Key *et al. Journal of Shipping and Trade* (2024) 9:11
https://doi.org/10.1186/s41072-024-00170-3

Journal of Shipping and Trade

ORIGINAL ARTICLE Open Access

Potential climate-induced impacts on trade: the case of agricultural commodities and maritime chokepoints

Ramon Key[1,2,3,4*], Ramiro Parrado[1,2,3], Elisa Delpiazzo[1,2,3], Richard King[5] and Francesco Bosello[1,2,3,6]

*Correspondence:
ramon.key@cmcc.it

[1] Centro Euro-mediterraneo sui Cambiamenti Climatici (CMCC), Edificio Porta dell'Innovazione - Piano 2, Via Della Libertà, 12, 30175 Venezia Marghera, Italy
[2] RFF-CMCC European Institute On Economics and the Environment, Edificio Porta Dell'Innovazione - Piano 2, Via Della Libertà, 12, 30175 Venezia Marghera, Italy
[3] Dipartimento di Scienze Ambientali, Informatica e Statistica, Università Ca' Foscari Venezia, Via Torino, 155, 30172 Venezia Mestre, Italy
[4] Instituto de Estudios Superiores de Administracion (IESA), Caracas, Venezuela
[5] Chatham House, The Royal Institute of International Affairs, London, UK
[6] Dipartimento di Economia, Università Ca' Foscari Venezia, Fondamenta S. Giobbe, VE, 873, 30121 Venezia, Italy

Abstract

This study assesses the potential macro-economic effects of climate change affecting operations in three maritime chokepoints, i.e., the Panama Canal, the Suez Canal, and the Turkish Straits. The analysis focuses on agricultural commodities. It couples a "logistics" model of maritime trade flows with a Computable General Equilibrium model considering three modelling alternatives: (1) increase of "iceberg trade costs", (2) shadow import tariffs, and (3) shadow export tariffs. Methodologically, we found a comforting qualitative agreement across methodologies in predicting the direction of changes in the main economic variables under scrutiny. However, negative GDP performances are more frequent and larger using the first method that also tends to predict lower import contractions than the other two methods. The impact assessment, examining storylines of climate-change-induced events delaying chokepoints operations, highlights that climate change impacts on chokepoints' operations can convey detectable effects on production and prices of agricultural commodities associated with negative GDP impacts worldwide. In addition, although trade re-composition generates winners and losers, total losses tend to prevail. The combined GDP losses of the three chokepoints can reach $34 billion (2014 prices) in 2030. It shows that weather events in remote locations, such as the Panama Canal, can have cascading effects on the EU, with potential losses of USD 2 billion $ in GDP. North Africa, Middle East and Sub-Saharan Africa are particularly vulnerable. They suffer from a drop in imports of agricultural commodities and GDP losses in all the three cases. This impact assessment emphasizes another mechanism at play that could increase the asymmetry and the adverse distributional impacts of climate change on agriculture.

Keywords: Trade, Chokepoints, Agricultural trade, Climate-change, CGE modeling

Introduction and background

The term "trade chokepoint" refers to narrow pathways connecting bodies of water or territories, highly transited and subject to congestion in such a way that they are critical to the world supply chain (US Energy Information Administration, EIA 2017; Wellesley et al. 2017). Maritime chokepoints are particularly important, because 80 per cent of

global trade by volume and over 70 per cent of global trade by value are carried by seaways and are handled by ports worldwide (Brooks and Faust 2018; UNCTAD 2019).

Early studies on maritime chokepoints concentrated on energy security (Rodrigue 2004), mainly in association with geopolitical risks, e.g. piracy (Shepard and Pratson 2020). However, the bulk of this literature focused on the direct impact on trade patterns and risk for trade (Emmerson and Stevens 2012; Meza et al. 2022) with only few contributions assessing potential macroeconomic implications (Komis and Hutzinger 2011), and none using a systemic approach as that offered by Computable General Equilibrium (CGE) modeling.

In recent years, climate change has emerged as an increasing threat to the food value chain, also through its potential impacts on trade routes (Werrel and Femia 2017; Walton 2019; GTR 2023), although climate change effects on maritime transportation in chokepoints have been registered at least since 1998 (Washington Post 1998). Pratson (2023) suggests that 55% of internationally traded maize, wheat, rice and soybean transit through at least one chokepoint. Considering H2 commodity disaggregation, top-10 commodities in value terms consist of intermediate and finished goods (e.g. electrical machinery, mineral fuels, mechanical machinery), while by weight top categories include basic goods, such as cereals. Moreover, estimates based on 2019 data show that the Suez Canal and the Turkish Straits are key chokepoints with 15.8% and 22.1% of cereal passing through them with respect to total trade between non neighboring countries, respectively.

However the economic impact assessment of trade restrictions for agricultural products in chokepoint is narrow, in our knowledge, limited to Bailey and Wellesley (2017), and Wellesly et al. (2017), where the emphasis is more on the magnitude of the risk associated with the interruption in chokepoints than on the cascading effects on the global economy. According to Zimmerman et al. (2018) trade could play an important role in climate change adaptation for ensuring food security. Open markets in international trade could ease the exchange between food surplus regions (high-latitude countries) and food deficit regions (low-latitude countries). In such a context chokepoints analysis for agricultural commodities will become more critical.

Since trade node disruptions can be interpreted as a specific case of non-tariff trade barriers, there is an extensive CGE modeling literature quantifying the higher order consequences (e.g. on Gross Domestic Product (GDP), production, competitiveness) of increasing (or decreasing) frictions in trade.

To model changes in trade openness, a typical approach is to translate quantity restrictions into shadow tariff-equivalent shocks on exports or imports, to then quantify the reaction of the economic system, through the CGE analysis (Elbehri and Pearson 2000; Elbehri 2005). An alternative, more commonly used for the analysis of non-tariff, non-quota barriers (e.g.: labels, certifications, technical and quality standards, customs procedures and inspections, government procurement measures (United Nations Conference on Trade and Development, (UNCTAD) 2015), or efficiency improvements in the transportation sectors, is to impose appropriate changes in transportation productivity or in "iceberg" trade costs (Andriamananjara et al. 2003; Rojas-Romagosa et al. 2015; Wangsness et al. 2017; Bekkers and Rojas-Romagosa 2018; Bekkers et al. 2018). This concept was developed by Samuelson (1952) and revived by Krugman (1991) to

explain the geographic concentration of industrial activity. Operationally, it is a parameter that accounts for transportation or "supply chain" costs. It captures the fact that to deliver a given "value" of a good in a destination country, a higher value should be shipped from the source country as part of it will be lost during the process. To calculate this parameter, gravity models are seldom coupled with the CGE analysis as in Rojas-Romagosa et al. (2015) and Bekkers et al. (2018). Here they compute the time savings on alternative Northern Sea Routes and interpret them as reductions in "iceberg trade costs" to finally estimate the associated cascading macroeconomic effect with a CGE model where the technical coefficient governing the productivity of transportation services has been modified.

Each different method to implement trade restrictions, or expansions has strengths and weaknesses. However, many authors have criticized the application of iceberg trade costs especially when trade changes to analyze are "large". Along this train of thought, Balistreri and Hillberry (2006) show that in gravity trade models the parameter could turn out to indicate that implausibly high values of production would "melt" in transit. A direct consequence is a weakness in formulating and evaluating policy actions (McCann 2005). Fugazza and Maur (2008) also discourage the use of productivity parameters to simulate the effects of non-trade barriers, deeming this acceptable only for moderate shocks. Rather, they advise the use of shadow taxes on imports and exports, as long as the variation in government consumption affected by the artificial variation in collected taxes is controlled. Finally, Walmsley & Strutt (2021) show that shocks to the efficiency parameter tend to overestimate impacts on GDP proposing an alternative method that considers changes in consumer willingness to pay when facing improving product quality because of bilateral trade agreements.

This paper contribution to the literature is three-fold. Firstly, we discuss and apply three alternative modelling approaches (i.e. endogenous "iceberg trade costs" or productivity in bilateral trade; endogenous import-shadow tax; endogenous export-shadow tax) to trade restrictions and non-tariff barriers in the ICES model to understand their macroeconomic consequences in a comparative static exercise. Secondly, we offer a macroeconomic perspective to chokepoint analysis in relation to climate change induced events. We consider the Panama Canal, the Suez Canal, and the Turkish Straits and focus on potential trade impacts of four agricultural commodities, i.e., rice, wheat, other grains, and oil seeds. Thirdly, as already stressed, this work closes a gap in literature to include not only direct impacts of closing maritime chokepoints but the cascading effect of the whole economy globally.

We simulate the occurrence of three event- based storylines that could be triggered by climate change causing trade disruption. They are implemented in the form of bilateral trade restrictions affecting the traded share of agricultural commodities transiting through the selected chokepoints. In the case of the Panama Canal, the simulation replicates the possible consequences of prolonged droughts which reduces navigation capacity similarly to what was observed in 2016 when the transit of big carriers was reduced for six months. The shock consists of a 54% reduction in annual trade. In the case of the Suez Canal, the simulation assesses the effect of high wind speeds and dust storms that can impede navigation similarly to what witnessed in March 2021. In that month strong wind provoked the grounding of the 400-m Ever Given container ship in the Suez Canal,

causing a blockage to this vital waterway with huge economic losses. During the six days it took to refloat the Ever Given an estimated $9.6 billion of trade was held up each day (BBC 2021) (nearly 19,000 vessels transited the Canal in 2019 (Guardian 2021)). The shock consists of a 6-week interruption of trade equivalent to 12% of annual trade. In the case of the Turkish Straits, we consider a similar size shock, given the fact that weather conditions, coupled with already heavy traffic congestion, have led to an increase in the number of accidents with the increase in regulations limiting traffic in case of extreme weather events. Notably, in the last decades there were at least 6 episodes of blockade of the Turkish Straits due to poor visibility conditions and snowstorm in winter months (Bailey and Wellesley 2017). Restrictions on the canal have also been associated with ship-to-ship accidents and oil spills, resulting from congestion, and various other factors, including climatic factors (Note by the Ministry of Foreign Affairs of the Republic of Turkey, MFA (2017). The most significant accident registered was the collision of two oil tankers in 1994, with a suspension in transit of 1 week, MFA (2017). Tonoğlu et al. (2022), present evidence that external environmental factors account for 37% of all the accidents registered in the Turkish Straits.

The paper is organized as follows. "Importance of the chokepoints for the agricultural products" section describes the importance of the three chokepoints in the context of agricultural good trade with a focus on the European Union (EU). "Methods" section describes the methodological approach, including a description of the models used. "Scenarios" section presents the scenarios analyzed. "Results" section describes the "higher order" or macroeconomic impacts of shocks affecting the chokepoints. In reporting the final impacts, we highlight changes in global trade, GDP, production of agricultural products and the food industry, and the prices of these commodities at the consumer level. Finally, conclusions are presented in "Discussion and conclusions" section.

Importance of the chokepoints for the agricultural products

Our analysis focuses on three maritime choke points, namely the Panama Canal (PAN), the Suez Canal (SUE), and the Turkish Straits (TUK). All three chokepoints (see Table 1) cover 35% of global imports of the all selected agricultural commodities, totaling 83 bill.$. Together they cover 23% of wheat, 56% of wheat, 36% of other grains, and 23% of oil seeds.

The relative importance of each chokepoint differs according to the type of commodity. The transit of rice through the Suez Canal is relatively important, reaching the highest share, 18% of global trade, among the other choke points considered. In the Turkish Strait, wheat is a relatively important commodity, reaching 30% of global trade. In the Panama Canal, there are two key commodities, Oil Seeds (13.7%) and other grains (13%).

Methods

To assess the economic effects of restrictions in chokepoint operability we coupled the Intertemporal General Equilibrium System with MRIO specification (from now on ICES-MRIO) model with the Chatham House Maritime Analysis Tool (CH-MAT) as shown in Fig. 1.

Table 1 Percentage shares of world total import value of selected agricultural commodities transiting through the selected chokepoints in 2018. *Source*: Elaboration based on UN-Comtrade (2024) and information provided by ChatHam House

% Share of world Imports	PAN (%)	SUE (%)	TUK (%)	All three CHP (%)
Rice	3.5	18.1	1.4	23.0
Wheat	7.5	18.1	30.2	55.8
Other Grains	13.0	11.5	11.1	35.6
Oil Seeds	13.7	5.4	3.3	22.5
All 4 comm	10.7	11.6	12.3	34.6
Bill.$	**PAN**	**SUE**	**TUK**	**All three CHP**
Rice	0.9	4.7	0.4	6.0
Wheat	5.2	12.5	20.8	38.5
Other Grains	5.7	5.0	4.9	15.7
Oil Seeds	13.7	5.4	3.3	22.5
All 4 comm	25.5	27.7	29.4	82.6

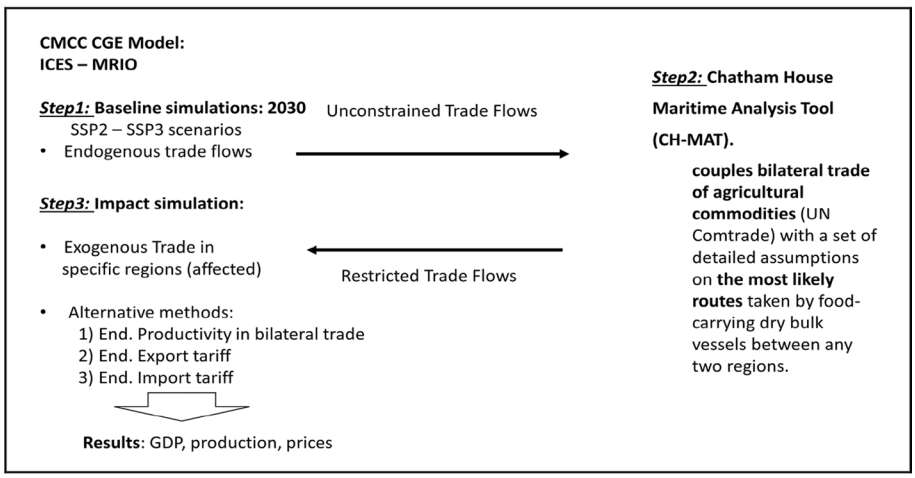

Fig. 1 Interlinkages between the ICES-MRIO model and the CH-MAT

ICES-MRIO is a multi-country multi-sector recursive-dynamic general equilibrium model based on models and databases from the Global Trade Analysis Project (GTAP), it is based on the GTAP-E model (Burniaux and Truong 2002) and GTAP database version 10a (Aguiar et al. 2019) calibrated in 2014. This database provides a series of interlinked Social Accounting Matrices (SAMs) with a comprehensive account of payments among productive sectors, final uses (private and public consumption, and investment), trade, and factor income distribution. For this analysis, we enriched the model database with the GTAP Multi Regional Input Output (GTAP-MRIO) database (Carrico et al. 2020). The MRIO framework harmonizes input–output (IO) tables for multiple regions and links trade flows directly from producers or firms in each region to importing firms and consumers in other regions. Accordingly, it extends the standard ICES Database by additionally distinguishing bilateral trade and tariff flows by agents (See Delpiazzo et al. 2021). This is an improvement over the original database, where imports could be traced

only by origins and destinations but not uses. In the current exercise the model features 32 regions, 26 sectors, and 8 endowments.

The Chatham House Maritime Analysis Tool (CH-MAT) is a (Excel-based) data-analysis tool for assessing the importance of maritime chokepoints to global food trade. The CH-MAT couples bilateral trade of agricultural commodities (from UN Comtrade) with a set of detailed assumptions on the most likely routes taken by food-carrying dry bulk vessels between any two regions. The routing assumptions are based primarily on distance and shipping time. Where two or more routing options are available a decision is made on whether to assign the totality of the region-to-region flow to one route or to split it between two. In those cases where the difference in shipping time between two routes is three days or greater, the shortest route is preferred; where two routing options are of comparable distance—with a difference in shipping time of less than three days—the region-to-region flow is split equally between both routes. The distance between two regions is calculated using the online searates.com tool.

The coupling between ICES- MRIO and CH-MAT is based on three steps. Firstly two simulation baselines, for SSP3 and SSP2, are projected until 2030. Under these SSPs we consider not only different socio-economic pathways but also different attitudes towards international trade. SSP3, indeed, represents a future with more fragmented international markets due to concerns on energy security and food provisioning. In the baselines trade flows are endogenously calculated by the model (step 1 in Fig. 1). Then, the shares of global food trade at risk for chokepoints disruptions calculated by CH-MAT are applied to the trade flows for agricultural commodities in the 2030 baselines (step 2 Fig. 1). Finally, the ICES-MRIO model is forced to restrict global food trade accordingly (step 3 Fig. 1) using three alternative methods: endogenizing (1) productivity in bilateral trade, (2) export tariffs, or (3) import tariffs.

The bilateral trade contraction affecting a particular commodity associated to a specific chokepoint, is calculated considering its share of bilateral trade transiting the chokepoint, and the share of annual trade affected in the chokepoint. The former share is provided by CH-MAT, the latter share derives from exogenous assumptions mimicking historical events, trends, and narratives described in Delpiazzo et al. (2021). Table 2 provides examples of these calculations for each chokepoint and selected trading partners and commodities. In this study, following CH-MAT data, on average, in each chokepoint, 350 bilateral trade flows of agricultural commodities are considered.

Scenarios

The macroeconomic assessment is produced through a comparison of contrasting scenarios, namely baselines and counterfactuals. Firstly, two baselines are run to quantify how the World economy will evolve up to 2030. Given the focus of the analysis, we consider two Shared Socio-Economic Pathways (SSPs) contrasting in their interpretation of international trade (O'Neill et al. 2014). On the one hand, the World will evolve according to the SSP2 scenario with a medium international trade openness; on the other hand, we assume an SSP3 evolution of the World economy with a lower degree of international trade cooperation due to food security and energy dependency fears. Specifications about targets and assumptions underlying the baselines are schematically reported in Table 3.

Table 2 Illustration of the input's shocks in the ICES- MRIO model. *Source*: based on Delpiazzo et al. (2021)

	Panama Canal	Suez Canal	Turkish Straits
Commodity	OilSeeds	Wheat	Other Grains
Main Trade Partner affected in volume (origin–destination)	USA—China	North EU—MENA	Ukraine—MENA
(1) % bilateral trade through choke point	75.1%	77.3%	100%
(2) % trade affected in choke point	54%	12%	12%
Nature of the event and duration	Extreme dry season (2016 the most recent) reduce for 6 months the transit of big carriers	Extreme winds reduce for 6 weeks transit of big carriers	Extreme weather (i.e. fog and snowstorms) worsens current congestion and delays
Specific bilateral trade Shock (to implement in ICES): = (1) *(2)	− 40.6%	− 9.3%	− 12.0%

The table is just an example, there are around 350 bilateral shocks for each chokepoint

Secondly, for each baseline we apply event- based storylines that represent plausible realistic future events, based on past episodes conditioned to socio-economic boundary conditions (van den Hurk et al. 2023). The approach is rooted in the concept of "climate storyline" used in the physical climate modeling research community to produce decision-relevant climate information (Shepherd et al. 2018). While in that context they were used for putting historic events in the context of a changing climate (Baldisseri Pacchetti et al. 2023), here we want to explore how these historic events connected to chokepoint disruptions could exacerbate their negative repercussions on the economic system supposing alternative economic development pathways.

The event based storylines are briefly summarized below.

Storyline #1: El Niño impacts the transit through the Panama Canal

A strong El Niño event brings long periods of dry weather to Central America, causing water levels to drop in the Gatun and Miraflores lakes leading to the introduction of depth restrictions on vessels transiting the Canal. Similarly, the 2016 El Niño-induced event affected nearly a fifth of vessels using the canal. On that occasion traffic was reduced by 5.6%.

We assume that the depth restrictions apply for six months during which 75% of annual agricultural throughput occurs and that the half of vessels affected are responsible for carrying 70% of all agricultural commodities. Therefore 53% (0.75×0.7) of annual agricultural produce transiting the canal is affected, that means an import reduction of $ 28,057 million globally. Notably, in 2024 annual trade through the Canal has been already cut by 33% on an annual basis.

Storyline #2: Storms affect the Suez Canal operability

Strong storm surges in the Red Sea's Gulf of Suez at the southern end of the canal would affect vessels in transit and lead to infrastructure damage at Port Taofik where

Table 3 SSPs baselines narrative along selected dimensions. *Source*: Based on DelpiazzoAuthor et al. (2021)

SSPs dimensions	SSP2	SSP3	ICES-MRIO used variables	Data source for targets
Total and labor population	Med	High	Total population and total labor force	Target growth rates are based on Kc and Lutz (2017)
Income growth	Med	Low	The total factor productivity is endogenously adjusted to achieve the targeted GDP	Target growth rate of GDP are based on Dellink et al. (2017)
Yield growth	Med	Low	Primary factor productivity for land	From Wang et al. (2020) we consider their estimates for regional specific land intensity
Energy efficiency	Med	Low	Intermediate input productivity parameters for energy commodities in all production sectors are diversified between developed and developing countries	For Med, we assume an annual increase by 0.56% and 0.63% for developed and developing countries, respectively (based on IEA 2011, 2012, and Bosello & Parrado 2014). For Low, these annual increases are lowered by 20%
Fossil fuels prices	Med	Med	Fossil fuels resources are endogenously adjusted to meet price targets	For Med, we consider trends in fossil fuels prices in the period 2014–2050 from EIA (2020) and then we extend it up to 2070. For High, we assume this trend decreases by 20%
International trade openness	Med	Low	Import tariff rate for all goods	For Low, the import tariff rates for all goods are increased with respect to the base-year, following assumptions by Fujimori et al. (2017). For Med, we assume no change to base-year tax rate
			Export tax for agricultural and energy goods	For Low, the export tax rates for energy goods (oil, coal, gas, oil products, and electricity) and agricultural goods are increased to represent the preference of internal consumption instead of exporting following assumptions by Fujimori et al. (2017). For Med, no change to base-year export tax rate for energy and agricultural goods is assumed

Med, Medium; Low, low; High, high

the Red Sea and Suez Canal meet. In 2021, when the Ever Given container ship was grounded in the Suez Canal. High wind speeds and a dust storm, aggravated by a rare heatwave in the region that dried the soil and made it more prone to becoming windswept, were blamed for blowing the vessel off course and reducing visibility for navigation. Although rare, strong winds have previously delayed shipping traffic or closed the Suez Canal on at least two occasions in December 2010 and February 2015. Direct attribution of discrete events to climate change remains challenging. However, it is possible that climate change could have contributed to the extreme large-scale weather pattern responsible for the 2021 sandstorm. Under the indicative future event, we assume such damages could render the canal unnavigable for six weeks while damage is repaired, and ships are re-floated. Under this scenario, 12% of

agricultural commodity throughput would be affected with an import fall quantified in $ 3100 million at the global level.

Storyline #3: Extreme weather events harms traffic through the Turkish Straits

Restrictions on the canal have been associated with ship-to-ship accidents and oil spills, resulting from congestion, and various other factors, including climatic factors (Note by the Ministry of Foreign Affairs of the Republic of Turkey, MFA (2017). Accordingly, since the beginning of its operations in 1936, the most significant accident in terms of magnitude was the collision of two oil tankers in 1994, which led to the closure of the canal for a week. Since then, safety measures have been introduced which have reduced the number of accidents from 50/year in the 1990s to 5/year at present. Tonoğlu et al. (2022) measure risk factors in Turkish Straits concluding that external environmental factors account 37.35%, human factors 40.76%, and internal environmental factors 21.89%.

Bailey and Wellesly (2017, Additional file 2: Appendix 2, page 101) list the weather events that caused channel closures between 2013 and 2017. These are not annual statistics, but examples of significant weather events that occurred in those years that led to closures of the Turkish Strait. These include low visibility caused by heavy snow, haze, and fob. A follow-up in the local press indicates that such disruptive weather phenomena continue to be reported. For example, Anadolu Agency (AA, 2018 and AA, 2024) reports for 2018 and 2024 that thick fog halted traffic in Istanbul's Bosphorus Strait. Harriyet Daily News, (HDN 2021) reports the closure of the Bosphorus Strait due to extreme winds. The Turkish State Meteorological Service (TSMS), TSMS (2024), states that the number of extreme events is increasing. In 2023, 1475 extreme events were recorded across Turkey, compared to 840 in 2018 and 461 in 2013. Although these extreme events are of all types and include heavy rain, floods, windstorms, hail, heavy snow, frost, fog, fire, etc. and refer to a national geographic area, they are a clear indication of a trend affecting Turkish straits. Under the indicative future event, we assume such extreme events could either trigger more accidents as the one experienced in 1994, or call for passage restrictions for six weeks. Under this scenario, a 12% shock similar to the Suez Canal.

Table 4 summarize the direct impact on imports and exports of agricultural commodities, respectively which have been replicated by the CGE model simulation.

Results

In reporting the results, for the sake of clarity we group the 32 regions analyzed into five macro-categories according to their trade status (in Additional file 1: Appendix A—Table 4), except for Europe which is considered as a single block. Consequently the groups are: (1) Europe (EU) (a mix of net exporters and net importers of agricultural commodities), (2) Absolute exporting countries (Abs.Exp), (3) Relative net exporting countries (Rel.Exp), (4) Absolute importing countries (Abs.Imp), and (5) Relative net importing countries (Rel.Imp). The group "Absolute exporters" consists of countries with a trade surplus (exports − imports > 0) in each of the agricultural commodities. The status of "Relative net exporter" refers to countries with a positive net export position considering the algebraic sum of all four agricultural commodities (total exports − total imports > 0), but with the possibility that one or more

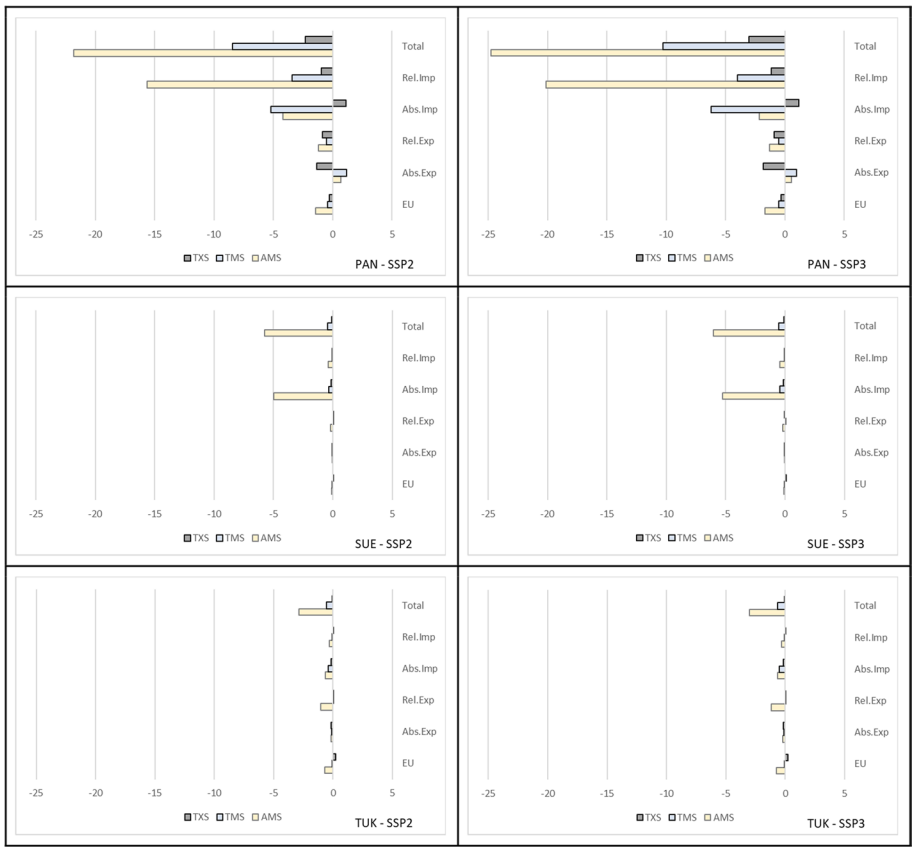

Fig. 2 GDP losses in $ billion for the alternative modeling approaches, regions, and SSPs

commodities show a negative trade balance. These conditions, mutatis mutandis, define absolute and net relative importers.

This section firstly reports aggregated effects on GDP, production, imports, exports, and prices of the selected agricultural commodities as stemming from the application of the three alternative approaches discussed. Secondly, it presents a more detailed regional analysis focusing on the three choke points considered in both SSPs.

Macroeconomic impacts: comparing methodologies to model trade restrictions

Impacts on GDP

Macroeconomic losses from chokepoints' restrictions are negligible in percentage change, ranging between − 0.02% of world GDP in the case of Panama Canal to − 0.004% in the case of Suez Canal, with a − 0.002% in the case of the Turkish Straits. Losses in global GDP vary significantly across methodologies, being higher, as expected from Walmsley and Strutt (2021), when they are implemented through the iceberg trade cost parameter (totalling $ 31 billions loss), see Fig. 2. Losses are recorded in most country groups, importers and exporters. However, the biggest losses are always on the importers' side. Importers' losses (absolute and relative) represent more than 80% of total losses.

Endogenizing import and export tariffs produce the second and third higher aggregated GDP effects respectively ($ 9.1 billions and $ 2.17 billions loss in 2030). They also highlight more potential winners within country groups from trade diversion after restrictions: these are the USA (absolute exporter) and Japan (absolute importer) in the Panama case, the EU and relative net exporters in the case of Suez, the EU and Russia (relative exporter) in the case of the Turkish Straits. Details on GDP impacts on specific countries are provided in Additional file 1: Appendix A—Table 5.

Notwithstanding within group heterogeneity, the different methodologies behave consistently with expectations in the aggregated country-group performances. Accordingly, a shadow tax on imports penalizes more absolute and relative importers, while a tax on exports, absolute and relative exporters. Iceberg trade costs tend to penalize more evenly, and more intensely both categories (see more on this below).

The three methods agree in pointing shocks to the Panama Canal as the major driver of GDP losses ($ 22 billion vs the $ 6 and 3 billion related to the Suez Canal and the Turkish Straits respectively using the iceberg cost method, $ 8 billion vs $ 0.5 and 0.6 billions of the Suez Canal and the Turkish Straits respectively, using the shadow import tariffs method; 2 billion compared to $0.1 billion and $0.07 billion for the Suez Canal and the Turkish Straits, respectively, using the shadow export tariff methods). These results are robust also when the Panama Canal is imposed a 12% contraction to its transits, as the rest of the other chokepoints, confirming, at least in the case of agricultural commodities, the node's higher global importance compared with the other two.[1]

Interestingly, in a "socio-economically fragmented" scenario like SSP3, the macroeconomic effects of chokepoint interruptions are more damaging than in the more open and collaborative "middle of the road" narrative of SSP2. Accordingly, the subsequent emergence of further trade flows contraction in SSP3 becomes more impactful. This outcome is more evident when the trade disruption concerns the Panama Canal, where the loss in total GDP increases roughly by 14% ($ 1–3 billion depending on the approach). The losses associated with the two other chokepoints increase around 7%.

Impacts on imports, exports and domestic production

Chokepoint restrictions implemented through shadow import tariffs have stronger effects on imported quantities than implementation through shadow export tariffs (Fig. 3). They also affect more acutely the imports of absolute and relative importers, than those of exporters. Moreover, they induce a stronger response in domestic productions to compensate for the declines in imported commodities than export tariffs, which are reducing the trade flows from exporters toward importers, but at the source. More specifically, shadow import tariffs increase domestic production both in the absolute and relative importers. On the contrary, shadow export tariffs, with the exception of the Panama case, increase domestic production only in absolute importers and by a lower amount. Symmetrically, exporters tend to respond with declines in domestic production either to an import or an export tariff. However, this decline is larger and common to both absolute and relative exporters in the case of an import tariff. Chokepoint transit

[1] Not shown, results available upon requests.

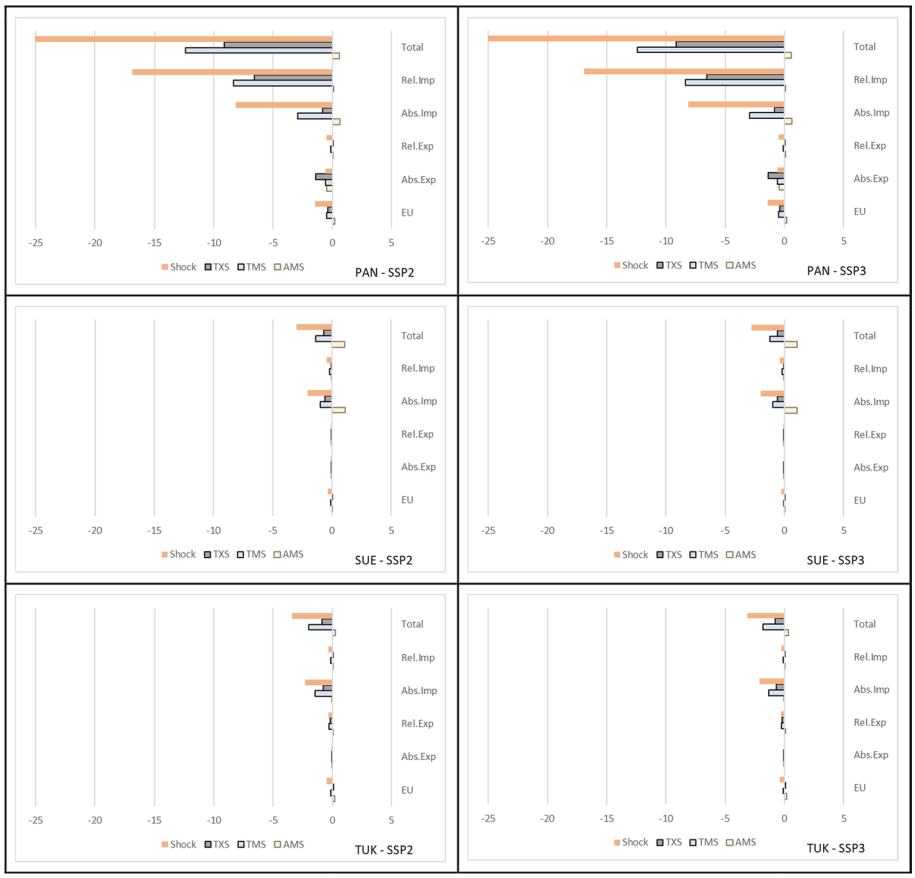

Fig. 3 Impact on imports of agricultural commodities in $ billion for the alternative modeling approaches, regions, and SSPs

restrictions have a net negative impact on export volumes too (see Fig. 4). Also in this case the larger effects of an import compared to an export tariff are confirmed. In line with expectations, exports from absolute exporters contract more than exports from absolute importers. All this hints that acting on the importer (demand) side triggers lower substitutability across suppliers (and probably across goods in household demand) than acting on the exporter (supply) side. The final outcome are the larger GDP losses in the former case.

Endogenization of iceberg trade costs operates in a quite different way. Increase in global domestic production is larger than with the tariffs (see Fig. 5), while global imports increase rather than decline. Higher iceberg trade costs mean that a higher value of the traded commodities is lost during the shipping process. Accordingly, to partly compensate for this, not only more should be produced domestically, but also imported. The net effect is a worsening in trade balances with a larger negative effect on GDP.

Figures 3 and 4 also report the value of the initial shocks on imports and exports deriving from the restrictions in the operability of chokepoints. They substantially differ from the final effects. This is a consequence of re-routing or importers-exporters substitution processes that are commented by chokepoint in the next section.

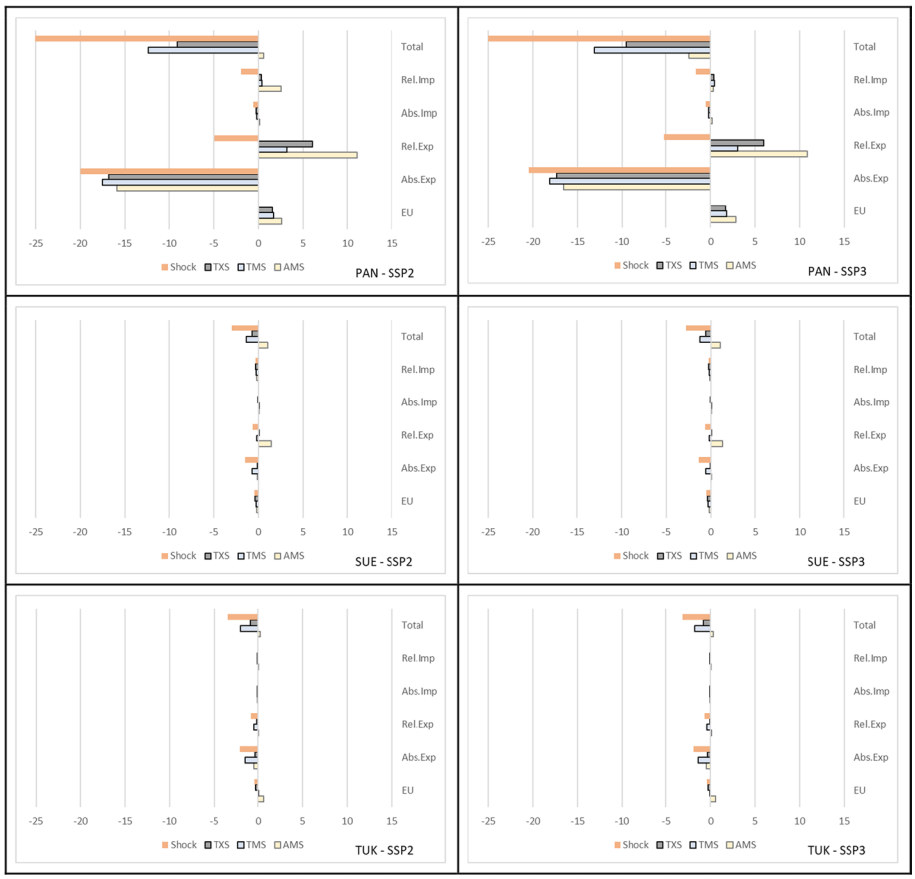

Fig. 4 Impact on exports of agricultural commodities in $ billion for the alternative modeling approaches, regions, and SSPs

Impacts on world prices

The iceberg trade cost and shadow export tariff methods, which are both negative supply shocks, show positive impacts on the prices of most agricultural products (see Fig. 6). Increases are larger in the case of the shadow export tariff, particularly for Other Grains (6.3% vs. 0.1%) and Oil Seeds (2.6% vs. 0.4%). In the case of the import tariff method, prices decrease in all agricultural commodities except rice. The larger decreases are observed in Oil Seeds and Other Grains (−1.2% and −0.8% respectively).

Macroeconomic impacts: Choke point analysis

Panama Canal

The transit restrictions in the Panama canal are those producing the largest negative GDP impacts. The EU, that, as a whole, is a relative importer, is an interesting case. Production and export of agricultural commodities increase in all EU regions, irrespectively of the way in which the restrictions are modeled. This highlights on the one hand the need to compensate domestically the curtailment from non EU suppliers, on the other the opportunity to substitute them. However, EU GDP declines particularly in Northern EU and Mediterranean EU. This occurs as the forced re-orientation towards agricultural

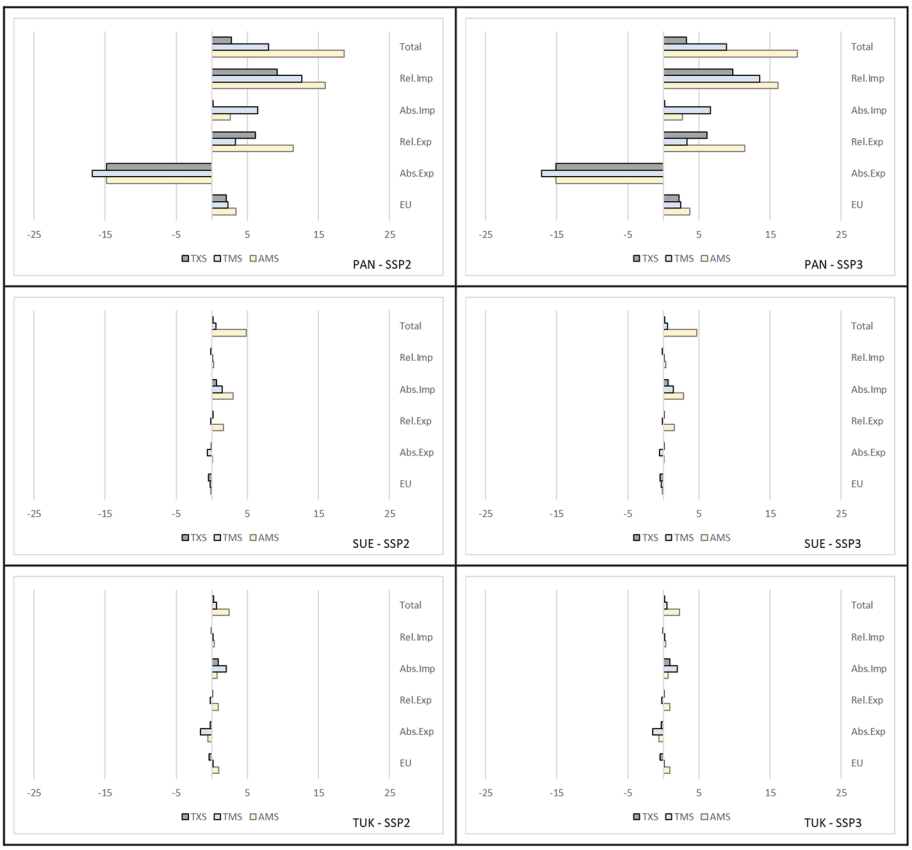

Fig. 5 Impact on production of agricultural commodities in $ billion for the alternative modeling approaches, regions, and SSPs

production and exports turns to be suboptimal, draining resources away from other more rewarding activities.

In the group of absolute exporters, the US and Argentina (the latter particularly in relation to oil seeds production and exports) are the most negatively affected. On the contrary, Ukraine exports, channeled mostly through the Bosporus, increase irrespectively upon the shock implementation method, reflecting re-routing effects in trade. When chokepoint disruption is implemented through tariffs, increased exports from India are also observed.

Among relative exporters, Canada is particularly exposed to shocks in the Panama Canal. Here it is worth stressing the increased production and exports of Brazilian oil seeds, mostly toward China and Thailand overcompensating the reduced imports from Japan, that is also particularly affected.

All the importers experience a decrease in imports, particularly in China for oil seeds, Middle East and North Africa (MENA) for wheat, South Korea for other grains.

Suez Canal

66% of EU rice imports transits through the Suez Canal. Suez reduced operability is indeed the more impacting on the EU rice domestic production that increases with a positive cascading effect on exports in all EU regions. The same applies to oil seeds. On

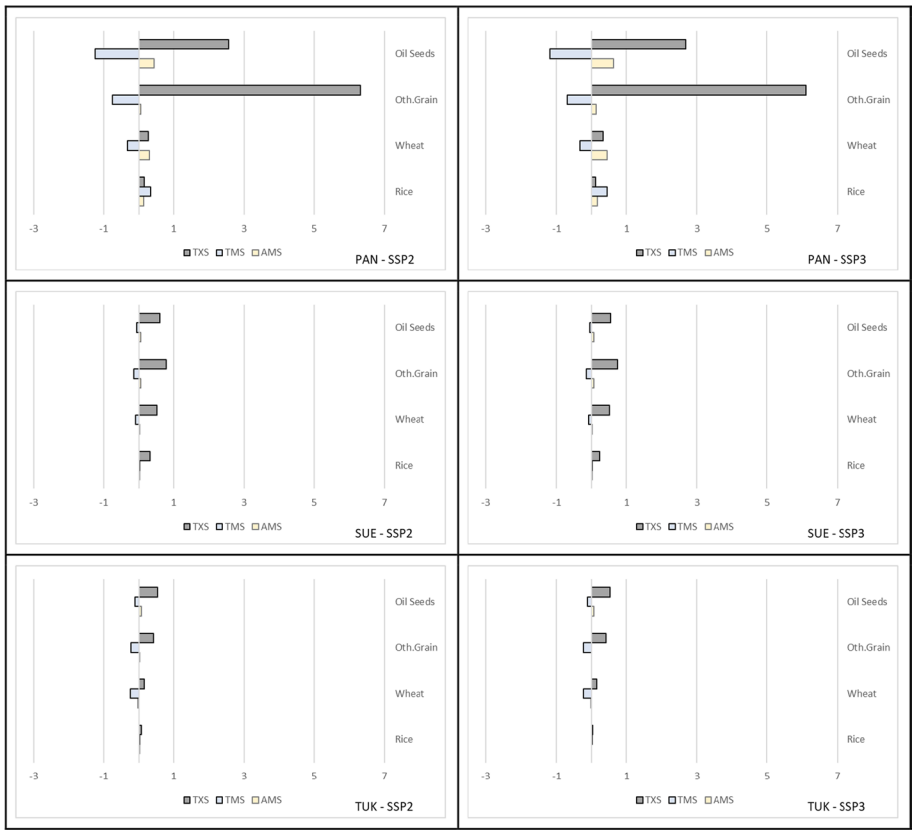

Fig. 6 Impact on world prices of agricultural commodities in percentage change (%), SSPs

the contrary, wheat production, import and exports increase only in the Mediterranean EU while declining, with few exceptions, elsewhere. This result indicates that the Mediterranean EU can substitute wheat trade with other suppliers that channel their commodities through Suez. These outcomes are robust across all restriction implementation methods. However, when observed, reduction in imports are larger using shadow import tariffs than using iceberg trade costs. All these adjustments translate anyway into a net GDP loss for the EU area (in almost all individual EU regions, particularly Northern EU) with the only exception of the restrictions simulated through shadow export tariffs that, as said, tend to do less harm to importers.

Among absolute exporters, India and Ukraine experience higher absolute losses in production and exports: the former in oil seeds, the latter in other grains, and wheat. An evident substitution/re-routing effect increases production and exports of cereals from the US, that of wheat from India, and that of oil seeds from Argentina. Net of these recompositions, however, the group GDP performance unambiguously worsens.

Turning to relative exporters the more evident result is the negative export performance of Russia both in wheat and other grains which is compensated by increased exports from Australia, Brazil, and Paraguay. Interestingly Canada records a negative wheat export as the country is directly affected in its exports to MENA, Sub-Saharan Africa (SSA), and Other Asian Countries but in general do not benefit from re-direction of trade.

The simulation thus emphasizes a re-orientation of cereal commodity production and export from the Eastern Countries towards the Americas.

Importers are also affected. With few exceptions they increase domestic production to compensate for the flow contraction. The absolute importer group performance is dominated by MENA and by the "Tigris Euphrates" region, that of relative importers by the SSA region and China.

Turkish Straits

Although the global macroeconomic impacts stemming from the simulated blockade of the Turkish Straits are the smallest across the three chokepoints, they are the highest, and negative, for the cereal exporting economies nearby like Russia, and Ukraine, but also for importers like Turkey, MENA, or the Eastern European Countries.

Differently from the Suez case, the EU now responds by increasing its production of wheat, and decreasing that of rice under all forms of shock implementation. Other grains production increases when restrictions are implemented through iceberg costs and shadow tariffs, that of oil seeds only with iceberg costs. Within the EU area, responses are differentiated, but all methods point to the decreased production and exports of wheat and other grains in the Eastern EU. All these adjustments translate in a net GDP loss particularly in Med-EU (independently of the method implementation). Restrictions simulated through shadow export tariffs tend to increase GDP in the North-EU.

Among exporters (absolute and relative) Ukraine and Russia, whose cereal trade is highly dependent upon transit through the Bosporus are the most negatively affected, particularly in wheat, and other grains. On the contrary, Argentina (in other grains), India (in wheat and other grains), Brazil (in other grains), the USA (in wheat and other grains), Canada (in wheat), due to their unaffected supply chain, find opportunities to substitute Russian and Ukrainian exports.

The drop in imports, widespread to all agricultural commodities, affects mostly Turkey, MENA, the Tigris and Euphrates area, in relation to wheat, and China.

Macroeconomic impacts: sensibility analysis

The sensitivity analysis we consider here consists of assessing the impact of a 12% trade restriction on the three chokepoints considered. Since a 12% shock had already been considered in the previous sections for the Suez Canal and the Turkish Straits, this is actually an additional simulation for Panama. In the case of this specific chokepoint, it consists in simulating a possible event that would be double the one recorded in 2016, when the traffic flow was reduced by 6%. This homogeneous shock serves to test the relative importance of these 3 shock points. We will refer in particular on this occasion to the results on GDP. The results now show a very similar impact on GDP between the Suez Canal and the Panama Canal, $5.7 billion and $5.5 billion respectively. The results now show a very similar GDP impact between the Suez Canal and the Panama Canal, $5.7 billion and $5.5 billion respectively when considering the impact on the iceberg-cost (method that reports the largest GDP reduction). When it comes to the rest of the methods used, the Panama Canal shows the largest losses, confirming the importance of the Panama Canal. In the case of the results for EU, it is highlighted, at least with the

Table 4 GDP losses in $ billion, original shock vs homogenous shock in 2030, SSP2 Scenario

	EU	Abs.Exp	Rel.Exp	Abs.Imp	Rel.Imp	Total
PAN (Original/Homogeneous)						
AMS	−1.4/−0.4	0.7/0.2	−1.2/−0.3	−4.2/−1.8	−15.6/−3.2	−21.8/−5.5
TMS	−0.4/−0.1	1.1/0.3	−0.5/0.1	−5.2/−1.3	−3.4/−0.7	−8.4/1.9
TXS	−0.3/−0.1	−1.3/0.3	−0.9/−0.1	1.1/0.01	−1.0/−0.4	−2.3/−0.3
SUE (Original)						
AMS	−0.12	−0.07	−0.18	−4.98	−0.39	−5.74
TMS	−0.04	−0.01	0.01	−0.34	−0.05	−0.43
TXS	0.06	−0.02	0.00	−0.13	−0.02	−0.10
TUK (Original)						
AMS	−0.70	−0.18	−1.04	−0.63	−0.28	−2.85
TMS	−0.02	−0.11	0.02	−0.41	−0.04	−0.55
TXS	0.20	−0.15	0.03	−0.17	0.01	−0.07

iceberg-cost method, that remote events in the Panama Canal can generate impacts that can be significant. Results are presented in the Table 4.

Discussion and conclusions

The study demonstrates that climate change impacts on chokepoints' operations can convey detectable effects on production and prices of agricultural commodities associated with negative GDP impacts worldwide. In addition, although trade re-composition generates winners and losers, total losses tend to prevail. The combined GDP losses of the three chokepoints can reach $34 billion (2014 prices) under the SSP3 scenario. This confirms the findings of other studies on the importance of these chokepoints for global trade, Pratson (2023). The study also reveals that weather events in remote locations, such as the Panama Canal, can have cascading effects on the EU, with potential losses of USD 2 billion $ in GDP. The restrictions in the Panama Canal increase transits through other nodes, the Suez Canal for instance, generating readjustments in the supply chain (production, exports, and imports). There are opportunities for the EU to increase production and trade in agricultural products with regions and countries connected to the Suez Canal. This situation suggests that further trade restrictions could lead to even greater losses for the EU.

Under the methodological viewpoint, this study compares three alternative ways to implement trade frictions, in our case related to direct or indirect climate change triggers, affecting operations in three key chokepoints for maritime trade: the Panama and the Suez Canals and the Turkish Strait. The analysis of cascading, indirect effects on regional production, import and export highlights a rather comforting agreement across methodologies in the *direction* of changes in the above mentioned variables. The iceberg trade cost method agrees in 77% of cases with that of tariffs. Import tariffs agree to 80% of export tariffs. The lowest concordance, that anyway remains between the 64% and the 76%, is found in the prediction of imports reaction. The lower agreement is obtained comparing the iceberg trade cost with the shadow import tariff method. The former approach tends to show a lower number of import contractions than the latter.

Changes *in absolute values* are, however, quite different compared to the iceberg trade cost method predicting (on average 4 to 5 times) larger impacts than the other two. This translates into different magnitudes and sometimes direction of the overall economic country performance as summarised by GDP. The lower import contraction, in particular, leads to slightly more frequent, but substantially larger GDP losses that, depending on the region and the chokepoint considered, are 2.6 to 57 times larger using iceberg costs than the tariffs.

Which method should be preferred? According to all the three approaches, exporters are expected to react to a more difficult chokepoint transit with lower domestic production and export, while importers respond with increased domestic production to compensate for the reduction in foreign supply. The more notable qualitative differences across methodologies can be found in the behavior of imports from importing countries—that according to the iceberg cost method may sometimes slightly increase while they clearly decline in response to higher tariffs—and in price reactions, that decrease in response to the import tariffs, but increase when export tariffs or iceberg costs are used.

The historical evidence, including the recent disruptive events in the global food production and distribution due to the Covid-19 pandemic, emphasizes significant increases in agricultural commodity prices in response to frictions in the supply chain (Elleby 2020). This tends to exclude, in this specific case, the use of shadow import tariffs. Then, comparing shadow export tariffs and iceberg trade costs, the latter sometimes highlights increases in imports which are rather difficult to justify. At the same time, the use of shadow export tariffs is not free from criticalities, the first being the revenues that are generated, whose effects have to be neutralized through appropriate redistribution to firms. In conclusion, to simulate trade frictions, our preference would be in favor of shadow export tariffs. However, the iceberg cost method can still offer useful indications of the upper bound for macroeconomic costs.

Turning to the impact assessment, the blockades of the Panama Canal appear to be more critical, originating the larger macroeconomic impacts, globally and for the different country groups. Among exporters, the US and Canada are the clear losers in favor of Ukraine and India. The EU area responds with increases in agricultural production and exports as well, but scores anyway, in aggregate, a slightly negative GDP performance. All the importers experience a decrease in imports, particularly acute in China for oil seeds, MENA for wheat, South Korea for other grains.

Trade restrictions on the Suez Canal tend to penalize Ukrainian, Russian, and partly Indian exports favoring the USA, Argentina, Australia, Brazil, and Paraguay. The drop in imports is particularly evident in the MENA, SSA, and in the "Tigris and Euphrates" area. The impacts on the EU are particularly evident in rice production that increases.

Operability restrictions of the Turkish Straits have the largest negative impacts for Russia and Ukraine whose cereal exports are mostly conveyed through that route. It tends to favor other exporters like Argentina (in other grains), India (in wheat and other grains), Brazil (in other grains), the US (in wheat and other grains), Canada (in wheat). The EU responds by increasing its production and export of wheat and decreasing that of rice under all forms of shock implementation. Within the EU area

also a substitution emerges between Mediterranean and Eastern European grain producers. A particularly concerning drop in imports, in agricultural commodities, affects mostly Turkey, MENA, the Tigris and Euphrates area in relation to wheat and China.

Being aware of the highly hypothetical nature of our exercise, we can conclude that the MENA, the Tigris and Euphrates area and SSA could be particularly vulnerable to climate change also under the point of view of chokepoint disruption. They suffer from a drop in imports of agricultural commodities in all the three cases. Although the absolute values of losses are moderate, these should be considered anyway of concern. Many of the countries affected are mid- and low- income countries. Furthermore, the negative impacts will add on top of crop yield losses induced by climate change that are also expected in those regions. Our simulations thus show that friction in the effectiveness of international trade to act as an impact-smoothing mechanism can occur.

This exercise thus highlights other mechanisms at play that could increase the asymmetry and adverse distributional effects of climate change on agriculture.

A natural follow up of this exercise is to extend the effect of frictions to all the different commodities transiting through the chokepoints. This will be possible once the CH-MAT model is expanded in this direction. A second enrichment will consist in implementing the negative shocks simultaneously to the different choke points to detect potential interaction effects. The third will be, obviously, to use input shocks which are less speculative and more grounded in climate and logistics sciences.

Policy implications

The expected increase in the frequency and intensity of extreme weather events (IPPC 2021) requires short and medium-term adaptation measures to be taken by the authorities responsible for managing these watercourses. The measures include investments in monitoring and control systems and investments in infrastructure. These include investments to improve the monitoring and forecasting systems for climatic variables by the authorities responsible for these channels, to improve their own- and third-party navigation systems (VTS), and to increase the response capacity of emergency teams. Investments in infrastructure involve dredging and enlargement of existing canals (Suez and Turkish Straits), and investments in water storage systems in the case of the Panama Canal. International cooperation is needed, not only for the design and construction, but also for financing.

Abbreviations

CGE	Computable general equilibrium model
CH-MAT	Chatham house maritime tool
EIA	Energy Information Administration (United States of America)
EU	European Union
GDP	Gross domestic product
ICES	Intertemporal computable equilibrium system
LNG	Liquid natural gas
MENA	Middle-East and North Africa
MRIO	Multi region input output
OECD	Organization for Economic Cooperation and Development
PAN	Panama Canal
SSP	Shared socio-economic pathway
SUE	Suez Canal
TUK	Turkish Straits

UNCTAD Inited Nations Conference of Trade and Development
USA United States of America

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s41072-024-00170-3.

Additional file 1. Appendix A. Tables.

Additional file 2. Appendix B: Equations in implementing the choke point shocks in the ICES model.

Acknowledgements
Each author has made substantial contributions to the conception OR design of the work; OR the acquisition, analysis, OR interpretation of data; OR the creation of new software used in the work; OR have drafted the work or substantively revised it. AND approved the submitted version (and any substantially modified version that involves the author's contribution to the study); AND to have agreed to be personally accountable for the author's own contributions and to ensure that questions related to the accuracy or integrity of any part of the work, even ones in which the author was not personally involved, are appropriately investigated, resolved, and the resolution documented in the literature.

Author contributions
Key R.: conception and design, modifications to the CGE model, simulation of multiple cases, processing and interpretation of results, analysis, draft of the work, revision and approved submitted version. Parrado R.: conception and design, creation of CGE model used, analysis, revision and approved submitted version. Delpiazzo E.: conception and design, interpretation of data, analysis, revision and approved submitted version. King R.: conceptions and design, simulation in the CH-MAT tool, interpretation of data, revision and approved submitted version. Bosello F.: conception, design, supervision, revision, substantial modification of draft work, revision and approved submitted version.

Funding
We acknowledge the CASCADES project (funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 821010) for funding this research.

Availability data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request. All data generated or analyzed during this study are included in this published article [and its supplementary information files].

Declarations

Competing interests
The authors declare that we have no competing interests.

Received: 8 January 2024 Revised: 14 March 2024 Accepted: 9 April 2024
Published online: 23 April 2024

References

Aguiar A, Chepeliev M, Corong EL, McDougall R, Van Der Mensbrugghe D (2019) The GTAP data base: version 10. J Glob Econ Anal 4(1):1–27
Andriamananjara S, Ferrantino MJ, Tsigas ME (2003) Alternative approaches in estimating the economic effects of non-tariff measures: results from newly quantified measures (No. 1506-2016-130792)
Bailey R, Wellesley L (2017) Chokepoints and vulnerabilities in global food trade. Chatham House, London, p 111
Baldissera PM, Coulter L, Dessai S, Shepherd TG, Sillmann J, Van Den Hurk B (2023) Varieties of approaches to constructing physical climate storylines: a review. Wiley Interdiscip Rev Clim Change. https://doi.org/10.1002/wcc.869
Balistreri EJ, Hillberry RH (2006) Trade frictions and welfare in the gravity model: how much of the iceberg melts? Can J Econ 39(1):247–265
BBC (2021) Suez blockage is holding up $9.6bn of goods a day. https://www.bbc.co.uk/news/business-56533250
Bekkers E, Francois JF, Rojas-Romagosa H (2018) Melting ice caps and the economic impact of opening the Northern Sea Route. Econ J 128(610):1095–1127
Bekkers E, Rojas-Romagosa H (2018) Non-tariff measure estimations in different impact assessments. Robert Schuman Centre for Advanced Studies Research Paper No. RSCAS, p 40
Bosello F, Parrado R (2014) climate change impacts and market driven adaptation: the costs of inaction including market rigidities. FEEM Note Di Lavoro 2014:064
Brooks MR, Faust P (2018) 50 years of review of maritime transport, 1968-2018: Reflecting on the past, exploring the future (No. UNCTAD/DTL/2018/1)
Burniaux JM, Truong TP (2002) GTAP-E: an energy-environmental version of the GTAP model. GTAP Technical Papers, p 18
Carrico C, Corong E, van der Mensbrugghe D (2020) The GTAP 10A multi-region input output (MRIO) data base
Dellink R, Chateau J, Lanzi E, Magné B (2017) Long-term economic growth projections in the shared socioeconomic pathways. Glob Environ Change 42:200–214

Delpiazzo E, Dasgupta S, Key R, Parrado R, Bosello F, Bodirsky B, King R (2021) Deliverable D3.4: macro-economic impact assessment of cascading effects of climate change, deliverable of the H2020 CASCADES project (Cascading climate risks: Towards adaptive and resilient European Societies)
Dixon P (2006) Evidence-based trade policy decision making in australia and the development of computable general equilibrium modelling. Centre of Policy Studies, Monash University, Australia
EIA, US (2020) International energy outlook 2020
EIA, US (2017) World oil transit chokepoints. US Energy Information Administration
Elbehri A, Pearson K (2000) Implementing bilateral tariff rate quotas in GTAP using GEMPACK
Elbehri A (2005) Implementing bilateral tariff rate quotas in GTAP using GEMPACK. GTAP Technical Paper
Elleby C, Domínguez IP, Adenauer M et al (2020) Impacts of the COVID-19 pandemic on the global agricultural markets. Environ Resour Econ 76:1067–1079
Emmerson C, Stevens P (2012) Maritime choke points and the global energy system. Charting a Way Forward, Chatham House Briefing Paper, London, p 4
Fugazza M, Maur JC (2008) Non-tariff barriers in computable general equilibrium modelling. United Nations Policy Issues in International Trade and Commodities Study Series No. 38
Fujimori S, Hasegawa T, Masui T, Takahashi K, Silva Herran D, Dai H, Hijioka Y, Kainuma M (2017) SSP3: AIM implementation of shared socioeconomic pathway. Glob Environ Change 42:268–283
GTR (2023) Chokepoints and climate change: future challenges for the Suez Canal. https://www.gtreview.com/supplements/gtr-mena-2023/chokepoints-and-climate-change-future-challenges-for-the-suez-canal/
Guardian (2021) How a container ship blocked the Suez canal—visual guide. https://www.theguardian.com/world/2021/mar/24/how-a-container-ship-blocked-the-suez-canal-visual-guide
Hertel T (2013) Global applied general equilibrium analysis using the global trade analysis project framework. In: Dixon PB, Jorgenson DW (eds) Handbook of computable general equilibrium modeling, vol 1. Elsevier, Amsterdam, pp 815–876
IEA International Energy Agency (2011) World energy outlook—2011, Paris
IEA International Energy Agency (2012) World energy outlook—2012, Paris
IPCC Intergovernmental Panel on Climate Change (2012) Managing the risks of extreme events and disasters to advance climate change adaptation. Special report of the Intergovernmental Panel on Climate Change, Cambridge
Komiss W, Huntzinger L (2011) The economic implications of disruptions to maritime oil chokepoints. Center for Naval Analysis
Krugman P (1991) Increasing returns and economic geography. J Polit Econ 99(3):483–499
McCann P (2005) Transport costs and new economic geography. J Econ Geogr 5(3):305–318
MFA (2017) Note on the Turkish Straits. Republic of Türkiye. Ministry of Foreign Affairs. https://www.mfa.gov.tr/the-turkish-straits.en.mfa
Meza A, Ari I, Al Sada M, Koç M (2022) Disruption of maritime trade chokepoints and the global LNG trade: An agent-based modeling approach. Marit Transp Res 3:100071
O'Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, Carter TR, Van Vuuren DP (2014) A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim Change 122:387–400
Parrado R, De Cian E (2014) Technology spillovers embodied in international trade: intertemporal, regional and sectoral effects in a global CGE framework. Energy Econ 41:76–89
Pratson LF (2023) Assessing impacts to maritime shipping from marine chokepoint closures. Commun Transport Res 3:100083
Republic of Türkiye Ministry of Foreign Affairs (2022) Note on the Turkish Straits. https://www.mfa.gov.tr/the-turkish-straits.en.mfa
Rodrigue JP (2004) Straits, passages and chokepoints: a maritime geostrategy of petroleum distribution. Cahiers De Géographie Du Québec 48(135):357–374
Rojas-Romagosa H, Bekkers E, Francois JF (2015) Melting ice caps and the economic impact of opening the northern sea route (No. 307). CPB Netherlands Bureau for Economic Policy Analysis
Samir KC, Lutz W (2017) The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100. Global Environ Change 42:181–192. https://doi.org/10.1016/j.gloenvcha.2014.06.004
Samuelson PA (1952) The transfer problem and transport costs: the terms of trade when impediments are absent. Econ J 62(246):278–304
Shepard JU, Pratson LF (2020) Maritime piracy in the Strait of Hormuz and implications of energy export security. Energy Policy 140:111379. https://doi.org/10.1016/j.enpol.2020.111379
Shepherd TG, Boyd E, Calel RA, Chapman SC, Dessai S, Dima-West IM, Zenghelis DA (2018) Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. Clim Change 151:555–571
Tonoğlu F, Atalar F, Başkan İB, Yildiz S, Uğurlu Ö, Wang J (2022) A new hybrid approach for determining sector-specific risk factors in Turkish Straits: Fuzzy AHP-PRAT technique. Ocean Eng 253:111280
UNCTAD (2015) International classification of non-tariff measures. United Nations Publications, Geneva
UNCTAD (2019) Review of maritime transport 2018 (2019) UNCTAD/RMT/2019
van den Hurk BJ, Pacchetti MB, Boere E, Ciullo A, Coulter L, Dessai S, Witpas K (2023) Climate impact storylines for assessing socio-economic responses to remote events. Clim Risk Manag 40:100500. https://doi.org/10.1016/j.crm.2023.100500
Walmsley T, Strutt A (2021) A comparison of approaches to modelling non-tariff measures. J Glob Econ Anal 6(1):1–33
Walton RB (2019) Simulating maritime chokepoint disruption in the global food supply. Theses and Dissertations. 2319. https://scholar.afit.edu/etd/2319
Wang X, Dietrich JP, Lotze-Campen H, Biewald A, Stevanović M, Bodirsky BL, Popp A (2020) Beyond land-use intensity: assessing future global crop productivity growth under different socioeconomic pathways. Technol Forecast Soc Change 160:120208

Wangsness PB, Rødseth KL, Hansen W (2017) A review of guidelines for including wider economic impacts in transport appraisal. Transp Rev 37(1):94–115
Washington Post (1998) Climate change: Overview. washingtonpost.com-staff. https://www.washingtonpost.com/wp-srv/inatl/longterm/climate/overview.htm
Wellesley L, Preston F, Lehne J, Bailey R (2017) Chokepoints in global food trade: assessing the risk. Res Transp Bus Manag 25:15–28
Werrell CE, Femia F (2017) Epicenters of climate and security: the new geostrategic landscape of the Anthropocene. Washington, DC, USA: Center for Climate and Security. https://climateandsecurity.org/wp-content/uploads/2017/06/4_dire-straits.pdf
World Bank (2023) Commodity price data. http://www.worldbank.org/commodities. Consultation, 6 July 2023
Zimmermann A, Benda J, Webber H, Jafari Y (2018) Trade, food security and climate change: conceptual linkages and policy implications. FAO, Rome, p 48

Publisher's Note

Ramon Key is currently a senior researcher (CGE modeler) at the Euro-Mediterranean Center for Climate Change (CMCC@Ca'Foscari). He was the Coordinator and Professor of the International Center for Energy and the Environment at the IESA School of Management 2016–2021. He is an economist who graduated from Universidad Central de Venezuela with a Ph.D. in Economics from the University of Colorado Boulder. He worked at Petróleos de Venezuela until 2014, where he was manager of economic analysis at the Corporate Planning Office. Before joining IESA, he was a Senior Economist at IDEA International in Panama, conducting fiscal risk analysis and budgeting for results in Latin American countries.

Ramiro Parrado is currently a Scientist of the Economic analysis of Climate Impacts and Policy (ECIP) Division at the Euro-Mediterranean Center on Climate Change (CMCC) and a member of the Trade & Competitiveness Research Committee of the Green Growth Knowledge Platform (GGKP). His main research fields are economics of climate change impacts and policy assessment; and computable general equilibrium modelling. He has contributed to the Deep Decarbonization Pathways Project (DDPP) as part of the Italian team. Ramiro is currently involved in several European Commission's Horizon 2020 projects. He has been involved in Sixth and Seventh Framework Programme integrated projects and has also collaborated with the Organisation for Economic Co-operation and Development (OECD). Ramiro joined CMCC in 2007 and he has been a Senior Researcher for the Climate Change and Sustainable Development Research Programme at the Fondazione Eni Enrico Mattei from 2006 to 2017, a visiting researcher at the Centre for European Economic Research/Zentrum für Europäische Wirtschaftsforschung GmbH (ZEW) in 2010, and a Guest Researcher for the Ecological and Environmental Economics Programme at The Abdus Salam International Centre for Theoretical Physics in 2006. Ramiro holds a PhD in Science and Management of Climate Change from Ca' Foscari University in Venice, a Master Degree in Economics from the Universidad Andina Simón Bolívar in collaboration with the econometrics department of the Université de Genève and a Degree in Economics at the Universidad Católica Boliviana.

Elisa Delpiazzo holds a Ph.D. in Economic politics with major in Quantitative Methods for Economic Policies from Catholic University in Milan. She gets a master's degree in Economics, Politics, and International Institutions from the University of Pavia. Currently she is Junior Scientist at CMCC@Cà Foscari in the ECIP division. Her research activity currently focuses on the evaluation of climate change impacts, adaptation and mitigation policies using Computable General Equilibrium models and on the economic evaluation of climate services. Previously she has collaborated with Fondazione ENI Enrico Mattei and CMCC Foundation since 2013.

Richard King is a research fellow in the Environment and Society Centre at Chatham House. He works on issues related to the sustainable uses of, and trade in, food, water, energy, and mineral resources. Prior to joining Chatham House, Richard was deputy head of research at Oxfam GB where he focused on issues related to economic, environmental, and social justice. He specialized in food and rural livelihoods, particularly in the contexts of climate change, resource constraints and market volatility. He has an MSc in Economics and Management of International Development from the University of Manchester and a BSc in Geography from the University of Durham.

Francesco Bosello graduated at the Ca' Foscari University of Venice, he received a Master degree in economics from the University College of London (UK) and a Doctoral degree in economics from the University of Venice. He is presently associate professor of economics at the Ca' Foscari University of Venice, and senior scientist at the Euro-Mediterranean Centre on Climate Change (CMCC) where he coordinates the Economic Analysis of Climate Impacts and Policy division. He is deputy director of the European Institute for Economics and the Environment a joint initiative between CMCC and the US Resources for the Future. Previously he has been associate professor at the University of Milan, and affiliate scientist at the

Fondazione Eni Enrico Mattei Milan. He is currently undertaking research activities in the area of climate change impact assessment and the design of optimal mitigation and adaptation strategies developing integrated assessment modelling tools and applied general equilibrium economic models. His other research interests are more broadly related to international environmental agreements and the economics of the environment and of sustainability.