Another food crisis? The Ukraine conflict, global wheat supply and food security

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Abstract

The food security impacts of the Ukraine crisis are likely to reverberate over months, if not years, to come. Recent decades have seen geographic concentration of global wheat production. At the same time, drought, other weather extremes and persistent pest and disease pressure, have exacerbated volatility in wheat yields, exports, and prices. The current crisis in Ukraine ushers in substantial new pressures on global wheat markets and tremendous risks for vulnerable populations around the world. If reductions in wheat exports from Ukraine and Russia are as severe as anticipated, global supplies of wheat will be seriously constrained. If fertilizer exports are also impacted, the resulting drop in global agricultural productivity will tighten global markets for wheat, other grains, and alternate food sources, and vulnerable people all over the world will face higher food prices, hunger, and malnutrition. Multidisciplinary research, including lessons learned in past crises, is needed to shape responses to the current crisis that protect modest progress made toward gender equality, biodiversity conservation, and dietary diversification. With these multi-layered crises in view, we propose essential actions to mitigate near-term food security crises, to stabilize wheat supplies in the medium-term, and to transition toward long-term agri-food system resilience. Large and sustained agricultural research investments must be a foundational element of any viable, food-secure future.

Geographic concentration and biophysical vulnerability in wheat production

As a primary commodity, wheat is a critical component of the global trade that underpins food security and functioning agri-food systems. Numerous wheat-producing countries across a range of production environments export wheat (Figure 1a) although the largest proportion of export-destined production occurs in a small number of countries (Figure 1b).

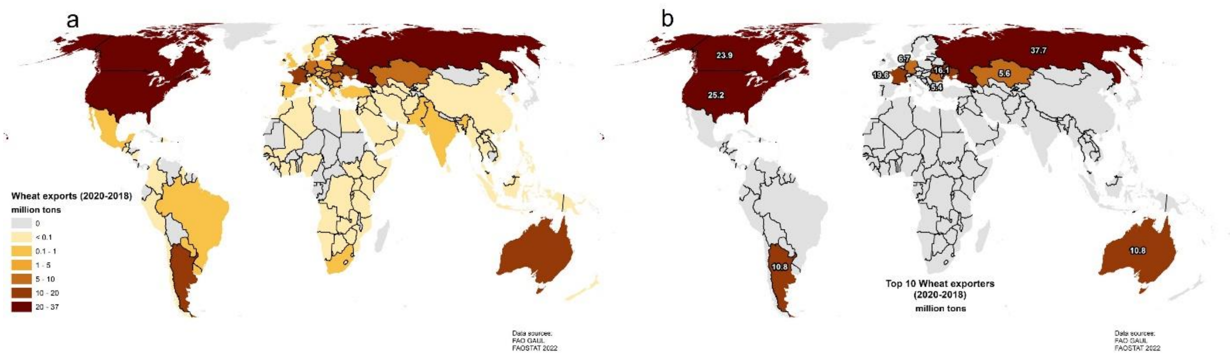

Figure 1. Global wheat exports as a 3-year (2018-2020) average in million tons across (a) all wheat exporting countries and (b) the top ten exporters. Maps were generated using ESRI Arcmap 10.8.1 using political country level boundary data from FAO (GAUL 2015) and food balances data from FAOSTAT (2022).

The dynamics of global wheat trade have shifted over time and export levels per country over the period 1960-2020 can be dynamically visualized: https://public.flourish.studio/visualisation/4955869/ (Sonder, 2022). Dominance of the wheat exports by a small number of countries places inherent vulnerabilities on the global food system. This has been observed when changes to wheat export policies led to price spikes and food-related crises (Martin & Anderson, 2011). The risks and vulnerabilities to food security are particularly acute for wheat-importing countries in the Global South. Figure 2, which traces global flows of wheat imports, indicates countries at greatest risk to food insecurity from reduced wheat supplies.

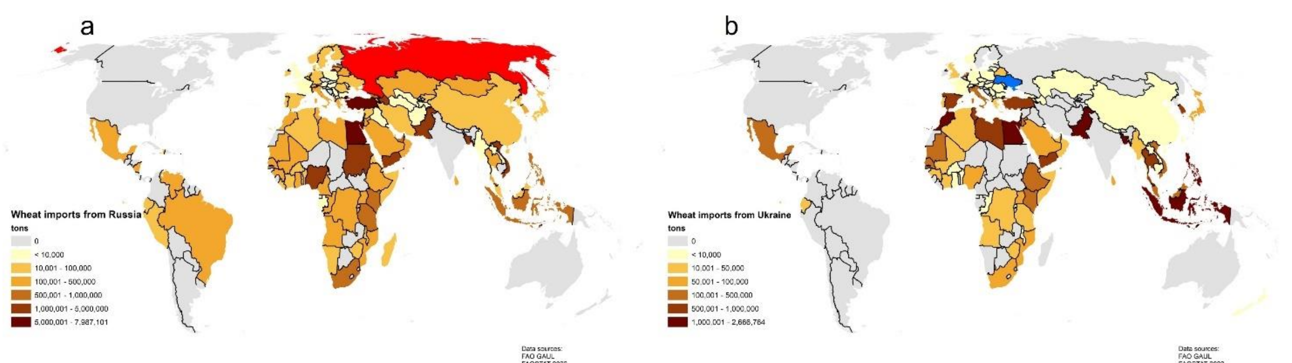

Figure 2. Global wheat imports in tons based on 3-year average (2018-2020) from (a) Russia and (b) Ukraine indicate countries with specific short-term vulnerability. Maps were generated using ESRI Arcmap 10.8.1 using political country level boundary data from FAO (GAUL 2015) and food balances data from FAOSTAT (2022).

The risks to global food security caused by the concentration of wheat exports responds, in part, to biophysical vulnerability caused by abiotic (e.g. climatic conditions) and biotic (e.g. pests and pathogen) stresses. The threats of climatic instability on wheat export potential, as well as on domestic and regional demand, are becoming more marked over time. For example, recent drought conditions in wheat production seasons in northern wheat-growing regions of the United States led to a reported 21% reduction in carryover of wheat grain in 2022, the greatest reduction since 2014 (USDA, 2022). This led to a February 2022 projection of reduced US export capacity (USDA, 2022). Similarly, in wheat-producing prairies of Canada, 2021 production fell by over 38% due to hot and dry conditions (Statistics Canada, 2021). Recent media reports from China indicate government expectations of reduced winter wheat production in 2022 due to delayed planting caused by heavy rains (Reuters, 06/03/22). In addition to abiotic factors, we also see the confounding negative effects of climate variability on pests and pathogens with major potential to lower global supply. Early reports indicate that this is currently happening with a large increase in wheat yellow rust (*Puccina striiformis* f. sp. *tritici*) in Nepal. This is currently the most damaging disease of wheat on the global scale. When taken as annual variations, these component effects can potentially be mitigated, but intensifying climate-related risks are increasing the likelihood of so-called multiple breadbasket failure (Janetos *et al.*, 2017).

The Ukraine crisis and wheat: spark for a food price shock?

In 2020, Russia and Ukraine produced 28% of the world's total wheat exports (FAOSTAT, 2022) and Russia is a globally important source of fuel and fertilizer. Since 2016, Russia has been the world's top wheat exporter, with exports rising from 26 million metric tons in 2016 to 37 million metric tons in 2020 (FAOSTAT, 2022). In 2021, Ukraine ranked as the world's fifth largest wheat exporter, exporting just under 20 million metric tons (FAOSTAT, 2022). At pre-crisis levels, the 3-year average (2018-2020) of wheat exported from Russia was 37.7 million tons and 16.1 million tons from Ukraine (Figure 1b; FAOSTAT, 2022). In 2008, food price spikes and food-related crises resulted, in part, due to policy actions by major wheat and rice exporting countries implementing, including export bans, taxes, quotas (Mitra and Josling, 2009).

The uncertain fate of Ukraine's 2022 wheat crop

Global wheat trade is dynamic, tying together the biophysical parameters of production with demand timepoints, quality specifications, and volume requirements for processors and consumers. Over 65% of Ukraine's wheat export occurs between July to November following the mid-year harvest (June to July). Even if the conflict were to subside before mid-year, displaced labor, lack of inputs and broken infrastructure will present major barriers to harvest. This raises questions regarding current supply potential: (i) What is the fate of the 6 million hectares of winter wheat crop currently growing across the arable land area in Ukraine? and (ii) What is the likely timeline and mechanism for distributing any resulting supply to meet specific country (as well as global) demand? Media reports indicate that there are significant quantities of wheat that are already contracted for export, but remain stuck in Ukrainian ports closed as a direct result of the current conflict. The potential and feasibility of spring planting is also unknown, although assumed to be a priority. Likewise, the introduction of export licensing may limit exports during the current season.

In addition, wheat export relies on a functioning governmental and logistics system, as well as operational ports and waterways. It was recently reported by Ukraine's Head of Maritime Administration that over 100 foreign-flagged ships were "blocked in Ukrainian seaports by the Russian navy" (Reuters, 28/02/2022). Damage to foreign vessels in port has also been widely reported, as has the seizure of Ukrainian ships and direct damage to Ukrainian port infrastructure. In particular, significant damage has been reported in ports on the sea of Azor which is typically the launching point for wheat exports to the Mediterranean, including Egypt, Lebanon, and Turkey. This raises significant concerns about existing consigned grain shipments, as well as shipments from the coming wheat harvest. At the same time, insurance premiums on shipping are increasing worldwide and are likely to have a knock-on effect on food prices (and prices of other goods). Drastic shortages of labor and broken transport, processing and warehouse infrastructure within Ukraine will reduce local supplies of wheat-based food and imply serious food security threats to the population of Ukraine.

Potential for restricted exports from Russia

Over the past two decades, Russian wheat production and export volumes have surged beyond expectations. As recently as 2010, predictions were that Russia would remain a relatively minor player in world wheat trade. "Tempered interest in recovering marginal land, farmers' financial constraints, limited infrastructure, conversion of grain area to fodder crops, issues with land ownership and tight competition in the world grain markets could potentially limit Russia's export opportunities in the coming decade" (FAS 2010). During the three years 2018-2020 Russia produced, on average, 78 million MT, compared to 44 million MT produced on average between 2000-2002. The area dedicated to wheat production has increased (shift from small grains) as well as higher productivity from improved technology and favorable weather. Investments in infrastructure, from increased port capacity, to improved rail capacity and on-farm storage have contributed to the growth in export. Russia is a major supplier to markets in the Middle East and Africa, with growing market ties to Latin America and Asia. Media sources announced a Russian temporary ban on gain exports (wheat, maize, rye, and barley) to ex-Soviet countries till mid 2022 (Reuters, 14/03/22). Financial sanctions imposed on Russia are likely to have a strong effect on the export of wheat and other vital crops as the financial industry that underwrites the country's commodity businesses are blacklisted and global maritime shipping companies announce cessation of operations in Russia (Foreign Policy, 02/03/22).

Risks to global wheat markets and vulnerable populations

The ongoing conflict in Ukraine has directly impacted the global wheat price, raising wheat futures at a near-linear rate to their highest levels since 2012 (Nasdaq, 2022). The current crisis poses extensive risk to over 100 million tons of global wheat supply. It has also increased demand for alternative grains such as maize, where Ukraine also accounts for 15% of total global exports (FAOSTAT, 2022). In the months leading up to the conflict, wheat prices were already elevated, influenced by relatively tight supplies in key exporting countries (Andrew and Swearingen 2022). Indirectly, the trade restrictions due to sanctions on Russia have increased worldwide energy and transport costs and restricted fertilizer exports, further elevating wheat prices and disrupting wheat markets. With over 2.5 billion people worldwide consuming wheat-based products the food security impacts of supply changes (linked to price) are likely to be inequitably felt.

Dependence on wheat imports from Russia (Figure 2a) and Ukraine (Figure 2b) imperils food security in lower- and middle-income countries in North Africa and the Middle East (Egypt, Libya, Algeria, Morocco, Yemen), the Mediterranean (Turkey, Azerbaijan), sub-Saharan Africa (Sudan, Nigeria), South Asia (Pakistan, Bangladesh), and throughout Southeast Asia. Egypt annually consumes 21 million tons of wheat of which over half is imported. In 2021, 50% of its import provision came from Russia and a further 30% came from Ukraine. Disruption to this supply is likely to have significant ramifications. Likewise, some of the most food-insecure countries in the world (Yemen, Sudan, Bangladesh) are highly reliant on wheat imports from Russia and Ukraine. This poses significant social and economic concerns for short-, medium- and long-term food security.

Given the chronic challenges of geographic concentration and biophysical vulnerabilities of global wheat sourcing areas, the Ukraine crisis could spark regional or global food shocks by disrupting wheat supply and hampering global agricultural productivity (Bentley, 2022). We are likely to see a range of negative effects over the short-, medium-, and long-term including:

- Severe food insecurity and economic impacts due to reduced global wheat supplies and price increases affecting all wheat-importing countries and humanitarian agencies such as World Food Program (WFP).
- Diminished global agricultural productivity due to fertilizer supply limitations and price escalation, especially in low-income, fertilizer-import dependent countries (e.g. Malawi).
- Tightened local and global markets for cereal grains and many other agricultural commodities with corresponding impacts on food traders and others involved in logistics and food processing.
- Higher food prices and expanded global hunger and malnutrition because of tighter fuel supplies driving up costs in agricultural production and value chains.
- Pressure on household budgets negatively affecting nutrition, health, education, and gender equality.

Few communities would remain unaffected by a global food shock given the highly interconnected nature of contemporary agri-food systems. However, negative effects will be experienced disproportionately in the most vulnerable countries, including those that are dependent on humanitarian food aid (Bentley, 2022).

Coordinated action to lessen short-term impacts and diversify global wheat supplies

With these multi-layered crises in view, we propose essential actions to mitigate near-term food security crises, to stabilize wheat supply, and to concurrently transition toward agri-food system resilience. Overall, we see three discrete, but interconnected opportunities: (1) mitigation of near-term food security effects; (2) increasing the resilience of global wheat supply across scales from local to global; and (3) a wider transition to system-level resilience.

1. Responding to food price shocks: Mitigating the immediate crisis

a. Increase productivity in traditional wheat-growing regions

Wheat is grown across a wide range of production geographies. Production can be stimulated to meet increasing demands in developed countries by expanding land area (or production per unit area) where there is capacity for high-performing wheat systems (e.g. predominantly in the Global North and irrigated areas in the Global South). Improving current production in lower productivity areas of wheat production (e.g. predominantly in rainfed environments in the Global South) can increase self-reliance in developing countries. In both cases, extensive learning around sustainable intensification and a broad basket of technologies variously referred to as agroecology, ecological intensification, regenerative agriculture, or nature-based solutions for agriculture, can and should be leveraged to shape more sustainable and resilient production without exacerbating environmental harms.

<u>Opportunities in the Global North</u> – In North America, yields have gradually risen despite a multi-decadal trend of declining wheat acreage in response to market conditions. In the United States, high demand for biofuels as well as advances in maize and soybean genetics in the last decade have incentivized farmers to switch from wheat to maize and soybean production (Searchinger *et al*., 2008; Liefert *et al*., 2010). Relative to maize and other high-fertilizer requirement crops, robust wheat yields can be obtained with modest fertilization. When fertilizer prices rise, growers respond by shifting their field crop acreage towards wheat. With global wheat stocks at a decadal low (50 million metric tons; Sowell & Swearingen, 2021), a substantial increase in wheat acreage is expected across Canada, the United

States, and Europe, where wheat yields are generally high, through displacement of other crops or conversion of land to agricultural use. Sizeable production gains are expected from expansion of cultivated wheat area as recent news reports indicate that farmers in several states in the United States are exploring options to expand wheat production (Reuters, 03/03/22).

Opportunities in the Global South – Global wheat supply can also be increased by reducing persistent yield gaps in areas where wheat is grown, but not achieving its full yield potential, especially in Asia and sub-Saharan Africa. Where average yields in the European Union and East Asia typically reach 5.3 t/ha, yields in South Asia and Africa (mainly Ethiopia and South Africa) are respectively 43% (2.3 t/ha) and 51% (2.7 t/ha) lower (Grote *et al.*, 2021). Suboptimal agro-ecological conditions such as temperature, rainfall, and soil quality are partly responsible for yield gaps. At the same time, yield potential in these areas is under increasing abiotic (such as drought, soil acidity and erosion) and biotic stresses (such as insects, fungi, and weeds), driven by changes in climate and land use (Waddington *et al.*, 2010; Lobell *et al.*, 2011). Increased disease pressure and reduced ability to effectively deploy control agents (such as fungicides for fungal infections) make the problem worse. Despite these conditions, better crop management practices such as increased use of improved seed, optimal fertilizer use, improved irrigation methods and pest and pathogen forecasting can lead to higher yields with environmentally sound practices (Sivanappan 1994; Waddinton *et al*., 2010; Araya *et al*., 2016). Bundled agronomic and breeding interventions can increase yields in low- and medium-productivity environments. These can be combined with Integrated Pest Management packages that are designed to concurrently tackle the negative effects on yield that result from compounding effects of pests and climate change. Value-adding activities, investments in rural infrastructure, and corrections to policies that drive down wheat prices (e.g. subsidies on improved wheat) could facilitate improvement in crop management.

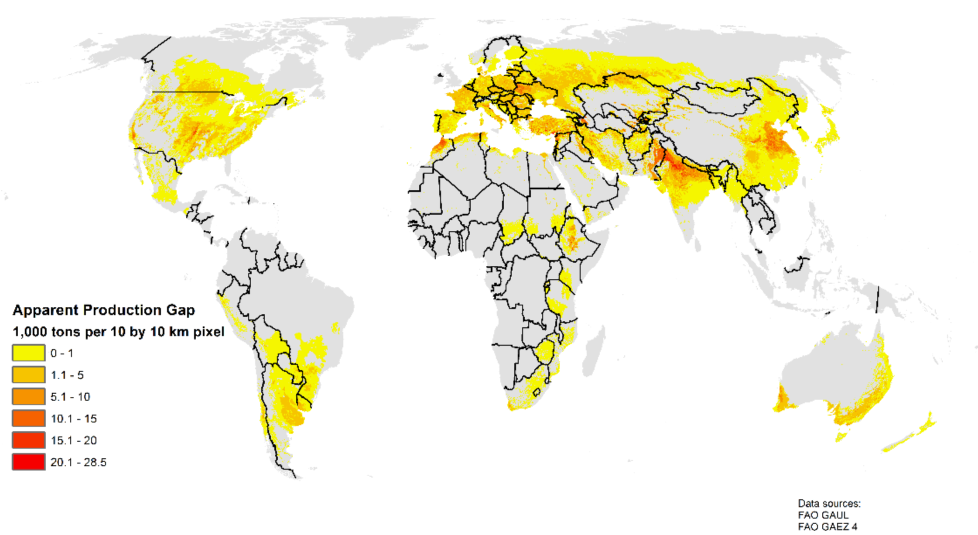

Figure 3. Assessment of productivity potential is inferred from analysis of apparent production gaps (Fischer *et al.*, 2021) across global wheat production regions. Current apparent production gap data uses sub-national statistics averaged from 2009-2011. The Apparent Production Gap represents the difference between what the International Institute for Applied Systems Analysis (IIASA) considers potentially achievable wheat yield and resulting production in a defined area. The achievable yield is determined by running crop models for location specific agro-climatic and edaphic conditions along with the reasonable use of inputs for both rainfed and irrigated areas at approximately 10 km resolution. The downscaled actual production and yield data derived from sub-national statistics are then generated at the same resolution and used to calculate both yield and production gap

for each 10 by 10 km pixel. Overall, this provides a high-level indication of areas where existing wheat production can be enhanced.

Efforts to boost yields in current wheat production areas would benefit from existing supporting infrastructure and knowledge (breeding, testing and seed systems). Wheat-producing regions worldwide have current productivity levels below theoretical maxima (Figure 3; Fischer *et al.*, 2021). For example, the USA Midwest has substantial potential for higher wheat yields, as does North Africa, the Indio-Gangetic Plain, Eastern China, Iran, and Turkey. The modalities of promoting increased production, however, will vary with environment and socio-economic context (Waddington *et al.*, 2010).

b. Coordinate grain supplies through market controls

For a long time, governments have resistant intervention in commodity markets to influence prices, utilization and production volumes, But, the rationale for market controls holds when high food prices exert negative impacts – in low-income countries, as well as on low-income people in wealthy countries – that become politically, socially, and economically unacceptable. Market interventions can be tailored to maintain production in different countries and regions. Coordinated and multilateral state approaches would be more effective than isolated interventions and could be addressed at the level of the United Nations.

Market controls on the demand side could conserve grain stocks for human consumption rather than industrial and livestock production. On the supply side, price guarantees for wheat and other grains could be (re-)instated to promote more stable and assured markets for farmers. Additional farm support – either subsidies and/or reduced taxes on agricultural inputs such as energy— could maintain a level of profitability without which farmers might disengage from production. In many second-tier producers like France and Germany, wheat production could be increased by encouraging crop switching, although collateral impacts on other markets would inevitably arise. Promoting wheat substitution for sugar beet in the northern hemisphere would push global supply toward sugar cane producers in the southern hemisphere (with non-trivial impacts on the sugar processing industry). Such policy approaches would be challenging, but not unthinkable under the evolving market circumstances.

c. Mitigate effects of rising grain prices through flour blending

Rising grain prices are likely to lead to increased flour costs, which will be passed on to final consumers and food-subsidizing governments. Use of lower-cost flour blends (referring here to blending of wheat flour with flour from another crop species) could partially offset flour price increases and, in some areas, reduce dependence on imported cereals by partially substituting wheat with indigenous, nutrient-rich and/or drought tolerant crops such as legumes, cassava, sorghum, and millet (Owusu *et al*., 2017; Monnet *et al*., 2019). Flour blends can be used for key staples such as bread, chapati (unleavened flatbread), or pasta as well as for biscuits or breakfast cereals (Noort *et al*., 2022).

Flour blending has been mostly explored as a means of improving human nutrition by increasing the protein, mineral, fiber, or vitamin content of flour. Food science discussions has addressed the implications of flour blending on cooking, texture, water absorption, color, aroma, or taste. Several studies have focused on consumer acceptance of blended flour products and the willingness to pay (Owusu *et al*., 2017; De Groote *et al*., 2021). A wheat-related food shock could justify rapid scaling up of research on this niche topic through testing and assessment of demand drivers. New research could explore the cost-reducing aspects of blending as the most relevant entry point for reaching low-to-middle income consumers in the Global South. Engagement of flour traders and processors would expand insight regarding consumer interest, costs of production, and potential revenues. High quality sourcing would depend on links with local farmers to ensure meeting production standards and volume requirements.

d. De-risk new sources of short-term supply

As the Ukraine crisis unfolds, many wheat-importing countries are seeking new wheat supply options and wheat-producing countries are seeking new sales opportunities. Some short-term constraints on grain availability may be reduced by bilateral agreements (e.g. by China, Bangladesh) to import Russian wheat, as well as commitments by countries increase export volume (e.g. India) in order to meet growing demand. However, when trade routes shift, the risk increases of geographically restricted pathogens and their variants entering new territories where phytosanitary measures may not yet be in place to detect these new emergent threats. For example, dwarf bunt of wheat (*Tilletia controversa*) has previously prevented large import volumes of Russian wheat into China, as it is not in the current pathogen distribution range (CABI/EPPO, 2012) and is a quarantine pathogen. Also, the risk to wheat yields posed by contaminated seed is substantial, as recently illustrated in the transmission of wheat blast from Brazil to Southeast Asia in 2016, causing severe outbreaks with yield losses up to 100% and affecting ~15% of Bangladesh's total wheat area (Islam *et al*., 2019). The disease has also now been recorded on wheat in Zambia, the first report of the pathogen in Africa (Tembo *et al*., 2020).

2. Increasing the resilience of wheat supply: local to global

a. Expand wheat production into new areas within agro-ecological boundaries

In areas that have a comparative advantage, expansion of wheat production into new areas can be a viable resilience strategy (e.g. in countries such as Sudan, Kenya, Nigeria, and Tanzania that produce wheat, but at a small scale). Comparative advantage in wheat production can derive from agro-ecological suitability, existing infrastructure or farmer support mechanisms, availability of germplasm for locally-adapted and climate-resilient varieties, systems for high-quality local seed production and distribution, or value chains for wheat-based products. *Ex ante* assessments of wheat production potential have shown that many developing countries have the biophysical resources to produce significant amounts of wheat (e.g. in the East African highlands and Southern Africa). This expansion should not mean opening more forest area for agriculture but rather informed use of marginal lands towards productive units.

Wheat expansion must also be aligned with national priorities. Following the 2008 and 2011 wheat price spikes, many countries charted pathways to wheat self-reliance. For example, throughout Africa many governments increased wheat planting areas from 2008 to 2009 (FAOSTAT Crop Production Data, 2008-2009). Some rural development frameworks and national food security plans include expanded wheat production as a food security strategy (e.g. as a double crop in Ethiopian midlands). The Government of Ethiopia has developed both a policy directive and implementation framework to achieve wheat self-sufficiency in a period of 3-5 years. The government has decided to significantly expand wheat production to less-densely populated lowland areas and to the midlands as a double crop where large tracts of land and significant water resources are available to support irrigated wheat systems. In 2021-22, irrigated wheat on about 400,000 hectares is expected to produce 1.6 million tonnes (New Business Ethiopia, 02/01/22). On the other hand, Rwanda's Fourth Strategic Plan for Agriculture Transformation (2018 to 2024; Aragie *et al.*, 2022), for example, recognizes the absence of a comparative advantage for expanding domestic wheat production. Instead, the focus in Rwanda is on higher-value crop cultivation for both domestic and export markets.

b. Support national and regional pathways to wheat self-reliance

As national agricultural planning shifts from a central focus on efficiency to a resilience-oriented model, there may be a stronger rationale for growing wheat in new areas where this is likely to provide elasticity and cost avoidance under food price crisis conditions. National planning may also consider the importance of regional wheat markets and agro-ecological 'territories' in developing appropriately scaled interventions. Facing an impending food crisis, governments may better appreciate opportunities presented by a regional seed sector approach to wheat seed research, regulation, multiplication, and distribution. Efficient humanitarian expenditure and international investment cannot often be framed as a national enterprise because economic activity, and agricultural systems in particular, span national boundaries (Poole, 2017).

National and international policies and regulatory frameworks shape public and private investments, prices of agricultural inputs and outputs, and the provision of agricultural services such as credit, logistics, education, and communications. Well-functioning seed systems, demand-driven agronomic support, and other elements of wheat self-reliance can be encouraged through shifts in local policy, regulatory, and sectoral contexts. Resilient systems for production and marketing of wheat and other crops depend on coordinated actions and investments by government agencies, NGOs, the private sector, and other value chain actors. In Mexico and Colombia, application of the Integrated Agri-food System Initiative (IASI) methodology (Govaerts *et al.*, 2021) has generated tactical plans for resilient staple crop supply based on synchronized public and private action at the national and regional level.

c. Provide comprehensive technical support

There are multiple lines of evidence that wheat yields can be increased two-fold or more in areas with agro-ecological suitability through improved agronomic practices including mechanization, crop rotations, weed control and increased/efficient use of inputs (Baudron *et al.*, 2019; Vasco Silva *et al.*, 2020). High returns are achievable from modest investments in improved seeds and agronomy, guided by information and communication technologies. Top-performing agronomic interventions include sowing seeds in rows, targeted use of fertilizer, improved pest control, and integration with legume crops and livestock systems. Nutrient use efficiency also needs to be optimized and circular systems hold promise. For example, recycling of urban wastes can cover a large portion of fertilizer needs in many countries. In Cairo, recoverable nutrients from human excreta would be sufficient to offset all of Egypt's annual phosphorus fertilizer imports (Trimmer and Guest, 2018). Ethiopia's slaughterhouse wastes would increase phosphorus supply by 50% (Simons *et al*., 2014).

It is also important to recognize that not all wheat grain is equal in terms of its processing attributes (Shewry and Hey, 2015). Depending on the desired end-use parameters and product usages in each region or area it is necessary for new varieties to meet specific grain quality criteria. Alongside this, accompanying input and management recommendations are required to allow producers to meet technical specifications for processing. With an estimated 15% of wheat grain production lost due to insufficient or inadequate storage, investments targeting grain waste can take advantage of relatively low-cost infrastructure (e.g. in-field storage; Njoroge *et al.*, 2019), especially in the Global South.

A comprehensive package of technical support for increased wheat self-reliance through biophysical optimization would encompass mechanization, crop management, input use, and highly productive, disease-resistant wheat varieties with threshold grain quality parameters. Continual provision of widely adapted resilient germplasm with complete packages of biological traits and acceptable processing characteristics (depending on local usage demands) is essential for supporting optimized production.

The CGIAR has a long history of providing improved germplasm to support global wheat production, accounting for over 40% of direct variety releases in South Asia, sub-Saharan Africa, West Asia, and North Africa between 1994 and 2014 (Lantican *et al.*, 2016).

While there are challenges to delivering advisory services, education, and access to input and output markets in the limited resource context of smallholder farms (Negassa *et al.*, 2013), these are the conditions which will enable wheat yield gains in response to rising demand. A wide range of digital and ICT tools are available to support farmer decision making. These offer the potential benefit of capturing data on preferences and decision making at a range of scales from farm to region. They can also be used to accelerate optimal input delivery, field management and pre-emptive wheat disease control. Recent innovations in digital-enhanced agricultural advisory services for wheat have met success in Ethiopia, which is the largest wheat producer in sub-Saharan Africa. To support equitable engagement in expanded wheat production systems, innovative outreach and input distribution tools must be designed and tested with attention to gender and social inclusion dynamics (Allen-Sader *et al*., 2019).

d. Support seed systems development

When functioning properly, wheat seed systems will give farmers access to varieties that are suitable to local growing conditions and that align with farmers' preferences (e.g. Rutsaert & Donovan, 2020). Many low-performing wheat production regions lack well-functioning seed systems and therefore do not adequately benefit from improved germplasm (i.e. low penetration of improved wheat seeds; low rates of varietal turnover; Krishna *et al*. 2014; Krishna *et al.* 2015). As a self-pollinated crop, saving and recycling of seeds over several years is common in many parts of the Global South, limiting replacement of varieties.

Seed systems, and agricultural input markets generally, reflect their socio-political contexts and dynamics in the wider economy. Given regional specificities, wheat seed system development cannot be easily globalized. This is particularly true for seed provision to small-scale, resource-poor farmers operating in risky and highly fragmented markets. Therefore, mapping existing wheat seed systems is a key step toward improved functioning including acquiring new data (possibly using 'citizen science'; Ryan *et al.* 2018) and analysing performance, competition, innovation, and gender and social inclusion dynamics (Spielman and Kennedy, 2016). In many cases, it is necessary to build a more efficient system on top of existing, if imperfect, seed systems, for example by linking informal seed enterprises (e.g. small-scale agro-dealers, which often provide a range of agricultural inputs and services) to more formalized seed systems.

The institutional architecture of seed systems innovation comprises formal public and non-governmental systems, and formal and informal commercial seed sectors and local market systems. Public-private partnerships are one means whereby the formal sector can engage with small- to medium-enterprises (SMEs; AGRA, Syngenta and CGIAR 2021). There are specific contexts, for example conflict-affected regions, where almost total private sector failure leaves public sector-NGO alliances (PUNGO partnerships) as the principal or only viable organizational model for seed systems and broader services delivery of all kinds within innovation pathways (Poole *et al*., 2018). Managing multistakeholder partnerships in such complex institutional environments requires integrating the perspectives and preferences of multiple stakeholders from among researchers, public sector organizations and regulators, small and not-so-small private enterprises, farmers, and even downstream market actors and food consumers.

e. Mainstream monitoring capacity

Satellite earth observation plays a major role in the provision of timely agricultural data, offering objective and transparent real-time data on crop conditions, planted area, and yield prospects across geographies and scales. As the crisis in Ukraine unfolds and field data become unavailable, remote satellite data are a vital tool for estimating cropping impacts in Ukraine and Russia for both the ongoing wheat season as well as for the upcoming spring/summer seasons (GEOGLAM 2022; Figure 4). These data are also pivotal for assessing production prospects in other wheat-producing areas, for early warning of potential supply shortfalls, and for quantifying interventions to increase wheat production to fill emerging supply gaps.

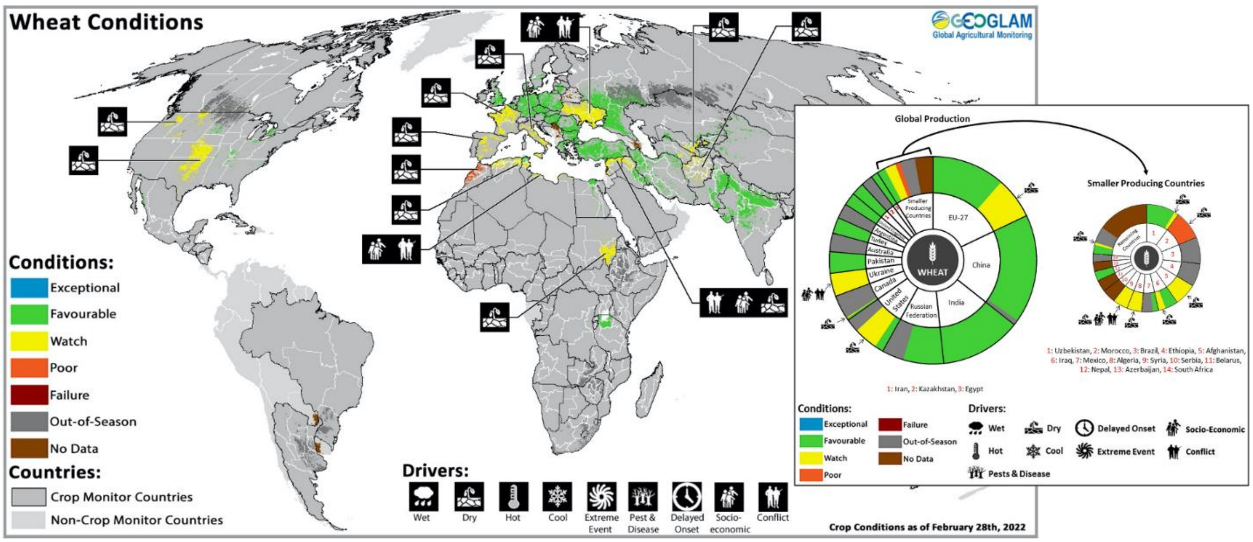

Figure 4. GEOGLAM Global Agricultural Monitoring of wheat conditions (as of 28th February, 2022), indicating areas with favorable production conditions and watch regions, including drivers of alert. Updates on production conditions are available via: https://earthobservation.org

While a major focus for satellite-driven monitoring systems is on quantifying the impact of weather on production prospects, they are increasingly being integrated with more granular ground data to support global pathogen surveillance activities. This will be increasingly important as expanded wheat production areas and shifting trade routes elevate the risk of pathogens appearing in new territories. Despite persistent calls, there remains a notable absence of a global inter-connected pathogen surveillance system for any major food crop, inhibiting the rapid deployment of effective mitigation strategies to curb the spread of any newly introduced threats (Carvajal-Yepes *et al*., 2019). Such a system would be particularly valuable in this volatile and fragile period, to prevent immediate alterations in trade choices having longer-term production consequences. The components of such a system already exist and could be rapidly mobilized, working with the many national and regional plant protection agencies worldwide to protect the remaining wheat supply chain in an impoverished market. The PlantVillage model (www.plantvillage.psu.edu) has shown how advances in AI, cloud computing and integrating satellite data makes a big difference in pest and pathogen mitigation and control. Satellite data derived advice from FEWS NET (https://fews.net/) is being cascaded to over 500,000 farmers per week in Kenya, and 8 million via TV with low-cost expansion to other countries like Burkina Faso, reaching 5 million on TV and 7 million on radio. An important discovery in implementation of this model was the role that young people play in helping farmers adopt and benefit from these technologies. This was critical to the successful control of the recent Desert Locust Crisis, saving food for 40 million people

(New York Times, 04/08/21). These young people, known as the PlantVillage Dream Team, now operate in 8 countries through the USAID Current and Emerging Threats to Crops Innovation Lab and this number will increase rapidly in the next 2 years. Further building on this, a genomics-based system for surveillance of threats in wheat seed exports could be implemented at the point of entry based on PCR testing and sequencing, which has become familiar to the world's population in the form of Covid-19 PCR testing for international travel.

3. Transition to system-level resilience

The steps described above to mitigate food shocks in the short-term and to stabilize local wheat supplies in the medium-term will not adequately protect the world from climate-related biophysical risks to food and nutritional security. In parallel, a transition toward long-term agri-food system resilience requires transformative investments in agroecosystem diversification, sustainable natural resource management, and low-GHG agroecosystems as well as meaningful actions toward achieving gender equality, nutritional sufficiency, and livelihood security. Large and sustained agricultural research investments must be a foundational element of any viable, food-secure future. For example, as the United States moves towards the re-authorization of the Global Food Security Act in 2023, there is important recognition of the interconnected threats (USAID, 25/03/21) and the critical role that research for development plays in enabling resilience (as highlighted in the 2022-2026 Global Food Security Strategy; USAID, 2022). This also stresses a cross-government approach and close engagement with critical partners like the CGIAR and national research agencies to deliver resilient agricultural systems that increase both national and global political stability.

a. Balancing food and agroecosystem diversity

Even before the current crisis, the UN Sustainable Development Goal 2 (SDG2) of 'Zero Hunger' by 2030 appeared to be well beyond reach, with the number of hungry people in the world increasing since 2014 (Poole *et al*., 2020). The world is also facing the reality of the 'triple burden' of hunger (undernutrition), hidden hunger (micronutrient and vitamin deficiency) and obesity (overnutrition) which reveals the underlying complexity of achieving equitable nutritional status. Evidence over time indicates that increases in agricultural productivity have not only reduced food prices, essential to poverty alleviation, but have also, by some measures and in combination with complementary interventions such as set-aside programs (Pierce *et al*., 2005; Rudel *et al.*, 2009), spared land area (Borlaug, 2007; Fuglie *et al.*, 2019). This tells us that the immediate food security priority should be on production and provision of low-cost staples such as wheat.

The essential role of cereals, and particularly wheat, in agri-nutrition is often overlooked (Poole *et al*., 2021; Bentley *et al*., 2022). Wheat provides both plant-based energy and protein at significant levels, while also supplying macro- and micro-nutrients, minerals, and oils in significant quantities given the volumes of wheat consumed in human diets. Wheat's provision of other potentially beneficial components (such as dietary fibre when consumed in wholegrain form) are also becoming more widely recognized (Ibba *et al.*, 2021). Taken together, despite political and social changes in support of wider diversification of farming systems and diets, for the foreseeable future, wheat will continue to remain as a significant income driver for rural communities and an essential energy and nutritional source for the world's population, and specifically for the world's poor.

However, it will be necessary to balance the need for increased wheat production with the need for climate change mitigation, biodiversity conservation, more resilient agroecosystems, and sustainable natural resource management. Expanding wheat production into unused or under-utilized land presents risks. Recent advances in spatial analytics and the growing availability of spatial information, allows for land suitability mapping for crops, including wheat (e.g., Sarkar *et al*., 2014; El Baroudy *et al*., 2016), to guide the expansion of production.

Informed decisions around agricultural crop expansion onto more marginal lands should involve careful attention to the role these spaces play in biodiversity conservation, carbon sequestration, and other ecosystem services. Jung *et al.* (2021) found that protecting the 30% of land most important for conservation globally can secure 60% of global biomass and soil organic carbon, reduce by 88% the extinction risk of terrestrial plants and vertebrate species and maintain 65% of clean water provision. Some of the priority areas identified (e.g. Ethiopian Highlands) overlap with areas with high apparent wheat production gaps (Figure 3).

While intensification is likely necessary to respond to the current crisis, the long-term resilience of wheat production systems depends on further research to identify promising approaches to increasing wheat production while improving resilience to climatic and other stressors, ensuring maintenance of dietary diversity, and balancing food security requirements with environmental impacts as much as possible. A rapidly expanding body of research on sustainable and ecological intensification, agroecology, and related topics can be used to navigate tradeoffs. Promising areas of further research include precision agriculture, wheat-legume intercropping (Tripathi *et al*., 2021; Mamine & Fares, 2020), conservation agriculture (Erenstein *et al*., 2012) and/or reduced tillage, and cereals-focused agroecological interventions—relatively underexplored up to this point (Sethuraman *et al*., 2021). Precision agriculture, and in particular precision nitrogen management, has been widely adopted by large-scale wheat farmers globally, permitting high yield with minimum environmental externalities (Diacono *et al.*, 2013; Lowenberg-Deboer and Erickson, 2019). The use of hand-held sensors could achieve similar results in small-scale farming contexts (Li *et al.*, 2009).

b. Recognize and address growing gender disparity

Gender-differentiated impacts of a looming food price crisis warrant attention, along with the gendered implications of responses. The food price crisis of 2008 exposed women's unique vulnerabilities, including their relatively limited control over resources and decisions, their heavy workloads that stand to increase in times of crisis, and their tendency to personally absorb food shocks by reducing their consumption when household food supplies fall short (Quisumbing *et al.*, 2011).

Proposed responses to wheat price spikes also have important implications for gender. For example, research suggests that flour blending impacts nutrition, often in positive ways. But there is a need for special attention to nutrition-related impacts on sensitive groups such as children and pregnant and lactating women. Additionally, although consumer preferences for blended flour for child nutrition are relatively well documented, preferences of other users are less well understood. Flour blending can lead to changes in processing and cooking times (Emire & Arege, 2012), which in many contexts could directly influence women's time allocations to these tasks as well as to the task of fuel collection.

Efforts to intensify wheat productivity or expand wheat production into new areas presents challenges in the context of gender relations. In many contexts, women tend to be more involved than men in production of crops for household consumption, while men are more likely to produce cash crops (de Brauw, 2015; Grassi *et al.*, 2015; Orr *et al*., 2016; Weltzien *et al*., 2019). Numerous studies have shown that men take increased control over crops, including crops traditionally managed by women, when the market value or productive potential of these crops grows (Carney, 2013; Geisler, 1993; Orr *et al*., 2016;

Weltzien *et al.*, 2019). Often, these shifts in control do not reduce labor requirements for women who are expected to continue supporting production despite their reduced control over decision-making and profits. As such, relatively high returns for wheat could shift or further cement control over production and derived benefits toward men. In India, women, who tend to have limited influence on decision making for wheat production in their own household, seek employment as laborers in wheat production on the farms of others. Such employment strategies may be threatened by agricultural mechanization (Farnworth *et al.*, 2022). Careful attention needs to be paid to the intrahousehold dynamics of wheat production, including gendered divisions of labor, access to markets for both inputs and final products, control over income derived from production, and how each of these elements shifts in response to changing price.

Gender-responsive design and monitoring of solutions will be needed at a minimum, to ensure that any food price spikes, or policy/programmatic responses do not disproportionately and negatively affect women. Gender-intentional solutions that actively address women's barriers to entry into growing wheat markets would need to go a step further. These might include explicit training of women farmers and targeted input supply and extension programs. These efforts would likely need to be paired with initiatives that either work to resolve women's broader resource constraints (especially related to land, inputs, and financial services) by transforming legal frameworks and social norms, or bypass these constraints by, for instance, supporting communal production pathways, including through women's groups.

c. Invest in knowledge systems for agri-food transformation

Enabled by decades of agricultural research, the world has managed to constrain the number and severity of food security crises through major gains in agricultural productivity. Scientists have led discussions on solutions to the complex challenge of increasing agricultural yields and ensuring stable, equitable food supplies. Investment in this work must be maintained to de-risk the status quo without undue tradeoffs to the environment, gender equity and livelihoods. At the same time, traditional research, which is often carried out in disciplinary silos and disseminated in academic journals, is not enough to support system-level transformation from efficiency to resilience in our globally complex, interconnected agri-food systems.

Knowledge and technology needs are extensive across production systems (e.g. wheat-legume intercropping; cereals-focused agroecological interventions), value chains (e.g. context-appropriate strategies for value addition: market development for inputs and services), monitoring systems (e.g. genomics-based surveillance), and social dimensions (e.g. gender implications of new production and consumption strategies; policy interventions). Investments are required in the science of agriculture as well as the science of effective policy interventions to reduce the risk of breadbasket failures (Janetos *et al.*, 2017), and specifically the risks to staple cereal crops such as wheat and maize. In the longer term, ensuring food security requires a renewed emphasis on larger scale investments in seed development, combating climate change, reducing losses pre- and post-harvest, and increasing the efficiency of food systems.

Generating such solutions depends on robust, multidisciplinary, and transparent research capabilities that fuel the transition to agri-food system resilience. CIMMYT, the global international wheat research center of the CGIAR, together with its partners has been working tirelessly to maintain wheat harvests around the world in the face of mounting disease pressures and climate challenges. The estimated benefit-cost ratio for wheat improvement research ranges from 73:1 to 103:1 (Lantican *et al.*, 2016).

Yet, research funding oriented toward agriculture in the Global South only rises when food crises occur, revealing the globalized risks of our highly interconnected agri-food systems, and then tapers as memories fade. For example, the funding peak for the CGIAR of $1 billion occurred in 2014 and was directly attributed to a surge in donor investment following the global food crisis (Alston *et al.*, 2020). This funding level then fell gradually to $737 million per year by 2020. Receiving only a small proportion of international agricultural research funding over time, the CGIAR has had limited ability to develop the long-term research capabilities that could mitigate or prevent short-term emergencies with medium- to long-term effects.

What do we expect to see from the current crisis? International attention is clearly focused on the many supply-related impacts of the current crisis (including, but not limited to wheat). It is likely that funding levels will increase to minimize food system impacts, including on the poor. New investment, particularly in the CGIAR, and CIMMYT, should both learn from the past post-crises' investment decisions and target more integrative solutions that build on their comparative advantage and delivery potential within the wider international agricultural landscape. One recent positive example is the $39 million investment by USAID to the Current and Emerging Threats to Crops Innovation Lab at Penn State. However, more funding is clearly needed to conduct and apply research for the necessary adaptive responses to multiple, intersecting threats.

Conclusion

Indications are that much of the Global South is about to face another food crisis grounded on price spikes in wheat. Major media outlets around the globe are once again featuring headlines related to issues of wheat supply. While it might have been difficult to predict the current conflict between two of the world's major wheat exporting countries, the underlying fact that too much of the Global South's wheat supplies depend on a few countries has been known to many for a significant amount of time. Layered onto the existing concentration of wheat-sourcing regions and the climate-induced vulnerabilities in these essential global breadbaskets, the crisis in Ukraine and trade sanctions are triggering a level of volatility that could easily overwhelm existing mitigation mechanisms.

Without doubt, the world's top priority must be to mitigate near-term food security crises. This will involve boosting production through expanded acreage (e.g. in high-performing systems in the Global North) and closing yield gaps in the Global South (e.g. improved management of rainfed wheat-based production systems, value chains that deliver affordable inputs and services). Policy incentives such as price guarantees and subsidized agricultural inputs have a role to play in boosting local production. Short-term food insecurity can also be addressed through demand-side interventions, to include market controls to conserve grain stocks for human consumption and incentives for the use of lower-cost flour blends).

As these actions are taken, CIMMYT, the CGIAR and partners have an urgent role to play in helping to design strategies to build a more resilient wheat supply at local to global scale. Without doubt the issues are complex, further complicated by persistent gaps in data and knowledge and difficult tradeoffs to assess. Core strategies include expanding wheat production into new areas based on comparative advantage, assembling high-functioning seed systems and other elements of local wheat self-reliance, and establishing monitoring capacity for tracking spatial patterns of wheat cropping. Yet, these steps alone will not adequately protect the world from worsening food and nutritional security. In parallel, a transition toward agri-food system resilience will involve meaningful actions toward balancing food supply needs with those related to climate change mitigation and adaptation, gender equality, nutritional sufficiency, and livelihood security.

None of these critical functions are guaranteed given the oscillating global investment in agricultural research. Intensifying pressures and deepening complexity in agri-food systems demand large, sustained research capabilities that deliver integrative solutions that allow farmers and other agri-food stakeholders to mitigate and withstand shocks and achieve viable livelihoods.

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