2022.

The scenarios are divided into three blocks to distinguish between:

1. The effects of the war in Ukraine resulting from a trade blockade between Ukraine on the one hand and Russia and Belarus on the other, extended to lower GDP and reduced agricultural production in Ukraine, and higher trade costs for exports from this country;
2. The economic impact of Western countries trade sanctions against Russia, lower GDP in and potentially reduced trade by Russia in cereals and oilseeds due to productivity decline and logistical problems;
3. The effects of a global increase in energy prices, since the day of invasion.

All scenarios are constructed in order, with each scenario retaining the assumptions of the previous scenario and then adding further assumptions to this scenario. By doing this, we isolate the impact of each set of model shocks and assumptions under (1), (2), and (3). This allows us to identify the largest impact on world food market prices and food security indicators.

Table 1 Scenario description, assumptions and implementation.

Scenario	Description of scenario	Assumptions and model implementation:
Ukraine impacts (Scen 1)	1a: Ukraine’s trade halt with Russia and Belarus 1b: 1a + Ukraine’s loss in production and GDP	Tariffs rise to reduce trade with 90% for all commodities A GDP loss of 33% is assumed (based on OECD ²⁹ , IMF ³⁰ and World Bank ³¹). This is achieved by a reduction of labour and capital with 30%, land yields with 50%, and population with 10%. Transport costs between Ukraine and rest of world rise 20% (assumption).
Ukraine and Russia impacts (Scen 2)	1c: 1b + Ukraine’s additional transport cost with rest of world 2a: Scen 1 + US & EU trade sanctions against Russia. 2b: 2a + Russia’s loss in GDP	US and EU tariffs rise 90% (or a converted %) in Russia for finance, aviation, water transport, energy, telecom, defence, iron & steel, high-end vehicle, fashion & art; also a 90% increase on US import tariff on Russian fish & seafood, alcoholic beverage, non-industrial diamond, coal, oil, LNG ^a . Real GDP in Russia falls 10% (based on OECD ²⁹ , IMF ³⁰ and World Bank ³¹). This is achieved by a reduction in total factor productivity (endogenous in this scenario and made exogenous for subsequent scenarios).
Ukraine, Russia, energy price impacts (Scen 3)	2c: 2b + Russia’s reduced exports on grains and oilseeds due to productivity declines and logistical problems. Scen 2 + world energy prices rise	Import tariffs (used as a proxy to model increased trade costs between Russia and the rest of the world) rise to reduce exports from Russia with 50% for wheat, other grains and oilseeds (assumption). Prices rise 20% in the world for coal, oil, and gas (assumption) ^b .

^aFor EU sanctions: <https://www.rvo.nl/onderwerpen/landen-en-gebieden/ruisland/sancties>, accessed on March 24, 2022; for USA sanctions: <https://www.skadden.com/insights/publications/2022/03/new-us-restrictions-impact-russia-related-imports>, accessed on March 24, 2022.

^bEstimated as a difference between the average Brent crude oil price level on 24th of February US\$92/Bbl - and US\$110/Bbl on June 17th 2022. (<https://tradingeconomics.com/commodity/brent-crude-oil>).

Firstly, this is true only of the aspects tested in the scenarios. Secondly, to determine which aspects are more important they need to be tested in isolation, as interaction effects could be important in the outcomes that are confounding with this additive approach. We did run all shocks in isolation and a comparison with the additive results show that the interaction effects are limited and therefore our additive results are a good indication of the importance of the shocks (see, Supplementary Methods, section additive versus isolated scenario set-up). The scenarios and their implementation are summarized in Table 1. A more elaborate description is given in the Method section and in the Supplementary Methods (Scenario set-up).

For the macroeconomic impacts, such as the expected negative impact on GDP for Ukraine and Russia, we rely on expectations based on OECD²⁹, IMF³⁰ and World Bank³¹. Sanctions and other trade impacts are achieved by introducing tariffs between the countries. Energy prices have risen sharply since June 2020 (Fig. 1), when the demand for energy fell sharply due to economic downturn due to strict covid measures. Energy prices increased in 2021 as the economy picked up after easing of covid measures and low stocks and deliberate policies by providers to keep prices at the same level kept supply tight (IEA report July and November 2021). Whether energy prices also increased in the months leading up to February 2022 due to the mounting military tension between Russia and Ukraine is plausible, but not identified as one of the factors that materially determined international energy prices according to IEA reports from 2021.

On the eve of the invasion day Brent crude oil was traded at US \$92/Bbl. In the first month after the start of the war, oil prices peaked at US\$127/Bbl only to fall again somewhat afterwards to stabilize around US\$ 110/Bbl in June 2022³². The latter implies a 20% increase in energy price since the eve of invasion day. This number is used in our energy price impact scenario as a proxy for the energy price increase due to the war, although also other factors might have contributed in this period. As we focus on the impact of war itself, we do not include the increase in energy prices before the war in our impact analyses but the level at the



Fig. 1 Development of world energy prices (Crude Oil Brent). The Brent Crude oil price (USD/Bbl) is a major benchmark price for purchases of oil worldwide. Source: <https://tradingeconomics.com/commodity/brent-crude-oil>.

day before the invasion is our starting point. As part of the energy price increase before the war might be due to Russia military tension, we performed a sensitivity analysis with the oil price of half a year before the start of the war (US\$76/Bbl, 24 August). The implied energy price doubles then to about 40% between 24th of August in 2021 and 17th of June in 2022). The results of this ‘double energy’ sensitivity analyses are described in the article and all the detailed quantitative results and graphs are embedded in the Supplementary Methods (results of high energy price sensitivity scenario).

We report model results on the impact of the scenarios on GDP, agricultural production, food exports and imports, world market prices, two food security indicators: food availability and food access, and two environmental indicators; land use change and GHG emissions. Results are presented for Ukraine, Russia and several countries that rely heavily on grain imports from Ukraine, Russia or both.



Fig. 2 Production volume developments. Production volume developments in percentage change (%) and in absolute change (million US Dollars) for wheat, oilseeds, and other cereals in the 'Ukraine, Russia, energy price impacts' scenario (scenario 3). Source: MAGNET results (data behind graphs are available in Supplementary Data 1).

Results

Overall economic impact. Due to the war GDP falls substantially in Ukraine and Russia, by 33% and 11% respectively in the period 2022-2024, but is limited in other countries (see, SI section additional results, Figure S3). Outside Ukraine and Russia, the impact on GDP is the strongest in Central Asia (-0.5%), a region of countries with strong trade ties with Russia. The increase in energy prices contained in Scenario 3 has the largest impact on the fall in GDP in all regions.

Impact on production. Figure 2 shows that in scenario 3 the decline in production in Ukraine and Russia is partly offset by additional supply from other regions, where production adjusts in response to higher world market prices. Production increases in other regions between 1% in Asia & Oceania to 11% in the rest of Africa. Most regions increase their production around 5% (EU, North America, Middle and South America, Middle East) to 7%-8% (Central Asia, North Africa). In scenario 1 and 2 world production of oilseeds and other grains falls slightly and that of wheat remains stable as relatively high wheat prices attract resources from other sectors. In scenario 3 that includes higher energy prices the production of oilseeds (especially in Rest of South and Southeast Asia, Asia and Oceania, and Middle and South America) even rises slightly due to additional demand for non-food applications such as biofuels. In scenario 1, production of wheat and other cereals increases in various regions of the world and slightly in Russia. Oilseed production grows mainly in Central and South America. If Russian effects are also included (Scenario 2), wheat production in Russia decreases substantially and production increases mainly in Central Asia, in addition to the regions where production also increases in the Ukraine effect scenario (scenarios 1 and 2 are depicted in SI section additional results, Figure S7 and Figure S8). The impact of the double energy price sensitivity scenario on production developments is limited, and only oilseed production is a bit higher due to increased demand from biofuels (See, Figure S14 in SI).

Impact on world market prices. International price impacts for primary products show a substantial rise of wheat, other cereals

(including maize) and oilseeds prices, of respectively 9.2%, 8.4%, and 5.0% (Fig. 3). This is due to several reasons. First, Ukraine's production fall in Ukraine impacts scenario leads to a substantial decline of the country's exports of wheat and other grains (i.e., maize), which impact world markets through its weighty global role of exporter of these commodities. Due to this decrease in Ukraine production and exports of wheat and other grains, world prices increase by, respectively, 2% and 4% (see Fig. 3, light blue bars). Oilseeds prices increase slightly less (1%) as Ukraine's share in world exports (of this product category) is less than for wheat and maize. Hereby, we have to remark that this is an aggregated category including key products for Ukraine such as sunflower seeds and oilseeds and less important products for Ukraine as soybean. The price effects for a specific product like sunflower seeds where Ukraine has a high market share will be higher. Second, Russia's decline of wheat, other grains, and oilseeds exports further exacerbates the impact on world market prices. Due to the Russia related shocks (scenario 2) wheat world prices are rising additionally by 4% and other grains world prices by an additional 1%. In both scenarios the prices of other crops increase as well due to higher production factor prices as the production of wheat and other grains in other countries (than Ukraine and Russia) expands. Especially land prices rise due to increased cereal production and demand for land. Third, increased energy prices (following the assumed 20% higher prices for coal, oil, and gas) in scenario 3 have a substantial impact on food prices; this scenario 3 adds 3-4%-points to global price increases for cereals and oilseeds. This is caused by higher energy and fertiliser cost in food production (production cost effect) and due to increased demand for biobased products (demand effect) for energy purposes, as the competitiveness of bio-based substitutes increases due to higher fossil energy prices. In the double energy price sensitivity scenario, wheat prices increase with an additional 3% to 11% and oilseeds and other cereals (including maize) increase with an additional 2.5% to 8%, and 12% respectively (See, Figure S15, in SI). The latter increase is higher as it includes additional biofuel demand.

Fertiliser price effects show to be strongly affected by our assumed energy price increase (implemented as an exogenous shock to the model). Fertiliser prices increase especially due to

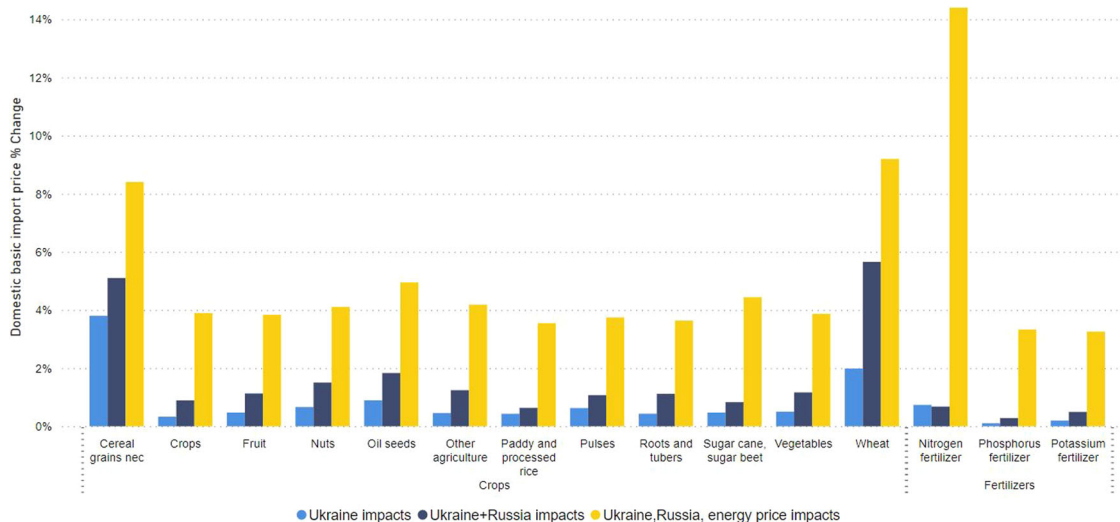


Fig. 3 Development of world crop and fertiliser prices. World crop and fertiliser prices developments (% change) in the ‘Ukraine impacts’, ‘Ukraine + Russia impacts’, and the ‘Ukraine, Russia, energy prices impacts’ scenarios. Source: MAGNET results.

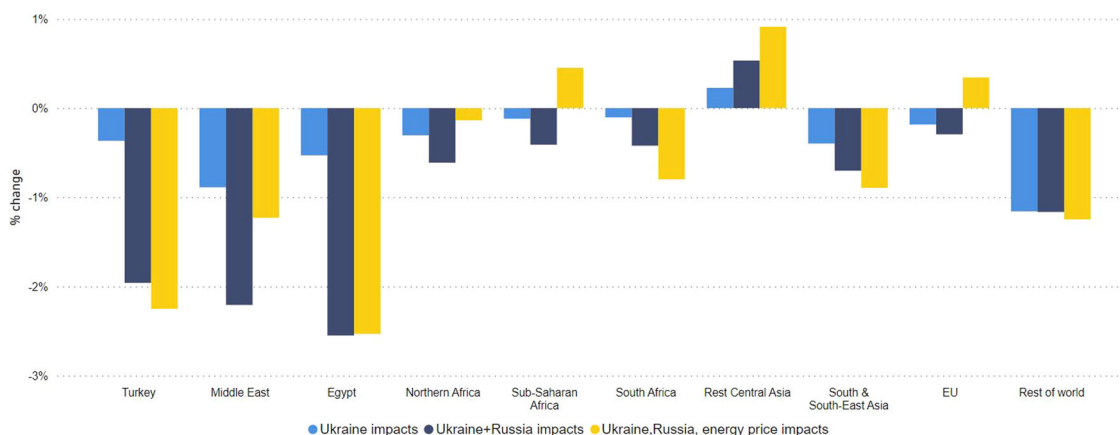


Fig. 4 Food availability developments. Food availability, which includes all domestically produced and imported food available for consumption at household level, is measured in kcal per capita per day, and depicted for the ‘Ukraine impacts’, ‘Ukraine + Russia impacts’, and ‘Ukraine-Russia-energy price impacts’ scenario. Source: MAGNET results.

higher energy prices in scenario 3. Nitrogen prices increase a lot as the production process uses a lot of gas. When gas prices increase by 20%, the fertiliser (nitrogen) prices go up by almost 14%. The increase in phosphorous and potassium prices are more modest with about 4% in scenario 3. In the double energy price scenario nitrogen prices almost double from 14% to 27% (See, Figure S15, in SI).

Impact on food availability. Food availability is decreasing in most low-income countries due to less supply from Ukraine and Russia (Fig. 4). The impact is the largest in Egypt, Turkey and the Middle East, as these regions rely heavily on imports from Ukraine and Russia. Russian export reductions on top of Ukraine’s reduced production and exports (scenario 2) greatly reduce the substitution and adjustment possibilities of import-dependent countries, with major consequences for food availability in these countries. Food availability in Europe has changed marginally. In the Ukraine effect scenario 1, food availability decreases by 0.2% and by 0.3% in scenario 2. Food availability does not change in the double energy price sensitivity scenario for the rest of the world (See, Figure S16, in SI), except that it improves slightly for oil producing countries (Middle East, Sub-

Saharan Africa (Nigeria)) and worsens a bit for South Africa and South and South-East Asia.

Impact on food access. Access to food (represented by a food purchasing power index) deteriorates by about 3–7% (Egypt, Turkey and Rest Central Asia) in most low- and middle-income countries in the Ukraine-Russia-energy prices scenario (Scen 3) (See lower panel, Fig. 5). Cereal diet prices go up by 5–10% and increase more than the wages of unskilled workers as they remain constant (Turkey, South Africa) or increase up to 4% (Egypt, Middle East, Sub-Saharan Africa). Wages in Egypt, Middle East and Sub-Saharan Africa (SSA) go up due to increased (oil) revenues due to higher energy prices (Nigeria is part of SSA). Higher food prices for cereals are the main reason for a substantial decrease in access to food in case poor people’s diet consists mainly of cereals. World market price increases for wheat and other cereals are directly translated into reduced access to food, since the wages of unskilled people increase less than cereal prices. For consumers who have a more varied diet with fewer cereals, whose prices are rising the most, the impact on food access is smaller. For the EU, for example, cereal prices rise by 4% and, given the relatively low proportion of income spent on food, this should not be a problem for the average citizen. However,

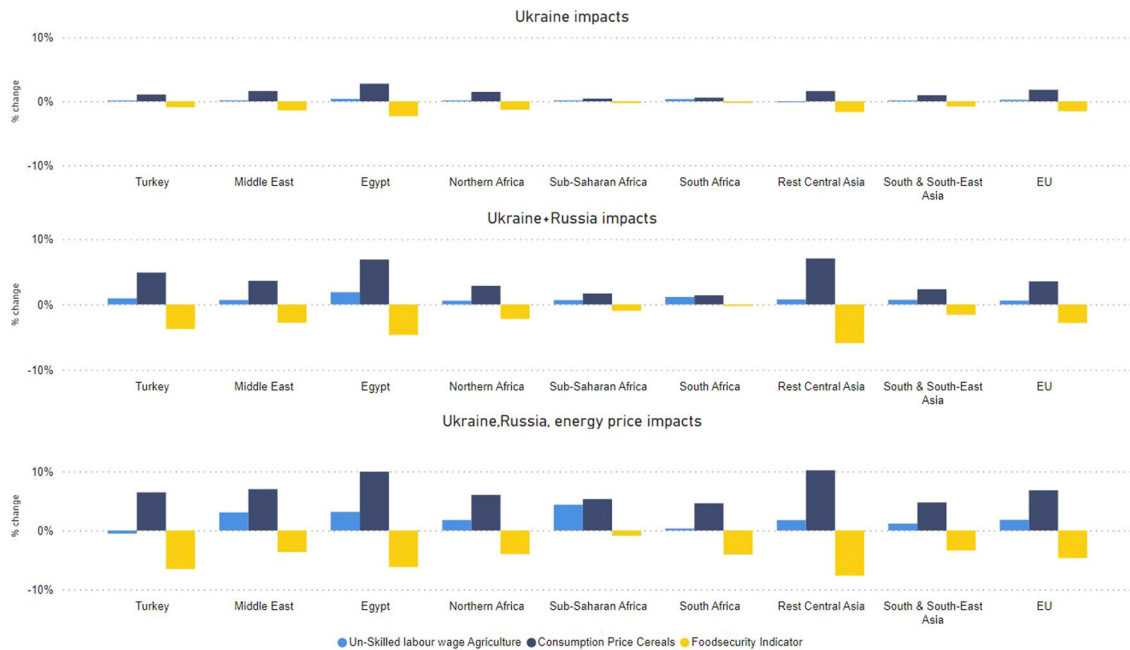


Fig. 5 Food access developments. Food access is measured by a food purchasing power index based on a cereal diet (including paddy rice, wheat and 'other grains') for unskilled (production) workers in the agricultural sector. Scenario results are presented for the 'Ukraine impacts', 'Ukraine + Russia impacts', and the 'Ukraine, Russia, energy prices impacts' scenarios. Source: MAGNET results.

higher food prices in combination with higher energy prices may reduce access to food for some low-income groups in the EU. In the double energy price scenario, the food purchasing power index deteriorates close to 10% for many countries due to the higher increase in cereal prices and the relatively unchanged unskilled wages in agriculture (See, Figure S17, in SI).

Impact on environment: Land use and GHG emissions

Impact on Agricultural land use. Land use is an important indicator of environmental impact. In the Ukraine impact scenario production declines in Ukraine cause agricultural land use to expand in the rest of the world with 6.2 Mha. The expansion is due to higher agricultural prices which induce higher production and therefore higher demand for land. Depending on the scarcity of land in a region this leads to higher land prices and/or land use expansion. Higher land use prices induce substitution effects away from land using more labour and capital and thereby increasing the yields (See, methodological section and Supplementary Methods (Model definition)). The land expansion is therefore highest in Middle and South America and in Rest of Africa where land area expansion possibilities still exist. In the Ukraine-Russia impact scenario land use in Russia decreases (8 Mha) and it expands in Middle and South America (3.5 Mha) and Rest of Africa (2.3 Mha) with an overall (net) increase of 2 Mha at world level. With higher energy prices (the third scenario) land use expansion is higher in all regions leading to an expansion of 6.6 Mha at world level. This increase in global agricultural land use is a bit lower than the findings of 11 Mha of Carriquiry et al.⁹, but much lower than the 227 Mha increase in the Alexander et al.¹⁰ study. The latter study uses much higher energy and fertilizer shocks as their analyses covers a longer period and includes the substantial energy price increases in the period before the war. A key driver for agricultural land use expansion is that higher energy prices lead to higher fertiliser prices (See, Fig. 3) and therefore less fertiliser use, which leads to lower yields and an upward pressure for land demand. Additionally, there is greater incentive for bio-energy sources to

replace fossil fuels which further drives demand for agricultural land. As land use is one of the main indicators of biodiversity and land use expansion for agriculture in general has a negative impact on biodiversity, the Ukraine war increases risk for biodiversity loss¹⁵. Global agricultural land use increases with 3 Mha in the double energy price sensitivity scenario to 10 Mha, as especially agricultural land uses expand a bit more in Middle and South America from 5 Mha to 6 Mha (See, Figure S18, in SI).

Impact on GHG emissions. Regarding the GHG emissions we separate the change in emissions related to land use change from all other sources included in our modeling framework as agricultural land use expansion in other parts of the world (see Fig. 6) is the key source of increasing emissions in previous studies. Land use emissions in the 'Ukraine impacts' and the 'Ukraine+Russia impacts' scenario increase with 0.6 Gt CO₂e and 0.2 Gt CO₂e, respectively (Fig. 7, dark blue bars). The total 6.6 Mha global land use expansion in the 'Ukraine, Russia, energy price' scenario (Fig. 6) leads to a substantial increase in land use related emissions of 0.6 Gt CO₂e which is lower than the 1.0 GT CO₂e result in Carriquiry et al.⁹.

The economy-wide modeling framework embeds various GHG emissions such as fossil energy related CO₂ emissions in all sectors of the economy and methane (CH₄) emissions related to, for example, animal and rice production (see, methodological section and the Supplementary Methods (Model definition)). Figure 7 illustrates that these emissions (light blue bars) are slightly negative in the 'Ukraine impacts' and the 'Ukraine+Russia impacts' scenario due to especially lower animal production. Overall, the total emissions go up in these scenarios, as the increase in agricultural land use related emissions is higher. In the 'Ukraine, Russia, energy price' scenario the higher energy prices lead to substitution away from fossil energy sources and to less demand for fossil energy intensive products due to relatively large price increases of these products. Figure 7 shows that therefore in the 'Ukraine, Russia, energy price' scenario these GHG emissions decrease in all regions, and especially Asia and Oceania, which include China. Higher fossil energy prices reduce

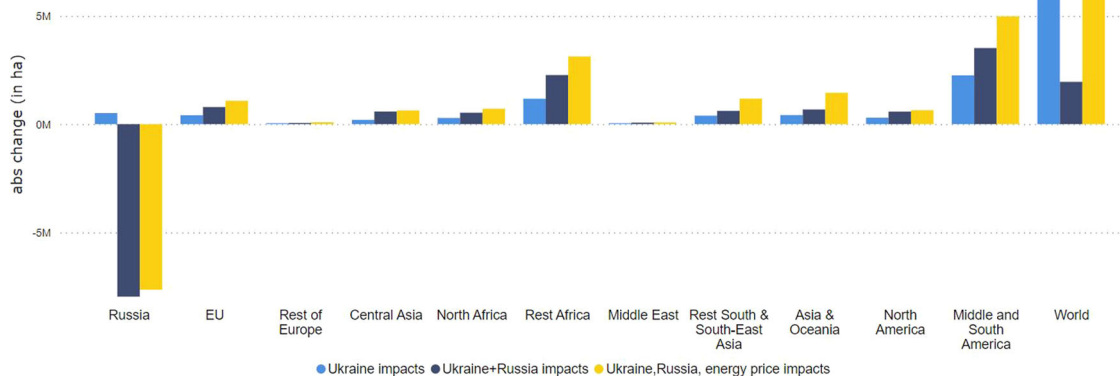


Fig. 6 Agricultural land use developments. Global and regional agricultural land use developments (absolute changes in ha) in the ‘Ukraine impacts’, ‘Ukraine + Russia impacts’, and the ‘Ukraine, Russia, energy prices impacts’ scenarios. Source: MAGNET results.

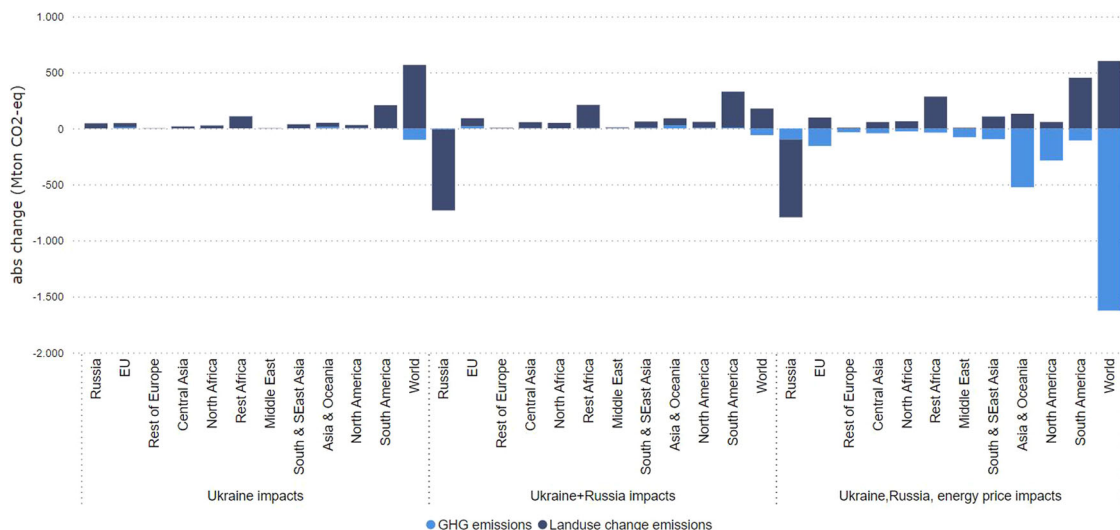


Fig. 7 Developments of GHG emissions. Developments of regional and global GHG emissions due to land use change (dark blue) and all other sources, such as changes in fossil energy use and animal production (light blue), in Mton CO₂-equivalent. Source: MAGNET results.

GHG emissions with 1.6 GT CO₂e at the global level. The reduction is by two thirds caused by lower emissions in the production and one third by lower emissions in the consumption of commodities. The lower production emissions of 1.1 GT CO₂e are achieved in the fossil energy sectors (0.62 GT CO₂e), transport (0.45 GT CO₂e) and manufacturing (0.04 GT CO₂e). On the consumption side, the consumption of gas is especially reduced by 11%. Overall, the total GHG emissions decline in this scenario as GHG savings 1.6Gt CO₂e are higher than the additional land use related emissions of 0.6 GT CO₂e. This is true for almost all regions except for South America and Rest Africa where land use related GHG emissions still dominate the other emissions. The land use related emissions are also higher than in other scenarios in South America as the higher energy prices lead to an increased demand for biofuels and therefore land use expansion. In the double energy price scenario land use related emissions increase from 0.6 GT CO₂e to 0.9 GT CO₂e and other GHG emissions decrease from -1.5 Gt CO₂e to -2.9 Gt CO₂e leading almost to a doubling of the decrease in GHG emissions from 1 GT CO₂e to 2 GtCO₂e (See, Figure S19, in SI).

Discussion

The absolute number of hungry and poor people (around 720–811 million people) has increased globally since 1990^{33,34}.

War and conflicts are the main drivers of food insecurity and hunger in the world³⁵. Two thirds of people that are acutely food insecure are living in 23 countries where war and conflicts were the main reason for food insecurity³⁴. They also estimate that, therefore, 47 countries are expected not to reach the United Nations zero hunger goal³³. The Russia-Ukraine war drove up the already high food prices, which were mainly driven by growth in population, income, and COVID³⁶. Higher food prices reduce food affordability and real income and can have severe implications on food security.

This study shows that the Ukraine-Russian conflict does not threaten food availability on the global level. The study emphasizes the global response of production and use and their impact on international grain and oilseeds markets as a result of the war. The strong decline in production and exports of grain and oilseeds in Ukraine and the decline in exports from Russia are largely offset by growing production elsewhere in the world and by substitution of wheat and other cereals with other food and feed products. However, net importing countries, especially those relying heavily on grain and/or oilseed imports from one or both warring countries, will pay more for imports, putting pressure on food availability and food access, especially for the poorest part of the population. These outcomes are dependent on assumptions in the model and on the scenario in which the course of the war and therefore its consequences for the food markets are highly

uncertain. Uncertainties are the length of the war, the part of production that is affected by the war and whether production can still be exported from Russia and Ukraine. Should the war situation continue, the consequences for the international food markets could be greater, although also larger production responses will be observed in the rest of the world. The estimated price impact (8%) for wheat is at the lower end of the price range estimated by FAO¹⁴ in which wheat exports from Ukraine and Russia fall by 25 million tons per year, other grains by 5 million tons and oilseeds by 3 million tons. The FAO scenario leads to 8–22% higher food and feed prices in the short term (in 2022/23 compared to baseline) and after five years (2026/27) to 10–19% higher wheat prices compared to baseline. Mottaleb et al.⁸ estimate that 50% reduction of Russia and Ukraine wheat exports could increase domestic prices by 15%. Carriquiry et al.⁹ find that reduced exports and production increase wheat prices by 7%. Our global price results are at the low end of these findings, and this can be explained by our longer period and because our CGE analyses allow for more substitution possibilities on the production and consumption side²⁵. Furthermore, Ukraine and Russia are both important suppliers and exporters of fertilisers (potassium, phosphorus and nitrogen)^{14,25}. The high fertiliser prices (14% up in case of nitrogen) caused by higher energy prices put more pressure on the food markets as nitrogen is an important source for high yields (essential for high protein wheat and therefore bread). Higher energy prices of 40% instead of 20% do not have a large effect on agricultural production, but induce especially higher fertilizer and food prices, which have especially a negative effect on food access and land use expansion.

With regard to the effects of the war on international food market prices, it should be borne in mind that prices of major food commodities already showed an upward trend in the course of 2020, which continued in 2021 (see also FAO³⁴). The increase of international food prices was mostly due to market conditions but also due to the high prices of energy, fertilizers and other agricultural inputs and services caused by an increase in demand resulting from recovery plans aimed at countering the recession triggered by the COVID-19 pandemic¹⁴. The consequences of the war for prices on the international food markets, as they manifested themselves in the first months after the Russian invasion, thus came on top of the historically relatively high price levels. World food prices appear to have peaked in late May 2022, when international prices for wheat and other key food commodities fell due to good summer harvests in some key grain-producing countries (Canada, Australia), followed by the Black Sea Grain Initiative, which in part has resumed exports through Ukrainian ports from August 2022. While this initiative is a positive development, the situation in Ukraine and the status of agricultural exports remains uncertain. Carriquiry et al.⁹ stress that the attack on the port of Odesa or, potentially, mines in the Black Sea have made grain shipments expensive and far below normal (less than 0.4Mt). In addition, countries (such as India for wheat and Indonesia for palm oil) have lifted export restrictions they had previously imposed in an attempt to stabilize their domestic price levels in response to rising international prices (for an analysis of these export restrictions on the international market³⁷). Thus, market and policy responses have contributed to the drop in international prices in June–August 2022 and thereby easing pressures on global food security.

Countries highly dependent on grain imports such as Turkey, Egypt, Pakistan, Sudan, and Tunisia have limited possibilities to expand wheat production due to the often short and (too) dry growing seasons and the limited water availability in these countries. Irrigated cultivation, preferably in combination with drought-resistant seeds, can boost production^{38–40}, but requires quite a bit of investment that, if made at all, may only contribute

to a greater degree of self-sufficiency in the longer term. For the time being, these countries will therefore remain dependent on imports and price fluctuations on the international markets will feed through to domestic food prices.

Countries such as Egypt, Turkey and those in the Middle East may have the institutions, capabilities and financial resources to access global supply sources other than Russia and/or Ukraine to stabilize domestic prices, but remain vulnerable to price increases on international markets if, at the same time, their own currencies depreciate against the dollar; this is what has happened in recent years in among others Egypt, Tunisia and Turkey and what has happened in the first half of 2022 too. The food security of import-dependent countries is therefore determined, in addition to price fluctuations on the world market, by the weak competitive position of a country, which is reflected in the development of its currency exchange rate.

In line with studies that investigate environmental effects of the Russia-Ukraine conflict, this article confirms that global agricultural land use expansion leads to more GHG emissions (0.6GT CO₂e), which is expected to increase the risk for biodiversity loss. Our economy wide study, in contrast to studies that focus on the agricultural sector only, enables also to calculate the GHG impact on the rest of the economy (1.6Gt CO₂e); this is relevant as higher fossil energy prices are likely to induce substitution effects towards renewable energy and using energy saving technologies. Our results show that the overall impact on GHG emissions of the war is positive as overall GHG emissions decrease with 1 GT CO₂e in the 20% energy price increase scenario and with 2 GT CO₂e in the 40% energy price increase scenario. As global GHG emissions were about 36.8 GT CO₂e⁴¹, the GHG savings are 4% in the 20% energy price scenario due to less use of fossil energy and 2.5% overall reduction including the higher land use emissions. This might be seen as considerable given empirical evidence in the past⁴². However, IEA⁴¹ states that CO₂ growth in 2022 was well below global GDP growth of 3.2% and equal to 0.9%. Energy price shocks and disruptions to traditional fuel trade flows were identified by IEA as key drivers for this result and increased deployment of clean energy technologies helped prevent an additional 550 Mt in CO₂ emissions. Furthermore, industrial production curtailment, particularly in China and Europe, also averted additional emissions⁴¹. These findings are in line with our scenario results, given that in this paper we use a comparative static analysis for the war specific shocks and do not include the overall economic GDP growth of 3.2%. The scenario results indicate, for example, that the GHG emissions decline relative to GDP, renewables contribute to the decrease in emissions, and emissions will be lower in especially China (Asia & Oceania) and EU. We find also that different substitution elasticities in the energy sector and different energy prices both affect the land use and the fossil related emissions in a broadly similar order of magnitude. Therefore, we argue that our finding that the increase in land use emissions is lower than the decrease in emissions associated with reduced fossil fuel use is not very dependent on these substitution elasticities and energy price uncertainties.

On Policy recommendations: The findings of this study warn the consequences of the ongoing armed conflict between Russia and Ukraine including reduced food affordability. Given the already high number of acute food insecure countries these developments worsen the situation in especially wheat and other cereals, importing countries and lead to violence and social unrest, as was the case during the 2005–2007 food crises³⁵. In the short-run international donor organizations should provide affordable substitutes for wheat and other cereals in poor import-dependent countries. In the longer term, net grain-importing countries need to build resilience to mitigate the effects of

subsequent international market disruptions. Policy measures to consider are, for instance, (increased) investment in roads and other market infrastructure (to reduce transaction costs and improve the functioning and efficiency of markets), and additional research and expansion efforts to increase the production of (drought-resistant) alternatives to wheat production to build resilience through diversification of their agricultural production portfolio. Market prices should guide production decisions in wheat exporting countries (e.g., China, India, USA, Canada, France, Argentina, Pakistan, Germany). Regarding food access income support or food safety nets might increase the food purchasing power of consumers. In many developed countries consumers are compensated for higher energy and food prices. This is not the case in many developing countries, where food access problems are most severe, as income support has large government budgetary consequences. For national governments and international donors' social security programs are essential policy tools to support poor people in food insecure countries.

An important insight has been with respect to the trade-offs between food security, climate change and biodiversity. The war conflict influences primarily negatively food security, but it also has potential negative consequences on biodiversity. The impacts are however geographically heterogeneous, while in case of food security, food net-importing countries are affected the most (e.g. Egypt, Middle East and Turkey), in case biodiversity, these are the land-abundant countries where production potential exists to compensate for food shortages on the international markets (e.g. Latin America). Different regions of the world are thus expected to suffer with different sorts of impacts (high social unrest vs biodiversity related risks). From the climate perspective the war conflict could be seen as stimulator of green transition and climate change mitigation. It is also apparent that using more biobased mitigation options to replace fossil energy based options leads to land use expansion and can therefore increase the risk for biodiversity loss⁴³. To prevent a higher risk for biodiversity loss land use conservation management will be important but this will create pressure for food¹⁵. All these trade-offs should be considered when assessing the impacts of economic shocks in general. Therefore, carefully selected policy bundles will be required to meet various policy targets.

Limitations: This study presents plausible ranges from Ukraine, Russia and energy prices impacts to give sense of production, price and food security impacts given the unknown outcome and end of war. Our analysis is not a short-term analysis but focusses on the medium term. The application of CGE methodology to analyze the impact of economic shocks provides several valuable insights but it also comes with a caveat as it assumes that markets have found a new equilibrium based on rational behaviour of all agents. It could be argued that in the short term, people do not behave rationally, and it is not easy to substitute produce from one region to another or shift cultivation from one crop to another but in the longer term this is possible. Therefore, the results thus indicate more permanent impacts after the initial deviations from equilibrium are resolved, and do not mimic short run developments. More short run developments are discussed in Carriquiry, et al.⁹ and Alexander et al.¹⁰. We assume that countries can respond given normal circumstances, but they might be constrained due to, for example, droughts as happened last year in South America. In case of droughts in major producing countries the increase in food prices will be higher. Regarding the assumptions we used crude oil prices as the point of reference and these analyses could be enhanced by taking additional assumptions on, for example, gas prices as these are important for fertilizers. With regard to the latter, a challenge is that gas price developments are much more local and dependent on local country specific (tax) arrangements. Food security is a

complicated issue and although we include food access or food affordability, the other two dimensions of food security, within the FAO definition^{44,45}, food utilization and food stability are not covered in this modeling study. For the food utilisation dimension the explicit modelling of micro and macronutrients at household level is needed in combination with clear guidelines of healthy diets. To better address food access, an explicit household dimension, covering both income and food expenditures at specific household level, is needed within the modelling framework. This provides insight into the distribution of food access among specific households, as more aggregated households might hide food access problems for specific households and therefore our analyses might understate its prevalence. Combining CGE analyses with household level micro-simulation models could enhance these analyses. To enhance the environmental impact linkages with spatial explicit land use models and specialized biodiversity models would provide more accurate and a broader range of results^{10,15}. However, as land use expansion is a key driver in biodiversity model the impact of the war on biodiversity will likely remain negative. To better understand the impacts of the war it is important to complement this study with indebted country case studies. In the CGE analyses we were limited in this regard as some food insecure and import-dependent countries in the Middle East and Africa are aggregated into regional groups. Country studies⁵⁻⁷ enrich the impacts of the Ukraine war and enable extra and distinct perspectives.

Methods

The Modular Applied GeNeRal Equilibrium Tool (MAGNET) model is a multiregional, multisectoral, applied general equilibrium model based on neoclassical microeconomic theory with a focus on the bioeconomy^{22,24}. It is an extended version of the standard Global Trade Analyses Project (GTAP) model⁴⁶. A distinguishing feature of MAGNET is its modular structure, allowing the model to be easily tailored to specific research questions, regions, and products of interest. As a global Computable General Equilibrium (CGE) model MAGNET covers the entire global economy, with extensions adding detail on food and biomass production and use not available from other CGE models. The core of MAGNET is an input-output model, which links industries in value-added chains from primary goods, over continuously higher stages of intermediate processing, to the final assembly of goods and services for consumption. Primary production factors are employed within each economic region, and hence returns to land and capital are endogenously determined at equilibrium, that is, the aggregate supply of each factor equals its demand. On the consumption side, the regional household is assumed to distribute income across savings and (government and private) consumption expenditures according to fixed budget shares. Private consumption expenditures are allocated across commodities according to a non-homothetic constant difference of elasticity expenditure function, and government consumption according to Cobb–the Douglas expenditure function. Modules relevant for the current study are the flexible nested constant elasticities of substitution (CES) production trees (allowing for more substitution possibilities than in the standard GTAP model, for example, energy sources and animal feed components). A key component for this Ukraine study is the treatment of land markets. Land supply is endogenous and allows land areas to expand and contract depending on demand and scarcity of the land endowment⁴⁷. In land abundant countries (e.g. Middle and South America) additional demand leads especially to land use expansion while in land scarce countries additional demand leads to higher land prices (See, Supplementary Methods (Model definition)). On the land demand side, land heterogeneity is introduced

by flexible nested Constant Elasticities of Transformation (CET) land allocation functions govern the movement of sluggish land across sectors depending on the ease of switching between different types of land use.

The MAGNET flexible production tree set up enables a modified treatment of energy demand, energy-capital and inter-fuel substitution, carbon dioxide accounting and taxation, since it has been specifically designed to be used in the context of greenhouse gases (GHG) mitigation policies^{48–51}. Energy inputs are combined with capital to produce an energy-capital composite; the latter is combined with other primary inputs in a value-added-energy composite. Energy use is split into fossil-based energy (gas, coal and nuclear) and fossil-based heat on the one side and renewable energy (wind, hydro and biomass) and bio heat on the other side. The detailed sector information for both electricity and heat enables a transition from fossil based to renewable (bio)economy. First and second-generation biofuels for road transport and aviation biofuels, biochemicals (bio plastics, bio pharmaceutical and biochemicals and innovative sectors like pe and pla bioplastic sectors) are introduced into the model, along with their directive targets for blending with fossil fuels^{23,52}. An emissions module calculates emissions of GHG gases – CO₂, N₂O and CH₄. Both combustion and non-combustion emissions are included in this accounting. Emissions can be tracked by gas type, fuel type, emitting sector and region. In addition to accounting for emissions, carbon taxes and marginal abatement curves (the possibility of switching to a lower emission intensity (if such option is technically feasible) because of e.g. carbon taxes). Land use expansion emissions are calculated based on mean carbon coefficients from Carriquiry et al.⁹ which implies that the additional 0.09 Gt CO₂e per Mha.

The ‘food purchasing power’ indicator, is calculated by relating price developments of a specific food consumption basket to income developments of a particular income group. We define (%) changes in food purchasing power as % change in income of specific income group minus % change in the price of a food basket. For the food basket, consumption of cereals (including paddy rice, wheat and ‘other grains’) is used as a proxy for the diet of less wealthy people, as rice is an important food component for poor people in Asia, while grains are important in Africa²⁴. Changes in the wages of unskilled (production) workers in the agricultural sector are used as a proxy for the income component of poor people.

Other features are a purchasing power adjusted constant difference of elasticity (CDE) demand function (adjusting income elasticities in baseline projections to attain a more plausible pattern in food demand when incomes rise substantially), and segmentation and imperfect mobility between agriculture and non-agriculture labour and capital are introduced in the modelling of factors markets (capturing diverging labour and capital price developments in agricultural and non-agricultural sectors). As MAGNET, like many other CGE models, in its default setting is specified for a medium-term impact (around five year) to long term impact. The default setting is reflected in various model specifications including parameterizations. To enable the model suitable for capturing certain short to medium term responses, we have made certain changes in the model settings. We add rigidity to the production system to as the requested time frame of two years is shorter than the normally considered adjustment period within this kind of analysis, by reducing the standard substitution elasticities between production factors by 50% relative to the level of the original GTAP and MAGNET elasticities (especially substitution elasticities between inputs in the production of agricultural, food and energy industries, including the substitution elasticities between fossil and renewable energy sources for electricity production).

Scenario set-up. We estimate the impacts of the Russian-Ukraine conflict on international food markets by incorporating assumptions into a scenario in which we match some already known consequences of the conflict such as trade restrictions and sanctions that were announced by the EU and US in March and April 2022. We build up the scenario in three blocks, in which we distinguish between (1) the effects of the conflict in Ukraine that arise from a trade stop between Ukraine on the one hand and Russia and Belarus on the other, extended with lower GDP and reduced agricultural production in Ukraine, and increasing trade cost for exports from the country (2) economic impacts of sanctions against Russia, resulting in lower GDP of and reduced trade by Russia in cereals and oilseeds, and (3) effects of a global energy price increase. All the scenarios build upon each other, by including all elements of the previous scenario and at the end representing the whole impact. In this way we can assess the contribution of the various assumptions on the world markets and prices and assess which part of the storyline will have the greatest impact on global food market prices and food security indicators. The three scenario building blocks are the following.

1. Impacts in Ukraine on GDP, agricultural production, and trade costs. Scenario 1a is a ‘Trade stop between Ukraine and Russia & Belarus’ and is a starting point is the assumption that in the coming years there will be no or only very limited trade between Ukraine on the one hand, and Russia and Belarus on the other, due to current hostilities and the mutual animosity between the countries that may persist for years to come. Scenario 1b extends scenario 1a with ‘Production and GDP loss within Ukraine’. The war in Ukraine displaced a third of the country’s population from their homes, of which approximately 4 m (around 10% of the total population) fled abroad. In addition, many buildings and an important part of the infrastructure were damaged. Economic activities continue to come to a standstill in large parts of the country due to the constant threat of war for the time being. This has major consequences for the country’s output levels and income-generating opportunities. We assume the direct economic impacts of the conflict are caused by a 30% decline in labour and capital endowments, which results in a substantial GDP fall. Agricultural production in Ukraine suffers in the short term from the war situation due to insecurity in the countryside, lack of inputs and working capital, and a shortage of labour. By 1 April, analysts estimate the number of areas with spring-planted grains and oilseeds will be so much less than in 2021 that the estimated total production of grains and oilseeds in 2022 is expected to be 50% lower than the record level of the previous season⁵³. Due to war damage and expected ongoing difficulties in obtaining sufficient inputs, it is likely that agricultural production will continue to be substantially less than in ‘normal’ years for the time being. We simulate the agricultural production fall by assuming an overall 50% decrease in crop yields (production/hectare) during the simulation period, which will reduce Ukraine’s exportable grain and oilseeds surpluses. Scenario 1c adds ‘Additional trade Cost Ukraine’. Exports are further reduced by assumed additional trade costs of 20% due to infrastructural damages, harbour blockages and high-risk insurance costs of transported goods.
2. Impacts in Russia on GDP and agricultural exports. In Scenario 2a ‘Russian trade sanctions’ are added. The EU, UK, USA, Canada and several other countries have denied Russia access to the international payment system SWIFT and international bank loans. Moreover, Russian banks’

assets are being frozen in the US, UK, EU and Canada⁵⁴. These financial sanctions will affect the country's investments, exchange rate and, consequently, imports. In addition, restrictions on technology exports (particularly in the energy, telecom, aerospace, and defence industries) have been imposed by the EU, US and some other countries that have macroeconomic implications. Scenario 2b adds 'GDP reduction Russia' following the expectations of various international organisations, we assume Russian GDP to fall by 10%^{29–31}. Scenario 2c adds 'Export reduction agricultural Russian exports. Russian agricultural production is assumed to be not directly affected by foreign sanctions related to the war with Ukraine, but restrictions on technology imports and services, in addition to financial restrictions and the withdrawal of Western-based multinationals active in the food industries in Russia can affect agricultural productivity. Lower productivity leads to less production and exportable surplus, which can affect international markets for agricultural commodities. In addition, news items in March indicate Russia considers export quota of grains and sunflower oil for 2022 to keep domestic prices stable, yet we do not include Russian banned exports or export restrictions in our simulations. Moreover, there are signs that exports of wheat and oilseeds (meal and oil) face logistic problems and are paralysed due to high insurance risks and international payments restrictions⁵⁵. We assume these factors will lead to a reduced Russian export of wheat and oilseeds by 50% each.

3. Impacts on global energy prices. Since Russia is a key player in the global energy market, the conflict and associated (threats of) sanctions may affect the energy markets substantially. The many market uncertainties make price projections extremely difficult for some fossil fuel price developments in February and March 2022. We assume international energy prices will increase by 20%, caused by the disruption in the relationship with Russia, and the consequences of sanctions on technology exports and financial restrictions, which put pressure on security of supply on the medium-term³². The USA and the UK have announced a ban on importing Russian oil and gas to be implemented by the end of 2022. The EU relies on Russia for 40% of its gas and has not targeted Russian energy exports (yet). Fertiliser prices are affected by energy prices and are endogenously determined by the model projection.

Data availability

The data that support the findings of this study are available from Global Trade Analyses Project (GTAP, <https://www.gtap.agecon.purdue.edu/databases/default.asp>), but restrictions apply to the availability of these data, which were used under license for the current study and so are not publicly available. More information on the MAGNET model is available on its website (<https://www.magnet-model.eu/>). The data are, however, available from the authors upon reasonable request and with the permission of Global Trade Analyses Project (GTAP). The data behind the Figures are provided in an additional data file (Excel) in Supplementary Data 1.

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Author contributions

H.v.M., S.v.B., and Z.S.-K. conceived and designed the experiments, H.B., D.C., and W.v.Z. performed the experiments with MAGNET, H.B. and W.v.Z. made the analyses tool, H.B. designed and made the graphical illustrations, all contributed to the analyses, and H.v.M., S.v.B. and Z.S.-K. wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information


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