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Cascading climate risks:
Towards adaptive and
resilient European Societies



Deliverable 3.6:

Report on preliminary impact and policy insights from model and sectoral case study analysis of WP3

Description:

This Deliverable provides a summary of, and distils key findings from, WP3 outputs to support policy analysis in WP6. Outputs of WP3 encompass the quantitative results of models applied to the exploration of the impacts of climate change on EU trade-linked systems, and qualitative analysis of stakeholder viewpoints - supplemented by information from the wider literature - which highlights key climate-linked concerns, potential responses, and interactions with policy. A synthesis section of the report aims to bring together outcomes of the analysis from each core research section and provides a summary of policy insights/implications. This summary, and the report as a whole, is intended to act as a starting point for (for food systems and soy supply chains) a more in-depth exploration of the policy environment that surrounds trade-linked cross-border impacts that will link to WP6 of the CASCADES project.

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Report on preliminary impact and policy insights from model and sectoral case study analysis of WP3

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1. Report overview

As highlighted via the examples provided in Carter et al. (2021) and West et al. (2021), trade-linked cross-border climate impacts have the potential to severely disrupt the European economy. Yet, the research landscape that surrounds these potential impacts remains in a relatively nascent stage. Importantly, whilst quantitative approaches can be applied in isolation to develop our understanding of cascading cross-border impacts, these should ideally be supplemented by the broader development of knowledge as to how initial climate triggers might evolve via trade systems, might interact with the actions and activities of supply chain actors, and how the wider policy landscape might act as an enabler or barrier to EU climate resilience.

The objective of this deliverable is to provide a set of preliminary policy insights resulting from a summary and synthesis of outputs from WP3 of the CASCADES project. Outputs of WP3 encompass the quantitative results of models applied to the exploration of the impacts of climate change on EU trade-linked systems, and qualitative analysis of stakeholder viewpoints - supplemented by information from the wider literature - which highlights key climate-linked concerns, potential responses, and interactions with policy.

The deliverable is divided below into three main sections. The first provides a synthesis and related policy implications based on a summary of the outcomes of research activities conducted in CASCADES WP3. Then, the remainder of the report is divided into discrete summaries of the analysis conducted. Analysis Section 1 summarises the quantitative outcomes of WP3 models. Analysis Section 2 summarises the qualitative components of WP3 within the form of three focal trade-linked case studies: a) food systems, b) the soy supply chain, c) energy transition minerals. The depth and breadth of these three case studies differs (more explanation on scope of coverage and methods applied can be found in Analysis Section 2). The Deliverable overall is intended to act as a starting point for (for food systems and soy supply chains) a more in-depth exploration of the policy environment that surrounds trade-linked cross-border impacts that will link to WP6 of the CASCADES project.

2. Synthesis and policy-linked implications

The analysis below, comprising quantitative outputs from CASCADES WP3 modelling work and qualitative evidence from the literature and expert interviews, provides an abundance of information regarding the potential exposure to, and resilience of, the EU to cross-border climate impacts. This is particularly the case in the context of agricultural and food trade and associated supply chains nested within the broader food system, which has been the focus of analysis conducted in WP3. Here, we summarise some of the key findings from across the work as a whole, drawing out points of intersection between the results of quantitative models and the opinions of stakeholders interviewed in the project. These findings reveal some considerations (highlighted in bold in the text below) relevant to ongoing policy development - and also research - that link to cross-border climate risks. We provide only initial insights and implications. Given the novelty of the topic, particularly in the eyes of many policy makers, additional work is warranted to analyse the way in which existing or emerging policy at EU or Member State scale should be developed or adapted to adapt to identified cross-border risks.

A first conclusion from this analysis is that uncertainty on the nature of cross-border climate impacts, their severity, and the way in which responses might manifest themselves, is high. Within model outputs we observe, for example (via the TWIST and soy analysis, see Sections 3.4 and 3.5), that different yield-projections from ISIMIP model combinations can result in very different (indeed, opposing) conclusions about the way in which food supply chains might be affected by climate change. Yet, despite some uncertainties of this kind, we also observe that more pessimistic results do not emerge just from single model parameterizations; multiple models suggest that significant negative outcomes could occur. Models also suggest that extreme climate change impacts are more likely. More recent model runs (e.g. from ISIMIP3b), which should provide improved projections, are also more pessimistic than earlier runs which is a cause for concern (Jägermeyr, 2021). This uncertainty, however, ultimately calls for a highly precautionary approach to be adopted; **no- or low-regrets measures (e.g. emergency reserves, monitoring systems, localised food supply systems, diplomatic measures to reduce the chances of market volatility etc.; see below for further discussion) to prevent, or at least prepare for, such crises should be considered.**

Uncertainties also abound across our interview participants' (see Section 4) responses. There were mixed feelings across the cohort of participants in soy and food systems about where key sources of risk might lie. For example, in our food systems case study, several stakeholders (in alignment with background literature such as Arvis et al., 2020) expressed the opinion that soy and oilseed supply chains (where the EU is relatively import dependent) might represent an area of particular risk. Yet, several (largely producer-side) soy stakeholders expressed a view that soy production was less vulnerable to risk compared to other crops. A challenge here in understanding the implications of these perspectives is that these uncertainties are likely to reflect both differences in levels of understanding of how 'threatened' a supply chain is (e.g. some downstream actors in the supply chain could not think of major shocks to date, but producers had countless examples), but also the perception of risk as experienced along the supply chain (e.g. producers might feel that they are better-off growing soy in comparison with other crops, whereas EU poultry farmers heavily dependent on imported soy feel relatively exposed). This makes it highly challenging to definitively assess which commodities or supply chains are most 'risky', but **underlines the importance - in order to try to promote understanding - of dialogue around perceptions of risk across and outside of the supply chain within common frameworks (such as the CASCADES conceptual framework).**

In order to overcome the challenges associated with uncertainty, it is also helpful to derive lessons from historical or current events; these can be enlightening in understanding the potential for climate change to result in equivalent shocks in future. This is something that the WP3 team has embraced as part of this work, drawing particularly on Covid- and Russia-Ukraine conflict-related examples across our quantitative and qualitative activities, with such examples often used by stakeholders to illustrate risk and responses. Yet, **whilst such examples can provide interesting insight and lessons for the future, they should also be used with caution;** a relative lack of exposure by the EU to historical shocks (or a lack of 'multi-breadbasket' shocks in the past) does not mean that the EU and its supply chains do not need to worry about the potential for more extreme, chronic, or

compound climate impacts that might arise in future. This again underscores the importance of applying the precautionary principle to such potential events.

In this study we observe that **models, such as those employed in CASCADES WP3, can provide important insights into the relative economic significance (including to the EU) of cross-border climate impacts.** However, within the context of the complex trade and economic systems that they represent, it is also clear that models are often subject to limitations and restrictions in scope. The conclusions they provide cannot be considered comprehensive. For example, the ICES CGE modelling framework (see Section 3) provides important insight into the potential for economic and production shocks to occur, but results are provided ‘in equilibrium state’, and therefore do not adequately capture the potential for significant disruptions ‘outside’ of these equilibria that may have important implications in terms of their cascading effects and policy responses. Such methods also assume ‘rationality’ of responses whereas, as highlighted in our interviews, it is often the unforeseen or irrational nature of human responses that is more concerning in times of crisis. Responses based on imperfect information, or skewed or limited perceptions of risk and response effectiveness, can magnify and drive risk in international trade systems. **‘Non-rational’, strategic and short-sighted responses – including by actors outside Europe – need to be factored into EU risk assessments and risk management strategies.**

The aggregated nature of the models employed in CASCADES WP3 also presents challenges for impact assessment; whilst incredibly useful for understanding the macro-economic implications of climate-driven changes in yield or disruptions in logistics, they are not granular enough to pick up the implications for more specific parts of the EU supply chain. Other modelling approaches (such as agent-based models, as one example) might be appropriate at such scales, and our interviews have also highlighted the **importance of developing models that can explore impacts at sub-sector level (which was often where stakeholders felt there might be important consequences for the EU arising from cross-border impacts).** Where quantitative work at such scales has been conducted (e.g. for soy, Section 3.5) analysis needs to continue to improve; for example to capture the explicit linkages between climate threats and actual impacts to infrastructure (participants revealed greater concern for waterways, for example, compared to road and rail infrastructure) and to encompass potential future structural changes in logistics and trade pathways that might be expected in addition to changes to crop-production.

A further, important, aspect warranting additional attention within model-based analysis is the potential for structural changes in trade and food systems that might arise during or after shocks; these ‘dislocations’ are not adequately captured within equilibrium-based models. For example, new trading relationships that might emerge received prominence in our interviews given the potential for these to affect geopolitics, and phenomena such as crop expansion and land use change (which have important implications for yields, but also greenhouse gas emissions) received attention within our soy case study. Overall, **the limitations described above in existing models are not surprising in the context of a nascent research field, but nonetheless warrant ongoing attention.**

The nature of how impacts are implemented within models is also important. CASCADES WP3 has modelled a number of different types of ‘shock’, from climate-driven yield changes, to the impacts of the Russia-Ukraine crisis, through to chokepoint disruptions. **It is important that shocks which crosscut the production, trade and consumption system continue to be explored; historically there has been a tendency to focus primarily on the longer-term impacts of climate change (e.g. yields).**

Going forward, attention also needs to be put to modelling the potential for ‘concurrent’ shocks to emerge. Here, analysis of climate-driven yield-changes linked to the ICES model, for example, did not also include the modelling of trade-related disruption of a similar type to that modelled in the separate Ukraine-Russia conflict scenarios. Yet, it is these ‘perfect storm’ type scenarios that have been highlighted as of particular concern in our stakeholder interviews (and such compound impacts are also highlighted in the recent palm oil example illustrated in Figure 15).

Furthermore, **model outcomes need to be elaborated beyond the implications for GDP or productive output so that they disaggregate impacts on different ‘groups’ of actors across the food system, including producers, traders and other companies, and consumers.** Our interviews reveal that many of the concerns stakeholders have in relation to cross-border impact relate not to the fact that the food (or soy) systems themselves will be vulnerable as a whole, but rather that impacts may affect particular communities or industries and/or may exacerbate inequalities. Also, for example, in the TWIST model outputs (Section 3.4), some scenarios result in increases in production variability under future climate change predictions, but decreases in price volatility. This type of result has potentially important implications for EU industry and policy (such as in relation to food storage facilities), and warrants further investigation. Finally, the translation of shocks to implement them within modelling frameworks is likely to require careful assumptions about how best to convert the shock into modelled parameters (particularly when models are constrained by their resolution or structure, see above). Alternative assumptions will potentially be valid, but will result in alternative results, highlighting **the importance, as the field continues to develop, of conducting sensitivity and intercomparison studies across models to gain consensus around common findings. Undertaking such work, however, is not trivial, and requires financial resourcing** such as long-term commitment from research funders.

A point of general coalescence across our models and case studies is the conclusion that, at a ‘systems’ level, cross-border climate impacts for the EU food system are expected to be relatively benign. The modelling work conducted suggests that there may be potentially important effects in terms of economic profitability or regional and sectoral productivity that might result from shocks, but impacts in percentage-terms are relatively minor across the scenarios modelled. These findings are in general alignment with previous studies. They also appear to align with the general views of stakeholders who, whilst expressing some concerns, appear to share some consensus around the fact that the EU food system should be relatively resilient in general terms. **These conclusions must take the model-linked limitations described above into account, also being mindful of the fact that whilst the risk of severe threats to EU food security may not be of high concern, this does not**

mean that threats do not exist at all. Model results reveal that impacts experienced internationally may be extreme (Thailand suffers an 88% fall in wheat output in one example of our model simulations), suggesting that even if more direct cross-border impact pathways into the EU are more limited in their severity there might be severe international repercussions to which the EU is linked more indirectly, via more complex cross-border and cross-sector cascades. Our soy case study, in particular, reveals some of the critical dependencies that exist at more granular levels, for example, for feed and poultry producers, whose business models are heavily reliant on soy and additives such as amino acids or vitamins. **Taken together, these examples illustrate that whilst at a ‘macroeconomic’ level the EU may not be as exposed as some other countries or regions, there remains a strong necessity for adaptation planning at both international and domestic scales.**

Additionally, whilst stakeholders perceive that, overall, historical shocks have shown that the EU food system demonstrates resilience, there is still much room for improvement on managing cross-border risks. Within our food system case study (see Section 4.1), interviews highlighted the potentially disruptive effects of ‘protectionist’ responses, and the soy case study interviews (Section 4.2) highlighted the fact that previous droughts have left producers without income. **Opportunities to enhance resilience should continue to be pursued regardless of the relative levels of vulnerability that the EU faces.** Moreover, shocks linked to the food system may not be direct and therefore may often be outside of the traditional ‘frames of reference’ of stakeholders or models. The example of the Russia-Ukraine war reveals that disruptions originating in energy and fertiliser sectors, and not (yet, at least) the direct effect of crop-export restrictions, likely had the greatest short-term impact on the food system overall. The Russia-Ukraine war also serves to remind us that situations may change unexpectedly and rapidly, leaving actors in the food systems with a lack of time to prepare for any shocks that might occur; the example of palm oil (see Section 4.1.3, Figure 15) serves as a case in point, with stakeholders at the time highlighting the potential severity of the lack of supply following the temporary export ban by Indonesia.

Our models and interviews agree that, where cross-border climate impacts do affect the EU food system, these are more likely to result in price rises (and/or increases in the volatility of prices) as opposed to acute food shortages. However, there was some perception in the interviews that the likelihood of shortages will ultimately depend on the magnitude of the shock. **It has been identified that reactions to such price rises will be very important. There are also important interactions here with the power relationships that exist across the food system.** For example, as observed in the soy case study, price rises may be borne unequally across producer, trader and consumer groups. The longevity and severity of price rises may also dictate who bears the cost. According to our case study participants, smaller-scale shorter-term shocks are potentially more likely to be borne by farmers on the producer end, or industry on the consumer side, but with more severe shocks perhaps requiring increases to retail food prices and intervention from government to support producers.

Another important factor, in terms of the distribution and effect of price rises, is the role of powerful producers and consumers in the global supply chain, which, along with the EU, includes countries such as the US and China. **Stakeholders in the food**

system case study highlight that these countries may be less well ‘prepared’ for shocks than the EU (which is perceived to have conducted more analysis on the potential consequences of cross-border impacts), indicating a need for rapid international knowledge exchange to ensure that globally-influential countries are as prepared as possible. A similar requirement can be observed regionally within the EU; our models predict different regional price and productivity effects within Europe depending on the nature and targets of cross-border impact. Our interviews reveal, however, that there may be differences in how much attention is given to climate resilience regionally across Europe. **Facilitating knowledge exchange across Member States is therefore important.**

The fact that price changes may vary regionally also has implications for the relative levels of competitiveness that may result locally and internationally following a shock, which may persist long after the initial shock has subsided. Changes in competitiveness have the potential to alter the structure of markets, re-balance production for export versus domestic use, or shift the sourcing patterns of companies. **These shifts might not present a fundamental risk to the EU, but will have implications for the structure of economies and employment systems that might have wide ranging effects for livelihoods and equity.** Food-related price rises co-occurring with inflationary pressures in other sectors (as observed during the Russia-Ukraine crisis where energy costs have also inflated) can also contribute to slow-downs in economic growth, rises in inflation, and cost of living increases. These are likely to exacerbate inequalities but also affect dietary habits and nutritional intake (by, for example, affecting food affordability).

Another important consideration is that there are likely to be ‘winners’ from cross-border climate impacts. This is revealed in model results, with some regions experiencing productivity increases or higher profitability in response to shocks affecting wider market dynamics. In our soy case study, traders particularly are identified as a group of actors who may benefit from increased commodity prices in global markets. **This has important policy implications. If some businesses/sectors benefit, but other sectors - or indeed consumers - suffer, then implementation of policy measures such as windfall taxes (as observed, for example, in response to the EU energy crisis) might be considered.** Participants also noted the lack of clarity around who bears the costs of disruption, highlighting **the importance of developing the monitoring of winners and losers in times of disruption so that compensation and support is targeted effectively.**

There was also a perception from our stakeholders that the winners and losers in any given crisis might depend on the scale of the shock as the dynamics of responses across the system are likely to vary under lesser or more extreme circumstances. As an example, the severity of shocks in soy production landscapes may dictate the extent to which protective loans or insurance payouts are made available to producers. **These sorts of dynamics are not currently well captured in the models applied in WP3; an area, therefore, for potential attention in future studies.**

Our participants indicate mixed views on levels of preparedness of the EU to cross-border impacts. There were examples of good practice identified by stakeholders, with several in industry pointing out that cross-border impacts were being considered in planning processes. This is either as a matter of course (for example,

weather-linked impacts were part and parcel of conducting business for some), or specifically because of the growing recognition that climate change has the potential to be highly disruptive to supply chain activities (including as a result of recent non-climate linked events that several stakeholders identified as having raised the profile of cross-border impacts). Several participants, however, highlighted that there was insufficient preparation overall, and particularly that there are differences in levels of preparedness across regions and sectors. We observed a tendency for several participants to revert to talking about steps to mitigate climate change (i.e. emissions reductions) in response to threats, rather than talking about direct adaptive responses to climate-linked shocks that might occur. Some participants also indicated that they felt that the size of shock would ultimately determine how prepared actors in Europe were. Others felt that, whilst there was activity taking place, sometimes this was more in the form of policy rather than concrete activity, and that many actors were using their risk assessment processes to gain competitive advantage, rather than there being action in a 'pre-competitive' environment. **Ultimately, these conclusions strongly suggest a need to share best practice activities across sectors, and across European Member States and internationally, so that consideration of cross-border risk becomes 'systemic'. International platforms, such as the World Bank, OECD, World Economic Forum and World Trade Organisation, were also identified by participants as important fora for such exchange.**

Another barrier to preparedness identified was a lack of data availability. This extends to improving the quantity and quality of relevant model outputs (which requires investment, see discussion above) but also in terms of supply chain transparency, which currently limits understanding of how supply chains are connected to areas of potential vulnerability. The EU (and other national governments) have active discussions ongoing around improving transparency and traceability in supply chains (including within so-called corporate 'due diligence' regulations) with a focus currently on improving knowledge of, and reducing, the EU's overseas environmental impacts. **In promoting transparency, such policy could be thought of as a potential 'win-win' for both sustainability and resilience. Incorporating climate-risk-specific requirements into such policies might also be considered in future.**

Stakeholders, however, presented mixed feelings on the introduction of further legislation, with some encouraging it, but others feeling that it might be too restrictive or add additional operational costs. Some stakeholders pointed out that legislation that restricts sourcing behaviours based on the environmental qualities of materials may, ultimately, have a negative impact on supplies into Europe in times of disruption. On the flip side, as revealed in our soy case study, climate change has the potential to lead to crop expansion, meaning that - arguably - such protections become even more important to prevent further greenhouse gas emissions from land use change (and thus further exacerbation of cross-border impacts). We have also seen in Europe, following the Ukraine invasion, the temporary derogation of policies designed to protect the environment during crises. **In sum, this highlights the importance of carefully designed policy that provides adequate protection without unduly burdensome costs or sourcing restrictions and with sufficient flexibility to be adaptable to changing conditions in times of crises.** Designing such policies will be an incredibly

challenging process, but stakeholders felt that **bad policy responses could present bigger risks than the impacts of climate change itself.**

There are a number of factors that will underpin the future resilience of the EU to cross-border climate impacts. **The ability to substitute materials with speed and low cost** was a factor identified by many stakeholders as important, and one that - within model simulations - allowed shocks in one area to be 'absorbed' by sourcing from another. Substitutability in some sectors (e.g. soy in poultry) or for some products (e.g. fertilisers, feed additives) will, however, be challenging. Whilst a move towards 'just in case' models for the food supply chain was mentioned as a mechanism to increase resilience, there was a feeling by many within industry that a move away from prevailing 'just in time' supply chain models may not be economically viable or may be subject to other constraints that mean it is impractical. **Supply chain resilience has emerged as a parallel objective alongside efficiency, but the trade-offs between the two objectives cannot be easily resolved, or controlled.**

A move towards greater domestic independence in production was also mentioned as an option that might enhance resilience (and, indeed, our simulation results suggest this helps reduce exposure to international chokepoint disruptions). But this also increases risk associated with any domestic climate shocks. Building resilience via other means, for example via the more efficient utilisation of proteins (such as reductions in meat consumption, or the overall resource-intensity of diets), or the introduction of new technologies in production landscapes (which need, importantly, to be mindful of tensions that may arise related to the potential for restrictive technology 'ownership' that may undermine producer freedoms) will also likely need to be part of the policy mix. **Ultimately, there is no-one-size-fits-all solution to enhancing resilience. Rather, developing a suite of policies ensuring that actors in the food system can distribute risk across commodities and landscapes will be necessary.**

Given that political decisions have been identified as critical determinants of how impacts might 'cascade' into the EU, the role of international diplomacy cannot be underplayed in the EU's policy response to cross-border climate impacts. Shocks may ultimately be driven by protectionist responses and, even where global crop balances are sufficient to meet global demands, politically-enforced constraints to trade may impact prices and supply. The EU's ability to respond to shocks occurring outside of its jurisdiction will also be influenced by the nature of its relationship with third-countries. **Utilising diplomatic channels to keep trade and other policy options 'open' in times of crises would therefore appear fundamental to reducing EU-specific and international consequences of climate linked shocks.** Equally, diplomacy and overseas development assistance will be critical tools in any situation where the EU, via its relative purchasing power, is buffered from impacts that lower-income countries are highly vulnerable to. **Limits in the efficacy and speed of current ODA provision were highlighted by some participants in our study, and require attention** if they are to improve producer resilience.

Overall, our analysis suggests that climate-linked cross-border impacts to the EU food and food-linked systems are likely to be 'manageable' if policy is carefully formulated to promote resilience within and outside the EU. This conclusion comes with the significant caveat that it assumes that the types of shocks that have

occurred in the past are of the similar form and severity under a more hostile future climate. The uncertainties expressed in model results and by stakeholders, however, mean that there is no guarantee that the magnitude of shocks will not be more severe, and there is in fact reason to believe that the nature and magnitude of future shocks will be qualitatively and quantitatively different to what Europe has experienced in the past. Overall, this highlights the need for a highly precautionary and internationally inclusive approach by the EU to identify and manage risks going forward.

The analysis conducted under CASCADES and summarised in this report highlights key risks facing the EU from cross-border climate change impacts via trade. In doing so, it also highlights some of the key uncertainties that need to be further explored, so that the nature and extent of specific risks is understood in enough detail to support specific adaptation responses by decision makers inside the EU. This will require a new wave of model-based analysis, as well as targeted analyses by specific DGs and other actors to rank and prioritise risks, and to identify and assess appropriate adaptation solutions.

3. Analysis Section 1: Quantitative outcomes of CASCADES WP3 models

This section presents a summary of the methods and results obtained from the quantitative modelling approaches applied in WP3 of the CASCADES project. All the analyses share a common focus on key impacts in the food supply chain that propagate in some form to impacts on Europe. They encompass: a macroeconomic analysis of the implications for the EU of climate-linked agricultural crop-yield changes, which utilises CMCC's Intertemporal Computable Equilibrium System (ICES) model; a similar analysis of the impacts of the Russia-Ukraine crisis, which utilises the same modelling framework; an analysis of the implications of climate-induced stresses on international logistics 'chokepoints'; an analysis of food price volatility that might result from cropping changes and their interactions with commodity storage, which utilises PIK's Trade With Storage (TWIST) model, and; an analysis of the threats to sub-national logistics networks for an EU-critical agricultural production landscape (Brazilian soy).

Below, each analysis and a summary of its results is introduced in turn.

3.1. Macroeconomic analysis of climate change impacts on agriculture

This work conducted a macro-economic assessment of cross-border climate change impacts using the global Computable General Equilibrium (CGE) framework of the CMCC Intertemporal Computable Equilibrium System (ICES) model and considered a range of socio-economic development and climate change scenarios based on Shared Socio-Economic Pathways (SSPs) and Representative Concentration Pathways (RCPs)¹. A new module in the ICES CGE model was developed for this analysis, which advanced treatment of bilateral international trade relationships and is based on the latest available data from the Global Trade Analysis Project (GTAP) Multi-Regional Input-Output (MRIO) database (Carrico et al., 2020) to better represent and track bilateral trade flows.

¹ The choice of scenarios follows the logic of the CASCADES Scenario Framework described in CASCADES Deliverable 2.1.

3.1.1 Methods overview

The Intertemporal Computable Economic System (ICES) model is a standard neoclassical recursive-dynamic general equilibrium model with the calibration year of 2014. The model utilises the GTAP 10a database (Aguar et al., 2019) that provides a series of interlinked Social Accounting Matrices (SAMs) to give a comprehensive account of payments among productive sectors, final uses (private and public consumption, and investment), trade, and factor income distribution. For this study, the ICES model was further enriched with the GTAP Multi Regional Input Output (MRIO) database (Carrico et al. 2020) which allows more detailed tracing of international trade flows among countries. This offers improvement over the original model, where imports could be traced only by origins and destinations, but not in terms of their uses.

The GTAP database features 141 countries/regions, but for computational reasons, regional aggregation occurs. Recursive dynamics of the simulation model are solved in five-year steps driven by capital accumulation processes led by endogenous current-period investment. The time span of the analysis is 2015-2070. Fuller descriptions of the methods that underpin the ICES model, and its developments for CASCADES WP3, are described in full in Deliverable 3.4.

Simulations are based on a combination of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). As a first step, social economic baselines are built by calibrating the economic model on the selected SSPs under current climatic conditions. In characterising SSPs, six dimensions are considered: population/labour force, income growth, land productivity, energy efficiency, fossil fuels prices, and international trade openness. RCP scenarios are then added to the socioeconomic baselines by introducing RCP-specific climate change impacts. These climate impacts are derived from the MAgPIE (Model of Agricultural Production and its Impact on the Environment) model (Dietrich et al. 2019; refer to Deliverable 3.4 for the MAgPIE parameterisations used). Modelled yield changes from MAgPIE are a weighted average of irrigated and rainfed yields without any management change, supposing a constant irrigated area. They therefore isolate the climate change effect on yields through a time period 2010-2100. The starting year 2010 is considered representative of the current climate situation (and is therefore used for the baseline), while future years represent incremental climate changes with respect to the current situation. Accordingly, climate change impacts on yields from MAgPIE are fed into ICES as incremental shocks on land productivity by crop. ICES has fewer agricultural sectors than MAgPIE, therefore a mapping between the two models is needed. Input data from MAgPIE are aggregated according to ICES regional aggregations.

A complete summary of the results from the combinations simulated is available in Deliverable 3.4, but below we present selected results from RCP6.0 which represent the most 'extreme' outcomes modelled.

3.1.2 Results summary

Implications of scale on results interpretation

According to results from the MAgPIE crop models, climate change can exert important negative impacts on crop yields. These are, however, highly differentiated per crop type and by production region. The geographical heterogeneity of impacts can be large across areas within the same country, and is particularly pronounced when large countries (for instance China, India, Russia, the US) are considered. It is

important to note that this heterogeneity, albeit captured by projections from spatially resolved crop models, is partly lost when macro-economic evaluation assessments are performed, as these evaluations are conducted at the country scale or larger. Therefore, an 'aggregation' or 'averaging' effect has the tendency to smooth extremes in impacts. Similarly, the economic evaluation performed on these 'average effects' is in turn an 'average' that has the potential to obscure local economic losses.

Projected yield impacts

Under RCP 6.0 by 2070, wheat yields appear to be most adversely impacted in some areas of Latin America, such as Mexico and Paraguay (roughly -33% and -26% compared to the baseline respectively), Sub Saharan Africa (roughly -6% compared to the baseline), and smaller Asian countries (roughly -19% compared to the baseline). In other world regions, wheat yields are expected to increase. For example, in the EU, wheat yields are projected to increase by 10%.

Rice yields are also projected to increase worldwide, except in the Tigris and Euphrates region where an almost 58% yield decline is expected. A developed-developing countries divide emerges in the case of other cereal crops: yields are basically unaffected by climate change in the US, the EU, Ukraine, or can moderately increase in Russia. On the contrary, aside from Argentina, yield losses are projected in Latin America (ranging between -4 and -8%), the Middle East and North Africa (-9%), the Tigris and Euphrates (-22%), Sub Saharan Africa (-2.6%), India (-7%), Indonesia (-8.5%) and Rest of Asia (-10.5%). Amongst non-cereal crops, sugar cane and beet and fibre crop yields appear the most negatively affected by climate change, whilst the picture for vegetable and fruits is mixed. For the latter, in the Asian region declines can reach around 9% in Thailand, 3% in Indonesia and 'rest of Asia'. In other regions yield gains are projected, with a maximum of 30% in Australia.

Projected aggregated economic impacts:

Impacts in the EU: Within the EU, climate change impacts on crop yields are mostly positive, albeit moderately so. Furthermore, in the EU, agriculture contributes a relatively low share (roughly 1.6%) to total GDP. The implications of these two factors are that there are only moderate macroeconomic effects to the overall EU economy from climate change transmitted by impacts on domestic (EU) agriculture. In 2070, under RCP6.0, these impacts range between a -0.03% change in GDP in the Northern EU to +0.08% in the Eastern EU. In addition, within the simulations, crop prices remain mostly unaffected or decline only slightly, which indicates overall that climate change impacts to domestic yields neither seem to pose a particular threat to EU food security nor will be a major driver of macroeconomic losses in the EU.

At the same time, however, cross-border impacts are relevant; the negative impacts on yields occurring outside the EU impact on the EU's GDP performance. In the Northern EU and Mediterranean EU regions, these external effects transform potential (very small) GDP gains in these areas into (very small) losses. Yet in the Eastern EU, external effects reinforce positive regional trends, roughly doubling the GDP gains that are experienced from domestic yield changes.

Impacts in the Rest of the World (ROW): Macroeconomic effects are also moderate outside of the EU. Under RCP6.0 by 2070, they range between an impact of -0.42% of GDP in Thailand to +0.5% of GDP in Argentina. Globally, most regions of the world

are expected to experience gains in GDP. However, regions expected to lose out, in addition to Thailand, include the Tigris and Euphrates region, Mexico, and smaller Asian countries.

Overall, whilst relevant, changes in GDP driven by climate-linked yield effects are simulated as low-to-moderate. However, an additional important insight from the macro-economic modelling results from an inspection of the role of trade openness. The results highlighted above stem from an 'SSP3' scenario built on a social economic narrative of 'fragmentation' and 'trade restriction'. In contrast, simulations conducted with scenarios SSP2 or SSP5, which assume greater degrees of 'globalization' and 'cooperation', indicate that any gains or losses experienced by economies are smoothed. Thus, whilst international trade can be a conveyor of impacts, it is also an impact dampener as it allows the redistribution of resources across sectors and internationally where they may be domestically scarce. Within the context of this simulation, however, this result must be interpreted with caution, and with an understanding of the theoretical underpinnings of the economic model used: this assumes 'perfect' market functioning that supposes, for example, perfect information transfer, no trade frictions, perfectly rational agents, and no demand- or supply-side excesses.

Projected sectoral impacts

Impacts in the EU: Economic impacts at the sectoral level are mostly driven by competitiveness effects and price differentials between the EU and non-EU areas. Such indirect or 'cascading' effects, which are transmitted by 'terms of trade' mechanisms, overwhelm the effects of climate-change driven yield effects on production quantities. This is particularly evident for EU rice production. Within the simulations, due to a net increase in global production, rice price declines. However, this decrease is not uniform across countries. Within the EU, declines are projected to be lower, which induces a loss of competitiveness of EU rice producers. In 2070 under RCP6.0, this can lead to a decrease in rice production, reaching -8% in the Mediterranean and -15% in the Eastern EU. Concurrently, EU rice exports can decline between 25% and 46%. The production of other cereal crops in our simulations is less affected. However, this loss of competitiveness also explains a simulated 13% and 3.6% contraction in oil seeds and sugar cane and beet production respectively in EU Mediterranean regions and a concurrent 17% and 6.5% decrease in exports of these two crop groups.

Impacts in the ROW: Crop production losses are generally lower than yield losses. This occurs because farmers can, to a certain extent, respond to land productivity losses using more labour, improved technologies, or fertilisers. With a focus on cereals, following adaptations of these kinds in 2070 under RCP6.0, many countries can still experience relevant crop production declines: Tigris and Euphrates (-27%) in the case of rice; Thailand (-88%), Mexico (-50%), Paraguay (-36%), Sub Saharan Africa (-12%), and smaller Asian Countries (-17%) in the case of wheat; Tigris and Euphrates (-6%) and Thailand (-15%) in the case of other cereals. These crop production declines induce localised price responses. Rice price declines are generalised (with the exception of yield shortfalls in locations mentioned above, rice yields increase at global scale, reducing global prices); however, wheat prices can increase by 74% in Tigris and Euphrates and 1.3% in Thailand. Other cereal crops prices are also projected to increase, especially in Mexico (almost 9%), Middle East and North Africa (4%), India (4%), the Tigris and Euphrates region (17%), Thailand (20%), Indonesia (8%), and the Rest of Asia (10%). These long-term price effect projections are a

significant and potentially concerning signal of possible climate-driven worsening of food insecurity in many lower-income world regions, which may exacerbate existing development concerns and tensions in these regions.

3.2 Macro-economic analysis of the impacts of the Russia-Ukraine crisis

In this analysis, six scenarios were simulated linked to the effects of the Russia-Ukraine crisis on the EU food system. The Russia-Ukraine crisis represents a topical and acute form of shock affecting the EU's food system, and it is useful to explore the implications of this crisis given that it is - whilst not climate driven - a pertinent example of the potential for impacts outside the EU to cascade into it via trade.

3.2.1. Scenario detail

Analysis was again conducted using the global CGE framework of the CMCC Intertemporal Computable Equilibrium System (ICES) model.

Table 1 summarises the manner in which each of the six scenarios was implemented with the CMCC model (for a description of the modelling framework see Section 2.1.1). This includes the modelling of a number of significant (but variable across scenarios) restrictions imposed by Russia on exports of fuel and food-linked materials to particular countries (e.g. NATO and NATO partner countries), plus restrictions in Ukrainian production and export outputs as a result of the crisis. Scenario 6 imposes the most frictions/restrictions overall, and Scenario 3 the lowest.

Table 1: Description of scenarios implemented within the ICES modelling framework.

Scenario Number	Description
Scenario 1	<p>100% Russian ban on fossil fuels export to EU, USA, JPN, CAN, AUS, UKR.</p> <p>100% Russian ban on fertilisers exports to NATO/NATO Partner Countries and 50% to RoW.</p> <p>100% Russian ban on oil seeds export globally.</p> <p>100% Russian ban on forestry and fishery exports to EU, USA, JPN, CAN, AUS, UKR.</p> <p>0.6% labour and capital loss in Russia.</p> <p>30% reduction in all factors of production in Ukraine to simulate production capacity disruption.</p> <p>90% Ukraine export reduction.</p> <p>Normal international trade flexibility (governed by the parameter fixing the substitutability of domestic vs imported commodities).</p>
Scenario 2	<p>Scenario 1 with additional international trade frictions (the parameter fixing the substitutability of domestic vs imported commodities is reduced 50%).</p>
Scenario 3	<p>Shocks of scenario 1 are halved.</p>
Scenario 4	<p>Shocks of scenario 2 are halved.</p>
Scenario 5	<p>Scenario 1 plus 100% Russian ban on cereal (Wheat & Other Grains) exports.</p>
Scenario 6	<p>Scenario 5 with additional international trade frictions (the parameter fixing the substitutability of domestic vs imported commodities is reduced 50%).</p>

3.2.2 Results summary

Impacts on GDP

According to the results of the model, the effects of the Russia-Ukraine war most strongly negatively affect - not unexpectedly - the two countries directly involved in warfare (Figure 1). Ukraine is projected to experience a GDP loss of 20 to 50% depending upon the scenario adopted, and Russia from 2 to 13%. The results for Russia are mainly driven by the sanctions and bans that Russia is assumed to impose on NATO countries, with sanctions therefore damaging not only to those subjected to them, but also to those that impose them. In the simulation, it emerges that Russia may not be able to perfectly substitute excluded Western markets with new buyers at convenient prices.

The third largest loser in the crisis in terms of GDP impacts is the EU area, with losses ranging between 0.15 to almost 2% (Figure 2). The losses are driven mostly by the high dependence of the EU on Russian energy imports. Indeed, the extension of the ban to cereal exports (Scenario 5 and 6) has only low incremental negative GDP effects. Within the EU, the 'Rest_Med_EU' region (that gathers small islands and Adriatic states) followed by the 'East_EU' region are, in relative terms, more negatively affected. The result for the 'North_EU' region is dominated by Germany's economic performance, while the 'Med_EU' by Italy's, with both countries heavy gas (and oil) importers from Russia.

Other NATO/NATO partner countries, such as the USA, Canada, Australia and Japan, are only marginally affected, even though Japan demonstrates a relatively higher sensitivity to the restrictions. These economies are much less reliant on Russian energy exports and on general trade with Russia. Macroeconomic effects are thus conveyed mostly by indirect price and trade redistribution effects on global markets. Regions not hit directly by the bans are marginally affected and often positively. This is due to the redirection of Russian exports (again mostly energy) to those countries. Net energy producers (Mexico and MENA) also show some mild potential gains, as they partly substitute Russian energy exports by increasing their supplies to Western markets. Eventually, a redistribution of energy import-exports occurs with moderate effects on overall economic performances. India is the only 'large' region with some GDP loss.

When frictions in international trade mechanisms are introduced (Scenarios 2 and 6) both GDP losses and gains are amplified. Frictions are modelled through a greater difficulty of substituting domestic with imported commodities, and in practical terms can be interpreted as a reaction against higher uncertainty, or a move towards more nationalistic sentiment. The effect is that trade is stickier and any economic 'changes' (positive or negative) remain more confined in the area of origin and are not smoothed by foreign exchanges.

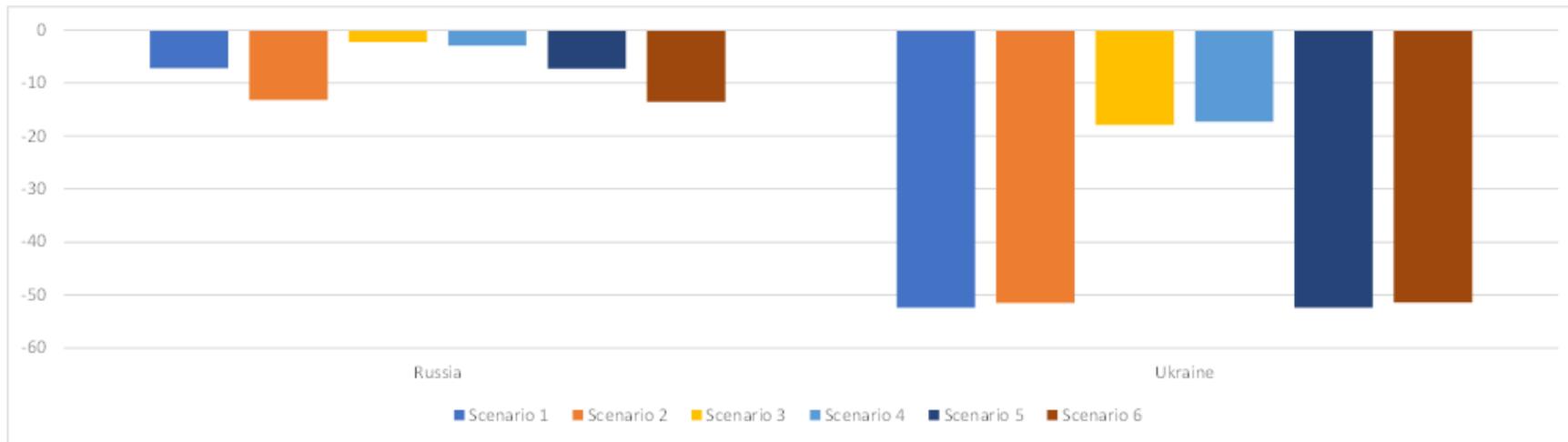


Figure 1: GDP Impacts: Russia and Ukraine (% change with respect to baseline).

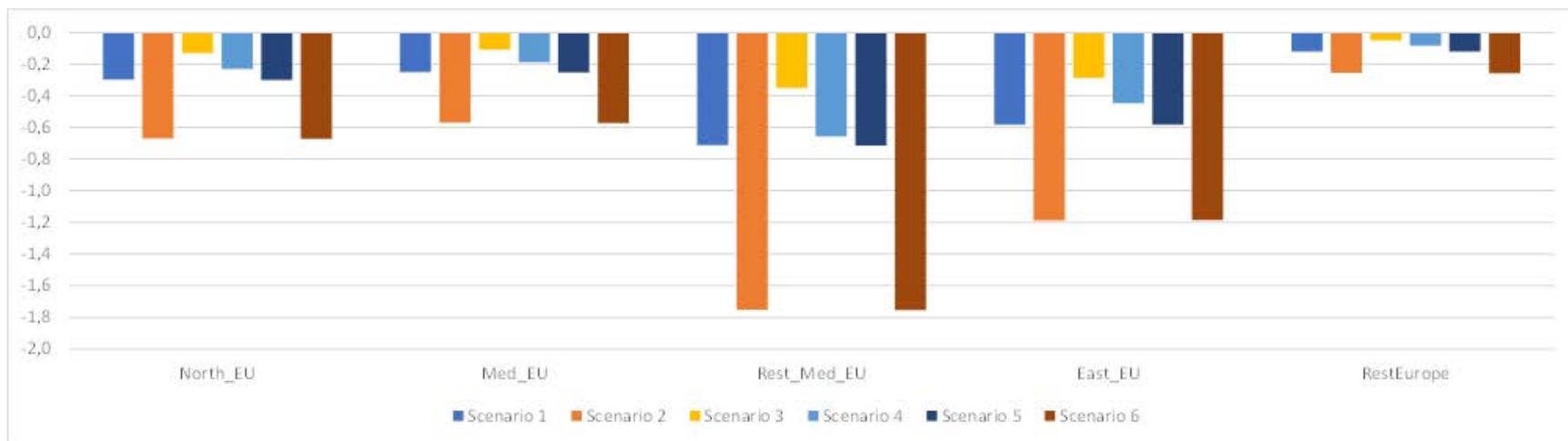


Figure 2: GDP Impacts: EU regions (% change with respect to baseline).

Impacts on prices

Before describing price effects, two disclaimers are warranted. Firstly, in the macroeconomic model, speculative effects and market imperfections are not considered. Accordingly, the fact that any strategic behaviours of suppliers in gas markets or those of operators in the raw material stock markets that can have the effect of driving up prices, are not captured. Similarly, the complex interactions between gas and electricity prices driven by contractual design/obligations in the energy markets (which in some countries serve to link gas and electricity prices) are not simulated. The second disclaimer refers to the 'type' of prices described by the economic model. These are real prices, therefore net of inflation. This should be considered by the reader as, in an inflationary period like that of the post covid recovery, real prices are considerably lower than current prices. As an example, as measured by the Harmonised Index of Consumer Prices (HICP), headline inflation in the Euro area reached 2.6% in 2021 and in February 2022 reached a historical high of 5.9%. In principle, this value has to be added to all the EU price figures reported below.

Notwithstanding the above, the Russia-Ukraine crisis induces an overall inflationary pressure on all produced commodities worldwide. As expected, a higher price increase is experienced by food and energy commodities. Figure 3 also shows that the ban on cereals ('Wheat' and 'OtherGrains'), despite moderate impact on GDP performance, is an important factor in commodity price as prices for these two commodities in Scenarios 5 and 6 are larger than in the other scenarios. Prices are affected more than the overall quantity of supply. Inflationary pressures are also noted to be higher where trade frictions are introduced (Scenarios 2 and 6). Overall, whilst all prices increase somewhat, world Oil Product prices can increase up to 7%, Gas 3.5%, Wheat up to 3% and Other Grains up to 8%.

Results for global price effects can be usefully complemented by national and macro-regional effects. Here, for the sake of synthesis, we report the worst outcomes that are related to a combination of Scenarios 5 and 6. We also do not comment on impacts to the 'Rest of Med EU' because that region includes smaller EU and EU island countries that comprise only a small fraction of the EU economy.

Results for **the EU area** are characterised by a significant increase in the price of energy commodities, interestingly more for oil and oil products than for gas, indicating a somewhat easier substitutability in terms of gas providers for oil. The 'Eastern EU' is the region most affected by this trend with a 38.8%, 33.9% and 33.5% increase in oil, oil products and gas prices respectively. 'Northern EU' and 'Med EU' regions are projected to experience a lower, but still significant, 5.5% increase in gas prices and 20% and 11.5% increase of oil prices in the two areas respectively. Energy prices drive up the prices of electricity, which increases on average by 2.5% in the EU area with a maximum of 6% in the 'Eastern EU' region, with important effects for energy intensive industry. Transportation sectors are also heavily affected, with road-rail transportation costs experiencing an average increase of 4% with a peak of 12% in 'Eastern EU'. Air transportation cost increases reach 18% and 12% in the 'Northern EU' and 'Med EU' regions respectively. Agricultural commodity prices also increase, but to a lesser extent. On average, price changes range between +1% and

2% with the exception of 'Eastern EU' where, for instance, oil seed prices can peak to +5.7%.

In Canada, USA, Australia, Japan, price trends are qualitatively similar to the EU, with the noticeable quantitative difference that increases in energy prices are lower, which also induces a lower cascading effect on the prices of energy intensive commodities and services. Japan, which remains a heavy energy importer, features an 8% increase in the price of oil products and 4% increase in the price of electricity, constituting a partial exception in the NATO-Pacific context. In contrast, Japan is less affected by spikes in agricultural commodities' prices than Canada, USA and Australia.

Middle- and Low-income countries show energy commodity price trends comparable with those of NATO-Pacific countries. Sub Saharan Africa and the Tigris and Euphrates regions are affected by the larger increases with a peak of 7% of oil and of 5% of electricity respectively. China is less affected, demonstrating only marginal increases in the cost of energy. This alludes to an important redirection of Russian export toward the Chinese market. Similar effects are not seen for India, but the model cannot simulate the opening of 'new' trade relations, just analyse existing ones. Results here are therefore likely indicative of the already high interconnection of the Russian and Chinese economies. Energy price increases cascade onto the production cost of all commodities, especially those of energy intensive industries and transportation. Impacts on food prices are particularly important for Middle- and Low-income countries. The cereal export blockade affects the Middle East and North Africa, Sub Saharan Africa and the Tigris and Euphrates regions most negatively. Here, agricultural commodity price increases range on average between 4% and 5%, which are comparable to those in the 'Eastern EU' region (the region experiencing the highest price increases in the EU).

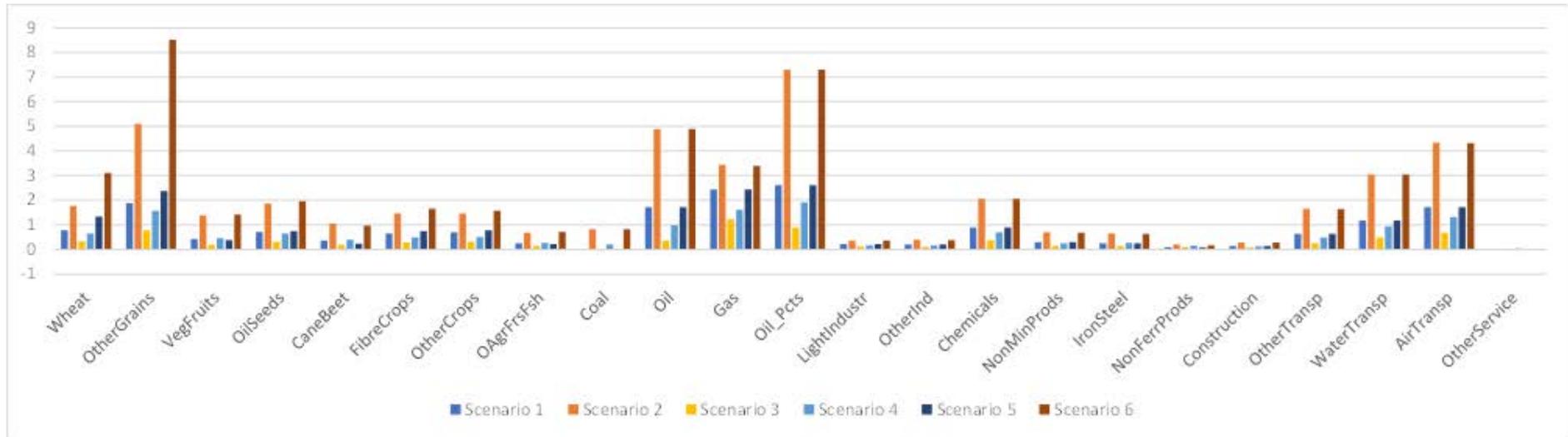


Figure 3. World commodity price effects across scenarios (% change with respect to baseline)

3.3 Analysis of stress on trade choke points

3.3.1 Overview

This analysis considered three plausible acute climate-induced shocks on three key global trade chokepoints of significance to EU agricultural imports – the Panama Canal, the Suez Canal, and the Turkish Straits. Chokepoints are defined as “critical junctures on transport routes through which exceptional volumes of trade pass” (Bailey and Wellesley, 2017). Within this analysis, each chokepoint is considered independently rather than being considered in a manner that could lead to compound impacts.

The objective of this analysis was to examine the impacts that these envisioned trade dislocations would have on annualised European food prices and the economic output of the European food industry. The modelling of these shocks takes place using the ICES CGE model described above (with the same model caveats and considerations applying). The simulations examine the ‘one-year’ economic implication of interruptions in the Panama Canal, the Suez Canal, and the Turkish Strait. Due to data availability, the focus is limited to effects on/conveyed by agricultural commodities. In the model these are represented by the crop families of rice, wheat, other grains, and oil seeds. Disruption is implemented in the form of a bilateral trade restriction affecting the traded share of the agricultural commodities transiting through the selected chokepoints. This is done in the model by endogenously changing a technical coefficient for bilateral trade ‘productivity’, which can be thought of as a parameter affecting the productivity of transportation. Chokepoint disruptions are thus incorporated as demand-side shocks for specific export flows.

The Panama Canal shock assesses the impacts of droughts and lower water levels in the canal that act to restrict throughput; the Suez Canal shock assesses the impacts of storm surges and dust storms that damage canal and port infrastructure; and the Turkish Straits shock assesses the impacts of climate-exacerbated conflict that lead to blockades.

The modelled dynamics of the shocks themselves are identical irrespective of the SSP/RCP combination examined within the ICES modelling framework – rare acute shocks of this nature are not well reflected in long-run climate models and the hazards described are plausible events in all future climates. The SSPs/RCPs modelled in ICES therefore determine the agricultural production and macro-economic contexts in which these shocks occur, and thus lead to differentiated impacts from the same assumed interruptions to trade corridors.

The analysis summarised below is based on a simulation of global trade patterns (relative shares of exports/imports to/from each country) as per the year 2018 and on global agricultural production (and other economic activity) under SSP2 in 2030.

Further background on the approach adopted, the rationale for the chosen shocks, and further presentation of results can be found in [CASCADES D3.3](#) (King, 2022).

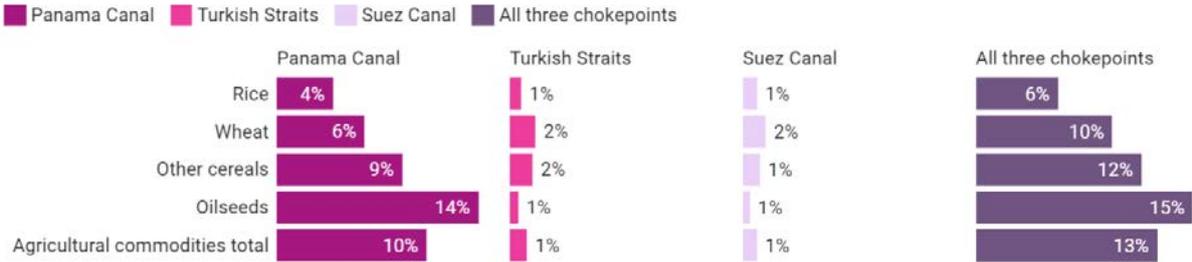
3.3.2 Results from SSP2, year 2030

Exposure via direct trade impacts to shipping activities

The EU’s imports of agricultural grains, oilseeds and fertilisers are less dependent on maritime chokepoints (across all eight chokepoints - not just those associated with the shocks modelled in this analysis) than imports from the world as a whole. EU imports accounted for 18%, by value, of all global imports between 2018 and 2020 but only 26% of these imports transited at least one chokepoint compared with 56% of global import activity.

The Panama Canal is of most significance to the EU from the perspective of soybean trade, and especially material exported from the west coast of Latin America. However, these trades still only account for 5.4% of EU soy imports, since most soy imports originate from the east coast of the Americas. This means that they can transit across the Atlantic unimpeded by any potential maritime chokepoint restrictions. The Turkish Straits are of the most significance to the EU from the perspective of its cereal imports (with 11% transiting via this route) and fertiliser imports (6% via this route) which reflects the high dependence on the Black Sea region for these commodities. Potential blockages to the Suez Canal are likely to be significant to the EU in terms of cereal imports (4.7% of total imports transiting) from the Global East. 38% of the value of global trade in agricultural commodities, excluding fertilisers, is expected to transit via these three focal chokepoints in 2030, with 20% expected to pass through the Panama Canal, 10% through the Turkish Straits, and 8% through the Suez Canal.

Within the scenarios modelled for this analysis, therefore, we would therefore expect - on a global scale - direct exposure to the envisioned Panamanian disruption to be much more significant than the other two shocks. This is due to both the higher aggregate value of agricultural commodities transiting the canal, and the fact that the magnitude of the simulated shock is envisioned to be the largest (note, the latter is a consequence of the hazard narratives constructed for this analysis; other plausible hazards with different durations and severities could result in different relative impacts). In total, 10% of the annual global trade in agricultural commodities in 2030 would be directly impacted if the Panama Canal’s throughput were throttled as envisaged, compared with just over 1% for the simulated Turkish and Suez disruptions (Figure 4).



Created with [Datawrapper](#)

Figure 4. Proportion of 2030 global trade at risk from envisioned chokepoint disruptions (SSP2).

Downstream market impacts

Direct exposure to disruption is one of the most important factors determining a country’s chokepoint-related risk. But the effects of disruption effects can also be transmitted indirectly through international markets, which can subsequently affect

domestic food prices (and ultimately cause broader welfare impacts and, for example, affect government legitimacy).

When the described chokepoint shocks were used as an input to the ICES CGE model, the impacts of the Panama Canal disruption resulted in generalised price increases for agricultural commodities and food industry products in Europe. The increases are greatest for ‘other grains’ and ‘wheat’ prices in the main ‘Mediterranean EU’ region and ‘Northern EU’, despite these regions (within the model) having limited direct exposure to the disrupted trades. Prices for oilseeds, to which Europe has the most direct import-disruption exposure, see the next largest increases, with prices in the ‘Rest of Europe’ and the ‘Eastern EU’ most affected (see Figure 5).

For the smaller Turkish Straits and Suez Canal disruptions, the price rises are less widespread across food groups, and in general there is a tendency towards price decreases more than increases². The decline in the price of wheat following the envisioned Suez incident is particularly marked (see Figure 5).

In terms of the impacts to the economic output of the food industry (Figure 6), in all regions of Europe there are very small negative changes associated with the Panama Canal dislocation. This is similar to the rest of the world, aside from in the Americas where the impacts are positive, most noticeably in Argentina and Canada³. The shock to the Turkish Straits results in little change to the food industry’s output, aside from for Black Sea countries where the impact is generally more negative, and with the noticeable exception of Ukraine, which sees a large increase in output⁴.

Within Europe, the food industry of the Mediterranean regions witnesses the largest negative impact. The most significant negative impacts are in the Middle East and North Africa while the most significant positive impacts are in Ukraine, Argentina and Canada. Overall, however, the results indicate that impacts on European food industry outputs are likely to be affected relatively lightly compared with other regions.

² The modelled reduction in trade flows through the Panama Canal is more significant than for the other two chokepoints. For the Panama disruption, this means that relative prices rise in the EU, and domestic industry increases production to compensate for the lower imports. In the case of the Turkish Strait and Suez Canal scenarios, there is a less disruption to trade, and the EU can also import the same commodities from other countries instead of increasing domestic production, e.g. the Panama Canal would constitute an alternative route to compensate for the disruption in the Turkish strait and the Suez Canal.

³ In Argentina, Canada, and also USA (which all are net exporter countries) in the chokepoint scenario there is a modelled fall in the demand for their exports, which explains price decreases. As agricultural prices go down the food industry pays a lower price for agricultural inputs. As a result, production in the food industry increases for those countries.

⁴ This scenario assumes a peaceful context, with unrestricted trade. Ukraine is an important net exporter country, negatively affected by reduced demand for its exports. Therefore, similarly to Canada, Argentina, and USA with respect to the Panama Canal, agricultural products are redirected from export markets to the local food industry.

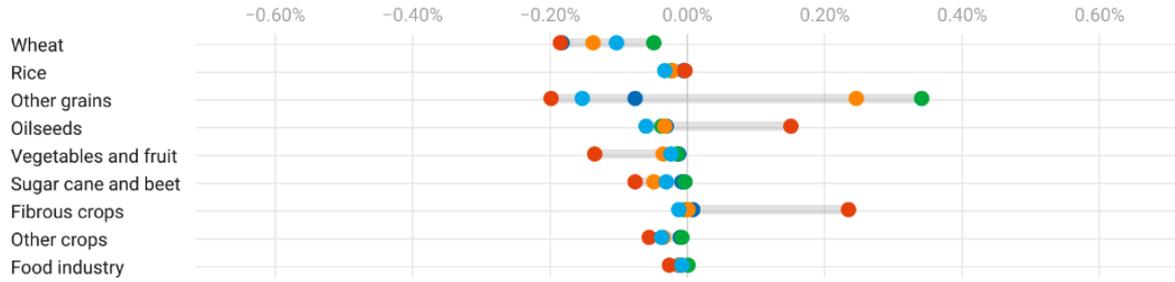
SSP2, 2030

● Northern EU ● Mediterranean EU (main) ● Mediterranean EU (rest of) ● Eastern EU ● Rest of Europe

Panama Canal



Turkish Straits



Suez Canal

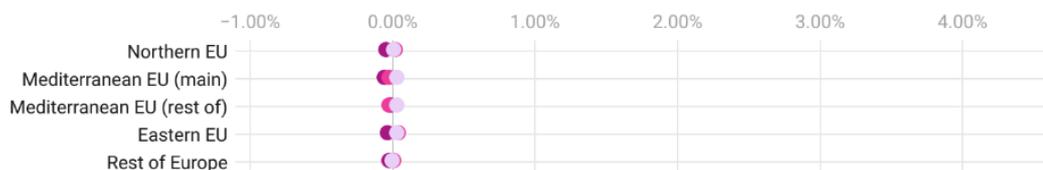


Figure 5. European price impacts from chokepoint disruptions.

SSP2, 2030

● Panama Canal ● Turkish Straits ● Suez Canal

Europe



Outside Europe

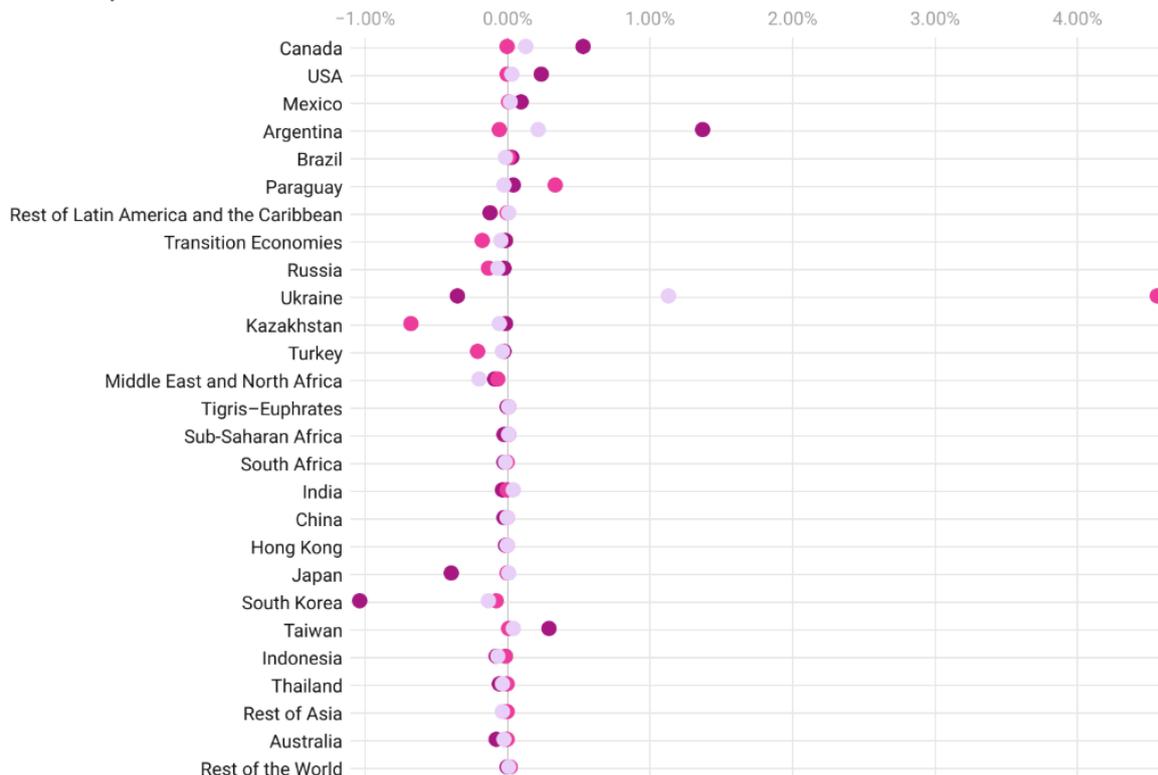


Figure 6. Change in food industry production associated with chokepoint disruptions.

Further analysis is required to better understand what is contributing to the positive and negative price movements from the disruption, their interregional distribution, how price changes translate into economic output changes for the food industry, and how different socio-economic and climatic conditions may also mediate this. We observe that some price effects are a result of production responses within Europe. For example, rice production increases and imports decrease following the Turkish and Suez disruptions. However, this European production dynamic, as modelled, assumes that the climate conditions on the continent are conducive to increased production. Should Europe, or any other region which demonstrates a production response, be affected by concurrent climatic impacts this could limit the ability of producers to respond rapidly in response to chokepoint-related impacts. It is also worth reiterating that the results from the ICES modelling framework reflect annualised changes whereas the shocks that are used as inputs are relatively short-lived and are likely to lead to acute disequilibrium price spikes and downstream disruptions that may be brief and are not captured explicitly within the model, but may nonetheless be impactful.

Appropriate risk-based management of maritime and coastal chokepoints, and the associated sectors that depend upon and manage them, will likely become even more important for future global food security. This is especially because demands for imported agricultural commodities (feedbacks which are not directly taken into account in the modelling framework applied here) are expected to increase alongside the risks to chokepoint disruption associated with underinvestment, weak governance, climate change and other emerging disruptive hazards. Recent events have shown that food supply chains are prone to challenges to their resilience and that critical logistical networks are increasingly prone to disruptive interruptions that are likely to demand active adaptation.

3.3.3 Extensions to chokepoint analysis

Subsequent to the analysis above, further modifications and extensions to the modelling framework were made to explore the effect of model changes and improvements. This included changing bilateral trade projections by replacing the initial historical (2018) chokepoint-linked trade data with projections that reflect trade volumes that are consistent with SSP2 and SSP3 scenarios in 2030 and 2050. These SSPs were additionally analysed in combination with crop-yield changes based on RCP2.6 and 6.0 pathways, which add the effects of yield changes to the trade shocks. Analysis of the dynamics triggered in agricultural markets, in terms of food price and product effects, is also extended with results available for Europe.

In general, the results indicate that %-GDP losses are small (a finding common with the initial analysis). The largest losses are felt by countries that are net exporters of agricultural commodities, such as Argentina (affected by the Panama disruption), Canada (affected by Panama and Suez) and Ukraine (affected by all chokepoint disruptions). Overall, shocks affecting the Panama Canal dominate GDP losses, which reflects both the importance of the node and the imposed size of the shock modelled for this chokepoint. GDP losses are larger in 2050 compared to 2030, and higher overall in RCP6.0 compared to RCP2.6.

Interestingly, within the results for the ‘socio-economically fragmented’ scenario captured by SSP3, the macroeconomic effects of chokepoint interruptions are less concerning than in the more open and collaborative ‘middle of the road’ narrative of SSP2. The fragmentation of SSP3 is simulated by introducing trade frictions in the form of a higher preference of consumers for domestic over imported commodities. This contributes to creating an environment within the model where trade is relatively less important, with lower import/export volumes overall. Accordingly, the subsequent emergence of trade flow contraction through the chokepoints after the simulated shocks is also less impactful.

In general, the EU economy, which overall is a net importing region, reacts to a contraction of import flows by increasing domestic production and, in some cases, exports if the import contraction is ‘sufficiently large’. In cases where import contractions are ‘sufficiently small’ it reacts with a decrease in production and sometimes an increase in import from alternative sources. The first pattern is particularly evident in the case of the negative shock affecting the Panama Canal. The production of wheat, other grains, and oil seeds increases together with exports in all EU regions, but especially in the Mediterranean EU. Rice, on the contrary, is only marginally affected due to its relatively modest transit to the EU through Panama. Stimulus to EU domestic rice production is more evident in the case of a

shock affecting the Suez Canal, through which more than 66% of EU rice imports transit. A similar effect can be observed for oil seeds production and exports that increase everywhere across the EU except in the Eastern EU region. On the contrary, production and exports of other agricultural commodities decline, while the Mediterranean EU increases the imports of wheat and other grains. A blockade of the Turkish Straits is the most impactful scenario for EU oil seeds domestic production and for wheat and other grains in Eastern EU (which is a relative net exporter).

Price effects across the scenarios are very small. In the Panama case, they generally increase, although negligibly, in all the EU regions. The maximum is a 0.52% increase in oil seeds prices experienced by the Mediterranean EU region. Increasing prices stimulate an increase in domestic production, but this is not sufficient to compensate for import contraction. Because grains and oil seeds are an essential input for the food industry, their rising prices impact the cost structure of the sector and translate into lower food production and increasing food prices for consumers. Though moderate, such effects may be potential sources of stress on low-income households that spend proportionately more of their income on food. Rice and oil seed prices also increase following the Suez Canal disruption, while those of wheat decline. Overall, these effects are sufficient to induce small declines in production costs and thus the prices imposed on the food industry in Europe that slightly increases its production in response. From an EU perspective, the shock on the Turkish strait is not sufficient to induce an increase in domestic production, with it being more convenient to partly change the source region to import from.

3.4 Analysis of food price volatility

This section presents the preliminary results of an analysis of the food price volatility using TWIST. This model estimates the annual global prices of a given crop (i.e. wheat, rice, soybean or maize) based on its production and consumption, accounting for storage. Note that this analysis is not specifically related to the impacts on price volatility to the EU market; instead the analysis is relevant to the EU because global market price volatility is also likely to be reflected in changes to EU food prices, given global-scale connectivity in commodity prices.

3.4.1 Methods

Inputs to the TWIST model (Schewe, Otto & Frieler, 2017) were prepared based on the ISIMIP (Inter-Sectoral Impact Model Intercomparison Project) 2b and 3b agriculture data according to the following steps: First, global production time series were generated by combining the irrigated and rain-fed crop yields from ISIMIP. This was done with respect to the land use patterns which define, for each crop, the actual irrigated and rainfed planted regions. To do so, we considered simulations under RCP6.0 (for ISIMIP2b) and RCP8.5 (ISIMIP3b) greenhouse gas concentration pathways from all the available crop and climate models participating in ISIMIP, unless they have missing data (e.g. in ISIMIP3b, the crop models CYGMA1p74 and pDSSAT were eliminated when analysing wheat). The resulting simulated production data were adjusted so that their respective averages matched the average of reported data (i.e. USDA PSD world production 1960-2022).

Following this, annual consumption time series and initial stock levels were constructed in such a way that the modelled long-term trade balance is similar to the historical situation (i.e. USDA PSD 1960-2022). This is necessary because the

TWIST model is calibrated to historical data, and raw simulation data may differ from historical data in terms of mean, variability, and trends. The initial stock level for the TWIST simulation is chosen such that its ratio to the simulated production is the same as the average ratio of starting stocks to production from the reported data (i.e. USDA PSD 1960-2022). By adding the production and consumption balance (i.e. what's left from the produced crops after consumption) to this initial value, TWIST estimates the ending stocks time series. Finally, the consumption time series is constructed such that for each year, consumption is the average of the simulated production from the five previous years to the five following years. This is done to ensure that production and consumption match on longer time scales, and we can focus solely on short-term (annual) fluctuations. In order to ensure that the stock-to-use ratio of the simulated data stays within the same range of the reported stock-to-use ratio, local adjustments were applied to the consumption.

After preparing these inputs, the production and consumption time series of each crop-climate model combination, as well as the corresponding initial stock level, were inserted into TWIST. The resulting price time series' were then analysed to study how the simulated future prices vary compared to the simulated historical prices, and how the variability of the prices relates to the variability of the production. To this end, the coefficient of variation, an indicator of the variability of a given population around its mean, was used. For both the prices and the production times series, the future period was defined as 2050-2099 and the historical periods as 1861-2005 and 1851-2015 for ISIMIP2b and 3b, respectively.

3.4.2 Results and interpretation

Figures 7 and 8 illustrate the difference in the coefficients of variation between the future and historical wheat production and wheat prices for ISIMIP2b and 3b, respectively. Results are colour-coded and grouped by crop models.

We note from Figure 7 that in ISIMIP2b (for most models, as seen by the negative coefficients), the simulated production quantities vary less in the future than in the historical period, and the simulated prices follow suit. We also notice that some climate models have a more pronounced impact on the production, e.g. HadGEM2-ES yields a remarkable decrease in production variability compared to other climate models, but this does not always result in a commensurate decrease in price variability. GFDL-ESM2M has a more remarkable impact on the price variability, in which two out of three cases are reduced more greatly than under HadGEM2-ES. This

makes the production quantities vary significantly less than other climate models. However, this impact is not consistent with regard to crop prices.

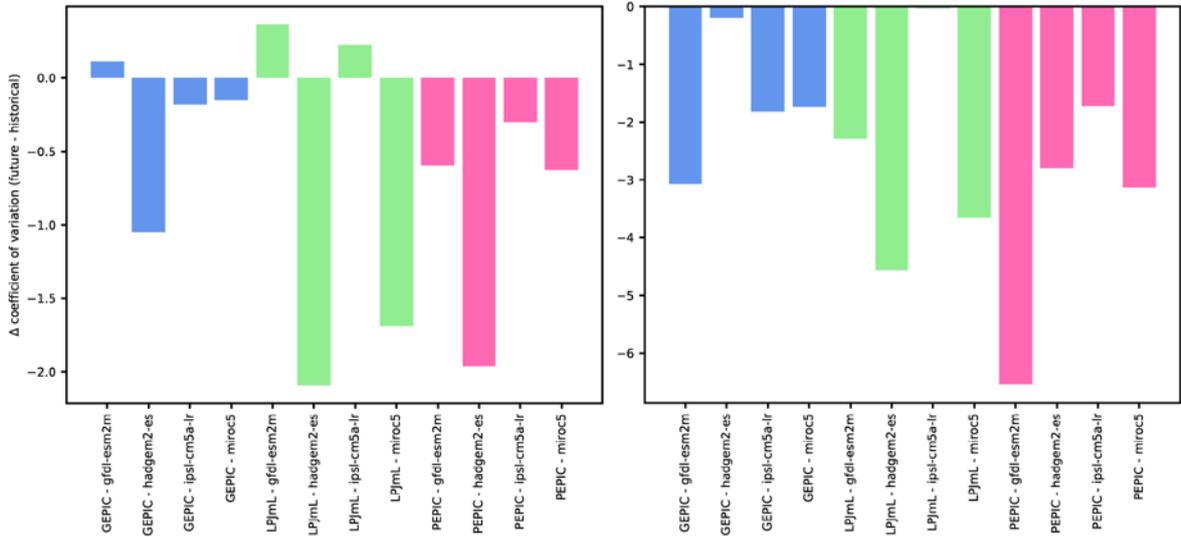


Figure 7. Difference in the coefficient of variation between future (2050-2099) and historical (1861-2005) production (left) and prices (right) using ISIMIP2b, RCP6.0 and the default sensitivity scenario.

On the other hand, in ISIMIP3b (Figure 8), the direction and magnitude of the change in price variability strongly depends on the crop model. Two crop models (CROVER and LDNDC) show a substantial increase in variability (of both production and prices), consistently across all five climate models. The increase can be as much as 20% in the coefficient of variation; corresponding to a dramatic level of volatility in the price time series, as illustrated by the example of the LDNDC-IPSL-CM6A-LR crop-climate model combination (Figure 9). Four crop models (EPIC-IIASA, LPjml, PEPIC, and PROMET) consistently show a decrease in price variability, though the magnitude of change is smaller than that of the decreases mentioned above for ISIMIP2b. Interestingly, a decrease in price variability does not always follow from a decrease in production variability. For example, in PEPIC-UKESM1-0-LL, global production variability actually increases, but price variability still decreases according to TWIST. The reason for this needs further investigation, but might be related to the role of storage and changes in the stocks-to-use ratio. The remaining three crop models show either increases or decreases in price variability depending on the climate model, and mostly with small magnitude.

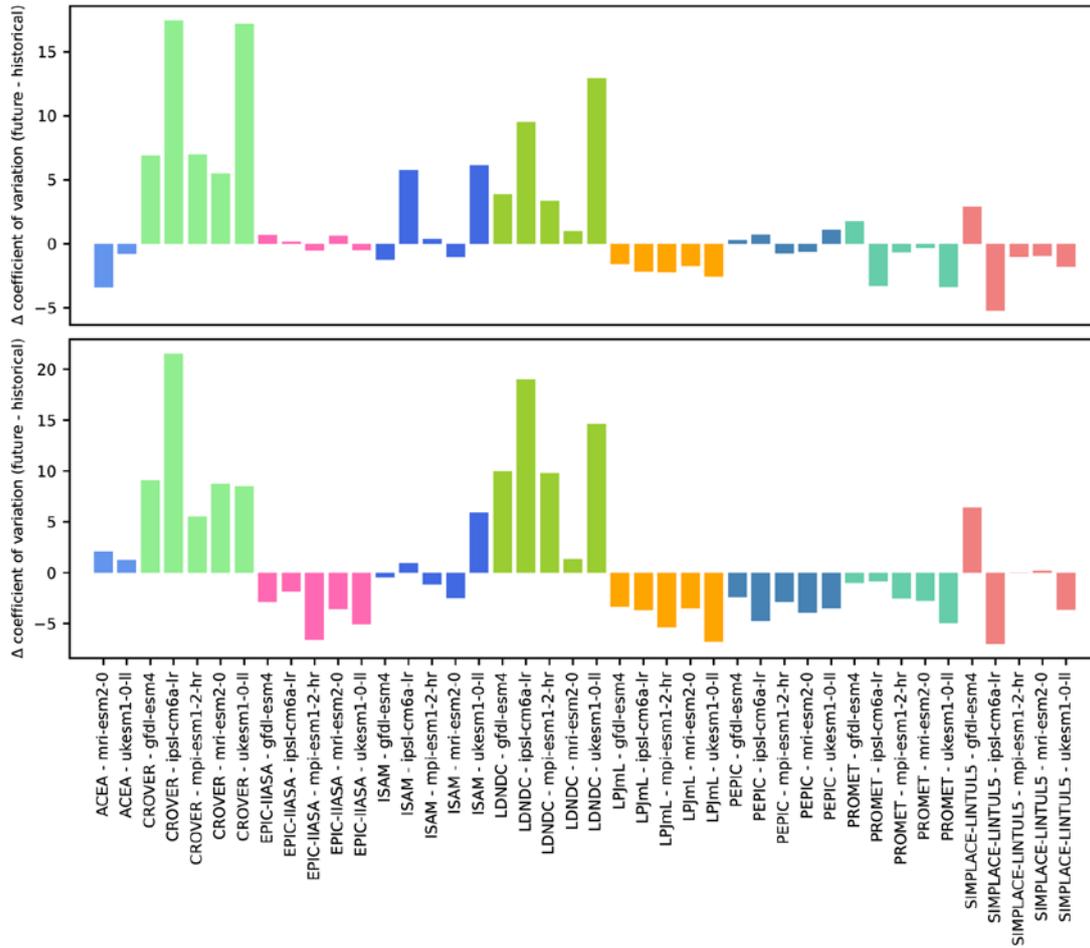


Figure 8. Difference in the coefficient of variation between future (2050-2099) and historical (1851-2015) production (top) and prices (bottom) using ISIMIP3b, RCP8.5 and the default sensitivity scenario.

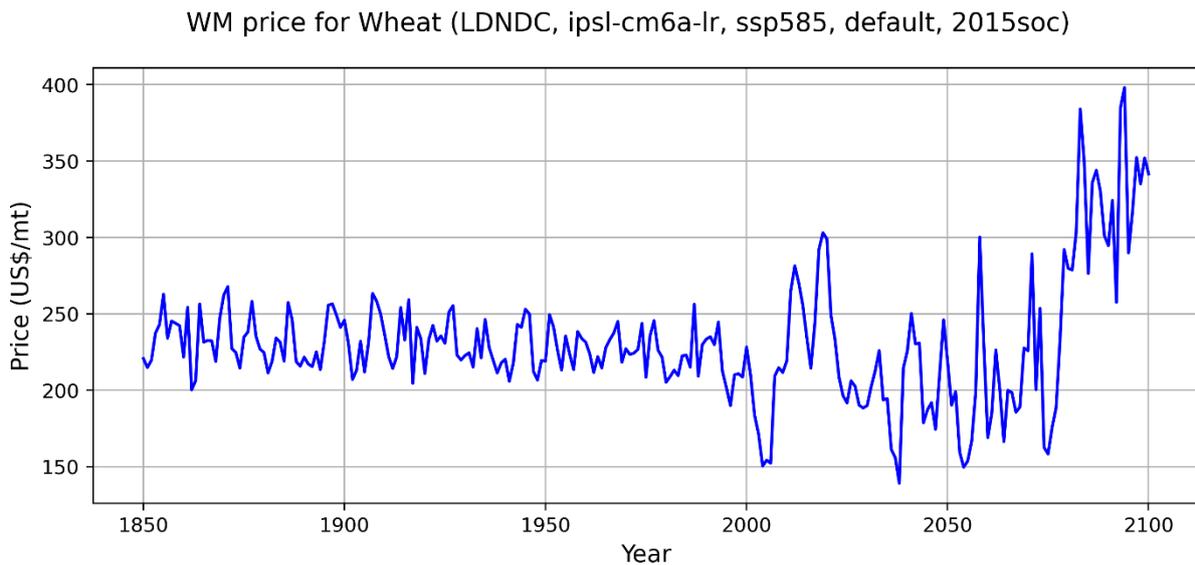


Figure 9. Simulated time series of annual wheat prices for a particular model combination with a very strong increase in price variability between historical and future periods.

In summary, the results from the climate-crop-price modelling chain indicate that the change in global staple food price variability strongly depends on crop model choice and (somewhat less) on the climate models. This is also reflected in the fact that ISIMIP3b shows different results than ISIMIP2b (which comprises fewer and partly different models). Some model combinations give increases in price variability of 15% or higher, while others show little change or small decreases in price variability. We are left with the question of what causes these differences between models? This will be investigated in upcoming research, but it can already be noted that the new generation of climate and crop models (ISIMIP3b) produce qualitatively different results than the previous one (ISIMIP2b), and that conclusions should preferably not be drawn exclusively on the basis of ISIMIP2b simulations, given multiple improvements incorporated in the models since then (e.g. Fan et al., 2020; Jägermeyr et al., 2021)

Given these variabilities, the question arises of what conclusions can be drawn from these mixed results? In face of this large uncertainty, a risk-based/precautionary perspective seems advisable. It is clear that - according to the simulation ensemble - there is a significant chance that climate change will lead to an increase in price volatility. Eight out of 41 model combinations in the more recent ISIMIP3b simulation round indicate an increase in price variability by about 8% or more; with two indicating an increase by about 20%. Such an increase should therefore be considered as a non-negligible risk.

The fact that it is not just a single crop model, nor just a single climate model, showing substantial increases in price variability, underlines that these results should not be disregarded as mere outliers, but should be seen as reason for concern about future food prices. Countries with strong import dependencies and low economic resources would be most at risk of domestic food price volatility, with many such countries located in Africa, West Asia, and Central America (Puma, Bose, Chon & Cook, 2015).

3.5 Soy logistics and climate shocks

This section describes the results from Deliverable 3.5: Soy supply chain exposure to projected climate change impacts in Brazil. Soy is an important EU import, used primarily as a key protein feed in the livestock industry. In CASCADES Deliverable 2.2, statistics were presented that showed oilseeds as one of three agricultural sectors in the EU where imports outweighed EU production (alongside stimulants, tobacco, spices; and fish and aquatic resources). Brazil is the world's largest producer of soybean and is the EU's largest source of oilseed imports. The analysis considered two aspects of climate change impacts: 1) Impacts to projected soy production, and 2) Impacts of extreme weather on the in-land transport of soy for export.

3.5.1 Climate impacts and production shocks

Different combinations of climate and crop models lead to very different results in the analysis of climate change impacts, but all model combinations were kept within the study in order to represent the full range of potential future scenarios. However, there is ultimately considerable uncertainty over which of these scenarios best projects future soy production and climate impacts. Ultimately, climate-crop impact modelling does not aim at providing 'forecasts' but only projections of possible

futures. As such, climate and crop models themselves do not necessarily adequately inform the assessment of how ‘extreme’ climate effects should be captured within downstream impact assessments (such as this one for soy supply chain impacts).

From projections of future soy production under climate change (ISIMIP 2b, RCP 6.0, Figure 10), we observe that whilst the average change in Brazilian soy production over the rest of this century is projected to be positive in three out of four climate models, high interannual variability means there are still certain years projected to have large and sudden drops in production. This suggests that stakeholders within the supply chain should be prepared for sudden shocks to production despite a seemingly ‘positive’ average yield projection (note, results for yield are subject to caveats around limitations in crop modelling, e.g. the positive influence of the CO₂ fertilisation effect is disputed).

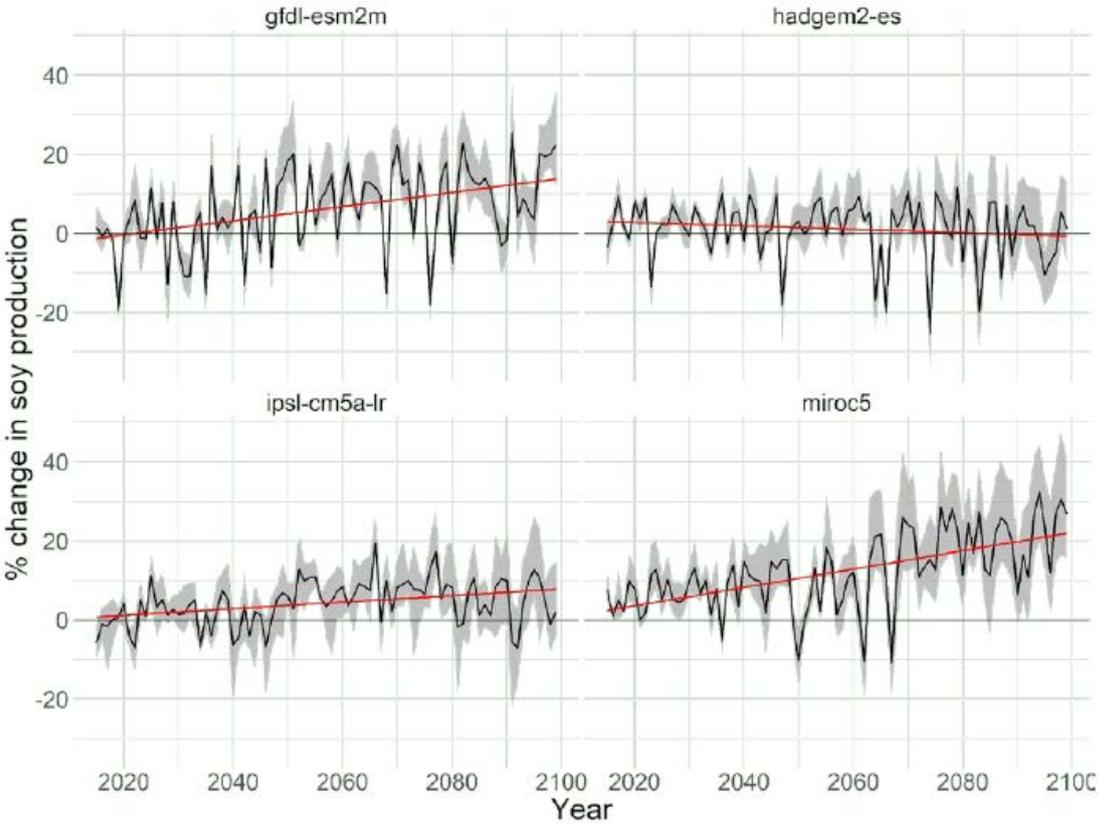


Figure 10. Projected Brazilian soy production, 2015-2099 (base period mean of 2006-2014), per GCM for RCP6.0.. Black line indicates the mean of four crop models. Ribbon indicates maximum and minimum crop model result. Red line indicates the linear regression line. Assumes 2015-17 soy production area in Trase data.

An additional concern, however, relates to the interface between yield changes overall in Brazil, and the specific sourcing locations within Brazil to which the EU might be linked. In other words, yields may increase in some areas but decrease in others which are more or less strongly linked to EU supply. Currently, the EU sources soy from across most of Brazil’s soy producing regions (Figure 11), and we find that the projected impacts on the current portfolio of EU soy imports are similar to the projected impacts on Brazil’s soy production as a whole. We did not attempt

to project future subnational sourcing patterns, but this would be an area for potential future work. Additionally, whilst the EU as a whole has a broad sourcing pattern, individual countries within the EU may source from more specific geographies which may not follow the national average impacts.

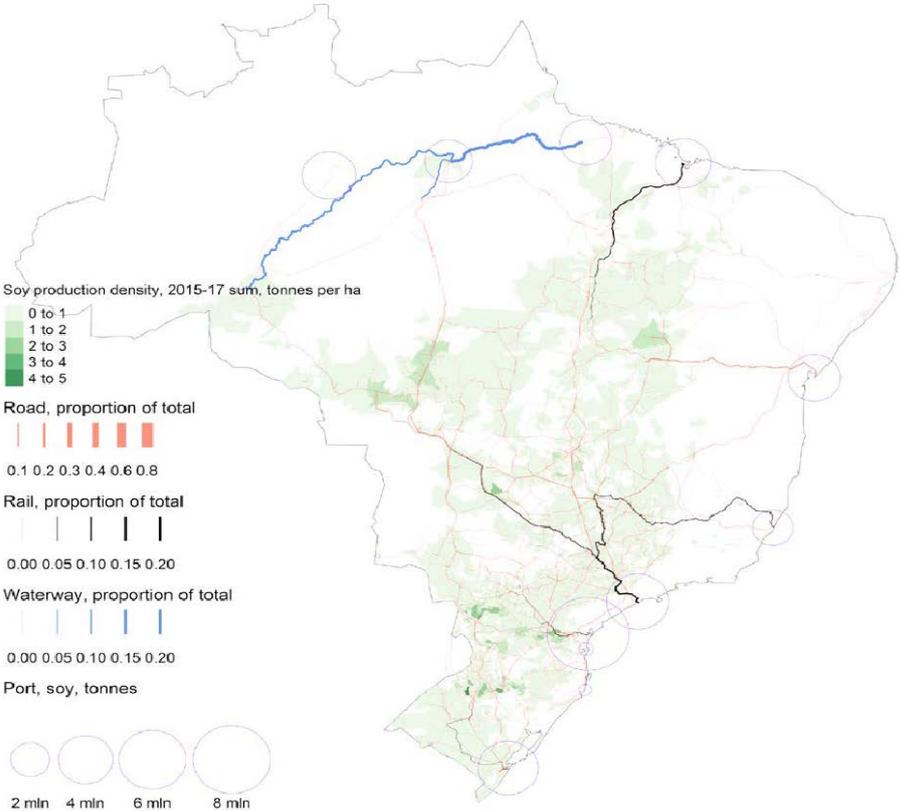


Figure 11. EU imports of soy from Brazil: production density and transport routes, both for EU import, 2015-2017.

3.5.2 Impacts on logistics

In terms of impacts to the in-land transport of soy, we considered the changing frequency of heatwaves, river floods and wildfires intersecting road, rail and river transport. Road, rail and river networks were derived from various datasets: Trase (2022) for volumes of soy flows from producing municipality to exporting port; Brazilian government shapefiles of rail and river networks, stations and ports; station and port capacity data; Open Street Map for optimised road routes; data on modal splits of soy arriving at the biggest ports. This data was used to estimate the most likely routes taken based on travel time, and the volumes of soy travelling by each mode and each route, in order to match the flow volumes described in the Trase data.

We find that the frequency of wildfires and river floods that intersect current transport routes for soy exported to the EU do not appear to increase over this century. However, heatwaves intersecting road and rail routes for EU exports are projected to increase in frequency over the century (see Figure 12). Heatwaves can cause damage to roads and rail, leading to transport disruption and eventual higher

transport costs. However, more information and analysis are needed on the severity of heatwaves in addition to their frequency, in addition to attention on the condition of road and rail infrastructure, and the capacity for adaptation to understand the full potential of acute climate impacts on soy transport networks.

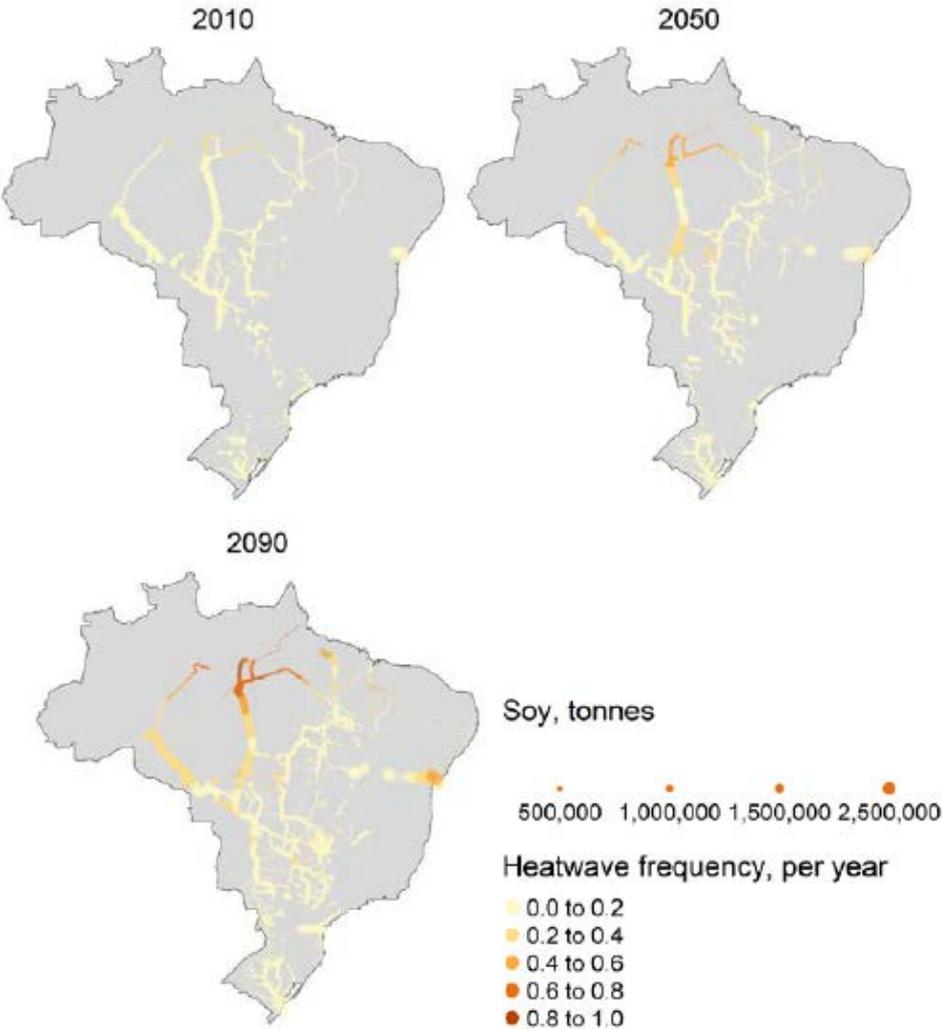


Figure 12. Frequency of heatwaves per decade along road routes for EU soy imports, 2010, 2050 and 2090. Year labels indicate the midpoint of an 11-year period, except 2010 which is a nine-year period. Size of each point indicates throughflow of soy, tonnes.

4. Analysis Section 2: Insights from literature and stakeholder interviews

The second analytical section of this report contains details associated with three distinct case studies which represent potentially important sources of cross-border climate impact for the EU mediated through trade and supply chains. These case studies were chosen in consultation with other members of the CASCADES project with regard to a) ensuring sufficient overlap with quantitative activities conducted in WP3, and b) areas of broader interest to the consortium and the project's stakeholders, e.g. as background material for the policy simulations at the Third CASCADES Core Workshop, which forms the central element of CASCADES stakeholder engagement. This resulted in the following three areas of study:

1. Trade-linked climate impacts and consequences for EU food systems;
2. Trade-linked climate impacts and consequences for the EU soy supply chain;
3. Threats to EU supply of critical energy-transition minerals.

The scope, methods and content related to the three case studies is presented separately below, but it is important to note that research effort was not directed equally to each case study. Most research activity (including a mix of primary and secondary qualitative research) was focused around the food systems case study in recognition of the fact that this was where most quantitative effort had been placed within WP3 (and therefore where it was felt qualitative effort would add greatest value to inform policy insights). The soy case study conducted additional primary qualitative research to supplement the quantitative analysis of the Brazilian soy supply chain; identified as a potentially important but discrete source of impact. Finally, only secondary research (in the form of a 'synthesis' of peer-reviewed and grey literature) was conducted for the energy-transition mineral case study, which is also not supplemented by any further mineral-specific quantitative analysis under WP3, but which reflects an important emerging risk topic among policymakers and stakeholders, particularly those involved in the transition to a low-carbon economy in Europe.

4.1. Trade-linked climate impacts and consequences for EU food systems

4.1.1. Introduction

Analysis conducted under Deliverable 2.2 of CASCADES (and summarised in West et al. 2021) revealed the important potential role of trade in agricultural commodities as both a potential pathway for climate impact into the EU, but also as a potential avenue to adapt to the impacts of local climate change. Analysis revealed that overall the EU is relatively self-sufficient when it comes to its food-linked supply chains, but this is not a homogeneous picture, with certain supply chains such as oilseeds, pulses and fisheries products (important, for example, to the EU's protein provision) having higher import-dependency, and with the EU particularly dependent on imports for fertiliser inputs to agriculture (Figure 13). The origin of several important materials, such as oilseeds, was also found to be highly concentrated geographically.

The quantitative analysis conducted in WP3 provides an overview of the potential risks to the EU economy that might be mediated by the trade in agricultural materials. The analysis, which takes place at a macro-economic scale and considers both chronic climate-linked changes in yield, but also the impacts of acute shocks

(in the logistics chokepoints and the Russia-Ukraine war examples) suggests that economic impacts overall associated with climate-change impacts on agriculture are likely to be somewhat minor from an EU economic perspective, but that there might be important consequences at the sectoral level. Other quantitative analysis conducted in WP3 also highlights the important potential for increased variability in food production and prices. The quantitative analysis conducted, however, is unable to consider the potential for acute (i.e. finer-scale than sectoral) supply-chain risks to arise, nor is it able to analyse the potential for ‘non-rational’ decisions to be made in trade or supply-chain policy. It also has limited scope in terms of the nature of impacts to the EU being considered, with a focus on economic performance. As such, the qualitative research that follows in this section aims to enrich our understanding of the potential consequences of climate impacts to take into account the broader implications to, and responses of, actors in the EU food system.

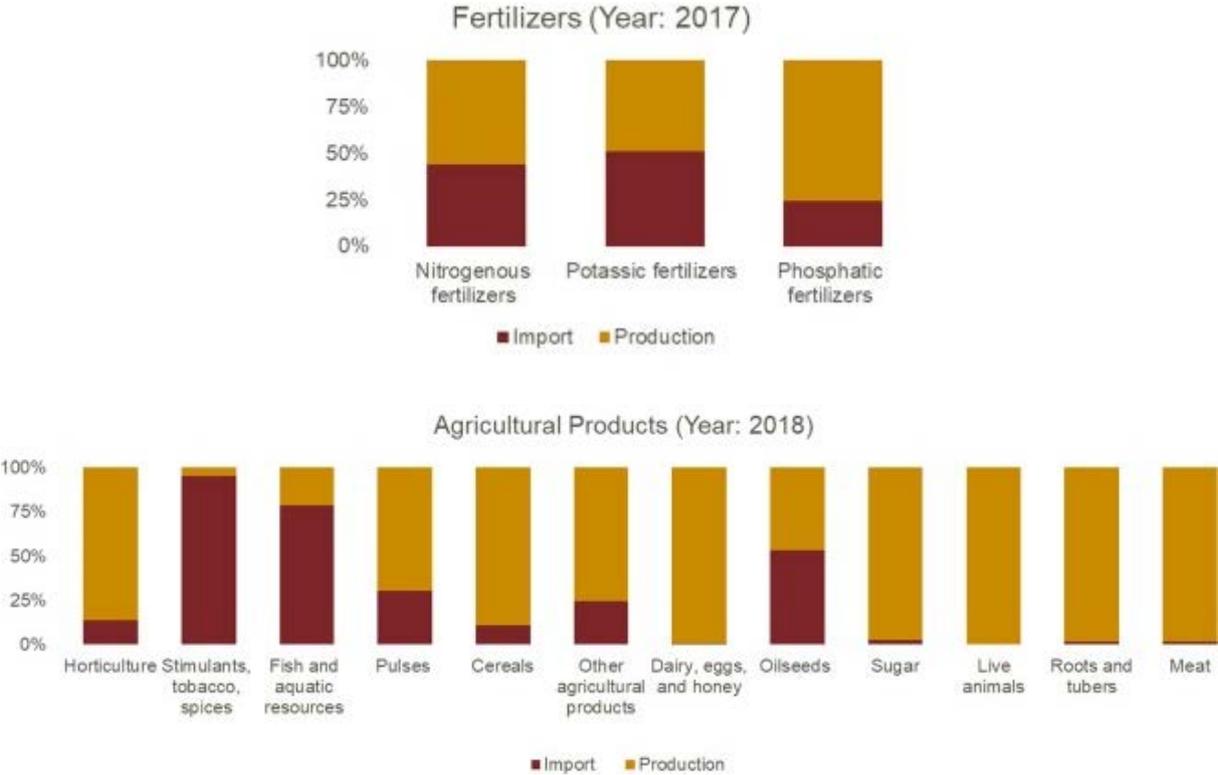


Figure 13. EU-dependency on imported and domestic agricultural materials. Adapted from West et al. 2021.

4.1.2. Methods

Whilst the intention of this case study is to broaden the scope beyond that covered in the quantitative assessment of WP3, it is of course impossible to consider all aspects of the food system (and climate change impacts emerging within it) within a

single case study analysis. For this reason, early in the process, the project team met to discuss the boundaries of analysis to be conducted. From this process emerged a simple 'food system map' which represents key nodes in the food-related impacts system (Figure 14). Within this diagram, climate impacts (green circles) are characterised in terms of slow-onset and extreme changes which may affect food production, transport and processing stages (yellow triangles). Lines between nodes represent impact and potential response transmission pathways. To narrow scope, a decision was made to exclude direct consideration of processing-linked impacts and instead to focus on agri-commodity production and transport risk primarily. This choice was dictated both by a need to select a scope which was feasible in the context of the project, but also because much food-processing activity will be conducted domestically within EU borders.

Three 'system impact' areas (orange octagons) were identified which relate to the potential trade-linked outcomes that might arise for the EU, linked to food supply, price and nutritional quality. These outcomes interact with broader socio-economic contexts and drivers (red pentagons) which - whilst not comprehensive - illustrate the complexity of the broader environment in which responses to food system impacts would be formulated. Responses themselves (purple diamonds) were roughly characterised by those that directly influence the original climate trigger, and those which operate in the food systems 'market' to, for example, minimise disruption. It was decided that the scope of outcomes, socio-economic and responses to be analysed within the case study should not be restricted *a priori*, as understanding the aspects of greatest relevance would be an important outcome of our qualitative analysis.

Following this stage, research was split into two strands: a) a (non-systematic, but breadcrumb-based) analysis of the peer-reviewed and grey literature to understand the extent to which scholars and practitioners have engaged with climate change-linked impacts on food/trade systems and to summarise key insights related to the magnitude of potential impacts to the EU and related responses; b) expert-interviews to elicit perceptions of climate/trade linked risks, their potential outcomes, and their interaction with policy.

For strand a) it was also decided to undertake evidence collection on the food/trade related consequences of the Russia-Ukraine crisis. This event, whilst not directly climate-linked, was brought into the scope of the case study given the important consequences for food security (which may provide future lessons for EU climate resilience), because it is also studied as an emerging case study in WP3 and 6 (see Section 3.2), and because of the prevalence of the example in the minds of stakeholders interviewed in research strand b).

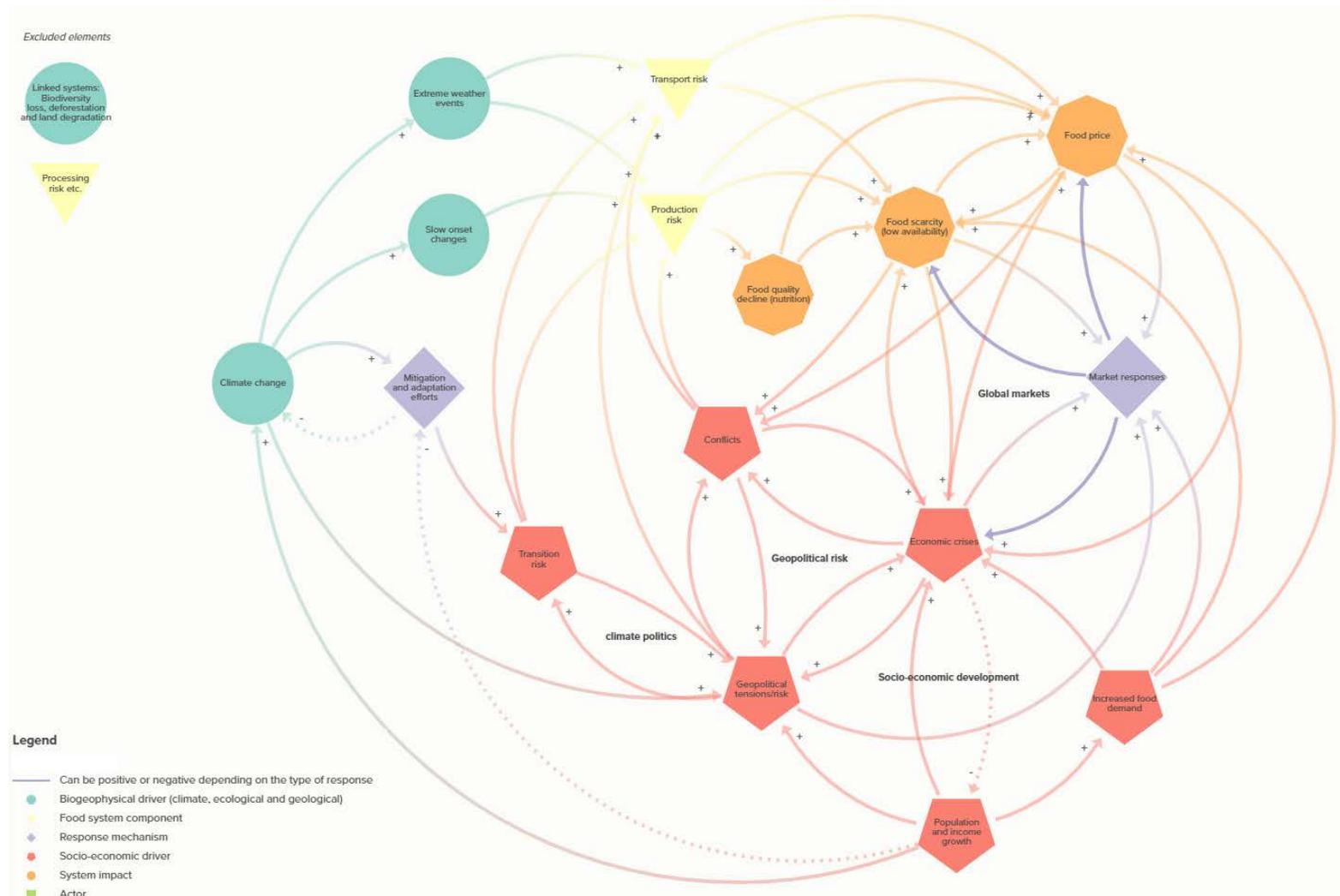


Figure 14. Simple food system map used to help the project team discuss and define scope of the EU food case study. Note that processing steps and interactions between climate change and other environmental risks (e.g. loss of biodiversity) were decided to be out of scope for our analysis.

For research strand b) we decided to undertake interviews using a series of open-ended questions aligned with the mapping undertaken (Figure 14), structured into three components for enquiry: i) perceptions of overseas and trade-mediated climate-linked impact, and the associated assessment of threat, linked to EU food security (price and/or supply) risk; ii) responses and mitigation mechanisms already in use to address cross-border risk; iii) how policies/practices of actors in the supply chain, and public policy, mitigates or exacerbates risk.

Interviews were conducted by various members of the research team. All interviews were recorded after verbal consent was obtained from the participant. A question template was used to guide the interviews (see Annex), but additional follow-up questions were also posed to participants to elicit more detailed responses and to explore relevant areas for further discussion. Participants were asked to briefly describe their current role and background, and provide detail about: the perceptions and relative threat of cross border climate risks (five questions), the mitigation and responses to cross border climate risks (two questions) and the interaction of policy and supply chain risks (two questions). The participants were then given a chance to ask any further questions they had, and to provide any additional information they felt was pertinent to the research. Interviews were typically an hour in duration, with interviewers alternating note-taking roles during the interview. The video recordings were rewatched to ensure the notes were correct and sufficiently detailed. Notes were also sent to the participants to confirm their accuracy and to provide the opportunity for stakeholders to provide any additional comments.

At the time of writing, thirteen interviews have been conducted. Participants are classified (Table 2) into representation from a number of organisational types in order to help identify the position of respondents within our results whilst protecting anonymity. These organisational types are coded to allow their association with the viewpoints highlighted in the results. To analyse the interview data collected, an inductive thematic analysis was conducted. Each interview script was reviewed, before relevant textual extracts were selected and sorted into broad categories/themes. As more scripts were analysed, the categories were refined and supporting quotes were selected.

Table 2. Organisational classifications, number of participants, and associated codes for interviews conducted for the food system case study.

Organisational Category	Type of organisation	Number of participants	Codes
Public Sector	EU/UK policy body (e.g. government department)	2	Pu-P1, Pu-P2
	Multilateral body	3	Pu-M1, Pu-M2, Pu-M3
Private Sector or Non-profit think tanks	Retailer	2	Pr-R1, Pr-R2
	Federation	2	Pr-Fe1, Pr-Fe2
	Consultancy	2	Pr-C1, Pr-C2
Non-Profits	Policy think tank	1	NP-T
	Finance	1	NP-Fi

4.1.3. Results

General Literature Review

Agricultural production and trade in a climate context

The literature recognises the importance of agricultural products in trade markets and potential vulnerabilities to climate change, with, for example, Lewis and Witham (2012) pointing out that commodity markets are sensitive to weather and climate variations which may affect supply, and thus price. Climate change is also recognised as having an uncertain effect on crop yields, with many studies predicting negative impacts but with certain crops and regions benefitting from changes in weather patterns and increases in CO₂ concentration (Lobell et al., 2011, Jägermeyr et al., 2021). Climate change will also increase the frequency of extreme weather disasters (EWDs) such as droughts, floods, and extreme temperatures (Stott, 2016), which is well recognised as likely to significantly negatively affect crop production (Brás et al, 2019, Beillouin et al., 2020, Vogel et al., 2019).

The existing literature points at the fact that globalised commodity markets and international connectivity through complex supply chains may allow supply and price disruptions to propagate easily, causing indirect impacts on regions that appear disconnected (Benzie et al., 2019, Wenz and Levermann, 2016). Furthermore, vulnerabilities created by just-in-time business models and globalised supply chains are highlighted by Wellesley et al. (2017), who focus on the presence of many strategic chokepoints (singular trade nodes with substantial trade flows that may be difficult to redirect if disrupted). Aside from these chokepoints, the stability and resilience of the global trade network is likely to be strongly conditioned by the structure of the network (Albert and Barabási, 2000). Dupas et al's (2022) analysis of the trade between 1986 and 2016 in cereals, oil crops, meat, fruits, vegetables,

coffee, and cocoa found that production and trade are highly centralised among a small number of countries. Ultimately, this leaves a growing number of net-importing countries sourcing from a decreasing number of top-producing countries, increasing their vulnerability to supply shocks. The EU finds itself in such a position for important agricultural commodities such as oilseeds and cereals (West et al. 2021).

In recent years, many nations have maintained relatively low or marginal food self-sufficiency, making them highly dependent on international markets (Puma et al., 2015). Weather-related food production shocks can spread easily throughout the global food system, leaving importing nations - particularly in the developing world - more vulnerable and less food secure (Puma et al., 2015, Suweis et al., 2015, d'Amour et al., 2016). These dynamics are magnified when exporting countries switch to a non-exporting state during times of food scarcity, as observed in the 2008 food price crisis (Puma et al., 2015), and linked to the more recent Russia-Ukraine conflict (see below).

As climatic conditions change in future, the suitability of certain crops may shift from their historical regions to new regions (Grüter et al., 2022), which is projected to lead to a shift in the distribution of agricultural production and therefore international trade (Porfirio et al., 2018). The world is currently still on track for a high-carbon emissions scenario, which Porfirio et al (2018) find (using RCP8.5) will lead to a more centralised international trade network, and increasing imports by developing nations. Other shifts are also expected in future; within their scenarios, Tuninetti et al (2020) expect demand for agricultural goods and their trade flows to grow substantially in the coming decades, as well as projecting a shift of the global trade network architecture from Western to Eastern economies that will place new strain on ecological systems.

Transboundary climate risk (TCR)

Challinor, Adger and Benton (2017) state that “transboundary risks are the products of borders and geography: risks are transmitted from one region to another through systematic environmental processes”. The literature also acknowledges that risks can have multiple direct and indirect pathways, cascading through complex socio-economic-ecological systems (Liu et al., 2015). A new area of literature investigating these cross-border risks is beginning to emerge, with studies covering impacts on sectors such as health, transport, governance, finance, and security (see Lawrence, Blackett and Cradock-Henry, 2020 for full review). However, Benzie et al (2019) claims that food-system assessments are methodologically complex, given high levels of uncertainty and the dynamic nature of the connected climate, food, and trade nexus. Additionally, to date, there is an inconsistent application of language across the nascent literature, with scholars calling for a shared lexicon and typologies (Benzie et al., 2019, Challinor et al., 2018), something that the CASCADES project has responded to via the development of its conceptual framework for cross-border climate impacts (Carter et al. 2021). Below, we focus on the coverage in the literature of food-linked transboundary climate risks/impacts, and their potential impacts on the EU mediated via the international trade system. Assessments and studies on transboundary climate impacts have been conducted at local, sub-national, national, and supranational levels.

At the local scale, Singh-Peterson et al. (2013) assessed the resilience of local food supply chains by collecting data on food prices in urban and rural areas of the Northern Rivers region in New South Wales, Australia, one week and then six months after a flooding and cyclone event. They found prices in urban-located large-chain supermarkets decreased, whilst prices in rural independent shops increased, suggesting a disparity in food security across development areas. Gotangco et al. (2017) conducted a qualitative appraisal of the rice, energy and water supply chains and the waste management chains of Metro Manila. Focus is placed on the “indirect vulnerability” of supply chains to short and long-term climate hazards, and the transboundary nature of vulnerabilities within the resource networks of cities and communities. Results highlight the difficulty in addressing issues that extend beyond the decision-making boundaries of local government units. The authors suggest a need for more vertical government coordination and horizontal, inter-sectoral, collaboration.

Challinor, Adger and Benton (2017) concludes (at the time of publication) that national climate assessments are still not adequately taking TCRs into account. Hedlund et al. (2018) sought to address the omission of TCRs in national-scale assessments by developing an index encompassing impacts to biophysical systems, the movement of people, financial flows, and international trade in order to quantify a nation’s risk exposure. Results from the application of this index indicate that the distribution of exposure to TCRs provides a much more complex picture of global vulnerabilities when compared to climate risk exposure within national borders. For example, small European nations (Netherlands, Luxembourg, Montenegro, Belgium and Malta) are present in the top thirty nations at risk to TCRs, whilst none of these nations are present in an index measuring domestic climate risk (ND-GAIN Index). A weakness of the index used in the study, however, is the absence of metrics concerning food system impacts as a whole; only a single cereal dependency metric is used.

A Foresight (2011) report examines the climate risks to the UK across various areas (foreign policy, security, finance and business, infrastructure, resources and commodities, health) up to 2030 and beyond. Using modelled forecasts of the effects of climate change on resources and commodities, the report finds that the UK’s low direct exposure to climate impacts places it in a relatively strong/competitive market position. However extreme weather effects, pathogens and pests are identified as areas of particular concern that could propagate through supply chains and affect commodity prices and supply. That said, the implications on the UK from these changes were found to be relatively insignificant over a 30-year period, in comparison with other potential drivers of change. Price volatilities are expected to mainly affect the UK through its international aid provision, due to its potential role in affecting food security in vulnerable world-regions. PwC (2013) also assesses the UK’s exposure to climate risks across several themes and sectors that are broadly aligned with the Foresight study (2011). This study uses expert opinion and current knowledge to provide an indicative comparison of domestic climate change threats with international threats between the 2020s and 2080s under a ‘Medium Emissions Scenario’. The authors suggest the international threats to the UK could be an ‘order of magnitude’ larger than domestic threats for business and food supply chains. In the short term, worsening extreme weather events are predicted to drive price volatility and supply disruptions. The authors state that by

the 2050s, climate change could force more pervasive systemic changes to the international commodity trade. Challinor et al. (2016) present a chapter on the international dimensions of climate change within the UK Climate Change Risk Assessment 2017. The authors review and discuss the UK's connections to climate risks from the perspective of the global food system, migration, and geopolitical events. They suggest that short-term food availability is unlikely to be a large issue, but food price volatility from extreme weather events will affect low-income households disproportionately. Longer term threats from changes in the global agricultural system are thought to be only partially predictable. The authors call for coordinated approaches across policy, industry, and research to build resilience as, at the time of writing, no national strategy existed. Latterly, the UK Government, however, has published the UK Climate Change Risk Assessment 2022 (HM Government 2022), which identifies that more action is needed (including in the form of a 'Resilience Strategy' in relation to "Risks to UK food availability, safety, and quality from climate change overseas" and indicates uncertainty in the magnitude of risks and/or opportunities that are likely to arise for the UK.

Vonk et al. (2015) produced a report for the Dutch government on the risks to the Netherlands of climate change abroad. Similar to other assessments detailed above, the report presents a summary of current knowledge and a qualitative assessment, with limited new research conducted. The authors suggest that the Netherlands will be relatively unaffected by many cross-boundary climate risks as most Dutch trade, investments and outsourcing takes place within Europe. However, trade with more vulnerable BRIC nations is expected to increase in future, potentially exposing the Netherlands to new climate risks. The report finds food security in the Netherlands will not be affected significantly given the status of its domestic production and predicts the impacts of any short-term disruptions will be minor. An exception here is for soy supply chains, where imports are more concentrated in vulnerable regions.

Kankaanpää and Carter (2007) present a report for the Finnish government on the global effects of climate change across many economic sectors. The direct implications of climate change for Finland's agricultural sector mostly includes the expansion of bioenergy and crop production in surplus land. Whilst the possible future indirect effects of climate change on Finland's economy and food security are briefly discussed, this early, overview report lacks analytical detail and quantification.

Horn et al. (2022) use several quantitative indicators to assess Sweden's food security and exposure to climate change risks through its imports. Their analysis indicates that Sweden's grain imports are most vulnerable, whilst animal products are least vulnerable to climate change beyond its borders.

Knittel et al. (2020) studied Austria's indirect exposure to climate change via sea level rise, heat-induced labour-productivity losses and changes in agricultural yields up to 2050 by running a computable general equilibrium model under different SSP and RCP climate scenarios. They find Austria's relative trade position improves, but in absolute terms climate change may negatively impact Austrian GDP and welfare, largely driven by effects on labour productivity, but with slight compensation provided from increases in agricultural yields at northern latitudes.

Mosnier et al. (2014) combine the global gridded crop model (EPIC) into GLOBIOM, a global economic land use model, to focus on the long-term climate risk exposure of Mongolia, China, Japan and South Korea up to 2050. Findings show that domestic production systems are likely to be negligibly, or even positively, affected by climate change. However, impacts on food availability could be negative after considering the role of imports, highlighting the importance of accounting for cross border risks in food availability assessments. Additionally, production and trade adjustments prompted by market price signals may reduce the impact of climate change impacts on food availability by allowing exports from regions benefiting from climate change to reduce deficits in regions suffering negative effects.

Adams et al. (2021) assess international trade dependencies – using a hybrid multi-regional input-output framework - across key agricultural commodities (maize, rice, wheat, soy, sugarcane and coffee), and explore how climate-projected changes to yields may result in risks to exporters and importers. Across the analysis, commodity production in the US, China and Brazil dominates international risk profiles. Results linked to the EU reveal projected negative impacts between EU Member States (e.g. French exports to Netherlands and Belgium for maize) and between the EU and international markets (e.g. from Thailand for rice, and from Brazil for soy and coffee). However, for wheat, France and Germany emerge as potential climate-change beneficiaries.

Overall, key issues linked to climate change that are presented in most national assessments include concerns around the impacts of price volatility on trade, trade disruptions, political and security implications, foreign policy impacts, and impacts on aid to partner countries (Benzie et al., 2019). At present, however, many of the existing national assessments conducted by research institutes or consultancies lack detailed description of the methodologies utilised, and often only provide marginal new research activity, instead primarily synthesising and applying current knowledge to qualitatively assess risks in a given national context.

Assessments of the EU as a regional bloc

Many model assessments of the *direct* impacts of climate change on the EU food system have been conducted. Most studies find that agricultural productivity in northern regions will benefit from both CO₂ fertilisation and increases in rainfall whilst the south suffers negatively (see Harrison et al., 2019, Knox et al., 2016, Beillouin et al., 2020, Hristov et al., 2020). In a systematic review, Knox et al. (2016) found the average increase in yield across seven major crop types in Europe was +8% by 2050, except for maize that decreased. Despite these positive projections, however, Brás et al. (2021) found that the frequency and severity of impact of extreme weather disasters (EWD) on European crop production between 1961 and 2018 has increased. As part of the Joint Research Centre's PESETA II project, Ciscar et al. (2014) ran climate and economic model simulations that integrated ten biophysical impact categories to assess the economic impacts of changes inside the EU. Findings suggest that effects are small with around a 2% reduction in GDP from climate-related damages. Domestic agriculture and labour productivity are modelled, but the negative price impacts of decreasing agricultural yields due to climate change outside the EU are not considered. Transboundary effects are only discussed

in this work from an internal perspective, i.e. member states' impacts on other member states.

Several studies have been conducted investigating the EU's exposure to TCRs. For example, an assessment of the indirect effects of climate change on the EU was commissioned by the European Commission Directorate-General for Climate Action (DG CLIMA) in 2012 (Amec, 2013). The report concluded that EU and member states' policy was not adequately taking climate 'spillover effects' into account. Additionally, it stated the EU would remain vulnerable to climate change impacts in neighbouring countries even if domestic adaptation was successful.

The JRC PESETA III project (Ciscar et al., 2018) follows on from the previous PESETA II project, and considers the impacts of yield changes due to climate change outside the EU on the EU agricultural sector. The model results indicate that all agricultural commodity prices decrease under scenarios with enhanced CO₂ fertilisation effects due to increased EU domestic production and enhanced international competitiveness. The EU's trade balance improves (becomes less import dependent) for cereal commodities, but agricultural incomes also drop on average by 16%, with most EU states experiencing decreases. Transboundary effects on energy demand, river flooding, labour productivity and agriculture were found to increase EU welfare losses by 20%, mostly linked to agriculture.

In the fourth edition of an EEA report on the EU's vulnerability to climate change impacts, cross border effects are discussed at length (Lung and Hildén, 2017). The report concludes the main areas for risk propagation are commodity price volatilities, supply chain disruption, the opening of new Arctic shipping routes, agricultural trade shocks affecting EU states in the Mediterranean region, non-agricultural trade shocks affecting small open EU economies, and migration from the MENA region. This report mostly presents a review of existing knowledge.

Benzie et al. (2019) build on Hedlund et al. (2018) to apply a Transnational Climate Impacts Index (TCI Index) to quantify cross-boundary climate risk and the EU's current exposure. Whilst, as described above, the index does not extensively integrate metrics related to agriculture or the food system, results show many EU countries are more exposed to climate-related risks than the global average.

Martinez et al. (2017) use agro-economic and climate models to explore near-future impacts of global crop yield and price changes on the EU. Despite large regional variations, overall average global production for staple crops increases due to CO₂ fertilisation effects. Commodity price changes in the opposing direction to crop production due to increases in projected availability. The authors highlight the omission of extreme weather events in their biophysical models, preventing the assessment of the impact of sudden shocks on the food system.

Ercin et al. (2019) map the EU's global dependency on water resources outside its borders and assess the impact of drought on crop imports. The EU's economy was found to be highly dependent on water, with around 38% of total water demand met from outside its borders. The authors conclude supplies of certain crops grown in water scarce areas such as soybeans, rice, sugarcane, cotton, almonds, pistachios, and grapes are vulnerable to future disruption. In similar work, Ercin et al. (2021) quantify the vulnerabilities of EU agricultural imports with an exclusive focus on drought risk under future climate scenarios. They find 44%+ of EU agricultural

imports become highly vulnerable and that drought severity in production locations will increase by 35% by 2050. Imports originating from Brazil, Indonesia, Vietnam, Thailand, India and Turkey were found to be most vulnerable.

Kulmer et al. (2020) use ISIMIP and multi-regional input-output (MRIO) models to study the climate change impacts on resource availability under future climate projections. Both direct and indirect 'impact channels' on crop production, people at risk of malaria transmission, labour productivity, and water availability are explicitly quantified. The authors find that crop production increases in the EU, although this varies from northern states to southern states, whilst dependency on imports increases due to growing consumption.

Brás et al. (2019) focus on the impact of supply shocks generated by EWDs by conducting an epoch analysis of historical production and yield data of selected crops in EU import locations. The study finds that droughts and heat waves had historic impacts of 3%, 8%, and 7% on the production of soybeans, tropical fruits, and cocoa respectively. They conclude that production reductions may potentially reduce EU caloric availability to an extent, but are not expected to fundamentally impair food supply. They stress the importance, however, of the related market volatilities that may occur.

The European Environment Agency is increasingly paying attention to transboundary climate risk, with a recent report (Arvis et al., 2020) presenting a literature review, an indicator-based quantitative analysis, and case study of EU agriculture. The report indicates that transboundary climate risks present only a moderate challenge for staple food security, whilst animal feed and 'luxury' crops (cocoa beans, coffee, exotic fruit, and bananas) are likely to be more vulnerable. The report does not analyse the demand-side impacts of current and future EU mitigation and adaptation policy.

Opportunities for future research

Most studies thus far have examined risks to broad components of economies and societies, such as trade, security and finance, and risks to the food sector have mainly been considered only at relatively low resolution. Whilst elements such as production, trade and price have been considered, there appears to be a relative absence of detailed studies of the TCRs from climate change-induced shocks to the food sector which disaggregates the system and its stakeholders into, for example, effects on growers, suppliers, traders, consumers and so on. There is also a general focus towards the impacts of longer-term climate trends over those of EWDs or sudden shocks to food systems. The effects and responses of production shocks and price fluctuations on specific stakeholders within the food sector in the EU have yet to be developed or studied.

Additionally, it is important to recognise that the studies conducted so far may depend on relatively outdated climate-crop model projections. Indeed, Jägermeyr et al. (2021) find that a new ensemble of crop and climate models that include warmer climate projections and more sensitive crop models show more pessimistic yields for many crops. This suggests that an integration of these results into TCR studies could identify greater vulnerabilities than previously observed.

There also appears to be disagreement within the literature on the role of breadbasket regions in promoting resilience and the related risks of breadbasket crop failure due to climate change. Anderson et al. (2021) finds the threat of multiple breadbasket shocks is decreasing, whilst Gaupp et al (2020) suggest the opposite. Gaupp et al (2019) find an increased likelihood of simultaneous breadbasket failure for wheat, soybean and maize under both 1.5 and 2°C warming scenarios. Caparas et al. (2021) find the probability of crop yield failures across global breadbaskets to be much higher by 2030 and beyond. They also find high water scarcity across crop breadbasket regions in India, China, and the United States, wherein the likelihood of crop failures would increase under scenarios of restricted irrigation. Detailed analysis about the nature of links between the EU and breadbasket regions, and their implication for climate risk exposure appears largely absent (but see Adams et al. 2021). The shifting suitability of certain crops under climate projections (Grüter et al., 2022) and the potential for realignment of trading relationships and supply chains also appears to remain relatively unexplored, which prevents the identification of future structural vulnerabilities that may not exist within present-day supply chain configurations.

Within the literature summarised above, policy recommendations appear overall to be discussed in a relatively cursory fashion. Some suggestions include policy to promote supply diversification, support for climate adaptation in trading partner nations, and the improvement of industrial and supply linkages with external neighbours. Benzie et al (2019) provide examples of some existing mechanisms for integrating concerns about TCRs such as the EU Civil Protection Mechanism, EU Adaptation Strategy, Water Framework Directive, EU Cohesion Fund and Structural Funds. Some authors suggest that harmonised trade policy and trade adjustments through market mechanisms will be adequate to mitigate against agricultural yield and price changes (Martinez et al, 2017; Hertel and Baldos, 2016; Elbehri et al, 2015). However, uncertainty exists overall in the role of trade, and thus trade policy, in mitigating food price volatility (Ferguson and Gars, 2020). Arvis et al. (2020) present a more detailed discussion of policy options, proposing the ‘systemic mainstreaming of climate analysis into trade negotiations’ and a restructuring of supply chains to bring production closer to home. However, policies implemented to protect national interests alone are deemed likely to cause negative impacts on a global scale (Challinor, Adger and Benton, 2017; Puma et al., 2015).

The Russia-Ukraine Crisis

The Russia-Ukraine crisis, coming shortly after the global Covid-19 pandemic, provides an example of what might be classed as an ‘extreme’ event that, whilst not attributed to climate change, serves as an opportunity to explore the consequences of disruptions to global and EU food supply. Geopolitical instability in the Ukraine and Russia has disrupted the supply of commodities from one of the world’s major breadbasket regions that is particularly relevant, by virtue of its proximity, for Europe. These disruptions can cascade, affecting the demand and supply of commodities from other breadbasket regions, exposing importing countries to indirect impacts. This analysis complements the quantitative work presented in Section 3.2.

The effects of the crisis, which occurred concurrently with other stresses on agricultural production and trade, are described below and are based on a synthesis

of reported events (from media outlets, industry and public-sector agencies). In reality, whilst the Russia-Ukraine war is the highest profile event linked to recent food-system impacts, the observed effects on the food system can be attributed to several interconnected aspects: the conflict, regional extreme-weather events around the globe, fertiliser scarcity, export restrictions, and supply-chain bottlenecks linked to the Covid-19 pandemic. Note that the summary below was compiled during the summer/autumn of 2022, and therefore reflects the situation at time of writing.

Russia-Ukraine conflict

The Russian invasion of Ukraine caused major disruption to world food supply chains, triggering significant price rises of many commodities (BBC, 2022). Russia and Ukraine provide a significant proportion of global wheat, maize, and sunflower oil exports (FAO, 2022a), albeit with production for export only accounting for ~1% of global grain consumption. Processing activities in Ukraine have suffered suspension, and Black Sea ports have suffered closure, preventing Ukrainian agricultural goods from leaving the country (FAO, 2022b). Black Sea commercial shipping activities have been severely restricted, increasing insurance premium rates for vessels sailing in the region, which has exacerbated maritime transportation costs (FAO, 2022a). It has been stated that the use of alternative export routes out of Ukraine through Europe could have a softening effect on prices (AHDB, 2022), however only small fractions of such exports reach global markets.

The economic sanctions imposed on the Russian Federation, a major energy exporter, also had the effect of significantly increasing global energy prices, impacting transport and input costs for many industries, including agriculture (UN - GCRG, 2022; FAO, 2022a). The World Bank estimates that, overall, war-driven food (specifically wheat and corn) price rises have caused an average real loss of 1.5% to global household incomes (Rijkers et al., 2022) and placed a projected additional 75-95 million people into extreme poverty (Mahler et al., 2022).

Importantly, the region's 2022/23 crop season is also uncertain as war damage, increased fuel and input costs, and a rise in animal diseases is predicted to hamper ongoing agricultural production in Ukraine, whilst continued export and import restrictions on agricultural inputs could impact Russian production (FAO, 2022a).

Fertilisers

Even before the conflict, many fertilisers increased in price through 2020-2021 driven by strong demand (e.g. to boost Brazilian and US soybean production), and increasing energy prices and shipping costs. The Russian Federation and Belarus, both affected by EU sanctions, supply large proportions of the world's nitrogen, potassic and phosphorus fertilisers (FAO, 2022a). These economic sanctions, as well as a suspension of Chinese fertiliser exports, caused fertiliser prices to reach record highs in April 2022 (Reuters, 2021). Nations dependent on Russian exports, particularly in Latin America, Central Asia, and sub-Saharan Africa, have been significantly affected (FAO, 2022b). High fertiliser prices are leading farmers to reduce their usage, which will lower crop yields and nutritional quality in the coming 2022/23 season, potentially driving prices even higher (UN - GCRG, 2022).

Trade restrictions

As of May 2022, the scale of export restrictions on food and fertilisers surpassed levels seen in the 2007-08 food crisis, affecting around 10.6% of total global traded calories (Laborde, Mamun & Parent, 2022). Between February and June 2022, 109 export restricting measures on fertilisers and food products had been employed across 63 countries (UN - GCRG, 2022). However, the relative openness of world markets has been extremely dynamic as time-limited restrictions can expire, whilst new restrictions can be rapidly implemented by nation states.

One prominent example of trade restrictions is linked to the palm oil supply chain (Figure 15). Palm oil price fluctuations over the past two years (at times, palm oil prices have been more than triple those in 2019; Trading Economics, 2022) can be attributed to a confluence of interconnected factors. Lower production output in Malaysia and Indonesia, two countries that represent approximately 85% of world production, has been a major factor. Border closures in Malaysia motivated by the Covid-19 pandemic have restricted the supply of foreign migrant workers, causing labour shortages. Structural issues such as the ageing tree profile have also hampered supply in the short and medium term (CPOPC, 2021). Severe flooding in Indonesia's Kalimantan province in Q3 2021 and seasonal year-end flooding in Malaysia have impacted harvesting and replanting (CPOPC, 2021; Raghu, 2021). Fertiliser prices have also trended upwards since 2020, causing small-farmers to reduce fertiliser application and impacting production (CPOPC, 2021). Elsewhere, recent poor harvests for many edible oils over 2019-2021, driven by extreme weather conditions and labour shortages, have caused surges in demand for palm oil as consumers moved away from scarcer oils. The Russian invasion of Ukraine almost entirely restricted sunflower oil exports from the Black Sea region, severely reducing global edible oil supplies, placing increased pressure on palm oil markets (Root, 2022). Demand has remained buoyed by large importers like India and China as their economies begin to recover from the pandemic, as well as via increases in Indonesia's B30 biodiesel mandate (CPOPC, 2021). The Russian invasion of Ukraine, beginning in February 2022 triggered extreme volatility in global commodity markets. Energy costs and severe supply chain disruptions further restricted global edible oil supplies driving rapid increases in agricultural commodities, including palm oil. Following the Russian invasion of Ukraine and its impacts on global commodity markets, there was a dramatic bull run leading to rapid palm oil price inflation. In response to these extreme prices, the Indonesian government imposed an export ban in April 2022. With Indonesia representing 60% of world supply, the ban put further strain on palm oil supplies. Social unrest began as farmers' livelihoods were severely impacted, and the export ban was lifted within a month, after which the Indonesian government announced a domestic market obligation that required producers to sell a proportion of their stock locally at a set price. The creation of a cooking oil stockpile was also announced. Export taxes and levies were also lowered and an export target of one million tonnes of palm oil products by the end of July was set, providing reprieve to record prices (AHDB, 2022).

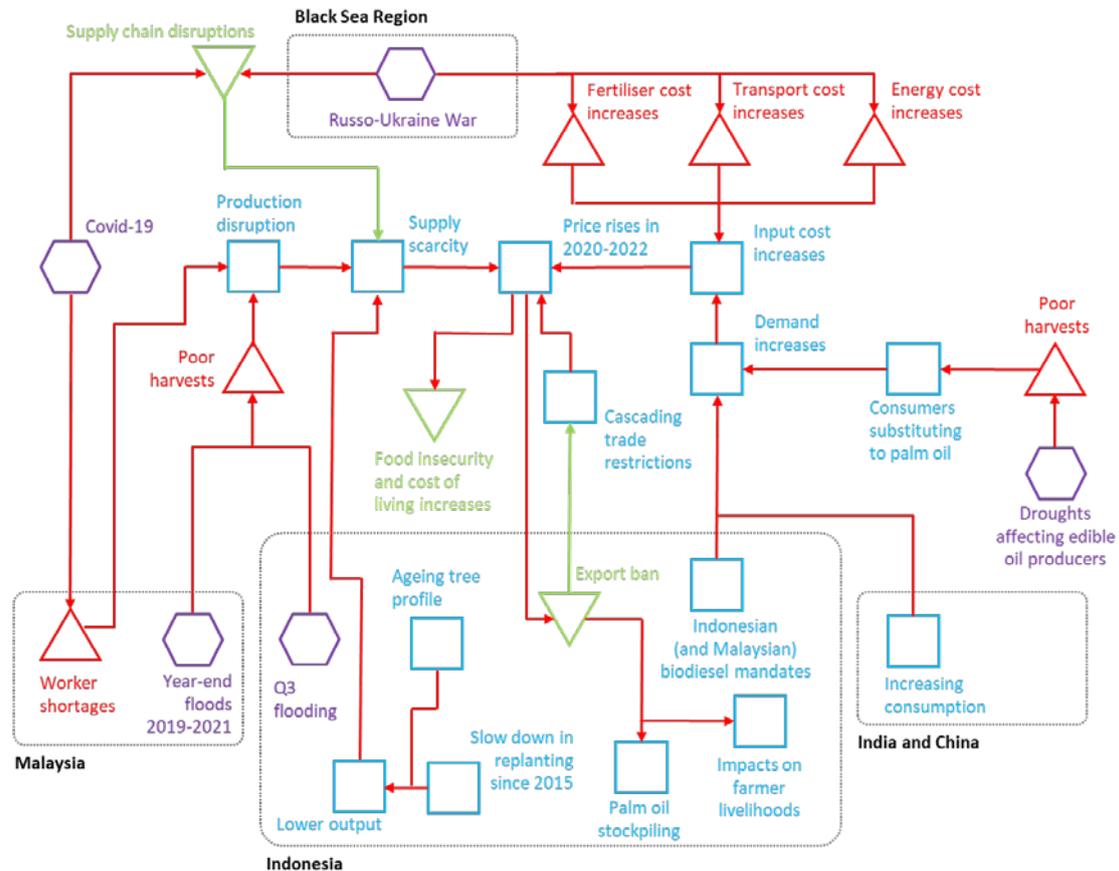


Figure 15. Illustration of impacts to palm oil prices and supply resulting from a confluence of climatic-, Covid-19- and Russia-Ukraine conflict-linked impacts, including the introduction of Indonesian trade restrictions.

Extreme weather and crop planting

To add to disruptions related to the Russia-Ukraine conflict, extreme weather in almost every major producing region in the world has placed additional pressure on world grain and edible oil supply (Gross and Durisin, 2022). Dryness in the US and the EU, wet and dry planting conditions in Canada, and droughts in many other countries have driven reduced projections of yield (USDA - FAS, 2022b; Gross and Durisin, 2022). Extreme heat throughout March to May 2022 in India, Pakistan, and large parts of South Asia, made 30 times more likely by climate change, resulted in a reduction in crop yields in key wheat breadbasket regions (World Weather Attribution, 2022; USDA - FAS, 2022b). This led the Indian government to reverse plans to export record quantities of wheat this year, instead instituting a wheat export ban. The decision was met with strong opposition from farmers unions and opposition parties within India, as well as internationally, provoking an easing of restrictions to neighbouring countries (Chowdhury, 2022). The ban affected many MENA and SEA nations that had switched their wheat sourcing to India from the Black Sea in response to the Ukraine conflict (USDA - FAS, 2022a).

Earlier this year, Brazil, Argentina and Paraguay (major Latin American producing countries) experienced drought periods driven by a second consecutive La Niña

weather event, causing a projected shortfall in many crops such as maize, soy, coffee and sugar (Hiba, 2022). These difficult weather conditions follow years of below-normal rainfall and almost three years of severe water deficit. Brazil soil moisture is at a 20-year low (USDA - FAS, 2022a), with the rivers that make up the Río de La Plata basin having been at extraordinarily low levels, preventing normal transportation (Hiba, 2022).

In contrast to most other regions, Russia and central Asian nations expect a bumper crop, enabling record wheat exports to many MENA nations (USDA - FAS, 2022a). China has also observed a bumper harvest of winter wheat, despite negative forecasts (Jingling and Lin, 2022; Gross and Durisin, 2022). In sum, according to the International Grains Council (IGC 2022), the outlook for world total grains (wheat and coarse grains) is placed at 2,256m tonnes in 2022/23, which represents a 1% lower year-on-year decrease but still the second largest on record. Much of the fall stems from a relatively steep drop in maize, with sizable losses expected in Ukraine, the EU and the US. In contrast, world production of wheat, barley and oats is expected to increase year-on-year. World grain trade is projected to contract by 4% year-or-year.

Observations across commodities

The disruption-linked dynamics of production and trade vary across specific agricultural commodities. For example, international prices of oilseeds and derived products began rising in late 2021, reaching near record highs in May 2022. This was mostly due to supply tightness and trade disruption (FAO, 2022b). For soybeans, drought conditions across Southern hemisphere production regions have suppressed production, and strong demand from US and China has buoyed prices. However, yields in the US and India continue to grow, offsetting these issues. Rapeseed supply remains restricted as droughts in Canada affect production. Australia expects a bumper harvest, whilst output in the EU is likely to also recover. Despite bumper harvests in Black Sea region, sunflower seed prices have been majorly affected by disruptions to Ukrainian shipments. Impacts to palm oil trade are described above. Production in palm and sunflower oil is expected to recover, potentially offsetting drops in soy and rapeseed oil outputs (FAO, 2022b). However, world prices will take time to decline (Gross and Durisin, 2022).

Maize production is concentrated in Argentina, Brazil, the US and Ukraine. Thus, Black Sea export disruption drove prices to record high prices in March 2022. Global production is expected to drop in 2022, due to lower output in the US, Ukraine, Russia, Argentina and South Africa (FAO, 2022b).

World meat production is expected to expand in 2022. However, prices across most meat indexes have risen due to tight global supply, animal disease and rising input costs. Trade is forecast to expand only marginally, reflecting the disruption to global supply chains (FAO, 2022b). World dairy production is also expected to increase in 2022, whilst trade could contract slightly. International prices for dairy products have been on an upward trajectory since mid-2020, reaching an eight-year high in April 2022. These increases have been driven by tight export supplies, and growing import demand. Lockdowns in China linked to Covid-19 led to slight drops in prices, but demand continues to outpace world supply (FAO, 2022b).

Economic impacts and responses

Price increases in food and energy commodities have had a knock-on effect on the global economy, with many countries entering into a contractionary period (USDA - FAO, 2022a; UN, 2022). The World Bank expects slow global economic growth and “for many countries, recession will be hard to avoid” (World Bank, 2022). Many central banks, including the US Federal Reserve, are instituting interest rate hikes to calm inflation, painting a bearish macroeconomic outlook for 2022. These rate increases have caused currency depreciations in 142 developing nations, eroding their purchasing power, further reducing accessibility to vital food imports (UN - GCRG, 2022).

Despite yield losses in some producing regions, total world food supply remains high (FAO, 2022b), with the main factors driving elevated prices related to supply chain and export restrictions (Aminetzah et al, 2022). Many people in regions reliant on Black Sea exports will continue to experience high prices until supply chains with new suppliers are established, which may take time. Extreme weather conditions and fertiliser scarcity effects, whilst having some impact already, are likely to affect availability more acutely in 2023, likely prolonging the current crisis (Aminetzah et al, 2022). A paper by the International Monetary Fund estimates that food and fertiliser price shocks may add \$9 billion in 2022 and 2023 to the import bills of the 48 most affected countries (Rother et al., 2022).

Aside from the implementation of trade restrictions described above, another short-term response to the current food system crisis has been for many countries (including those in the EU) to implement domestic fiscal support (European Council, 2022; Rother et al., 2022). The EU has also changed policy to allow land set aside for biodiversity improvements to be brought into agricultural production, as well as reducing biofuel mixing requirements (European Commission, 2022a).

Insights from Stakeholder Interviews

Whilst the questions conducted within interviews were structured into perceptions of impact exposure, responses, and policy interfaces (as described in the methods section above), analysis of the interview transcripts has taken place using an inductive approach, resulting in the development of ‘themes’ which describe the coalescence of comments around particular topic areas and the shared and contrasting perspectives on trade- and climate-linked food systems resilience.

To date, thirteen interviews have been conducted, and we have sought to gather insights from a cross section of those with policy and private-sector based experience. We do not, however, claim that this set of interviews will be fully representative of viewpoints or activities linked to the EU food system. A more extensive research effort to ensure representation of a greater and broader set of opinions would be necessary to understand the current state of activity and opinion that exists across the various facets of what is ultimately a large and complex system.

The impact of the Covid pandemic and the Russia-Ukraine conflict

Some questions in our lines of enquiry asked stakeholders to reflect on the interfaces between climate change and other potential shocks to the food system. However, even before enquiring about other forms of impacts, several participants drew attention to recent disruptions to the food system which they felt illustrated

characteristics that might also be observed following potential climate-related shocks. Participants (Pr-C1, Pu-P1) highlighted that these crises demonstrate the linkages that exist between geopolitical security, food security, raw material security and climate mitigation goals, with impacts from these crises likely to be analogous to future cascading shocks (Pr-Fe1, Pu-M1). A cross-section of participants acknowledged that a key challenge was that the current disruptions in the food system were driven not only by distinct - isolated - events, but by a broad confluence of factors including the Russia-Ukraine war and subsequent disruptions in the Black Sea, increasing global food demand from countries such as India and China, Covid-19 and lockdown disruptions, ad-hoc supply chain disruptions, high energy prices, and crop-yield reductions internationally related to weather events. In the words of one participant (Pu-M2), “It’s been one bad thing after another”.

Impacts associated with these crises observed by private-sector stakeholders (Pr-C1, Pr-R1, Pr-R2) included a recognition that they had resulted in supply chain ‘tightness’ such as causing transport disruptions, delays in just-in-time supply chains, and threats of additional disruption linked to export controls. One private-sector-linked participant (Pr-C1) also shared concerns that the geopolitical consequences of the crises might result in a reduction in free trade, and increasingly non-aligned trade blocs, which would have the consequences of reducing overall food security.

Several participants (Pr-Fe1, Pu-P1, NP-T, Pr-C2, Pu-M2) expressed the opinion that the Covid-19 pandemic and Russia-Ukraine conflict (and its consequences) provided lessons for food systems stakeholders and also had helped to place the potential for food supply chain vulnerabilities and EU overseas dependencies on the policy agenda. In the words of one stakeholder (Pu-P2), the pandemic helped to highlight the issue, but the Russia-Ukraine crisis “blew the lid off”. This sentiment was reinforced by another stakeholder with links to EU policy (Pu-P1) development: “The immediate impact of war and geopolitics is more striking[...]. The war has had a dramatic impact on global food security [...] but in the long run climate change remains a key driver for yields and extreme events”. Several participants (Pr-Fe1, Pu-P1, NP-T, Pr-C2, Pu-M2) also mentioned that these events had prompted reviews of food security and/or contingency plans at both EU-policy level and within the private sector. At the private-sector level this has included more reflection and investment of resources around climate risk and resilience into ESG (Environmental, Social, Governance) processes (Pr-R1, Pr-R2).

However, one participant (NP-T) with experience of working on EU food systems policy, expressed the opinion that these crises had actually made the EU aware of its relative levels of internal resilience and has reinforced a ‘productivist’ approach which is not necessarily conducive to a more thoughtful future approach to climate risk. A couple of stakeholders (Pu-M2, Pr-Fe2) observed that the pandemic had demonstrated the ability for companies to quickly adjust their supply chains, indicative of a level of existing resilience in the system.

Primary EU food system vulnerabilities, shocks and risks

The central challenge associated with ensuring EU food system resilience was summarised by one stakeholder (Pr-C2) as “security of supply at the right price”. Key threats to this security identified included climate risks to production activities in

the form of extreme weather events (e.g. extreme cold/heat, water availability) which were identified by some stakeholders (Pr-R1, NP-T) as the main source of risk.

However, logistics risks were also identified by some stakeholders (Pr-R1, Pr-C1), particularly with regard to port infrastructure that was felt to be vulnerable both to long-term sea-level rise, but also short-term damage from extreme weather events. Concerns were expressed about the availability of funds to promote adaptation in response to such vulnerabilities. The Suez Canal/Evergreen disruption was explicitly mentioned (Pr-Fe1) as one example, with the potential to cause backlogs in supply. Perishable products (with high importance for retailers, for example) were identified (Pr-R1) as the product category that might be particularly vulnerable to such logistics shocks.

Several stakeholders (Pu-P1, NP-T, Pr-C2, Pr-R2) articulated the feeling that, overall, the EU is likely to be fairly self-reliant for many commodities (e.g. cereals) but that vulnerabilities might be higher for certain commodities. These commodities are roughly divided into oilseed products used for animal feed or as oils for human consumption (i.e. soy and palm oil) that are not grown in sufficient quantities and/or competitively within the EU itself but for which there is high demand, and non-essential but high-value commodities grown in non-temperate climates such as tea, coffee and tropical fruits. Fertilisers, on which the EU is quite import-dependent, were also identified as a potential source of vulnerability.

In addition to the identification of certain commodities, a couple of private-sector-linked participants (Pr-C2, Pr-R2) identified particular countries that they felt were sources of vulnerability, such as Brazil, Ecuador, Colombia and Sub-Saharan Africa. The primary motivation for the identification of these countries was that they were associated not with particular climate-threats but rather a relative lack of visibility associated with supply chains sourcing from these regions, accompanied by a perception that climate-policy may also be underdeveloped in such regions.

Finally, climate transition risks were mentioned by several stakeholders (NP-Fi, Pr-R1, Pr-R2), with the potential introduction of carbon taxes, and an overall move towards decarbonisation in supply chains likely to put pressure on production costs.

Notwithstanding all the above, several stakeholders (Pu-M2, Pr-R1, Pr-C2) expressed a feeling that there was a large degree of uncertainty surrounding the nature of climate change and its consequences for the EU food system. These uncertainties extend to the impacts and outcomes of potential shocks themselves, and the likely responses that might take place (Pu-M2, Pr-R1, Pr-Fe2). There was also uncertainty (Pu-M2, Pr-R1) surrounding the nature of who will ultimately bear the costs of disruption (e.g. private sector actors, producers, or the EU public), with examples including the feeling from one stakeholder that it is not necessarily obvious that price increases in the supply chain would be passed directly to consumers (Pu-M2). There was also a feeling expressed (Pu-M2) that vulnerabilities in the system may arise where they are unexpected, and that indirect or unusual causal pathways will be especially difficult to plan for. Another stakeholder linked to the private sector (Pr-C1) expressed sentiment that a contribution to uncertainty is that in the last few decades, extreme weather events have not really taken place at global scale (i.e. large-scale concurrent events occurring internationally), despite what might be expected under future climate scenarios. A stakeholder (Pu-M2) felt that, ultimately,

the magnitude of the shock was likely to dictate the efficacy of responses, and that it was likely that future shocks would 'cluster' and, therefore, for the EU to be resilient, it must prepare to respond to multiple events. Furthermore, shocks were seen as likely to affect producers and consumers differently across sectors, adding to the complexity and potential uncertainty. That said, the same stakeholder (Pu-M2) felt that gradual climate change effects were likely to be relatively easy to anticipate and prepare for, with larger companies, for example, able to buffer any incurred production losses and price increases.

One private sector stakeholder (Pr-Fe2) highlighted that the EU's policy decisions have the potential to increase vulnerability; particularly where they deviate from international standards which can make sourcing more difficult. The EU's policies on pesticides and on sourcing products with zero-deforestation were given as examples.

Outcomes of shocks

Some stakeholders (Pu-M3, Pr-C1) expressed the opinion that significant overseas climate shocks are unlikely to lead to a situation of absolute food scarcity as there is sufficient food availability globally and market dynamics mean that price rises are likely to help regulate demand. One stakeholder (Pr-Fe2) commented that the potential for supply shortages is likely to depend on the precise nature of sourcing location and the potential for substitutability, which may vary across commodities. Additionally, one stakeholder (Pr-C1) expressed the opinion that only a very significant supply reduction would have a large impact on prices. A government-linked stakeholder (Pu-P2) indicated that the Global North might see temporary shortages, but these food systems are likely to be relatively resilient in the long run, with another indicating that they felt that food supply chains were perhaps more resilient than other sectors overall (Pu-M3).

Several examples of shorter-term outcomes emerged from the interviews, including the potential for short-term losses of supply or supply delays to result in the sourcing of substandard products which may also degrade longer-term standards and consumer expectations (Pr-C2). Various participants mentioned that any short-term rises in consumer prices might have an impact on the affordability of food, and that this is likely to have effects that are unevenly distributed towards poorer citizens across EU member states. Within supply chains, outcomes might include difficulties in fulfilling contracts, including invocations of *force majeure* clauses due to delivery delays (Pr-C1). It was also pointed out that short-term drops in productive output could affect supply chains in the longer term (NP-Fi). Substitution of products was mentioned as an option, but the viability of this is dependent on the elasticity/flexibility of product demand (Pr-R1, NP-Fi), with some items (e.g. bananas) simply not substitutable on a like-for-like basis, and with others having particular valued properties (e.g. nutritional values) which are non-trivial to replace (Pr-Fe2). Processing facilities may also not be able to quickly switch between materials, or even at all, depending on the technologies available (Pr-Fe2). Outcomes are likely to be heavily product-dependent, with shocks to cereals or oilseeds having the potential to ripple into other product supply chains, and with impacts to other commodities such as meats, fruits and vegetables having potential implications for dietary intake (Pu-P1, NP-Fi, Pu-M2). Within commodity markets as well, shocks in one region may impact other regions via shifts in demand (Pr-Fe2). In relation to

impacts of food quality, it was felt that aside from crop-production effects there might be the potential for supplies of important chemical inputs to be disrupted (an example of chemicals required for water purification was given; Pr-Fe1), that food-borne disease and infection risk might increase (Pr-Fe1, Pu-P1), and that it may prove difficult to maintain the quality of imported goods under certain conditions (e.g. cold storage requirements might need to increase to avoid spoilage in instances of heat waves; Pr-Fe1).

Examples of longer-term outcomes included the feeling that shocks to the food trade system may catalyse regionalisation (e.g. within Latin America or Africa), protectionism and a move away from 'export-oriented' markets (Pu-M1), with concerns also about the potential for migration into the EU noted (Pu-M1, Pr-Fe1). The potential for longer-term international and domestic political instabilities to arise following instances of food insecurity was also mentioned (Pu-M1). Other political shifts, such as the potential for governments to take back protected lands into production to expand domestic supply with weakening or disregard to environmental controls, was also noted (Pu-M2). One stakeholder pointed out that, in severe cases, it may simply not be possible to return to sourcing from places affected by extreme shocks (Pr-Fe2).

A common theme in terms of outcomes in general was the feeling that it may be the policy responses to shocks that are ultimately more of a threat than the initial shock itself. A 'short-termist' reaction to shocks and crises was felt to be a possibility (Pr-C1), with concerns that autocentric reactions, such as export restrictions, can be highly damaging (Pr-Fe2). One stakeholder also observed that, commonly, responses to shocks have tended to prioritise the farming sector instead of consumers (Pu-M2). However, there was also a feeling that shocks could bring out positive attributes, with previous disaster responses acting as a template for future shocks: governments and industry in coordination with a focus on restoring markets and adopting an 'all hands on deck' approach (Pr-C1). However, whilst there was also a feeling that the EU could use its fiscal power to "throw money at" problems that arise, this could also lead to unintended consequences if it leads to a damaged global reputation and could result in reductions in 'soft power' if lower-income countries ultimately lose out (Pu-M2).

The EU's ability to respond to climate-linked food-system vulnerabilities

Stakeholder opinion on the awareness of the potential for cross-border climate impacts was mixed. Some stakeholders suggested that they thought this was somewhat low, but others (e.g. NP-Fi, Pr-C2, Pr-R1, Pu-M1, Pr-Fe2) claimed the opposite. Ultimately, there is likely to be quite a large degree of heterogeneity across the EU food system in terms of awareness of vulnerabilities and risks, which extends to different levels of awareness within sectors (Pr-Fe2, Pr-R2). It was also noted that, whilst climate change and food security have recently been heavily on the policy agenda, this has been slightly overtaken by geopolitical instabilities (Pu-P1). It was clear from the evidence provided by participants that effort is being taken within the EU to reduce vulnerabilities to climate change and other threats to EU food security. One participant from a multinational organisation (Pu-M1) expressed the opinion that "The EU is ahead of the curve in many ways, and this is helpful globally", i.e. it provides an opportunity for other countries to learn from EU activities and should help to strengthen global food systems resilience. Specific

examples given by one participant (Pu-P1) included the use of satellite information to help anticipate the impacts of weather-related events on food supply, and commitments across member states to share analyses of markets and climate events. Within the private sector, activities to increase resilience were also apparent, although one stakeholder (Pr-R2) expressed concerns that the capacity available to support the integration of climate risk assessments into corporate decision making varied geographically across Europe, with, for example, private sector actors in Eastern Europe not as well positioned in comparison with organisations in the West.

Several ongoing activities and policy processes were mentioned by stakeholders with links to EU policy. This included identification of the EU food security contingency plan (European Commission, 2022b; Pu-P1) as a mechanism to improve coordination between EU authorities and Member States, to establish channels for public-private collaboration, and to act as a forum for gathering together Member States, third countries and supply chain operators. In the words of one participant from the EU policy space (Pu-P1), the EU seeks an approach of “cooperating multilaterally wherever we can, acting autonomously wherever we must”.

In the context of the current food crises, policy interventions were mentioned (Pu-P1), including the fact that the latest communication on EU food security and food systems (European Commission, 2022a) has stated a need to decrease import dependencies. Concurrently, however, there is heated debate around how this is realised, with controversial derogations of biodiversity laws within farming policy aiming to allow production on areas previously set aside for conservation purposes. Relaxations have also been made to allow EU states to reduce biofuel mixes in fuels (European Commission, 2022a).

One participant with links to the private sector (Pr-C2) expressed an opinion that changes in policy and practice to build resilience are likely to generate new opportunities for the EU, for example the development of new markets and new supply chain relationships. They also felt that the EU could play a role in supporting smallholder farmers to ensure long-term value creation within their production systems with spillover benefits for wealth creation, the development of better quality food for local communities, and the regeneration of ecosystems.

Current challenges linked to adapting to climate risk in EU supply chains

Notwithstanding the uncertainties that surround the specific magnitude of climate-related threats to the EU food system and its supply chains, our interviews have made it clear that food systems stakeholders are part of a system which faces significant challenges at present (and likely into the future). These challenges have the potential to undermine the building of enhanced resilience to climate change: “When everyone is in fire-fighting mode, it essentially undermines [an] ability to mitigate this [food insecurity/crises], so you would get these feedback loops” (Pu-P2) and “Part of the challenge is that it's a moving target.” [on addressing current and future food security issues] (Pu-M3). One stakeholder commented that the market cannot be depended on to fix such issues (Pr-Fe1). However, at the level of international governance, several participants (Pu-M1, Pu-M3, Pr-C2) observed a negative outlook for international cooperation: “There has been a crisis of multilateralism in recent years; we would like to think that as global change comes along, we need to work together and can't just all hunker down and hope we can

solve the problem.” (Pu-M3). Feelings were also expressed that many countries are simply using resources inefficiently due to poor policy design and unsustainable practices (Pu-M2), and have low capacity to implement adaptation programmes (Pu-M1). A problem also observed, was that there is an unhelpful dichotomy between high-income countries focusing on climate mitigation and low-income countries focusing on adaptation (Pu-M3).

At the EU-level, there was some commentary that the lead-in times for overseas countries receiving funds for climate adaptation (the explicit example of India was given) was often too long (NP-Fi) and that the pace of policy development was also too slow and lacked urgency (Pr-Fe1, NP-Fi). Others felt that EU countries were too inward-facing (NP-T) and that work on environment, climate adaptation and mitigation, and the mobilisation of resources was usually siloed from work on trade, which meant it was too narrowly focused (Pu-P, Pu-M1). A lack of clarity was also observed on the willingness of governments to invest in redundancies in the food system, or for it to respond to the issue that sustainably-sourced products will usually come at a premium and someone must be prepared to pay (Pr-C1). One stakeholder observed that in the current context, governments are increasingly acting in a populist manner which might be: “good for the country but bad for the people” (Pr-Fe1).

At the private sector level, the issue that companies often adopt short-time horizons in their decision making was observed (Pr-Fe1). A specific example (Pr-R2) included the impacts of current inflation and the energy crisis that mean that farmers are facing pricing pressures which potentially jeopardise decarbonisation plans. Another observation was that company supply chain roadmaps, whilst increasingly incorporating net-zero targets, still lack adequate incorporation of climate risk (Pr-R2). A lack of consensus across industry on how to approach mitigation and adaptation, combined with a lack of overall knowledge, was also identified as a barrier to faster action by retailers (Pr-R1). Data-related challenges were also a common theme, with difficulties associated with monitoring and auditing complex supply chains, and with trade-information or information provision from large companies often being opaque (Pr-R2, Pu-M1). Retailers have many products, with excessive information gathering likely to be difficult and prone to slowing down operations with implications for consumers and the EU economy (Pr-R1). The different product lines involved in retail supply chains also entail a tailored approach, but this is time-consuming and often ultimately requires information from the first node in the supply chain that can be difficult for actors downstream to reach (Pr-R2). A feeling was also expressed by various stakeholders that corporate action overall was inadequate and sometimes subject to greenwashing. Some companies were observed to be taking action, with others not responding (Pr-R1), and a number of commitments were observed but often with a lack of detailed work on the development of specific actions (Pr-C1). One stakeholder observed that companies are primarily motivated by avoiding brand risks and ensuring security of supply rather than addressing climate risks (Pr-C2). That said, in some instances, positive activity is clearly taking place, with companies conducting climate risk assessments seeking continuous improvement and supply chain diversification, encouraging communication across suppliers and engaging with processes such as the Task Force on Climate-Related Financial Disclosure or with local authorities on infrastructure adaptation plans (NP-Fi, Pr-R1). As one stakeholder observed,

however, “action that is occurring is [often] internal” (Pr-C1), with companies competing on their climate measures rather than these being discussed in, for example, trade associations.

Proposals for increasing resilience

There was a relatively wide-ranging set of opinions and suggestions related to improving resilience, which is to be anticipated given the breadth of stakeholders included in the interview process. Several stakeholders (Pu-M1, Pu-M3, Pr-Fe1, Pr-C2) mentioned a need to integrate ‘systems thinking’ more fully into decision making processes, with enhanced international cooperation across both public and private bodies. A need for additional diversification in EU supply chains was also mentioned by a cross-section of stakeholders, with one stakeholder commenting that all policy needs to be well designed in order that diversity of supply chains is maintained overall (Pr-Fe2). However, one stakeholder with links to the private sector (Pr-C2) pointed out that different food commodities have different levels of integration (e.g. poultry is heavily integrated compared to e.g. beef or cocoa) and therefore effective adaptation is likely to require a tailored approach across each context. On the production-side of supply chains, a couple of stakeholders from multilateral organisations (Pu-M1, Pu-M3) mentioned a need to ensure that extension services and local infrastructure is fully functioning, and pointed out the need to improve farmer resilience to climate by improving production, mitigation and adaptation activities.

In the policy domain, stakeholder comments also reflected a complexity of options and a mix of opinions. Some stakeholders (Pu-M3, Pu-C2) expressed a requirement for stronger regulations (“Policy needs to be legislative rather than voluntary”) with policies properly implemented to prevent perverse incentives. However, another stakeholder (Pr-R1) expressed that, whilst policy from the EU that facilitates the provision of reliable information to companies would be useful, regulations that impose too much specificity/standardisation could be damaging as there would simply be too many product-lines to monitor: “If interventions are too disruptive then this will increase the costs and will be problematic. This risks losing individual company efforts”. The benefits of policy to incentivise improvement to data collection and provision was mentioned by various stakeholders, although one stakeholder (Pr-Fe2) pointed out that ‘chain of custody’/traceability requirements are not resource-neutral, and might therefore also lead to fewer suppliers being able to meet data demands which might lead to negative effects for resilience. Other suggestions for improved EU policy included: (Pr-C2) a reframing in farming subsidies from a productivity-approach towards improving ecosystems and allowing farmers to access new revenues; (Pr-C2, Pu-M1) using trade policy/trade relationships and market signals as a mechanism to influence exporting countries’ climate and resilience policy linked to critical commodities; and (Pr-Fe1) refusing to engage with partners who do not implement climate objectives.

At the private sector level, suggestions for improved resilience included a call (Pr-C2) for actors (specifically retailers), via pre-competitive collaboration and with the support of organisations, such as the World Economic Forum and World Bank, to align and harmonise their supply-chain strategies in cases where their sourcing profiles are similar. A call from a stakeholder linked to the finance sector (NP-Fi) was for the continued development of tools to allow investors to assess companies’

climate-resilience policies and actions. A retailer (Pr-R2) also expressed a requirement for more retailers to develop contingency plans for disruptive climate-linked scenarios. An observation was also made about the role that financial institutions can play in promoting more attention on the issue in the private sector, with requests from the finance sector for companies to support risk assessments likely to increase a focus on long term sustainability over short term investments to avoid the risk of stranded assets (Pr-C2).

Several stakeholders mentioned that just-in-time (JIT) supply chains may be a source of vulnerability, with one private-sector-linked stakeholder (Pr-Fe1) articulating that they should transition to “just-in-case”. Yet, others (Pr-C1; NP-T) expressed scepticism about the efficacy of creating new stores, with one (NP-T) indicating that they felt JIT supply chains had coped with the Covid-19 pandemic relatively well. Some stakeholders (Pu-M3, Pr-C1) expressed concerns that such redundancy would overall be a negative for food security, preventing the efficiency of ‘surplus-to-deficit’ flows, and increasing prices overall. Instead, they suggested a need for greater flexibility in supply, allowing buyers to switch contracts and reroute supplies. One stakeholder (Pr-C1) expressed doubt over the ability for government-supported storage to be effective in responding to shortfalls, saying “if these are not available to the market [...] they can’t make a difference in climate-linked events”. Tensions between climate policy and related productivist vs trade liberalisation and redundancy vs flexibility arguments were noted by some stakeholders (Pr-C1, Pu-M3).

The influence of extra-EU bodies

Several participants were representatives of public sector multilateral bodies, and identified policies and programmes relevant to climate risk adaptation and food security. These included (Pu-M1) the UNDP Green Commodities Programme (UNDP 2022a), which covers a variety of food products and aims to provide a national platform for producers and food-system stakeholders to discuss sustainability in value chains. UNDP’s ‘Climate Promise’ initiative (UNDP 2022b) was also highlighted as a mechanism to improve nationally determined contributions to climate change mitigation and promote movement towards alternative livelihood mechanisms whilst reducing impacts on the environment. In the context of these initiatives, however, concerns were raised (Pu-M1) about structural constraints that may determine their success, such as the availability of financing and other resources, and a lack of access to lending markets. The G20’s Agricultural Market Information System (AMIS) was also highlighted (Pu-P1, Pu-M3) as a useful platform for increased transparency and policy response for food security. Additionally, the WTO Conference in Geneva in 2022 and its associated declaration on resilience in the food system (WTO 2022) was highlighted (Pu-M3) as a sign that “countries are taking baby steps in the right direction”, and that the WTO is “constantly ‘oiling the cogs’ of world trade and helps to ease tensions”.

Whilst the importance and influence of such multilateral arrangements and institutions was recognised, several stakeholders expressed concerns about their ability to provide leadership towards climate resilience. One stakeholder (NP-T) expressed the opinion that organisations such as the OECD, FAO, WTO and UNFCCC can “crystalised action but very rarely lead” and another (Pu-P1) stated that whilst

they are able to issue recommendations, these can have limited effectiveness if members of these organisations take unilateral sovereign decisions.

There was a general feeling that several ‘institutions’ have great influence in the food system and are likely to be critical to building EU food-trade-linked climate resilience. This included superpowers such as the US, but increasingly also other large importing and exporting countries such as China and India. A couple of participants (Pr-Fe1, Pr-C1), however, suggest that the EU is relatively ahead of the US with respect to activity around climate resilience linked to food supply chains in both public and private contexts. Large multinational companies were also often identified as strong influencers of market activities, implying that sending clear market signals on the Scope 3 agenda and the broader issues of climate resilience is likely key to unlocking activity. The role of larger multinational companies in sending signals to smaller companies was also identified (Pr-R1) with a statement made that this could shape the ambition of the EU and its private sector: “Big players can provide clear messages to smaller companies”.

The importance of extra-EU institutions was underlined also by a recognition across stakeholders of the fact that the EU food system itself sits within a broader global system of interconnections, with the potential for risks to cascade across many sectors which together could influence policy effectiveness. Additionally, some ‘mega-trends’ were observed (e.g. by Pr-Fe1) who noted that societal change across Asia and Africa is likely to have important implications for climate change resilience, particularly as the EU becomes a smaller player and might be competing for resources with larger consumers such as China (Pr-Fe2).

On trade and trade policy

As described earlier in this report, a topic of continued debate is the role of trade either as a mechanism to exacerbate or to act as a buffer to cross-border climate impacts. Several stakeholders commented on the role of trade and trade policy as both a potentially positive and negative force. For example, one stakeholder (Pr-C1) expressed the opinion that the current world trade system remains relatively free and flexible, but that political currents are moving against free trade, which is concerning from a food security perspective. The opinion was also expressed (Pu-M3) that a diverse economy (i.e. one with extensive trade) is more resilient to all types of shocks than a concentrated one, with growth in international production allowing for resilience and flexibility (Pr-C1).

An opinion was also expressed (Pu-M3) that some actors had misconceptions about trade-linked policy. For example, it was felt that the World Trade Organisation *is* able to take and/or provide support for effective action to improve resilience so long as the measures implemented by nations were not protectionist; but with a fear within many developing countries that ‘green protectionism’ was arising. Furthermore, the stakeholder felt that a false dichotomy was being put forward between the roles of trade vs domestic production for building resilience, against the reality that growth in demand outstrips the capacity for domestic supply.

From an EU perspective, the EU’s trade relationships were observed as a possible positive force (Pu-M1), providing market signals and incentives for lower income countries towards mitigation and adaptation. Economic partnership agreements were mentioned as a mechanism for the provision of support (Pu-M1). In contrast it

was felt that the EU switching sourcing regions away from high-risk areas may lead to an increase in global inequality that might generate ‘pushback’ with poorer nations who require support. Also, on the less positive side, it was noted that activity to increase climate resilience of EU supply chains may make it less competitive in current global markets (Pr-R2).

Several participants highlighted the fact that the EU’s resilience to climate-linked food trade vulnerabilities is likely to be heavily influenced by political decisions. One stakeholder articulated that political decisions can leave policies in place (such as agricultural- and trade-subsidy policies) that are counterproductive to climate resilience (e.g. by continuing to promote high meat consumption): “a lot of politics are involved” (Pu-M2). The same stakeholder (Pu-M2) highlighted the importance of international organisations maintaining cordial relationships with governments, requiring diplomatic and political sensitivity. Two stakeholders (Pu-M2, Pu-P1) mentioned concerns that, when disruption hits, political pressure can rapidly change outcomes (“When times are calm we can make nice agreements; when there is political pressure this changes things.”; Pu-M2) and means that prior agreements get broken; the change in Indonesian palm oil export policy was cited here as an example.

4.2 Trade-linked climate impacts and consequences for the EU soy supply chain

4.2.1. Introduction

The case study of soy examines the Brazil-EU soy supply chain to understand how future potential cross-border climate change impacts might affect the EU in a specific commodity example. This example was selected due to the high reliance of the EU on imports of soy, as domestic production of soy is much lower than consumption, and soy is a key ingredient in livestock feed (Kuepper and Stravens, 2022). As of 2020, Brazil is the largest producer of soy globally, and the largest source of EU soy imports (Chatham House, 2020), and was therefore chosen as the focus of this study.

Whilst previous work has focused on projected impacts of climate change on Brazilian soy production and transport (see Deliverable 3.5, and summary above), in this case study we used semi-structured interviews to understand in more detail where the impacts of supply chain shocks are experienced, and how stakeholders respond to and prepare for future shocks.

The questions we aimed to investigate are:

- How do stakeholders in the soy supply chain respond to shocks?
- What are the consequences of shocks for different stakeholders?

4.2.2. Methods

The findings from this case study are drawn from interviews with stakeholders representing a wide range of organisations involved in the production, transport, processing and use of soy. To select participants, we first conducted a stakeholder mapping exercise (see Figure 16) drawing on prior knowledge and soy supply chain literature. As this is a study on cross-border climate change impacts, we only focused on the Brazil soy used for export to the EU. This, therefore, does not include the consumption of soy within Brazil, or other sources of soy consumed by the EU. Stakeholders were categorised based on their position in the supply chain,

and geographical location. Based on this mapping exercise, we defined four stakeholder groups: producers (stakeholders involved in the production and initial processing of soy, e.g. crushers producing soy meal and soy oil), intermediaries (stakeholders involved in the trade and transport of soy from Brazil to the EU), consumers (stakeholders based in the EU who buy soy from Brazil, from the feed manufacturers to the end consumers) and policymakers (established either in the EU or Brazil, offering an outside perspective on the supply chain as a whole).

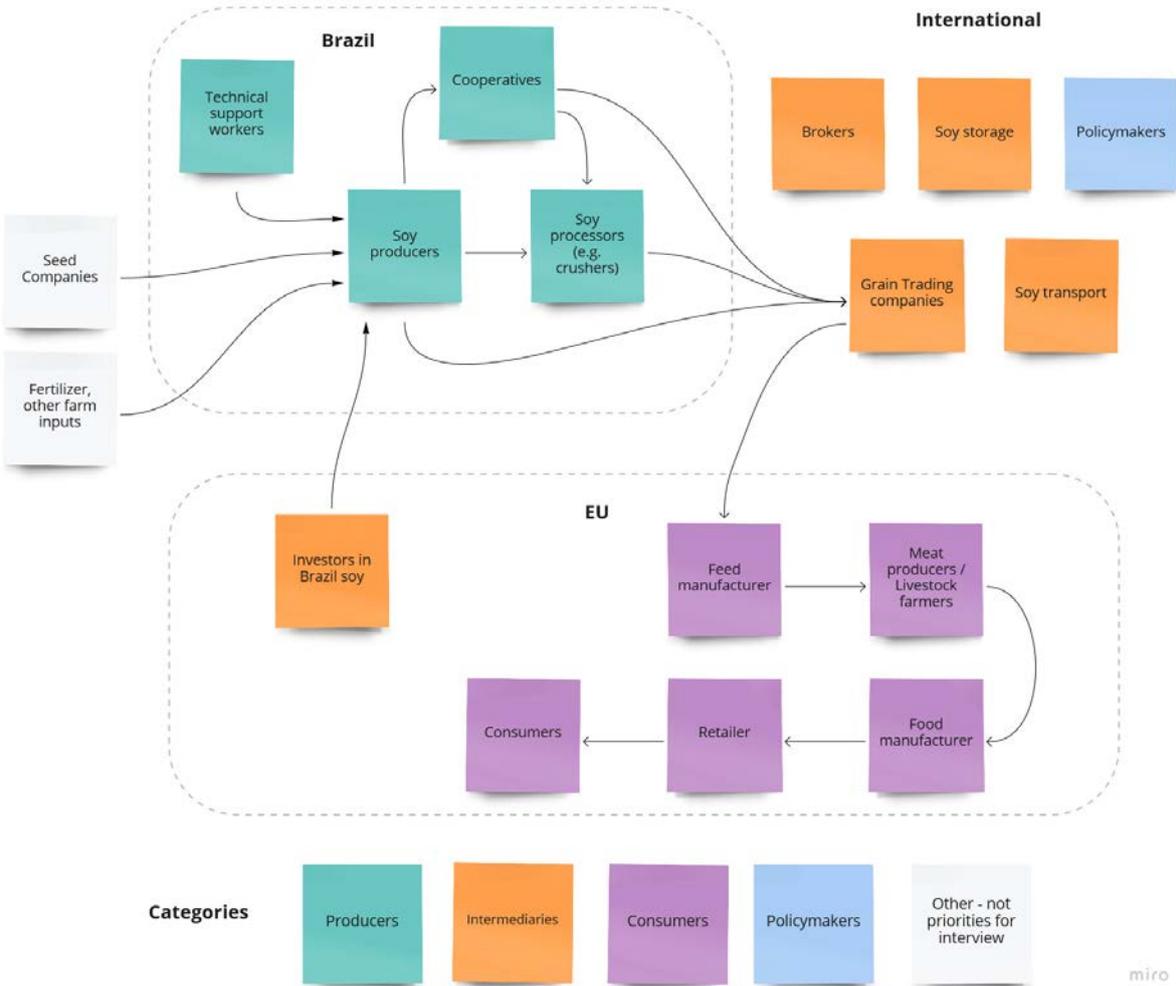


Figure 16. Stakeholder mapping diagram for the Brazil - EU soy supply chain case study.

This report discusses the findings from fifteen interviews (see Table 3). Purposive sampling was used to recruit participants from interviews, with snowball sampling from the initial interviewees. As the interviews progressed, we targeted recruitment towards stakeholder groups with the fewest completed interviews, aiming to hear from as broad a range of stakeholders from across the supply chain as possible. Due to the small sample size, the intention is not for the sampled participants to be representative of the entire supply chain, but to provide as many different perspectives and insights as possible.

Each interview took place over Zoom in English, ranging from 30 minutes to 1 hour, and took place June - September 2022. The fact that interviews were only offered in English (due to time, language skills and budget limitations) limited the potential pool of participants and, in some cases, may have led to misunderstandings of the questions⁵, and these factors should be acknowledged when interpreting the results.

The interviews were semi-structured, allowing for questions to be adapted to the stakeholder group in question, and for exploration of new topics raised by the participants (Adams, 2015). The interview guide is included in an Annex, and the questions were structured into four sections: role and background of the participant, experience of past shocks on the soy supply chain, planning for shocks in the future, and policy responses to shocks.

Interviews were recorded via Zoom and transcribed, then coded using NVivo version 20.6.1.1137 with both a priori and emergent codes (Elliott, 2018). A priori codes were based on the original aim and questions, and emergent codes were developed during the coding process. Interview participants were anonymised at the transcription stage, and were given labels representing their stakeholder group (Pro-X for participants in the producer group, I-X for intermediaries, C-X for consumers, and Pol-X for policymakers).

Table 3. Overview of stakeholders interviewed for the soy case study

Stakeholder Group	Number of participants	Example stakeholder sub-groups
Producers	2	soy cooperative, seed and inputs company
Intermediaries	5	grain trader, soy processor, storage, trader group
Consumers	5	feed producer, livestock farmer representative, retailer
Policymakers	3	EU policymaker, Brazilian research organisation, soy farmer researcher

4.2.3. Results

What shocks have affected the soy supply chain in the past?

Participants reported a wide range of different shocks over approximately the past five years, including the Russia-Ukraine conflict, the Covid-19 pandemic, the rising price of fertilisers, the role of financial speculation, changing exchange rates, swine flu, the China-US trade war, Brazilian trucker strikes and multiple different weather (or ‘climatic’) impacts on both soy production and transport. This immediately highlights that weather impacts on the soy supply chain are rarely acting in isolation; they combine with other geopolitical and financial disruptions, and

⁵ Time was allowed in the interviews for additional explanation where it was felt misunderstanding was at risk of occurring.

experiences of all of these shocks informed the participants' responses during the interviews.

In terms of past weather shocks on the soy supply chain, participants mostly reported shocks relating to either lack of or excess precipitation. Droughts affecting soy yields and excess rain hindering the harvesting and transport of soy were the two most common examples of climate shocks mentioned. Many participants highlighted that both of these shocks occurred in the 2021-2022 growing season (the recency of which potentially causing more participants to name these shocks). In this example, southern states experienced drought as a result of La Niña, leading to a reduction in Brazil's total harvest from an initial forecast of 140-145 million tonnes to 125 million tonnes (participant C-1). This was described by locals as something "they hadn't seen [...] from [the] last 15 years" (Pro-2). Another participant (I-1) estimated that in the 2021-2022 harvest, the "south region" had a 50% reduction in production. At the end of the season, excess rainfall delayed harvesting (particularly in the Matopiba region; Pol-1) and meant that part of the crop was damaged (Pol-2). Participant C-1 also described the phenomenon of heavy rains preventing harvest in the context of Argentina.

In addition to the impacts of climate on production and harvest, some participants also mentioned the impacts of weather on the transport of soy. Storms can damage loading facilities or boats on the water, divert ships and delay docking (C-1, Pro-1, I-3), as well as damaging railways and bridges (I-4). Droughts can lower river levels, reducing the volume of soy that boats can carry and increasing shipping costs (C-1, I-1, I-4), while drought followed by heavy rain can increase sedimentation in rivers, blocking passages for boats (participant I-4). However, the impact of weather on the transport of soy was not always recognised as a shock, or at least an important one, such as in the case of participant Pol-2, who suggested that there was not much climate risk to the transport of soy. Whilst participants I-1 and I-3 recognised that weather could clearly affect waterways, they were sceptical about the potential for weather to affect roads and railways.

Some participants found it difficult to think of any weather-related examples of past shocks on the soy supply chain (C-3, C-4 and I-6). It is interesting to note that all three participants were in the consumer or intermediaries groups, and positioned further from the point of production. Participant C-4 explained: "I think it's gonna be very difficult to pinpoint a climate shock that has impacted the entire industry for commodities, such as massively produced commodities as soy and palm oil." In addition, participant I-3 acknowledged that drought affects yields, leading to a shortfall in supply, but added that whilst historical droughts have reduced yield and production, "it's not a massive crop failure", and that other producers could step in to fill gaps in supply. Both of these responses considered shocks in the context of global soy production, whilst other responses considered smaller scale shocks.

Price versus supply

Participants had a range of different outlooks regarding the soy supply chain's ability to withstand shocks, with one explanation for this is that participants had different definitions of a shock. For some participants, a shock represented a physical disruption to supply, whilst other participants were primarily concerned about changes to the price of soy. For example, participant I-6 was optimistic about

the supply chain's ability to withstand shocks, but clearly framed their optimism in the context of continuity of supply: "For these years, we've never seen the supply chain broken. There's never been a disruption in the continuity." This participant justified their answer through their experience of continued supply of soy despite previous shocks of high oil and freight prices in 2008, the pandemic, and again in 2022 during a period of high energy and freight prices: "in the pandemic, when we saw negative prices for oil, most ships were abandoned because there was no demand. Supply of soy meal kept working like a Swiss clock."

Participant I-6 was based in the EU, and explained that the relative wealth of the EU meant that consumers could afford an increase in the cost of food, and soy supply would continue even if prices increase. The relative wealth of the EU as a whole was echoed by participants I-4 and Pol-3, although participant I-4 highlighted this in the context of EU consumers being willing to pay for, and able to afford, sustainability regulations. In the case of participant Pol-3, speaking in the context of the wider EU food system, they suggested that they were "not sure we have a real shortage or a big threat to food supply - yes, feed supply, yes, but food supply, [...] I'm not sure we are in such a dramatic situation with this kind of thing." For this participant, a worst case scenario might not be less meat available in supermarkets, but higher prices for meat, illustrating that the main concern from the perspective of end-consumers in the EU was around price rather than supply.

Ultimately, supply and price are closely related: interruptions in supply cause prices to increase, "if there is nothing, the price is expensive. If there is a lot, the price is going to be lower" (I-4). What is interesting to note, is that some stakeholder groups 'suffer' from a disruption in supply but not from an increase in prices (grain traders, those involved in the transport of soy), whilst other stakeholder groups are affected by higher prices (those who buy soy as an input for their industry, and stakeholders who buy their products). The following section explores this concept in more detail, by breaking down what a supply chain shock might mean for different stakeholder groups.

Consequences of shocks for different stakeholders

For soy producers, the short-term consequences of weather-related shocks mainly relate to a lower than expected harvest of soy, which could have direct impacts on the producers via loss of income (Pol-1). The consequences also depend on the contracts the producer has agreed to; it is common for soy farmers in Brazil to agree to the sale of a significant percentage of their harvest in advance (I-4), partly to protect themselves from the risk of lower future soy prices (I-1). Soy producers do not sell 100% of their expected crop in advance, in case of a harvest loss (I-4) or a higher future soy price. In the event that they are unable to fulfil a contract they have already agreed to, grain traders may first need to check that a harvest loss has occurred (I-1, I-4), followed by a renegotiation of the contract (Pro-1, I-1). Soy farmers could face debt (Pol-1, Pro-1), a fine, a court process with the grain trader (I-1), or the contract may be rolled over to the following year (I-1, I-4). Participant I4 explained that the choice of response from the grain trader depends on the size and type of producer: with a family farm you may roll the contract to the following year, "because it makes no sense to go against someone who is not going to be able to solve it". However, with a larger corporation "you are not going to be that risky", and they would be asked to comply with the commitment or pay the price difference for buying the same volume of soy on the market. Participants specified that the impact

on producers also depends on how widespread the shock is. If it affects a small area of soy production, the affected producers are more likely to shoulder the cost personally. However, if soy yields had decreased over a large region of Brazil, for example, the Brazilian government may step in to support farmers by, for example, offering loans (Pro-1), but soy prices will also increase (due to the reduced supply of soy on the market), leading to a slight balancing effect for producers who did harvest some soy. In some cases, soy producers may take multiple years to recover financially: “it’s not only the impact on the specific year where the shock has happened. But also, that had a kind of spillover for one or two or three years until the farmer gets recovered” (I-1). Participant Pol-2 underlined the importance of other factors affecting the soy price for farmers in Brazil, such as the dollar-exchange rate; as Brazilian farmers bought their inputs in dollars, a high dollar exchange rate meant farmers had to spend lots of money on inputs, and faced financial difficulties if they did not harvest enough. However, the high dollar exchange rate also meant that if the farmers did have soy to sell, they would have a good income from this.

Whilst participant Pol-3 stated that “any uncertainty on the price, any adjustment, any response through crisis adjustments to a shock is creating a situation of uncertainty where everybody loses because in uncertainty you lose”, which specifically included traders, multiple participants suggest that an increase in the price of soy would not have negative financial consequences for the traders themselves (I-2, Pol-2). Participant I-2 explains: “I think as grain prices rise, their profitability rises as well.” However, shocks to the transport of soy can have big consequences for traders as the costs are significant for this stakeholder group (I-1, I-3, I-4). This point is made by participant I-3, who states “let’s say if there’s a diesel price increase, that’s something we [...] the processors or the movers of physical goods would have to absorb and there’s only little leeway in fact to price it on further in the chain.” Transport and logistics costs for grain traders not only increase as a result of direct impacts on infrastructure, but can also increase indirectly as a result of crop failure. Participant I-3 explained that the effects of lower yields from drought are typically seen as lower production towards the end of the crop year. As the producing areas of soy are in both the northern and southern hemispheres, production happens at different times of year, and a drop in production at the tail end of the US crop year, for example, will in turn lead to “a pull on freight, modes of transportation, receiving [storage] space for the crops as they come off the land, earlier than normally” (I-3) in Brazil and Argentina. If the logistics system is started up a month earlier than normal, this affects soy prices, but also the supporting infrastructure, transport, and elevators. The participant explained this happens every year, however events such as crop failures exacerbate the issue (I-3).

Soy and logistics prices may also affect European soy processors’ decisions regarding crushing. Participant I-4 explained that as Argentina provides the cheapest soybean meal, a shock to Argentina’s soybean meal production or an increase in Argentinian logistics costs would alter the ‘crush margin’. If this ‘crush margin’ is positive, Europe imports more soybean to process domestically; a negative margin means Europe will import more soybean meal instead (I-4). In this instance, European crushers tend to crush rapeseed instead (I-4). A decision on whether to crush soy or not also takes place in Brazil, where the profit for value added processing depends on the relative prices for soy and soybean meal (I-1).

Many participants agree that whilst traders might not feel the direct impact of rising soy prices, the effects would be felt on the consumer end of the supply chain (I-2, C-5). Participant I-2 specified that 'consumer' could refer to both intermediate consumers, such as livestock farmers, as well as the end consumer. However, participant I-6 highlighted that it is not always possible to transfer increasing costs down the supply chain. For the feed sector, participants explained an increase in soy prices leads to a big increase in input costs. EU poultry feed is made up of cereals (such as wheat, barley, oats, maize) and oilseeds (soy, rapeseed or sunflower). Soy is preferred to rapeseed or sunflower due to its high amino acid content (C-2) and low cost (I-2). Participant C-3 stated that amino acids can also be produced synthetically, and these would be used to a greater or lesser extent based on the relative prices of ingredients. For example, participant C-1 described that Brazil's reduced harvest in the 2021-2022 season "affected the feed sector because soya prices rose from £350 a tonne to £500 a tonne [...] so that there will have been a point in time when we were using less soya and more amino acids." This participant also raised the example of droughts affecting the transport of soy in Argentina, leading to "a noticeable increase in cost" for the feed producing sector in the EU.

For livestock farmers, feed is an important input. Participant C-2 explained that sheep and cattle are less dependent on feed than pig and poultry, as they can be grass fed. Chicken feed "represents almost 70% of the cost of production of chicken" (C-3). This participant stated that current higher feed prices are a consequence of the Russia-Ukraine war, which increased costs for cereal producers in the EU and around the world, increasing feed costs by more than 200 euros per tonne. Consequently, the participant estimated that the retail price for chicken breasts would increase by 50% for consumers. Participant C-3 explained that in the example of the Russia-Ukraine conflict, passing this increase in costs to the consumer or the retailers was difficult due to competition at the time from cheaper poultry produced in Ukraine, where feed costs had not risen and trade had been recently liberalised with the EU. They explained that in many countries, the small number of big retailers meant that they had a "good bargain capacity ... so sometimes it is quite difficult for [EU poultry meat producers] to pass the price." Participant C-5 also explained the difficulty of passing increased costs down the supply chain in the case of chicken: "sometimes the problem is that retailers are not willing to pay more and they have a big power in contract because we are selling super fresh products without the possibility of storage of the product ... even if we have big companies, we are under the power of the retailers". The reflection of participant C-4, a retailer in the UK, appears to confirm that retailers may not feel these shocks as much as feed producers or livestock farmers: "I don't really see the case for a shock, which would impact us. Given that we have, you know, so many thousands of suppliers who source from all over the world. And yeah, I think that that kind of flexibility is built into the system, certainly at the far end of the supply chain that we operate in".

Where the shocks are felt along the supply chain is highly context dependent. As participant I-4 explained, "depending on the kind of shock, the prices are going to go back to the producer, or to the client". The participant continued: "when the shock has impacts on several countries, most likely it will go [to] the end buyer". However, if only one location faced a shock, "the price impact will go back to the farmers, the producers". The participant gave the example of the ongoing drought in Argentina, that at times has reduced the load soy barges were able to carry along

rivers, making it more expensive to transport soy from Argentina. Other producers of soy (Brazil, US, Paraguay) haven't had the same problem. Therefore, buyers have not been willing to pay the increase in transport costs, and as a result, Argentinian farmers have to absorb the increased freight costs. From a global perspective, price adjustments will give signals to reorient trade and affect production decisions (Pol-3). In order to adapt and respond to these shocks, it is important to identify who losers and winners are.

Responding to and preparing for shocks

Responses to potential shocks identified by participants were relatively wide ranging. These are described below, but summarised also in Table 4 along with an indication of their potential positive or negative impacts across stakeholder groups (excluding potential implementation costs) and implementing party.

Soy producers in Brazil respond differently depending on the characteristics of the farm. Participants Pol-1 and Pol-2 both highlighted that large capitalised producers (or "agribusiness", Pol-2) may have insurance to cope with instances of low harvests, whereas smaller producers (Pol-1 calls these "medium-large", but they are smaller than the largest agribusinesses) often do not have enough money to pay for insurance. Participant Pro-1 also observed that few farmers have insurance, agreeing with the above participants that this is due to it being too expensive but also due to a perception that the weather is normally stable in the majority of areas. However, even having insurance will not fully protect farmers, which also contributes to low uptake: participant Pol-2 explained that in the January 2022 harvesting season, in their region, most of the farmers who made an insurance claim didn't receive any money as their harvests were not bad enough. Participant Pol-2 stated that many farmers reluctantly sign up to insurance when obligated to do so when taking certain loans from cooperatives, the government or banks. For smaller producers without insurance, participant Pol-1 explained that "generally ... they just abandon or they sell their properties and move to another place when they can buy another farm with a very low price." This participant explained that climate change was driving these patterns, for example in the case of farmers in areas of drought without irrigation, moving to a new state and potentially opening new areas of soy production, in some cases needing to convert land first. Participant C-1 also highlighted the dynamic of new soybean producing areas appearing as a result of negative weather impacts on soybean supply, because an increase in soybean prices provides an incentive for soy growers to plant more acreage. In these cases, participant C-1 added, soy farming may move into areas that are less fertile, and weren't previously profitable under lower soy prices. However, other factors also play a part here: for example, high fertiliser prices might prevent farmers from increasing production of soy. Participant C-1 discussed this in the context of the Russia-Ukraine conflict, but did add the caveat that this might apply more to cereal crops than soy, as soy does not need as much fertiliser.

Table 4. Potential responses to shocks identified via interviews, and how they may (excluding costs of implementation) affect stakeholders in the supply chain. Green = benefit, orange = mixed impact, red = negative impact. X = implemented by indicated stakeholder group.

Responses	Stakeholder groups			Implementation constraints/considerations
	Pro	I	C	
Soy farmer insurance	X			<i>High costs for farmers; historical issues with payouts</i>
Plant more soy acreage	X			<i>Environmental risks, farmers take on risk</i>
Technologies for soy production	X			<i>Requires investment, could be limited by extent of climate impact</i>
Irrigation	X			<i>High costs for farmers</i>
Storage	X	X	X	<i>High costs</i>
Futures contracts	X	X	X	<i>Relative impact depends on what happens to future prices</i>
Monitoring yields/supply chain		X	X	
Using flexibility of supply		X	X	<i>Can be limited by policy, prices, etc.</i>
Climate mitigation	X	X	X	<i>Efficacy depends on time horizon adopted</i>
Diversifying transport modes				<i>Implemented at government level</i>
Diversifying protein sources (food and feed)		X	X	<i>Mixed (orange) may depend on the specific stakeholder</i>

Technology also plays a part in soy farmer responses to climate shocks. Participants suggested technologies and practices to improve water retention in the soil (Pro-2, I-1), research on the best planting time (I-1, Pol-2, Pro-2), improved weather forecasting and precision agriculture (Pro-2), and technology to produce potable water during water scarcity (I-6). Other participants (I-4, Pol-2, Pro-1, Pro-2) suggested seed technology could help adapt to climate impacts. Participant Pro-2 argued that new soybean varieties and biotechnology would help to increase soy yields despite negative climate change impacts, while participant Pro-1 described the current development of soybean varieties which can better cope with dry and hot summers, adding that farmers are increasingly looking for better varieties to deal with diseases, as well as extreme weather conditions. Development of soybean varieties were also mentioned by stakeholders at the consumer end of the supply chain, in order to produce more soy grown locally within Europe, potentially making use of warmer conditions under climate change (C-1, C-2, C-3, C-5). However, both biotech and seed technologies require forward planning: it takes approximately

twelve years from discovery to launch for biotech, and three to four years for a cultivar (Pro-2). When asked, participant Pro-2 was not sure whether climate change projections were used in the development of new soy cultivars. They also highlighted the importance of farmers having their own seeds, and that improving seed sovereignty and the number of soybean varieties available would offer farmers the opportunity to select the seeds that they need in order to combat climate change.

Irrigation, a key tool for combating drought issues, is something farmers are already increasingly investing in if they can afford it (Pol-1). Irrigation is less common in southern Brazil though, where it is only used for growing soybean seeds (for planting) due to high costs, long distances from water bodies, hilly topography, and because drought is more infrequent compared to central Brazil (Pol-2). Participant Pro-1 said irrigation is often too expensive and there are limitations due to water use restrictions from rivers in certain areas. Storage is also an option which soy farmers and traders see as beneficial, yet expensive (Pro-1, I-3). There is a risk of physical deterioration of the crop in storage (I-3), and participants gave differing views on how long soy can be left in storage (Participant Pro-1 suggested up to one year as long as temperature and moisture are controlled; I-3 up to two years if drying the beans to reduce moisture content). In reality, soy is often stored for only a few months, because most farms plant a second crop, and need to empty the storage between harvests (Pro-1). Further along the supply chain, participant I-2 agreed that storage “can play a really important role” in mitigating the effects of shocks, however adding that, in some cases, storage of crops in the wrong place can cause problems (such as grain stored in Odessa during the Russia-Ukraine conflict), and that it is important to consider the level of transportation around the storage location. In the feed sector, participant C-1 mentioned they were considering increasing storage for some feed inputs (such as amino acids), but were not prioritising soy storage for the moment (due to a perception that soy was not the ingredient most at risk). Also, in the feed sector, participant C-2 explained that increasing storage capacity across the supply chain can be challenging due to the required assurance standards. Current storage of soy and feed in general are relatively low compared to food stocks, in part due to the profit-driven nature of the supply chain (Pol-3).

For grain traders, one key response to potential shocks in the soy supply chain is through knowledge and monitoring of the supply chain. For example, participant I-1 described how grain trading companies assess climate risks related to their operations (warehouse, logistics corridors) and monitor soy yields, including in the field and using remote-sensing satellite images. This historical data informs how grain traders buy soy in different regions: in high risk regions, they operate more on the spot market after harvest, and in regions with lower climate risks, they expose themselves more in advance (I-1). Participant I-3 stated their grain trading company reviews their strategy plans every five years for multiple climate change scenarios and impacts on soy yields. In contrast, participant I-4 described how grain traders use short-term forecasts of yields and weather shocks: “to plan [for] the worst shock... you will take it as it comes...” The participant described the speed of the response of traders as critical to be ahead of others in the market, highlighting a key role for having the most up to date knowledge of the supply chain. Other stakeholders along the supply chain also mentioned the role of monitoring yields

and harvest prospects, including participant C-2 who explained that everyone in the feed sector had been looking at USDA data since March 2022 (the past few months before interview) “because we know that we’re going to have to be looking further afield to buy our materials”. In some cases, grain traders can also play a key role in the exchange of information, for example in the context of the Russia-Ukraine war, participant I-2 explained that some traders were involved in discussions with the World Trade Organisation or the UN crisis response group in order to help assess where grain stocks were, and help alleviate a global food crisis, as they had information on supply chains flows to which many governments might not have access.

In response to shocks, grain traders, feed producers and retailers draw on flexibility of supply from different origins (I-3, I-4, C-4, C-5, Pol-3). Participant I-3 stated, “if the US [...] had a massive crop failure then Argentina and Brazil could step in.” Participant Pol-3, an EU policymaker, explained that the system so far was “complex enough and diversified enough in every instance, not only on the production of food but also on the logistics, the type of organisation, or the different players in the food chain”, referring to all elements of the supply chain, and not only for soy but also other feed inputs such as amino acids and vitamins (which, the participant explained, are currently sourced from a small number of countries due to profit reasons). A more diversified supply chain might mean higher costs though (Pol-3). The participant stated that despite higher costs, at this time, the Commission were favouring “diversity of everything, diversity of types of farming and types of supply chain is important.” Several participants stressed the importance of multiple different modes of transport and multiple potential export corridors, for example, in the case of Brazil, creating more railroads in the north (I-1). In some cases, companies are planning to build new silos and new ports (I-2) or improving current infrastructure (Pro-1). At the consumer end, participant C-4, a retailer, explained that “flexibility is built into the system, certainly at the far end of the supply chain that we operate in”, and that “it’s relatively easy for any supermarket to switch suppliers.” However, whilst some participants highlighted the existing flexibility of the current system, other participants did mention limits to this flexibility, for example due to GMO or deforestation legislation. Participant C-2 stated that climate change may also cause countries to consider sourcing materials from different geographies. Many participants raised the issue of producing more soy domestically (or within Europe). In contrast, participant I-6 argued that it is not possible to grow enough protein in Europe to satisfy demand, and they identified policies to improve self-sufficiency as something that could negatively affect the soy supply chain.

Another theme raised by many participants was the shift towards diversifying protein sources for both human and animal consumption (I-2, C-1, C-2, C-3, Pol-3). Participant I-2 described how grain traders are making “big investments” in plant-based protein diets for human consumption, diversifying their product portfolios to include products such as pulses, reflecting a wider shift towards less meat-intensive diets. Examples of alternative protein sources for livestock include using waste streams from food and other industrial production (co-products), algae, seaweeds, insects, processed animal protein (PAP) and processing grass in ways that make it digestible for pigs and poultry (C-2, C-3). Yet, participant C-2 explained that availability, consistency and safety are the major concerns when choosing alternatives. Changing ingredients in feed is already commonly practised to some

extent in response to the changing relative prices of ingredients, for example using less soy and more synthetic amino acids, rape meal and sunflower seed extract when soy prices are high (C-1, C-3, C-5). However, many participants also underlined the difficulty of replacing soy in pig and poultry feeds (C-1, C-3, C-5, I-2): “soy has got an extremely good amino acid profile in terms of it's a very high quality protein, it's available at relatively economic prices, although as we mentioned, prices are close to historic highs at the moment. But it's still difficult to find an alternative protein that can compete on availability and price at the moment” (C-1). Another difficulty in replacing soy is that current poultry breeds are adapted to soy, something which has developed over the last 20-30 years, although breeding companies are already working on changing this, as they anticipate that soy will be used less in the future (C-3).

One of the most common answers to the question of responses to shocks was climate change mitigation and other sustainability measures (C-5, I-2, I-3, Pro-1, Pro-2). For example, participant C-5, from the EU poultry sector, explained that reducing their own environmental impact was an important step. For the poultry industry, C-5 explained that this also meant a tension between intensive and organic agriculture. Other participants explained that mitigating carbon emissions and reducing deforestation through soy production was necessary (I-1).

Participant I-1 suggested that the topic of climate risk to the soy supply chain for traders was still an early internal discussion: whilst grain traders might be at the stage of internally discussing how to measure their exposure to climate risks on their business, they were not yet discussing these issues sectorally. They compared this to the discussion on greenhouse gas emissions, which began internally but is now a sectoral-wide discussion, and something traders were working together on to generate data that they couldn't do individually (I-1). Participant C-3, from the EU poultry sector, also identified that this was a relatively new topic to the sector, and suggested that one approach to responding to shocks was raising awareness of these risks within the sector(s).

Expectations for future shocks

In terms of future climate change impacts, there was generally a strong expectation that climate change would impact the soy supply chain, but it was not always clear exactly how: “we all think we know what climate change is, but we don't really understand it” (I-6). Many participants across the supply chain (C-1, C-3, I-1, I-3, I-4, Pro-1) highlighted an increase in the frequency and magnitude of weather extremes and/or shocks (C-1). On the producer side, participant Pro-1 stated that farmers in central Brazil are concerned by future droughts and extreme heat, and intermediaries (I-1 and I-3) identified that climate shocks would have a direct impact on soy production. The longevity of climate change impacts was also identified as a reason why climate change may be a bigger risk than other potential future shocks to the soy supply chain: “[We saw the] market bounce back after the financial crisis. Also with Covid, it became under control and supply chains reorganised themselves. But if you've reached the tipping point [...] that is irreversible. So that's why I think it's much bigger” (I-3). Participant I-3 also identified climate-induced legislation (e.g. legislation and regulation around mitigation actions, a carbon tax on transport, companies imposing net zero targets, reducing water use) as posing a risk to the soy supply chain. Several participants (C-2, C-5 and I-6) also expected future

changes to the demand for soy, highlighting a gradual increase in pressure on people (in the EU) to move towards more plant-based diets, implying a reduction in soy demand linked to meat production from the EU, “and we can see that starting to come into the policy environment” (C-2). This was a trend participants identified taking place over the medium to long-term, for example participant C5 expected that in the medium-long term “the Greta Thunberg generation [...] will have more vegetarian people.” However, participants (C-2, Pro-2) balanced this idea by suggesting demand for meat was growing globally.

Climate change impacts on transport were also identified by some participants, particularly those involved in grain trading (I-3, I-4). For example, participant I-3 stated that weather conditions under climate change would affect the movement of goods via waterways and ocean transportation. Participant I-4 was more concerned by climate change impacts on transportation compared to soy production, because they felt seed technology would solve soy production problems, but “how to move the cargo is going to be broadly the next big challenge. I am very worried that in 10 years we will not have this river, or the other river – or in five years. Because that implies a complete change of flow inside the country and of course on the economics behind”. Participant C-2 also highlighted the importance of transport for feed producers, given that many feed mills are in continual operation. However, participant C-3 did not see the case for climate change to affect cargo transport, instead highlighting social aspects such as strikes (also mentioned by participant I-1) or lack of staff affecting transport, giving the example of the lack of staff in the UK after Brexit. Participant I-6 mentioned that increased extreme precipitation events under climate change could affect the storage of soy due to “water access to the storage locations” and extreme heat could lead to an increase in vermin. Participant I-1 mentioned the effect of droughts on electricity prices via hydropower, and therefore impacts on the processing of soy.

Certain participants portrayed an optimism about future shocks to the soy supply chain. Participant Pol-1 described Brazilian farmers as not expecting future shocks to production: “if you ask them about the future shocks and the possibilities that something could break their harvest, they would say that they are not concerned about this, because now they are earning a lot of money [...] so they will see the future when the future comes.” In comparison to other crops such as coffee and fruits, participant Pro-1 stated that grains (including soy) have experienced relatively fewer shocks, and when they do experience a bad harvest, it is only a partial loss, not the whole crop as would happen for coffee or fruit during a frost, for example. Participant C-3 also suggested that optimism may come from the fact that many supply chain actors “are from a generation where everything was available in large quantity. And I think we enter a new era, let's say, where we will face a lot of more disruptions”. Participants also identified the positive impact climate change may have on the ability to grow soy at higher latitudes, for example in Eastern Russia and expanding the areas available to grow soy in China (I-3). The participant also identified that climate change could open up new shipping routes, such as the northern passage north of Canada. However, they qualified these positive consequences with a warning: “the question is, you need to look beyond that [...] if temperature rise is driving that, that means that other regions are going to be a problem. And the longer-term effect of rising temperatures, [...] that's going to be a problem. So, yes, it opens opportunities, but you have to be careful about

celebrating that, because there's important ramifications that you have to take into account.”

Climate change was only one of many future shocks participants discussed. Other future shocks suggested by the participants include: the effect of the Russian-Ukraine conflict (C-3) and its effect on gas prices, raising costs for manufacturers of other feed ingredients such as synthetic amino acids (C-1); high oil prices raising transport costs (I-1); competition from the bio-energy sector for soy, raising prices (C-2); lack of staff in all aspects of the feed supply chain, and especially in the UK after Brexit (C-3); the role of China in shaping global demand and creating speculation (C-5); and the threat of pests and diseases that are resistant to current biotech (Pro-2).

Policy links and recommendations

The ability of the supply chain to respond to shocks interacts with the current policy context. Several participants discussed the recent ‘due diligence’ consultations in the EU and UK (i.e. the EU draft legislation that imports of certain products must be deforestation-free, and the parallel UK draft secondary legislation that imports must be free of illegal deforestation). Many participants were supportive of the aims of these policies (C-1, C-3, C-4, I-3). However, participants also raised concerns about how this might affect responses to shocks and raise the price of soy (C-1, C-2, C-3, C-5, I-6) and/or costs for soy farmers (Pol-1), as well as the risk of substitution effects (if the EU doesn’t buy deforested soy, other importers will; participants I-3, Pol-1). For example, participant C-1 stated that it “will probably restrict to some extent where we can get soya from although I have to add we’re already trying to eliminate deforestation from our supply chains anyway. So as [agri-food business], it probably won’t have a big impact but yeah, it’s not going to make responding to a shock in the supply chain any easier.” Participants C-2, C-3, and I-3 explained that a strict enforcement of the due diligence policy could cause the EU and UK to source soy from North American countries instead of South American countries. Similarly, trade choices are restricted by EU or Member State GMO or pesticide regulations (C-2, C-3). These regulations may be changed during supply chain shocks. For example, during the Russia-Ukraine war, there was a temporary acceptance of certain previously banned pesticides, which “allowed to immediately order extra boats of maize from Argentina and then alleviated the prices immediately” (Pol-3), as well as debates in the EU over whether to relax GMO-free rules (C-3).

When discussing policy related to supply chain shocks, several participants mentioned the need for flexibility in the supply chain. Participant C-2 explained “if the policy restricts flexibility, then again, that creates challenge in the system really.” Similarly, participant I-3 stated that whilst they didn’t have specific policy recommendations, they would “really welcome policy that allows markets still to function [...] they have an important role to minimise the price risk, which keeps the cost down, so food is affordable because of that.” Participant I-4 and Pol-3 both argue for the markets to solve problems rather than through policy regulation: in the scenario of soy harvest failures in both the southern and northern hemispheres “the function of the market is to lower demand via prices, so that’s why I said that everything on this sector is either solved economically, more than regulation” (I-4); “I think most of the answer will come from price adjustments so people will change

their feed rations [...] the farmers will take other decisions, so a lot of it will be just absorbed by price adjustment, without needing a public intervention” (Pol-3).

Existing policy addressing shocks in the soy supply chain is rare, and in Brazil, participant Pol-2 stated that there was currently an absence of policies to help soy producers deal with harvest shocks. Several interviewees suggested policy ideas which might support soy producers to reduce shocks: policies to protect river water levels linked to irrigation (I-4, Pol-1); incentivising a better use of fertilisers, or using a second generation of fertilisers with fewer negative impacts, to reduce contamination of water bodies (I-4); improving transport infrastructure in Brazil, such as bridges (I-4) and rail transport, particularly from soy producing regions to the northern ports (I-1); and policies to support farmers implementing conservation measures, which would help yields in the long term (Pro-2).

In the EU, there is current work by the EU Commission to create a crisis framework “to facilitate preparedness to possible shocks that will affect [food security in the EU]” (Pol-3), which has an emphasis on both preparedness and response. Participant Pol-3 also described the support available when particular stakeholders in the supply chain are facing extra costs; for example the EU offered a “a €500 million package in March [2022] to compensate farmers for their extra costs in terms of agriculture inputs, not only feed, anything”, and Member States are also allowed to use their national budgets for this as part of temporary crisis frameworks. On the importer side, participant C-2 highlighted the need to ensure policy coherence across countries or nations, for example, in England and Scotland. Participant Pol3 explained that policy responses depend on how ‘long-term’ the shock is. For example, the EU would respond differently if it was an isolated shock, compared to a shock that might increase in frequency in the future. Participant Pol-3 explained: “sometimes the shock is not purely a short-term one [...] it’s a shock that is reflecting a real structural evolution [...] So then you have to think about, is it worth continuing producing this way or if I have to help them get out of the production if needed [...] this means [...] monitoring and knowing very well your market [...] to disentangle what is short-term from long-term. Climate change adaptation means changes of patterns of production and systems of production everywhere. [...] We have to think about, if we intervene, are we slowing down the necessary adjustment?” This underlines the importance of monitoring and forecasting the markets and production: something which is done by many actors, including the EU, the FAO, the OECD, China, the US and the UK (Pol-3). The spatial scale of a shock will also affect how governments respond. Participant Pro-1 explained that, in Brazil, for example, in the situation where a whole region is facing crop losses (rather than a smaller isolated shock), the government could intervene to provide loans.

4.3 Threats to EU supply of critical energy-transition minerals

4.3.1. Overview of mining and energy transition

Europe will make a radical transition towards a low carbon economy over the next few decades; the roadmap of which is laid out within the European Green Deal (European Commission, 2019). This transition will require significant quantities of new clean energy infrastructure: batteries, electric vehicles, wind turbines and photovoltaic systems, cables and hydrogen networks. Yet, these low carbon technologies have higher mineral demands relative to traditional fossil fuel energy

technologies, resulting in a surge in demand for energy transition minerals. Electric cars require approximately six times more minerals compared to a conventional car (International Energy Agency (IEA), 2021), and electric car production is expected to drive 50-60% of the demand (Gregoir and van Acker, 2022).

The impact of this transition on mineral demand is expected to vary; some models predict that this could be up to almost 500%, with significant increases predicted for those minerals essential for battery technologies such as lithium, cobalt, graphite (Hund et al., 2020), as well as nickel, Rare Earth Elements (REEs) and copper (Gregoir and van Acker, 2022). Hund et al. (2020) describe four main categories for demand risk for minerals important for energy technologies:

1. Medium impact: These are least impacted by demand as they are used in only a few energy technologies. They may still be important, but are less responsive to demand fluctuations. An example includes neodymium.
2. High-impact: These are only used in a small number of energy technologies, however their future demand will increase significantly. For example, under a 2°C climate scenario, production of lithium needs to increase by 488% by 2050 from 2018 levels. These are predominantly battery minerals, and include lithium, cobalt and graphite.
3. High-impact cross-cutting: These are both expected to see significant increases in demand and they are used across a wide variety of technologies. However, because demand for these are constantly high, they are not as vulnerable to demand fluctuations. An example here includes aluminium.
4. Cross-cutting: These are widely used minerals across a range of different energy technologies, and therefore are least affected by technology changes. One example is copper, which is widely used in, for example, electricity cables, and therefore has a high overall demand. Its total demand might increase regardless of the rate of a low carbon energy transition, and be even greater than those that are specifically influenced by the transition.

Minerals in category two are the most vulnerable to demand fluctuations by a low carbon energy transition, and therefore pose the greatest supply chain risks. A significant challenge is to ensure that supply of these critical energy transition minerals meet this growing demand.

Europe is reliant on global supplies of many critical minerals for its energy transition. The European Commission has set a target to be self-sufficient in its electric car battery production requirements by 2025 (Automotive News Europe, 2020), however only 3% of batteries are currently produced in Europe and it imports 90% of its lithium-ion batteries (Gregoir and van Acker, 2022). The production and processing of many energy transition minerals are highly concentrated in only a few countries, and different countries and geographical areas dominate different supply chains: Latin America is rich in lithium, copper, aluminium, nickel, iron ore and silver; China produces and processes over 90% of REEs (Coulomb et al., 2015; Zeeshan, 2021); and Africa has large reserves including cobalt, platinum and bauxite (World Bank Group, 2017). While copper can expect an increase in diversification of sources, with planned increasing production in the US, Democratic Republic of the Congo (DRC) and Indonesia, this is not the case for all critical minerals (IEA, 2021). Monopoly of supply with a lack of future planned sourcing

diversification leads to a high degree of reliance on a few supplying countries, creating bottlenecks and supply chain vulnerability.

Bottlenecks and/or external shocks to supply chains, such as the impact from climate-extreme events or geopolitics, could therefore have significant cascading effects for Europe, increasing the chance of supply chain disruptions (European Commission, 2020). The Russia-Ukraine war has already created a crisis for titanium supplies to Europe, impacting on the aerospace industry following European sanctions on Russia (Venckunas, 2022). Subsequent effects could include price fluctuations; delays in technology development, use and roll out; changes in consumption or substitution of minerals and metals; and impacts on innovation. Significant supply risks to Europe have already been identified for a number of minerals, including lithium, cobalt, REEs, copper and nickel (Gregoir and van Acker, 2022). As such, supply chain resilience for these minerals is paramount for Europe's sustainable future.

This section of the report presents a literature review examining climate impacts on the mining sector and its subsequent implications for European supply chains. It will then focus on three mini-case studies of lithium, cobalt and REEs, as examples of critical minerals in category two of Hund et al.'s (2020) model for a low carbon energy transition. These case studies examine the potential wider climate, social and political ramifications of EU supplies of these minerals. The section concludes with policy recommendations to support increasing mineral supply chain resilience⁶.

4.3.2. Climate-linked impacts on the mining sector

Climate change is having a significant impact on mining sector operations, presenting both risks and opportunities. Increasing intensity and frequency of climate extreme events is already having, and could further, impact on mine infrastructure and operation activities, transport routes and energy systems. Such climate events include: increasing flood events eroding open cast mines, bursting tailing dams, flooding road networks (Carbon Disclosure Project (CDP), 2019), and increasing the occurrence of other natural disaster events such as landslides (Odel, Bebbington and Frey, 2018); increasing sea level rise flooding ports and coastal processing plants; rising temperatures thawing permafrost, reducing availability of ice roads and therefore affecting haulage timeframes; and increasing drought and water scarcity putting significant strain on water-intensive operations, such as lithium extraction (CDP, 2019). These impacts also have further implications for employee health and safety, management of environmental resources such as water, and increasing conflict with local communities as a result of decreasing availability and quality of these resources. On the other hand, identified opportunities under climate change have recognised that increasing melting of Arctic ice provides increasing access to this area for mining (CDP, 2019).

These climate extreme events have financial implications for mining companies, with water scarcity cited as a recurrent financial issue: 44% of mining companies reporting to the CDP stated that they have experienced water-related financial losses

⁶ Note that, because minerals have not formed a substantive component of the rest of the work conducted in WP3 of CASCADES (e.g. quantitative modelling, stakeholder interviews), we do not elaborate further on energy-transition minerals within Section 2 of the report which aims instead to synthesis findings from across the food/agricultural-linked work of WP3.

of US\$11.8 billion over the previous five years. Additionally, 54 companies reported spending US\$6 billion between them on water risk mitigation projects in 2018. This constitutes 14% of their combined capital expenditure, however the true cost of water mitigation in the mining sector could be much greater, as only 48% of companies have disclosed this information to the CDP. One specific example of the financial impact of climate change is Freeport-McMoRan Inc, who reported an estimated spending of US\$1.4 billion on a desalination plant and pipeline as a result of water scarcity in their operations region in Chile. This represented 70% of the company's expenditure in 2018 (CDP, 2019).

The top financial impact events reported to the CDP in 2019 were flooding (20%), severe weather events (12.5%), increased water scarcity (9%), drought (9%) and declining water quality (9%). These climate impacts are also imminent: companies reported to the CDP in 2019 that they expect 61% of climate risks to occur in the next three years, with 50% of risks having a high probability of occurrence. Climate change should therefore be a priority to the mining sector. Yet, a report by the David Suzuki Foundation in 2010 highlighted a disparity in awareness of climate impacts among executives, therefore potentially reducing the responsiveness of the sector to climate change (in Nelson and Schuchard, no date). However, it is likely that this awareness gap has been addressed since this report was published, given the widespread rise in sustainability management among the private sector.

Further, climate impacts have indirect consequences on mining operations. Increasing temperatures increases the likelihood of temperature-related health conditions and accidents, as well as increased exposure to transmittable diseases (Nelson and Schuchard, no date). As such, decreases in worker's productivity and capacity have knock-on implications for mining outputs. Additionally, local environmental and resource stresses around mining sites also facilitates increasing conflict between mining companies and local communities as these communities become more vulnerable to climate change and increases competition for resources (Nelson and Schuchard, no date). These conflicts can prevent further and new mining operations, as demonstrated in Portugal where local communities are opposing new lithium mines (Gregoir and van Acker, 2022), and they can affect the political environment of the local region (Delevingne et al., 2020).

Overall, it is evident that climate change constitutes a significant risk to EU mineral supply chains, with respect to both the physical extraction and operations of mining, and the economic challenges of operating in degrading environmental conditions. Indirect social impacts can have further implications for mining operations, and are therefore integral when considering the broader changing landscape under climate change. This section of the report now explores three minerals, lithium, cobalt and REEs, in detail to examine their specific climate, social and political vulnerabilities, and the resulting potential impact on EU supply chains. These minerals were identified as being of specific interest to the EU given the dominance of supply from one country, importance for a low carbon energy transition, and significant climate and/or environmental and/or social risks associated with their supply chains.

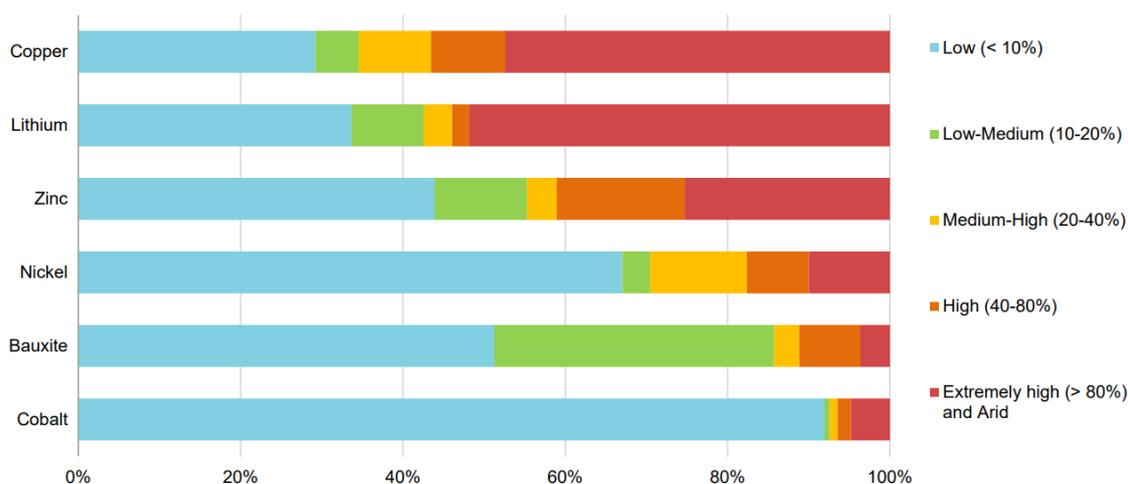
4.3.3. Lithium

Where?

Europe imports lithium predominantly from the Salar de Atacama region in Chile and Australia, although other smaller sources are utilised (Gregoir and van Acker, 2022; IEA, 2021; Coulomb et al., 2015; Zhu, 2019). China processes around 60% of the global lithium supply, mostly from Australia (IEA, 2021).

Climate impacts

Approximately half of lithium mining globally is located in areas of high water stress, while Australian mining operations are additionally impacted by extremely high temperatures (Figure 17; IEA, 2021). The Salar de Atacama is one of the most arid regions in the world, and therefore even small changes in precipitation and water availability have significant ecological and social consequences for the region (Odel, Bebbington and Frey, 2018). 65% of the entire water supply in the Salar de Atacama is diverted for lithium extraction (Hiburg and Hall, 2021), making the region highly vulnerable and sensitive to mining practices. Further implications for water shortages in the region include compromising of brine lagoon structures and their ecological integrity (Fox, 2020). On the other hand, increasing temperatures increase glacial melt water runoff, providing greater water availability (Odel, Bebbington and Frey, 2018).



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Note: Water stress levels are as defined in the Aqueduct 3.0 dataset according to the ratio of total water withdrawals over the total available surface and groundwater supplies.

Source: IEA analysis based on WRI Aqueduct 3.0 dataset.

Figure 17. Share of production volume by water stress level for selected minerals, 2020.

Source: IEA, 2021.

Social impacts

The significant competition for water between mining companies and local communities has created conflicts, particularly during periods of increased water stress associated with reduced rainfall or increased evaporation (Garces and Alvarez, 2020). This additional water stress from mining operations compromises the ability of local farmers to grow crops and support livestock, and therefore presents a threat to food security in the area (Hiburg and Hall, 2021). Continuing lithium extraction

with current water injustices is driving greater inequality between the Global North and South (Jerez, Garcés and Torres, 2021).

Implications for EU supply chains

Estimates of the demand increase for lithium required for Europe’s energy transition varies; Gregoir and van Acker (2022) reports that the EU will need around 3,500% more lithium by 2050, while other forecasted are for 60 times more by 2050 (Irish Times, 2020). This demand is predominately for electric vehicle manufacturing (IEA, 2021). Europe has set a target to domestically supply 55% of its lithium requirements by 2030, however planned expansion of lithium mining in Portugal has been met with opposition from local communities, which threatens achieving this target (Gregoir and van Acker, 2022).

4.3.4 Cobalt
Where?

Europe predominantly imports cobalt ore from DRC, with small amounts from Zambia, Madagascar and Canada (IEA, 2021; Gregoir and van Acker, 2022). However, in 2020, China either owned or financed 15 out of 19 cobalt mines in DRC (Zeeshan, 2021). 70% of Europe’s cobalt supply is processed in Finland and Belgium (Gregoir and van Acker, 2022), however China processes around 70% of the global supply of cobalt, therefore making DRC and China the most significant influencers of cobalt production (IEA, 2021; Figure 18).

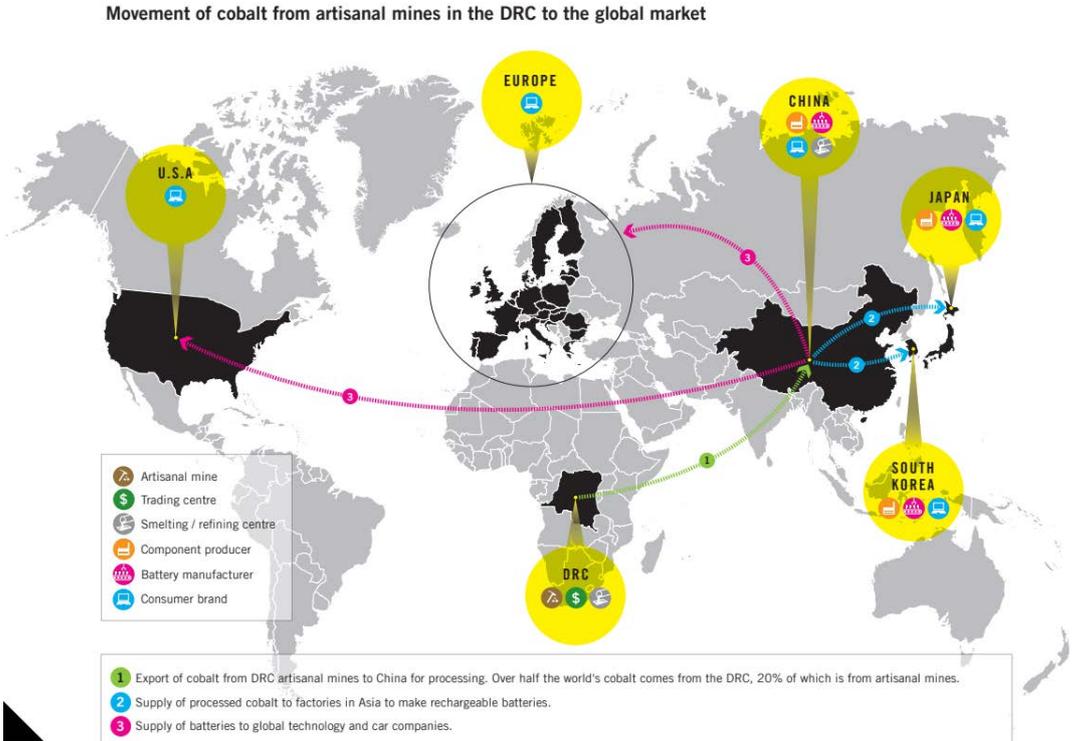


Figure 18. Movement of cobalt from artisanal minter in the DRC to the global market. Source: Amnesty International (2016).

Climate impacts

We found no information in the literature regarding the direct climate impacts on mining in the DRC. Generic expectations cited include extreme heat in West Africa and China that are likely to impact on workers' health and productivity, increasing cooling costs, and having indirect consequences through increasing political instability in these areas (Delevingne et al., 2020).

Social impacts

Human rights abuses in DRC cobalt mining are widely reported. Amnesty International (2016) reports a lack of health and safety regulations and practices in the mines, as well as a lack of personal protective equipment while in the mines and for handling hazardous substances such as the cobalt ore. The result is a high risk of fatal accidents and chronic health conditions in workers, including "hard metal lung disease". Further, child labour is widespread, with children exposed to violence and physical abuse, drug abuse and sexual and financial exploitation (Amnesty International, 2016).

Only 26% of the DRC population have access to drinking water, making it one of the lowest water access rates in the world (Rüttinger et al., 2017). Water practices from the mining sector exacerbate this: releasing wastewater containing sulphuric acid into water bodies; mineral washing, which deposits ore and dust particles into the water; as well as miners depositing their domestic waste into local drinking water sources (Montejano 2013 and UNEP, 2011 in Rüttinger et al., 2017). This results not only in inaccessibility of water for the population, but declining fish stocks for food and income, and increased outbreaks of diseases and breathing conditions in the local communities (Rüttinger et al., 2017).

Implications for EU supply chains

There is a low potential for domestic cobalt production within the EU, therefore the EU will remain reliant on DRC (Gregoir and van Acker, 2022). Cobalt demand will be dependent on the development of cathode battery chemistry and growth of the electric vehicle market (IEA, 2021). However, Turcheniuk et al. (2018) forecast that cobalt demand will be so high that DRC reserves could run out by 2030, while EU demand for cobalt is expected to increase by 15 times by 2050 (Irish Times, 2020). Van den Brink et al. (2020) have identified that the cobalt supply chain is at high risk due to the dominance of DRC and China, who are considered to be 'medium' to 'strongly' politically unstable. Further risk is due to cobalt almost exclusively mined as a by-product of either nickel or copper mining, therefore making the cobalt supply chain reliant on these markets (Van den Brink et al., 2020). On the other hand, the presence of 80 artisanal cobalt mines provides some mitigation to this supply chain concentration risk (Van den Brink et al., 2020).

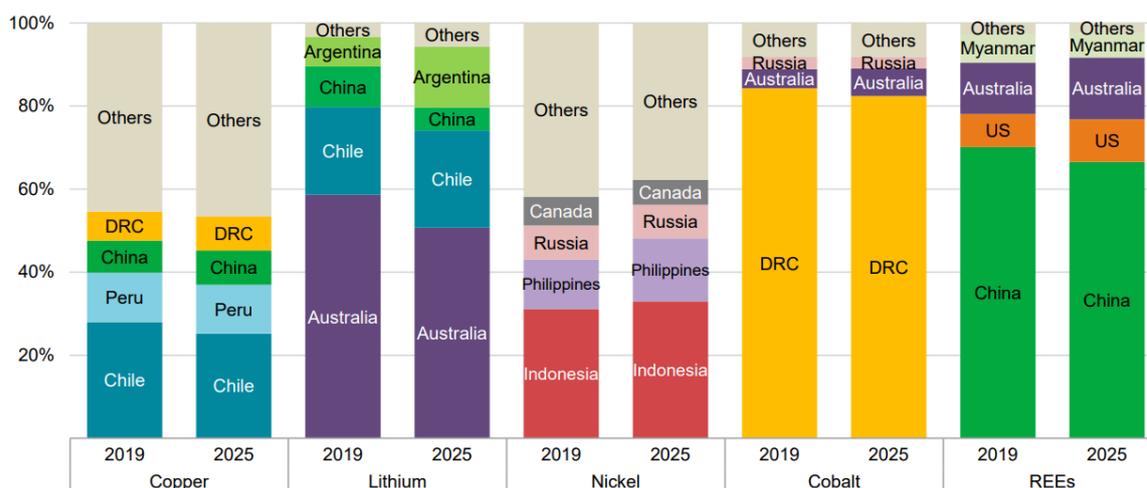
4.3.5 Rare Earth Elements (REEs)

Where?

China is the main producer of REEs, with around 80% of the supply (Gregoir and van Acker, 2022) although this appears to be reducing (from over 90% reported by Coulomb et al. in 2015) and processes up to 90% (Zeeshan, 2021). Other projects for REE extraction and refinement are in Australia, the US and Africa (Gregoir and van Acker, 2022; IEA, 2021; Figure 19).

Climate impacts

REEs are widely recognised as being central to a low carbon economy transition, with supply of these playing a crucial role in meeting climate targets (IEA, 2022; Serpell, Paren and Chu, 2021; Cardenes, 2018; Phadke, 2019). Yet despite this, it does not appear as if direct climate impacts on the REE mining sector have been examined by the literature.



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Note: Due to the availability of data on projections for future production, REEs here comprise neodymium, praseodymium, terbium and dysprosium only. DRC = Democratic Republic of the Congo; US = United States; Russia = Russian Federation.

Source: IEA analysis based on the project pipeline in S&P Global (2021) complemented by World Bureau of Metal Statistics (2020) and Adamas Intelligence (2020) (for REEs).

Figure 19. Major producing countries of selected minerals, 2019 and 2025. Source: IEA, 2021.

Social and environmental impacts

Production and processing of REEs produces radioactive and toxic materials (IEA, 2021), with production of one tonne of REE oxide requiring disposal of 1.4 tonnes of radioactive waste (Talan and Huang, 2022). REE mining (waste) products significantly destroys ecological regions, both physically and chemically, through run-off and leaching of these toxic and radioactive products, with further pollutants from mining activities such as drilling producing aerosols and fugitive dust which elevate cases of cancer, respiratory problems and contaminate food sources (Serpell, Paren and Chu, 2021). Increasing environmental standards for extraction and processing of REEs are paramount for an environmentally and socially sustainable supply chain and renewable energy technologies, yet Serpell, Paren and Chu (2021) also report that if China decides to increase its environmental standards, the cost of REEs will significantly increase.

Implications for EU supply chains

The EU does not currently mine any REEs and only refines minimal volumes of it (Gregoir and van Acker, 2022). Potential sourcing areas which have projects developing to produce REEs are in Sweden, Norway and Greenland, however these

are currently facing a number of obstacles, including permit issues and local opposition. Other potential global supply and refining sources could include Australia, North America and Africa (Gregoir and van Acker, 2022; Figure 20). A lot will depend on whether China continues to dominate the REEs and permanent magnets market, or whether diversification of sourcing and processing can mitigate this. China also has national policies which prohibit foreign investment for exploring or mining of REEs (PWC, 2012). This bottleneck, including China’s lack of transparency on price and the market (IEA, 2021), creates a potential significant vulnerability to the REE supply chain which is creating concerns for China’s control over electronics and wind turbines (Irish Times, 2020). However, while global prices increased in 2010 due to China’s restrictions on exports of neodymium, a REE, this rapidly decreased again after a number of months despite China not relaxing its export restrictions. This indicates that there may be some supply chain resilience (Sprecher et al., 2015).

	Production	Reserves
China	105,000	55,000,000
Brazil	0	22,000,000
Australia	10,000	3,200,000
India	N/A	3,100,000
United States	4,100	1,800,000
Malaysia	200	30,000
Russia	2,500	(Listed in other countries)
Thailand	2,000	N/A
Other countries	N/A	41,000,000
Total	124,000	130,000,000

Source: USGS 2016, 135.

Note: N/A = not available.

Figure 20. REE production volumes in metric tonnes. Source: USGS 2016.

A further challenge for the REE market, is that all naturally occurring REEs are present within the same ore. This therefore means that a growth in, for example, the neodymium market does not necessarily drive investment, as there are costs associated with disposing of waste products in the form of less valuable REEs (IEA, 2021).

4.3.6. Conclusions and policy recommendations

It is evident from the literature that energy transition minerals will experience significant increases in demand over the coming decades as Europe transforms to a low carbon economy. However, extreme climate events pose potentially significant shocks to EU supply chains, presenting operational and financial challenges to mining companies. Despite this, there appears to be a gap in the literature examining the specific impacts, mitigation responses and solutions to extreme climate events on mineral supply chains. This is particularly concerning for minerals

critical to a low carbon economy transition, such as lithium, cobalt and REEs. Further research could explore how climate change impacts mining at different spatial scales, with case studies, and responses from companies and governments (Odel, Bebbington and Frey, 2018). Further, bottlenecks, through dominance of one or a few countries for sourcing or processing, present further challenges, particularly if these face significant environmental issues or potential political instability. The ability of companies to mitigate and adapt to these shocks will therefore dictate the rate of the low carbon economy transition, and subsequently the EU's ability to meet its targets.

There are a number of policy recommendations for both mining companies and policy makers that have been identified from the review of literature that may further mineral supply chain resilience:

Mining companies:

- Increase sustainable use of water through reducing water consumption, loss (such as through water leaks and evaporation), and recycling (Delevingne et al., 2020).
- Explore and invest in ecosystem services and green infrastructure to improve local hydrological processes, such as wetlands to improve ground water drainage (Nelson and Schuchard, no date; Delevingne et al., 2020).
- Invest in grey infrastructure projects to mitigate water risks, such as flood-proof mine designs which have improved drainage infrastructure, adapting haulage roads to encourage speed drying, dams and desalination plants (Delevingne et al., 2020).
- Initiate and promote collaboration within industry and communities to develop local and regional climate adaptation strategies (Nelson and Schuchard, no date).
- Work with stakeholders and local communities to promote understanding and co-develop solutions to local concerns.

Policy makers:

- Work with mining companies to incentivise and remove financial and technological barriers to sustainable mining practices (Hund et al., 2020).
- Increase investment in research and development for recycling and reusing minerals in order to reduce the pressure of increasing demand for minerals (Hund et al., 2020).
- Implement a minerals tax as historically prices have been too low to encourage recycling of minerals (Sprecher et al., 2015).
- Promote research and development for mineral by-products, such as excess REEs, given that all REEs are present within the same ore (Sprecher et al., 2015).

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Annex

Food system stakeholder interviews: interview guide

Introductions

1. In a few sentences, could you describe what your current role is in your organisation, and your background?

Perceptions of risk and relative threat

2. To what extent do you think that potential cross-border climate risks or impacts are recognised within your area of work? How would you describe levels of awareness overall?
3. Reflecting on the potential for impacts overseas to affect the EU via trade, what do you believe are the key vulnerabilities in the EU food system that could be affected by climate impacts outside the EU?
4. How concerned are you about the role climate change might play in comparison with other forms of disruption that may take place outside the EU?
5. What do you think the most likely outcomes would be of significant climate-linked shocks that might occur internationally?
6. *For the private sector only:* Have you/ your organisation undertaken any assessment of future cross-border climate risks? Please describe them, and your likely response to them.

Mitigation/ responses

7. In the context of your experience within [your company/ organisations], what responses have you observed (by governments or others) to overseas climate change linked risks, extreme weather-related, or similar shocks in the past? If so, please describe how.
8. Are you aware of any steps being taken to mitigate the impact of future cross-border climate-related shocks? If so, what are these steps?

Interactions in the supply chain and with policy

9. Do you think EU policy, or associated policy linked to trade/supply chains, is likely to help or hinder the response to shocks to the EU food system linked to overseas climate impacts? Why?
10. Beyond the EU, who or what else do you think will influence the effectiveness of policy or supply chain responses to cross-border climate impact?

Closing

11. Is there anything you feel you would like to add/you feel is important for us to know, that hasn't yet come up during this conversation?

Soy supply chain stakeholder interviews: interview guide

Introductions

1. In a few sentences, could you describe your current role in your organisation, and your background?

Past shocks

2. Could you describe an example of when your organisation/ the soy sector experienced a production/supply shock? (Ideally climate-related, but other types of shock can also be included here)

3. Is this example typical of other supply/production shocks you have faced?

Planning for shocks in the future

4. What type of shocks do you anticipate occurring to the soy supply chain in the future?

a. What types of shocks are you most concerned about?

b. How does climate change compare to other shocks?

c. Within climate shocks, are you most concerned about gradual changes or sudden short-term shocks?

5. How does your organisation plan for these shocks (in the short and long term)?

a. What responses are planned in the event of a future shock?

b. To what extent can storage play a role in mitigating the effects of shocks?

6. Do you consider more extreme scenarios, or the most likely scenarios? (e.g., soy production failure in multiple producer countries)

Policy

7. Is current policy (EU policy or other soy- or trade-related policy) likely to help or hinder responses to shocks in the soy supply chain?

a. What policy responses would you like to see put in place?

Closing

8. Is there anything else you would like to add which you think is important in the context of this research, and which you have not had a chance to discuss yet?

9. Do you have any questions for us?

10. Finally, do you know of any other people working in the soy supply chain who might be willing to be interviewed as part of this research?