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Europe's cross-border trade, human security and financial connections: A climate risk perspective

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ABSTRACT

As the impacts of climate change begin to take hold, increased attention is being paid to the consequences that might occur remotely from the location of the initial climatic impact, where impacts and responses are transmitted across one or more borders. As an economy that is highly connected to other regions and countries of the world, the European Union (EU) is potentially exposed to such cross-border impacts. Here, we undertake a macro-scale, risk-focused literature and data review to explore the potential impact transmission pathways between the EU and other world regions and countries. We do so across three distinct domains of interest - trade, human security and finance - which are part of complex socio-economic, political and cultural systems and may contribute to mediate or exacerbate risk exposure. Across these domains, we seek to understand the extent to which there has been prior consideration of aspects of climate-related risk exposure relevant to developing an understanding of cross-border impacts. We also provide quantitative evidence of the extent and strength of connectivity between the EU and other world regions. Our analysis reveals that - within this nascent area of research - there is uncertainty about the dynamics of cross-border impact that will affect whether the EU is in a relatively secure or vulnerable position in comparison with other regions. However, we reveal that risk is likely to be focused in particular 'hotspots'; defined geographies, for example, that produce materials for EU consumption (e.g. Latin American soybean), hold financial investments (e.g. North America), or are the foci for EU external action (e.g. the Middle East and North Africa region). Importantly, these domains will also interact, and - via the application of a conceptual example of soybean production in Argentina based on a historical drought event - we illustrate that impact and response pathways linked to EU risk exposure may be complex, further

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heightening the challenge of developing effective policy responses within an uncertain climatic and socioeconomic future.

1. Introduction

With extreme weather events having devastating impacts on communities and livelihoods (IPCC, 2012; Mann et al., 2017), the consequences of human induced climate change are already apparent (IPCC, 2014; Estrada and Perron, 2019; Hausfather, 2021; IPCC, 2021). The potential implications of climate change impacts for risk mitigation and adaptation is a relatively nascent area for research and policy; whilst global economies and societies are now intrinsically connected (Federico and Tena-Junguito, 2016; Shirley, 2016), assessments and responses to climate impacts risks have largely been considered nationally or locally (Benzie et al., 2016). This is changing, with research demonstrating the potential for cross-border exposure to climate change impacts (Hedlund et al., 2018; Benzie et al., 2019). In particular, recognition that impacts may 'cascade' into focal countries from overseas is becoming more prominent in national assessments (e.g. Vonk et al., 2015; Hildén et al., 2016; Challinor and Benton, 2021). Recently, a new conceptual framework for exploring the cross-border impacts of climate change has been developed (Carter et al., 2021); defined as consequences of climate change that occur remotely from the location of their initial impact, where impacts and sometimes responses to those impacts (such as adaptation) are transmitted across one or more borders.

Benzie et al. (2019) provide an overview of the attention such issues have been paid across the European Union, developing and applying a 'transnational climate impact' (TCI) index linked to four impact pathways: *biophysical* (cross-border ecosystems, e.g. river basins), *trade* (via international markets), *finance* (flows of public/private capital) and *people* (migration across borders). The latter three pathways are linked to complex socio-economic, political and cultural systems which may act to mediate or exacerbate risk exposure; understanding these pathways in more detail is critical to ensure risk preparedness. Whilst Benzie et al. (2019) use data-driven indicators to quantify risk exposure via these pathways, an extensive assessment of the potential for these pathways and connections between Europe and the rest of the world to be affected by climate impact has not yet been conducted. Addressing this, our paper provides a macro-scale, risk-focused review of potential impact transmission pathways between the European Union (EU) and other world regions across three distinct domains of interest: *trade*, *human security* (expanded from Benzie et al., 2019's *'people'* to encompass broader humanitarian and development concerns linked to overseas regions, cf. Adger et al. 2014) and *finance*:

Trade is fundamental to the EU, enabling the influx of materials that would be otherwise unavailable to meet demand (European Commission, 2021a). Many international supply chains are involved in the production, shipping and processing of materials; these are critical for food security and for industries such as manufacturing (European Environment Agency, 2017; Fiott and Theodosopoulos, 2020; Eurostat, 2021). This complex, widespread distribution means that trade is an obvious source of risk to the EU economy; disruptions occurring almost anywhere in the world could affect EU supply chains (Adams et al., 2020). How have these risks been considered in the literature, and are there important dependencies at the macro-economic scale acting as a significant risk source for Europe?

Climate change affects human, national, and international security in ways that interact with trade and financial risks (Buhaug, 2016; Gilmore, 2017; Mach et al., 2019; Scheffran et al., 2019). Whilst – from a human security standpoint - already-vulnerable countries will likely be most exposed to the direct effects of climate change (Busby, 2019; Ide et al., 2020; Detges, 2017), their exposure may have indirect effects on others' foreign policy objectives. This is particularly true for foreign powers with a stake in the development and political stability of an affected country. Climate impacts on human security, development and peace in focal regions with connections to Europe are thus highly relevant for European policy. What might these impacts look like and how might they propagate across sectors and borders?

Exposure of the European financial sector to climate change, via global chains of securities and financial contracts, introduces a further source of risk for Europe. European insurance and reinsurance firms are particularly exposed to climate risk, given they specialise in 'managing risk'. EU financial actors are highly exposed to economic activities in extra-EU countries that are subject to physical and transition risk, and could drive carbon stranded assets (Mercure et al., 2018, Cahen-Fourot et al., 2021, van der Ploeg and Rezai, 2020). Actors can be exposed to risk directly (e.g. bank A lends to an affected firm) or indirectly (e.g. bank B holds equity in bank A; Battiston et al. 2016), thus financial interconnectedness can amplify a climate shock by reverberating it across financial networks (Battiston et al., 2017). To what markets is Europe most exposed, and how does the sector currently consider and manage climate-linked risks?

Our analysis across these domains takes the form of: a methodological synthesis of evidence to define potential risk sources; conceptualisation - via a case study - of how cross-border impacts may interact across our focal domains; and conclusions on this synthesis and how it should inform future work. We begin with a) literature and b) data reviews to understand the extent of prior consideration of climate-related risk exposure relevant to developing an understanding of cross-border impacts, and to provide quantitative evidence of the extent and strength of connectivity between the EU and other world regions. Analysis reveals hotspots of potential risk which we envisage being useful for informing where further investigation into risk pathways might take place, rather than undertaking a granular or exhaustive assessment of exact pathways via which climate-risk might manifest itself. Inspired by the domain-linked dynamics and connections described in our review (and a historical event), our analysis then moves on to c) an illustration of how climate impacts may intersect our focal domains, based on a scenario linked to a historical drought affecting the soy supply chain. Finally, d), we highlight common themes and concerns that emerge from our review, and implications for future research and policy.

2. Methodological details

The methods underpinning this paper consist of a literature review and analysis of data across our three focal domains. From these resources, insights were derived by a domain-specific team (Trade: Stokeld, Croft & West; Human Security: Detges & König; Finance: von Jagow, Campiglio, Duranovic & Monasterolo) to highlight the manner in which cross-border impacts have previously been considered across domains, and points of domain-specific connectivity, overseas interests and/or dependencies that the data reveal. Section 3 of the paper describes the outcomes of these reviews; synthesised by the expert teams. In addition, Section 4 builds on this synthesis by describing a hypothetical future example of cross-border climate impact exposure, inspired by the insights of our review and a historical drought affecting the soybean supply chain which has cascading impacts across our focal domains.

2.1. Literature searches

We conducted an integrative (or narrative) review (Torraco, 2005; Snyder 2019), designed to enable the exploration of how climate-linked cross-border processes and dependencies have been previously considered across our three focal domains, with the aim of informing new perspectives on cross-border impacts to which the EU might be exposed. Whilst aligned, searches differed depending on the exact timing of the review and due to discipline-specific differences in the scope and forms of literature available. For example, the review conducted for the finance domain included repositories specific to social and economic sciences. For all domains, a constraint was put on searches so that they resulted in recent articles linked to cross-border climate risk exposure. A description of the search terms adopted, repositories used by each team, and additional details is included in Supplementary Information (SI1a), but in summary: the trade team searched for literature considering trade activities that also encompassed climate impact or climate risk; the human security team searched for literature relating to climate change across conflict, migration, economic wellbeing and food security sub-domains; and the finance team searched for literature linking cross-border finance or financial activities and climate risk.

The research groups screened literature from the prior decade, with the screening activity taking place between January and March 2020. Teams were encouraged to seek EU-linked studies, but this was not a firm requirement of the process; initial screening highlighting that constraining literature to the EU would be too restrictive within what is a relatively embryonic research area. Research teams employed search terms with sufficient breadth to encompass the relevant body of information sought, but with enough specificity to avoid excessive irrelevant results. Following initial screening, all teams undertook triage to select articles of most relevance for full review, with additional papers or reports added via snowballing processes (i.e. review of references within initial literature) and/or via the addition of seminal resources of which the teams were previously aware.

A literature record is contained in SI1b.

2.2. Data compilation and review

For the trade domain, initial data collection and review was undertaken based primarily on the Chatham House's Resource Trade dataset (Chatham House, 2020; that in turn uses UN Comtrade statistics; UN Comtrade, 2020) which provides a comprehensive overview of international trade (in physical and financial units). The EU27 was chosen as the focal importing bloc. In order to consider dependency on overseas versus domestic production, we supplemented the trade statistics with production statistics (from FAO and Eurostat) for products produced within the EU27. Other sources of information included data on specific logistics types (from Eurostat), and the Chatham House 'chokepoints' report (Bailey and Wellesley, 2017).

Data analysis for the human security, development and foreign policy domain includes assessment of data that summarises the asylum dynamics and migration into, and overseas development assistance (ODA) spending by, the EU27. Sources for this data include the United Nations and OECD.

Analysis of financial exposure is based on a number of sources, including the International Monetary Fund (IMF) which provides data (in $, USD) for individual EU countries on outward foreign direct investment (FDI) and cross-border portfolio investments. Additional data on industry-breakdowns is provided by the Eurostat database (available only for the EU28 rather than EU27, and provided in euros, EUR) and contains classifications for selected countries only: Brazil, Canada, China, Hong Kong, India, Japan, Russia, Switzerland and the United States). No equivalent open-access sectoral classifications are available for portfolio investments.

In contrast to the literature review, our data exploration focuses primarily on EU-linked connections. Data sources and time series covered are further summarised for all domains in SI2.

3. Europe's connections across trade, human security and finance domains

3.1. Trade risk

3.1.1. Trade risk: Literature insights

Several papers refer to trade-linked transmission pathways in similar terms to those conceptualised in Carter et al. (2021), but use inconsistent terminology. For example, a 'cascade of impacts' has been described where vulnerabilities exacerbate impacts at each supply chain stage (Gitz and Meybeck, 2016); 'a cascade of risks' where physical impacts lead to economic and social impacts (UN FAO, 2016). A first approximation of exposure to 'transboundary climate impacts' was developed at country level by Hedlund et al. (2018), with results illustrating far-reaching entanglements of risk in a globalised world. In a recent report, which describes the 'indirect cascading effects' of climate change impacts occurring in a remote region (Lung et al., 2017), the cross-border impacts of climate

change which have (or are projected to have) potential implications in Europe are explored. Among the six major pathways identified in the study, three are trade related: trade of agricultural commodities; of non-agricultural commodities; and infrastructure and transport.

A typical pathway of trade-related risk transmission identified in the literature is where climate change affects the production of traded commodities, resulting in impacts on supply, price spikes and increased market volatility (Gitz and Meybeck, 2016). For example, Lewis and Witham (2012) examined wheat and barley markets and concluded that market stability in all regions will be affected by climate change. Challinor et al. (2018) recognise that market and policy *responses* to climate trends and events can often have greater consequences than the climate impact itself. In addition, climate change impacts on production can also lead to changes to global trade patterns. Jones and Olken (2010) examine the consequences of climate-shocks on economic activity, finding substantial impacts on poor countries' exports, but not on richer countries'. Furthermore, impacts are concentrated in exports of agricultural products and light manufacturing (such as footwear, electrical goods, plumbing, wood products). Ahammad et al. (2015) project *increases* in trade and exports under climate change, despite decreases in global production, arguing that trade will have an 'enhanced role' in the redistribution of scarce agri-food commodities. Mosnier et al. (2014) find that when imports are considered, the overall climate change impact on food availability per country could be of opposite sign to the direct domestic impacts. For example, whilst South Korea and Japan are projected to experience positive impacts on domestic production, their total crop calorie availability is projected to be reduced under two of the three models used in the study, due to high dependence on staple crop imports.

Transportation infrastructures and operations will be directly affected by an increase in the frequency and magnitude of extreme events due to climate change, potentially causing market instability (Challinor et al., 2017). Potential infrastructure impacts *within* Europe include airport and seaport inundation due to higher sea levels and extreme weather events, whilst transportation along the rivers Rhine and Danube could face fewer drought-related disruptions relative to the present climate (Ciscar et al., 2014). Europe relies heavily on maritime shipping for its trade, with maritime 'chokepoints' therefore of potential concern (Bailey and Wellesley, 2017). Indirect effects from climate change for Europe's energy and material supply are also expected in relation to the projected thawing of Arctic permafrost, opening up potential new trading routes (Lung, et al., 2017; Challinor et al., 2016).

According to Hedlund et al.'s (2018) transnational climate impact index, the EU (EU28) has a higher than average exposure across a number of indicators, including trade openness. The EU's trade profile and high levels of engagement in global economies mean that external events could have profound impacts on welfare inside the EU28 (Benzie et al., 2019). Climate-induced changes in global prices for food and feed are also of great importance for Europe, which relies to a considerable extent on imports (Lung, et al., 2017). The Mediterranean region in Europe has been identified as the most susceptible to shocks in flows of agricultural commodities, owing to its relatively high dependence on food imports from outside Europe and the prominent role of the food sector in its economy (Amec, 2013).

Sources disagree about the potential risks to EU agricultural production that will ultimately influence the EU's trade balance. Baldos and Hertel (2015) state that the effects of climate change are likely to increase the productivity of European agriculture, but Lewis and Witham (2012) propose that crop production in Europe may decrease due to projected increases in the drought frequency. Furthermore, Elbehri et al. (2015) highlight the importance of time-horizons in risk assessment; outlining that yield increases in higher latitude regions will only occur until mid-century before declining. Trade flows are expected to increase from mid-to-high-latitudes in the direction of low-latitude regions, where declines in yields are expected in the short term (Elbehri et al., 2015). A substantial number of Europe's major trade partners (e.g. India, Indonesia, Nigeria and Vietnam) are estimated to exhibit an overall vulnerability to climate change that is larger than any European country (Lung, et al., 2017).

A major theme is that trade may help alleviate the impacts of climate change, for example by balancing agricultural production gains and losses across regions (Elbehri et al., 2015; Gitz and Meybeck, 2016). Baldos and Hertel (2015) find that market barriers have significant implications for future food security in the presence of climate change impacts, with the range of malnutrition outcomes being substantially smaller with tightly integrated markets. However, it is important that trade's potential as an adaptation mechanism is critically considered. Ferguson and Gars (2020) find that, historically, a 1% increase in exporter country production led to only a 0.5% increase in exports, and argue that trade has played a relatively limited role in mitigating production shocks in the past. The UN FAO (2016) highlights that access to trade markets depends on the poorest countries and populations having sufficient purchasing power.

Several policy recommendations emerge from the literature, including that countries should diversify their sources of supply, encourage a wider spatial distribution of production, and support crop research and climate adaptation (Baldos and Hertel, 2015; Gitz and Meybeck, 2016; Puma et al. 2015). Policies implemented to protect national interests alone are likely to cause negative impacts on a global scale (Challinor et al., 2017; Puma et al., 2015) and harmonised trade policy is seen as a key solution in response to climate change (Elbehri et al., 2015). An important policy consideration linked to equity is that poorer nations and individuals are least able to adapt to evolving risk under climate change, and climate change is expected to exacerbate existing imbalances (Elbehri et al., 2015; Challinor et al., 2016; UN FAO, 2016). Least developed countries are projected to suffer greater import losses in more connected networks (Puma et al., 2015). In the food sector, poor net food buyers will experience the worst impacts of climate change (Gitz and Meybeck, 2016).

3.1.2. Trade risk: Data insights

The price of traded goods fluctuates markedly and - whilst this may take place in response to sourcing restrictions, and therefore price changes are an important consideration – the mass of imports likely better reflects the relative levels of risk exposure associated with commodity sourcing, given the importance of many commodities in industrial outputs. We therefore focus primarily on summarising the data in terms of material dependency (equivalent monetary Figures are provided in SI3.1). Fig. 1 provides a breakdown of

imports into the EU27 by aggregated commodity group for the year 2018, and – given the link to food security (highlighted as a risk in the literature) - agricultural products (including fertiliser sources) are shown in additional detail. From an EU perspective, fossil fuels dominate, followed by metals and minerals, then agricultural products.

In Fig. 2, we align the contribution of imported material with EU27 primary production (i.e. removing any processed material production that may itself depend on imported material). At the aggregate commodity scale the EU27 appears relatively self-sufficient, but it is evident that for fertilisers and fossil fuels the EU27 is highly import-dependent. Whilst self-sufficiency in the EU27 is high for agricultural products overall, this is not the case across all sub-categories, with e.g. products of fisheries, oilseeds, stimulants and spices having relatively large import contributions.

Import dependencies have fluctuated over the past fifteen years (Figures provided in SI3.1). With the exception of a decrease in 2009 (possibly due to the financial crisis of 2007–2008) agricultural product imports have increased year on year, and fertiliser and forestry product imports have also recently increased. Monetary values do not always track changes in mass closely, illustrating the potential for commodity prices to change rapidly in global trade markets.

Products of horticulture, oilseeds and cereals are likely to be nutritionally important to the EU. Fig. 3 shows the sources of these commodity groups. The majority of imports are sourced from just a handful of locations: the ten largest sources of material for oilseeds comprise 87% of extra-EU imports in 2018, for cereals it is 92% and for horticulture products 80%. When aggregations are broken down (Tables are provided in SI3.1 for products in the oilseeds, cereals and horticulture classifications) they continue to reveal this pattern of restricted sourcing. For example, for several important 'bulk' commodities (e.g. soybeans, palm oil, maize) imports are concentrated from five or fewer (sometimes geographically co-located) countries. Whilst for other commodities (e.g. rice, nuts and fruits) there is more diversity, climate change impacts in certain geographic regions could have an 'outsize' impact on the sourcing of important materials.

The transport routes and reception points via which materials enter the EU are important when considering the potential for climate change to disrupt trade. Whilst routes may adapt, logistics infrastructure typically has long-term utility and is unlikely to be easily substituted. Data for imports and exports by travel mode (see SI3.1) reveal the importance of maritime routes for the EU. It is

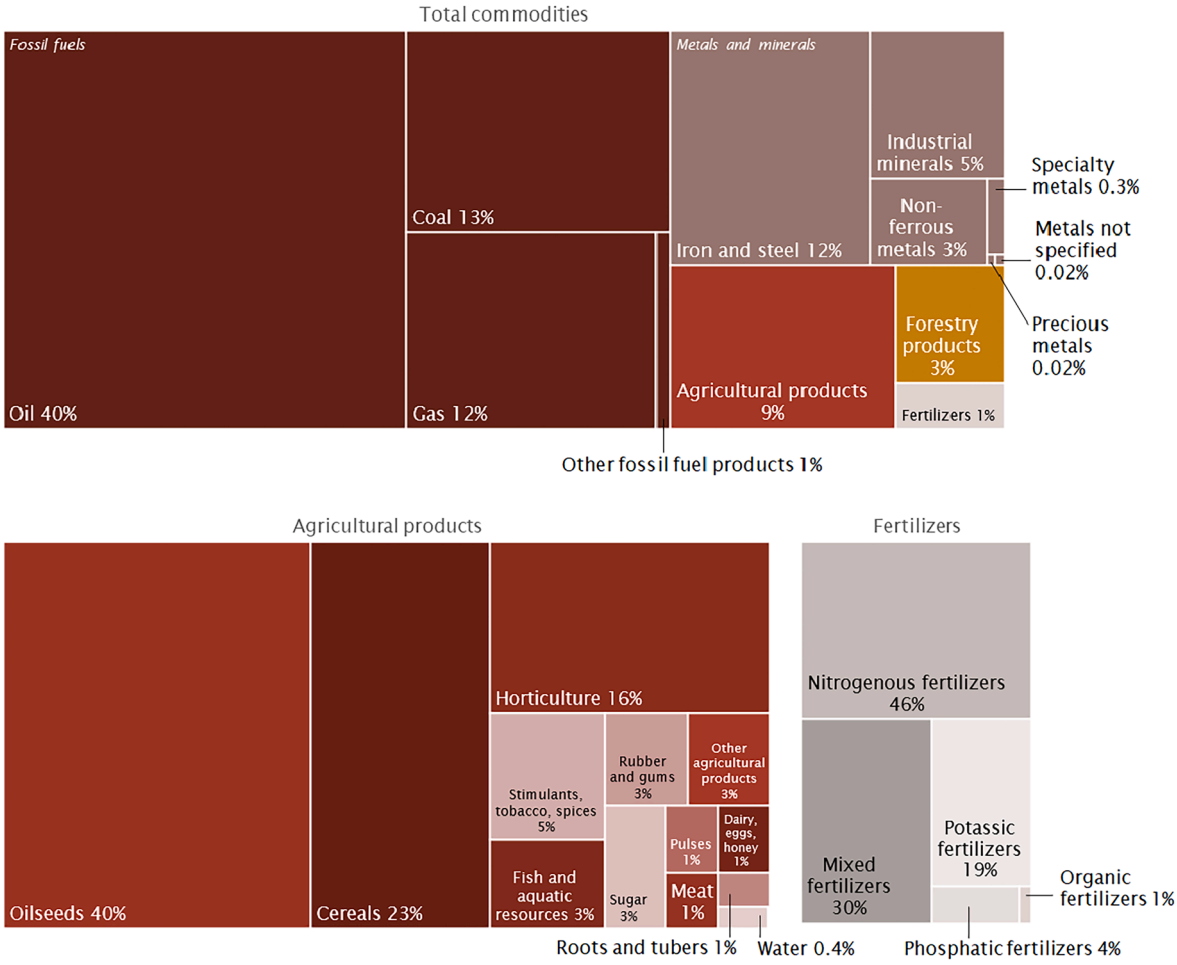

Fig. 1. Contribution of commodity groups to EU27 imports (based on mass) in 2018. Source: Chatham House Resource Trade.

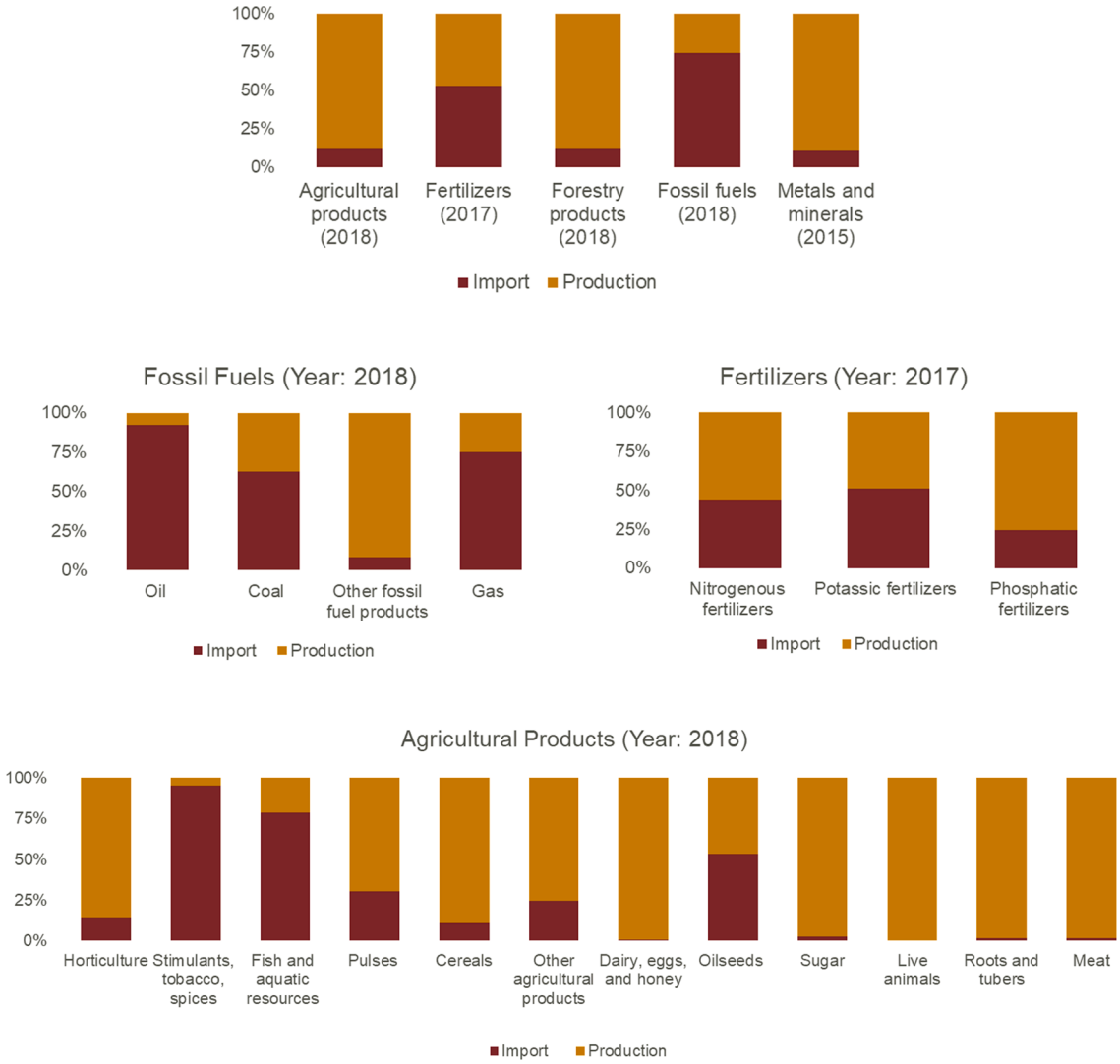

Fig. 2. Relative contribution of imports to material dependency (imports plus production) in the EU27. Different baseline years are due to the different timestamps associated with primary production datasets utilised. Sources: Chatham House Resource Trade, Eurostat, FishstatJ, USGS.

apparent that maritime trade via selected ports in the Netherlands and Belgium are particularly important; in 2018 Rotterdam handled almost three times as much material as the next most important port (Antwerpen), with dependence on these two ports increasing markedly in recent history. Bailey and Wellesley (2017) analyse disruption risks in global food trade and highlight maritime, coastal and inland chokepoints that are systemically important to international trade. Fourteen food trade chokepoints of global strategic importance are identified but EU countries are rarely mentioned among the most exposed or vulnerable countries. The exception is Cyprus (which has a high cereal import dependency ratio, and a high proportion of imports passing through at least one maritime chokepoint). Within Europe, the Dover Strait, the Turkish Straits, Black Sea ports and the Black Sea rail network are identified as of strategic importance in terms of connectivity, with the criticality of Turkish Straits being high given the lack of obvious alternative maritime routes. The Black Sea region is highlighted as requiring significant investment in transport infrastructure, which is currently deterred by regional instability.

3.2. Risk to human security

3.2.1. Risk to human security: Literature insights

Our literature review identifies a number of impacts that are immediately relevant from a humanitarian or development perspective; agriculture, fisheries and pastoralism all face significant challenges due to changing climatic conditions. Across the literature, rising temperatures (Hertel, Burke and Lobell, 2010; Tirado et al., 2010; Al-Amin and Ahmed, 2016), temperature shocks (Letta, Montalbano and Tol, 2018) and general shocks to agricultural production – for example, extreme weather (Al-Amin and Ahmed,

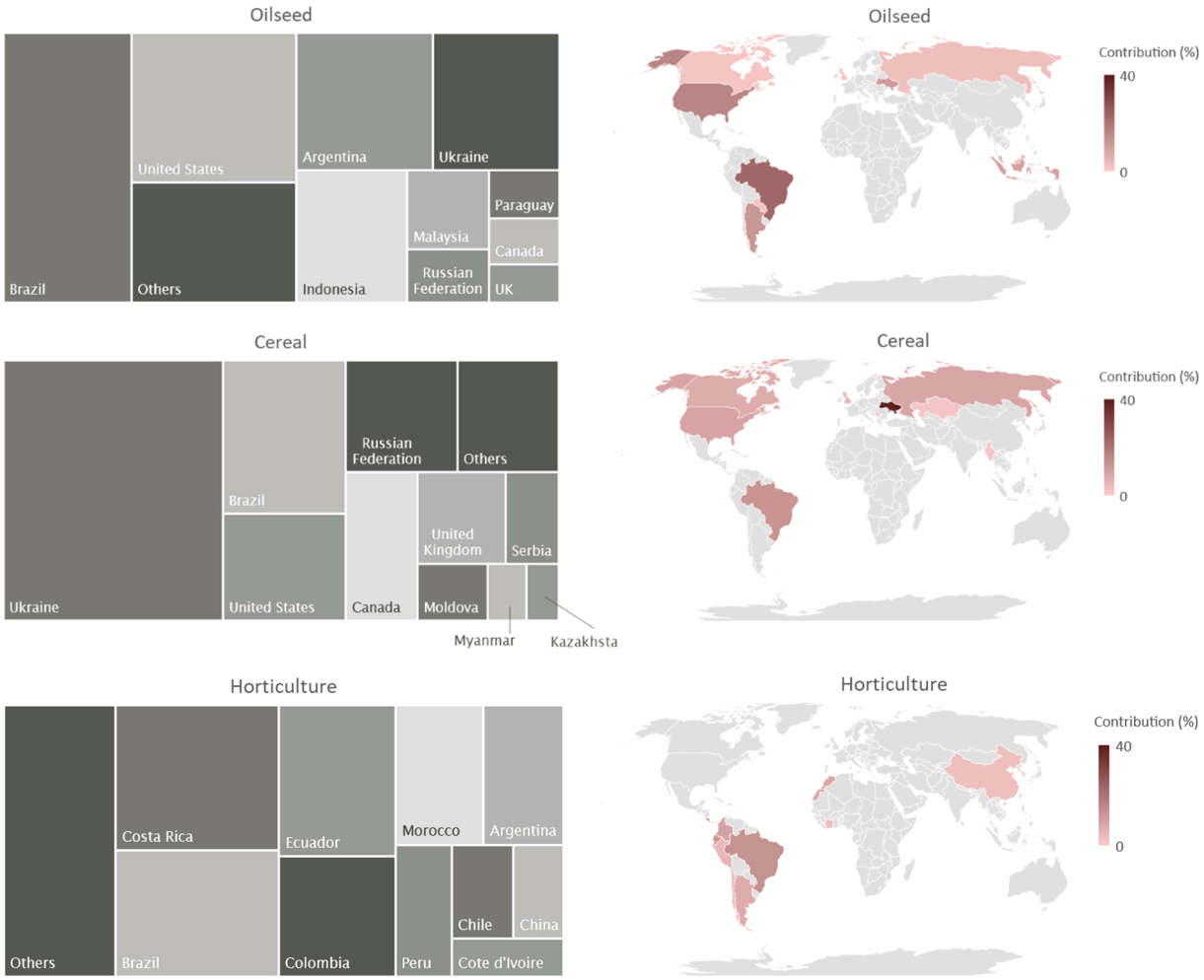

Fig. 3. Import sources of selected agricultural commodities into the EU27 from non-EU27 countries in 2018. Source: Chatham House Resource Trade. (Maps copyright: DSAT Editor, DSAT for MSFT, GeoNames, Microsoft, Microsoft Automated Stitching, Navinfo, Navteq, Thinkware Extract, Wikipedia. Powered by Bing.)

2016; Berchoux et al., 2019) - are shown to reduce yields and labour productivity. Postharvest losses, and pests and diseases, are also expected to rise (Tirado et al., 2010; Srivastava, 2019). Farmers' incomes are not predicted to fall in all regions (Hossain et al., 2019), but the livelihoods of many are endangered (Hertel, Burke and Lobell, 2010; Hossain et al., 2018; Berchoux et al., 2019), while rising food prices will potentially impose severe economic hardship on buyers and importers (Hertel, Burke and Lobell, 2010; Letta, Montalbano and Tol, 2018) and reduce access overall (Tirado et al., 2010; Campbell et al., 2016). Climate change is thus likely to offset some progress made by the international community towards reducing hunger (Krishnamurthy, Lewis and Choularton, 2014; Mason-D'Croz et al., 2019; Wiebe, Robinson and Cattaneo, 2019). Pastoral livelihoods are also at risk of becoming unviable due to the impact of reduced precipitation on the vegetation on which livestock feed (Martin et al., 2014). For many, fish make a substantial nutritional contribution (Dasgupta et al., 2017; Lauria et al., 2018); reductions in quality or biomass due to salinization (Dasgupta et al., 2017) and warming (Tirado et al., 2010; Lauria et al., 2018; Campbell et al., 2016) may thus compound reductions in broader food quality that may follow increases in CO_2 and temperature (Campbell et al., 2016; Srivastava, 2019). Furthermore, extreme weather events such as cyclones may destroy fish stocks and reduce biodiversity (Hossain et al., 2018). Campbell et al. (2016) note that due to a heavy focus on crop production in the extant literature, the impacts of climate change on livestock, fisheries and pests – and accordingly on associated livelihoods – might be significantly underestimated. These potential impacts to agriculture, fisheries and pastoralism are likely to challenge development progress in affected regions.

We can also identify a number of challenges to peace and political stability. The literature demonstrates the potential for indirect effects of climate change and extreme weather events on the risk of violent conflicts; some papers articulate a link between droughts and/or decreased rainfall and increases in conflict and political violence, although this is at the sub-national rather than the interstate level (Fjelde and von Uexkull, 2012; von Uexkull, 2014; Raleigh, Choi and Kniveton, 2015; Abel et al., 2019). Where climatic changes are linked to increased conflict and violence, rising food prices (Raleigh, Choi and Kniveton, 2015) and lower agricultural production

(von Uexkull, 2014; Wischnath and Buhaug, 2014) are the predominant explanations. Yet, the link between climate change and conflict itself is not without contention (e.g. see Salehyan and Hendrix, 2014; Selby et al., 2017), and governance is highlighted as important in determining patterns of conflict or cooperation in the wake of adverse climate change (Zografos, Goulden and Kallis, 2014). Consensus seems to exist that climate change in itself is not a strong predictor of violence; the interaction of climate with other social and economic factors needs to be considered to explain climate-linked violence when it occurs.

Ultimately the social and economic context, which strongly influences the resilience (or vulnerability) of affected people, matters a great deal. For example, if agriculture and other food production's relative role is critically important as a source of nutrition and income, the implications of climatic impacts on human security, conflict, migration and development will likely be larger (Hertel, Burke and Lobell, 2010; Ide et al., 2014; Wischnath and Buhaug, 2014; Letta, Montalbano and Tol, 2018; Falco, Galeotti and Olper, 2019; Berchoux et al., 2019; Wesselbaum and Aburn, 2019). Rainfed agriculture is especially at risk from climatic change, and where it is the primary mode of agricultural production, impacts will be even more pronounced (von Uexkull, 2014). Conversely, water infrastructure and irrigation capacities, or the proximity to cities and services, can attenuate climate-related risks for rural populations (Parsons and Chann, 2019; Berchoux et al., 2019). Similarly, countries that rely more on buying or importing food will be more exposed to negative impacts from rising food prices, while exporting nations might see incomes rise in the wake of climate-induced production shocks (Hertel, Burke and Lobell, 2010; Hossain et al., 2019; Wiebe, Robinson and Cattaneo, 2019). Personal and household characteristics are also important to consider. Higher levels of poverty (Tirado et al., 2010; Gray and Mueller, 2012; Campbell et al., 2016; Letta, Montalbano and Tol, 2018) and dependence on natural resources (De Silva and Kawasaki, 2018) increase the potential impact of external shocks; relative losses are higher whilst resilience and adaptive capacity tend to be lower for groups already facing hardship.

As climatic pressures disrupt livelihoods and increase the risk of conflict, migration in search of alternative sources of income, or in reaction to an imminent threat, may increase. This can create new political challenges, for example if migrants are met with animosity or even violence in receiving areas, or exploited by traffickers. The literature is nuanced here; sources indicate that migration increases as a result of shocks to agricultural productivity (Falco, Galeotti and Olper, 2019) and to livelihood opportunities (Ahsan, Kellett and Karuppannan, 2016; Koubi et al., 2016; Wesselbaum and Aburn, 2019), but the overall picture is less clear-cut. Firstly, migration patterns vary over time following an impact (such as a climatic event). Short-term decreases in out-migration might be followed by longer term increases and vice versa, so analysis over longer periods of time likely offers a more accurate portrayal of the changes to mobility resulting from shocks or other climate triggers (Wesselbaum and Aburn, 2019; Call et al., 2017). Overseas social networks, which increase the resilience of populations in sending countries, may also reduce the need to migrate (Nawrotzki et al., 2015). While a number of studies attribute increases in migration to slow onset climatic changes (Hugo, 2011; Ahsan, Kellett and Karuppannan, 2016) - especially to sea level rise (Adams and Kay, 2019) and increasing temperatures (Wesselbaum and Aburn, 2019; Call et al., 2017) - others highlight that extended periods of extreme precipitation, i.e. droughts or long wet periods, or slow-onset events like soil and water salinisation, may reduce migration (Gray and Mueller, 2012; Suckall et al., 2015; Koubi et al., 2016; Call et al., 2017). Explanations include the higher potential for adaptation in the case of slow-onset events, or reduced agricultural productivity and incomes that prevent migration for affordability reasons (Suckall et al., 2015; Koubi et al., 2016; Call et al., 2017).

3.2.2. *Risk to human Security: Data insights*

From a European perspective, the above impacts will be particularly relevant when they emerge in regions with close ties to the EU - e.g. through migration, political commitments and partnerships. Migration statistics from non-EU countries to the EU27 (Fig. 4)

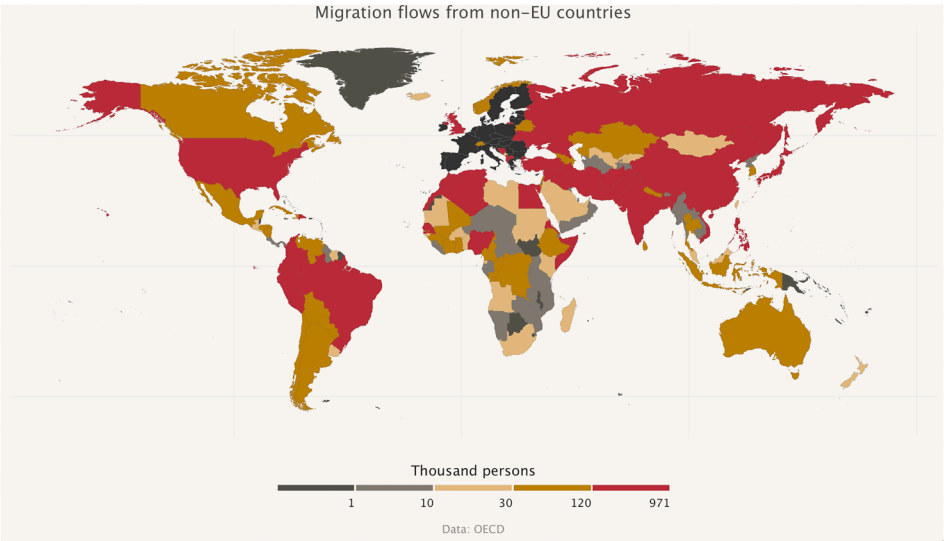

Fig. 4. Total number of migrants reaching the EU27, between 2007 and 2016. Source: OECD.

reveal that large numbers of migrants originate from large, populous nations, countries in the European neighbourhood, and those with language and/or colonial-era ties to the EU27. We observe that absolute migrant numbers from Sub-Saharan Africa are comparatively low, possibly due to smaller population sizes in origin countries, the predominance of intraregional migration and migration to Middle East and North Africa (MENA), as well as restrictive EU immigration policies (see Puig Cepero et al., 2021). Analysis suggests that migratory movements to the EU27 correlate strongly with total migration stock data (see SI3.2), and somewhat strongly with the mobility patterns of refugees and asylum seekers, suggesting that mobility towards the EU is shaped by pre-existing networks and diasporic ties, which are likely to continue to have influence on Europe's connection to other regions.

Data comparing outward movements to the EU27 and to other OECD countries (see SI3.2) reveal that migrants from North Africa, Eastern Europe and parts of the Middle East have moved much more often to the EU27 than to other OECD destinations. This underlines the importance of neighbourhood effects on migration to the EU and - assuming that these patterns do not change rapidly over time - indicates where people displaced by climate change in those regions might move.

Besides migration, forced displacements are important in the context of climate change and its potential to aggravate humanitarian and political crises. Over the past decade, EU27 countries have been a main destination for refugees from Eastern Europe, Central Asia, the Balkans, West Africa and the MENA region, as well as individual countries elsewhere. The data (see SI3.2) also reveal fluctuation over time; while nearly 60% of all East Asian refugees sought refuge in EU27 countries in the early 2000 s, this number has dropped to 20% in recent years, whereas preferences for the EU as a safe haven have remained relatively stable in Southern Asia, the Caribbean and Eastern Africa. This indicates the relevance of time- and region-specific factors and events, such as localised crises and conflicts or changes in asylum, visa, and other immigration laws that influence mobility patterns and that can be unpredictable. Nevertheless, the data suggest that existing diasporic, linguistic and historical ties, and previous migration experiences, will likely continue to influence mobility patterns. All else being equal, we can therefore assume that humanitarian and political crises may affect migration to Europe more if they erupt in the immediate European neighbourhood.

Overseas development assistance (ODA) is another important marker of EU involvement in, and connection to, non-EU countries. Fig. 5 shows that, over the past ten years, ODA has flowed in large amounts to countries in the European neighbourhood, (e.g. Morocco and Turkey) and fragile countries (e.g. Iraq, Afghanistan, Democratic Republic of Congo), as well as to large South and East Asian countries (e.g. India, China). Important sums have also flowed to former colonies and countries with close cultural and language ties, such as those in Africa and Latin America. In general, the largest sums have flowed to countries from which larger migrant populations within the EU originate, pointing to a connection between international development cooperation and diasporic ties. When considered on a per capita basis (see SI3.2), European ODA has disproportionately flowed to populations in Africa and the immediate European neighbourhood, suggesting that European development cooperation places greater emphasis on this region than on regions further away. Over time, levels of total ODA spending have remained relatively stable or have slightly increased for most regions of the world, except for Western and Central Africa and Western Asia where they have fluctuated more markedly (see SI3.2). Fluctuations are likely the response to conflicts and political crises with spending shaped by ethical considerations and humanitarian (rather than risk-based) motivations, historical ties and political priorities. Indeed, vulnerable sectors from a climate-security perspective have made up a relatively small part of overall ODA spending over the past twenty years, although we observe a slight increase in the relative importance of spending on emergency response recently (see SI3.2). ODA spending on peace and stabilisation, in particular, has only represented a very minor portion of total ODA spending, even though it is highly linked with EU27 members' military involvement in, and support to, non-EU countries (see UCDP, 2020).

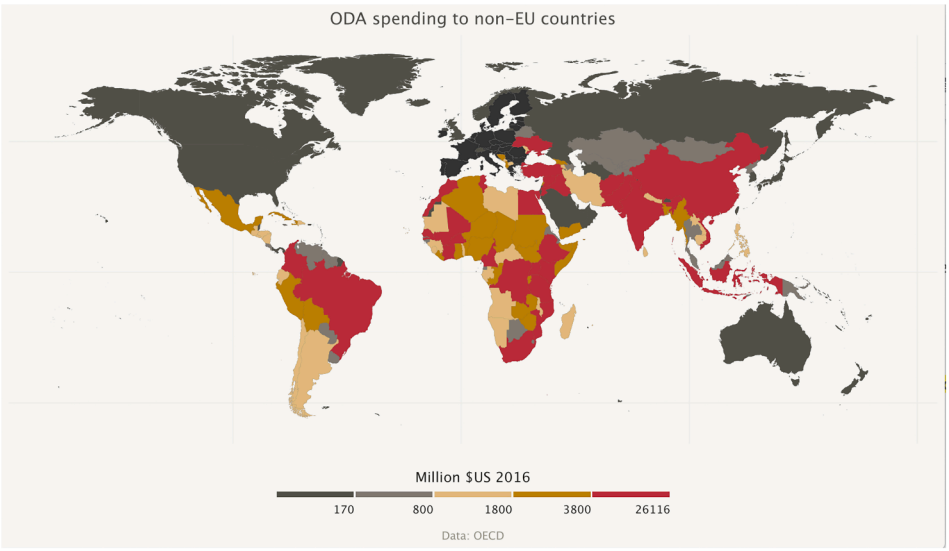

Fig. 5. Total gross overseas development assistance from the EU27 to non-EU countries, between 2008 and 2017. Source: OECD.

3.3. Finance risk

3.3.1. Climate finance and economic risks: Literature insights

Since the 2015 Paris Agreement, there has been growing awareness among financial authorities, investors and policy makers that climate change represents a new form of risk for global financial stability (Carney, 2018; NGFS, 2019; TCFD, 2017). Climate-related financial risks stem from the exposure of financial actors to economic activities that are climate relevant, either because they are exposed to potential losses in profitability due to disaster risk (i.e. physical climate risk), or due to climate policies, regulatory and technological shocks in the low-carbon transition (i.e. transition risk; NGFS, 2019). Economic activities that are exposed to physical climate or transition risks are likely to affect the profitability and financial stability of investors (Battiston et al., 2017). Several international financial initiatives have recognized the importance of disclosing and assessing climate-related financial risk for investors (e.g. TCFD, 2017; Acclimatise and UNEP FI, 2018). In this regard, a group of over 90 central banks and financial institutions have joined the Network for Greening the Financial System (NGFS, 2019) and the relation between climate risks and financial stability is attracting considerable attention by academics, central banks, financial regulators (hereafter financial authorities) and the private sector.

A large focus has been on climate transition risk. Climate stress tests have been developed in the academia (Battiston et al., 2017) and more recently by financial authorities (Weyzig et al., 2014; Vermeulen et al., 2019). Analyses of physical climate risks are more recent. Following Dietz et al. (2016)'s assessment of 'climate value at risk', financial authorities (NGFS, 2019; Bank of England, 2015; Bank of England, 2019; PRA, 2018) and private actors (Mercer, 2019; Four Twenty Seven, 2017; Acclimatise and UNEP FI, 2018; Lepousez et al., 2017) have begun to develop tools to disclose and assess physical climate risks (and interlinkages to other natural system dependencies, such as biodiversity; Koumbarakis et al., 2020). None of these methodologies, however, focus specifically on the cross-border effects of climate-related financial impacts, which thus represents an avenue for future research given the cross-border nature of portfolios.

Climate-related financial risks are expected to eventually cascade into public finance and sovereign risk. Benson and Clay (2004) undertake a wide-ranging review of the economic and financial effects of natural disasters, finding that governments (and the wider financial system) of countries hit by disaster can offset some reduction in income through aid flows and remittances. However, aid flows do not always constitute additional payments; instead being, for example, substitutions from other development investment. Similarly, Osberghaus (2019) conducts a review which analyses the effect of natural disasters on international financial flows, focusing largely on remittances and foreign aid in-flows; both increasing as the result of natural disasters. While these flows do bolster the affected country's financial system and short-term stability, the long-term impact of disaster on financial flows is less clear. Kleindorfer (2010) addresses the potential for risk to be embedded in finance-linked information flows, explaining how scientific uncertainties (or 'epistemic risks') concerning climate change shape investors' choices around vulnerable assets. Botzen et al. (2019) review the economic costs of natural disasters, including those exacerbated or induced by climate change, and point to a handful of studies using input–output models that analyse the impact of productivity shocks. The simple non-dynamic structure of most of these models suggests that they oversimplify the processes by which economic costs are transmitted, and adjustment of assumptions with varying levels of complexity leads to the emergence of opposing results even for the same disaster. Mahalingam et al. (2018) stress the difficulty in estimating 'flow losses' (i.e. losses occurring as a result of lost economic output), as such assessments rely on sophisticated statistical methods. Though historical catastrophes have resulted primarily in 'stock losses' (i.e. losses from destroyed capital stock) rather than flow losses, the latter are expected to play a much larger role in the future because disruptions to productivity are amplified through trade and economic interconnectedness, which have been increasing.

A key area of the literature relates to the likely importance of public and private insurance facilities in climate risk exposure. Huang et al. (2018) find that firms in world regions with higher physical risks use policies to hedge against operating cash flow volatility and hold higher cash reserves than peers in less risky areas. Wolfrom and Yokoi-Arai (2015) stress that insurance policies contribute to reducing the economic fallout of adverse climatic events, calling for governments to increase disaster insurance coverage in high risk regions. But with increasing magnitude and frequency of events, local insurance markets may reach capacity. In-depth analysis of the links between physical climate risks and financial risks (International Association of Insurance Supervisors, 2018) laudes the expertise of insurers in dealing with natural catastrophes but worries of an unexpected increase in events and corresponding losses. At present (and even without these potential additional future pressures on the industry), 70% of weather-related losses are uninsured, leaving a 'protection gap'. Acclimatise and UNEP FI (2018) report that it is almost impossible to estimate this gap with certainty due to data scarcity. Regardless of current levels, future climate change may well result in less, rather than more, coverage; a Bank of England (2015) report shows that severe weather events have previously led to withdrawals from property insurance.

Any increased reliance on insurance schemes increases the industry's desire for collateral, exposing dilemmas in reconciling financial stability with climate risks, which are addressed by critical geographers and political economy researchers. Taylor (2020) investigates insurance-linked securitization (ILS) in Florida; real estate at risk from hurricanes is securitized and sold to individual and institutional investors. Given the location of ILS buyers in regions and countries outside of Florida (in the United States and Europe, mostly), this can create cross-border impact transmission channels. Leichenko et al. (2010) conceptualize financial impacts from climate change, and from the 2007–2008 financial crisis, in which they analyse the interactions between global environmental and economic risks and their tendency to spread vulnerability. They conclude that increasingly globalized links, paired with a deregulation of industry practices, have increased vulnerability to physical climate risk, especially in real estate markets.

Increasingly, governments have reacted to insurance market overburdening by introducing intergovernmental insurance schemes. Joyette et al. (2015) evaluate the introduction of a regional catastrophe insurance scheme for the Caribbean. Thirawat et al. (2018) consider the Southeast Asian region, recommending a move away from national catastrophe insurance to the establishment of a global

risk sharing facility for climate change impacts. However, given the obvious difficulties in negotiating such a facility, existing instruments (i.e. the Association of Southeast Asian Nations plus three (ASEAN + 3) Catastrophe Risk Insurance Facility (ACRIF) and the Association's catastrophe bonds (ASEAN + 3 CAT bonds)) are considered alternatives to achieve similar goals. Negotiations around the development of a global climate change risk sharing mechanism have traditionally taken place at the UNFCCC COP. Radulescu et al. (2016) explore the Warsaw International Mechanism for coping with loss and damage in the developing world, which was finalized during COP19 in 2013. It encompasses knowledge exchange and data sharing about the socioeconomic impacts of natural disasters and response strategies; processes such as physical risk management and warning systems; and support in the form of capacity building via new and existing institutions, technology and finance.

3.3.2. Finance risk: Data insights

Foreign *direct investment* (FDI) is a category of cross-border investment associated with a resident in one economy having control or a significant degree of influence on the management of enterprise in another economy. In 2018, total EU27 outward FDI was 10 trillion USD, and is highly concentrated overall in 'Non-EU European Countries' (39%) and 'North and Central America' regions (31%; see SI for further details). The country with the highest outward EU FDI is the United States (US), with 24% of total stock. The United Kingdom ranks second with 21% and other countries of importance are Switzerland (11%), Brazil (4%), Canada (4%), Russia (3%), Bermuda (3%), Singapore (2%), and China (2%). Approximately 87% of FDI is held as equity, with 13% held as debt (Fig. 6). Whilst, in theory, debt positions pose less risk (because in the event of insolvency these are repaid first and can be backed by collateral), adequately assessing relative risk requires detailed data on the individual companies and financial instruments, outside of the scope of this paper.

Outward FDI positions of EU27 countries increased from 5.8 to 10 trillion USD between 2009 and 2018, which can be primarily attributed to 'North and Central America' and 'Non-EU European Countries' regions (see SI3.3). In 2009, the EU27 FDI in the US amounted to 1.2 trillion USD, but was double this in 2018; the resulting share of the 'North and Central America' region within total EU outward FDI positions increased from 26% to 31%. FDI in the 'Non-EU European Countries' region also rose sharply in absolute terms, although the relative importance of this region and other regions of the world have remained similar over time.

Within the US (which held 2.5 trillion EUR in 2017), the financial services sector held the largest share of EU28 (see Section 2; EU27 data unavailable) outward FDI, followed by manufacturing and telecommunications. The second largest recipient was Switzerland (1 trillion EUR), particularly within financial services and manufacturing. FDI in Brazil totaled 340 billion EUR and was mainly held in service sectors (financial, rental and leasing services, particularly) and telecommunications, but also in mining and quarrying, and manufacturing industries. Total outward FDI in Canada amounted to 300 billion EUR, with most in financial services activities and mining and quarrying. The largest share of total EU28 FDI in Russia (270 billion EUR) was allocated to mining and quarrying activities, with Russia's energy sector (oil and gas) also having become a major focus of cross-border investment. For China's 180 billion EUR of EU28 FDI, more than 10% was allocated to financial services, but positions in manufacturing enterprises in China are also very pronounced (over half total EU28 FDI in China in 2017). High shares of total outward FDI allocated in climate-relevant economic

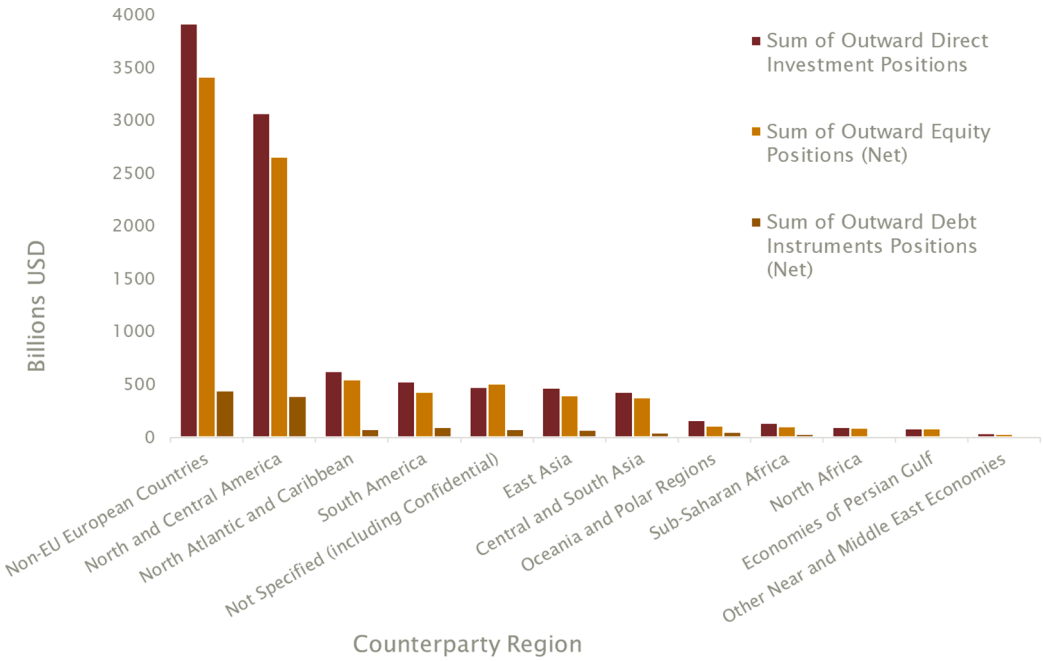

Fig. 6. Shares of equity and debt instruments in total outward FDI from the EU27 (excluding Bulgaria and Romania for which data is unavailable). Source: CDIS.

activities could in principle lead to high exposure of investors who finance such activities (e.g. via stocks). Furthermore, physical climate shocks to manufacturing firms and other capital-intensive activities can lead to substantial losses in the portfolios of actors exposed to them.

Foreign *portfolio investment* refers to the purchase of securities and other financial assets by investors from another country. Total extra-EU portfolio investment of EU27 countries amounts to approximately 9.8 trillion USD. This is highly concentrated (44% of the total) in the 'North and Central America' region (see SI3.3), with around 3.9 trillion USD in the US. The 'Non-EU European' region has the next largest share, followed by distributions to East Asia and offshore financial centres in the 'North Atlantic and Caribbean' region. 18% of total cross-border portfolio instruments of the EU27 are held in the UK, 5% in Japan, 3% in the Cayman Islands, and 3% in Switzerland. In contrast to within the FDI positions of the EU27, debt securities form a relatively important component of the extra-EU portfolio investments, although this varies by destination (see Fig. 7). The majority (4.9 trillion of 5.5 trillion USD) of non-EU portfolio investments in debt securities have a long-term (over one year) maturity (see SI3.3). In theory, in the context of climate risk exposure, longer term debt-linked investments may be thought of as higher-risk given that divestment opportunities will be lower in the midst of a crisis.

The EU27′s portfolio investments in extra-EU countries increased by more than 60% between 2009 and 2018, primarily attributable to investments held in the 'North and Central America' and 'East Asia' regions (see SI3.3). During this period, portfolio investments in US financial securities increased from 2.1 trillion USD to 3.9 trillion USD, and in Japan from 280 billion USD to 530 billion USD. Via these shifts, the share of US securities in total portfolio investments of the EU rose from 35 to 40%, and the relative importance of the 'Non-EU European Countries' region in cross-border portfolio investments of the EU decreased (from 34% to 26%). Relative shares held in other regions have remained relatively stable. The EU financial sector is particularly exposed to climate risks via portfolio investments because the main investors in cross-border portfolio investments are EU financial actors. In contrast, firms have substantial outward FDI positions via holdings in their foreign subsidiaries. This interconnectedness of EU financial actors can lead to amplified losses from negative climate-risk-related shocks and a substantial systemic risk that may impair the EU financial system's stability (Battiston et al., 2017).

4. Intersecting risk domains: A conceptual example

Previous sections provide evidence of the forms of risk that Europe may be exposed to across trade, human security and finance, and illustrate European connectivity to the rest of the world that will affect the specific nature of climate-linked impact (and response). It is apparent that interactions between the EU and other nations are likely to be complex and multi-faceted and that the manifestation of cross-border climate impacts will be subject to considerable uncertainties. It is also clear that the domains themselves do not sit in siloes; interactions between them will impact on risk transmission and the EU's responses. To illustrate the potential for impact transmission to intersecting domains, and inspired by our review, we turn to a theoretical example of a future cross-border impact. This example is informed by a historical event – a drought in Argentina, which is a key exporter of soybean to the EU. We use the conceptual framework of Carter et al. (2021) to explore the transmission of cross-border impacts and responses. Here, an initial impact in one

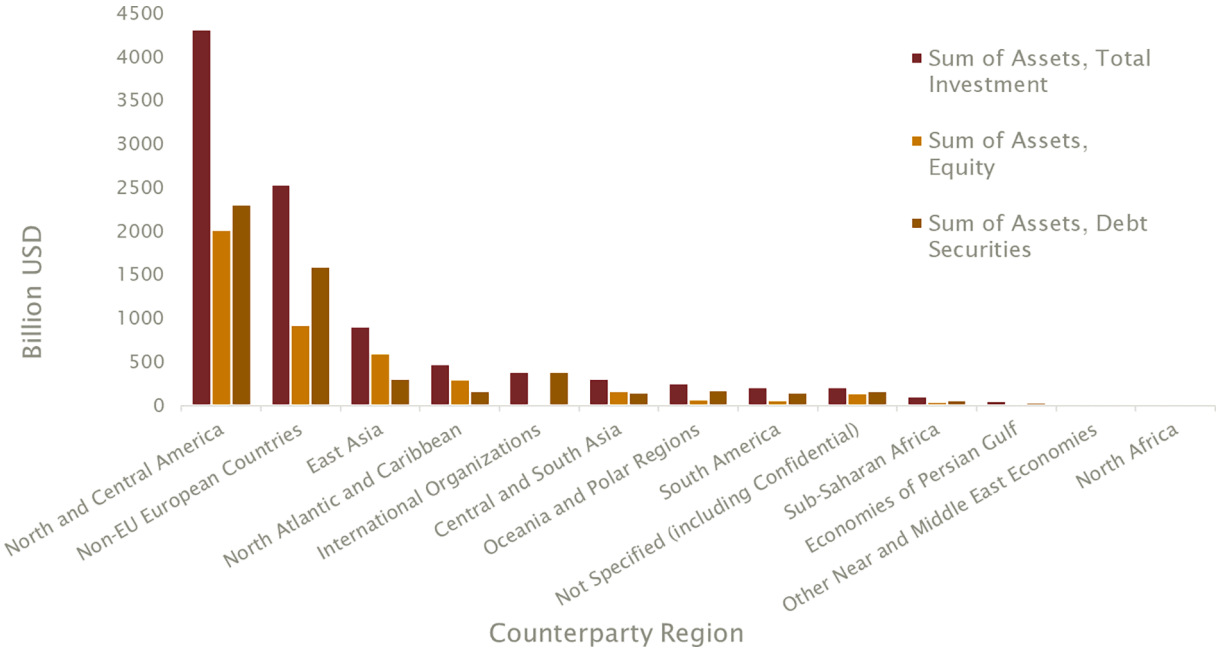

Fig. 7. Shares of equity and debt instruments in total outward portfolio investment positions from the EU27 (excluding Croatia for which data is unavailable). Source: CPIS.

region due to a climate trigger is propagated via an impact transmission system comprising impacts on interconnected system components, resulting in a recipient risk in another region. Adaptive responses for ameliorating that risk are via a response transmission system.

We provide background to the historic case (and cascading impacts and responses) in SI4.1, but in the main text present a potential

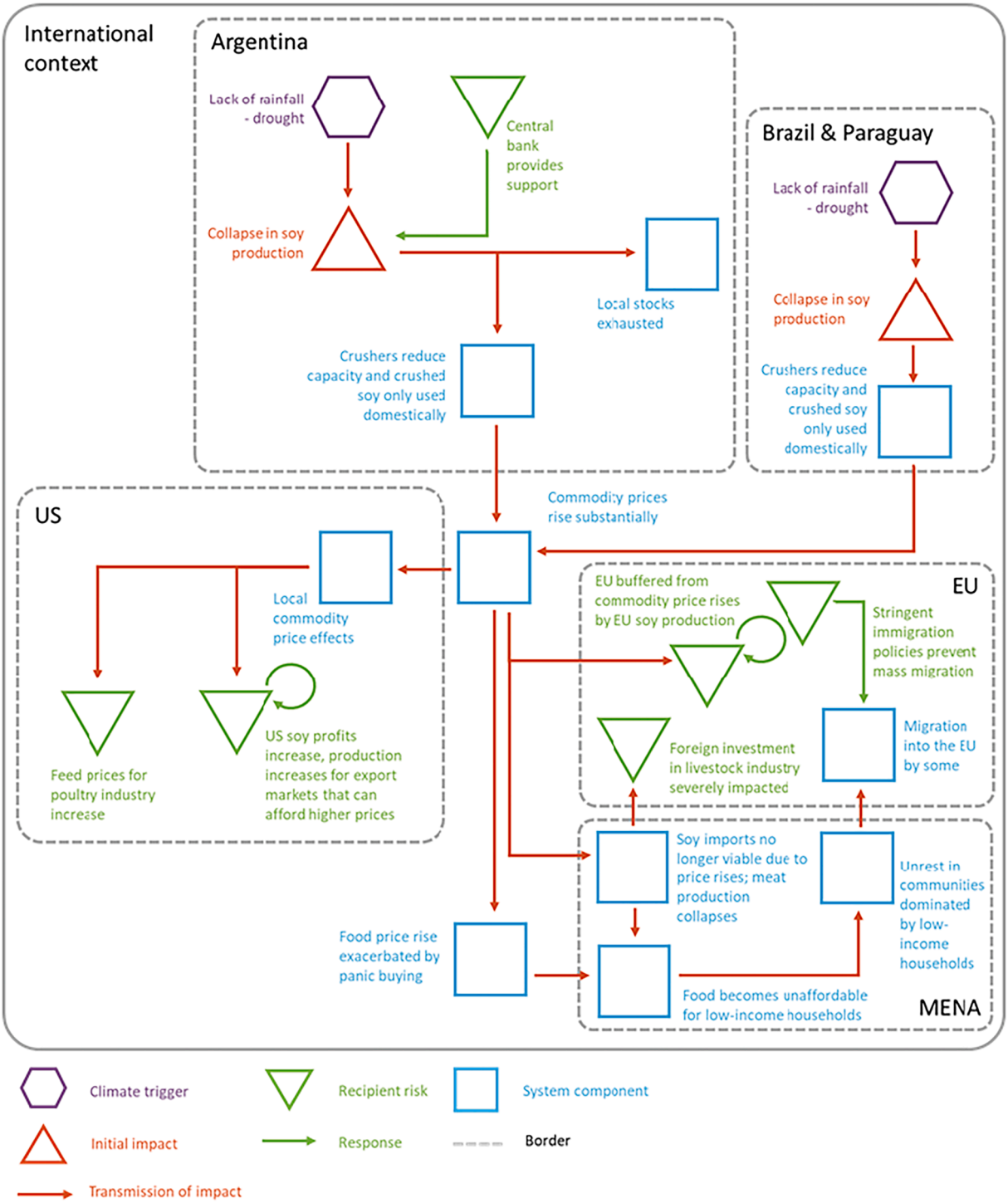

Fig. 8. Simplified representation of impact and response transmission pathways associated with a potential future drought in Argentina (and other parts of South America) under a scenario inspired by SSP3. Dynamics of the US and Brazil & Paraguay are presented for comparison with the historic case (see SI). Diagram based on the conceptual framework of Carter et al. 2021.

future scenario inspired by Shared Socioeconomic Pathway Scenario 3 (SSP3; an additional example with SSP5 is also provided in SI4.2). The scenario takes place in 2050, to allow sufficient restructuring of the baseline socio-economic context along SSP lines (but the date is non-critical). SSP3 'Regional Rivalry - A Rocky Road' (Riahi et al., 2017) presents a future world of resurgent nationalism, with increased regional conflicts and competitiveness and a focus on domestic security (i.e. market barriers exist that Baldos and Hertel (2015) highlight as having potentially significant implications for future food security; see Section 3.1.1). Countries focus on achieving security goals within their own borders at the expense of international development. Investments in education and technology decline, economic development slows and consumption is materially-intensive, with inequalities in society persisting or worsening. Populations are growing rapidly in developing countries but slowly in industrialized nations. Low international priority for addressing environmental concerns leads to high levels of environmental degradation in some regions.

4.1. Argentinian soy and extreme drought under SSP3

We start with the assumption that climatic events in Argentina will be wider-ranging under any probable future climate scenario than those experienced historically (cf. Lange et al., 2020). This has two primary implications for Argentina: a) it is less able to depend on reserve stocks of soy in comparison to the historic case (see SI4.1), and b) production booms in the wider region (e.g. as experienced in Brazil in the historic case) do not occur; indeed, these regions also see productivity decreases. We also assume that the agri-commodity exporters of current importance to global consumption (e.g. Argentina, Brazil, US; see SI4.1) remain so. Our impact recipient of primary interest is the EU, but we also consider consequences for other regions.

In our scenario (see Fig. 8), production technologies have been slow to progress and environments associated with soy are degraded; crop-resilience is low overall. Global soy consumption is very high; global meat consumption (which depends on soy as animal feed) is higher than ever, although substantially lower per capita in low-income countries. A lack of technological innovation in Argentina aligns with an absence of financial investment by Europe, with better opportunities seen to exist in emerging economies. The EU retains some investment in the financial markets of Latin America, but insurance schemes in the region do not cover agricultural systems as lack of crop resilience is deemed too high a risk (c.f. Section 3.3.1).

Under SSP3, the priority for Argentina is to ensure that domestic supplies of soy continue to be met despite lower productivity. This is at the expense of exports, which cease following the climate shock, and soy crushing substantially decreases due to limited supply. As in the historic case, trading companies who own these facilities see reduced profits. However, the ownership structure of traders has shifted to be dominated by state-backed Argentinian companies (as opposed to being subsidiaries of global multinationals as might be expected in a more integrated global market). Foreign direct investment from the EU in these companies is therefore relatively restricted, meaning that EU shareholders are minimally affected.

Because the drought is widespread, export markets in Paraguay and Brazil are also affected, cutting a significant proportion of the global supply. The US remains a major soy producer and exporter, and – given rising concerns in the EU about food security - the EU and China are also now major producers, but primarily for domestic consumption. US, Chinese and EU prices for soy therefore remain relatively stable given their comparative self-sufficiency, but the lack of material in global markets means that prices for other importing nations rocket. Price rises follow for other commodities as protectionism and panic-buying effects ripple across the broader food system. Inequalities which persist in the global system mean that lower-income countries are no longer able to rely on overseas soy markets and soy-dependent livestock production systems that have been prioritised in previous years to increase access to high-protein food sources suddenly fail. Investment in these low-tech livestock facilities by EU-based investors is high given their attractive proposition as a source of growth in regions of increasing demand.

Meat production in these lower-income countries falls; affluent populations in these countries are still able to consume imported meat products, but the majority go without whilst also struggling with general food price rises. This consumption inequality leads to some insecurity and localised frustration with governments. Protests and civil unrest are seen in regions of the world where existing inequalities are high, including in the MENA region. This worsens resilience against future shocks and increases the political and social fragility of communities. The attractiveness of the EU (see Section 3.2.2), and perception that inequalities are lower, leads to attempts at outward migration from the MENA region by families who can afford to do so. However, nationalist immigration policies within Europe create additional hardship for those seeking to migrate.

The consequences of the initial climate impact are wide-ranging in this example, interacting across all domains, and with primary eventual risk to the EU linked to human security and some downstream financial concerns, rather than trade (and thus can be considered an example of a *multi-regional, escalating cascade*; adopting the terminology of Carter et al., 2021). Whilst acknowledging the simplistic nature of this 'thought experiment', it serves to illustrate that consequences for EU supply chains, financial interests, foreign policy and human security concerns may be felt a relatively long, and indirect, way along an impact transmission pathway, and that policy responses must be cognisant of the interactions between domains as well as connections within them.

5. General discussion

Common themes emerge across the distinct domains explored in this paper that can help to inform considerations of cross-border impact going forward. Firstly, the informational landscape underpinning risk assessment is currently insufficient; overall, there is limited consideration of cross-border impacts, including in the European context. Consequently, our literature review adopted a global focus, and there were pockets of more focused study (for example, some consideration of transboundary effects in the trade domain, and growing consideration of climate-linked financial implications for business). Whilst gaps remain (for example, a relative lack of coverage of non-agricultural concerns linked to trade and human security issues), this is a rapidly developing field. Cross-border

impacts are now recognised in the EU Adaptation Strategy (European Commission, 2021b), and additional bodies of research are emerging; for example, consideration of potential cross-border climate-linked impacts occurring via unsustainable sovereign debt (aka. sovereign risk; Volz et al. 2020; Dunz et al. 2021; Gallagher et al., 2020). There is uncertainty in the literature about whether international connectivity exacerbates risk. For example, trade is seen as a source of risk, but also a potential form of risk mitigation (Baldos and Hertel, 2015; Willner et al., 2018). The dynamics of how climate affects food security, conflict and migration is another point of contention warranting additional attention; whilst impacts on livelihoods and wellbeing do not necessarily lead to conflict, climate change will undoubtedly compound pressures on communities and contribute to a worsening of existing risks or the creation of new ones (Detges et al., 2020). Data are also patchy; within the finance domain, very limited information is available publicly on the nature of investments by sector (detailed consideration of risk exposure would require more specific data on individual companies and financial instruments), and the international supply chains of critical commodities are notoriously lacking in transparency (Gardner et al., 2019). As highlighted in our finance-linked review, however, the relative lack of focus on cross-border impacts within research does not mean that existing tools and resources cannot be adapted to explore these dynamics.

Another emergent theme is that risk is likely concentrated in certain sectors or geographies. For example, our trade analysis reveals high dependency on certain commodities, often with limited geographic distribution of sourcing. In the case of oilseeds, a handful of countries produce the bulk of supply destined for the EU. A similar phenomenon is observed in the finance domain, with certain countries receiving the bulk of EU investment. In the human security domain, it appears that specific regions, such as MENA, will likely be risk hotspots, due to their proximity, cultural and political ties and relative levels of fragility resulting from historical conflict and inequality (Desmidt, 2021; Knaepen, 2021). The observed geographic concentration of risk could form a double-edged sword for the EU. On the one hand, dependence on a confined geography for certain products (in contrast to recommendations to diversify supply to ensure resilience; Gephart et al., 2016; Marchand et al., 2016) could leave it vulnerable to localised climate impacts. On the other hand, if specific risk locations can be isolated then responses can potentially be more effectively targeted, whether via overseas investment, development assistance or by the actions of supply chain stakeholders. More specific risk locales are likely to emerge as one moves from a 'macro-level' view of risk exposure (as presented in this paper) to more granular analysis. For example, localised effects of climate-linked food-security may spillover into Europe but may primarily affect bordering countries; particular insurance companies might be exposed more to climate change than others given the presence of insurance-specialisms, and the potential for food-stuff substitution means that only certain sectors of the economy might be affected by supply or price issues.

A related point, emphasised by our analysis, is that the EU does not operate in a vacuum; its exposure to risk will be heavily influenced by the context and actions of others. The commodities imported into Europe will also be imported by other countries, international investors will be shareholders in companies and markets to which European actors are exposed, and other regions of the world have diasporic links and political interests in countries which are priorities for the EU. The EU is arguably in a relatively comfortable position internationally; it may, for example, be a net benefactor from climate change from a trade perspective, with agricultural yield impacts being relatively benign in comparison to other world regions and trade balances potentially shifting so that the EU becomes a net exporter to other world regions (Hristov et al., 2020; Elbehri et al., 2015). Price rises are also a likely consequence of trade disruption (Lewis and Witham, 2012; Gitz and Meybeck, 2016), and lower-income economies are likely to be more sensitive to disruptions in food price (Verschuur et al., 2021; Falkendal et al., 2021). However, exact consequences for the EU will vary depending on the policies and responses of others; future international 'protectionism' may exacerbate problems for the EU (e.g. Challinor et al. 2018), whereas international risk-sharing (cf. Section 3.3.1) may distribute the burden. Additionally, scale matters: low-income families in the EU may be very sensitive to relatively small food price rises and countries within the EU with higher import-dependency (e.g. Cyprus; see Section 3.1.2) may experience larger effects.

Across all three domains, evidence exists of temporal changes in Europe's linkages to the rest of the world, including increased imports of particular commodities, rising migration from particular regions, or trends in investment destinations. These shifts have typically been 'gradual', and therefore we may expect future dependencies and connections to remain somewhat similar in the short term. Given that severe weather events and other human-induced climate impacts are already increasing in severity (IPCC, 2021; Mann et al., 2017), risk assessments on current connections are critical. For example, although evidence of climate-linked migration is limited, data indicate it is likely that the EU will remain an attractive destination for migrants from certain countries, particularly if the EU economy is less badly affected by climate change overall. Furthermore, researchers should pay close attention to how historical and short-term shocks have impacted the European economy; the historical Argentinian soy shock (see SI4.1) had marginal effects on Europe, but the impacts of the current Covid-driven semiconductor shortage (Attinasi et al., 2021; where parallel lessons could be learnt of relevance to climate-change responses; van den Hurk et al., 2020; Ringsmuth et al., *this issue*) are greater. The severity of initial (climate) shocks will play their part, but equally important are the forms of connections, the roles of actors in those connections and the responses of actors whether in private or public sectors.

Detailed analysis of how historical impacts have reached Europe, along with exploration and modelling of future scenarios, will be beneficial in understanding how European connections may evolve and adapt in the future. As illustrated in this paper, cross-border connectivity and cross-domain interactions can be highly complex, presenting a challenge for decision takers when attempting to mitigate or respond to climate impacts of this form. The conceptual framework provided by Carter et al. (2021) provides a structure for exploring, and analysing, these risks and - as demonstrated (Section 4) - is amenable to the exploration of historical examples and to projections of analogous examples in future scenario space. Given the nascent nature of this research, analysis will benefit hugely from the collective intelligence (Mulgan, 2018) of a broad and diverse group of stakeholders (Reed et al., 2018), who can provide knowledge input to, and feedback on, science-based results. Such knowledge co-production requires innovative methods of stakeholder engagement such as social/policy simulations (Duke and Geurts, 2004) or serious games (Mochizuki et al., 2021; Solinska-Nowak et al., 2018), which can play a vital role in dissemination of research results. Application of the conceptual framework of cross-

border impacts within a policy simulation environment has the potential to greatly assist policy development and risk management practices, e.g. via participant exposure to the potential ramifications of cascading impacts occurring in one region or domain, and then via exploration of policy and practical responses that might arise in light of these impacts. One such attempt to develop an informative simulation tool for decision makers - the "Cascading Climate Impacts" policy simulation - is described in SI5. Similar forward looking analysis is important for understanding how risks may emerge and shift, what pathways and nodes might act as important policy leverage points to reduce risk, and how these will play out alongside global megatrends (Retief et al., 2016; Artuso and Guijt, 2020) and a transition to a low-carbon economy (Rockström et al., 2017).

6. Conclusion

This paper provides a review and analysis (using both qualitative and quantitative sources) of trade-, human security- and finance-related dynamics and EU connections with the rest of the world that may underpin cross-border transmission pathways for climate impact. Whilst non-exhaustive, we provide insight into forms and locales of critical risk exposure: for trade, imports of important commodities such as fossil fuels, minerals and agricultural products might be impacted directly or indirectly by climate change events, with sourcing of some products geographically restricted; for human security, the dynamics of climate are complex and likely to emerge against a backdrop of pre-existing social and economic fragilities; and for finance, the EU's investment portfolio is unequally distributed globally, with existing financial protections likely inadequate to deal with future risk.

Whilst these domains are important sources of risk to Europe in their own right, they do not exist in siloes; impacts initially affecting one domain may have implications in another. As illustrated by our conceptual example, impact and response pathways may be complex, further heightening the challenge of developing effective policy responses within an uncertain climatic and socioeconomic future. Therefore, within this nascent research area of cross-border climate impacts, research, policy and industry must react by developing a deeper understanding of transmission pathways linked to impact sources that will be of critical importance for understanding and responding to future crises.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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