Supplementary Information for

The Russia-Ukraine war threatens food affordability, but reduces carbon emissions

Contents

Supplementary Methods

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. In this way, it can be shown 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

1a Trade stop between Ukraine and Russia & Belarus

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.

1b Production and GDP loss within Ukraine

The war in Ukraine displaced a third of the country's population from their homes, of which approximately 4m (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 significant 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 season (APK-Inform, 4248. April 1, 2022). Due to war damage and expected ongoing difficulties in obtaining sufficient inputs, it is likely that agricultural production will continue to be significantly 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.

1c 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

2a Russian trade sanctions

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 Canada (BBC, 6 April 2022). 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.

2b GDP reduction Russia

Following the expectations of various international organisations **we assume Russian GDP to fall by 10%.**[1]

2c 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. 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 restrictions (APK-Inform, 21 March 2022). 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 significantly. The many market uncertainties make price projections extremely difficult – see Box 1 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-term (IEA, 2022).[2] The 20% is calculated as the difference between the average Bent crude oil price level on 24th of February US$92/Bbl - and US$110/Bbl on June 17th 2022. Oil price development has been very volatile, since invasion and June 2022 (e.g. peaking at US$127/Bbl in March 2022) but appeared to stabilize somewhat around US$110/Bbl (https://tradingeconomics.com/commodity/brent-crude-oil). 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.[3]

Text box: Fossil fuel price developments

[1] For instance, OECD Economic Outlook estimations of the impact of the war in Ukraine build on simulations that incorporate ex-ante domestic demand declines of 15% in Russia and 40% in Ukraine, leading to the expectation that GDP declines are likely in the same order of magnitude. Shocks that are assumed to last for at least one year (OECD, 2022). In their updated (in April) 2022 Outlooks, IMF and World Bank expect GDP to decline in both countries in the same range or even a bit stronger (IMF, 2022; World Bank, 2022).

[2] IEA reports that Russian oil continues to flow to Europe, which is mostly governed by term deals and being delivered by trade agreements made before the invasion. But the agency states that 'new business has all but dried up. Buyers are avoiding Russian crude because of concerns about shipping safety, insurance and sanctions. Urals crude from Russia is being offered at record discounts, but uptake is limited so far, with Asian oil importers for the most part sticking to traditional suppliers in the Middle East, Latin America and Africa'. Moreover, the organisation claims that 'The prospect of large-scale disruptions to Russian oil production is threatening to create a global oil supply shock. We estimate that from April, 3 mb/d of Russian oil output could be shut in as sanctions take hold and buyers shun exports. OPEC+ is, for now, sticking to its agreement to increase supply by modest monthly amounts. Only Saudi Arabia and the UAE hold substantial spare capacity that could immediately help to offset a Russian shortfall' (https://www.iea.org/reports/oil-market-report-march-2022)

[3] There are also indications that Russia considers a ban on the export of fertilisers: early February Russia announced a temporarily restriction on export ammonium nitrate, for two months, to 1 April 2022 (https://www.agroberichtenbuitenland.nl/actueel/nieuws/2022/02/09/export-of-ammonium-nitrate-from-russia-is-restricted). RF exports about 4m tonnes of ammonium nitrate, which is about 40% of the world's ammonium nitrate exports. Russia also accounts for 14% of the global urea market and 21% of the potash market. Russia is considering more trade bans such as restrictions on Russian exports of telecoms, medical, vehicle, agricultural, and electrical equipment, as well as some forestry products such as timber to 'unfriendly countries' among which are the EU and the US (Russia hits back at Western sanctions with export bans - BBC News). Our scenarios do not include Russian export and/or import bans.

Oil prices (Brent futures prices, considered as benchmark for many other oil types and other [fossil] fuels and energy sources) have been stable at around USD 60 per barrel (Bbl) during the period 2017-early 2020. Prices fell to a record low in April 2020 (USD 21/Bbl, due to the Covid crisis) but since then an upward trend brought prices to USD 80/Bbl at the end of December 2021. Oil prices continued to increase in Jan-Feb 2022 to reach USD 100/Bbl on 25 February and have been volatile but went up to USD 127 on 8 March before tumbling more than 20% to touch below USD 100/Bbl on 16 March 16 and went up again to reach USD 120/Bbl on 23-25 March. Energy prices are determined by both market developments and political decisions (e.g. OPEC). Volatile fossil fuel prices make forecasts very uncertain.[4]

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. The four scenarios, their components, their description, and implementation are given in Table 3.1.

Table S.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	Tariffs rise to reduce trade with 90% for all commodities
	1b: 1a + Ukraine's loss in production and GDP	A GDP loss of 33% is assumed (based on OECD (2022), IMF (2022) and World Bank 2022). This is achieved by a reduction of labour and capital with 30%, land yields with 50%, and population with 10%.
	1c: 1b + Ukraine's additional transport cost with rest of world	Transport costs between Ukraine and rest of world rise 20% (assumption).
Ukraine and Russia impacts (Scen 2)	2a: Scen 1 + US & EU trade sanctions against Russia.	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 *.
	2b: 2a + Russia's loss in GDP	Real GDP in Russia falls 10% (based on OECD (2022), IMF (2022) and World Bank 2022). This is achieved by a reduction in total factor productivity (endogenous in this scenario and made exogenous for subsequent scenarios).
	2c: 2b + Russia's reduced exports on grains and oilseeds due to productivity declines and logistical problems.	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).
Ukraine, Russia, energy price impacts (Scen 3)	Scen 2 + world energy prices rise	Prices rise 20% in the world for coal, oil, and gas (assumption). **.

* For EU sanctions: https://www.rvo.nl/onderwerpen/landen-en-gebieden/rusland/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. ** Estimated as a difference between the average Bent crude oil price level on 24th of February US$92/Bbl - and US$110/Bbl on June 17th 2022. Oil price development has been very volatile, since invasion and June 2022 (e.g. peaking at US$127/Bbl in March 2022) but appeared to stabilize somewhat around US$110/Bbl (https://tradingeconomics.com/commodity/brent-crude-oil).

[4] For instance, the US Energy Information Agency projects a decline of Brent oil prices up to USD 89/Bbl in 2023, based on the expectation that global oil inventories will build at an average rate of 0.5m Bbl/d from 2Q22 through the end of 2023, despite an expected reduction of Russia's oil production. The agency stresses its price forecast is highly uncertain. (https://www.eia.gov/outlooks/steo/)

Model definition

We used the Modular Applied General Equilibrium Tool (MAGNET) for our analysis. MAGNET is a multi-regional, multi-sectoral applied computable general equilibrium (CGE) model (see, Woltjer et al. 2014). It is an advanced recursive dynamic version of the Global Trade Analysis Project (GTAP) model (Corong et al., 2017) which has been extended to allow integrated assessments focussing mainly on food and biomass production. As a CGE model, MAGNET solves through adjusting prices such that all markets for factors (land, labour, capital, natural resources) and commodities (good and services) simultaneously clear. Producers (one for each sector-region combination) respond to changing prices for inputs (factors and intermediates) based on profit maximization. With constant returns to scale production producers operate under zero-profit conditions. Representative private households (one for each region) respond to changing incomes earned with factor sales and changing prices of commodities for consumption based on utility maximization limited by the household’s income constraint. International trade flows are modelled bilaterally between all regions with regional sourcing of imports governed by the Armington assumption which allows two-way trade flows. Figure S1 outlines the structure of MAGNET with the interactions between production, trade, and consumption.

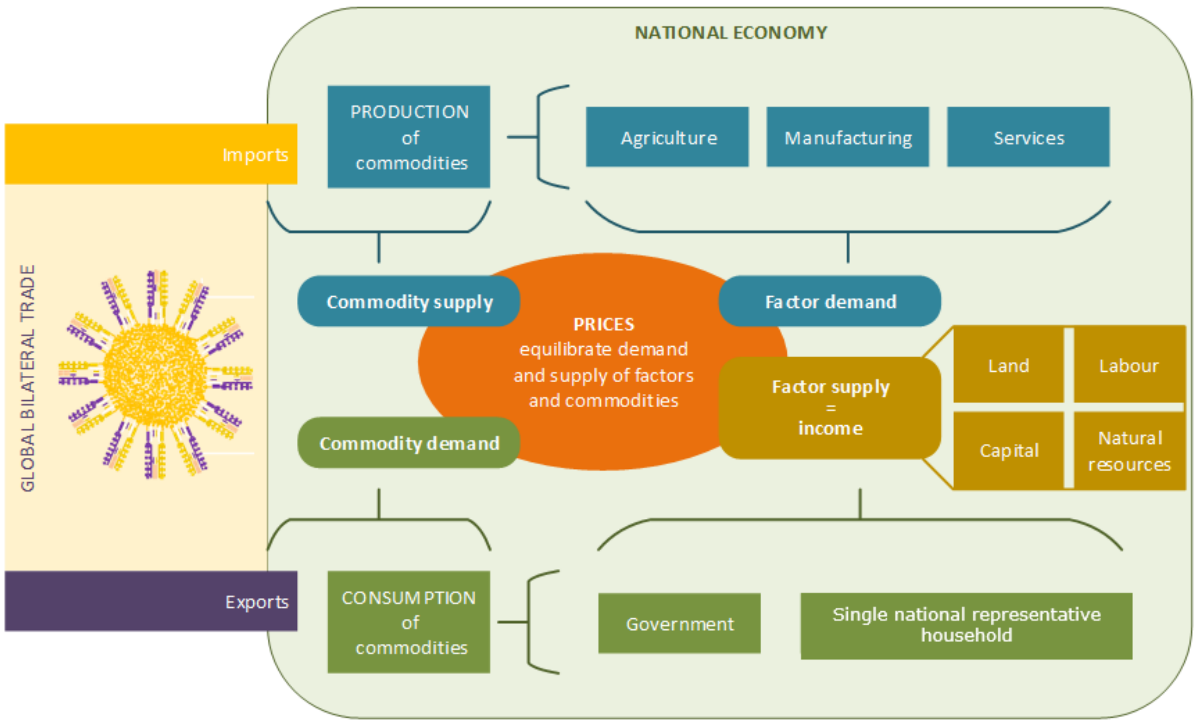

Figure S1 Schematic outline of the structure of MAGNET and the circular flow of money and commodities through the global economy.

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 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. Modules relevant for the current study are the flexible nested CES production trees (allowing for more substitution possibilities than in the standard GTAP model), endogenous land supply (allowing land areas to expand and contract depending on demand), flexible nested CET land allocation (governing the movement of sluggish land across sectors depending on the ease of switching between different types of land use), purchasing power adjusted CDE demand function (adjusting income elasticities in baseline projections to attain a more plausible pattern in food demand when incomes rise substantially), and segmented factor markets (capturing diverging labour and capital price developments in agricultural and non-agricultural sectors).

As the requested time frame is shorter than the normally considered adjustment period within this kind of analysis, the standard substitution elasticities between production factors are reduced by 50% relative to the level of the original GTAP and MAGNET elasticities.

Specific features of MAGNET important for the analysis of agricultural markets

Land supply: MAGNET implements a land supply curve which specifies the relationship between land supply and land price. As demand increases, more land will be used for agricultural production leading to land scarcity and therefore increased land prices. Total land supply is exogenous in the standard GTAP model. In this extended version, total agricultural land supply is modelled using a land supply curve specifying the relationship between land supply and a land rental rate in each region (van Meijl et al., 2006, Woltjer et al. 2014). Land supply to agriculture can be adjusted by idling agricultural land, converting non-agricultural land to agriculture, converting agricultural land to urban use, and agricultural land abandonment.

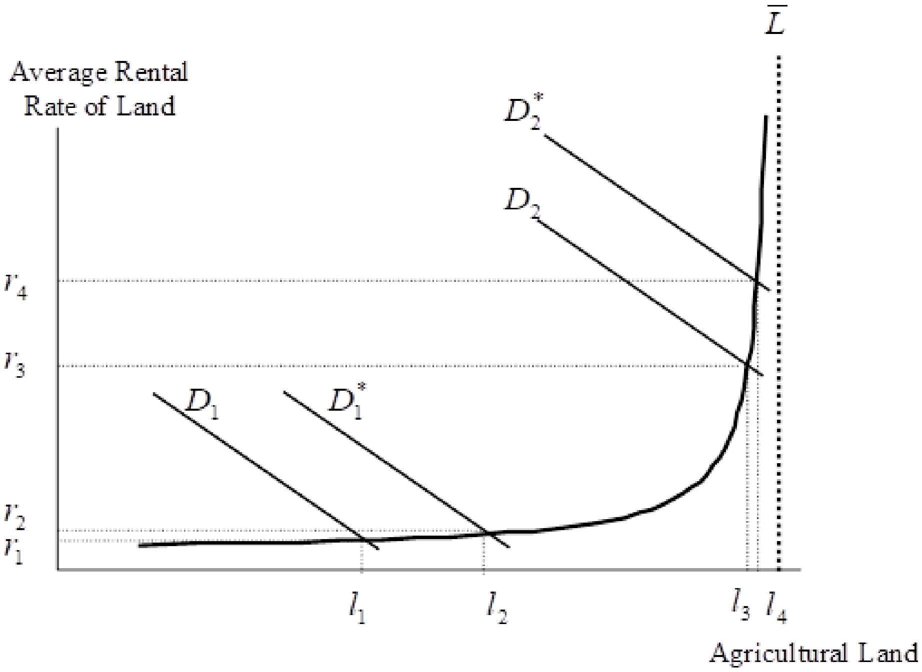

Figure S2 Impact of increased land demand for biofuel crops on land markets

Figure S.2 gives the general idea behind the land supply curve. When agricultural land use approaches potential land use (), farmers are forced to use less productive land with higher production costs (strongly increasing part of the supply curve). As a consequence, in land-abundant regions like South America and for members of NAFTA, an increase in demand from D1 to D1* (left-hand side of Figure S.2) results in a large increase in land use (from l1 to l2) and a modest increase in rental rates (from r1 to r2), while land scarce regions like Japan, Korea and Europe experience a small increase in land use and a large increase in the rental rate (right-hand side of Figure S.2; shift from D2 to D2*). These land price differences will influence competitiveness of agricultural production. The key problem is the empirical implementation of this land supply curve for all major regions in the world, as land price data are not available on a global scale. Van Meijl et al. (2006) used biophysical data, such as spatially varying land productivity, from the

IMAGE model to approximate the supply curve (asymptote). Elasticies are partially estimated (see, Woltjer et al. 2014)

Land allocation: MAGNET assumes different substitutability amongst groups of land use types, with the degree of substitutability varying across but not within the groups and considers three hierarchical land use type groups (nests). Land heterogeneity is introduced by using a Constant Elasticity of Transformation (CET) function. To analyse the impact of biofuels and fertilizers, the functioning of the land market is particularly crucial. Birur et al. (2007) used agro-ecological zones in combination with an exogenous land supply, following the methodology outlined in Lee et al. (2005). We propose an alternative to traditional methods by introducing a new demand structure that reflects the different degrees of substitutability between agricultural land uses according to the crops considered (Huang et al., 2004). The standard version of GTAP represents land allocation in a CET structure (Figure S.3) assuming that the various types of land use are imperfectly substitutable, but with equal substitutability among all land use types. For our purposes, the land use allocation structure is extended by taking into account that the degree of substitutability differs between types of land (Huang et al., 2004) using the more detailed OECD's Policy Evaluation Model (PEM) structure (OECD, 2003) (Figure S.3). It distinguishes different types of land in a nested 3-level CET structure. The model covers several types of land use with different suitability levels for various crops (i.e. cereal grains, oilseeds, sugar cane/sugar beet and other agricultural uses).

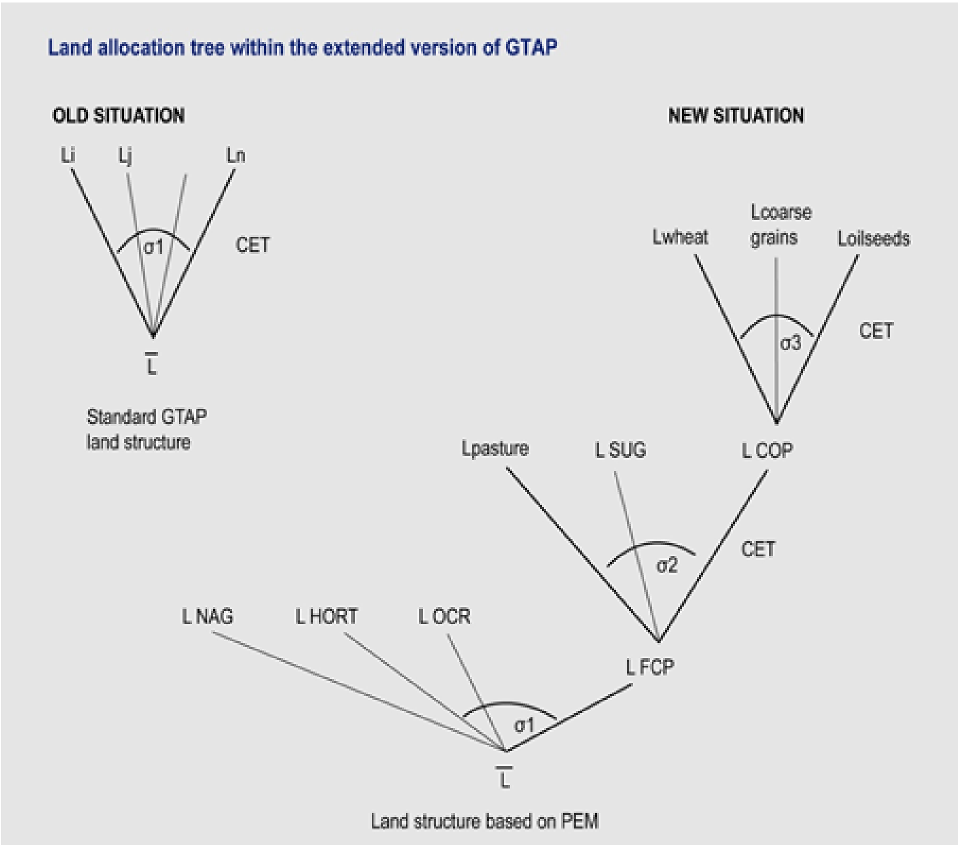

Figure S3 Impact of increased land demand for biofuel crops on land markets

Following the PEM approach (OECD, 2003), there is nested substitutability between land for horticulture (LHORT), other crops (LOCR) and field crops and pasture (LFCP), between land for pasture (Lpasture), sugar crops (LSUG) and cereal, oilseed and protein crops (LCOP), and between land for wheat (Lwheat), coarse grains (Lcorse grains) and oilseeds (Loilseed).

The lower nest assumes a constant elasticity of transformation between 'vegetables, fruit and nuts' (HORT), 'other crops' (e.g. rice, plant-based fibers; OCR) and the group of 'Field Crops and Pastures' (FCP). The transformation is governed by the elasticity of transformation σ1. The FCP-group is itself a CET aggregate of Cattle and Raw Milk (both Pasture), 'Sugarcane and Beet' (SUG), and the group of 'Cereal, Oilseed and Protein crops' (COP). Here, the elasticity of transformation is σ2. Finally, the transformation of land within the upper nest, the COP-group, is modeled with an elasticity σ3. In this way the degree of substitutability of types of land can be varied between the nests. Agronomic features are captured to some extent. In general it is assumed that σ3> σ2 >σ1, which implies that it is easier to change the allocation of land within the COP group, while it is more difficult to move land out of COP production into, say, vegetables. The values of the elasticities are taken from PEM (OECD, 2003).

Segmented factor markets: Perfect capital and labour mobility between agricultural and non-agricultural sectors, as assumed in the standard GTAP, implies equal remuneration for these production factors. This is not supported by empirical evidence (De Janvry et al., 1991). In MAGNET factor markets are divided into agricultural and non-agricultural labour and capital. By doing so MAGNET accounts for differences in wages and returns to assets between the agricultural and the non-agricultural sector taking into account that these are larger in the short term than in the long term. Therefore, capital and labour market segmentation is introduced by specifying a CET structure (Keeney and Hertel, 2005). The elasticities of transformation have been calibrated to fit estimates of the elasticity of labour supply from PEM (OECD, 2003).

Consumption: A dynamic CDE expenditure function is implemented that allows for changes in income elasticities when purchasing power parity (PPP)-corrected real GDP per capita changes (see Hertel (2007) for more details on the CDE function).

A flexible CES tree production structure: All types of CES trees can be easily implemented. At this moment most sectors have the possibility to substitute between different production factors and between capital and energy. The petroleum sector has the possibility to substitute between ethanol, biodiesel and fossil fuels. The animal feed sector can substitute between (grass) land and animal feed from crops, and within animal feed from crops between different types of animal feed, including relevant by-products that change with biofuel production like DDGS, oilcake and molasses. The agricultural sectors can also substitute between land and fertilizer, while the ethanol sector can substitute between different feedstocks. In this study, we use a two-level nested structure to represent substitution possibilities between pasture land and compound feed for animal production (first level) and substitution between compound feed feedstocks (second level). Furthermore, we use a one-level nested CES structure to account for substitution among ethanol feedstocks. The blending sector and the fertilizer composite are explained below.

Linkage between crop and livestock sectors: Livestock sectors are linked in various ways to the crop sectors. First, livestock sectors use crops (e.g. wheat, coarse grains, oilseeds, other crops) in their feed mix to raise the animals. In the feed mix agricultural crops compete with compound feed, oilcakes, molasses and by-products from biofuel production (DDGS). Secondly, crop and livestock sectors both compete in the land, labour and capital factor markets. Pasture land can be converted to crop land and vice versa (see, Figure S.3). The nested land structure implies that it is more difficult to convert pasture land into crop land and vice versa than to convert for example wheat in coarse grains land within the LCOP nest. There is no link in the model that allows using organic fertilizers (e.g. manure) from the animal sectors in the crop sectors.

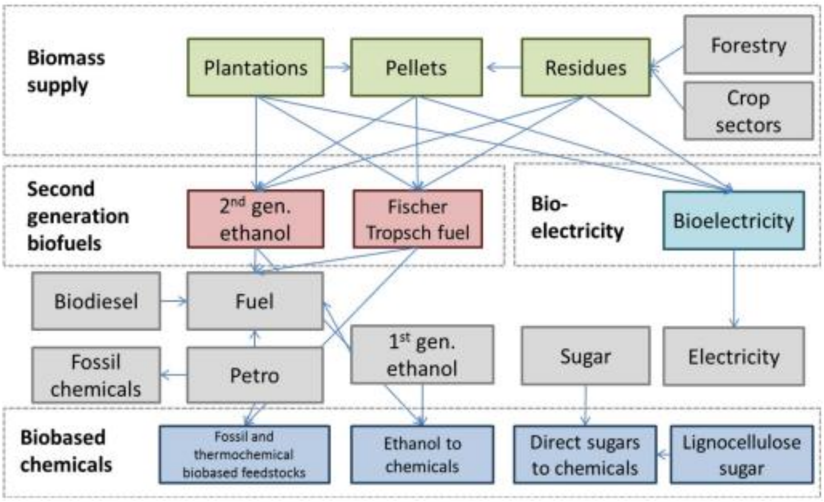

Figure S4 Overview of fossil and bio-based sectors and linkages in MAGNET

Energy: 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 (e.g., OECD, 2013, Doelman et al. 2019). 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 (see below, Banse et al. 2008, Van Meijl et al. 2018).

The GTAP database that is used in MAGNET was expanded with several new sectors. These new sectors cover the supply of biomass and the conversion of biomass to electricity, second-generation biofuels and bio-based chemicals. A simplified overview of these new sectors and the linkages between these sectors and with the existing sectors in MAGNET is provided in the figure below (Figure S.4). The coloured boxes represent the new sectors introduced in MAGNET. The grey sectors are existing sectors in MAGNET, as described in Woltjer and Kuiper (2014). The arrows show the deliveries between sectors. The fuel sector in the graph below mixes conventional fuels from the petro sector with first- and second-generation biofuels. Specific introduced biomass supply sectors are residues, plantations and pellets. A chemicals sector (not shown in the figure) mixes bio-based and conventional chemicals. Three attractive and representative pathways were identified:

• Direct sugar to chemicals
• Ethanol to chemicals
• Thermochemical-based feedstocks

The electricity producing sector in MAGNET is split into seven source sectors:

- Electricity biomass
- Electricity coal
- Electricity gas
- Electricity wind and solar
- Electricity nuclear
- Electricity hydro and geothermal
- Electricity distribution and transport.

An emissions module calculates emissions of GHG gases – CO_2, N_2O and CH_4. 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) as a result of e.g. carbon taxes). Land use expansion emissions are calculated based on mean carbon coefficients from Carriquiry, et al. (2021) which imply that the additional 0.09 Gt CO2e per Mha.

Fertilizers: In MAGNET the fertilizer sector has been disaggregated from the chemical sector. Fertilizer is used in the crops sectors as a substitute of land. This allows for intensification taking place based on land rent and agricultural prices. With respect to policies, the model allows depicting of all types of quantity and price based policies that are relevant for the sector. Examples are subsidies or taxes on fertilizer use in each of the agricultural sub-sectors, tariffs and subsidies on fertilizer trade, and subsidies or taxes on production or inputs in the fertilizer sector. MAGNET has been extended to explicitly account for the three macronutrients: nitrogen (N), phosphorus (P2O5) and potassium (K2O) (Von Lampe et al. 2014). The three macronutrients enter MAGNET as separate sectors, which implies that the original chemical sector in the GTAP database is split into four sectors (nitrogen, phosphorus, potassium and rest of chemicals). The output value of fertilizers is derived using the following fob prices as reference prices: Urea (HS 31102.10) for nitrogen, DAP (HS 3105.30) for phosphorus, and MOP (HS 3104.20) for potassium. Bilateral tariff data obtained from the MacMap database for Urea, DAP and MOP, serve as reference bilateral tariffs for nitrogen, phosphorus and potassium, respectively. The production technology for the three fertilizer sectors is derived from IFA (2013b). There are regional differences in the production technology of nitrogen in particular which are due to regional deviations in natural gas prices. The rest of chemicals sector is then calculated residually. Data adjustments in MAGNET are implemented in the model's underlying Social Accounting Matrix (SAM). For the rest of the chemicals sector, taxes and subsidies are adjusted accordingly so that the SAM remains balanced. The model assumes that fertilizers can substitute for land in crop production, thereby accounting for extensification vs. intensification of agricultural production. Empirical evidence with regard to the value of the land-fertilizer substitution elasticity is scarce and disperse. A higher value of the substitution elasticity between land and fertilizers would generally result in more pronounced reductions of fertilizer use following an elimination of fertilizer support policies. This would result in lower yields and higher land use. The substitution elasticity between land and fertilizers are set at 0.15 for developed countries and at 0.85 for developing countries.

Biofuels: A specific biofuel module has been developed that allows the representation of first-and second generation biofuels for transport and their respective support policies (e.g. Banse et al. 2014, Woltjer et al. 2014). MAGNET has the possibility to apply all types of subsidies, quotas and tariffs that can be used routinely in a GTAP-type model. MAGNET's dedicated module on biofuel policies involves the possibility to implement biofuel mandates in transport. Although the GTAP database includes several transportation sectors these do not cover all fuel used for transportation. Firms, private households and the government purchase petroleum products which are partly used for transportation and partly for other uses like heating. In order to implement a biofuel policy the model needs to account for demand for petroleum products by the transport sectors as well as demand for petroleum products by households and government. Data on biofuel use in transport are calculated from the IEA database. MAGNET includes first- and second generation ethanol and biodiesel as separate sectors. Biofuel consumption data are taken from the World Energy Outlook. The model assumes that ethanol is produced from grains (wheat, coarse grains) and sugar beet or sugarcane, whereas biodiesel is assumed to be made entirely from crude vegetable oil. Furthermore, the model includes by-products of the biofuel processing activities, such as oilcakes (by-product of crushing oilseeds) and DDGS (a by-product of producing ethanol from grains). These by-products are used as intermediate inputs in livestock production.

A more extensive documentation of the MAGNET model can be found in Woltjer et al. (2014).

Regional and sectoral aggregation used in MAGNET model simulation

Regional aggregation

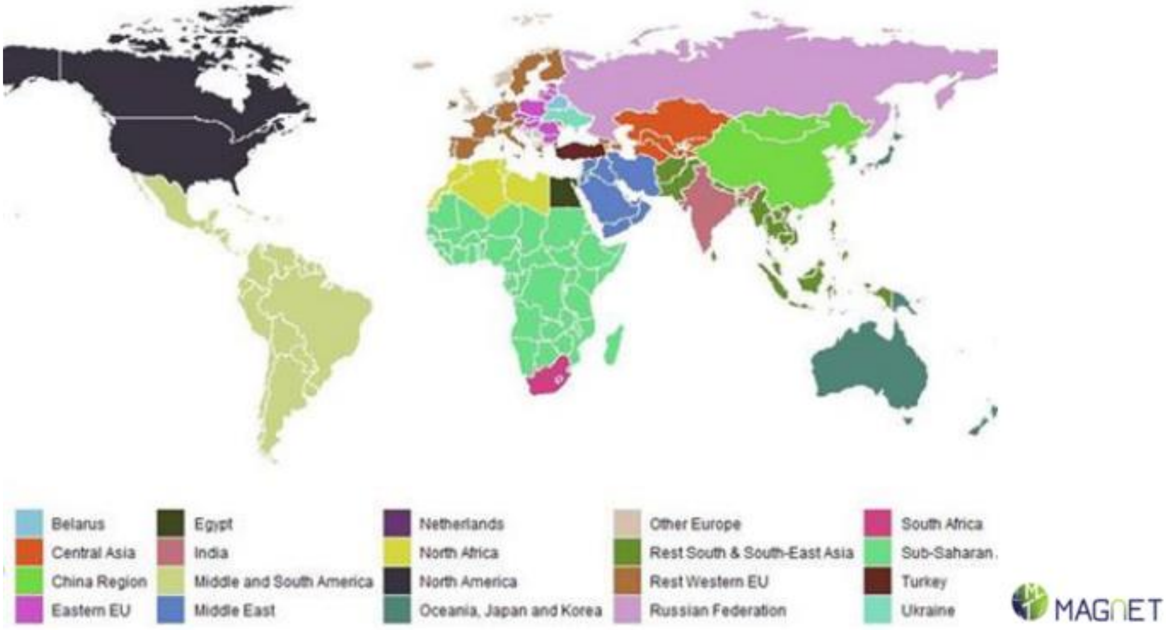

Figure S5 Regional aggregation of MAGNET model used within this study

Figure S.5 shows the regional MAGNET aggregation used within this study (a more elaborated description is given in the Appendix). Twenty regions covering the whole world are distinguished with a focus on the Ukraine war impacts on food security. As key players Ukraine, Russia and Belarus are identified. Impacts are expected in neighbouring regions such as Eastern EU, Turkey, Middle East, Central Asia and in the China region. For food security reasons Turkey, Egypt, (rest of) North Africa, Middle East, Sub-Saharan Africa and Rest of South and South-east Asia are distinguished. Table S3 and Table S4 in the Appendix provide a detailed description of which countries belong to the regions specified above.

For explanatory convenience, some countries and regions presented in Figure S4 have been combined into more aggregated regions which are used to show the results in the graphs. The more aggregated regions and which MAGNET regions they contain are described in Table S2.

Table S2 Regional aggregation used in world market graphs

Aggregated regions	**Model regions**
Ukraine	Ukraine
Russia	Russia
EU	EU14, Eastern EU, Netherlands
Rest of Europe	Other Europe
Central Asia	Belarus, Central Asia, Turkey
North Africa	Egypt, Northern Africa
Rest Africa	Sub-Saharan Africa, South Africa
Rest South & South-East Asia	Rest South & South-East Asia
Asia & Oceania	Asia & Oceania
North America	North America
Middle and South America	Middle and South America
World	World

TableS3 ***Model*** *region mapping (MAGNET to GTAP)*

Regional Aggregation	Description	Mapped GTAP region
OCJK	Oceania, Japan and Korea	aus, nzl, xoc, jpn, kor, xtw
CHR	China Region	chn, hkg, mng, twn, xea
RSEA	Rest South & South-East Asia	brn, khm, idn, lao, mys, phl, sgp, tha, vnm, xse, bgd, npl, pak, lka, xsa
IND	India	Ind
NAM	North America	can, usa, xna
MSA	Middle and South America	mex, arg, bol, bra, chl, col, ecu, pry, per, ury, ven, xsm, cri, gtm, hnd, nic, pan, slv, xca, dom, jam, pri, tto, xcb
EU14	Rest Western EU	aut, bel, dnk, fin, fra, deu, grc, irl, ita, lux, mlt, prt, esp, swe
EU12	Eastern EU	bgr, hrv, cyp, cze, est, hun, lva, ltu, pol, rou, svk, svn
NLE	Netherlands	nld
REU	Other Europe	gbr, che, nor, xef, alb, xer
BLR	Belarus	blr
RUS	Russian Federation	rus
UKR	Ukraine	ukr
FSU	Central Asia	xee, kaz, kgz, tjk, xsu, arm, aze, geo
ME	Middle East	bhr, irn, isr, jor, kwt, omn, qat, sau, are, xws
TUR	Turkey	tur
EGY	Egypt	egy
NAF	North Africa	mar, tun, xnf
SSA	Sub-Saharan Africa	ben, bfa, cmr, civ, gha, gin, nga, sen, tgo, xwf, xcf, xac, eth, ken, mdg, mwi, mus, moz, rwa, tza, uga, zmb, zwe, xec, bwa, nam, xsc
ZAF	South Africa	zaf

Table S4 ***Model*** *region mapping (MAGNET to ISO)*

Regional Aggregation	Description	Mapped ISO region
OCJK	Oceania, Japan and Korea	AUS, CXR, CCK, HMD, NFK, NZL, ASM, COK, FJI, PYF, GUM, KIR, MHL, FSM, NRU, NCL, NIU, MNP, PLW, PNG, PCN, WSM, SLB, TKL, TON, TUV, UMI, VUT, WLF, JPN, KOR, BVT, ATA, IOT, ATF
CHR	China Region	CHN, HKG, MNG, TWN, PRK, MAC
RSEA	Rest South & South-East Asia	BRN, KHM, IDN, LAO, MYS, PHL, SGP, THA, VNM, MMR, TLS, BGD, NPL, PAK, LKA, AFG, BTN, MDV
IND	India	IND
NAM	North America	CAN, USA, BMU, GRL, SPM
MSA	Middle and South America	MEX, ARG, BOL, BRA, CHL, COL, ECU, PRY, PER, URY, VEN, FLK, GUF, SGS, SUR, GUY, CRI, GTM, HND, NIC, PAN, SLV, BLZ, DOM, JAM, PRI, TTO, AIA, ATG, ABW, BHS, BRB, CYM, CUB, DMA, GRD, HTI, MSR, ANT, KNA, LCA, VCT, TCA, VGB, VIR
EU14	Rest Western EU	AUT, BEL, DNK, ALA, FIN, FRA, GLP, MTQ, REU, DEU, GRC, IRL, ITA, LUX, MLT, PRT, ESP, SWE
EU12	Eastern EU	BGR, HRV, CYP, CZE, EST, HUN, LVA, LTU, POL, ROU, SVK, SVN
NLE	Netherlands	NLD
REU	Other Europe	GBR, CHE, NOR, SJM, ISL, LIE, ALB, AND, BIH, FRO, GIB, GGY, VAT, IMN, JEY, MKD, MCO, MNE, SMR, SRB
BLR	Belarus	BLR
RUS	Russian Federation	RUS
UKR	Ukraine	UKR
FSU	Central Asia	MDA, KAZ, KGZ, TJK, TKM, UZB, ARM, AZE, GEO
ME	Middle East	BHR, IRN, ISR, JOR, KWT, OMN, QAT, SAU, ARE, IRQ, LBN, PSE, SYR, YEM
TUR	Turkey	TUR
EGY	Egypt	EGY

NAF	North Africa	MAR, TUN, DZA, LBY, ESH
SSA	Sub-Saharan Africa	BEN, BFA, CMR, CIV, GHA, GIN, NGA, SEN, TGO, CPV, GMB, GNB, LBR, MLI, MRT, NER, SHN, SLE, CAF, TCD, COG, GNQ, GAB, STP, AGO, COD, ETH, KEN, MDG, MWI, MUS, MOZ, RWA, TZA, UGA, ZMB, ZWE, BDI, COM, DJI, ERI, MYT, SYC, SOM, SDN, SSD, BWA, NAM, LSO, SWZ
ZAF	South Africa	ZAF

Sectoral aggregation

The sectoral aggregation includes the key crops for Ukraine and Russia such as wheat, other cereal grains (includes maize) and oilseeds. Oilseeds includes all varieties of oilseeds and is therefore a mixture for products were Ukraine and Russia are important such as rape and sunflower seeds, and some where this is not the case (e.g. soybean). In addition to these key crops the aggregation includes rice, vegetables, sugar crops, rice, other crops. Cattle, pork, poultry and other cattle and related processed products are separated within the livestock sectors. Another 50 sectors cover the rest of the economy including the energy sectors (coal, gas, oil) and fertiliser sectors (N, P and K). A detailed description of all sectors is given in Table S5.

Table S5 ***Commodity*** *mapping*

Commodity Aggregation	**Description**	**Disaggregated MAGNET sets**	**Mapped GTAP sets**
pdr	Paddy and processed rice	pdr	<-
wht	Wheat	wht	<-
grain	Cereal grains nec	gro	<-
veg	Vegetables	v_f, veg	<-
oils	Oil seeds	osd	<-
sug	Sugar cane, sugar beet	c_b	<-
oagr	Other agriculture	pfb	<-
crops	Crops nec	ocr	<-
othctl	sheep,goats,horses	ctl	<-
pigpls	Pig and other animal product	oap	<-
milk	Raw milk	rmk	<-
wol	Wool, silk-worm cocoons	wol	<-
frs	Forestry	frs	<-
wfish	Wild fish	fsh	<-
coa	Coal	coa	<-
c_oil	Crude oil	oil	<-
gas	Gas	gas	<-
manu	Manufacturing	oxt, nmm, i_s, nfm, fmp, ele, eeq, ome, mvh, otn, omf, cns	<-
othcmt	Meat: other cattle,sheep,goats,horse	cmt	<-
othmt	Other meat product nec	omt	<-
vol	Vegetable oils and fats	vol	<-
dairy	Dairy products	mil	<-
pcr	Processed rice	pcr	<-
sugar	Sugar and molasses	sgr, mola	sgr, sgr
ofd	Processed food	ofd, b_t	<-
othind	Other industry	tex, wap, lea, lum, ppp	<-
petro	Petroleum, coal products	p_c, aviaf, ftavia	p_c, p_c, p_c
chm	Chemical products	chm, bioch	chm, chm

bph	Basic pharmaceutical products	bph, bioph	bph, bph
rpp	Rubber and plastic products	rpp, lsug, pe, pla, bfchem, biopl	rpp, sgr, chm, chm, chm, rpp
ely	Electricity	ely, edt	ely, ely
gas_dist	Gas manufacture, distribution	gdt	<-
ser	Services	wtr, trd, cmn, ofi, ins, rsa, obs, osg, edu, dwe	<-
foodserv	Food services	afs, ros, hht	<-
trans	Transport sector	otp, wtp, atp, whs	<-
fruit	Fruit	fruit	<-
nuts	Nuts	nuts	<-
roots	Roots and tubers	roots	<-
pulses	Pulses	pulses	<-
feed	Animal feed	feed	ofd
cvol	Crude vegetable oil	cvol	vol
biog	Biogasoline	biog, bf_g, bf_s, bf_m	p_c, p_c, p_c, p_c
biod	Biodiesel	biod, bf_o	p_c, p_c
fert_n	fertilizer nutrient n	fert_n	chm
fert_p	fertilizer nutrient p	fert_p	chm
fert_k	fertilizer nutrient k	fert_k	chm
ftfuel	ftfuel 2nd gen biofuel	ftfuel	p_c
eth	ethanol 2nd gen biofuels	eth	p_c
ely_c	electricity from coal	ely_c	ely
ely_g	electricity from gas	ely_g	ely
ely_n	electricty from nuclear	ely_n	ely
ely_h	electricty from hydro	ely_h	ely
ely_w	electricty from wind and solar	ely_w	ely
bioe	bioelectricity 2nd gen	bioe	ely
res	residue sector	res	p_c
pel	pellet sector	pel	lum
plan	Plantation	plan	frs
pltry	poultry sector	pltry	oap
pulmt	poultry meat	poum	omt
cattle	cattle sector	bfctl	ctl
bfmt	beef meat	BFCMT	cmt
aqcltr	Aquaculture	Diad, Fresh, Crust, Marin, Molus	fsh, fsh, fsh, fsh, fsh
fishp	Fish processing	Fishp	ofd
heat	heat	heat	ely
bioh	bioheat	bioh	ely
ddgs	Biogasoline byproduct	ddgs	p_c
oilcake	Oil cake byproduct of cvol used as animal feed	oilcake	vol
r_pdr	residue pdr	r_pdr	pdr
r_wht	residue wheat	r_wht	wht
r_gro	residue gro	r_gro	gro
r_osd	residue osd	r_osd	osd
r_ocr	residue ocr	r_ocr	ocr
r_frs	residue frs	r_frs	frs
r_veg	residues vegetables	r_v_f, r_veg	v_f, veg
fishm	fish meal	fishm	ofd
r_frt	residue fruits	r_frt	fruit
r_nuts	residue nuts	r_nuts	nuts
r_root	residue roots	r_root	roots
r_puls	residue pulses	r_puls	pulses

Additive versus isolated scenario set-up

To determine which scenario 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 tested the hypothesis whether there is a big difference between the additive approach we used in our paper and running the scenario's in isolation. Table S6 shows the results for the prices as these are the variables causing equilibrium in our model. As can be seen from the table below the two approaches give very similar results indicating that the interaction effects are not very significant. We have chosen for the additive approach as we perceive this more logical. First there was there war the most direct impact on Ukraine itself. This was followed by the trade implications for Russia due to for example trade sanctions. Because of these sanctions the energy prices rose. There are interaction effects but our tests by running the shocks separately show that the interaction impacts are small.

Table S6 Impact on commodity prices: Additive versus isolated scenario set-up

Commodity	Scenario	Separate approach	Additive approach	Difference
Cereal grains nec	Ukraine impacts	3.80%	3.80%	0.00%
Cereal grains nec	Russia shocks	1.31%	1.30%	0.01%
Cereal grains nec	price shocks	4.10%	4.42%	-0.32%
Crops	Ukraine impacts	0.33%	0.33%	0.00%
Crops	Russia shocks	0.56%	0.56%	0.00%
Crops	price shocks	3.34%	3.44%	-0.10%
Fruit	Ukraine impacts	0.47%	0.47%	0.00%
Fruit	Russia shocks	0.65%	0.65%	0.00%
Fruit	price shocks	3.21%	3.30%	-0.10%
Nuts	Ukraine impacts	0.66%	0.66%	0.00%
Nuts	Russia shocks	0.85%	0.84%	0.01%
Nuts	price shocks	3.20%	3.29%	-0.09%
Oil seeds	Ukraine impacts	0.89%	0.89%	0.00%
Oil seeds	Russia shocks	0.96%	0.94%	0.02%
Oil seeds	price shocks	4.46%	4.63%	-0.17%
Other agriculture	Ukraine impacts	0.45%	0.45%	0.00%
Other agriculture	Russia shocks	0.79%	0.79%	0.01%
Other agriculture	price shocks	3.45%	3.55%	-0.10%
Paddy and processed rice	Ukraine impacts	0.43%	0.43%	0.00%
Paddy and processed rice	Russia shocks	0.18%	0.20%	-0.02%
Paddy and processed rice	price shocks	3.46%	3.49%	-0.03%
Pulses	Ukraine impacts	0.63%	0.63%	0.00%
Pulses	Russia shocks	0.45%	0.44%	0.01%
Pulses	price shocks	3.24%	3.31%	-0.07%
Roots and tubers	Ukraine impacts	0.43%	0.43%	0.00%
Roots and tubers	Russia shocks	0.68%	0.68%	-0.01%
Roots and tubers	price shocks	2.92%	3.02%	-0.09%
Sugar cane, sugar beet	Ukraine impacts	0.47%	0.47%	0.00%
Sugar cane, sugar beet	Russia shocks	0.36%	0.36%	0.00%
Sugar cane, sugar beet	price shocks	4.77%	5.00%	-0.23%
Vegetables	Ukraine impacts	0.50%	0.50%	0.00%

Vegetables	Russia shocks	0.66%	0.66%	0.00%
Vegetables	price shocks	3.17%	3.27%	-0.10%
Wheat	Ukraine impacts	1.99%	1.99%	0.00%
Wheat	Russia shocks	3.69%	3.67%	0.02%
Wheat	price shocks	3.91%	4.27%	-0.36%
Nitrogen fertilizer	Ukraine impacts	0.74%	0.74%	0.00%
Nitrogen fertilizer	Russia shocks	-0.06%	-0.06%	0.00%
Nitrogen fertilizer	price shocks	12.97%	13.65%	-0.69%
Phosphorus fertilizer	Ukraine impacts	0.10%	0.10%	0.00%
Phosphorus fertilizer	Russia shocks	0.16%	0.18%	-0.01%
Phosphorus fertilizer	price shocks	2.95%	3.04%	-0.08%
Potassium fertilizer	Ukraine impacts	0.20%	0.20%	0.00%
Potassium fertilizer	Russia shocks	0.29%	0.30%	-0.01%
Potassium fertilizer	price shocks	2.70%	2.77%	-0.07%

Additional scenario results

GDP effects are presented in two panels in Figure S3 because country effects differ in scale. The top panel shows GDP effects in Ukraine and Russia. Ukraine's GDP decline (about 30%) is due to the (assumed) strong decline in the labour and capital endowments, which holds for all three scenarios. Russia's GDP decline (about 10%) is based on our interpretation of IMF expectations about the country's potential recession, emerging in scenario 2 and 3. Outside Ukraine and Russia, GDP impacts are limited, with strongest impacts on 'Central Asia' of -0.5%. The assumed increase of energy prices (Ukraine, Russia, energy prices impact, scenario 3) has a strong GDP impact in all regions. For example, for the EU GDP declines by 0.2% in the energy price scenario, whereas GDP effects are about 0.0% in scenario 1 (Ukraine impacts) and scenario 2 (Ukraine+Russia impacts).

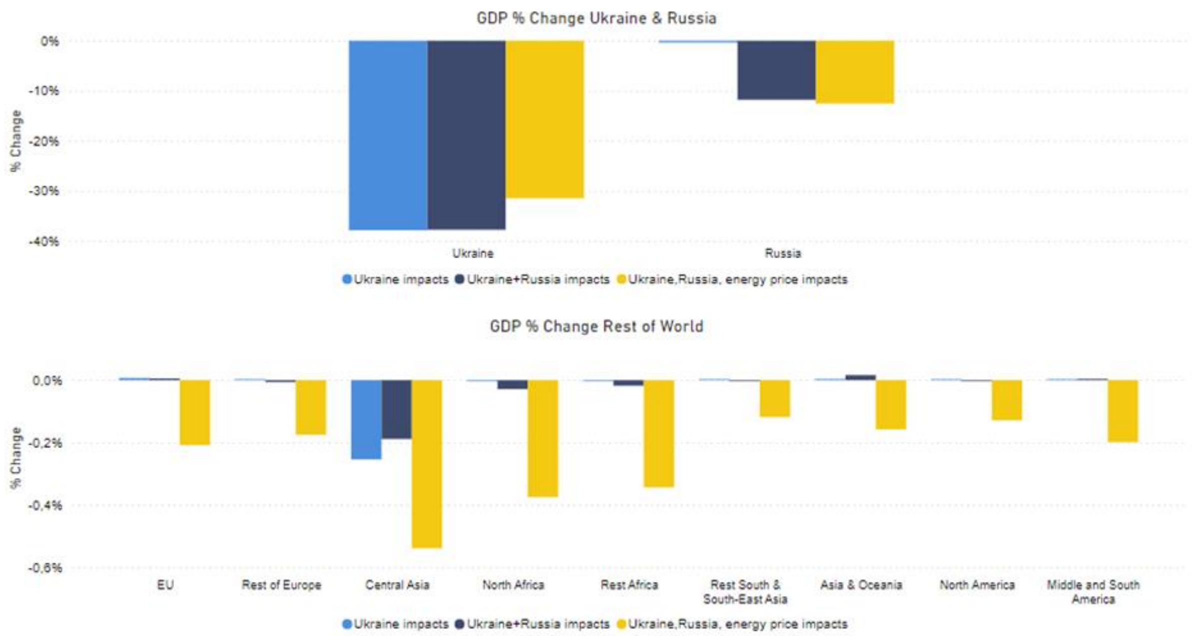

Figure S6 GDP developments (% change)

Production

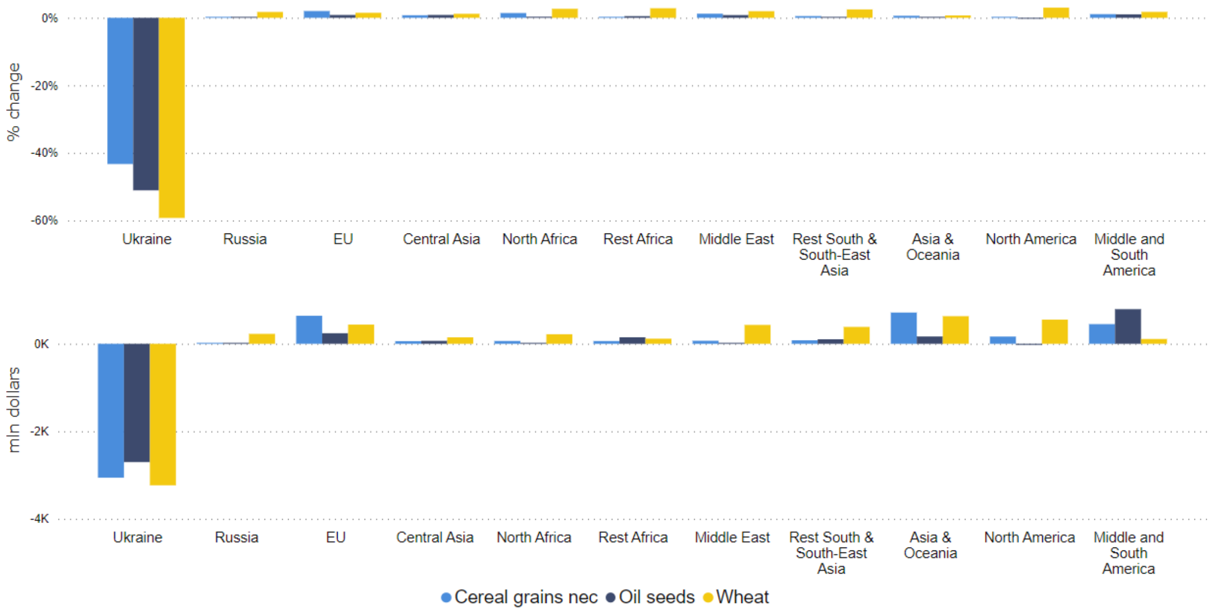

Figure S7 Production volume developments (% change in upper panel, absolute change (million US dollars) in lower panel)) for wheat, oilseeds, and other cereals in the Ukraine impacts scenario (scenario 1)

In the Figure above and below the production effects are also shown when only Ukraine impacts (scenario 1) and Ukraine-Russia impacts (scenario 2) are applied. If only Ukraine impacts (scenario 1) are applied, then Figure S4 shows that different regions slightly increase production. Wheat production is expanding in Asia and Oceania, North America, Rest of South, Europe, Middle East, Southeast Asia, and also a little in Russia. For other grains, production expands especially in Europe, Asia, and Oceania, and Middle and South America. Oilseed production expands especially in Middle and South America. Figure S5 (below) shows the impacts of the Ukraine-Russia scenario (scenario 2) in which wheat production in Russia in particular is negatively affected and production increases mainly in Central Asia and the regions that also do so in scenario 1. Some additional Figures on world price decomposition, trade and consumer prices impacts are provided below to provide additional information, although they are not refered to in the main text.

Figure S8 Production volume developments (% change in upper panel, absolute change (million USD) in lower panel)) for wheat, oilseeds, and other cereals in the Ukraine Russia impacts scenario (scenario 2)

World price decomposition

Figure S9 Decomposition: World price impact of agricultural commodities in each scenario (% change).

Trade in Ukraine impacts and Ukraine-Russia scenarios

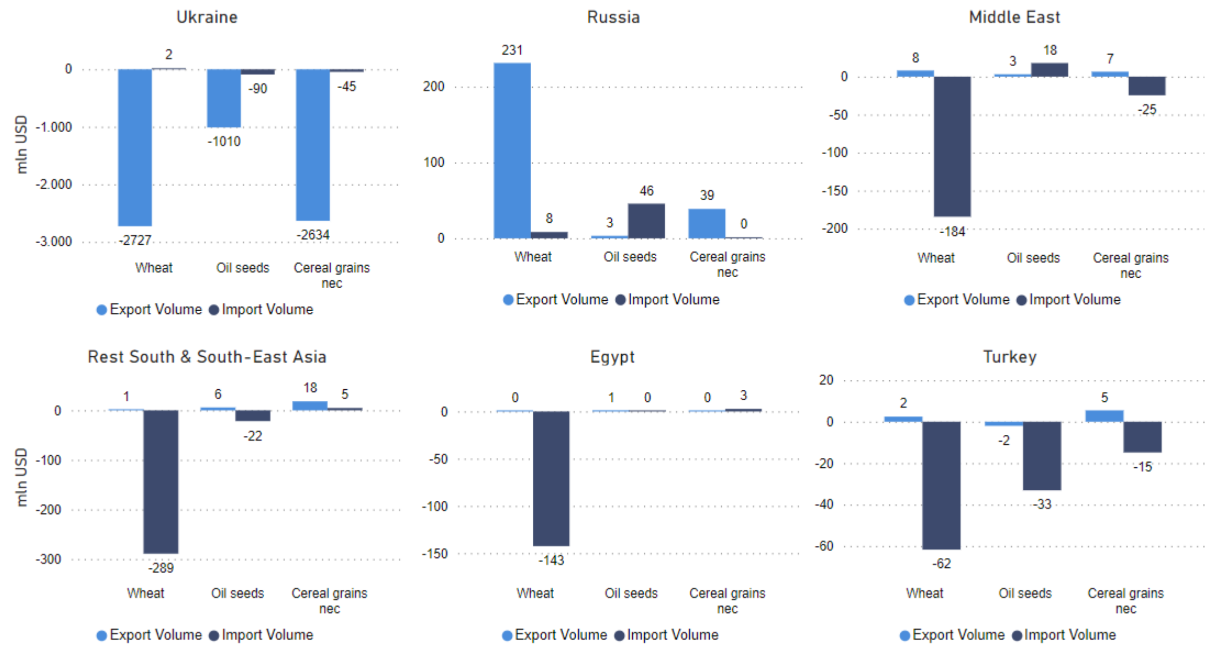

Figure S10 Changes in exports and import of wheat, other cereals and oilseeds, Ukraine impacts scenario (scenario 1, absolute change in million USD)

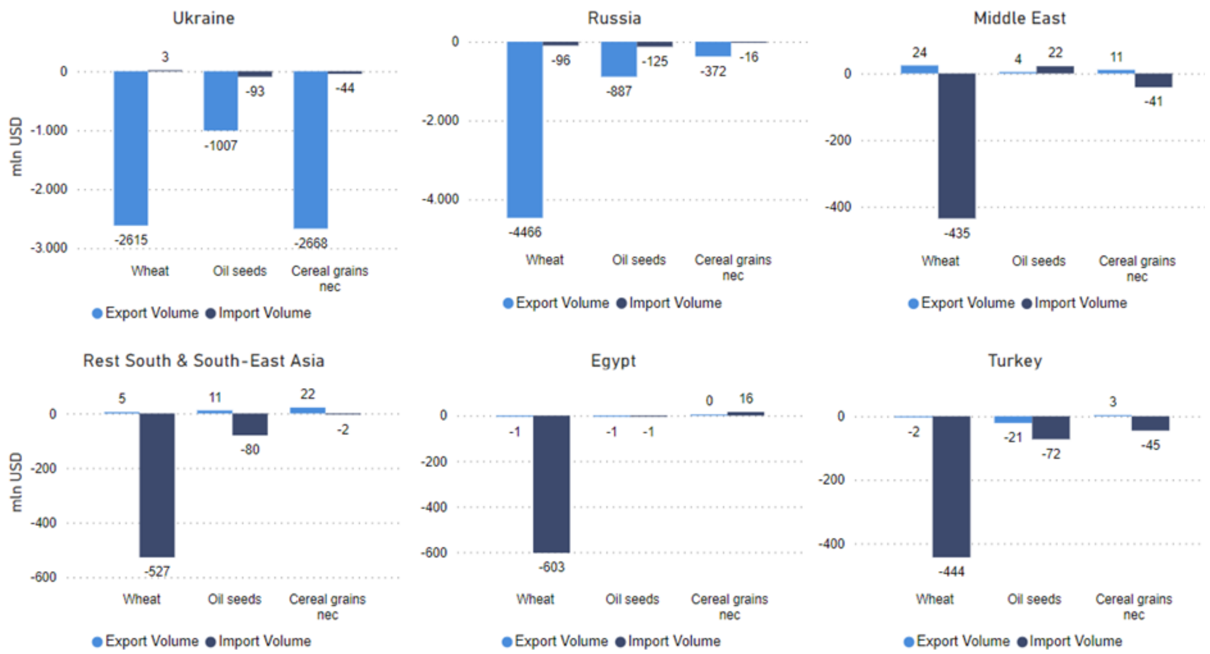

Figure S11 Changes in exports and import of wheat, other cereals and oilseeds, Ukraine+Russia impacts scenario (scenario 2, absolute change in mln USD)

Consumer price impacts

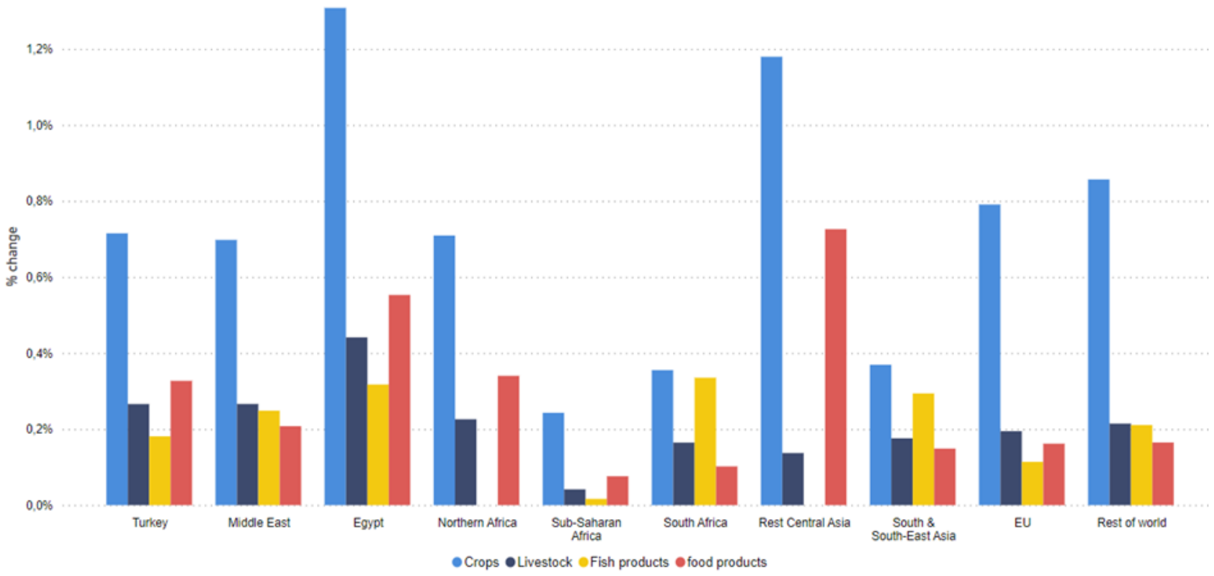

Figure S12 Basic consumer price impacts for different groups of agri-food products in Ukraine impact scenario 1 (% change)

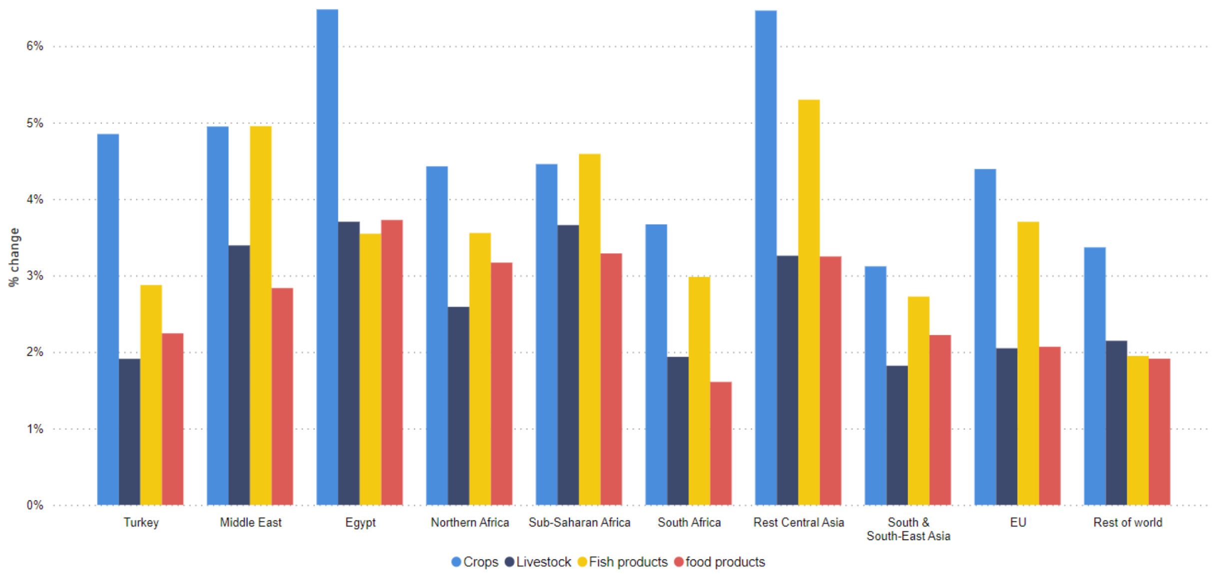

Figure S13 Basic consumer price impacts for different groups of agri-food products in Ukraine, Russia, energy prices impact scenario 3 (% change)

Results of high energy price sensitivity scenario

The standard energy scenario assumes an energy price increase of 20% (on the eve of the invasion day Brent crude oil was traded at US$92/Bbl and stabilized around US$ 110/Bbl in June 2022, IEA, 2022). As part of the energy price increase before the war might be due to Russia military tension we performed a sensitivity analyses 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 and 17th of June). The results of the sensitivity analyses are presented in this section.

Figure S14 Production volume developments (% change in upper panel; absolute change (USD million) in lower panel) for wheat, oilseeds, and other cereals in the Ukraine-Russia-double-energy price impact scenario (scenario 3)

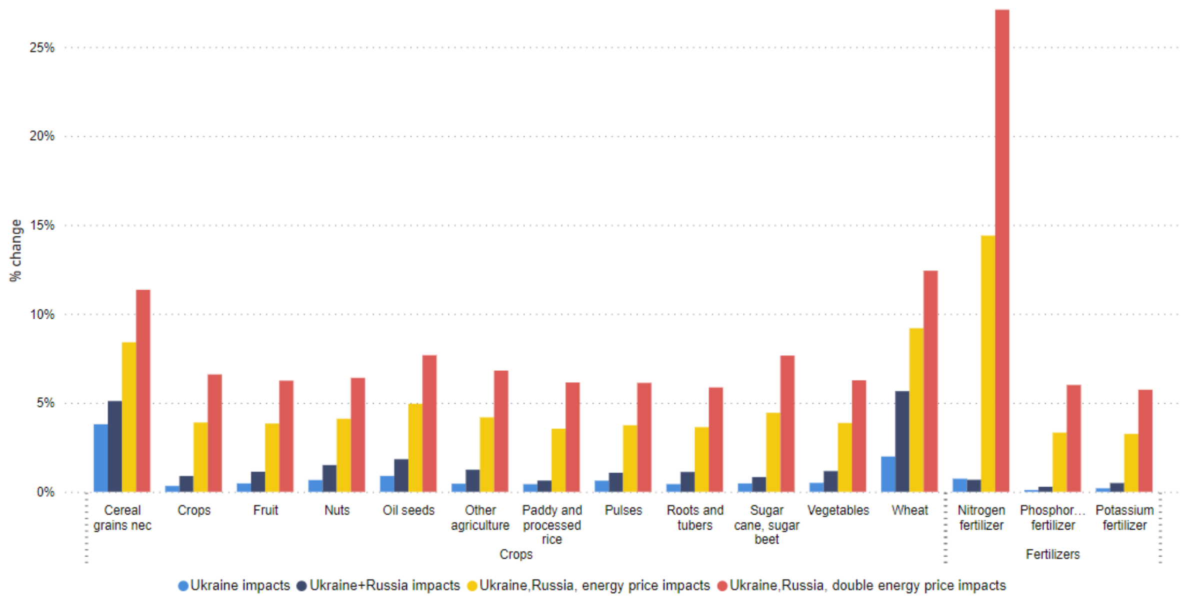

Figure S15 Development of world crop and fertiliser prices, including high energy price sensitivity scenario (% change)

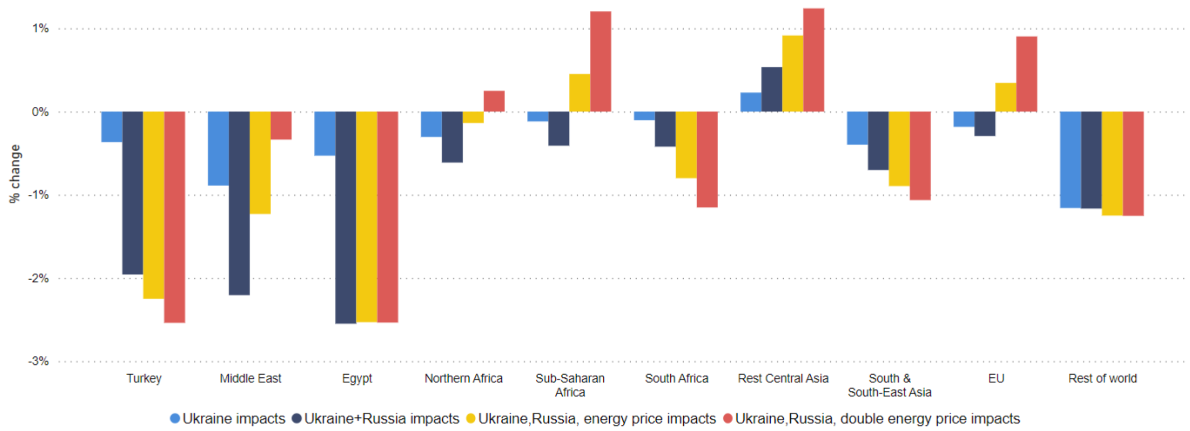

Figure S16 Indicators for food availability within Ukraine-Russia-double-energy price impact sensitivity scenario

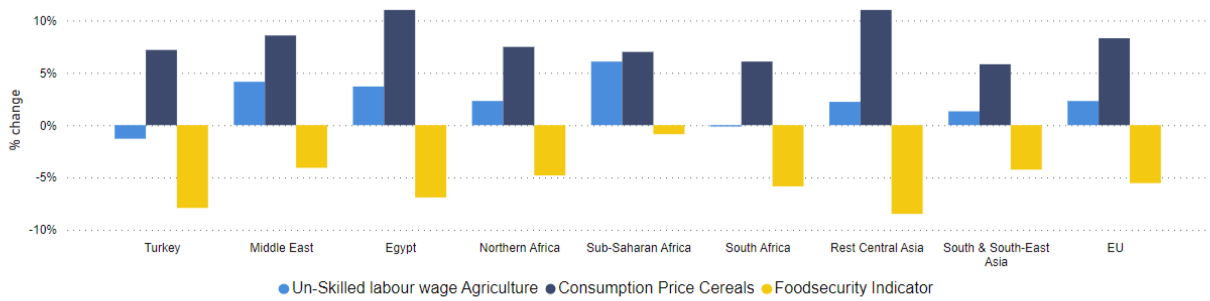

Figure S17 Indicators for food access, based on a cereal diet (including paddy rice, wheat and 'other grains') for unskilled (production) workers in the agricultural sector. Ukraine-Russia-double-energy price impact sensitivity scenario.

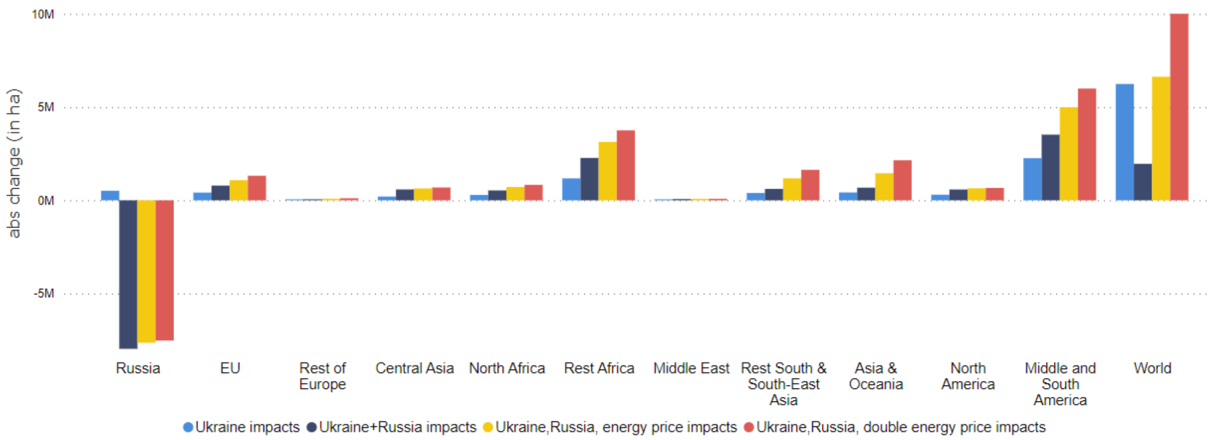

Figure S18 Developments of global and regional agricultural land use (ha), including high energy price sensitivity scenario.

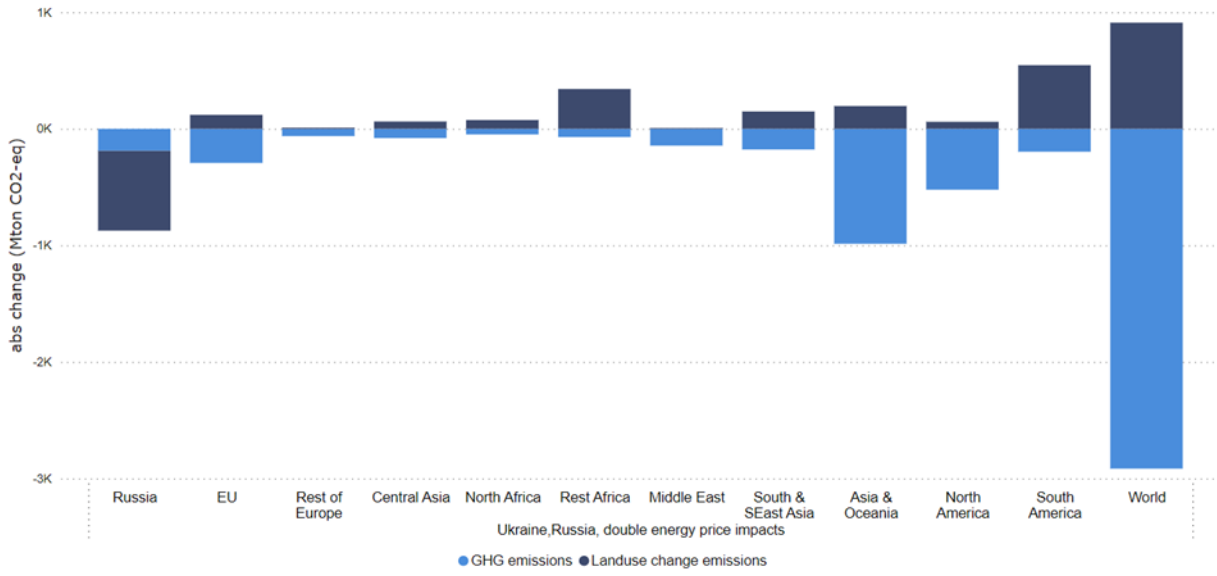

Figure S19: Developments of regional and global GHG emissions due to land use change (dark blue) and all other sources (e.g. fossil energy use (e.g. fertilizer use) and animal production, light blue), high energy price sensitivity scenario, Mton CO2-equivalent.

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