Climate change, trade, and global food security

A global assessment of transboundary climate risks in agricultural commodity flows

SEI report
September 2021

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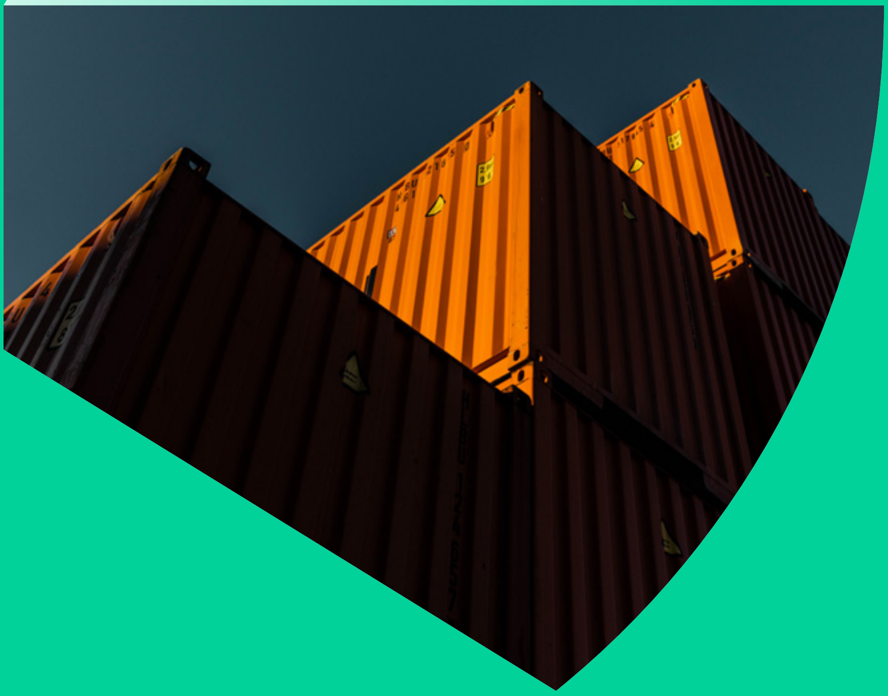

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Cover photo: © Aron Yigin / Unsplash

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Acknowledgements
The authors of this report would like to acknowledge the important contributions of a number of individuals who have supported this work. In particular, the authors would like to thank Richard Klein, Åsa Persson, Henrik Carlsen, Adis Dzebo, Katy Harris, Declan Conway, Robert Falkner, Marion Dumas, and Jiayi Zhou, in addition to several thoughtful reviewers and engaged colleagues for their helpful reflections throughout. The authors would like to specifically thank Christian Bunn for providing access to relevant data for climate risk and coffee production. The authors would also like to acknowledge FORMAS, a Swedish research council for sustainable development (Climate adaptation governance in a globalized world, Grant No. 211-2012-1842), MISTRA, the Swedish Foundation for Strategic Environmental Research (Mistra Geopolitics programme), and the Grantham Research Institute, London School of Economics and Political Science, (Kevin M. Adams, Research Fellowship) for their financial support.

All data and results included in this report are available to access for non-commercial use at: https://www.sei.org/projects-and-tools/tools/data-transboundary-climate-risks-agricultural-commodity-flows

Cite as
Adams, K.M., Benzie, M., Croft, S. & Sadowski, S. (2021). Climate Change, Trade, and Global Food Security: A Global Assessment of Transboundary Climate Risks in Agricultural Commodity Flows. SEI Report. Stockholm Environment Institute, Stockholm.
https://doi.org/10.51414/sei2021.009

Executive summary

Key messages

- **Transboundary climate risks to global food security are critical and mounting but until now have remained largely unrecognized by the global community. This assessment reveals how these risks are distributed via international trade in six key commodities, linking producers and consumers thousands of kilometres apart.**
- **Traditional approaches to managing trade risk, such as substitution and diversification, will be ineffective in a world that is facing accelerating climate change impacts simultaneously.**
- **There is a high potential for increasingly tense geopolitical dynamics, as countries – particularly large agricultural producers – reckon with their own vulnerability to climate change and strive to maintain their current market shares.**
- **Assessing, managing, and reducing these risks will require a cooperative multilateral approach. Responses that only account for national self-interest could undermine global resilience and exacerbate the global adaptation challenge.**
- **A global systemic view is essential for planning and implementing equitable and effective adaptation. Achieving systemic resilience requires a level of international cooperation that is currently missing from global adaptation efforts. International organizations must do more to orchestrate and coordinate adaptation.**
- **The material risk posed to food security in countries at all levels of development – but especially in low income, import-dependent countries – makes adaptation to transboundary climate risk a matter of public policy. Public and private adaptation strategies need to be better aligned to achieve a just transition to a more resilient world.**

Introduction

The impacts of climate change do not respect national borders. Transboundary climate risk has critical implications for biophysical resources, financial flows, human mobility, infrastructure, national security, and trade.

In a globalizing world, we can no longer consider climate change adaptation to be a solely national or local issue. Rather, as our communities and economies become more interconnected, our exposure to the adverse effects of a warming world is shared. Building climate resilience must be treated as a global challenge that can deliver mutual benefits.

This report provides a first systematic, quantitative assessment of transboundary climate risks to trade in key agricultural commodities, namely maize, rice, wheat, soy, sugar cane, and coffee. The assessment is global in scope and allows for comparison of significant trading relationships, exporters, importers, and markets, providing a basis for policymaking and setting priorities in risk management.

Agriculture is one of the most exposed sectors to climate change, both over the short-term, as extreme weather events increase in frequency and severity, and the long-term, due to broader shifts in climatic patterns including temperature and precipitation.

Not only does climate risk affect farmers whose livelihoods depend on crop yields, but also the complex network of actors who then depend on those agricultural products for food security or as inputs to other economic activities. In a globalizing world, much of the food we eat – as well as the feed and other inputs that become the food we eat – is produced significant distances from where it is consumed. Before arriving on supermarket shelves, it is traded on international markets, and travels through global supply chains. Global food security relies on a broad range of interdependent activities all around the world, including the stability of markets.

To date, there has been limited research into transboundary climate risks and international food trade. This is a crucial gap, given that food security around the world depends on trade in staple foods, and that the risks to this trade will only increase as the impacts of climate change become more evident.

Methodology

This report develops a novel methodology for assessing climate risks to global trade in agricultural commodities. The analysis projects the extent to which the impacts of climate change will affect yields of major agricultural commodities in particular countries over time, combined with a measurement of commodity-specific trade dependency. In this way, this report provides a uniquely nuanced picture of how climate risk propagates through global food trade networks.

The assessment rests on a "stress test" approach and is described in full detail in the report. However, it is important to note that owing to methodological constraints, the assessment measures only long-term trends in agricultural production due to climate change and does not assess the impact of extreme weather events, or risks to infrastructure such as storage facilities or transportation. Overall, this means that results presented are likely a conservative assessment of climate risks to future food production and trade.

Climate risks to global trade in key commodities

Climate change will dramatically impact agricultural production all around the globe. In some cases, warmer temperatures will reduce yields, while in some limited circumstances agricultural productivity may increase. Overall, this assessment suggests that the risks are many times greater than the opportunities.

This assessment projects a global yield reduction resulting from climate change across five of the six commodities considered:

Maize	-27.0%
Rice	-8.1%
Wheat	+13.9%
Soy	-7.2%
Sugar cane	-58.5%
Arabica coffee	-45.2%
Robusta	-23.5%

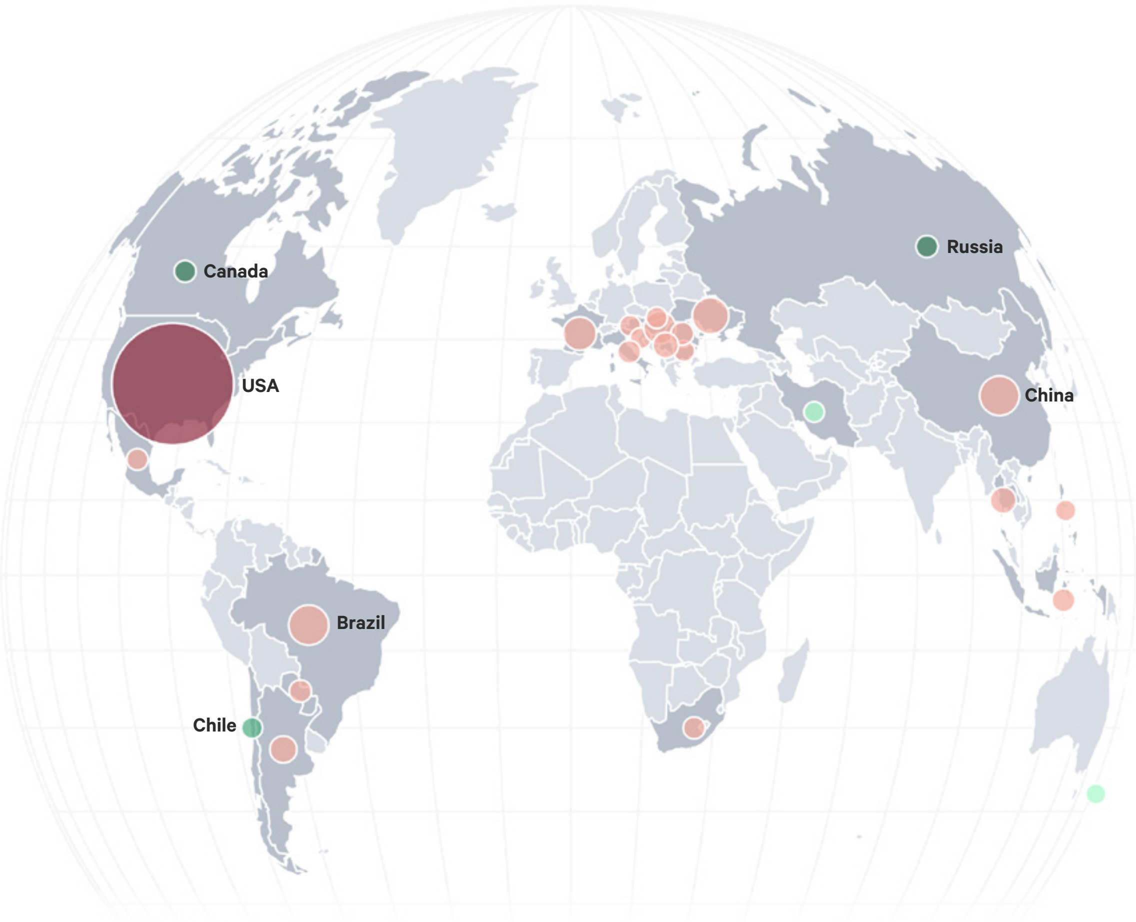
Recognizing that maize, rice and wheat play a critical role in achieving global food security, this report underscores that climate change not only creates risks for producing countries, but also for consumers of all kinds, often at significant distances from a commodity's point of origin.

The maize and rice markets are highly exposed to climate change. Wheat production appears more stable in general, but may require redistribution to Europe and parts of South America and Asia at significant cost and with negative consequences for existing producers.

Our results indicate that climate risks to global food security are disproportionately transmitted from a small number of countries: Brazil, China and the US for exports of maize; Thailand and the US for exports of rice; and the US again for wheat. Highly embedded commodities, like soy and sugar cane, pose an indirect risk to food security in all consumer countries by threatening to drive price increases and shocks across a basket of products.

These challenges have profound implications for markets, countries, and firms around the world. For example, in the maize market, climate change could lead to a 45.5% reduction in US production. Such an outcome would likely drive-up maize prices worldwide, adversely impacting US producers and the American economy, in addition to consumers in Jamaica, Costa Rica, and Japan, who are highly dependent on US-grown maize.

Top global exporters of risk for **maize**



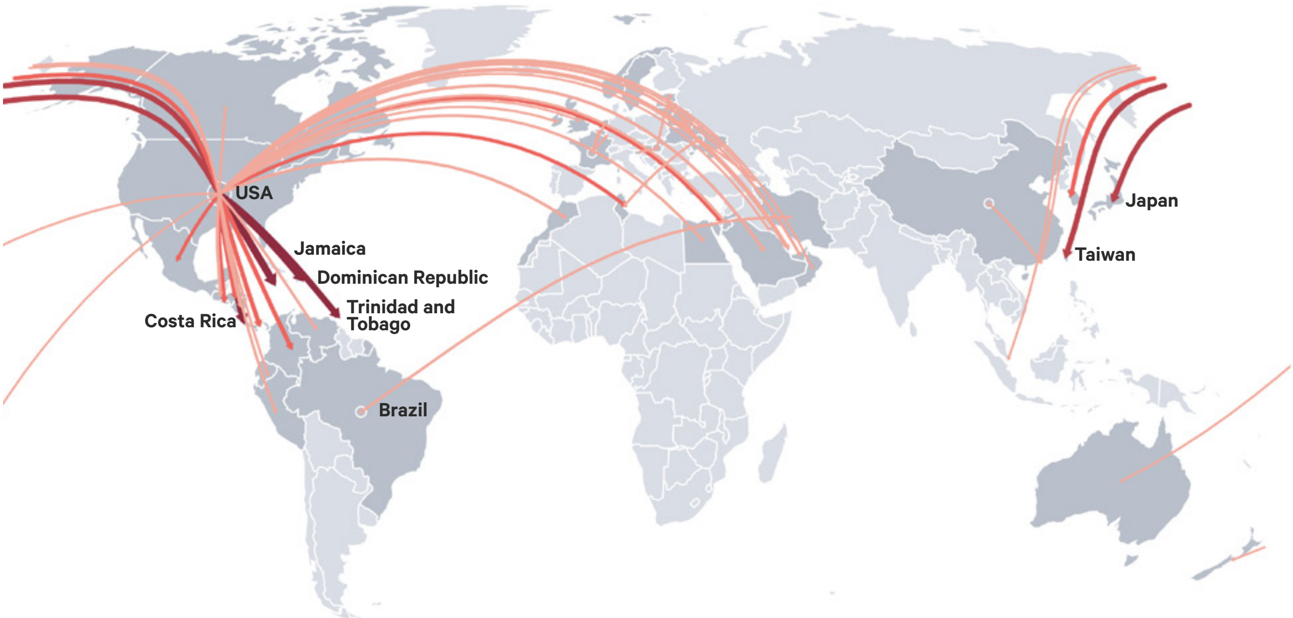
43:1 RISK TO OPPORTUNITY RATIO

226.2 MN TONNES TOTAL GLOBAL FLOW

-27.2% IMPACT OF CLIMATE CHANGE ON PRODUCTION

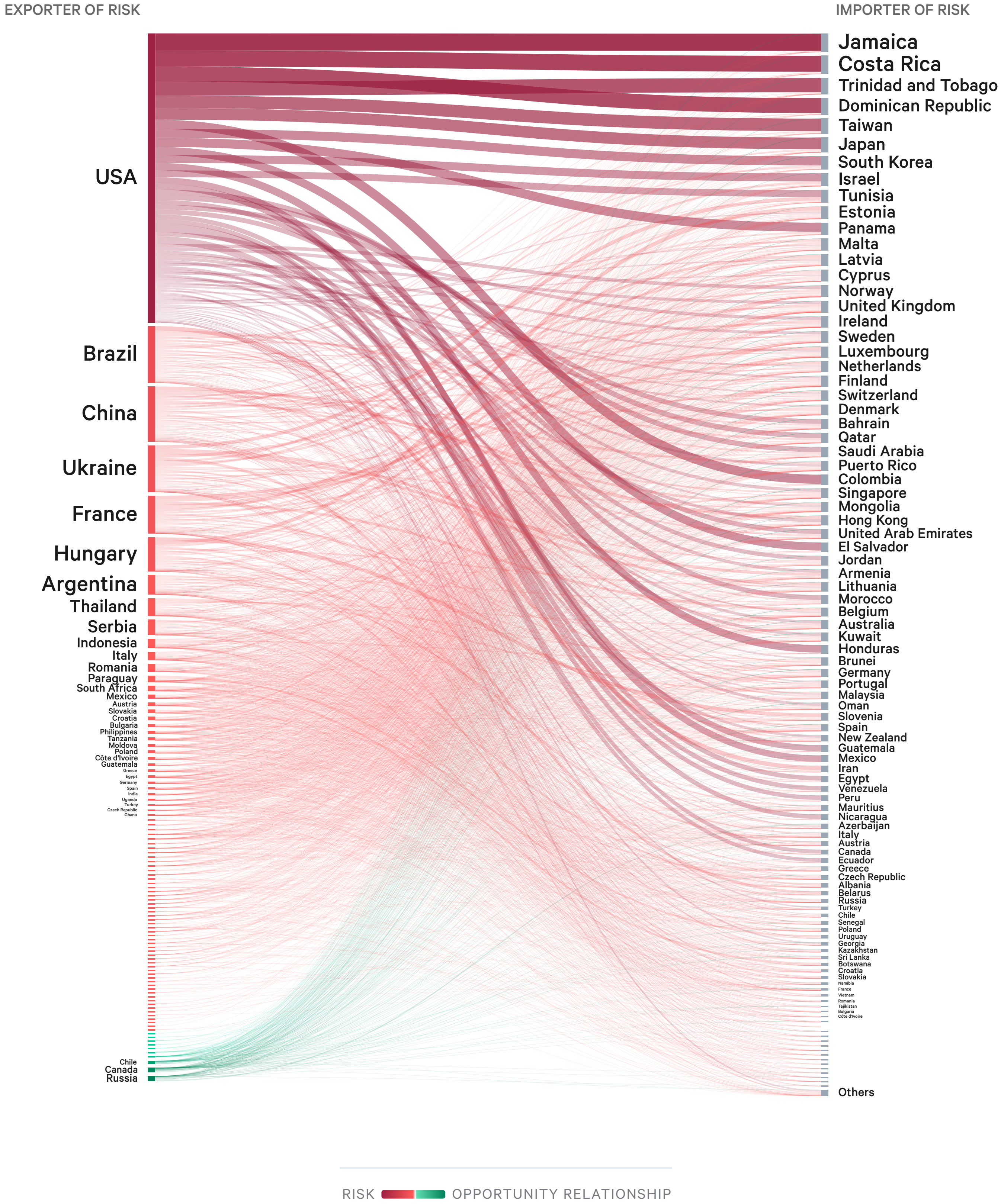
#	EXPORTER	TOTAL SHARE OF GLOBAL RISK (%)	EMBEDDED EXPORTS (TONNES)	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	USA		64.18mn	-45.5%
2	Brazil		20.33mn	-22.1%
3	China		32.81mn	-15.5%
4	Ukraine		9.66mn	-29.5%
5	France		8.25mn	-32.2%
6	Hungary		4.55mn	-45.0%
7	Argentina		18.04mn	-6.8%
8	Thailand		3.14mn	-48.7%
9	Serbia		6.11mn	-41.4%
10	Indonesia		3.47mn	-21.0%
11	Italy		1.61mn	-32.1%
12	Romania		1.97mn	-34.3%
13	Paraguay		1.85mn	-24.5%
14	South Africa		2.36mn	-8.7%
15	Mexico		1.88mn	-35.6%
16	Austria		0.99mn	-29.2%
17	Slovakia		0.53mn	-39.9%
18	Croatia		0.34mn	-40.3%
19	Bulgaria		1.08mn	-17.9%
20	Philippines		1.26mn	-25.3%
...	...		...	...
5	Iran		0.10mn	23.5%
4	New Zealand		0.14mn	69.7%
3	Chile		0.52mn	67.1%
2	Canada		4.49mn	17.0%
1	Russia		1.58mn	12.7%

Top 50 high-risk bilateral trade relationships for **maize**

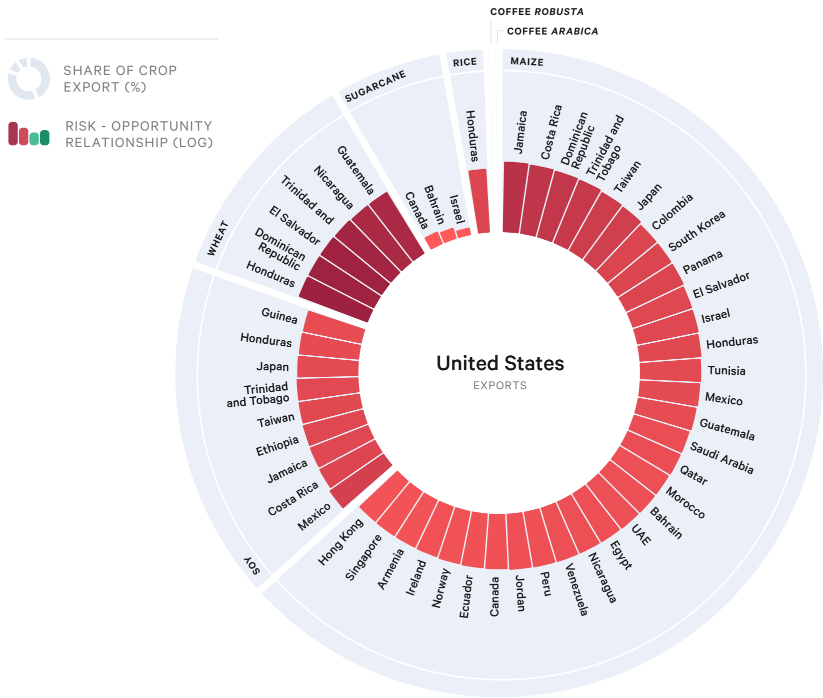


#	EXPORTER	IMPORTER	RISK TO BILATERAL TRADE	EMBEDDED TRADE FLOW (TONNES)	IMPORTER'S TOTAL STOCK	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	USA	Jamaica		0.28mn	0.32mn	-45.5%
2	USA	Costa Rica		0.42mn	0.53mn	-45.5%
3	USA	Dominican Republic		0.83mn	1.13mn	-45.5%
4	USA	Trinidad and Tobago		0.09mn	0.13mn	-45.5%
5	USA	Taiwan		2.85mn	4.62mn	-45.5%
6	USA	Japan		16.99mn	29.64mn	-45.5%
7	USA	Colombia		2.19mn	4.84mn	-45.5%
8	USA	Republic of Korea		4.99mn	11.13mn	-45.5%
9	USA	Panama		0.30mn	0.66mn	-45.5%
10	USA	El Salvador		0.59mn	1.49mn	-45.5%
11	USA	Israel		0.72mn	1.81mn	-45.5%
12	USA	Honduras		0.37mn	1.00mn	-45.5%
13	USA	Tunisia		0.26mn	0.78mn	-45.5%
14	USA	Mexico		10.49mn	33.29mn	-45.5%
15	USA	Guatemala		0.71mn	2.44mn	-45.5%
...	...		...	...	...	...
25	Brazil	Iran		2.48mn	5.67mn	-22.1%
26	USA	Jordan		0.13mn	0.62mn	-45.5%
27	USA	Canada		2.98mn	15.68mn	-45.5%
28	USA	Ecuador		0.30mn	1.65mn	-45.5%
29	Hungary	Slovenia		0.11mn	0.62mn	-45.0%
30	Hungary	Estonia		0.02mn	0.09mn	-45.0%
...	...	...	...	...	...	...
45	USA	Australia		0.26mn	1.85mn	-45.5%
46	USA	Sweden		0.09mn	0.64mn	-45.5%
47	Ukraine	Belarus		0.19mn	0.88mn	-29.5%
48	USA	New Zealand		0.07mn	0.55mn	-45.5%
49	France	Netherlands		0.71mn	3.80mn	-32.2%
50	France	Belgium		0.58mn	3.16mn	-32.2%

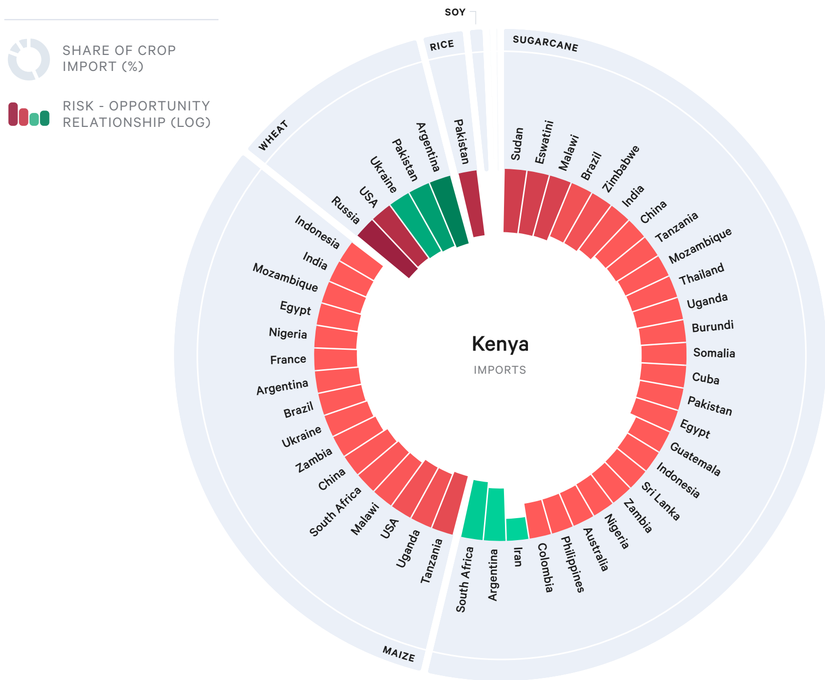
Risk and opportunity in bilateral trade relationships for **maize**



Key trade relationships and climate risk for US exports



Key trade relationships and climate risk for Kenyan imports



Notable spatial patterns also emerge from the results. Countries like Kenya and Bolivia are exposed to high climate risks from within their regions. Latin America and the Caribbean are highly dependent on risky imports from the US. Regional patterns persist, but are less prominent, for highly globalized countries like the UK, Germany and Singapore.

The trade links that transmit transboundary climate risk are not random: they reflect historical, regional and geopolitical ties between countries. Adaptation to reduce these risks will be facilitated and constrained by these same geopolitical factors. For example, Singapore's management of high climate-risk trade dependencies on China, the US and Brazil cannot be seen in isolation from its other commercial, political and strategic relationships with those countries.

Implications

The findings of this report underscore the systemic nature of climate risk to agricultural commodity trade and global food security. Unlike other challenges experienced in international trade, climate change risk is present everywhere, simultaneously. Climate change will increase the risk of compound events, potentially affecting multiple major breadbasket regions in the same season. Even under nearer term scenarios, the stress put on agricultural commodity trade by uncertain, variable, and decreasing yields due to climate change is likely to heighten volatility and threaten the stability of commodity markets.

Our results indicate which countries will be most exposed to these risks, across a range of commodities, but the entire system of commodity trade is likely to suffer repeat crises, unless adaptation efforts succeed in building systemic resilience to climate change.

The high likelihood of negative impacts on commodity production worldwide radically reduces the space in which actors will be able to diversify, substitute and hedge agricultural commodity trade risks. For most countries, the orthodox supply chain management logic of replacing high-risk suppliers with more resilient ones is unlikely to be a plausible strategy in a competitive world facing systemic risks from a changing climate.

> The high likelihood of negative impacts on commodity production worldwide radically reduces the space in which actors will be able to diversify, substitute and hedge agricultural commodity trade risks.

Awareness alone is unlikely to lead to the needed adaptation that will deliver systemic resilience. In fact, awareness of TCRs in global food trade, to which this assessment contributes, might encourage actors to pursue a course of narrow self-interest that does more to exacerbate systemic risk than reduce it.

A retreat from global integration and a return to protectionism, regionalization and geopolitics could destabilize markets further, likely to the detriment of those countries who can least afford to compete in such a world, including those that have been heavily incentivized in recent decades to open up to global markets as a solution to the challenge of achieving food security. Not only would this represent a major injustice, but it would also not be in any country's long-term interest to undermine systemic resilience in this way.

However, the same results can support a different conclusion: international trade helps all countries to diffuse the risk from climate change. Free and open access to international markets will help all participants to meet the daunting challenge of achieving food security in a world challenged by climate change, population growth, and changing diets. Markets are mechanisms of interdependence: the deep reach of agricultural commodity markets, into and across countries at all levels of development and in all continents, reminds us that collective resilience is a function of the resilience of all countries, including those with the least ability to invest in resilience themselves. It reiterates the importance of ensuring successful adaptation at all scales and in all places and articulates clearly the shared benefits of investing boldly in adaptation.

We do not yet know what a "climate resilient" trade profile looks like. We do not know what balance of domestic production and access to international markets, or what number, or which type of trade partner, will offer the most resilience against uncertain but systemic risks in the global agricultural commodity trade. What we do know is that there is a pressing need for multilateral cooperation to address these risks and develop effective, coordinated responses.

Policy responses

Overall, there is a clear global benefit from successful, equitable and just adaptation to climate change, particularly in key exporting countries. That places responsibility on producer countries to consider the wider systemic effects of domestic, planned adaptation. This also underscores the need for international value chain actors and their investors to ensure that private, autonomous adaptation contributes to achieving "just resilience" at both local and global scales. And it places responsibility on the international community to provide the necessary political, legal, institutional, financial and logistical support to facilitate adaptation in countries that lack capacity, and to build robust structures for international cooperation to jointly address these shared, systemic risks.

Whereas climate change adaptation has traditionally been pursued as a nationally driven, or even local, territorial, process, our results invite decision makers to rethink the value of global cooperation on adaptation.

Fortunately, there are mechanisms that can help countries build systemic resilience to climate change, principally via the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement. In particular, Article 7 of the Paris Agreement establishes the Global Goal on Adaptation (GGA) to enhance adaptive capacity and resilience and reduce vulnerability. It also frames adaptation as a "global challenge", recognizing its "regional and international dimensions." There is ample space in this context to include the important transboundary elements of climate risk.

Giving serious consideration to TCRs would necessitate that Parties to the UNFCCC, many of whom may view adaptation as a secondary or even marginal concern in the negotiations, re-consider the value of a truly global approach to adaptation.

This report reveals that all countries have a shared interest in building climate resilience: importers benefit when exporters are able to adapt to the impacts of climate change and sustain their agricultural production. Therefore, importers will want to see – and consider what they can do to facilitate – successful adaptation in other countries, particularly those with which they trade. This raises new questions for the allocation and disbursement of international climate finance for adaptation. In addition to allocating finance to single countries, important global or international systems – such as the global maize market – can be identified and adaptation finance contributed toward building resilience in that system, to the benefit of all who participate in it.

Looking ahead

This report provides a basis from which to ask challenging questions about the governance of climate change risk in an interconnected world. For example, which government agencies should "own" responsibility for adapting to transboundary climate risk? And what is the appropriate division of labour between the state and private enterprises in managing trade-related climate risk? It should also spark needed policy debate about how the international community will rise to meet this emerging challenge. This includes:

- how the UNFCCC intends to operationalize the Global Goal on Adaptation, particularly in view of the Global Stocktake
- how the WTO will meaningfully incorporate elements of climate change and sustainability into its work, and
- how countries will conduct diplomacy in a context where multilateralism and global cooperation remain under threat, but climate action is high on the political agenda.

Transboundary climate risks via trade are critical and mounting. They have remained largely unaddressed by the global community due to the territorial focus of most adaptation research and practice – obscured behind a veil of trade statistics. This report invites public and private stakeholders into a new discussion about meeting the global adaptation challenge in ways that enable all people to share in the benefits of systemic resilience.

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1. Introduction

Global climate change remains one of the most pressing social and environmental challenges of the 21st century. According to the Intergovernmental Panel on Climate Change (IPCC), the past 50 years has seen unprecedented changes to global mean temperatures, sea levels, and ice cover, driven centrally by the anthropogenic emissions of greenhouse gasses around the world (IPCC, 2013). Even with immediate and decisive action, global mean temperatures are likely to climb to more than 1.5°C above pre-industrial levels before mid-century, while some regions like the Arctic could see temperatures rising by 5°C or more (IPCC, 2018). In this context, it is crucial that as we continue to invest in reducing emissions, there is a parallel mobilization to adapt to life in a warming world.

Adaptation to climate change has long been considered especially salient for developing countries,[1] which are particularly vulnerable to the adverse effects of climate change given the strong correlation between vulnerability and economic development (IPCC, 2014). Adaptation planning has often been conducted at the national, subnational, or local levels because of its highly context-specific nature (Adger et al., 2005), the epistemic development of the adaptation sciences (Benzie & Persson, 2019), and the state-oriented structure of the United Nations Framework Convention on Climate Change (UNFCCC), the central multilateral forum for negotiating international climate policy and facilitating climate action. Yet there is growing recognition in both the scholarly and policy communities that many climate risks are transboundary in nature, flowing across international borders just as resources, goods, and people do (Benzie et al., 2018; Challinor et al., 2017; Liverman, 2016; Oppenheimer et al., 2014).

Agriculture is one of the most exposed sectors to climate change, both over the short-term, as extreme weather events increase in frequency and severity, and the long-term, due to broader shifts in climatic patterns.

A key instance of this is agricultural trade. Agriculture is one of the most exposed sectors to climate change, both over the short-term, as extreme weather events increase in frequency and severity, and the long-term, due to broader shifts in climatic patterns including temperature and precipitation (IPCC, 2019). Notably, these adverse effects not only impact farmers whose livelihoods depend on crop yields, but also the complex network of actors who then depend on those agricultural products for food security or as inputs to other economic activities. In a globalizing world, much of the food we eat – as well as the feed and other inputs which become the food we eat – is produced significant distances from where it is consumed; before arriving on supermarket shelves it is traded on international markets, and travels through global supply chains. In this way, achieving global food security involves a broad range of interdependent activities all around the world, including the stability of markets, which allows food to be purchased at affordable prices.

Transboundary climate risks (TCRs) in agricultural trade are far from a theoretical concern. Among the many causes of the 2007–2008 global food price crisis were changes to weather patterns, including droughts and flooding, which markedly reduced global grain stocks (Mittal, 2009). In conjunction with other factors, this reduction in grain and the accompanying hike in prices led major exporters to ban or restrict exports in an effort to stabilize domestic markets (Dawe & Slayton, 2011). In the global rice market, this led to India banning rice exports, panic-buying in the Philippines, and substantial export restrictions in Viet Nam, bringing about soaring prices for rice in Senegal, a nation highly dependent on imported rice for food security (Benzie & John, 2015). This cascading series of events culminated with widespread social instability and protests that posed risks for human security and threatened the businesses of private sector actors involved in rice processing and trade.

Despite growing concern about TCRs worldwide, research on the issue is still in its infancy, and to date has been primarily conceptual or qualitative (e.g. Challinor et al., 2017; Galaz et al., 2017). A good deal of early work has aimed to identify plausible TCR "pathways", or discrete mechanisms, through which risks may be transmitted. Hedlund et al. (2018), for example, consider four such pathways: biophysical resources, trade, financial flows, and human mobility, while others (e.g. INFRAS, 2019)

1 In this paper we adopt the term "developing countries" as it is commonly used in the United Nations Framework Convention on Climate Change (UNFCCC) .

have added infrastructure and national security to this list. Of these pathways, scholarly inquiry has disproportionately focused on identifying and assessing biophysical risks, such as risks to shared river basins or streams, which have been explored in the literature for a long time and have a strong proximity to research on global environmental change (Dalin & Conway, 2016; Kahsay et al., 2018).

In contrast to research into biophysical TCRs, research on teleconnected TCRs – where the countries in question do not share a physical border – is more limited (Moser & Hart, 2015). National governments have shown particular interest in the trade pathway, and several have undertaken basic assessments of their own risk profiles, often using dependency on cereal imports as a proxy for exposure to TCRs in trade, or linking high-level vulnerability indicators, such as the ND-GAIN Country Index, to their trade portfolios (e.g. Gledhill et al., 2013; Hildén et al., 2016; INFRAS, 2019; Prytz et al., 2018; PWC, 2019). Rigorous qualitative research has also sought to explore trade TCRs in specific contexts, such as in supply chains for Jamaican tilapia (Canevari-Luzardo, 2019), or to identify "choke in points" for global food trade where high-volume trading routes may be vulnerable to climate risks (Bailey & Wellesley, 2017). Others have taken broad quantitative approaches to this issue, using partial equilibrium models and other economic tools to generally explore the links between climate change, agriculture and trade, rather than examining the constellation of trade TCRs to which countries, companies, and communities are presently exposed (Janssens et al., 2020; Nelson, Valin, et al., 2014; Nelson, van der Mensbrugghe, et al., 2014). While this sample of existing research is not exhaustive, it underscores the need for a systematic, quantitative assessment of TCRs in key agricultural commodities. Such an assessment must be global in scope, allowing for the comparison of significant trading relationships, exporters, and markets, as well as providing the basis for policymaking and setting priorities in risk management.

Achieving global food security involves a broad range of interdependent activities all around the world, including the stability of markets, which allows food to be purchased at affordable prices.

In this report we endeavour to fill this crucial information gap, answering the question: how are transboundary climate risks currently distributed in global agricultural commodity flows? In Section 2 we describe in detail a novel methodology for assessing TCRs in agricultural commodity flows and identify the sources of data used in this assessment. In Section 3 we present the results of this approach for six important global agricultural commodities: maize, rice, wheat, soy, sugar cane, and coffee. We identify key sources of climate risk in agricultural commodity exports, high-risk bilateral relationships, and consider important differences between commodity markets. In Section 4 we discuss the implications of this work, both for international climate policy and future research, before providing brief concluding remarks in Section 5.

2. Methods and data

To determine how TCRs are distributed in agricultural commodity flows requires, first, an understanding of these flows between countries and, second, a measure of how climate change may impact those flows.

On the former, there are number of plausible approaches for quantifying the flows of agricultural commodities, the most straightforward of which is a simple measurement of trade between countries by either volume or value. Leaving aside questions about the accuracy of bilateral trade statistics across diverse jurisdictions (e.g. Federico & Tena, 1991; Morgenstern, 1968), the issue is complicated significantly by continued globalization, economic integration, and the emergence of international supply chains: it is significantly more difficult to determine the country of origin for modern goods than for commodities used in early trade models, such as British cloth or Portuguese wine (De Backer & Miroudot, 2014; Koopman et al., 2010). For instance, how should a cup of coffee be recorded whose beans were grown in Rwanda, imported by a Dutch trader, roasted in Italy, and drank in Sweden? Often, national trade statistics will capture only one of these stages, depending on a country's role in the production process. This may allow Sweden to assess their exposure to climate risks in Italian coffee roasteries, but would omit key upstream elements like rising sea levels affecting the Port of Rotterdam, or changing precipitation patterns reducing coffee yields in Rwanda.

To remedy this, experts have turned to multiregional input-output (MRIO) analysis, which combines multiple regional and national input/output tables to construct a fuller portrait of the economic interdependencies between sectors and economies worldwide (Leontief, 1936; Miller & Blair, 2009). These techniques can be extended to capture the environmental ramifications of complex economic relationships between countries (Lenzen et al., 2012; Wiedmann et al., 2015). MRIO analysis includes the necessary breadth and depth to cover entire supply chains. However, it is often limited in resolution, in terms of both geographic scope and coverage of products and sectors.

In view of the shortcomings of each of the approaches above, Stockholm Environment Institute's Input-Output Trade Analysis (IOTA) model (see Croft et al. 2018) takes a hybridized approach. The IOTA model – which is a hybridized physical-financial MRIO modelling framework - provides both the commodity specificity and resolution of production that is available in global trade databases, as well as the full supply chain coverage of MRIO analysis. Importantly, rather than reporting the raw tonnage of commodity flows between an exporter and importer, IOTA data therefore captures the extent to which the outputs of a producer country are embedded in the goods or services of a consumer country. For example, sugar or soy grown in one country can be used as feed or another input in the manufacture of food and drink products in a second country, which are then consumed in a third country. IOTA data traces this sequence of exchanges to identify the origins of embedded materials that are consumed in each country. In this way the origin of highly embedded commodities can be revealed, for example the soy that was used to feed cattle that were subsequently processed into leather products. This, in turn, allows environmental risks to be traced even at extremely fine scales, all the way from production to consumption (Croft et al., 2018; Godar et al., 2015; Stokeld et al., 2020).

Importantly, it is not only the amount of embedded commodity flow between producers and consumers which is relevant when considering risk, but the dependency of a consumer on a producer's output. For example, while Jamaica and Hong Kong consume similar amounts of maize produced in the US (see Section 3), Jamaica has less than half the population of Hong Kong, which consumes more maize overall and relies on imports from a wider variety of sources. Jamaica is therefore more dependent on US maize than Hong Kong.

Import dependency is already widely used in the context of agricultural commodity trade, specifically cereal import dependency ratios, which aim to measure agricultural self-sufficiency and are a well-regarded indicator of food security. Import dependency is calculated by Equation 1, where I represents total imports, D total domestic production, and E total exports:

$$(1) \quad \frac{I}{D+I-E}$$

In order to determine the dependency of a particular consumer on a particular producer, the import dependency calculation can be modified, yielding Equation 2, where f_{pc} represents the flow of a commodity from a producer p embedded in the economy of a consumer c, D_c the total domestic production of the same commodity by the consumer, and I_c the total imports of the commodity by the consumer:

$$(2) \quad \frac{f_{pc}}{D_c+I_c}$$

The combination of total domestic production and total imports can be considered a consumer's available stock of a commodity. Exports have been deliberately excluded from this function, as a consuming country may have the option to divert exports for domestic consumption if faced with shortfalls, as has been observed empirically. By comparing the flow of a commodity to a consumer's available stock, Equation 2 provides a quantitative measure of specific dependency, or the dependency of a consumer on the output of a specific producer for a given commodity.

For this study, IOTA data are used for six key agricultural commodities: maize, rice and wheat, which are staples in diets worldwide; soy and sugar cane, which are highly embedded in the production of other goods including soy as feed for many animal products; and coffee,[2] a luxury good. Data for these commodities are included for the years 2004, 2007, 2011, and 2014,[3] for 221 producing countries and regions and 141 consuming countries and regions (Croft et al., 2018; for a full list of countries and regions see Annex I). For each producer-consumer pairing, data on commodity flows are averaged across each of the four years in an effort to capture general relationships between producers and consumers rather than annual variability.[4] Notably, while there is variation in commodity flows and trade patterns over time, recent research suggests that these tend to be more stable than previously realized, particularly for traders and other companies with large market shares who exhibit a high degree of "stickiness". Data suggests that this actor-level stickiness is due in-part to established professional and contractual relationships (Reis et al., 2020). Owned or leased physical infrastructure and facilities, as well as experience with a specific market or context, may also play an important role. Regardless, we carried out a robustness test (see Annex II) in which we compared two sets of IOTA data, for 2004/2007 and 2011/2014. The test suggested that variations in commodity trade over time, particularly before and after the Great Recession, are of limited relevance to this assessment. These data can be used to operationalize all three components of Equation 2.

How, then, do we account for climate change risk in such an assessment, both conceptually and practically? In mathematical terms, a simple adjustment can be made to Equation 2 by including Δ_p, representing the change in output in the producing country for a commodity due to climate change, yielding Equation 3:

$$(3) \qquad \frac{f_{pc}}{D_c + I_c} * \Delta_p$$

Operationalizing Δ_p can be somewhat more challenging. Climate change can impact the agricultural output of a producer in two main ways: through reduced yields, or through damage to key infrastructure such as storage facilities or transportation networks. On the first, extreme weather events, as well as changing climatic patterns over the long-term, are likely to be the main causes of reduced yields (IPCC, 2019). Quantitatively assessing the likelihood and severity of shocks to agricultural systems is methodologically distinct from projecting long-term shifts, given the different timescales involved and the probabilistic nature of extreme weather events. While bridging these bodies of work remains a critical project for the impacts modelling community, such an endeavour is outside the scope of this report. Similarly, assessing climate risks to infrastructure requires linking models of extreme weather events under climate change to (often very limited) data on storage, transportation, and shipping at extraordinarily fine scales, which is also beyond our scope. As such, this report focuses exclusively on long-term changes to agricultural commodity yields as a result of climate change. This is a clear limitation of the approach and suggests that results presented may be in some important ways a conservative estimate of TCRs embedded in agricultural commodity flows.

There are a number of global gridded crop models (GGCMs) that aim to project the impacts of climate change on agricultural yields over the long-term. GGCMs differ from one another in several material ways, including their conceptual foundations and operationalization of key parameters. Further, analysts must also consider potential differences in model inputs, including the greenhouse gas emissions scenario, known as the representative concentration pathway (RCP), and the global circulation model (GCM), which determines how a specified RCP will translate to differences in key atmospheric parameters, including temperature and precipitation. The systematic evaluation of GGCMs has been the subject of the Agricultural

2 Coffee data is provided as green coffee and apportioned by species (i.e., *C. arabica* or *C. robusta*) to each producer using production statistics from the International Coffee Organization (ICO, 2020).
3 The most recent four time periods for which IOTA data was available.
4 There are two notable exceptions. First, in 2006 Serbia and Montenegro separated to become two separate countries. Averages are taken individually for Serbia and Montenegro for the years 2007, 2011, and 2014, while 2004 is excluded. Second, in 2011 Sudan separated into Sudan and South Sudan. Only 2014 data is included for Sudan and South Sudan.

Model Intercomparison and Improvement Project (AgMIP), which has sought to identify and explore many of these divergences and uncertainties (Rosenzweig et al., 2013). In a landmark 2014 paper, AgMIP researchers found a high degree of agreement between GGCMs across major agricultural producers in high and low latitudes, but noted that significant uncertainty remained in mid-latitude areas, with regard to both the direction and magnitude of anticipated change (Rosenzweig et al., 2014). While many prominent assessments of climate change vulnerability use multiple GGCMs, AgMIP results suggest that it may not be appropriate to combine GGCMs by taking mean averages, because means calculated across diverse models where the direction of change is uncertain will regress toward zero, thus risking underestimates or omissions.[5] Instead, a more reliable approach is to select an individual GGCM, or a panel of GGCMs, for which results are reported individually for each. Relatedly, Burke et al. (2014) have raised concerns over differences between GCMs and the preponderance of the Hadley Center model (HadGEM2–ES) in economic assessments of climate change impacts. In a systematic comparison of GGCMs for wheat, Asseng et al. (2013) found that higher levels of uncertainty exist between GGCMs as compared to downscaled global circulation models, suggesting the careful selection of an appropriate GGCM is of greater importance for assessing transboundary climate risks in agricultural commodity flows. Further, Janssens et al. (2020) found that across a wide array of crops the HadGEM2-ES model consistently produces more negative (i.e. higher risk) projections than other GCMs.

As an exercise in risk assessment this report aims to operationalize Δ_p (i.e. climate risk) by explicitly maximizing the climate risk signal, similar to a "stress-test". Therefore, following Janssens et al. (2020) and others (e.g. Rosenzweig et al., 2014; Schlenker et al., 2006; Schlenker & Roberts, 2009; Stokeld et al., 2020; Zhang et al., 2017) this assessment uses the HadGEM2-ES GCM, which projects higher climate risks to agricultural production than other comparable models. Also following Janssens et al. (2020), this assessment employs the Environmental Policy Integrated Model (EPIC) GGCM with CO_2 fertilization (Leclère et al., 2014), both because the model includes nitrogen forcing, a critical driver of GGCM divergence (Rosenzweig et al., 2014), and because it models five of the six agricultural commodities we assessed: maize, rice, wheat, soy and sugar cane. For coffee, this assessment uses the Bitter Cup model, which differentiates between the coffee species *C. arabica* and *C. robusta* and is the only existing GGCM for global coffee production (Bunn et al., 2015).[6] Results are presented for RCP8.5, which is both widely used by similar assessments (Janssens et al., 2020; Rosenzweig et al., 2014) and is understood to represent the closest approximation of business-as-usual approaches to climate mitigation and current emission trends (Riahi et al., 2011; Schwalm et al., 2020). While the veracity of RCP8.5 has recently been the subject of intense debate, given the increasing adoption and implementation of climate change mitigation policies worldwide (see Hausfather & Peters, 2020a, 2020b), its use is well aligned with this paper's "stress-test" approach and is balanced in part by the omission of climate-induced extreme weather events on both agricultural yields and infrastructure, as noted above.

One plausible alternative considered, in keeping with this report's stress-test approach, was to use a risk optimization function across GGCMs, wherein the most negative GGCM for each producer-crop pair would be selected and used in the assessment. To take a specific example, while the EPIC GGCM for rice shows a modest increase (+0.2%) in Vietnamese rice production under the chosen specifications, the GEPIC GGCM shows a substantial decrease (-23.5%). A risk optimization approach would select the GEPIC projection for Vietnamese rice and use this value alongside the EPIC projection in Thailand. On one hand, the benefit of this approach would arguably be a more accurate representation of plausible climate risks to Vietnamese rice, better accounting for the uncertainties described by the full suite of GGCMs. For Vietnam, or any of their major trading partners, it is in their interest to be aware of and prepare for these higher-risk scenarios. On the other hand, risk optimization is conceptually dubious for assessing global or

5 The most prominent such assessment is the ND-GAIN Country Index, which uses a set of five GGCMs. It is unclear from the accompanying technical report how the GGCMs in question are integrated in the "Food–Exposure" component, raising questions about the reliability of using ND-GAIN or its relevant sub-indicator for the purpose of this assessment.

6 Unlike EPIC and other similar GGCMs that produce projected crop yields, the Bitter Cup GGCM produces projected land area suitable for coffee production. Bitter Cup data is processed and operationalized in the same manner as the data that are produced by the EPIC GGCM.

systems-level dynamics where the relationships between all countries in a commodity market are at issue. While it is useful for Vietnam to prepare for multiple climate risk scenarios, it is less useful to prepare for a future rice market where Vietnamese production is described by the one model and Thai production by another, as these worlds are fundamentally incongruent. The most robust approach for considering systems-level dynamics is to utilize internally consistent climate risk projections.

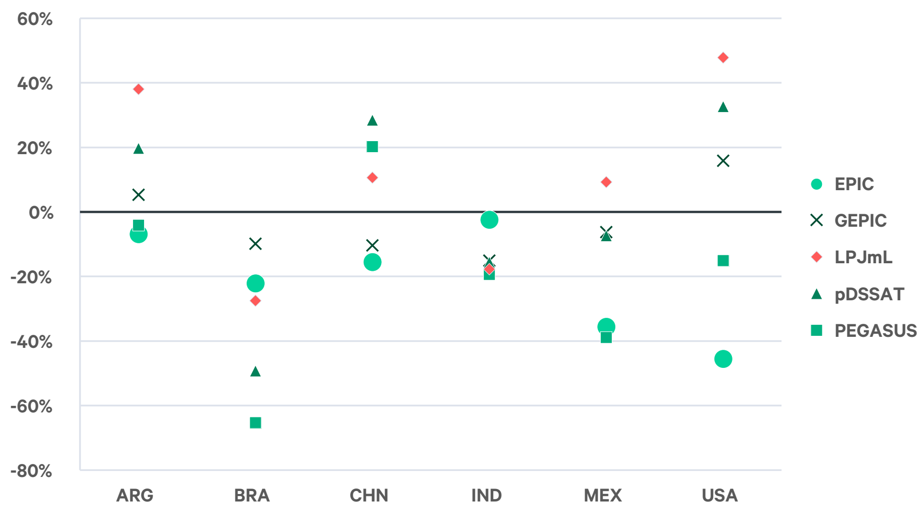
In view of these challenges, and as noted above, this report presents results using the EPIC GGCM for maize, rice, wheat, soy, and sugar cane, in part because this GGCM projects a higher degree of climate risks to agricultural production than other models. We assessed relevant climate impact data for each selected agricultural commodity using the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) data portal[7] and extracted data for all producing countries and regions using zonal statistics in R, generating projected percentage changes in yields by comparing a set of baseline years (1980–2010) to a long-term projection (2070–2099).[8]

To be clear, the selection of the EPIC GGCM obscures a number of uncertainties in our assessment. Below, we present climate risk projections from a range of GGCMs which illustrate these uncertainties.

Several plausible scenarios exist where Chinese maize may substitute for US production shortfalls, or vice-versa.

Among major maize producers (Figure 1), there is a high degree of uncertainty across GGCMs, except for Brazil (accounting for 7% of global production) and India (2%), for which all GGCMs project a decrease in maize production. Mexico (2%) has a similar level of agreement if the LPJmL model (which does not account for nitrogen stress) is excluded. The largest producers, the United States (38%) and China (20%) have wider ranges, each with two GGCMs projecting maize decreases and two GGCMs projecting increases. Notably, these projected differences are not correlated across GGCMs for the US and China, and several plausible scenarios exist where Chinese maize may substitute for US production shortfalls, or vice-versa. In line with this paper's stress-test approach, the EPIC GGCM generates the most-risky projections for each producer. This does suggest, however, that results for maize should be interpreted cautiously, particularly with regard to future political economic dynamics and potential competition in the maize market.

Figure 1. Projected climate risks across GGCMs for major **maize** producers. Note: Major producers are defined as producers who account for ≥2% of total global maize production. Data presented are generated using the HadGEM2-ES GCM and RCP8.5 over the long-term (2070–2099). GGCMs in green include nitrogen stress, while GGCMs in red (i.e. LPJmL) do not include nitrogen stress, following Rosenzweig et al. 2014.



7 See: https://esg.pik-potsdam.de/projects/isimip/
8 Because data for Bitter Cup GGCM are only available through 2050, a medium-term projection (2040–2050) is used.

For major rice producers (Figure 2), Bangladesh (7% of global production) and Thailand (5%) are projected to consistently decrease production among GGCMs which include nitrogen stress. For other producers the variability across projections is more significant – and may even range between positive and negative changes – including for China and India, which account for 28% and 21% of global rice production, respectively. Among the models that include nitrogen stress, the pDSSAT GGCM typically generates the most positive projections of changes to rice yields, while the EPIC GGCM typically generates the most risky projections. A notable exception is Viet Nam (6%), which is projected to have a slight increase in rice production under the EPIC model, but a significant decrease under the GEPIC model, as noted above in this section.

For major wheat producers (Figure 3), the largest differences between GGCMs are driven by the PEGASUS model, which predicts significant positive changes for Canada (4% of global production) and Russia (8%). The EPIC model generates the most risky projections for both China (17%) and the United States (8%), as well as a slightly positive projection for India (12%). Only one model, pDSSAT, projects a decrease in Indian wheat production.

For major soy producers (Figure 4), there is significant agreement among GGCMs for two of the three largest producers: Argentina (18% of global production), which is projected across all models to increase production, and Brazil (27%), which is projected to decrease production across all models that include nitrogen stress. The United States (35%) has a higher degree of variability, though with the EPIC and pDSSAT models projecting roughly similar magnitudes of production decrease.

Figure 2. Projected climate risks across GGCMs for major **rice** producers. Note: Major producers defined as producers who account for ≥2% of total global rice production. Data presented are generated using the HadGEM2-ES GCM and RCP8.5 over the long-term (2070–2099). GGCMs in green include nitrogen stress, while GGCMs in red (i.e. LPJmL) do not include nitrogen stress, following Rosenzweig et al. 2014.

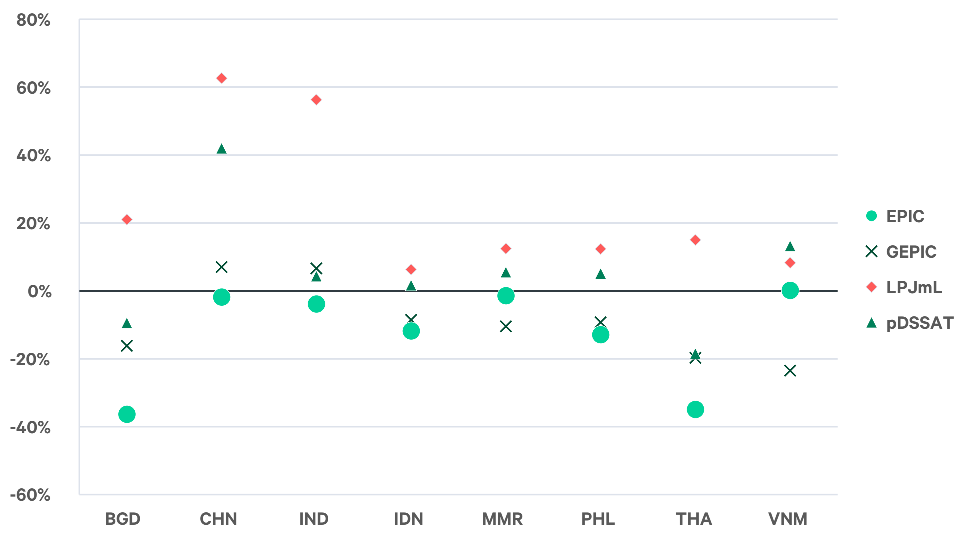


Figure 3. Projected climate risks across GGCMs for major **wheat** producers. Note: Major producers defined as producers who account for ≥2% of total global wheat production. Data presented are generated using the HadGEM2-ES GCM and RCP8.5 over the long-term (2070–2099). GGCMs in green include nitrogen stress, while GGCMs in red (i.e. LPJmL) do not include nitrogen stress, following Rosenzweig et al. 2014.

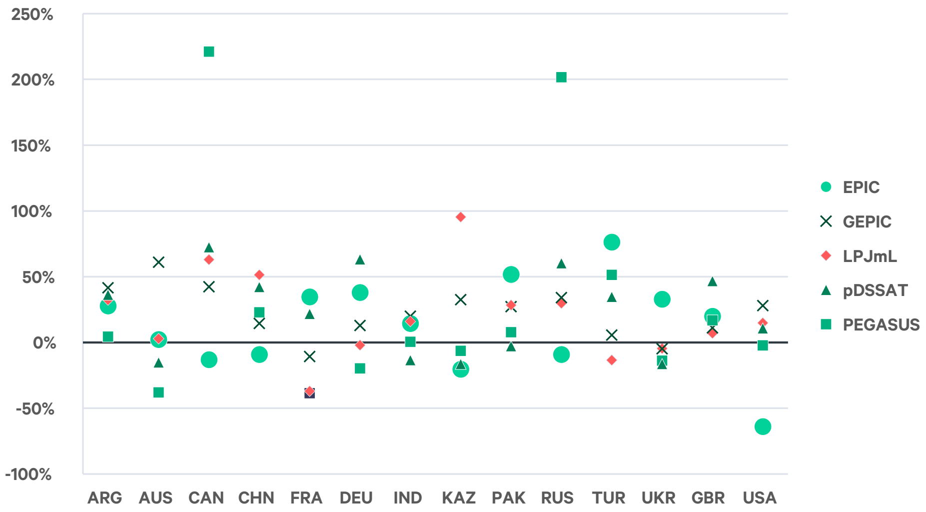
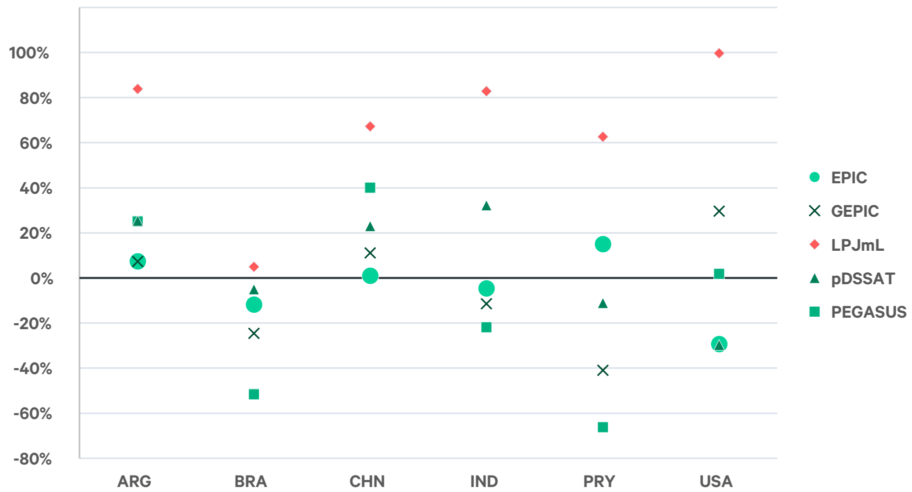


Figure 4: Projected climate risks across GGCMs for major **soy** producers. Note: Major producers defined as producers who account for ≥2% of total global soy production. Data presented are generated using the HadGEM2-ES GCM and RCP8.5 over the long-term (2070-2099). GGCMs in green include nitrogen stress, while GGCMs in red (i.e. LPJmL) do not include nitrogen stress, following Rosenzweig et al. 2014.

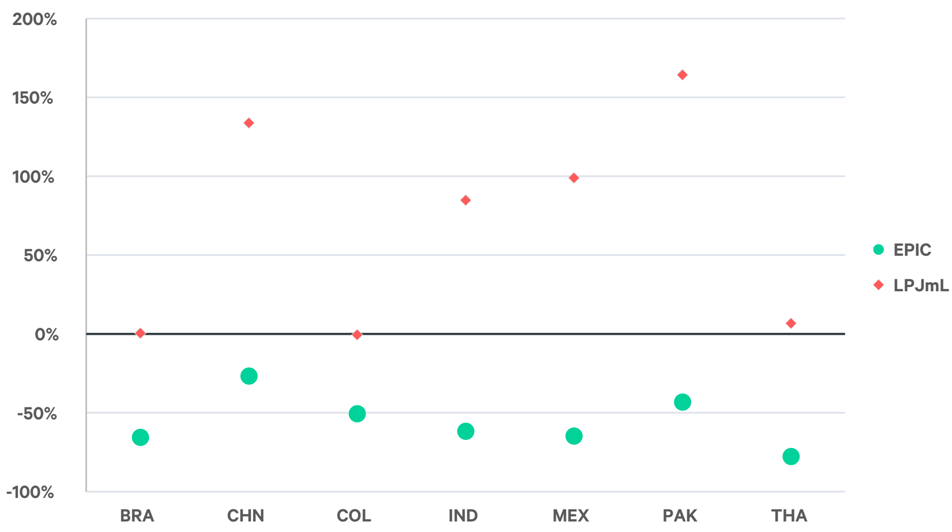


Finally, for major sugar cane producers (Figure 5), where only two GGCMs are available, the EPIC model generates consistently negative projections of sugar cane yields, while the LPJmL model (which again excludes the critical feature of nitrogen stress) generates consistently positive projections. This includes for the two largest producers, Brazil (37% of global production) and India (19%).

These findings from a full suite of models support the selection of the EPIC GGCM as the primary input for this report's assessment. The crop-specific climate risk values for all producer countries are compiled in Annex III.

With all parameters operationalized, Equation 3 is calculated for each pair of producing/consuming countries and regions, for each agricultural commodity. The resulting unitless value provides an indicative measure of climate risk embedded in a particular agricultural commodity flow. These values can then be summed for: a given commodity market to determine the balance between climate risk and opportunity; for a given consumer country and crop to determine exposure; or for a given producer country to determine overall contribution to risk and instability in a particular market. This allows for fruitful comparison between agricultural commodity markets, as well as individual trade relationships, consumers, or producers.

Figure 5: Projected climate risks across GGCMs for major **sugar cane** producers. Note: Major producers defined as producers who account for ≥2% of total global sugar cane production. Data presented are generated using the HadGEM2-ES GCM and RCP8.5 over the long-term (2070-2099). GGCMs in green include nitrogen stress, while GGCMs in red (i.e. LPJmL) do not include nitrogen stress, following Rosenzweig et al. 2014.



3. Results

In this section we first consider how TCRs are currently distributed in the markets of the world's most important staple foods: maize, rice, and wheat. We then turn to the results for embedded commodities: soy and sugar cane, and finally consider coffee, a luxury commodity with distinct characteristics.

TCRs in the maize market appear to disproportionately originate from North America, Latin America, and Europe, with Brazil, China, and especially the United States occupying key roles.

There are a number of important considerations for interpreting the results in this section. First, the risk-to-opportunity-ratio presented for each commodity captures the balance of positive and negative trade relationships on a global level. The more unbalanced the ratio, the bigger the risk embedded in the current system, and the higher the likelihood of market instability, price rises, and food security challenges. For maize, the risk exceeds the opportunity by 47 times. This means that the risk embedded in current maize trading relationships is 47 times greater than the potential opportunities. This ratio considers not only the climate risks to producers, but also dependency: how many risky relationships exist (and how risky are they) relative to positive ones? As such, the ratio can be understood as reflecting the relative stress on a given market, based on existing trading relationships and the prospects for negative or positive climate change impacts. In coffee, for example, we see that there are hardly any countries which are expected to produce more, while most trade relationships are highly concentrated with very few very risky producers. This drives a particularly extreme imbalance compared to other crops, suggesting the potential for very high stress in the coffee market over time.

The data for the total global flow of commodities is an average of the years 2004, 2007, 2011, and 2014, while the projected impacts on crop production are determined by comparing a set of baseline years (1980–2010) to a long-term projection (2070–2099). For a full explanation, see the complete methodology in Section 2.

3.1 Staple commodities: maize, rice and wheat

Beginning with maize, assessment results suggest that production may decrease by approximately 27.2% in the long-term, with risks due to climate change in some countries and regions outweighing increases to production in others by a ratio of 43:1 (Figure 6). Keeping in mind that this assessment does not account for changes to the behaviour of producers or consumers during this time frame (rather, it represents TCRs as they are currently distributed), this suggests that investing in key producers to combat these risks may be an important adaptation strategy. TCRs in the maize market appear to disproportionately originate from North America, Latin America, and Europe, with Brazil, China, and especially the United States occupying key roles. In contrast, Russia, Canada, and Chile all stand to see increases in maize production, though far below those needed to offset shortfalls elsewhere. Investment in these key countries, either to build resilience and minimize losses for producers at-risk, or to support the scale-up in production of would-be beneficiaries, may serve to reduce TCRs in the global maize market.

Figure 7 shows the top 50 high-risk bilateral relationships in the maize market, which are dominated by US exports. Many of the riskiest links extend from the US to small island states in the Caribbean and countries in Latin America, as well as to Israel, with whom the US maintains especially close diplomatic relations. To take one example, of the 0.32 million tonnes of maize consumed by Jamaica each year, 0.28 million tonnes are produced in the US. In conjunction with the exposure of US maize production to climate change, this dependency suggests that Jamaica is highly exposed to TCRs that originate in the United States. Similar dynamics are also observed within Europe, including Hungarian exports to Slovenia and Estonia, as well as French exports to the Netherlands and Belgium.

The global rice market exhibits similar dynamics to the maize market (Figure 8), though shows a less extreme decrease to production in the long term (8.1%) and has a more favourable risk-to-opportunity ratio (6:1). Climate risk in the rice market appears to be geographically concentrated in Southeast Asia and Latin America, regions where rice is an important component of most local cuisines. In particular, Thailand appears to be a critical exporter of TCR in the rice sector, owing to the size of its production, concentration of trading relationships, and high exposure to climate change. In contrast, both India and China are similarly important producers but appear less exposed to climate risks. Russia could plausibly benefit in the rice sector, alongside North Korea, which already produces an amount of rice similar to the US or Indonesia. Viet Nam, another critical rice producer, does not appear in the top-five potential beneficiaries for rice production due to an especially small projected increase in production due to climate change, +0.2%.

Bilaterally, risky trade relationships also appear to originate primarily in Thailand or the US (Figure 9). The US is shown to be a key source of risk for Honduras, El Salvador, Guatemala, and Mexico, while Thailand trades with a broad array of countries, including small islands in the region such as Brunei, African states like Senegal and Ghana, and European countries such as Norway, the Netherlands, Germany, and the UK.

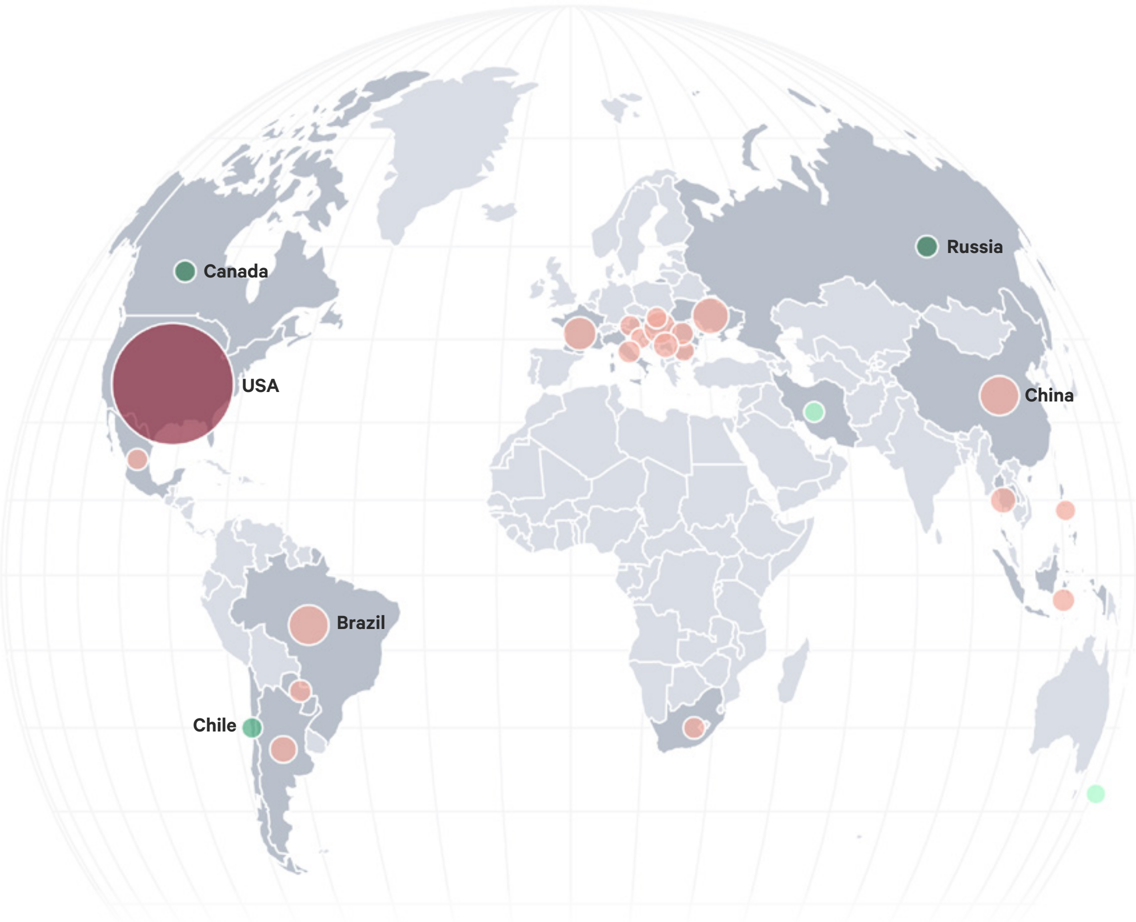
Several African countries, in particular Nigeria, appear to be particularly exposed to risks from US wheat production.

Of the three staple crops assessed in this study, the global wheat market appears to have the most promising outlook under climate change, with a roughly balanced risk-to-opportunity ratio (Figure 10). As is the case for maize, the United States appears to be a critical source of TCRs in the wheat market, far surpassing Canada, Russia, and China, who also expect production decreases but of a lesser magnitude. Several countries in East Africa could also expect significant decreases to wheat yields, impacting their relatively smaller production bases. In contrast, France emerges strongly as a potential beneficiary for wheat production and trade, alongside Germany and Ukraine in Europe, Uzbekistan in Central Asia, and Argentina in South America.

In keeping with the global picture, the United States is also the origin of a large majority of the riskiest wheat production-consumption relationships (Figure 11). As is the case with maize, many of the riskiest relationships for wheat appear to be with Caribbean small islands and other Latin American countries, as well as with countries in Asia. What is different to the case of maize is that our results identify several African countries as particularly exposed to TCRs from US wheat production, including Nigeria, which consumes 3.63 million tonnes of wheat per year, of which roughly 2.46 tonnes come from the United States.

Recognizing that maize, rice and wheat play a critical role in achieving global food security (Shiferaw et al., 2011), these results suggest that climate change not only creates risks for producing countries but also transmits those risks through agricultural commodity trade to consumers of all kinds, and can do so over significant distances. The maize and rice markets appear to be highly exposed to climate change, and while wheat production seems more stable, the cost of redistributing wheat production to Europe and parts of South America and Asia needs to be taken into account and would likely entail significant negative consequences for existing producers.

Figure 6. Top global exporters of risk for **maize**



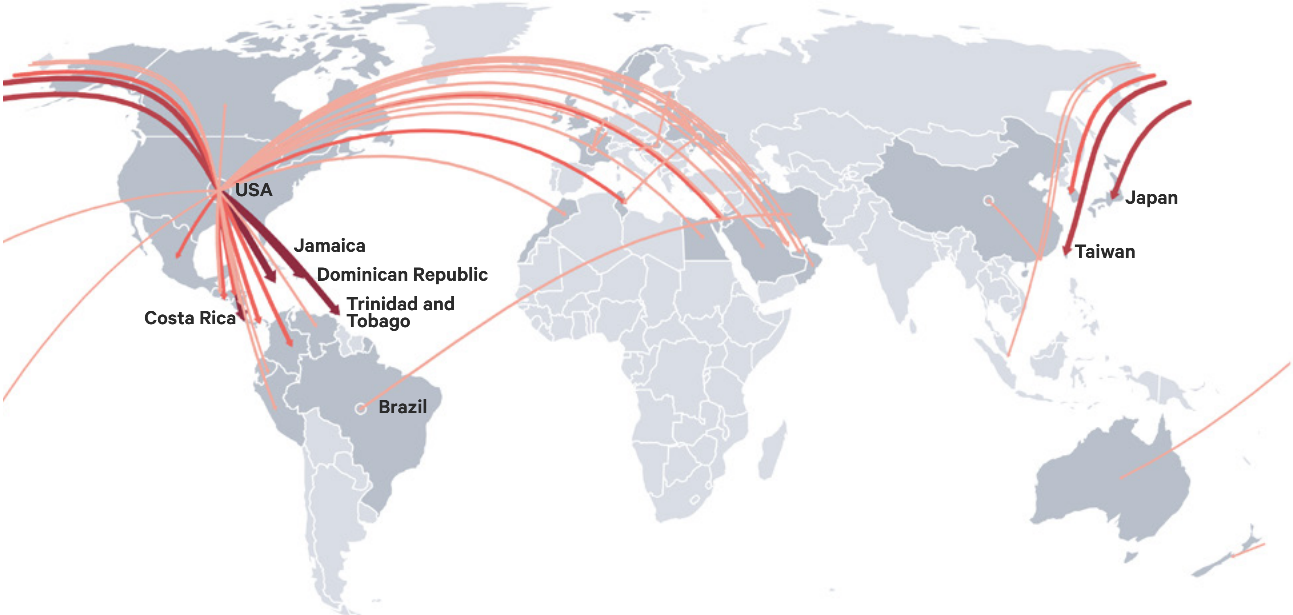
#	EXPORTER	TOTAL SHARE OF GLOBAL RISK (%)	EMBEDDED EXPORTS (TONNES)	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	USA		64.18mn	-45.5%
2	Brazil		20.33mn	-22.1%
3	China		32.81mn	-15.5%
4	Ukraine		9.66mn	-29.5%
5	France		8.25mn	-32.2%
6	Hungary		4.55mn	-45.0%
7	Argentina		18.04mn	-6.8%
8	Thailand		3.14mn	-48.7%
9	Serbia		6.11mn	-41.4%
10	Indonesia		3.47mn	-21.0%
11	Italy		1.61mn	-32.1%
12	Romania		1.97mn	-34.3%
13	Paraguay		1.85mn	-24.5%
14	South Africa		2.36mn	-8.7%
15	Mexico		1.88mn	-35.6%
16	Austria		0.99mn	-29.2%
17	Slovakia		0.53mn	-39.9%
18	Croatia		0.34mn	-40.3%
19	Bulgaria		1.08mn	-17.9%
20	Philippines		1.26mn	-25.3%
...	...		...	...
5	Iran		0.10mn	23.5%
4	New Zealand		0.14mn	69.7%
3	Chile		0.52mn	67.1%
2	Canada		4.49mn	17.0%
1	Russia		1.58mn	12.7%

43:1 RISK TO OPPORTUNITY RATIO

226.2 MN TONNES TOTAL GLOBAL FLOW

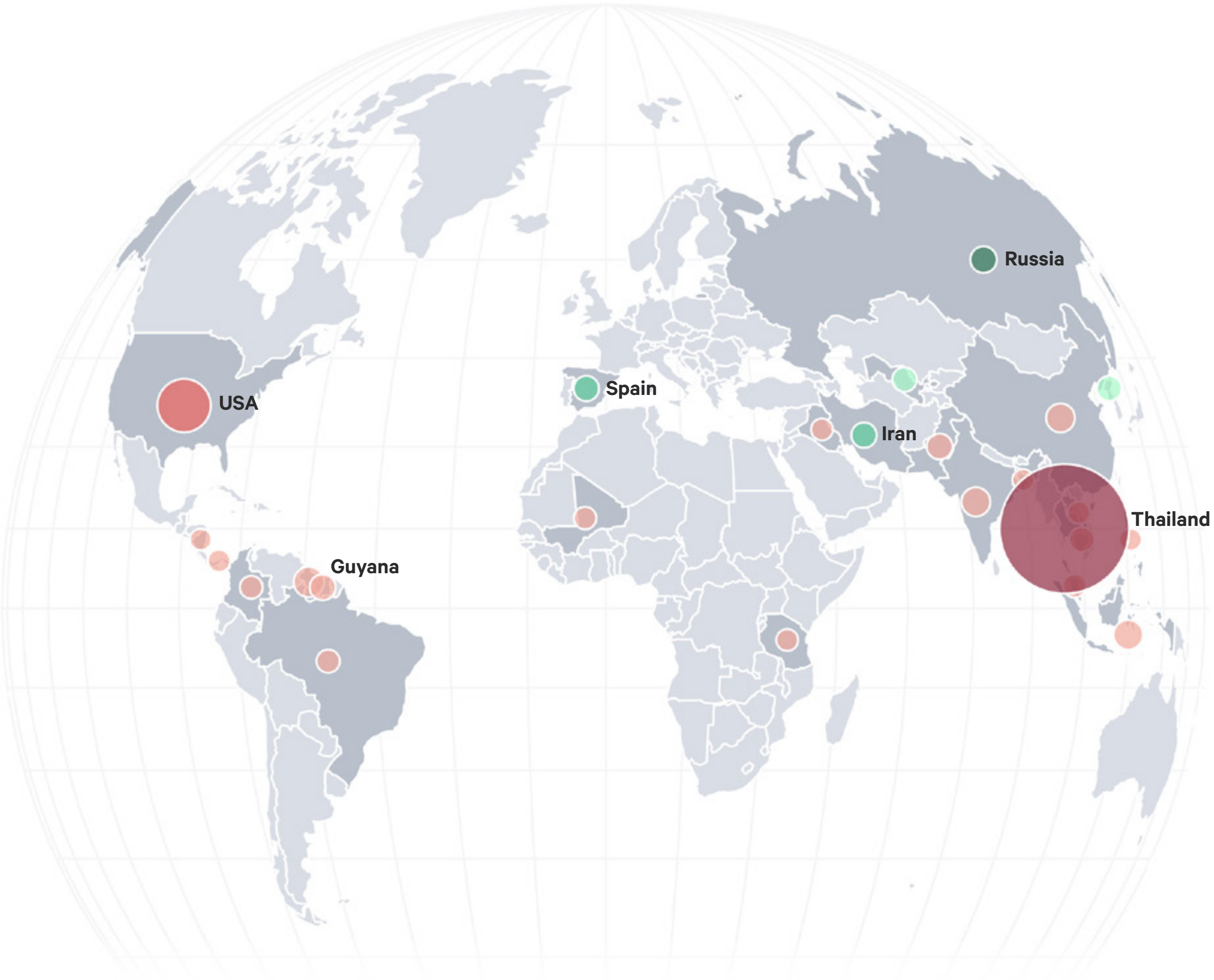
-27.2% IMPACT OF CLIMATE CHANGE ON PRODUCTION

Figure 7. Top 50 high-risk bilateral trade relationships for **maize**



#	EXPORTER	IMPORTER	RISK TO BILATERAL TRADE	EMBEDDED TRADE FLOW (TONNES)	IMPORTER'S TOTAL STOCK	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	USA	Jamaica		0.28mn	0.32mn	-45.5%
2	USA	Costa Rica		0.42mn	0.53mn	-45.5%
3	USA	Dominican Republic		0.83mn	1.13mn	-45.5%
4	USA	Trinidad and Tobago		0.09mn	0.13mn	-45.5%
5	USA	Taiwan		2.85mn	4.62mn	-45.5%
6	USA	Japan		16.99mn	29.64mn	-45.5%
7	USA	Colombia		2.19mn	4.84mn	-45.5%
8	USA	Republic of Korea		4.99mn	11.13mn	-45.5%
9	USA	Panama		0.30mn	0.66mn	-45.5%
10	USA	El Salvador		0.59mn	1.49mn	-45.5%
11	USA	Israel		0.72mn	1.81mn	-45.5%
12	USA	Honduras		0.37mn	1.00mn	-45.5%
13	USA	Tunisia		0.26mn	0.78mn	-45.5%
14	USA	Mexico		10.49mn	33.29mn	-45.5%
15	USA	Guatemala		0.71mn	2.44mn	-45.5%
...	...		...	...	...	...
25	Brazil	Iran		2.48mn	5.67mn	-22.1%
26	USA	Jordan		0.13mn	0.62mn	-45.5%
27	USA	Canada		2.98mn	15.68mn	-45.5%
28	USA	Ecuador		0.30mn	1.65mn	-45.5%
29	Hungary	Slovenia		0.11mn	0.62mn	-45.0%
30	Hungary	Estonia		0.02mn	0.09mn	-45.0%
...	...	...	...	...	...	...
45	USA	Australia		0.26mn	1.85mn	-45.5%
46	USA	Sweden		0.09mn	0.64mn	-45.5%
47	Ukraine	Belarus		0.19mn	0.88mn	-29.5%
48	USA	New Zealand		0.07mn	0.55mn	-45.5%
49	France	Netherlands		0.71mn	3.80mn	-32.2%
50	France	Belgium		0.58mn	3.16mn	-32.2%

Figure 8. Top global exporters of risk for **rice**



#	EXPORTER	TOTAL SHARE OF GLOBAL RISK (%)	EMBEDDED EXPORTS (TONNES)	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	Thailand		18.08mn	-34.9%
2	USA		2.42mn	-31.4%
3	Guyana		0.55mn	-35.5%
4	Indonesia		3.46mn	-11.8%
5	India		10.57mn	-3.9%
6	China		20.01mn	-1.8%
7	Suriname		0.22mn	-44.4%
8	Pakistan		2.61mn	-4.6%
9	Cambodia		0.65mn	-24.9%
10	Malaysia		0.45mn	-22.2%
11	Brazil		0.30mn	-25.9%
12	Colombia		0.21mn	-41.9%
13	Mali		1.43mn	-58.4%
14	Panama		0.09mn	-14.9%
15	Laos		0.19mn	-27.9%
16	Philippines		0.58mn	-12.9%
17	Iraq		0.32mn	-39.2%
18	Tanzania		1.82mn	-12.4%
19	Nicaragua		0.05mn	-31.4%
20	Bangladesh		0.08mn	-36.3%
...	...		...	...
5	Uzbekistan		0.22mn	38.6%
4	North Korea		2.34mn	23.1%
3	Spain		0.27mn	40.1%
2	Iran		0.18mn	67.0%
1	Russia		0.14mn	60.2%

6:1 RISK TO OPPORTUNITY RATIO

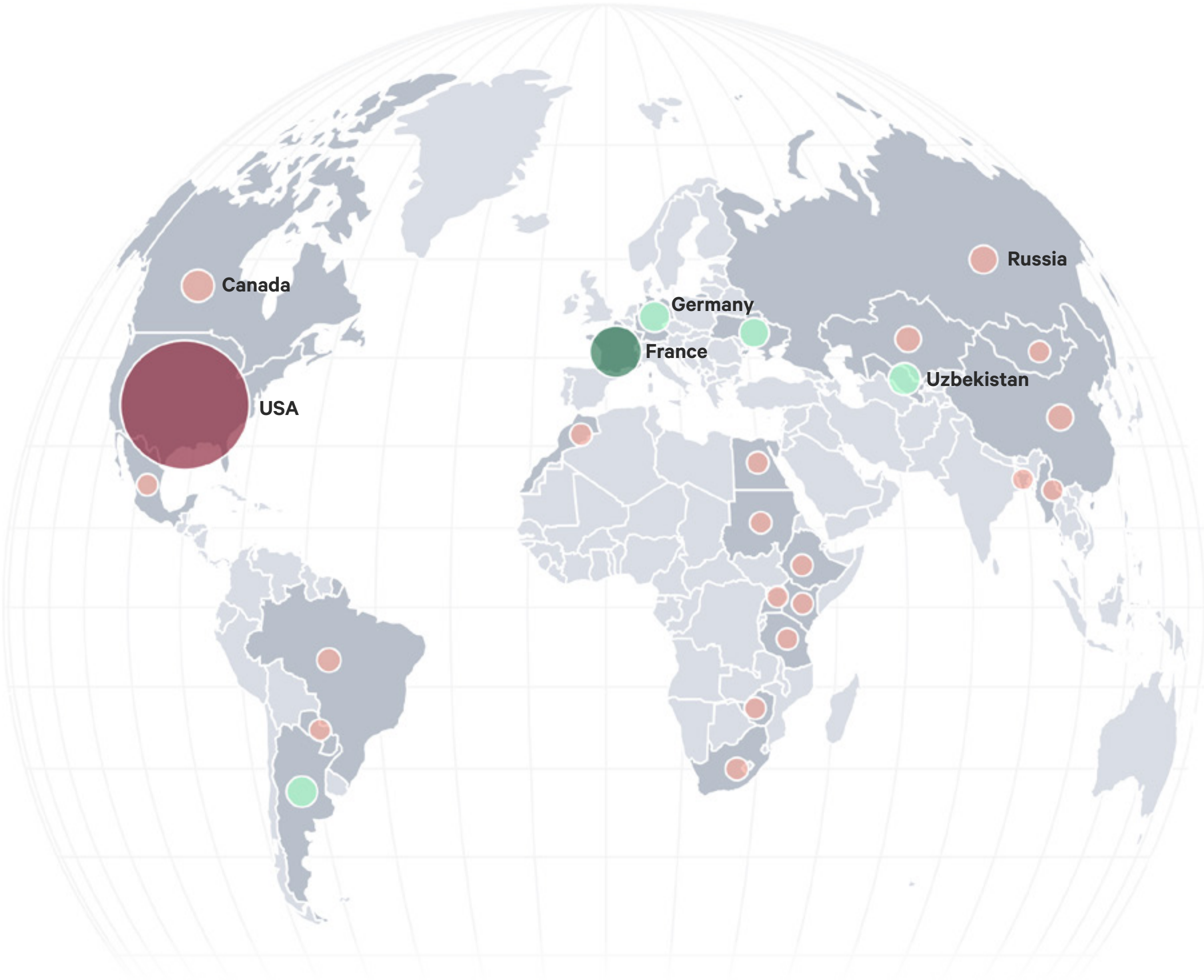
123.3 MN TONNES TOTAL GLOBAL FLOW

-8.1% IMPACT OF CLIMATE CHANGE ON PRODUCTION

Figure 9. Top global exporters of risk for **rice**

#	EXPORTER	IMPORTER	RISK TO BILATERAL TRADE	EMBEDDED TRADE FLOW (TONNES)	IMPORTER'S TOTAL STOCK	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	Thailand	Brunei Darussalam		0.10mn	0.13mn	-34.9%
2	Thailand	Benin		0.66mn	0.85mn	-34.9%
3	Thailand	Georgia		0.07mn	0.10mn	-34.9%
4	USA	Honduras		0.10mn	0.17mn	-31.4%
5	Thailand	South Africa		1.10mn	2.01mn	-34.9%
6	USA	El Salvador		0.08mn	0.15mn	-31.4%
7	Thailand	Togo		0.15mn	0.30mn	-34.9%
8	USA	Guatemala		0.08mn	0.15mn	-31.4%
9	Thailand	Cameroon		0.17mn	0.36mn	-34.9%
10	USA	Mexico		0.73mn	1.41mn	-31.4%
11	Thailand	Senegal		0.75mn	1.71mn	-34.9%
12	Guyana	Trinidad and Tobago		0.02mn	0.05mn	-35.5%
13	Thailand	Ghana		0.44mn	1.15mn	-34.9%
14	Guyana	Jamaica		0.03mn	0.09mn	-35.5%
15	Thailand	Tunisia		0.02mn	0.04mn	-34.9%
...	...		...	...	...	...
25	Suriname	Trinidad and Tobago		<0.01mn	0.05mn	-44.4%
26	USA	Jamaica		0.02mn	0.09mn	-31.4%
27	Thailand	New Zealand		0.04mn	0.19mn	-34.9%
28	Thailand	Nigeria		1.20mn	6.20mn	-34.9%
29	Thailand	Norway		0.04mn	0.22mn	-34.9%
30	Thailand	Switzerland		0.07mn	0.39mn	-34.9%
...	...	...	...	...	...	...
45	Thailand	Netherlands		0.09mn	0.72mn	-34.9%
46	Thailand	Estonia		<0.01mn	0.02mn	-34.9%
47	Thailand	Puerto Rico		0.01mn	0.09mn	-34.9%
48	Thailand	Germany		0.29mn	2.47mn	-34.9%
49	Thailand	United Kingdom		0.26mn	2.28mn	-34.9%
50	Thailand	Zambia		<0.01mn	0.05mn	-34.9%

Figure 10. Top global risk exporters for **wheat**



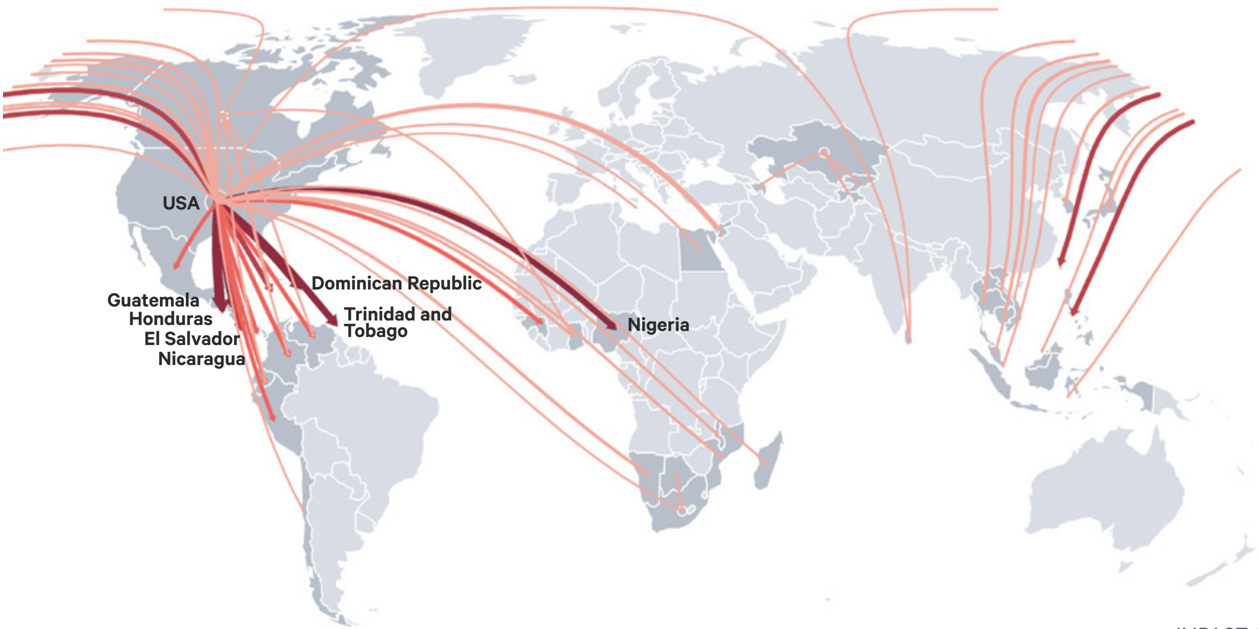
1:1 RISK TO OPPORTUNITY RATIO

249.2 MN TONNES TOTAL GLOBAL FLOW

+13.9% IMPACT OF CLIMATE CHANGE ON PRODUCTION

#	EXPORTER	TOTAL SHARE OF GLOBAL RISK (%)	EMBEDDED EXPORTS (TONNES)	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	USA		31.50mn	-64.0%
2	Canada		20.86mn	-13.0%
3	Russia		22.37mn	-9.1%
4	China		17.43mn	-9.2%
5	Kazakhstan		8.58mn	-20.3%
6	Brazil		1.45mn	-58.3%
7	South Africa		0.27mn	-18.3%
8	Morocco		0.87mn	-32.6%
9	Egypt		0.71mn	-21.7%
10	Zimbabwe		0.01mn	-58.8%
11	Sudan		0.47mn	-88.7%
12	Ethiopia		0.21mn	-45.7%
13	Tanzania		0.11mn	-62.2%
14	Kenya		0.13mn	-36.4%
15	Mexico		0.60mn	-10.2%
16	Myanmar		0.16mn	-25.8%
17	Paraguay		0.49mn	-8.4%
18	Mongolia		0.22mn	-23.1%
19	Bangladesh		0.16mn	-29.4%
20	Uganda		<0.01mn	-62.3%
...	...		...	...
5	Ukraine		10.36mn	32.9%
4	Argentina		9.07mn	27.8%
3	Germany		9.25mn	38.0%
2	Uzbekistan		6.30mn	194.2%
1	France		22.44mn	34.6%

Figure 11. Top 50 high-risk bilateral trade relationships for **wheat**



#	EXPORTER	IMPORTER	RISK TO BILATERAL TRADE	EMBEDDED TRADE FLOW (TONNES)	IMPORTER'S TOTAL STOCK	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	USA	Honduras		0.19mn	0.23mn	-64.0%
2	USA	Dominican Republic		0.42mn	0.51mn	-64.0%
3	USA	El Salvador		0.23mn	0.27mn	-64.0%
4	USA	Trinidad and Tobago		0.12mn	0.15mn	-64.0%
5	USA	Nicaragua		0.09mn	0.12mn	-64.0%
6	USA	Guatemala		0.39mn	0.53mn	-64.0%
7	USA	Nigeria		2.46mn	3.63mn	-64.0%
8	USA	Costa Rica		0.12mn	0.19mn	-64.0%
9	USA	Jamaica		0.17mn	0.31mn	-64.0%
10	USA	Taiwan		0.88mn	1.69mn	-64.0%
11	USA	Philippines		1.47mn	2.90mn	-64.0%
12	USA	Colombia		0.62mn	1.45mn	-64.0%
13	USA	Guinea		0.07mn	0.17mn	-64.0%
14	USA	Venezuela		0.65mn	1.67mn	-64.0%
15	USA	Panama		0.10mn	0.27mn	-64.0%
...	...	...	...	...	...	...
25	USA	Israel		0.36mn	1.87mn	-64.0%
26	USA	Mozambique		0.08mn	0.42mn	-64.0%
27	USA	Malawi		0.02mn	0.11mn	-64.0%
28	USA	Jordan		0.17mn	0.99mn	-64.0%
29	USA	Brunei Darussalam		<0.01mn	0.03mn	-64.0%
30	Kazakhstan	Tajikistan		0.54mn	1.32mn	-20.3%
...	...	...	...	...	...	...
45	USA	Chile		0.18mn	2.11mn	-64.0%
46	USA	Sri Lanka		0.09mn	1.08mn	-64.0%
47	USA	South Africa		0.31mn	3.60mn	-64.0%
48	Canada	Colombia		0.60mn	1.45mn	-13.0%
49	Canada	Sri Lanka		0.42mn	1.08mn	-13.0%
50	Canada	Jamaica		0.11mn	0.31mn	-13.0%

3.2 Embedded commodities: soy and sugar cane

The global soy market has a risk to opportunity ratio of roughly 2:1 (Figure 12). Considering that soy is an essential component of many feedstocks and plant-based protein substitutes, climate risks in this market are likely to impact consumers and food security less directly than in markets for maize, rice and wheat, but may manifest instead in the meat industry, for example. In this case, both the US and Brazil appear to contribute disproportionately to TCRs in the soy market, with the US far surpassing Brazil and both outstripping Bolivia, their nearest rival. It is plausible that Argentina's soy industry, which produces a similar amount of soy to the US and Brazil, could benefit from climate change. The same goes for Canada, whose initial production base is smaller, but which may experience a particularly high increase in soy yields.

The US appears to be the source of many of the highest-risk trading relationships in the soy market, following a broadly similar pattern to its wheat production (Figure 13). Brazil registers several high-risk relationships as well – primarily with Europe – in addition to one entry from Bolivia to Colombia.

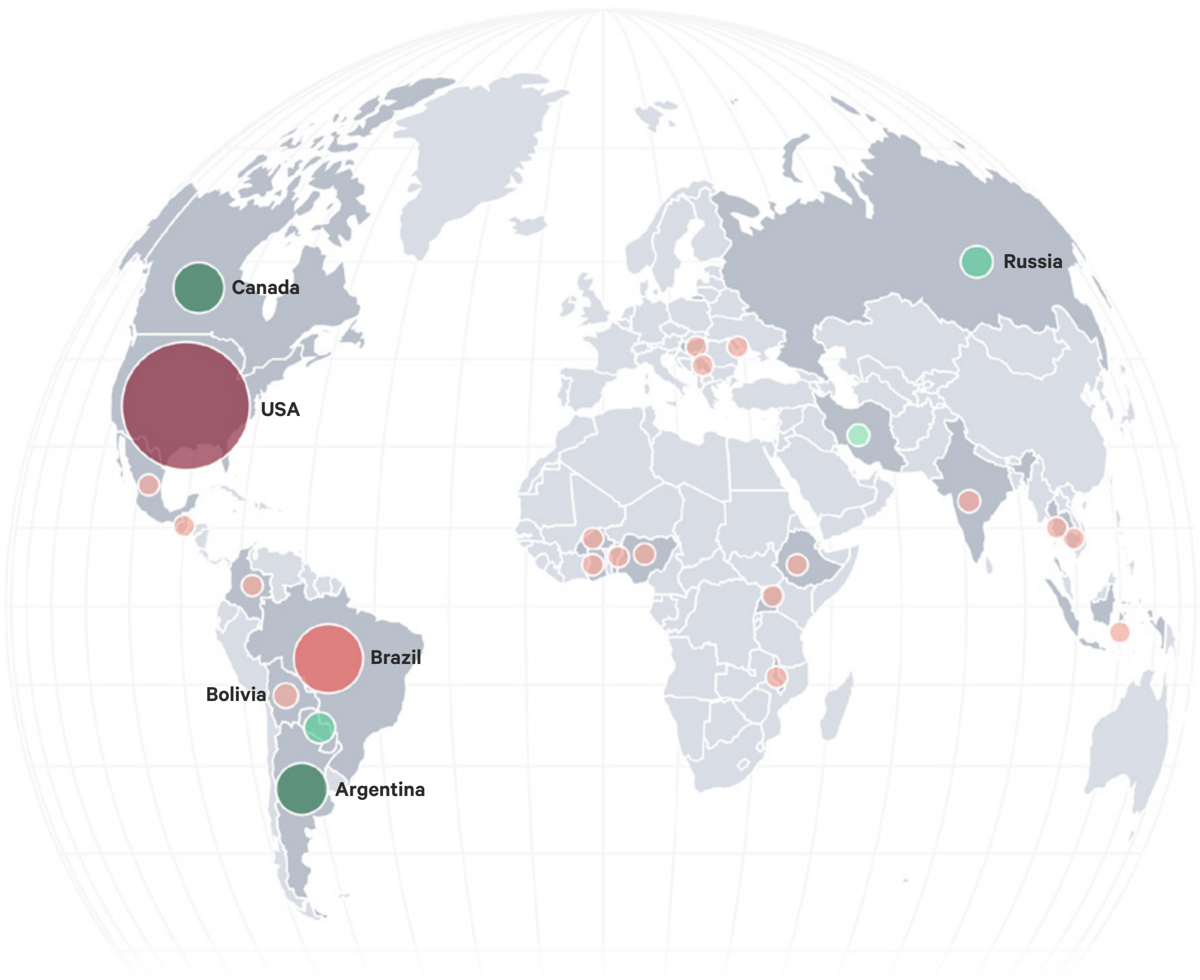
For sugar cane, both exposure to climate risk and opportunities for growth are concentrated in the Global South, with Brazil, Thailand, India, Cuba, and China – all major growers – likely to introduce significant risk to the global market.

Sugar cane, which is primarily used as a food additive, is exchanged in relatively higher volumes than the other crops considered, and also appears to be highly at risk due to climate change (Figure 14). Both exposure to risk and opportunities for growth are concentrated in the Global South, with Brazil, Thailand, India, Cuba, and China – all major sugar cane growers – likely to introduce significant risk to the global sugar cane market in a warming world. In contrast, both Argentina and South Africa appear well-placed to make up a degree of this shortfall, with Argentina in particular already producing high quantities of sugar cane.

The bilateral risks tell a somewhat different story, with Zimbabwe topping the chart due to high-dependency relationships with its neighbours Namibia and Botswana (Figure 15). Brazil and Thailand unsurprisingly account for the majority of the other high-risk relationships, particularly Brazilian exports to Europe and Thai exports to Southeast Asia.

Because both soy and sugar cane are often embedded in the production of other goods rather than directly consumed, additional research is required to understand the precise implications of TCRs for agricultural production, trade, and food security. Future research should focus on identifying the sectors, companies, and products which are exposed to TCRs in order to shed further light on these highly complex supply chains. The role of soy in feedstock and various meat (or meat-alternative) supply chains is a particularly important candidate for future work.

Figure 12 – Top exporters of global-risk for **soy**



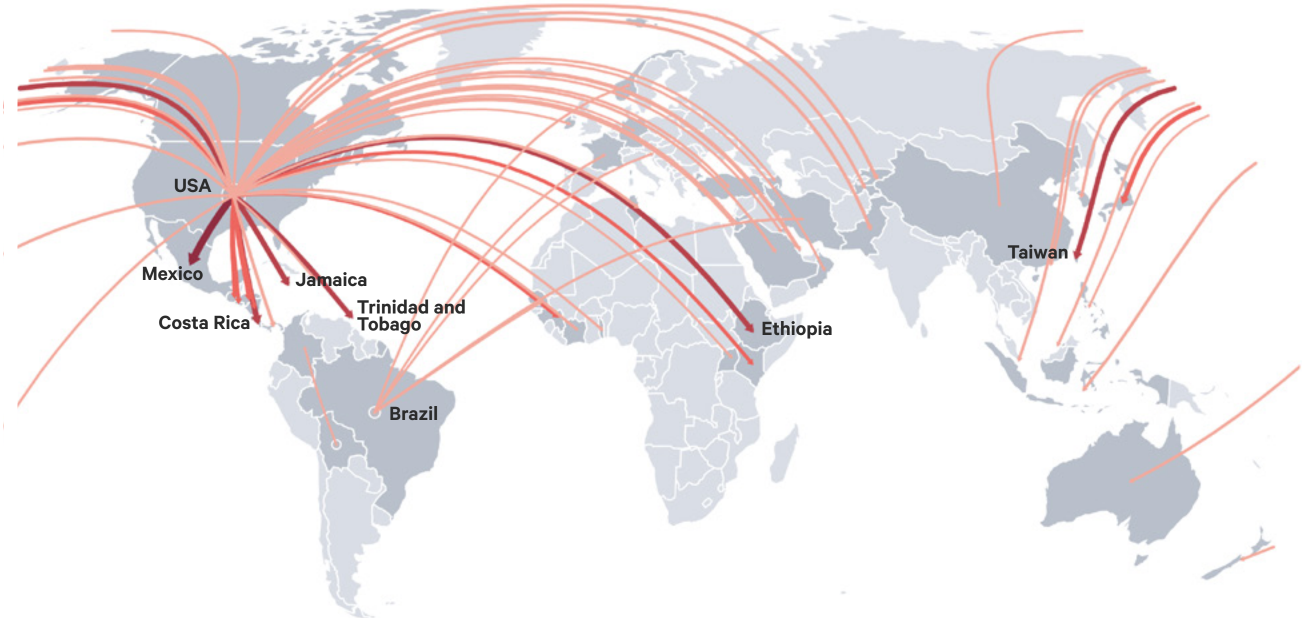
2:1 RISK TO OPPORTUNITY RATIO

156.2 MN TONNES TOTAL GLOBAL FLOW

-7.2% IMPACT OF CLIMATE CHANGE ON PRODUCTION

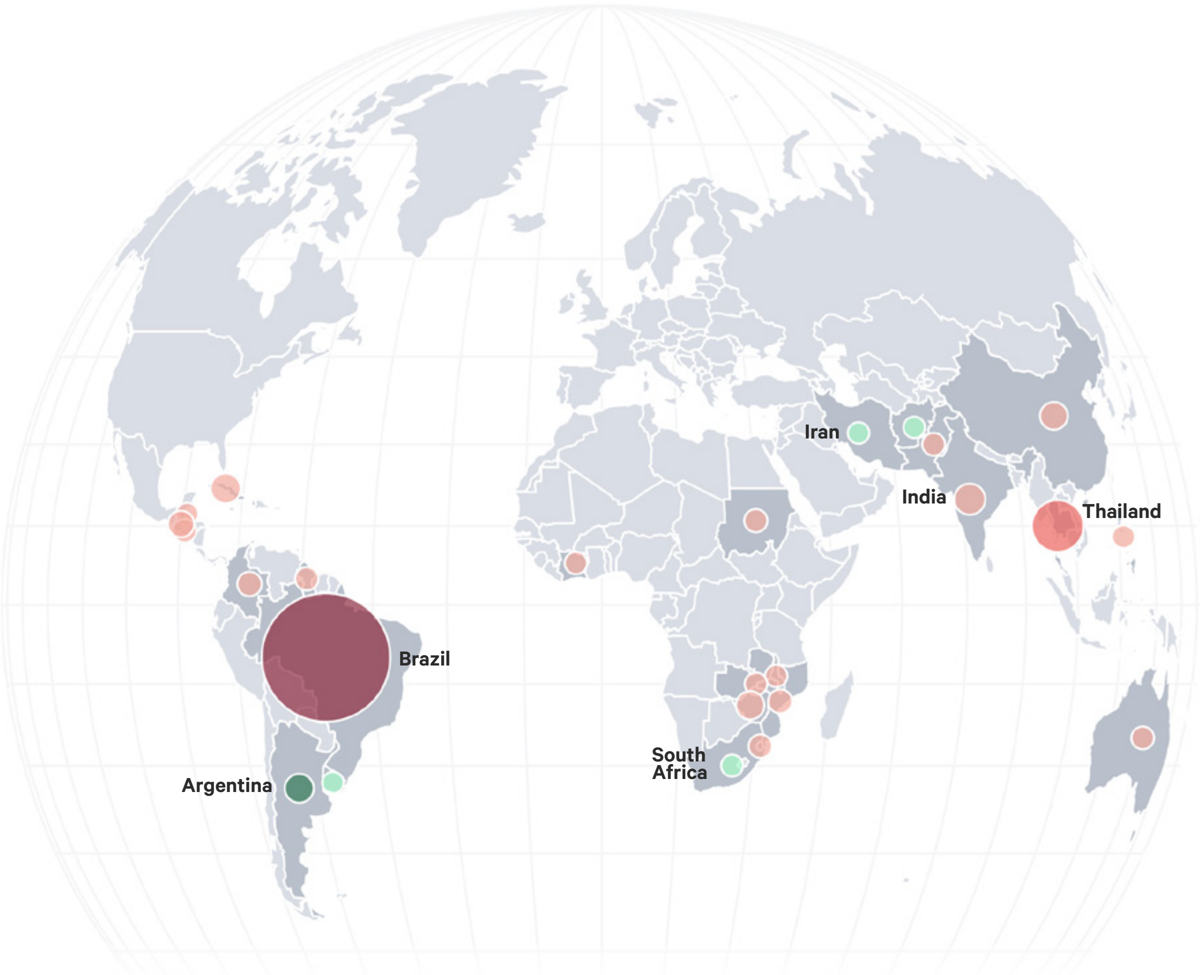
#	EXPORTER	TOTAL SHARE OF GLOBAL RISK (%)	EMBEDDED EXPORTS (TONNES)	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	USA		44.63mn	-29.3%
2	Brazil		49.47mn	-11.8%
3	Bolivia		1.41mn	-25.1%
4	India		1.56mn	-4.6%
5	Malawi		0.02mn	-14.5%
6	Indonesia		0.36mn	-7.4%
7	Nigeria		0.08mn	-29.3%
8	Uganda		0.04mn	-15.6%
9	Serbia		0.43mn	-5.2%
10	Hungary		0.04mn	-16.7%
11	Ghana		0.03mn	-33.9%
12	Thailand		0.04mn	-37.9%
13	Guatemala		<0.01mn	-26.8%
14	Benin		<0.01mn	-36.0%
15	Burkina Faso		<0.01mn	-55.9%
16	Cambodia		0.03mn	-24.6%
17	Moldova		0.07mn	-2.0%
18	Ethiopia		0.02mn	-12.5%
19	Mexico		0.01mn	-24.5%
20	Colombia		0.01mn	-16.8%
...	...		...	...
5	Iran		0.01mn	70.0%
4	Paraguay		6.37mn	15.1%
3	Russia		0.26mn	88.3%
2	Canada		3.11mn	119.6%
1	Argentina		41.66mn	7.5%

Figure 13. Top 50 high-risk bilateral trade relationships for **soy**



#	EXPORTER	IMPORTER	RISK TO BILATERAL TRADE	EMBEDDED TRADE FLOW (TONNES)	IMPORTER'S TOTAL STOCK	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	USA	Mexico		5.25mn	6.32mn	-29.3%
2	USA	Costa Rica		0.18mn	0.27mn	-29.3%
3	USA	Jamaica		0.08mn	0.14mn	-29.3%
4	USA	Ethiopia		0.06mn	0.10mn	-29.3%
5	USA	Taiwan		1.55mn	2.72mn	-29.3%
6	USA	Trinidad and Tobago		0.05mn	0.09mn	-29.3%
7	USA	Japan		4.71mn	9.04mn	-29.3%
8	USA	Honduras		0.06mn	0.13mn	-29.3%
9	USA	Guinea		0.01mn	0.02mn	-29.3%
10	USA	Kenya		0.03mn	0.07mn	-29.3%
11	USA	El Salvador		0.11mn	0.28mn	-29.3%
12	USA	Guatemala		0.16mn	0.40mn	-29.3%
13	USA	Nicaragua		0.03mn	0.07mn	-29.3%
14	USA	Pakistan		0.17mn	0.46mn	-29.3%
15	USA	Panama		0.09mn	0.25mn	-29.3%
...	...	...	...	...	...	...
25	USA	Tunisia		0.26mn	0.81mn	-29.3%
26	USA	Brunei Darussalam		<0.01mn	<0.01mn	-29.3%
27	USA	Saudi Arabia		0.35mn	1.16mn	-29.3%
28	USA	Hong Kong		0.23mn	0.76mn	-29.3%
29	USA	Turkey		0.66mn	2.22mn	-29.3%
30	USA	New Zealand		0.06mn	0.22mn	-29.3%
...	...	...	...	...	...	...
45	Brazil	Slovenia		0.09mn	0.14mn	-11.8%
46	Brazil	France		3.04mn	4.91mn	-11.8%
47	Bolivia	Colombia		0.40mn	1.43mn	-25.1%
48	USA	Jordan		0.10mn	0.44mn	-29.3%
49	USA	Ireland		0.07mn	0.30mn	-29.3%
50	USA	Germany		1.38mn	6.12mn	-29.3%

Figure 14. Top global exporters of risk for **sugar cane**



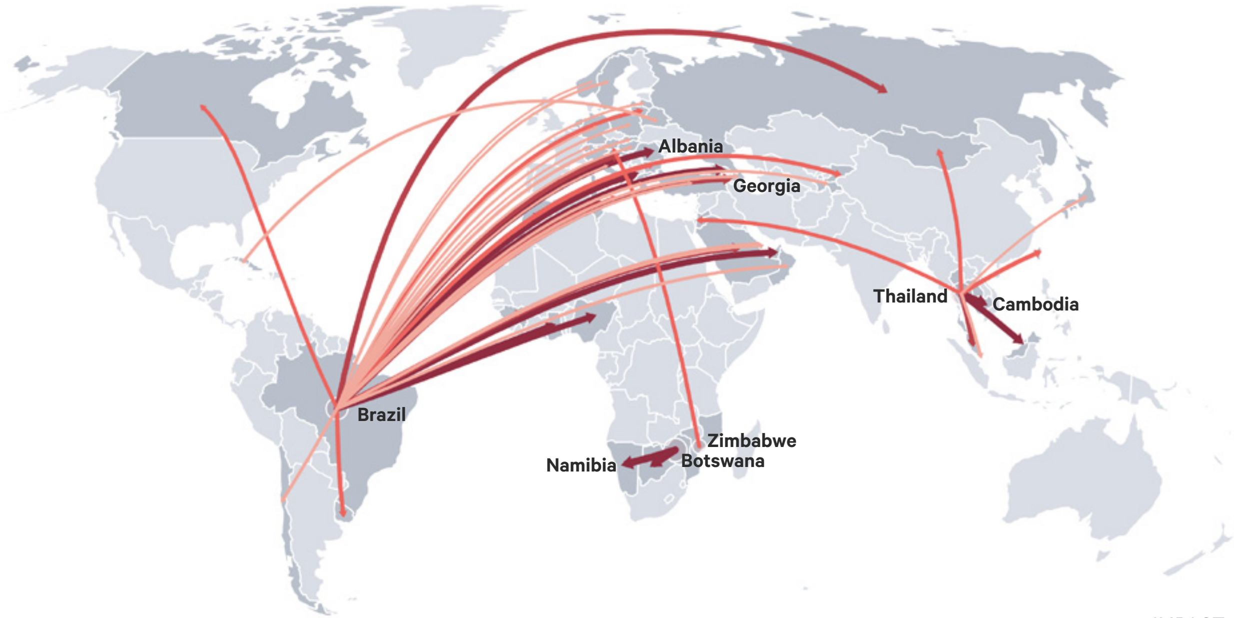
#	EXPORTER	TOTAL SHARE OF GLOBAL RISK (%)	EMBEDDED EXPORTS (TONNES)	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	Brazil		206.00mn	-65.6%
2	Thailand		50.81mn	-77.6%
3	India		12.02mn	-61.7%
4	Cuba		16.35mn	-65.3%
5	Zimbabwe		1.96mn	-75.1%
6	China		17.38mn	-26.7%
7	Guatemala		9.70mn	-74.5%
8	Colombia		7.51mn	-50.5%
9	Mozambique		1.13mn	-76.8%
10	El Salvador		1.38mn	-78.8%
11	Eswatini		5.13mn	-35.4%
12	Guyana		3.22mn	-63.9%
13	Sudan		5.81mn	-76.6%
14	Philippines		4.15mn	-58.7%
15	Pakistan		2.67mn	-43.0%
16	Australia		9.13mn	-11.0%
17	Zambia		0.78mn	-75.2%
18	Belize		1.10mn	-76.0%
19	Côte d'Ivoire		0.74mn	-75.6%
20	Malawi		0.92mn	-77.6%
...	...		...	...
5	Afghanistan		0.08mn	34.7%
4	Uruguay		0.07mn	74.5%
3	Iran		0.45mn	6.6%
2	South Africa		3.59mn	15.4%
1	Argentina		6.58mn	74.9%

25:1 RISK TO OPPORTUNITY RATIO

422.7 MN TONNES TOTAL GLOBAL FLOW

-58.5% IMPACT OF CLIMATE CHANGE ON PRODUCTION

Figure 15. Top 50 high-risk bilateral trade relationships for **sugar cane**



#	EXPORTER	IMPORTER	RISK TO BILATERAL TRADE	EMBEDDED TRADE FLOW (TONNES)	IMPORTER'S TOTAL STOCK	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	Zimbabwe	Namibia		0.22mn	0.25mn	-75.1%
2	Zimbabwe	Botswana		0.14mn	0.15mn	-75.1%
3	Thailand	Cambodia		1.88mn	2.28mn	-77.6%
4	Brazil	Albania		0.48mn	0.50mn	-65.6%
5	Brazil	Georgia		3.41mn	3.68mn	-65.6%
6	Thailand	Brunei Darussalam		0.08mn	0.10mn	-77.6%
7	Brazil	Ghana		4.10mn	4.55mn	-65.6%
8	Brazil	Tunisia		2.04mn	2.28mn	-65.6%
9	Brazil	United Arab Emirates		12.78mn	14.27mn	-65.6%
10	Brazil	Nigeria		12.04mn	13.45mn	-65.6%
11	Brazil	Romania		2.43mn	2.72mn	-65.6%
12	Brazil	Morocco		6.51mn	7.36mn	-65.6%
13	Brazil	Armenia		0.22mn	0.26mn	-65.6%
14	Brazil	Russian Federation		27.53mn	33.04mn	-65.6%
15	Brazil	Saudi Arabia		4.48mn	5.41mn	-65.6%
...	...	...	...	...	...	...
25	Thailand	Jordan		0.62mn	1.18mn	-77.6%
26	Brazil	Canada		5.92mn	9.64mn	-65.6%
27	Brazil	Malta		0.04mn	0.07mn	-65.6%
28	Brazil	Bulgaria		0.40mn	0.70mn	-65.6%
29	Thailand	Singapore		0.80mn	1.69mn	-77.6%
30	Brazil	Chile		1.61mn	2.89mn	-65.6%
...	...	...	...	...	...	...
45	Brazil	Latvia		0.03mn	0.07mn	-65.6%
46	Brazil	Netherlands		1.14mn	2.59mn	-65.6%
47	Brazil	Bahrain		0.06mn	0.13mn	-65.6%
48	Brazil	Switzerland		0.44mn	1.03mn	-65.6%
49	Brazil	Germany		3.26mn	7.70mn	-65.6%
50	Brazil	Norway		0.31mn	0.73mn	-65.6%

3.3 Luxury commodities: coffee

The international coffee market is somewhat distinct from the crops considered thus far. Coffee is a luxury good, primarily consumed in developed countries, though its popularity is increasing worldwide. *C. arabica* is considered to be a higher-quality coffee variety and primarily used in coffee houses and speciality roasteries, while *C. robusta* is an essential component in many instant coffees or blends, in addition to being consumed in emerging markets. The global coffee supply chain is somewhat more complex than those for maize, rice, or wheat (but relatively simpler than those for soy or sugar cane) because coffee is grown by producers, often purchased by cooperatives, distributed by traders, then roasted and consumed. In this way, there are many private actors engaged in the international coffee market who are potentially exposed to climate risks that manifest further along the supply chain.

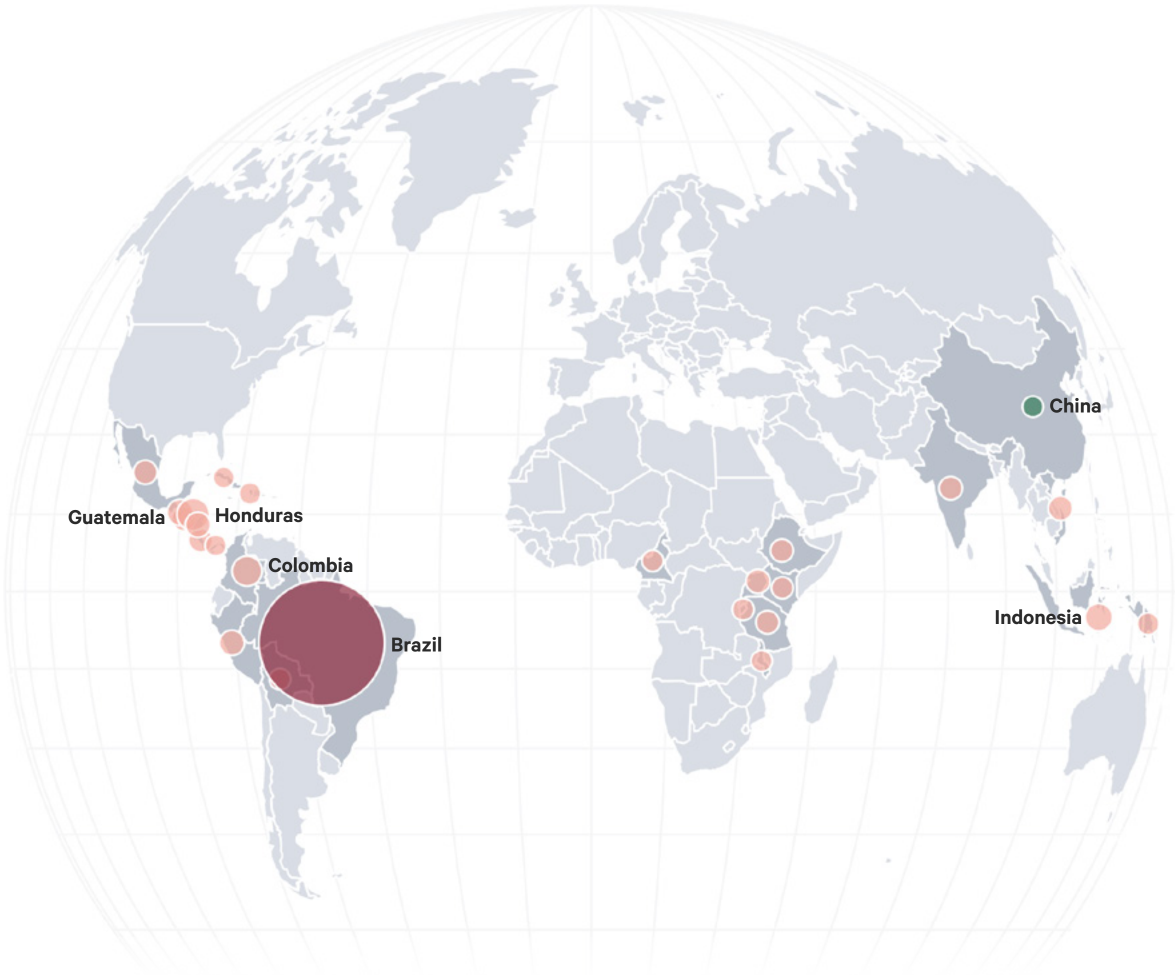
Globally speaking, both Arabica and Robusta coffee are extremely at risk from climate change, with very few increases to coffee production anticipated in a warming world (Figure 16, Figure 17). In the Arabica market, Brazil is by far the most critical source of risk, while in the Robusta market this role is shared evenly between Viet Nam, Brazil, and Indonesia. Throughout regions suitable for coffee production – the world's "coffee belt" – marked decreases in coffee yields are expected.

Throughout regions suitable for coffee production – the world's "coffee belt" – marked decreases in coffee yields are expected.

In bilateral terms, there are also apparent differences between the Arabica and Robusta markets. For the former, Brazil is the point of origin for nearly all of the riskiest relationships, including with trading partners in South America (e.g. Argentina, Uruguay), Europe (e.g. Italy, Sweden, Germany), and Africa (e.g. Tunisia, South Africa), where the demand for high-quality and speciality coffees is greater (Figure 18).

In contrast, TCRs in the Robusta market are more acute for trading partners in the Global South where coffee consumption cultures are continuing to evolve. This includes exports from Viet Nam and Indonesia to Africa (e.g. Senegal, Morocco, Mozambique) and Southeast Asia (e.g. Cambodia, Brunei) and Brazilian coffee exports to other South American countries (e.g. Argentina, Uruguay, Bolivia) (Figure 19).

Figure 16. Top global risk exporters for **Arabica coffee**



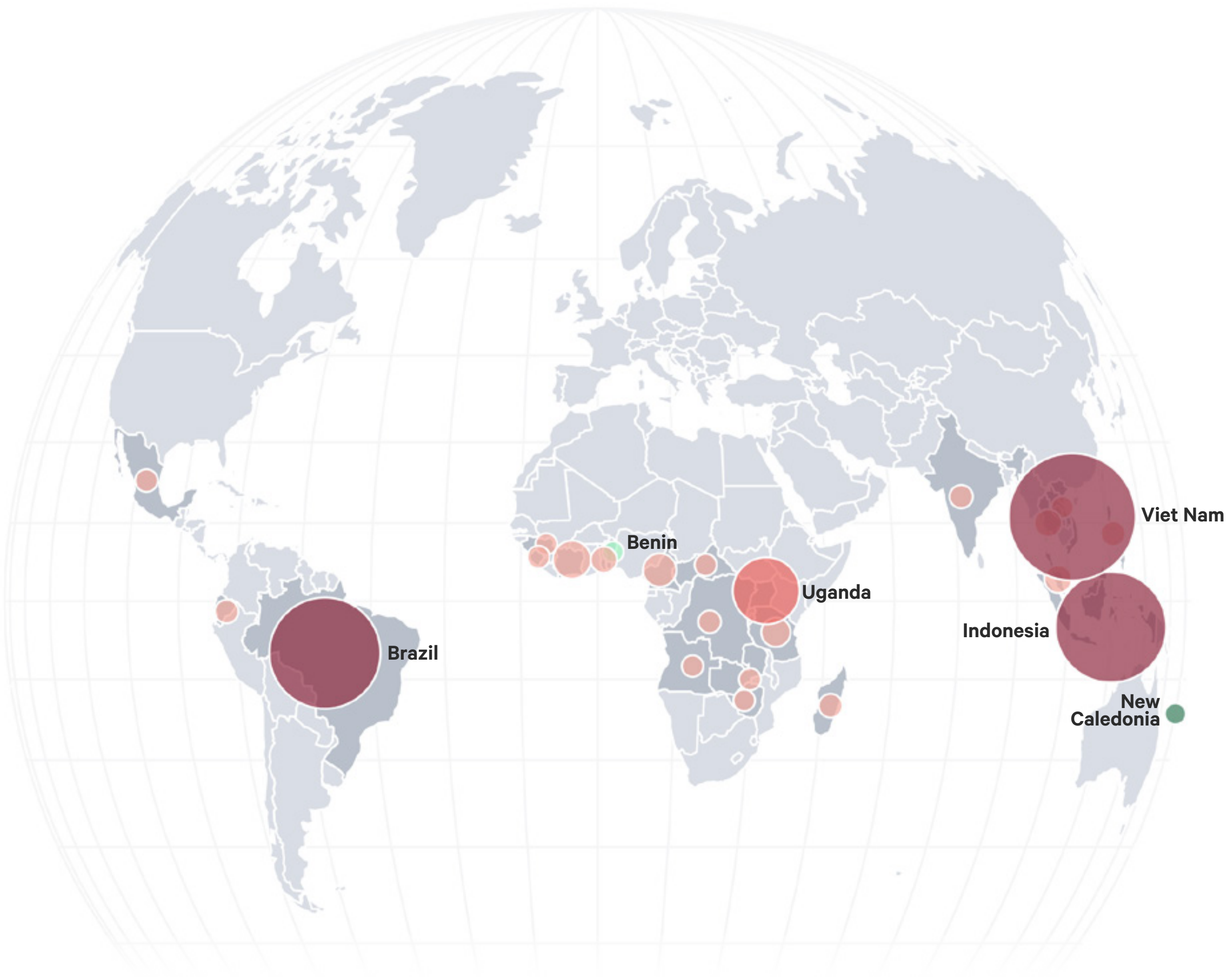
#	EXPORTER	TOTAL SHARE OF GLOBAL RISK (%)	EMBEDDED EXPORTS (60KG BAGS)	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	Brazil		23407k	-63.7%
2	Honduras		3125k	-62.8%
3	Colombia		9522k	-21.9%
4	Indonesia		1117k	-35.7%
5	Guatemala		3804k	-34.5%
6	Peru		3635k	-24.5%
7	Nicaragua		1318k	-74.2%
8	Viet Nam		261k	-52.5%
9	Costa Rica		1728k	-43.9%
10	El Salvador		1119k	-76.3%
11	Uganda		610k	-58.6%
12	Mexico		1976k	-43.9%
13	India		933k	-18.5%
14	Tanzania		548k	-52.0%
15	Ethiopia		3359k	-9.2%
16	PNG		1023k	-16.6%
17	Haiti		627k	-60.8%
18	Burundi		1203k	-28.7%
19	Kenya		717k	-12.8%
20	Panama		85k	-53.6%
21	Bolivia		142k	-60.1%
22	Cuba		200k	-78.5%
23	Cameroon		84k	-80.6%
24	Malawi		28k	-65.3%
...	...		...	...
1	China		546k	2.2%

1560:1 RISK TO OPPORTUNITY RATIO

3.7 MN TONNES TOTAL GLOBAL FLOW

-45.2% IMPACT OF CLIMATE CHANGE ON PRODUCTION

Figure 17. Top global exporters of risk for **Robusta coffee**



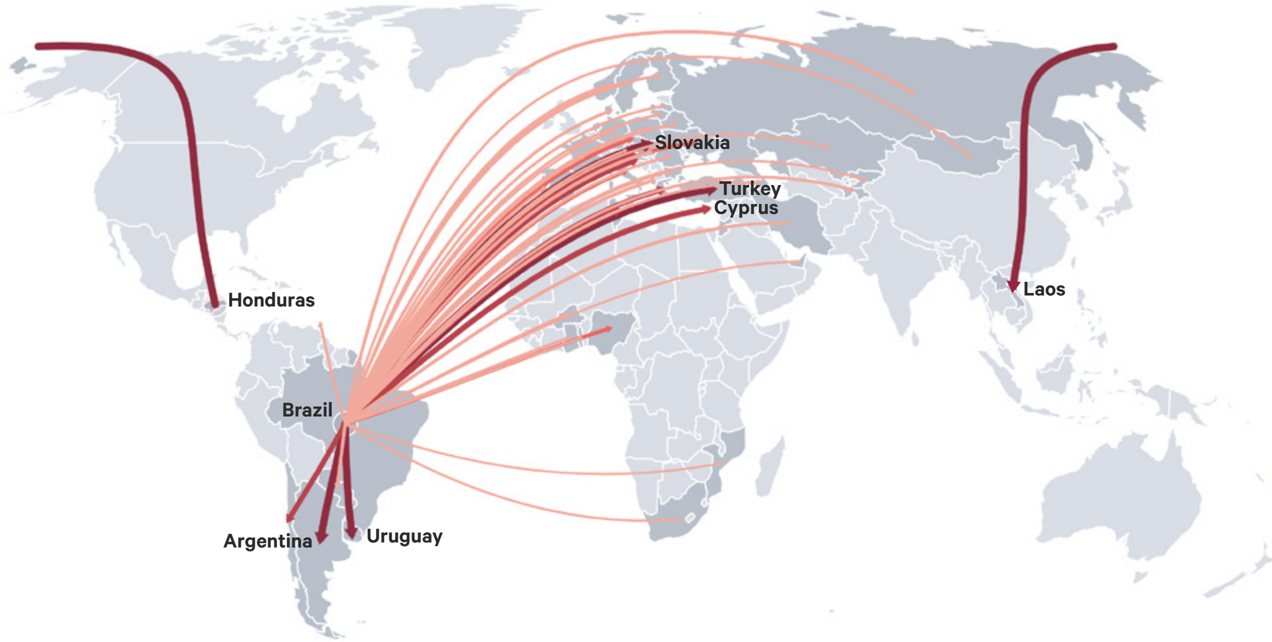
#	EXPORTER	TOTAL SHARE OF GLOBAL RISK (%)	EMBEDDED EXPORTS (60KG BAGS)	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	Viet Nam		8434k	-26.0%
2	Brazil		6992k	-19.0%
3	Indonesia		6330k	-21.6%
4	Uganda		2442k	-32.9%
5	Côte d'Ivoire		1662k	-32.0%
6	Cameroon		561k	-47.5%
7	Tanzania		413k	-24.5%
8	Thailand		428k	-25.7%
9	Malaysia		239k	-26.3%
10	Togo		131k	-19.2%
11	Philippines		267k	-24.8%
12	Madagascar		290k	-15.6%
13	Ecuador		85k	-26.3%
14	India		2077k	-1.2%
15	DRC		320k	-51.7%
16	Sierra Leone		436k	-36.6%
17	Mexico		104k	-23.0%
18	Laos		67k	-31.5%
19	CAR		99k	-49.8%
20	Zambia		19k	-13.5%
21	Zimbabwe		8k	-12.5%
22	Guinea		18k	-30.3%
23	Angola		161k	-26.7%
...	...		...	...
2	Benin		<1K	3.4%
1	New Caledonia		<1K	20.4%

336772:1 RISK TO OPPORTUNITY RATIO

1.9 MN TONNES TOTAL GLOBAL FLOW

-23.5% IMPACT OF CLIMATE CHANGE ON PRODUCTION

Figure 18. Top 50 high-risk bilateral trade relationships for **Arabica coffee**



#	EXPORTER	IMPORTER	RISK TO BILATERAL TRADE	EMBEDDED TRADE FLOW (60KG BAGS)	IMPORTER'S TOTAL STOCK (60KG BAGS)	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	Honduras	Laos		22k	23k	-62.8%
2	Brazil	Argentina		251k	273k	-63.7%
3	Brazil	Slovakia		362k	394k	-63.7%
4	Brazil	Uruguay		21k	23k	-63.7%
5	Brazil	Turkey		309k	375k	-63.7%
6	Brazil	Cyprus		29k	39k	-63.7%
7	Brazil	Slovenia		135k	184k	-63.7%
8	Brazil	Croatia		87k	123k	-63.7%
9	Brazil	Greece		361k	510k	-63.7%
10	Brazil	Tunisia		54k	77k	-63.7%
11	Brazil	Chile		88k	125k	-63.7%
12	Brazil	Nigeria		22k	39k	-63.7%
13	Brazil	Czech Republic		94k	171k	-63.7%
14	Brazil	Ukraine		41k	76k	-63.7%
15	Brazil	Italy		1951k	3645k	-63.7%
...	...	...	...	...	...	...
40	Brazil	Mongolia		<1k	3k	-63.7%
41	Brazil	Norway		190k	444k	-63.7%
42	Brazil	Sweden		474k	1109k	-63.7%
43	Brazil	Kazakhstan		9k	22k	-63.7%
44	Brazil	Germany		2774k	6616k	-63.7%
45	Brazil	France		1051k	2536k	-63.7%
46	Brazil	Netherlands		637k	1538k	-63.7%
47	Brazil	South Africa		56k	137k	-63.7%
48	Brazil	Kyrgyzstan		<1k	2k	-63.7%
49	Brazil	United Arab Emirates		55k	139k	-63.7%
50	Brazil	Mozambique		2k	4k	-63.7%

Figure 19. Top 50 high-risk bilateral trade relationships for **Robusta coffee**

#	EXPORTER	IMPORTER	RISK TO BILATERAL TRADE	EMBEDDED TRADE FLOW (60KG BAGS)	IMPORTER'S TOTAL STOCK (60KG BAGS)	IMPACT OF CLIMATE CHANGE ON PRODUCTION
1	Viet Nam	Senegal		119k	128k	-26.0%
2	Uganda	Rwanda		<1k	2k	-32.9%
3	Viet Nam	Mozambique		23k	26k	-26.0%
4	Uganda	Switzerland		425k	657k	-32.9%
5	Viet Nam	Cambodia		37k	51k	-26.0%
6	Indonesia	Namibia		11k	13k	-21.6%
7	Viet Nam	Ghana		56k	82k	-26.0%
8	Indonesia	Armenia		14k	17k	-21.6%
9	Indonesia	Georgia		43k	54k	-21.6%
10	Brazil	Argentina		75k	88k	-19.0%
11	Brazil	Slovakia		108k	127k	-19.0%
12	Brazil	Uruguay		6k	8k	-19.0%
13	Viet Nam	Hong Kong		103k	181k	-26.0%
14	Viet Nam	Puerto Rico		9k	17k	-26.0%
15	Brazil	Bolivia		2k	2k	-19.0%
...	...	...	...	...	...	...
25	Tanzania	Kenya		10k	21k	-24.5%
26	Brazil	Sweden		141k	241k	-19.0%
27	Viet Nam	Japan		1251k	2976k	-26.0%
28	Indonesia	Morocco		98k	195k	-21.6%
29	Viet Nam	Taiwan		94k	228k	-26.0%
30	Viet Nam	Malawi		<1k	3k	-26.0%
...	...	...	...	...	...	...
45	Togo	Burkina Faso		3k	6k	-19.2%
46	Indonesia	Iran		32k	77k	-21.6%
47	Indonesia	Brunei Darussalam		3k	9k	-21.6%
48	Viet Nam	Ukraine		17k	52k	-26.0%
49	Viet Nam	Canada		145k	455k	-26.0%
50	Viet Nam	United Kingdom		386k	1223k	-26.0%

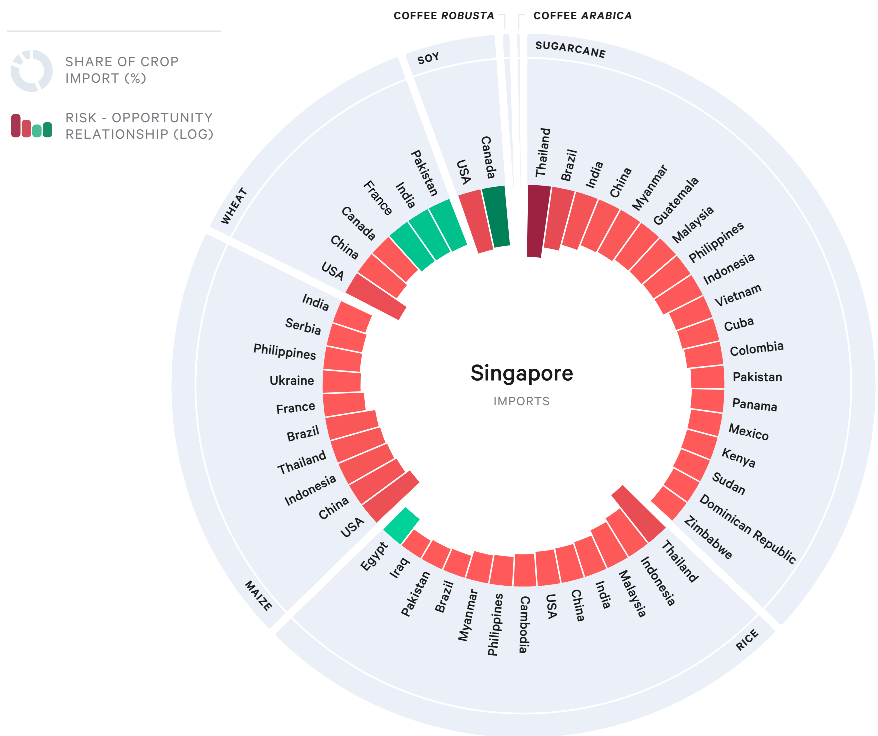
3.4 How are specific countries exposed to risk?

While different agricultural commodity markets are exposed to different degrees of risk, due to both market structures and differences in the extent to which producers and crops are exposed to climate change, it remains that countries have significant control over their own agricultural policy and climate change adaptation strategies. As such, it is also pertinent to consider how specific countries – importers and exporters – are currently exposed to TCRs across crop markets. In this section we discuss a selection of countries, both as importers and as exporters, which capture a wide variety of experiences and contexts and provide a useful starting point for exploration.

Selected importers

Beginning with the importer's perspective, it is instructive to consider a country like Singapore, which, while classed as a Small Island Developing State, is relatively wealthy compared to many of its peers. As an island nation, Singapore is substantially dependent on food imports and has strong trade links with a number of Asian countries. As shown in Figure 20, Singapore consumes a high volume of sugar cane, followed by descending quantities of rice, maize, and wheat. Importantly, our results show that risks to Singaporean rice consumption arise in largest part from (but not limited to) its relationship with Thailand. These risks are not balanced by opportunities afforded from other rice producers (e.g. Egypt), nor from other crops like maize or wheat. Singapore's most adverse relationship in both the maize and wheat markets is with the United States, though neighbours China and Thailand are also key trading partners. The above suggests that there is a significant need – and opportunity – for dialogue between Singapore and Thailand, particularly regarding sugar cane and rice, as well as with other key producers in the region. This assessment also suggests that dietary changes (e.g. increasing wheat consumption relative to rice consumption) may reduce exposure to TCRs.

Figure 20. Key trade relationships and climate risk for Singaporean imports



A common supply chain risk-management strategy is to diversify imports, and it may be incorrectly presumed that already diversified importers, particularly well-off ones, would be insulated from climate risks.

The United Kingdom (Figure 21) shares some important characteristics with Singapore, notably being an island nation that is heavily (albeit less) import dependent. Of the six crops considered, the UK consumes primarily wheat products for which increases in European production – particularly from France and Germany – may offset risks generated by trading relationships with the US, Canada, China, and Russia. After sugar cane, maize makes up another substantial portion of UK imports, followed distantly by soy and rice. Excluding wheat consumption, it appears that risks of decreased production overshadow possible opportunities elsewhere, even in cases like maize imports where the British import profile is highly diversified. This is a key point, because a common supply chain risk-management strategy is to further diversify imports, and it may be incorrectly presumed that already diversified importers, particularly well-off ones, would be well-insulated from climate risks in their trading relationships.

The picture for Sweden and Germany (Figures 22 and 23) is strikingly similar to the UK, reflecting the central role of wheat in diets across all three countries. The strong trading relationships across Europe are evident, although Brazil, China, and the US again appear as key partners for food trade. While these wealthy European nations are not typically viewed as highly exposed to climate change risks, this assessment suggests that exposure to TCRs in agricultural trade remains high along entire supply-chains, particularly for commodities other than wheat, and even where imports are already diversified. Because EU Member States share patterns of exposure and the European trading bloc may be better equipped than individual Member States to engage with large producers like Brazil, China and the US, there could be a role for the EU in supporting its Member States to manage TCRs. However, this poses particular problems for the UK, which has left the EU and may struggle to negotiate favourable trade deals that robustly consider climate risk and sustainability with these much larger economies.

Figure 21. Key trade relationships and climate risk for British imports

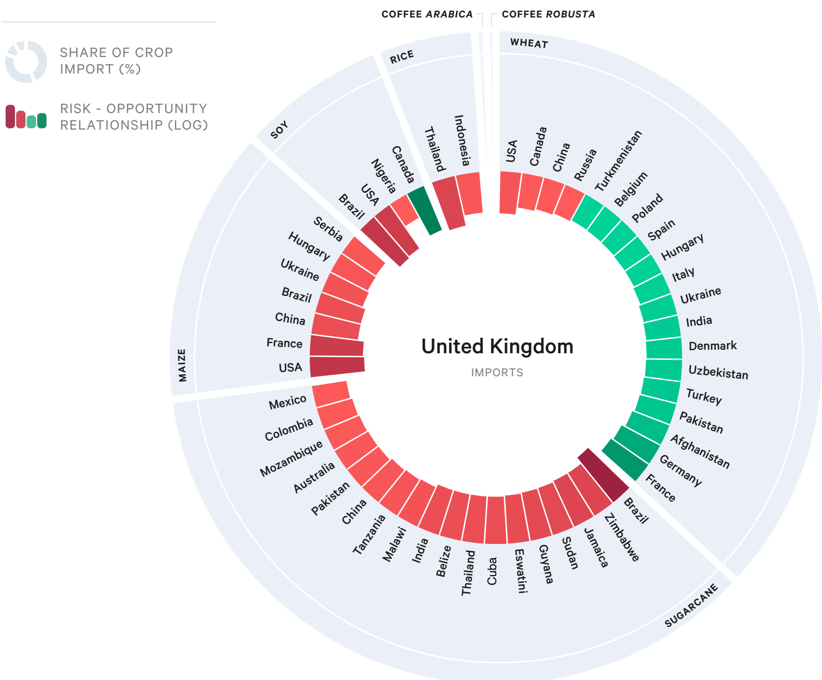


Figure 22. Key trade relationships and climate risk for Swedish imports

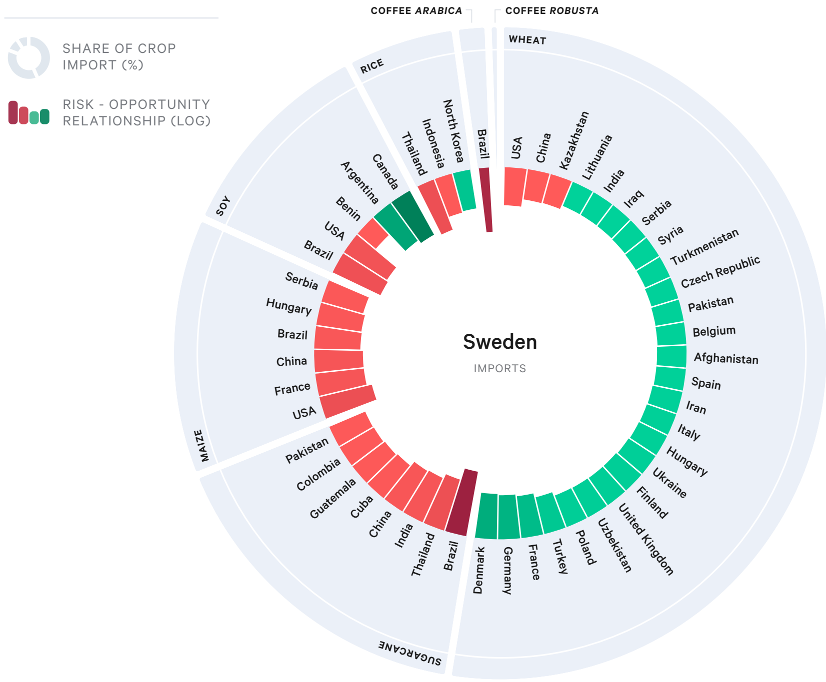
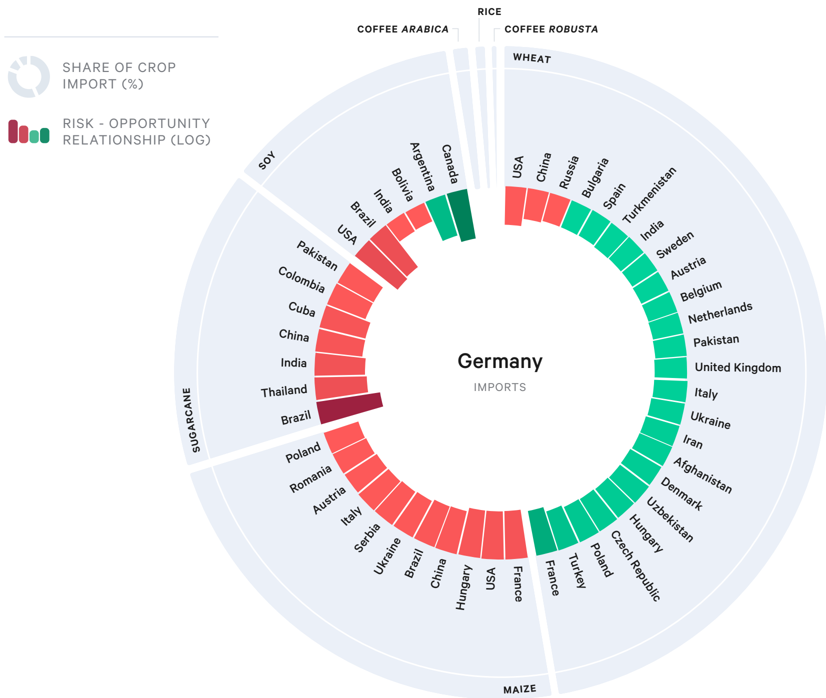


Figure 23. Key trade relationships and climate risk for German imports



Kenya, in contrast, imports a substantial amount of sugar cane and maize, followed distantly by wheat and rice (Figure 24). As with Singapore, Germany, Sweden and the UK, a strong regional pattern can be seen in the Kenyan economy, including strong relationships with Eswatini, South Africa, Sudan, and Tanzania. Soy imports are distinctly low, owing to relatively lower levels of meat consumption than in Europe, particularly of soy-fed livestock. Wheat poses challenges for Kenya in that many of its imports originate in Russia or the US, while Ukraine, Pakistan, and Argentina are well-placed to make up for potential shortfalls.

Morocco (Figure 25), compared to Kenya, imports a much higher proportion of wheat products from a wide variety of trading partners, and has a number of opportunities for improved trade with Europe given its location on the Atlantic coast. Morocco, however, relies heavily on Brazil for its supply of sugar cane, suggesting that diversifying the sources of import may be a useful tool to reduce this acute risk, though it is unclear which potential trading partners may be able to make up the shortfall.

Bolivia is landlocked between Brazil, Peru, Paraguay, Chile, and Argentina and trades predominantly with partners in the region, though it holds significant risk in its trade relationships with the United States, particularly in maize, soy, and wheat (Figure 26). By volume, Bolivia imports substantially more sugar cane than any of the six commodities considered, with Brazil, Colombia, and Paraguay playing especially critical roles. As in Europe and Southeast Asia, this points to the value of regional cooperation on agricultural trade, which could prove crucial for managing climate risk.

Figure 24. Key trade relationships and climate risk for Kenyan imports

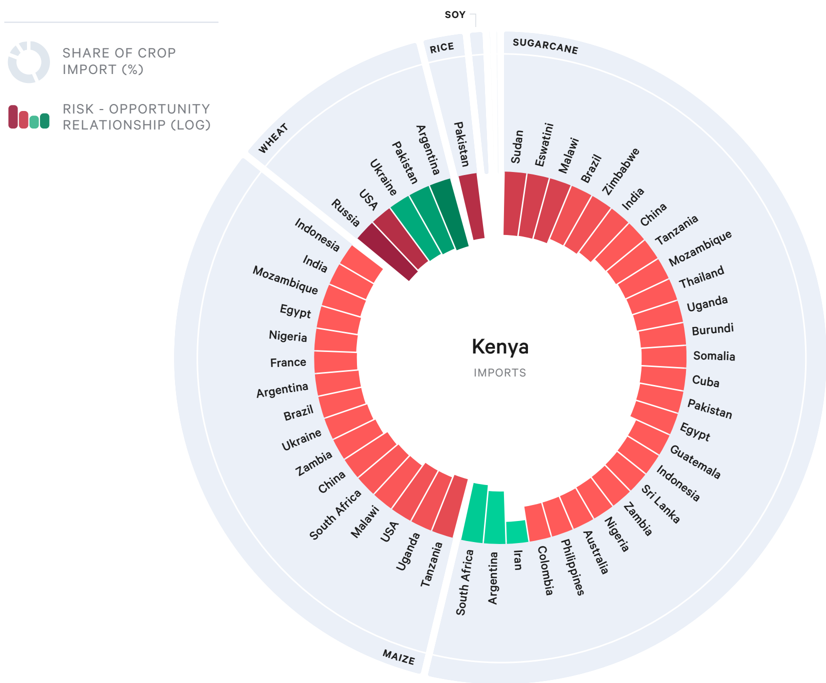


Figure 25. Key trade relationships and climate risk for Moroccan imports

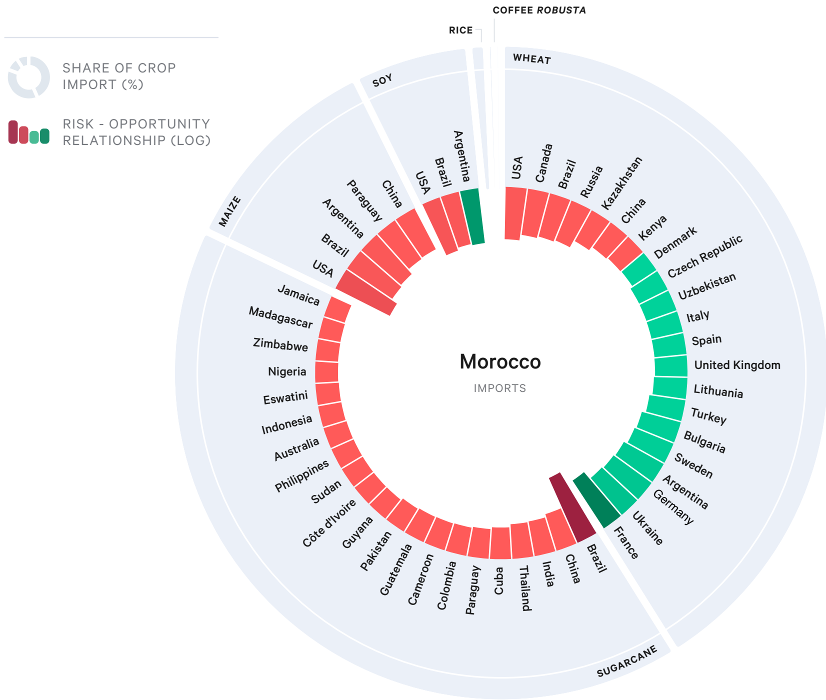
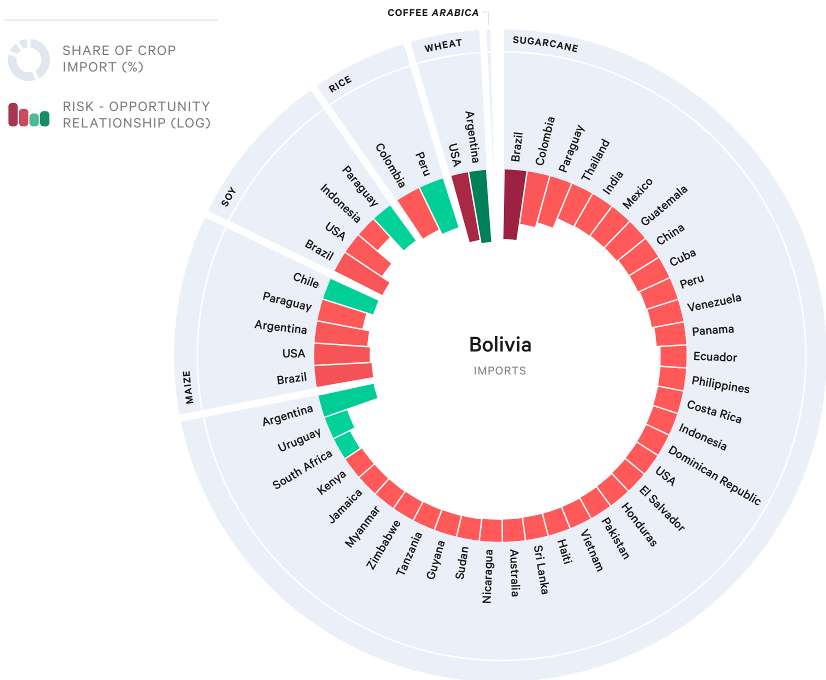


Figure 26. Key trade relationships and climate risk for Bolivian imports



China acts as a source of risk for a more diverse group of trading partners than the US, including several Asian, African, and European consumers.

Key exporters

On the exporter side, the United States is a critical player across a number of crop markets (Figure 27). In particular, the US is a significant source of risk in the maize, soy, and wheat markets, with many high-risk relationships to Caribbean and Latin American consumers, often due to a high degree of trade dependency.

China is also a key source of global risk, particularly for rice, maize, wheat and sugar cane (Figure 28). China is somewhat unique in terms of the inter-linkages between economic sectors.

Figure 27. Key trade relationships and climate risk for US exports

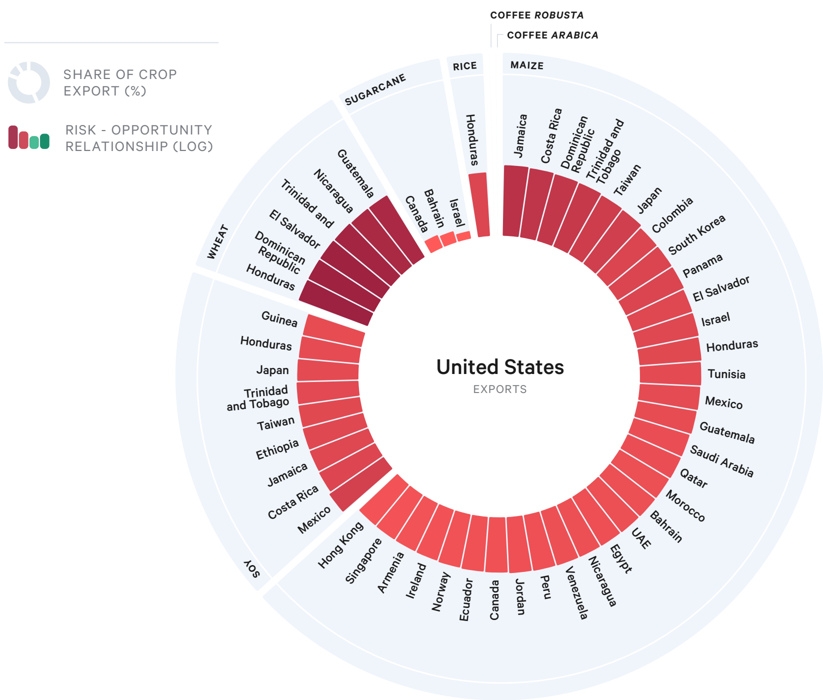
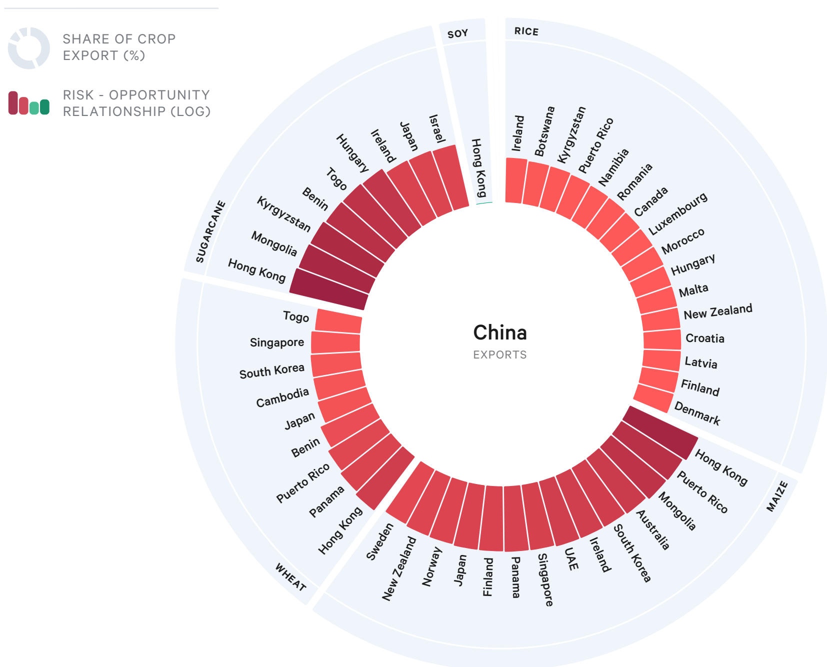


Figure 28. Key trade relationships and climate risk for Chinese exports



Our assessment methodology captures embedded flows for all commodities, but Chinese-grown crops in particular are highly embedded in other exports from China, including for non-agricultural products[9]. Our results show that China acts as a source of risk for a more diverse group of trading partners than the US, including several Asian, African, and European consumers. Notably, Hong Kong has the most risky relationship with the Chinese mainland via its consumption of embedded maize, wheat, and sugar cane.

In contrast, Russia is one of the largest exporters that could plausibly experience an overall increase in agricultural production due to climate change, including of maize, soy, and rice (Figure 29). These increases, particularly if coupled with additional adaptation measures and efforts to scale-up production, may partially compensate for reduced yields in other countries that are major producers. However, Russia currently predominantly produces wheat, and climate change impacts are expected to reduce wheat production in Russia. While shifting resources to produce other crops might be seen as an opportunity, it could come at the cost of supporting a wheat sector under stress.

Figure 29. Key trade relationships and climate risk for Russian exports

9 This is a key strength of using the IOTA model; these interlinkages are captured from production to consumption, and this underscores the need to further examine the embedded nature of economic interrelationships that drive these risks through trade.

Brazil (Figure 30) is a crucial source of risk for sugar cane and soy, as well as for coffee, though the latter is produced in significantly smaller volumes. Importantly, while many Central and South American importers display a high degree of exposure to TCRs originating in Brazil, a broader look at its exports suggest that this is exposure is not limited to the region.

Figure 30. Key trade relationships and climate risk for Brazilian exports

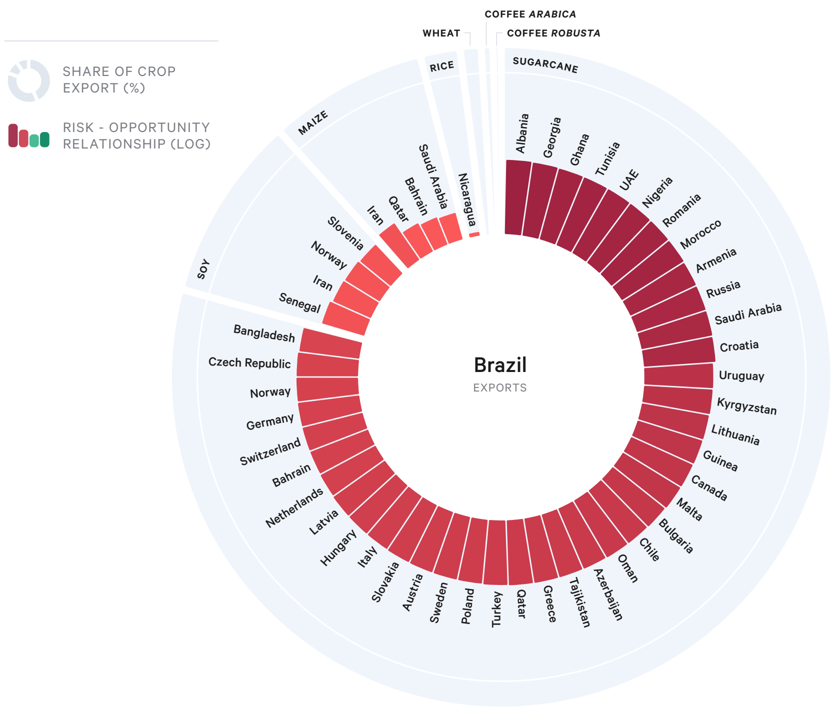
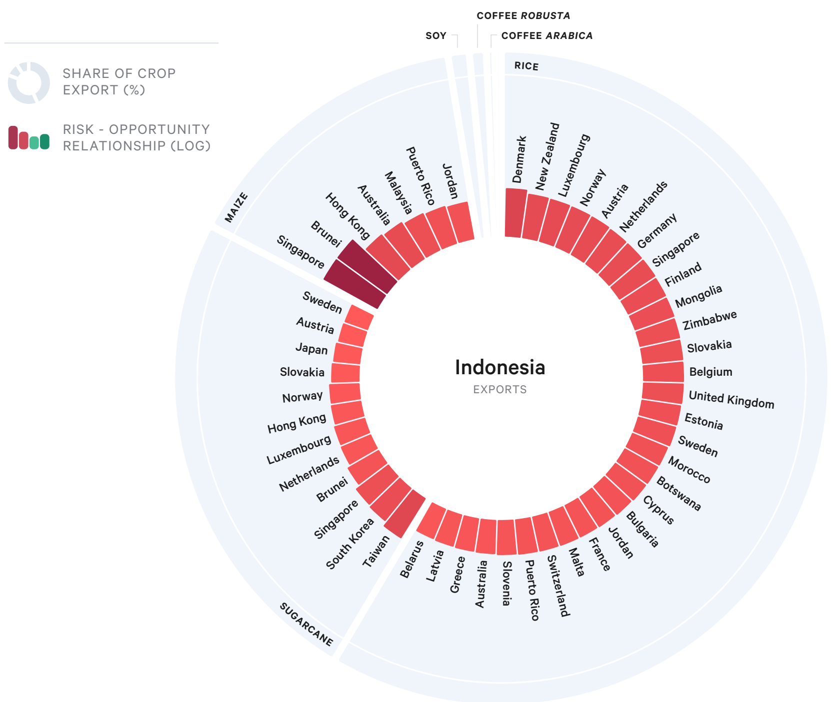


Figure 31. Key trade relationships and climate risk for Indonesian exports



Among rice producers in Southeast Asia, Indonesia and Thailand (Figure 31 and Figure 32) appear to be key sources of risk, while small increases in Viet Nam (Figure 33) do little to offset those potential losses. For all these key exporters, decreased yields of a primary agricultural export are a major concern, and are likely to have significant economic ramifications. It also raises difficult questions about both the climate risk posed to trading partners and the overall economic stability of these major commodity producers.

Figure 32. Key trade relationships and climate risk for Thai exports

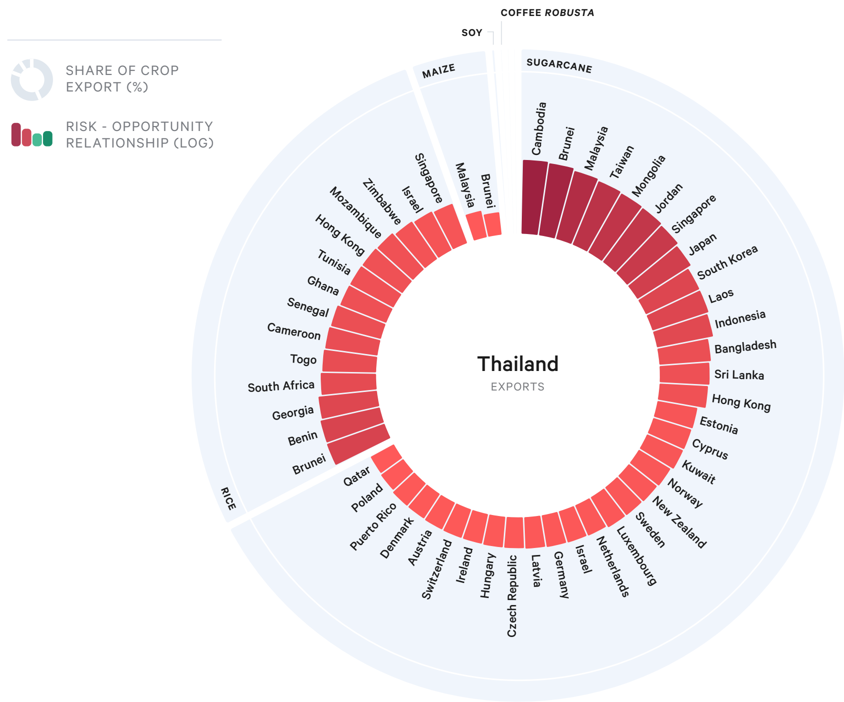
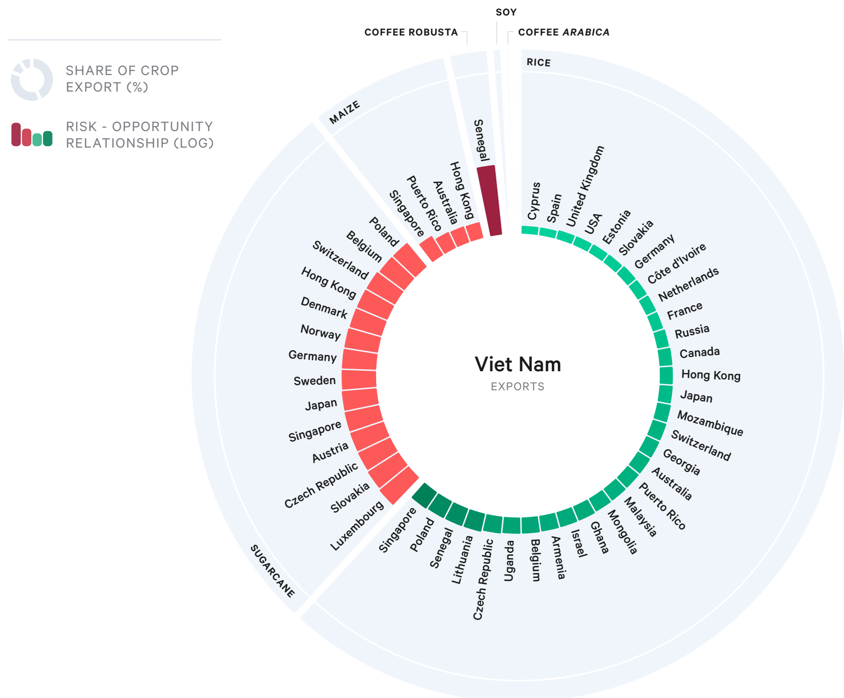


Figure 33. Key trade relationships and climate risk for Vietnamese exports



4. Discussion

The results in this report underscore that transboundary climate risks (TCRs) in agricultural commodity flows are a serious global challenge that are in need of further study and exploration and deserve the urgent attention of policymakers.

Broadly speaking, it is clear that producers, consumers, and commodity markets are exposed differently to TCRs. Our results also suggest that many global consumers disproportionately depend on the success of adaptation in large agricultural exporters – e.g. the US, China and Brazil as significant "sources" of risk for multiple commodities, and Russia as a potential export beneficiary. At the same time, developing countries (e.g. Kenya, Morocco, Bolivia – see section 3.4) probably face a greater adaptation challenge as a result of climate risks to imports than more industrialized countries (e.g. UK, Sweden, Germany). Yet it is also apparent that TCRs affect all countries, regardless of their level of development, wealth, or power. In a globalizing world, climate change adaptation is not only a challenge for developing countries, but an issue that concerns countries everywhere.

Many global consumers disproportionately depend on the success of adaptation in large agricultural exporters – in particular the US, China and Brazil.

4.1 Important considerations for interpreting results

Uncertainty

This study reveals the potential sources, flows and imports of climate risk via trade in agricultural commodities. In carrying out the study we have had to confront various forms of uncertainty (as described in Section 2), which it is necessary to recall when interpreting and discussing these results. In Section 2 we described the wide range of yield projections in different global gridded crop models (GGCMs) for six major commodities. For certain crops, the choice of model determines not only the size of future yield changes, but even whether yields are expected to increase or decrease, with low agreement across in a number of key countries available models (Figures 1–5). For the reasons given in Section 2, we opted to select one GGCM for our analysis, but it is important to reflect that the distribution of TCRs described in Section 3 would imply a different set of responses if alternative, or multiple, GGCMs were used to provide inputs on the risk signal (i.e. the potential change in production of key crops as a result of climate change).

The "stress test" approach we have developed enables us to make internally consistent claims about the potential change in risk distribution according to a specific future (i.e. that described by the EPIC[10] model under a future greenhouse gas emissions scenario of RCP8.5). However, a fuller, if potentially more complex and nuanced, set of insights would be provided by analysis that considered a range of different GGCMs, including, for example, if a risk optimization approach were employed (i.e. using "worst case scenario" projections for each producer country, across a range of GGCMs).

10 And the Bitter Cup model for coffee, which is not covered by the EPIC model, nor readily substitutable for any of the other crops considered.

In a globalizing world, climate change adaptation is not only a challenge for developing countries, but an issue that concerns countries everywhere.

The fact that none of the selected crop models adequately represent the role of extreme weather events in crop production is a major barrier to producing more accurate assessments of transboundary climate risks to food trade. Extreme events, such as droughts, heatwaves and floods, play a major role in agricultural production and are often the initial impacts that, alongside socio-economic factors, trigger major crises in global agricultural markets (Timmer, 2010; Von Braun & Tadesse, 2012). The exclusion of extreme weather events in the production element of our risk assessment likely means that we are underestimating future changes in the availability of commodities for global markets and consumers, and therefore underestimating the overall systemic risk. As noted in Section 2, we are also unable to account for damage to supply chain infrastructure (e.g. at farm level, and in the storage, processing, port and retail stages) in our assessment of trade-related risk. These two omissions suggest that the true picture of TCR distribution via agricultural commodity trade may be more extreme, more widespread and more complex than our results imply.

Notwithstanding the conceptual and practical barriers noted here and in Section 2, future assessments that can incorporate multiple GGCM results will improve the treatment of uncertainty in trade-related TCR assessments and may therefore help to improve our understanding of the scale and significance of potential risks. One fruitful avenue could be to design and develop online support tools that allow decision makers and planners to select and compare multiple datasets, including different GGCMs.

Another major type of uncertainty is accounting for future technological and socio-economic change. New technology and methods may significantly influence the productive capacity of agriculture for any or all of the six commodities examined in this study. The potential for such developments, which are dependent on future socio-economic pathways, is not captured in our analysis.

The future socio-economic state of the world will also determine the level of risk to agricultural markets and the distribution of risk via markets. Most simply, the level of regional and international integration and cooperation will determine whether – and under what conditions – global commodity markets operate. Structural changes to these markets, which in our analysis are assumed to continue as today, will directly alter the flow of TCRs between countries.

Furthermore, socio-economic factors for individual households, including income, health, lifestyles and diet, will determine future demand for and consumption of key commodities. At the macro level, combined with population growth, these factors will also influence the overall demand for food worldwide, which may also be a significant driver of risk in agricultural commodity markets. It would therefore be interesting to explore the influence of alternative configurations of international trade networks under specific socio-economic futures, for example using a wider variety of Shared Socioeconomic Pathways (SSPs) on the distribution of TCRs in agricultural commodity markets.

Commodity classes

The differences in scale of risk and patterns of risk distribution for maize, rice, wheat, coffee, sugar cane and soy are a result of many factors. These include crop sensitivity to climate change, the location and vulnerability of major producers, and the structure of the commodity market itself. The six commodities also present different types of climate risk to consumers, given the different role each commodity class plays in food security.

- **Staple crops: maize, rice and wheat** are consumed worldwide as an integral part of the daily diet of billions of people.[11] Changes in the price and availability of these commodities directly affect peoples' food and nutritional security. Changes in commodity prices are easy to track and rapidly and directly influence the price consumers pay at market. These staple crops tend to be produced via heavily mechanized commercial agriculture and traded on global markets. Climate risks to these commodities are therefore a matter of international and national government policy, national security and high politics.
- **Embedded crops: sugar cane and soy** are consumed in huge quantities, but very little of that is in its raw form. Both crops are highly embedded in processed food and drink, which makes up a growing share of household diets worldwide, and as feed for dairy and meat production (in the case of soy). Changes in the price and availability of these commodities indirectly impacts peoples' food security by increasing the overall price of their full "basket" of food and drink. It is more difficult for consumers to track changes in the price of embedded commodities: some may be absorbed or passed on by companies in the supply chain; the change in price of specific products will depend on the extent to which a commodity is embedded in them (as well as the price and availability of substitutes). Embedded crops tend to be produced by heavily mechanized commercial agriculture and traded on global markets. Climate risks to these commodities are more likely to be a matter of private-sector risk management in supply chains and behaviour change among consumers.
- **Luxury crops: coffee** is widely and increasingly consumed, as a popular, legal stimulant, often with deep cultural significance. Changes in the price and availability of luxury commodities do not influence food or nutritional security. Changes in commodity price are easy to track and will largely be a matter for private sector supply-chain companies and consumers. Luxury crops are often produced by smallholder farmers and traded via relatively short supply chains.

Given the clear differences between these three commodity classes, the nature of the risks – and the responses to those risks – will be quite different.

4.2 Policy responses to transboundary climate risk

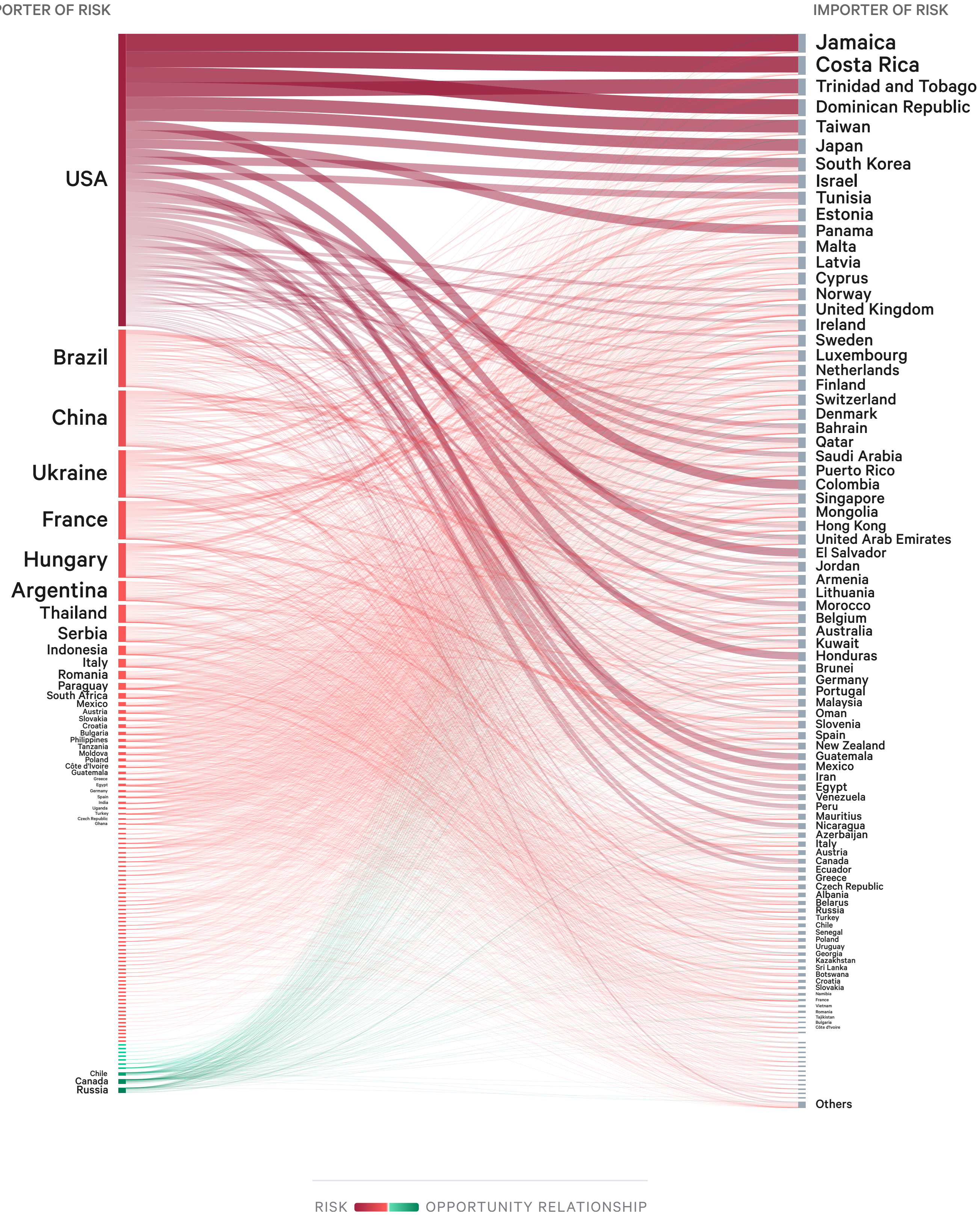
Available options

By highlighting countries' potential exposure to TCRs, our results invite the question: what can be done – and by whom – to manage or reduce these risks?

Where our analysis reveals a country to be engaged in a high-risk trade relationship, diversification seems an obvious option. As is well-studied in the literature on supply chain risk management, a useful way to mitigate risk is often to identify key bottlenecks in important supplies or processes and establish reliable alternatives, such that any individual failure does not precipitate a broader system failure (Anupindi & Akella, 1993; Babich et al., 2007; Behzadi et al., 2018; Hendricks et al., 2009; Schmitt et al., 2015). The challenge with TCRs, however, particularly when we consider long-term climatic shifts, is that risk is correlated among producers; for example, a decrease in US maize yields by the end of the century is not independent from a decrease in Brazilian maize or Chinese maize. This is illustrated in Figure 34, which provides a full portrait of TCRs in the maize market,[12] including those producers that are expected to increase production due to climate change (shown in green). Here, it is readily apparent that at-risk consumers would struggle to diversify their supplies, especially if other consumers intend to do the same.

11 These crops are also much used in food and drink production (i.e. they can be highly embedded).
12 Similar diagrams are produced in Annex IV for the other agricultural commodities included in this assessment.

Figure 34. Risk and opportunity in bilateral trade relationships for **maize**



Results such as those in Figure 34 highlight the systemic nature of climate risk to agricultural commodities. As a phenomenon driven by changes to the global climate system, climate risk is present everywhere, simultaneously. Furthermore, climate change will increase the risk of compound events, potentially affecting major breadbasket regions in the same season (Raymond et al., 2020; Zscheischler, 2020; Zscheischler et al., 2020).

The high likelihood of negative impacts on commodity production worldwide radically reduces the space in which actors will be able to diversify, substitute and hedge agricultural commodity trade risks. The orthodox supply chain management logic of replacing high risk suppliers with more resilient ones is unlikely to be a plausible strategy, at least for most countries, in a world facing systemic risks from a changing climate. This topic is picked up again below, where we discuss the geopolitical implications of our study.

> The orthodox supply-chain management logic of replacing high-risk suppliers with more resilient ones is unlikely to be plausible in a world facing systemic risks from a changing climate.

An alternative to diversification may be to pursue agricultural self-sufficiency or to otherwise reduce dependency on international supply chains. While both these strategies are commonly cited in national climate change adaptation plans, they are challenging to achieve for a number of reasons. For instance, the climatic conditions in some countries are simply inappropriate for producing some commodities. In the case of coffee, it is implausible for the UK to pursue a self-sufficiency strategy, even in the most extreme warming scenarios. There are also limits to expanding domestic production in countries even where the conditions are suitable. Senegal, for example, has high potential to produce more rice to reduce the risk posed by climate change to its massive rice imports, particularly in its “rice belt” where the Senegal River can be used for irrigation. However, full self-sufficiency would imply expanding rice production into rain-fed areas that are ill-suited to rice production. This kind of response would displace non-rice farming, intensifying and concentrating Senegal’s climate risk exposure into a single commodity. Another way to reduce import dependency risk may be to diversify diets away from high risk commodities towards more climate-resilient alternative domestic staples, at the same time as seeking to balance domestic production with access to international markets (see e.g. Benzie & John, 2015).

Small or landlocked countries with limited room for agricultural expansion (e.g. Belgium, Singapore) or countries with climates or agricultural sectors that are not suited to large scale production (e.g. United Arab Emirates, Tajikistan) will struggle to build resilience through a self-sufficiency strategy.

Notwithstanding the systemic constraints mentioned above, consumer countries may seek to optimize or hedge their exposure by carefully considering it in their bilateral and multilateral trade deals, as well as via more regional integration. Enhancing the capacity to cope with shocks, for example through strategic increases in storage capacity for staple crops, or even via insurance and other risk management mechanisms, may provide solutions to those countries with sufficient capacity, ability to pay, and the political independence to make such arrangements.

TCRs to agricultural commodity trade will also be managed to a large extent by private companies. At the organizational scale, traditional practices for managing supply chain risk, such as diversification and contracting, may remain effective, but could become increasingly difficult for companies as their clients, suppliers, and competitors all pursue similar strategies. At a broader scale, it is especially unclear whether such autonomous adaptation in international markets is sufficient for managing and absorbing risk faced by consumers.

Coping with uncertainty

While our analysis provides insights on the potential sources, flows and imports of TCRs in commodity trade, it is not yet possible to provide a detailed description of the risks, for example in terms of probability or timing. What is clear, however, is that responses will need to vary depending on a country's trade profile and the nature of the climate risk in each commodity that it imports.

For example, sugar cane is the most highly traded of the six commodities by volume (422.7 million tonnes) and faces the biggest worldwide yield losses as a result of climate change (-58.5%). Some increased production is expected, but the overall risk-to-opportunity ratio for sugar cane is 25:1 (see Figure 14). Many countries export sugar cane and most importing countries currently have a fairly diverse import profile. Bolivia, for example, imports sugar cane from 96 different countries, eight of which are projected to increase their production as a result of climate change (i.e. Argentina, Uruguay and South Africa – see Figure 26). The rest are expected to suffer yield declines. Bolivia is a global hotspot of climate risk exports for sugar cane, and its imports of Brazilian sugar cane are most at risk. So how at-risk are Bolivian consumers?

The answer depends on the timing and probability of the risks. Recalling that our results are based on long-term yield averages, in the near term it is likely that sugar cane yield losses in some of Bolivia's 96 trading partners will be compensated for by healthy yields in others; a diverse trade portfolio enables an importer to spread low-level risk across a number of trade partners. However, under a more extreme or longer term scenario, Bolivia might expect concurrent yield losses in the majority of its trading partners, bringing into doubt the ability of the remaining exporters to substitute and make up the shortfall. In our long-term scenario (2070–2099), 88 of the 96 exporters will have suffered yield declines, which will not be compensated by the marginal increases among the remaining eight exporters. All else being equal, by the end of the century significant price rises should be expected, and Bolivia may not be able to access enough sugar cane to meet demand.

At the same time, multiple other importers will also be struggling to meet sugar cane demand from international markets. Some producers might halt exports in order to meet domestic demand; others might prioritize trade with powerful or high-paying countries, some of whom may be panic buying and stockpiling sugar cane, magnifying the risk for other players in the market and potentially tipping the entire system into a temporary or new state of crisis. This might leave a relatively low-income country like Bolivia floundering.

Even under nearer term scenarios, the squeeze put on agricultural commodity trade by uncertain, variable, and decreasing yields as a result of climate change are likely to heighten volatility and threaten the stability of commodity markets. Our results give an indication of which countries will be most exposed to these risks, across a range of commodities, but the entire system of commodity trade is likely to suffer repeat crises, unless adaptation efforts are able to build systemic resilience to climate change.

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The case of sugar cane, and Bolivia, raises an important point: we do not yet know what a "climate resilient" trade profile looks like. We do not know what balance of domestic production and access to international markets – or what number, or which type of trade partner – will offer the most resilience against uncertain but systemic risks in the global system of agricultural commodity trade. What our results do show, however, is that by combining insights on commodity trade and consumption with projections of climate impacts on production, we can begin to assess the level and distribution of exposure to this risk. The results imply that risk will be shared by countries of all income levels and in all regions of the world, suggesting that more and improved international cooperation will be needed to manage and reduce these risks.

Enhanced international cooperation

The insights provided by our results highlight the need to address climate risks to food security via international agricultural commodity trade at a system level. The distribution of exposure to these risks and their sources are so diverse and complex that bilateral or single-country responses are likely to be ineffective. No country alone has the remit or reach to adequately adapt to TCRs.

Bilateral adaptations may also be counter-productive, for example if the adaptation efforts of individual countries secure import-resilience for the one, but at the expense of the many. The potential for this kind of transboundary maladaptation further justifies international cooperation on building resilience.

Whereas climate change adaptation has traditionally been pursued as a nationally driven or even local, territorial, process, our results invite decision makers to rethink the value of global cooperation on adaptation. Fortunately, there are mechanisms that can help countries build systemic resilience to climate change, principally via the United Nations Framework Convention on Climate Change (UNFCCC) and its Paris Agreement. Article 7 of that agreement establishes the Global Goal on Adaptation (GGA) to enhance adaptive capacity and resilience and reduce vulnerability. It also frames adaptation as a “global challenge” and recognizes its “regional and international dimensions,” suggesting there is ample space to include the important transboundary elements of climate risk. Among its other features, the Paris Agreement invites and requests Parties to submit national reports about the climate risks they face and their intended contributions to adaptation (i.e. Adaptation Communications, and via their periodic submissions of Nationally Determined Contributions), which will be reviewed and made available under the Agreement’s Enhanced Transparency Framework. Collective progress towards achieving the Global Goal on Adaptation will be made as part of the five-yearly Global Stocktake (GST; Article 14). The Paris Agreement also sets out the need for developed countries to provide financial and technological support to others to support resilience building, and the need for mechanisms to do so. Giving serious consideration to TCRs would necessitate that Parties to the UNFCCC, many of whom may view adaptation as a secondary or even marginal concern in the negotiations, re-consider the value of a truly global approach to adaptation.

> Countries have a shared interest in achieving climate resilience: importers benefit when exporters are able to adapt to the impacts of climate change to maintain the production of agricultural commodities.

The existence of transboundary climate risks – and the specific risks to global food security via impacts on agricultural commodity trade – add weight to arguments for increased ambition and accelerated action to implement the Paris Agreement. For example, countries that are highlighted in this report as being exposed to TCRs via their dependence on imported commodities now have added motivation to ensure that producer countries successfully adapt. They also have added incentive to mitigate their own emissions, which is the only sure way to reduce the overall climate risk to which global commodity systems are exposed. How, then, can countries support and encourage adaptation in other countries, including their trading partners?

Adaptation finance for resilience in the food system

Our results reveal that some countries have a shared interest in achieving climate resilience: importers benefit when exporters are able to adapt to the impacts of climate change to maintain the production of agricultural commodities. Therefore, importers will want to see – and consider what they can do to facilitate – successful adaptation in other countries, particularly those with which they trade. This raises new questions for the allocation and disbursement of international climate finance for adaptation.

First, if Importer A (e.g. a country in Africa dependent on rice imports to maintain its food security) benefits from successful adaptation in Exporter B (e.g. a major rice exporting country in Asia), will Importer A be willing to allocate some of its fair share of adaptation finance to Exporter B – for example to adapt rice farming practices to protect against drought risk? Or would Importer A be willing to directly invest in adaptation in Exporter B in order to improve the climate resilience of agricultural production upon which it relies?

The answer to these questions will depend, among other factors, on the development status of Importer A. Least Developed Countries and developing countries do not have the financial capacity to directly invest in adaptation in other countries, despite an incentive to do so. Principles of historical responsibility, equity and vulnerability underlie the provision and allocation of climate finance under the UNFCCC, yet the transboundary dimension of climate risk expands and complicates the interpretation of what "particularly vulnerable" means. Should vulnerability to trade-related climate risks be considered in the allocation of climate finance? If so, how might these and other transboundary climate risks be assessed and how might vulnerability to TCRs be compared against vulnerability to more direct impacts? And how might the shared benefits of this kind of adaptation investment be assessed? How much benefit would be enjoyed locally to the adaptation investment, and how much would "flow", via trade or other climate risk pathways, to the importer?

Climate finance to address TCRs could also be new and additional to current climate finance goals that are intended to help developing countries adapt to the direct impacts of climate change. Building resilience to TCRs should not be used as a reason to reduce or re-allocate finance away from particularly vulnerable countries; to do so would be to undermine the principles of the UNFCCC. Instead, additional finance could be deployed to build resilience to TCRs, which have generally been excluded from national and international assessments of adaptation costs and therefore represent an extension to existing climate finance targets. New finance mechanisms may be needed to raise and allocate finance for adaptation to TCRs.

Second, where bilateral risk relationships are not evident or traceable, how might climate finance be invested to reduce TCRs? For example, in the case of Bolivia's dependence on sugar cane imports, it would be prohibitively complex – and potentially unjust – to allocate a share of Bolivia's finance to each of its 96 sugar-cane exporting partners. Instead, climate finance for systemic resilience is needed.

In addition to allocating finance to single countries, important global or international systems – such as the global rice market – can be identified and adaptation finance allocated toward building resilience in that system, to the benefit of all who participate in it.

In the case of the global rice market, upon which many countries, including many developing and Least Developed Countries depend for their food security, new and additional climate finance could be raised and allocated to build resilience in the rice market as a whole. For example, a World Rice Market Climate Stabilization Mechanism could be established (perhaps created under the auspices of an existing climate fund, like the Green Climate Fund, or an existing food security body like the World Food Programme). Multilateral and bilateral donors could capitalize the mechanism, the governance of which could be shared between donor and recipient countries, as well as other relevant actors, for example the Food and Agriculture Organization of the United Nations (FAO). Investments by the Mechanism would be made on behalf of all participants in the market to increase the market's resilience to climate-related shocks. Projects could include:

- investment in new, open-access crop varieties and farming techniques
- capacity building programmes at various levels
- investment in farming and supply chain infrastructure in key exporting countries
- grain storage facilities and mechanisms in key import-dependent regions
- investments in domestic supply chains – e.g. in machinery, processing facilities, marketing local produce, or loans – in countries that depend heavily on imports of certain commodities
- creating insurance schemes for import-dependent countries and regions
- developing infrastructure for trade at the regional level
- investing in schemes to diversify diets away from high risk imported staples.

All of these measures can help to build resilience to TCRs in agricultural commodity flows, and as such could be considered legitimate recipients of adaptation finance.

Creating adaptation funds for systems, as opposed to countries, may help to leverage private investment, which is needed to reach the necessary level of investment in resilience-building in the coming years. The allocation of public and private finance via system-level funds may also help to address problems such as divestment and capital flight from high-risk countries, where investments in adaptation are needed most. Allocating climate finance to protect public goods[13] in this way would be a significant innovation in the governance of climate finance. Currently, neither bilateral donors nor recipients are incentivized to focus on system-level resilience. Such approaches are perhaps most appropriate in the case of staple crops, which play a key role in the food security of billions of people, and less suited to luxury crops. Of course, system-level financing mechanisms would face various technical as well as political obstacles, but greater discussion about the role of international finance in building systemic resilience (rather than only local) is clearly overdue.

The promise and perils of adapting to transboundary climate risks

As the systemic nature of TCRs in agricultural commodity markets begins to manifest, it will be essential to consider how the tools of multilateralism and diplomacy can help to manage these risks and, conversely, how such tools might be used in the service of self-interested actors, thus reinforcing structures of global inequality or erecting new ones.

Awareness alone is unlikely to lead to the sort of adaptation that will deliver systemic resilience. In fact, awareness of TCRs might encourage actors to pursue a course of narrow self-interest that does more to exacerbate systemic risk than reduce it. Looked at one way, our results could imply that open international agricultural commodity markets are increasingly prone towards volatility, that supply of these commodities will be squeezed with increasing intensity in future, and that the only sensible strategic course of action is to securitize supply.

> A return to protectionism, regionalization and geopolitics would be likely to destabilize markets further, probably to the detriment of those countries who can least afford to compete.

An actor with the requisite geographical, climatic, financial and political capacities may be lured by the false promise of securitization and/or “self-sufficiency”: a return to geopolitics. Some of our results suggest that this is a realistic concern.

Specifically, our assessment reveals that three major agricultural producers – namely the United States, Brazil, and China – contribute disproportionately to TCRs in agricultural commodity flows, owing to their large production bases, exposure to climate change impacts, and multitude of trade relationships with smaller nations. In contrast, Russia, Canada, and Argentina appear well-placed to increase agricultural production in a warming world. It is plausible that a key feature of pursuing global food security in the 21st century is an ongoing competition among large agricultural producers for increased market share and competitive advantage as climatic patterns shift. Data on future risk flows may encourage powerful actors to securitize access to the most resilient flow of vital agricultural commodities, for example by including clauses in bilateral trade agreements, or via state-supported commercial relationships. It may even encourage powerful producing countries to increasingly use commodity trade as an instrument of power.

13 International markets are an example of transnational public goods, also referred to as “multi-level public goods”, though they do not strictly qualify as “global public goods” because not all countries participate in all markets.

A retreat from global integration and a return to protectionism, regionalization and geopolitics would be likely to destabilize markets further, probably to the detriment of those countries who can least afford to compete in such a world, including those that have been heavily incentivized in recent decades to open-up to global markets as a solution to the challenge of achieving food security. Not only would this represent a major injustice, but it would also not be in any country's long-term interest to undermine systemic resilience in this way.

However, the same results can support a different conclusion. International trade helps all countries to spread the risk from climate change. Free and open access to international markets will help all participants to meet the daunting challenge of achieving food security in a world challenged by climate change and population growth. Markets are mechanisms of interdependence. The deep reach of agricultural commodity markets, into and across countries at all levels of development and in all continents, reminds us that collective resilience is a function of the resilience of all countries, including those with the least ability to invest in resilience themselves. It reiterates the importance of ensuring successful adaptation at all scales and in all places and articulates clearly the shared benefits of investing boldly in adaptation.

Our research implies that it is in the interest of all to invest in the resilience of agricultural trade systems.

In contrast to the geopolitical reading of our results, a just transition for climate change adaptation (e.g. Lager et al., 2021) will adopt a system-level view of resilience in which no country pursues a food security strategy that undermines the ability of any other country to achieve the same. In fact, our research implies that it is in the interest of all to invest in the resilience of agricultural trade systems.

4.3 Future research

Based on our analysis, we have identified a number of potentially useful new research avenues, including:

- Consideration of climate change, trade and global food security under a range of future socio-economic scenarios, including the dynamic effects of state and non-state responses to climate risks within the context of those futures.
- Analysis of risk ownership and the multilevel governance of adaptation to transboundary climate risk, including the division of labour between state, non-state and system-level actors in managing TCR via trade, as well as risk ownership and adaptive capacity within government institutions for managing complex systemic climate risk.
- Further exploration of uncertainties that this study has identified but not examined, including the inclusion of multiple GGCMs, extreme event indices and alternative socio-economic scenarios in quantitative analysis.
- Assessments of the effects that widespread adoption of more sustainable diets[14] would have globally on the distribution of climate risk via trade, as well as of the effects that more local, diversified, traditional or indigenous household diets would have on transboundary climate risk in importing countries.
- Development of an interactive decision-support tool that would make data such as those used in this study easy to access and explore, especially by adaptation planners and practitioners.

14 E.g. the Planetary Health Diet recommended by the EAT-Lancet Commission: https://eatforum.org/eat-lancet-commission/eat-lancet-commission-summary-report

5 Conclusion

In a globalizing world, we can no longer consider climate change adaptation to be a solely national or local issue. Rather, as our communities and economies become more interconnected, our exposure to the adverse effects of a warming world is shared, and building climate resilience must be treated as a global challenge.

This report provides the first quantitative global assessment of transboundary climate risk in agricultural commodity flows. We have developed a novel methodology for measuring these risks and applied that methodology to provide a detailed overview of the ways in which climate change risk is currently embedded in existing patterns of global agricultural trade.

Our results show that climate risks to global food security are disproportionately, but not exclusively, sourced from a small number of key exporting countries, namely maize grown in Brazil, China and the US, rice from Thailand and the US and wheat from the US. Highly embedded commodities pose an indirect risk to food security by threatening to drive price increases and shocks across a basket of products, in all consumer countries. The US is a key source of risk for countries across the world when it comes to soy, whereas Brazil stands out as important for European soy consumers. Many South-South trading relationships demonstrate high risks in the sugar cane market (e.g. Zimbabwe's dependence on Namibia and Botswana, or many South-East Asia countries' dependence on Thailand) – a pattern that is mirrored in the case of Robusta coffee, whereas countries throughout the world (especially in the global North) are highly dependent on Brazilian Arabica coffee.

There is an obvious global benefit from successful, equitable and just adaptation at the national and local scale, particularly in key exporting countries.

Various spatial patterns also emerge from our results. Countries like Kenya and Bolivia are exposed to high climate risks from within their regions. Latin America and the Caribbean are highly dependent on risky imports from the US. Regional patterns persist but are less prominent for highly globalized countries like the UK, Germany and Singapore. The trade links that transmit transboundary climate risk are not random: they reflect historical, regional and geopolitical ties between countries. Adaptation to reduce these risks will be facilitated and constrained by these same geopolitical factors. For example, Singapore's management of high climate-risk trade dependencies on China, the US and Brazil cannot be seen in isolation from its other commercial, political and strategic relationships with those countries. Overall, there is an obvious global benefit from successful, equitable and just adaptation at the national and local scale, particularly in key exporting countries. That places a duty of responsibility on those countries to consider the wider systemic effects of both domestic, planned adaptation and private autonomous adaptation. It also places a responsibility on the international community to provide the necessary political, legal, institutional, financial and logistical support to facilitate adaptation in countries that lack capacity, and to build robust structures for international cooperation to jointly address these shared, systemic risks.

As with any risk assessment methodology, our approach is not without its limitations; further innovation is required to incorporate the impacts of extreme weather events on agricultural production, as well as on key trade-related infrastructure. And it is crucial – particularly for those engaged in policy and decision-making – to consider the uncertainty associated with the use of climate change impacts models in order to understand these results in context. Also, because this has been a static assessment of TCRs, additional research is required to understand how adaptation efforts, ranging from investment in agricultural technologies and climate-smart production methods to shifting trade portfolios or local diets, may influence exposure to TCRs.

Still, this report takes an important stride for the growing body of literature on TCRs. It provides a basis from which to develop more complex assessment methodologies, and to begin to ask challenging questions about the governance of climate change risk in an interconnected world. It should also spark needed policy debate about how the international community will rise to meet this emerging challenge. This includes how the UNFCCC intends to operationalize the Global Goal on Adaptation, particularly in view of the Global Stocktake, how the WTO will meaningfully incorporate elements of climate change and sustainability into its work, and how countries will conduct diplomacy in a context where multilateralism and global cooperation remain under threat, but climate action is high on the political agenda.

Looking ahead, there is a clear need for future research on this topic to inform the efforts of decision-makers. Countries and firms alike should urgently begin work to identify their exposure to TCRs, including but not limited to the context of agricultural commodity flows. The global community must urgently develop a more accurate understanding of how international trade will (re)distribute climate risks and opportunities to the food and nutritional security of the world's poorest people, including food insecure people in middle and even higher income countries.

There is a duty of responsibility on large exporters to consider the wider systemic effects of domestic and private adaptation, and on the international community to support countries that lack capacity, and to build robust structures for international cooperation to address shared systemic risks.

In parallel, there are significant opportunities to advance methodologies for assessing TCRs, many of which have been noted in section 4.3. Researchers may also wish to further explore the determinants of exposure to TCRs, as well as identify concrete adaptation options and analyse their efficacy, costs, and implications, at household and local scale, all the way up to national policy and international level. In particular, there is a need to consider whether adaptation efforts at all scales genuinely reduce climate risks, rather than simply redistributing them to other vulnerable countries or communities (Atteridge & Remling, 2018). In other words, we should adopt a transboundary, systemic view, not only when assessing the scale and dynamics of climate change impacts and risk, but also when assessing the efficacy, equity and justice dimensions of adaptation responses.

Likewise, TCRs raise a number of interesting and policy-relevant questions for scholars of global environmental governance. There is a high need to understand the appropriate ownership of TCRs, especially in terms of the state and the private sector, as well as to provide the basis for the legitimate authority to govern risk management in different contexts. Further work is also required to explore the existing policy regimes and frameworks which may be well-suited to managing TCRs and the potential for synergies and conflicts as those units interact. And critical scholarship should play a strong role in exploring how power structures and international political economy – in the context of geopolitics, as well as international organizations and corporations – articulate within these governance processes.

Taken together, these questions cut to the heart of the central issues within global environmental governance and foreign affairs: who controls the distribution of environmental harms and benefits, under what circumstances, and to what effect. In this way, TCRs and their management can both reveal important aspects of the evolving nature of governance and occupy the centre of modern efforts to remake multilateral cooperation in a globalizing, warming world.

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Annex I List of countries and regions included in this study

Table 1. List of included countries and regions

Producing countries and regions	Consuming countries and regions
Afghanistan	Australia
Albania	New Zealand
Algeria	Rest of Oceania
American Samoa	China
Angola	Hong Kong, Special Administrative Region of China
Anguilla	Japan
Antigua and Barbuda	Republic of Korea
Argentina	Mongolia
Armenia	Taiwan
Aruba	Rest of East Asia
Australia	Brunei Darussalam
Austria	Cambodia
Azerbaijan	Indonesia
Bahamas	Lao People's Democratic Republic
Bahrain	Malaysia
Bangladesh	Philippines
Barbados	Singapore
Belarus	Thailand
Belgium	Viet Nam
Belize	Rest of Southeast Asia
Benin	Bangladesh
Bermuda	India
Bhutan	Nepal
Bolivia, Plurinational State of	Pakistan
Bosnia and Herzegovina	Sri Lanka
Botswana	Rest of South Asia
Brazil	Canada
British Virgin Islands	United States of America
Brunei Darussalam	Mexico
Bulgaria	Rest of North America
Burkina Faso	Argentina
Burundi	Bolivia
Cabo Verde	Brazil
Cambodia	Chile
Cameroon	Colombia
Canada	Ecuador
Cayman Islands	Paraguay

Producing countries and regions	Consuming countries and regions
Central African Republic	Peru
Chad	Uruguay
Chile	Venezuela, Bolivarian Republic of
China	Rest of South America
China, Taiwan Province of	Costa Rica
Cocos (Keeling) Islands	Guatemala
Colombia	Honduras
Comoros	Nicaragua
Congo	Panama
Cook Islands	El Salvador
Costa Rica	Rest of Central America
Côte d'Ivoire	Dominican Republic
Croatia	Jamaica
Cuba	Puerto Rico
Cyprus	Trinidad and Tobago
Czechia	Rest of Caribbean
Democratic People's Republic of Korea	Austria
Democratic Republic of the Congo	Belgium
Denmark	Bulgaria
Djibouti	Croatia
Dominica	Cyprus
Dominican Republic	Czech Republic
Ecuador	Denmark
Egypt	Estonia
El Salvador	Finland
Equatorial Guinea	France
Eritrea	Germany
Estonia	Greece
Eswatini	Hungary
Ethiopia	Ireland
Falkland Islands (Malvinas)	Italy
Faroe Islands	Latvia
Fiji	Lithuania
Finland	Luxembourg
France	Malta
French Guyana	Netherlands
French Polynesia	Poland
Gabon	Portugal
Gambia	Romania
Georgia	Slovakia
Germany	Slovenia

Producing countries and regions	Consuming countries and regions
Ghana	Spain
Greece	Sweden
Greenland	United Kingdom
Grenada	Switzerland
Guadeloupe	Norway
Guam	Rest of European Free Trade Association
Guatemala	Albania
Guinea	Belarus
Guinea-Bissau	Russian Federation
Guyana	Ukraine
Haiti	Rest of Eastern Europe
Holy See	Rest of Europe
Honduras	Kazakhstan
Hong Kong, Special Administrative Region of China	Kyrgyzstan
Hungary	Tajikistan
Iceland	Rest of Former Soviet Union
India	Armenia
Indonesia	Azerbaijan
Iran, Islamic Republic of	Georgia
Iraq	Bahrain
Ireland	Iran, Islamic Republic of
Israel	Israel
Italy	Jordan
Jamaica	Kuwait
Japan	Oman
Jordan	Qatar
Kazakhstan	Saudi Arabia
Kenya	Turkey
Kiribati	United Arab Emirates
Kuwait	Rest of Western Asia
Kyrgyzstan	Egypt
Lao People's Democratic Republic	Morocco
Latvia	Tunisia
Lebanon	Rest of North Africa
Lesotho	Benin
Liberia	Burkina Faso
Libya	Cameroon
Lithuania	Côte d'Ivoire
Luxembourg	Ghana
Macao, Special Administrative Region of China	Guinea
Madagascar	Nigeria

Producing countries and regions	Consuming countries and regions
Malawi	Senegal
Malaysia	Togo
Maldives	Rest of Western Africa
Mali	Rest of Central Africa
Malta	South Central Africa
Martinique	Ethiopia
Mauritania	Kenya
Mauritius	Madagascar
Mayotte	Malawi
Mexico	Mauritius
Micronesia, Federated States of	Mozambique
Mongolia	Rwanda
Montenegro	Tanzania, United Republic of
Montserrat	Uganda
Morocco	Zambia
Mozambique	Zimbabwe
Myanmar	Rest of Eastern Africa
Namibia	Botswana
Nauru	Namibia
Nepal	South Africa
Netherlands	Rest of South African Customs Union
Netherlands Antilles (former)	Rest of the World
New Caledonia	
New Zealand	
Nicaragua	
Niger	
Nigeria	
Niue	
North Macedonia	
Northern Mariana Islands	
Norway	
Oman	
Pakistan	
Palestine	
Panama	
Papua New Guinea	
Paraguay	
Peru	
Philippines	
Poland	
Portugal	

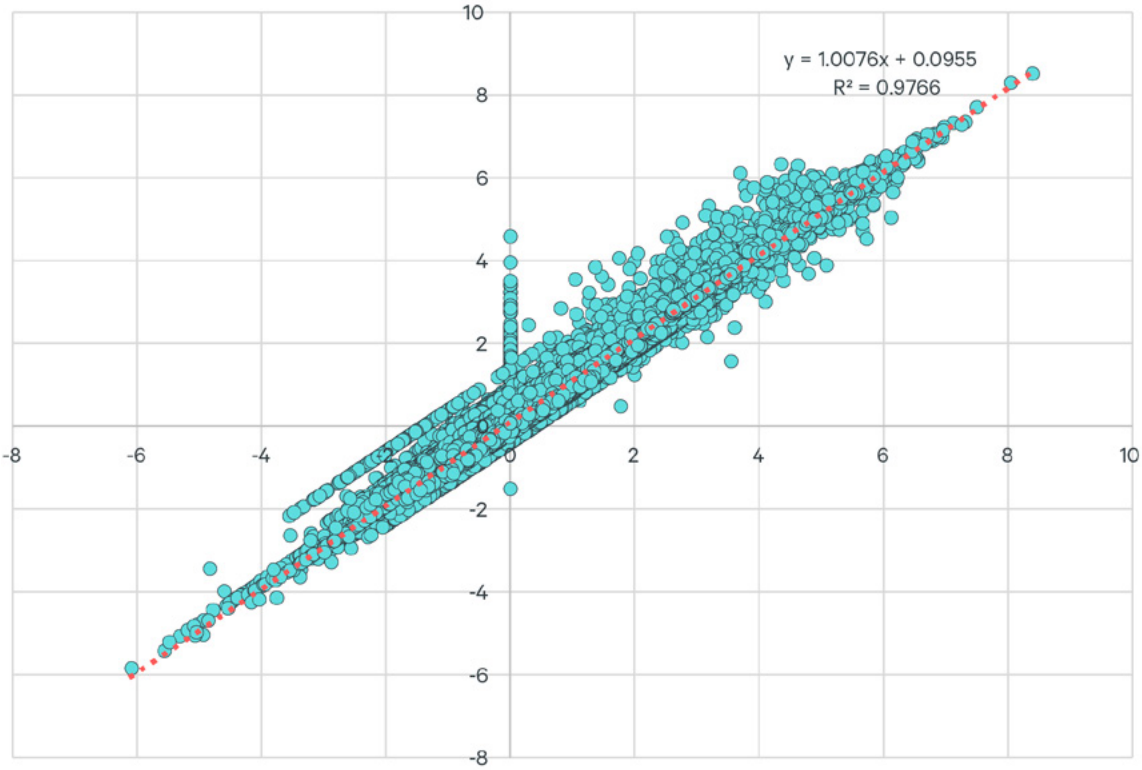
Producing countries and regions	Consuming countries and regions
Puerto Rico	
Qatar	
Republic of Korea	
Republic of Moldova	
Réunion	
Romania	
Russian Federation	
Rwanda	
Saint Helena, Ascension and Tristan da Cunha	
Saint Kitts and Nevis	
Saint Lucia	
Saint Pierre and Miquelon	
Saint Vincent and the Grenadines	
Samoa	
Sao Tome and Principe	
Saudi Arabia	
Senegal	
Serbia	
Seychelles	
Sierra Leone	
Singapore	
Slovakia	
Slovenia	
Solomon Islands	
Somalia	
South Africa	
South Sudan	
Spain	
Sri Lanka	
Sudan	
Suriname	
Sweden	
Switzerland	
Syrian Arab Republic	
Tajikistan	
Thailand	
Timor-Leste	
Togo	
Tokelau	
Tonga	
Trinidad and Tobago	

Producing countries and regions	Consuming countries and regions
Tunisia	
Turkey	
Turkmenistan	
Turks and Caicos Islands	
Tuvalu	
Uganda	
Ukraine	
United Arab Emirates	
United Kingdom of Great Britain and Northern Ireland	
United Republic of Tanzania	
United States of America	
Uruguay	
Uzbekistan	
Vanuatu	
Venezuela (Bolivarian Republic of)	
Viet Nam	
Wallis and Futuna Islands	
Yemen	
Zambia	
Zimbabwe	

Annex II Robustness check: IOTA data on agricultural commodity flows over time

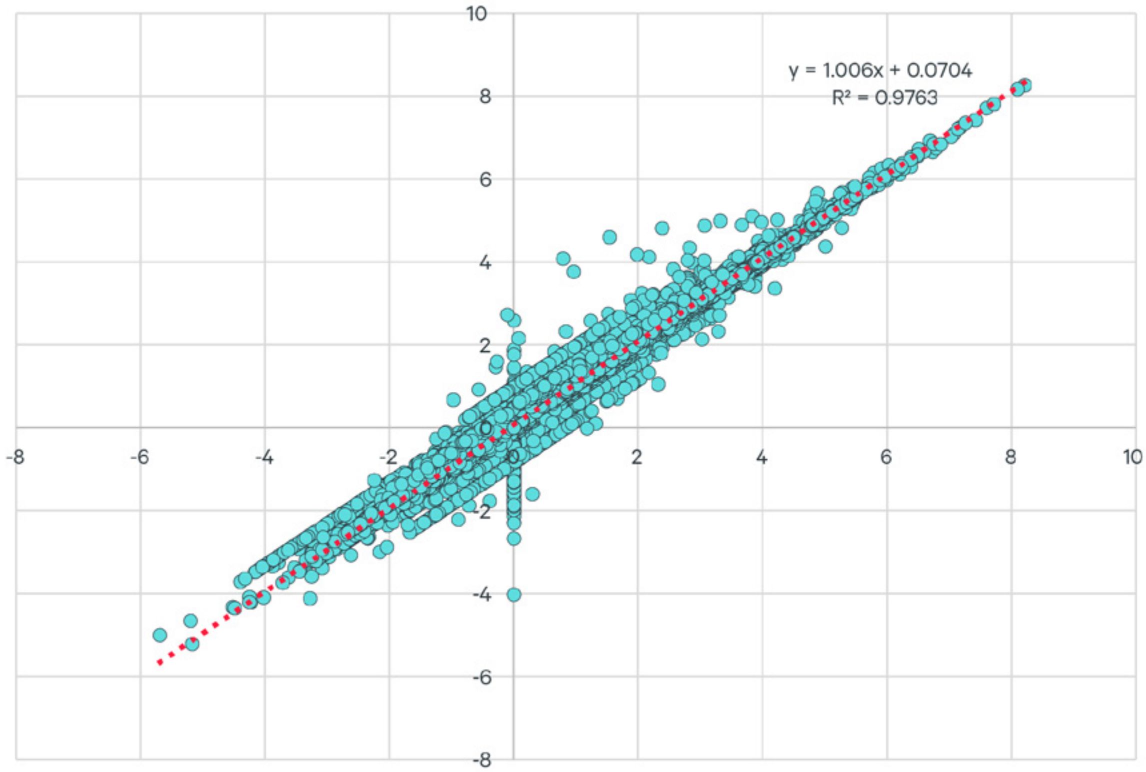
For maize, taking the difference between 2011/2014 and 2004/2007 observations, 90% of differences exist within the range –14.56 to +1775.43 tonnes, while 99.7% exist within one standard deviation of the mean. This suggests a modest increase over time in most producer/consumer relationships resulting from a modest increase in global maize production, with some exceptions.

Figure 35. **Maize** IOTA data robustness test. Comparison of 2004/2007 Average (log) to 2011/2014 average (log), R2=0.9766. Serbia, Montenegro, Sudan, and South Sudan excluded, 30599 observations at two time points.



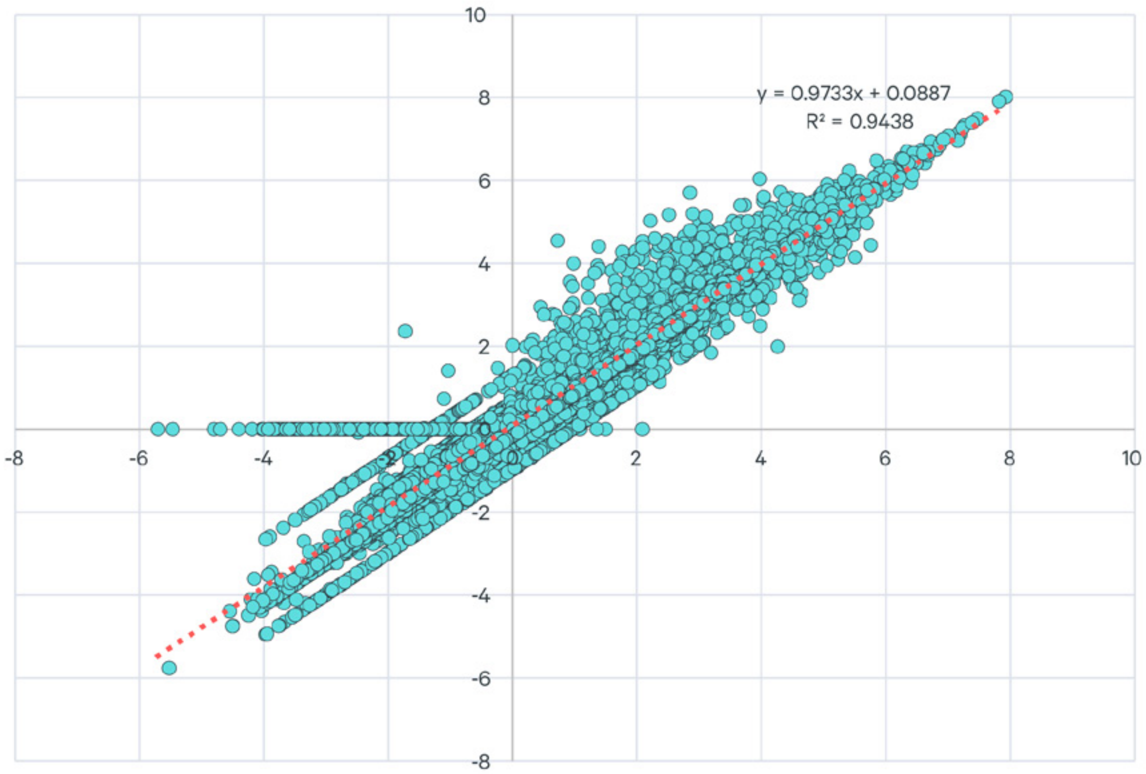
For rice, taking the difference between 2011/2014 and 2004/2007 observations, 90% of differences exist within the range -3.24 to +327.04 tonnes, while 99.8% exist within one standard deviation of the mean. This suggests a modest increase over time in most producer/consumer relationships resulting from a modest increase in global rice production, with some exceptions.

Figure 36. **Rice** IOTA data robustness test. Comparison of 2004/2007 average (log) to 2011/2014 average (log), R2=0.9763. Serbia, Montenegro, Sudan, and South Sudan excluded, 30599 observations at two time points.



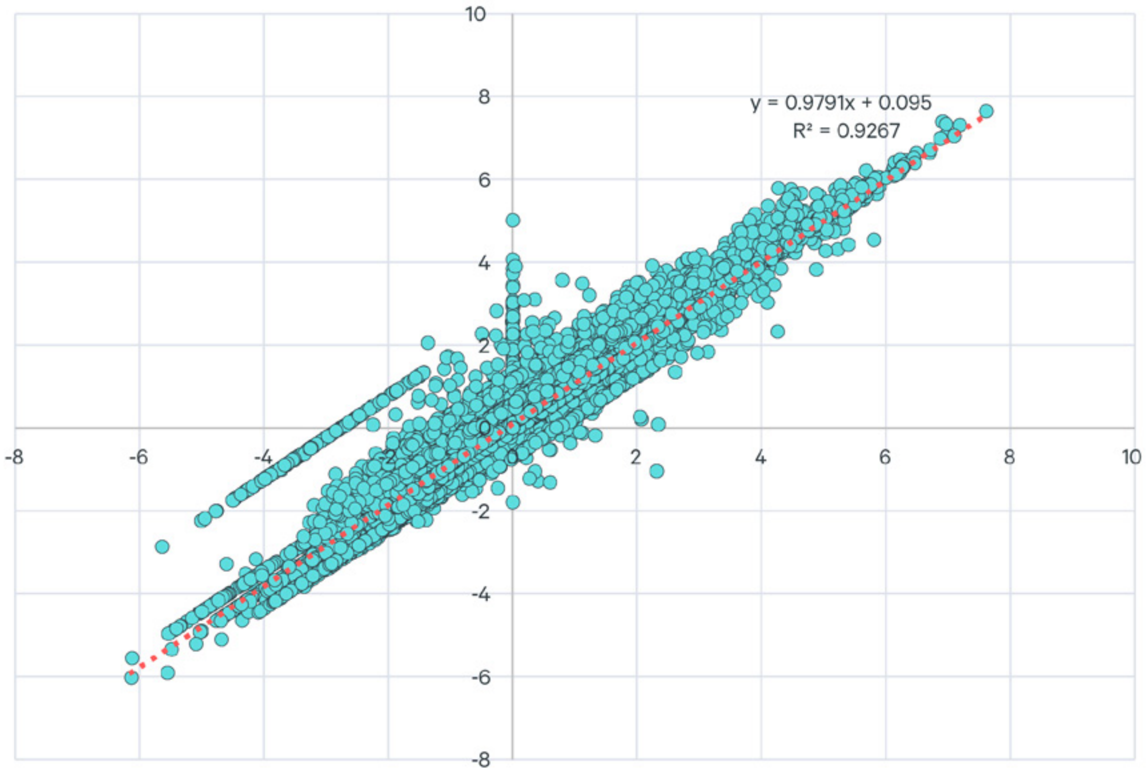
For wheat, taking the difference between 2011/2014 and 2004/2007 observations, 90% of differences exist within the range -84.02 to +1425.58 tonnes, while 99.5% exist within one standard deviation of the mean. This suggests a modest increase over time in most producer/consumer relationships resulting from a modest increase in global wheat production, with some exceptions.

Figure 37. **Wheat** IOTA data robustness test. Comparison of 2004/2007 average (log) to 2011/2014 average (log), R2=0.9438. Serbia, Montenegro, Sudan, and South Sudan excluded, 30599 observations at two time points.



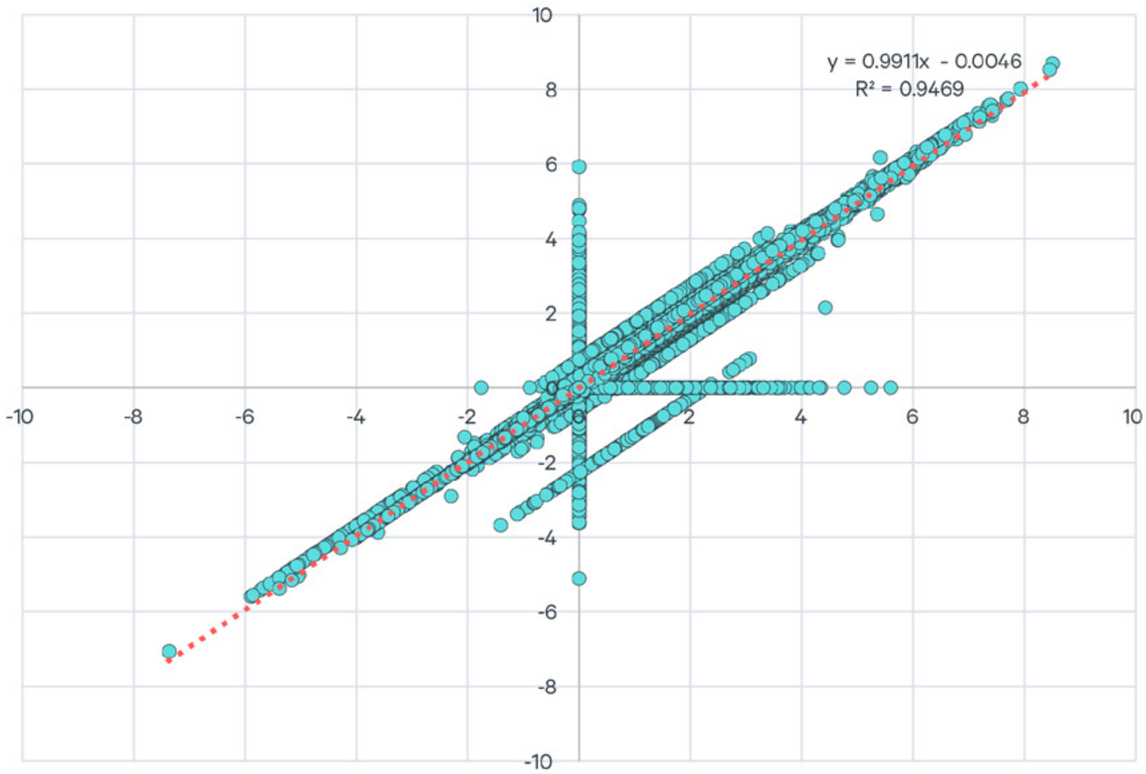
For soy, taking the difference between 2011/2014 and 2004/2007 observations, 90% of differences exist within the range -0.88 to +170.77 tonnes, while 99.7% exist within one standard deviation of the mean. This suggests a modest increase over time in most producer/consumer relationships resulting from a modest increase in global soy production, with some exceptions.

Figure 38. **Soy** IOTA data robustness test. Comparison of 2004/2007 average (log) to 2011/2014 average (log), R2=0.9267. Serbia, Montenegro, Sudan, and South Sudan excluded, 30599 observations at two time points.



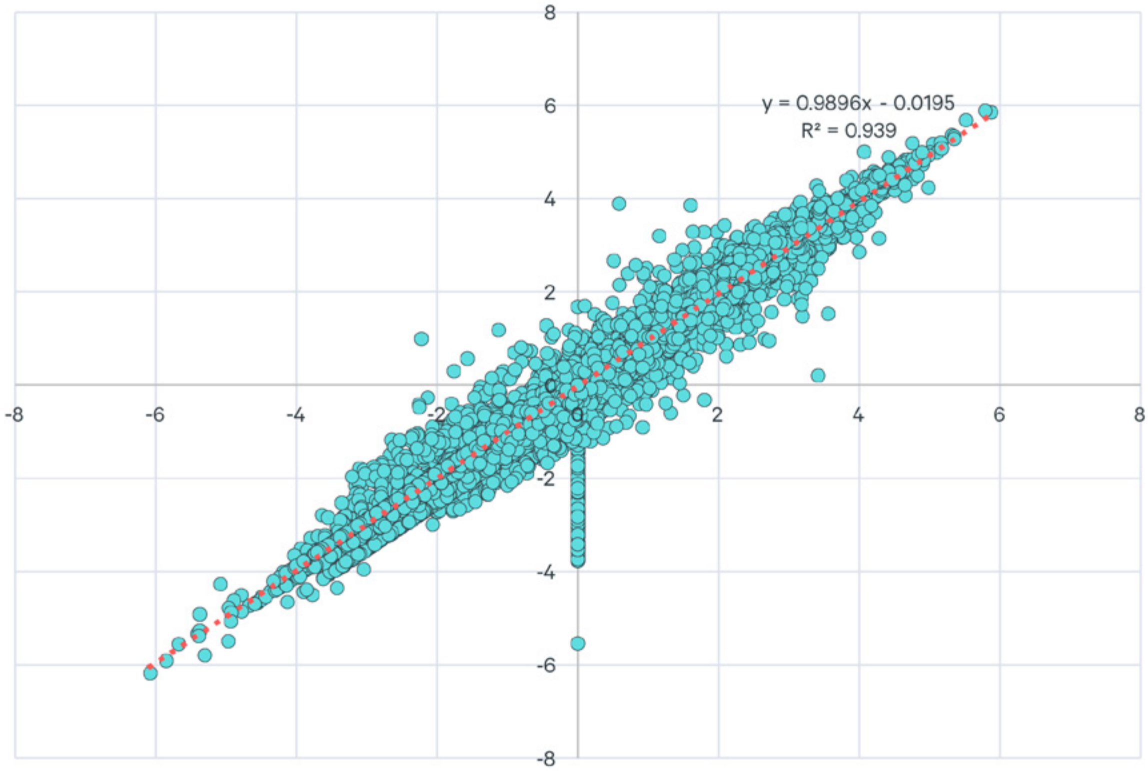
For sugar cane, taking the difference between 2011/2014 and 2004/2007 observations, 90% of differences exist within the range -134.60 to +503.21 tonnes, while 99.8% exist within one standard deviation of the mean. This suggests a modest increase over time in most producer/consumer relationships resulting from a modest increase in global sugar cane production, with some exceptions.

Figure 39. **Sugar cane** IOTA data robustness test. Comparison of 2004/2007 average (log) to 2011/2014 average (log), R2=0.9469. Serbia, Montenegro, Sudan, and South Sudan excluded, 30599 observations at two time points.



For green coffee, taking the difference between 2011/2014 and 2004/2007 observations, 90% of differences exist within the range -5.41 to +4.90 tonnes, while 99.2% exist within one standard deviation of the mean. This suggests a modest increase over time in most producer/consumer relationships resulting from a modest increase in global coffee production, with some exceptions.

Figure 40. **Coffee (green)** IOTA data robustness test. Comparison of 2004/2007 average (log) to 2011/2014 average (log), R2=0.939. Serbia, Montenegro, Sudan, and South Sudan excluded, 30599 observations at two time points.



Annex III Projected climate impacts on producers and yields of major agricultural commodities

Table 2. Projected climate impacts on producers and yields of major agricultural commodities. Maize, rice, wheat, soy, and sugar cane data are projected for the long-term (2070-2099) using the HadGEM2-ES GCM, RCP8.5, and the EPIC GGCM. Coffee data are projected for the medium-term (2040–2050) using RCP8.5 and the Bitter Cup GGCM.

Producing countries and regions	Maize	Rice	Wheat	Soy	Sugar cane	C. Arabica	C. Robusta
Afghanistan	17.4%	60.1%	215.0%	60.5%	34.7%	N/A	N/A
Albania	-35.9%	-14.5%	28.3%	-11.2%	-16.9%	N/A	N/A
Algeria	-3.4%	28.0%	12.3%	33.7%	-17.8%	-21.9%	-9.7%
American Samoa	N/A	N/A	N/A	N/A	N/A	N/A	5.3%
Angola	-16.6%	-9.4%	-69.0%	-0.8%	-65.0%	-55.6%	-26.7%
Anguilla	N/A	N/A	N/A	N/A	N/A	361.4%	190.1%
Antigua and Barbuda	-25.0%	-9.4%	-81.6%	3.3%	-42.6%	59.1%	34.1%
Argentina	-6.8%	-0.8%	27.8%	7.5%	74.9%	-24.7%	-4.7%
Armenia	-26.6%	-7.2%	40.0%	-1.2%	-27.8%	N/A	N/A
Aruba	-3.7%	-17.8%	-90.2%	-22.8%	-37.3%	107.4%	83.4%
Australia	-20.4%	-4.4%	2.4%	-7.2%	-11.0%	-16.7%	-2.4%
Austria	-29.2%	4.3%	28.8%	11.9%	-27.8%	N/A	N/A
Azerbaijan	-5.6%	13.5%	58.5%	18.5%	-25.6%	N/A	N/A
Bahamas	N/A	N/A	N/A	N/A	N/A	-36.1%	-20.2%
Bahrain	-0.5%	10.7%	36.1%	14.4%	34.7%	-9.7%	68.8%
Bangladesh	-37.3%	-36.3%	-29.4%	-35.2%	-70.7%	36.7%	-5.3%
Barbados	-33.0%	-18.1%	-79.2%	-11.2%	-51.9%	-77.2%	1.9%
Belarus	-28.2%	0.5%	19.1%	10.5%	-25.8%	N/A	N/A
Belgium	-16.4%	21.5%	34.6%	27.7%	-15.7%	N/A	N/A
Belize	-50.1%	-36.3%	-55.9%	-26.7%	-76.0%	-82.2%	-33.6%
Benin	-46.0%	-36.5%	-95.9%	-36.0%	-75.1%	-56.3%	3.4%
Bermuda	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Bhutan	5.8%	64.3%	0.8%	68.1%	-6.1%	9.0%	5.3%
Bolivia, Plurinational State of	-28.2%	-29.9%	-45.1%	-25.1%	-50.7%	-60.1%	-30.7%
Bosnia and Herzegovina	-27.4%	1.7%	39.5%	9.3%	-31.7%	N/A	N/A
Botswana	1.9%	16.1%	-20.2%	20.6%	-57.2%	-7.5%	-12.3%
Brazil	-22.1%	-25.9%	-58.3%	-11.8%	-65.6%	-63.7%	-19.0%
British Virgin Islands	N/A	N/A	N/A	N/A	N/A	0.0%	22.1%
Brunei Darussalam	-25.3%	-14.3%	-88.3%	-5.7%	-67.1%	14.4%	-11.7%
Bulgaria	-17.9%	18.2%	30.0%	19.5%	-29.4%	N/A	N/A
Burkina Faso	-63.2%	-54.8%	-97.2%	-55.9%	-85.6%	-6.5%	93.0%
Burundi	-15.1%	2.4%	-44.1%	11.8%	-52.4%	-28.7%	6.1%
Cabo Verde	N/A	N/A	N/A	N/A	N/A	-25.0%	17.0%
Cambodia	-34.8%	-24.9%	-92.6%	-24.6%	-76.9%	-57.6%	-27.1%

Producing countries and regions	Maize	Rice	Wheat	Soy	Sugar cane	C. Arabica	C. Robusta
Cameroon	-29.5%	-21.6%	-81.0%	-21.0%	-66.5%	-80.6%	-47.5%
Canada	17.0%	78.7%	-13.0%	119.6%	7.1%	N/A	N/A
Cayman Islands	N/A	N/A	N/A	N/A	N/A	-38.0%	-7.1%
Central African Republic	-35.1%	-26.3%	-86.2%	-26.7%	-69.5%	-87.4%	-49.8%
Chad	-29.0%	-11.4%	-85.3%	-14.3%	-74.9%	-14.6%	14.1%
Chile	67.1%	123.2%	15.9%	137.6%	101.6%	-1.0%	-2.2%
China	-15.5%	-1.8%	-9.2%	1.0%	-26.7%	2.2%	0.4%
China, Taiwan Province of	-10.5%	4.0%	-7.5%	1.2%	-36.1%	-11.1%	12.2%
Cocos (Keeling) Islands	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Colombia	-16.1%	-41.9%	-62.1%	-16.8%	-50.5%	-21.9%	-12.6%
Comoros	N/A	N/A	N/A	N/A	N/A	-30.5%	21.8%
Congo	-28.4%	-17.4%	-84.6%	-15.5%	-61.6%	-90.0%	-47.1%
Cook Islands	N/A	N/A	N/A	N/A	N/A	-13.9%	274.9%
Costa Rica	-29.1%	-15.9%	-69.7%	-12.8%	-73.9%	-43.9%	-24.8%
Côte d'Ivoire	-40.1%	-34.7%	-90.7%	-35.9%	-75.6%	-73.4%	-32.0%
Croatia	-40.3%	-11.4%	37.5%	-1.5%	-31.4%	N/A	N/A
Cuba	-53.6%	-34.7%	-96.3%	-44.3%	-65.3%	-78.5%	-45.2%
Cyprus	47.3%	93.5%	73.7%	93.5%	5.5%	N/A	N/A
Czechia	-24.9%	3.5%	26.3%	10.2%	-36.3%	N/A	N/A
Democratic People's Republic of Korea	-5.7%	23.1%	0.7%	17.3%	-11.5%	N/A	N/A
Democratic Republic of the Congo	-17.1%	-6.8%	-87.4%	-7.6%	-60.0%	-76.2%	-51.7%
Denmark	3.0%	45.2%	20.8%	49.6%	-22.8%	N/A	N/A
Djibouti	N/A	N/A	N/A	N/A	N/A	-11.8%	2.5%
Dominica	-3.6%	8.5%	-22.4%	4.1%	-25.4%	-54.0%	3.3%
Dominican Republic	-30.8%	-15.3%	-66.2%	-12.8%	-66.0%	-37.0%	-22.9%
Ecuador	-4.6%	-2.0%	-32.1%	9.7%	-8.8%	-26.7%	-26.3%
Egypt	-22.2%	4.1%	-21.7%	2.6%	-0.3%	-16.5%	-3.1%
El Salvador	-57.7%	-46.1%	-93.5%	-38.8%	-78.8%	-76.3%	-45.6%
Equatorial Guinea	-19.1%	-4.9%	-70.3%	5.2%	-40.2%	-78.9%	-36.9%
Eritrea	-16.2%	-15.6%	-78.2%	-14.1%	-68.7%	-30.6%	12.8%
Estonia	-22.8%	26.4%	-6.1%	40.4%	-22.5%	N/A	N/A
Eswatini	5.4%	6.7%	-22.4%	14.7%	-35.4%	-8.1%	-31.9%
Ethiopia	-24.8%	-14.3%	-45.7%	-12.5%	-41.4%	-9.2%	16.7%
Falkland Islands (Malvinas)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Faroe Islands	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fiji	N/A	N/A	N/A	N/A	N/A	-60.3%	-3.9%
Finland	8.7%	127.9%	43.3%	177.8%	-10.9%	N/A	N/A
France	-32.2%	5.6%	34.6%	11.8%	-18.6%	N/A	N/A
French Guyana	-25.4%	-27.6%	-97.5%	-3.9%	-83.5%	-80.7%	-34.8%
French Polynesia	N/A	N/A	N/A	N/A	N/A	-50.7%	13.0%
Gabon	-24.8%	-16.4%	-82.9%	-10.8%	-50.8%	-88.8%	-37.4%

Producing countries and regions	Maize	Rice	Wheat	Soy	Sugar cane	C. Arabica	C. Robusta
Gambia	-52.1%	-34.8%	-37.7%	-47.3%	-68.1%	-22.2%	68.8%
Georgia	-20.6%	-2.2%	19.5%	6.4%	-25.2%	N/A	N/A
Germany	-9.5%	20.2%	38.0%	25.8%	-23.7%	N/A	N/A
Ghana	-41.7%	-34.1%	-96.6%	-33.9%	-74.8%	-59.4%	-20.2%
Greece	-37.9%	-10.9%	54.5%	-8.9%	4.3%	N/A	N/A
Greenland	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Grenada	-52.0%	-38.4%	-90.1%	-42.9%	-62.3%	-59.6%	5.7%
Guadeloupe	-25.3%	-7.6%	-63.7%	1.5%	-34.6%	-62.8%	-3.2%
Guam	N/A	N/A	N/A	N/A	N/A	130.0%	9.7%
Guatemala	-47.2%	-34.0%	-68.5%	-26.8%	-74.5%	-34.5%	-32.2%
Guinea	-42.3%	-31.7%	-89.5%	-31.5%	-79.3%	-61.4%	-30.3%
Guinea-Bissau	-51.5%	-40.1%	-47.6%	-41.8%	-75.5%	-14.0%	-1.6%
Guyana	-38.0%	-35.5%	-92.1%	-29.7%	-63.9%	-73.3%	-21.9%
Haiti	-21.6%	-6.1%	-74.2%	-4.0%	-65.7%	-60.8%	-27.0%
Holy See	-19.7%	18.1%	43.5%	21.2%	-28.1%	N/A	N/A
Honduras	-51.5%	-36.5%	-85.6%	-29.8%	-75.1%	-62.8%	-27.3%
Hong Kong, Special Administrative Region of China	-31.3%	-19.6%	-9.0%	-4.3%	-63.9%	-8.7%	44.9%
Hungary	-45.0%	-19.6%	48.9%	-16.7%	-41.1%	N/A	N/A
Iceland	N/A	N/A	N/A	N/A	N/A	N/A	N/A
India	-2.4%	-3.9%	14.5%	-4.6%	-61.7%	-18.5%	-1.2%
Indonesia	-21.0%	-11.8%	-87.6%	-7.4%	-61.5%	-35.7%	-21.6%
Iran, Islamic Republic of	23.5%	67.0%	138.4%	70.0%	6.6%	-13.8%	-6.5%
Iraq	-55.6%	-39.2%	108.6%	-34.4%	13.2%	N/A	N/A
Ireland	40.5%	182.4%	5.4%	177.9%	10.5%	N/A	N/A
Israel	19.9%	63.5%	21.8%	60.2%	5.1%	N/A	N/A
Italy	-32.1%	0.3%	38.5%	8.7%	-24.0%	N/A	N/A
Jamaica	-15.0%	-0.2%	-71.9%	-3.5%	-56.1%	-65.6%	-14.2%
Japan	0.2%	11.7%	17.4%	11.3%	-23.2%	-8.0%	64.8%
Jordan	79.5%	101.4%	44.2%	110.2%	33.7%	N/A	N/A
Kazakhstan	-15.1%	4.6%	-20.3%	12.2%	-5.4%	N/A	N/A
Kenya	-1.6%	-28.1%	-36.4%	-24.2%	-35.9%	-12.8%	8.0%
Kiribati	N/A	N/A	N/A	N/A	N/A	784.4%	505.3%
Kuwait	-61.7%	-63.0%	152.5%	-72.6%	73.2%	-17.7%	-0.8%
Kyrgyzstan	21.6%	70.3%	47.3%	85.0%	3.1%	N/A	N/A
Lao People's Democratic Republic	-43.6%	-27.9%	-66.4%	-28.5%	-75.8%	-58.7%	-31.5%
Latvia	-16.3%	26.7%	5.5%	39.8%	-21.3%	N/A	N/A
Lebanon	31.4%	82.4%	72.2%	72.7%	6.6%	N/A	N/A
Lesotho	-1.8%	21.7%	-41.9%	51.0%	86.6%	19.6%	-8.1%
Liberia	-25.8%	-28.3%	-85.1%	-24.5%	-69.9%	-74.8%	-31.7%
Libya	46.3%	89.4%	30.5%	89.5%	1.3%	-24.8%	-10.7%
Lithuania	-20.2%	13.6%	11.3%	23.7%	-22.0%	N/A	N/A

Producing countries and regions	Maize	Rice	Wheat	Soy	Sugar cane	C. Arabica	C. Robusta
Luxembourg	-16.0%	17.0%	35.5%	25.3%	-27.1%	N/A	N/A
Macao, Special Administrative Region of China	-32.0%	-20.3%	-7.9%	-3.3%	-64.7%	81.4%	N/A
Madagascar	-12.2%	-1.3%	-36.9%	12.4%	-47.1%	-46.6%	-15.6%
Malawi	-11.8%	-23.0%	-61.3%	-14.5%	-77.6%	-65.3%	-37.0%
Malaysia	-28.4%	-22.2%	-87.8%	-14.2%	-60.7%	-58.9%	-26.3%
Maldives	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Mali	-63.3%	-58.4%	-96.1%	-62.1%	-86.7%	-5.6%	18.6%
Malta	89.9%	145.9%	58.8%	148.9%	-1.2%	N/A	N/A
Martinique	-13.4%	-6.5%	-76.1%	2.1%	-45.3%	-60.2%	-3.5%
Mauritania	-65.7%	-57.9%	-41.0%	-57.7%	-74.1%	-5.6%	9.1%
Mauritius	N/A	N/A	N/A	N/A	N/A	-54.4%	18.3%
Mayotte	N/A	N/A	N/A	N/A	N/A	N/A	-4.6%
Mexico	-35.6%	-24.3%	-10.2%	-24.5%	-64.6%	-43.9%	-23.0%
Micronesia, Federated States of	N/A	N/A	N/A	N/A	N/A	61.2%	22.4%
Mongolia	16.6%	45.3%	-23.1%	63.1%	55.3%	N/A	N/A
Montenegro	-22.0%	10.6%	58.1%	13.7%	-19.3%	N/A	N/A
Montserrat	N/A	N/A	N/A	N/A	N/A	154.0%	229.5%
Morocco	-17.2%	24.4%	-32.6%	29.7%	-1.9%	-42.6%	-1.2%
Mozambique	-21.9%	-15.9%	-51.0%	-8.3%	-76.8%	-80.6%	-42.2%
Myanmar	-10.2%	-1.4%	-25.8%	-7.1%	-71.2%	-26.0%	-14.4%
Namibia	-19.6%	-10.0%	-9.7%	-11.4%	-74.1%	-18.2%	-9.7%
Nauru	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Nepal	1.7%	24.7%	3.3%	7.8%	-47.5%	5.4%	6.5%
Netherlands	-2.3%	32.7%	27.6%	24.2%	-12.5%	N/A	N/A
Netherlands Antilles (former)	-14.9%	6.0%	-58.3%	5.1%	-41.3%	78.4%	52.6%
New Caledonia	N/A	N/A	N/A	N/A	N/A	-56.6%	20.4%
New Zealand	69.7%	113.6%	42.3%	95.7%	148.3%	N/A	N/A
Nicaragua	-43.9%	-31.4%	-89.9%	-25.9%	-78.9%	-74.2%	-40.0%
Niger	-40.9%	-30.6%	-92.2%	-32.2%	-71.7%	-5.6%	11.1%
Nigeria	-38.1%	-28.1%	-87.4%	-29.3%	-76.0%	-60.0%	-14.6%
Niue	N/A	N/A	N/A	N/A	N/A	-44.0%	19.7%
North Macedonia	-41.3%	-21.7%	28.0%	-21.4%	-21.9%	N/A	N/A
Northern Mariana Islands	N/A	N/A	N/A	N/A	N/A	-13.0%	85.0%
Norway	28.3%	180.5%	8.3%	222.7%	12.9%	N/A	N/A
Oman	5.4%	33.3%	-11.2%	23.7%	-15.8%	-25.6%	10.3%
Pakistan	-14.7%	-4.6%	51.8%	-1.4%	-43.0%	-8.3%	0.8%
Palestine	39.5%	93.7%	42.2%	87.7%	19.1%	N/A	N/A
Panama	-26.9%	-14.9%	-79.3%	-14.2%	-65.5%	-53.6%	-30.9%
Papua New Guinea	-18.0%	-14.2%	-73.9%	-5.4%	-40.3%	-16.6%	-17.1%
Paraguay	-24.5%	-20.4%	-8.4%	15.1%	-22.2%	-69.4%	-17.3%

Producing countries and regions	Maize	Rice	Wheat	Soy	Sugar cane	C. Arabica	C. Robusta
Peru	0.3%	27.6%	-2.5%	18.1%	-3.2%	-24.5%	-20.1%
Philippines	-25.3%	-12.9%	-55.3%	-10.6%	-58.7%	-53.6%	-24.8%
Poland	-18.5%	10.5%	34.8%	16.8%	-31.3%	N/A	N/A
Portugal	5.3%	65.9%	26.3%	65.9%	-20.9%	N/A	N/A
Puerto Rico	N/A	N/A	N/A	N/A	N/A	-68.1%	-28.7%
Qatar	-7.3%	-4.8%	12.5%	-1.0%	17.6%	-6.5%	10.2%
Republic of Korea	-6.2%	10.2%	2.0%	1.0%	-32.2%	N/A	N/A
Republic of Moldova	-32.8%	-4.6%	34.1%	-2.0%	-29.3%	N/A	N/A
Réunion	N/A	N/A	N/A	N/A	N/A	-19.3%	28.3%
Romania	-34.3%	-1.7%	27.5%	3.9%	-34.2%	N/A	N/A
Russian Federation	12.7%	60.2%	-9.1%	88.3%	-3.5%	N/A	N/A
Rwanda	-17.1%	-4.8%	-32.7%	1.9%	-34.2%	-21.8%	4.0%
Saint Helena, Ascension and Tristan da Cunha	N/A	N/A	N/A	N/A	N/A	1118.4%	30.9%
Saint Kitts and Nevis	-14.9%	6.0%	-58.3%	5.1%	-41.3%	-48.2%	107.2%
Saint Lucia	-25.2%	-15.6%	-77.7%	-14.4%	-47.7%	-80.3%	-1.3%
Saint Pierre and Miquelon	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Saint Vincent and the Grenadines	-36.1%	-24.4%	-91.1%	-27.2%	-45.2%	-70.3%	14.8%
Samoa	N/A	N/A	N/A	N/A	N/A	13.6%	-13.3%
Sao Tome and Principe	N/A	N/A	N/A	N/A	N/A	-42.6%	24.9%
Saudi Arabia	28.4%	71.1%	12.3%	74.5%	-8.6%	-25.8%	-12.9%
Senegal	-57.8%	-43.2%	-43.0%	-53.0%	-72.2%	-15.7%	55.1%
Serbia	-41.4%	-12.2%	33.3%	-5.2%	-37.0%	N/A	N/A
Seychelles	N/A	N/A	N/A	N/A	N/A	0.1%	89.4%
Sierra Leone	-34.3%	-24.5%	-93.6%	-23.2%	-76.9%	-51.5%	-36.6%
Singapore	-26.0%	-16.1%	-96.4%	-7.3%	-61.4%	18.0%	0.9%
Slovakia	-39.9%	-5.1%	32.8%	4.0%	-35.9%	N/A	N/A
Slovenia	-31.3%	-6.6%	36.5%	1.0%	-36.1%	N/A	N/A
Solomon Islands	N/A	N/A	N/A	N/A	N/A	-49.5%	-23.7%
Somalia	-20.9%	16.3%	-53.0%	17.6%	-36.2%	-41.6%	33.7%
South Africa	-8.7%	7.4%	-18.3%	11.8%	15.4%	-11.3%	-8.1%
South Sudan	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Spain	-16.5%	40.1%	22.6%	41.6%	-15.4%	-21.9%	29.4%
Sri Lanka	-8.4%	0.8%	-71.9%	-6.1%	-66.5%	-41.6%	-18.4%
Sudan	-45.5%	-37.0%	-88.7%	-37.2%	-76.6%	-33.6%	15.6%
Suriname	-62.4%	-44.4%	-97.0%	-38.3%	-58.2%	-61.8%	-10.6%
Sweden	1.6%	74.8%	51.4%	96.1%	-16.3%	N/A	N/A
Switzerland	-11.4%	34.9%	33.9%	33.3%	-14.3%	N/A	N/A
Syrian Arab Republic	-28.8%	-6.2%	98.1%	-3.8%	21.2%	N/A	N/A
Tajikistan	-3.9%	40.3%	95.3%	39.2%	12.8%	N/A	N/A
Thailand	-48.7%	-34.9%	-90.0%	-37.9%	-77.6%	-54.7%	-25.7%
Timor-Leste	-15.0%	2.2%	-91.7%	4.6%	-72.6%	-55.1%	-19.4%

Producing countries and regions	Maize	Rice	Wheat	Soy	Sugar cane	C. Arabica	C. Robusta
Togo	-42.9%	-32.7%	-96.5%	-31.2%	-72.2%	-77.5%	-19.2%
Tokelau	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Tonga	N/A	N/A	N/A	N/A	N/A	-3.7%	89.3%
Trinidad and Tobago	-22.0%	-8.1%	-88.1%	-3.7%	-61.7%	-78.6%	-22.3%
Tunisia	9.5%	42.8%	25.3%	45.0%	-26.8%	N/A	N/A
Turkey	-30.5%	0.8%	76.4%	7.5%	11.7%	N/A	N/A
Turkmenistan	21.8%	68.2%	263.1%	69.4%	89.5%	N/A	N/A
Turks and Caicos Islands	N/A	N/A	N/A	N/A	N/A	-20.1%	10.1%
Tuvalu	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Uganda	-31.0%	-23.7%	-62.3%	-15.6%	-33.5%	-58.6%	-32.9%
Ukraine	-29.5%	-3.8%	32.9%	1.7%	-24.9%	N/A	N/A
United Arab Emirates	-35.4%	-19.1%	-11.3%	-24.7%	5.2%	-18.0%	-7.8%
United Kingdom of Great Britain and Northern Ireland	36.5%	149.8%	20.0%	153.5%	33.8%	N/A	N/A
United Republic of Tanzania	-27.4%	-12.4%	-62.2%	10.2%	-67.3%	-52.0%	-24.5%
United States of America	-45.5%	-31.4%	-64.0%	-29.3%	-11.4%	-33.0%	-4.3%
Uruguay	0.2%	5.8%	10.5%	5.5%	74.5%	-10.2%	23.6%
Uzbekistan	4.0%	38.6%	194.2%	41.1%	45.7%	N/A	N/A
Vanuatu	-8.2%	8.8%	-9.2%	9.9%	34.4%	-24.4%	7.9%
Venezuela (Bolivarian Republic of)	-44.3%	-47.0%	-82.7%	-43.8%	-69.5%	-55.3%	-22.9%
Viet Nam	-3.8%	0.2%	-70.5%	-2.2%	-70.4%	-52.5%	-26.0%
Wallis and Futuna Islands	N/A	N/A	N/A	N/A	N/A	N/A	121.9%
Yemen	-12.8%	-0.7%	-43.9%	3.4%	-43.6%	-33.3%	-10.3%
Zambia	-5.4%	-5.9%	-23.0%	7.3%	-75.2%	-4.9%	-13.5%
Zimbabwe	0.0%	3.7%	-58.8%	10.8%	-75.1%	-43.8%	-12.5%

Annex IV Trade flows and transboundary climate risks for the rice, wheat, soy, sugar cane and coffee markets

Figure 41. Risk and opportunity in bilateral trade relationships for **rice**

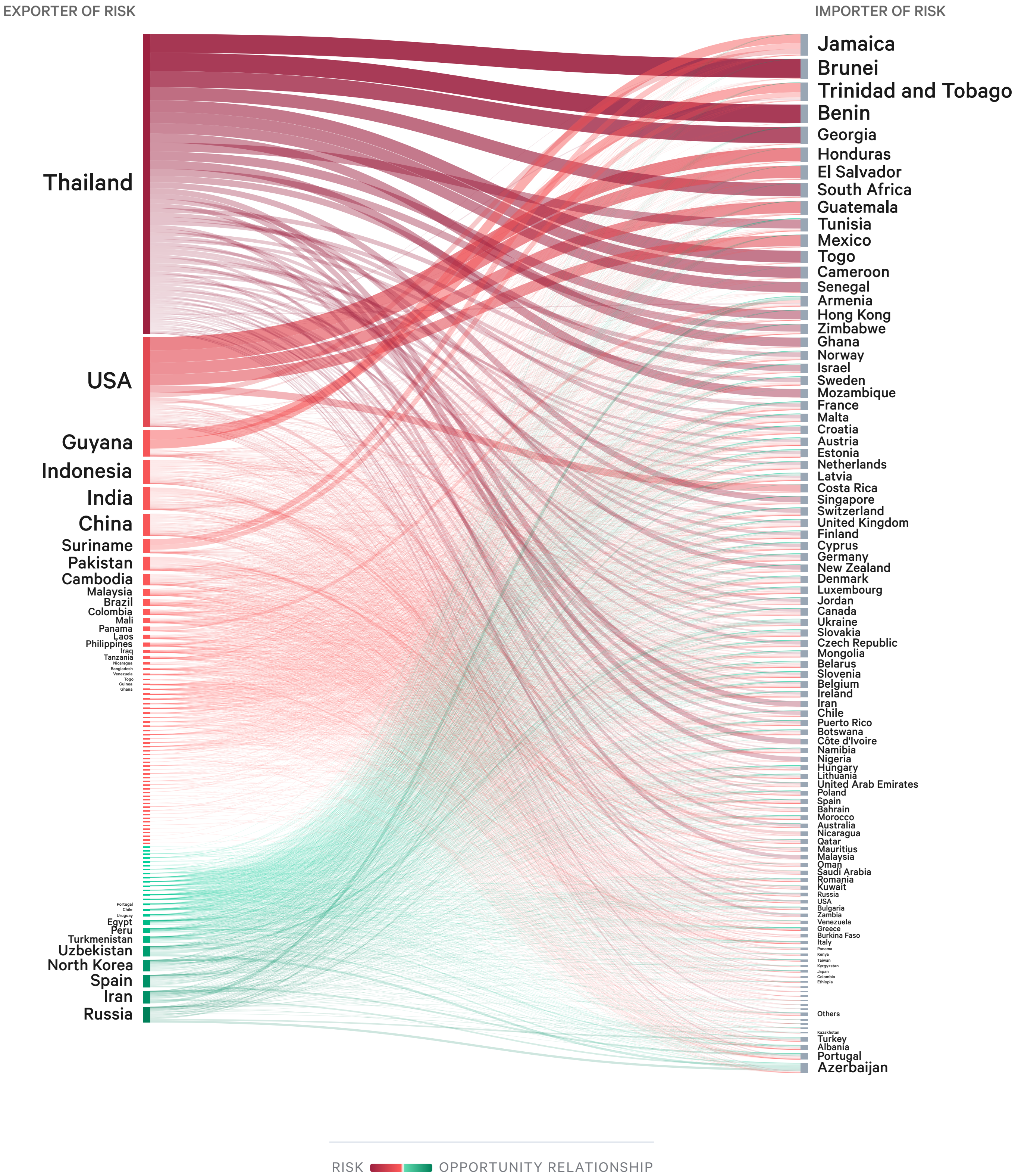


Figure 42. Risk and opportunity in bilateral trade relationships for **wheat**

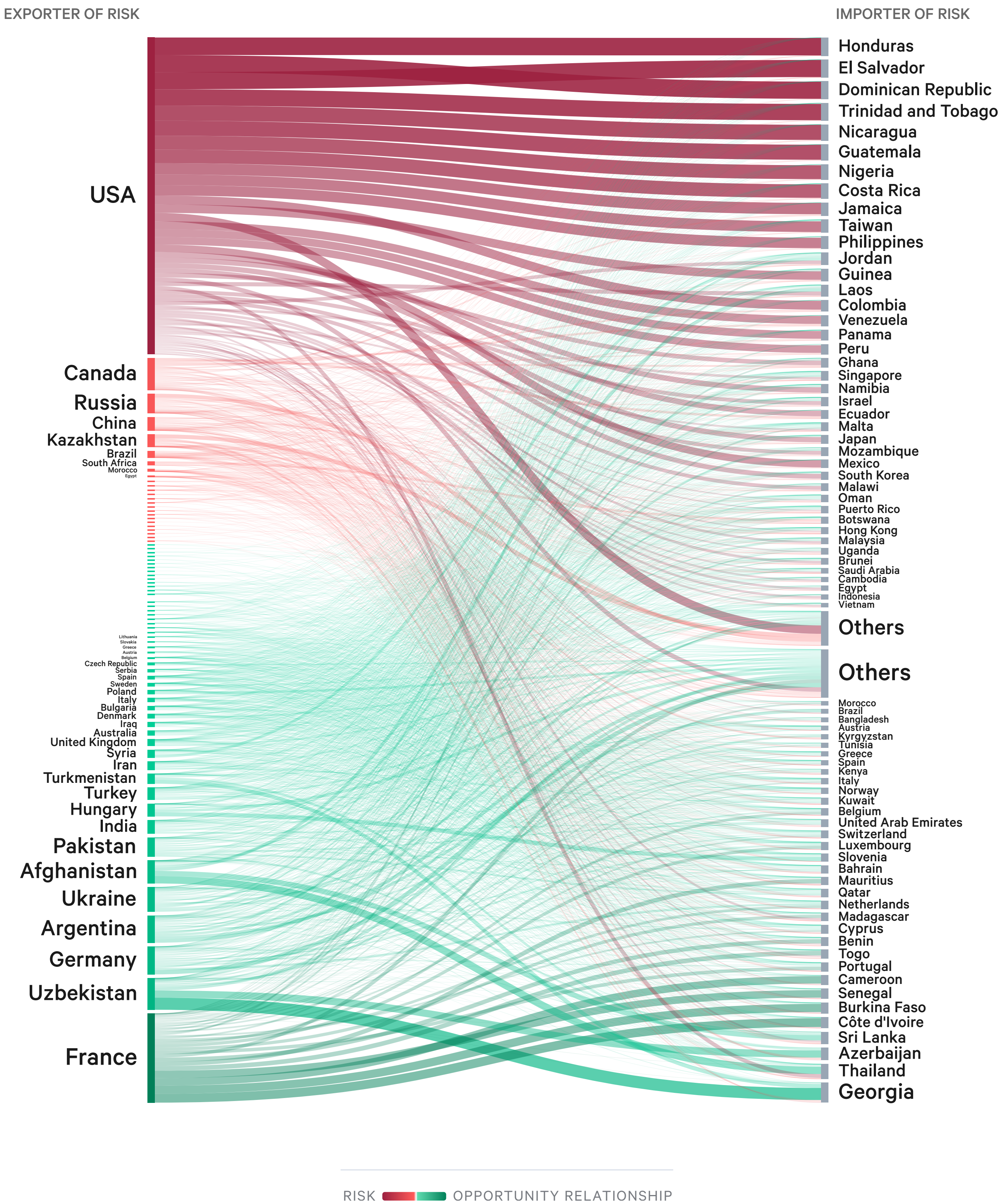


Figure 43. Risk and opportunity in bilateral trade relationships for **soy**

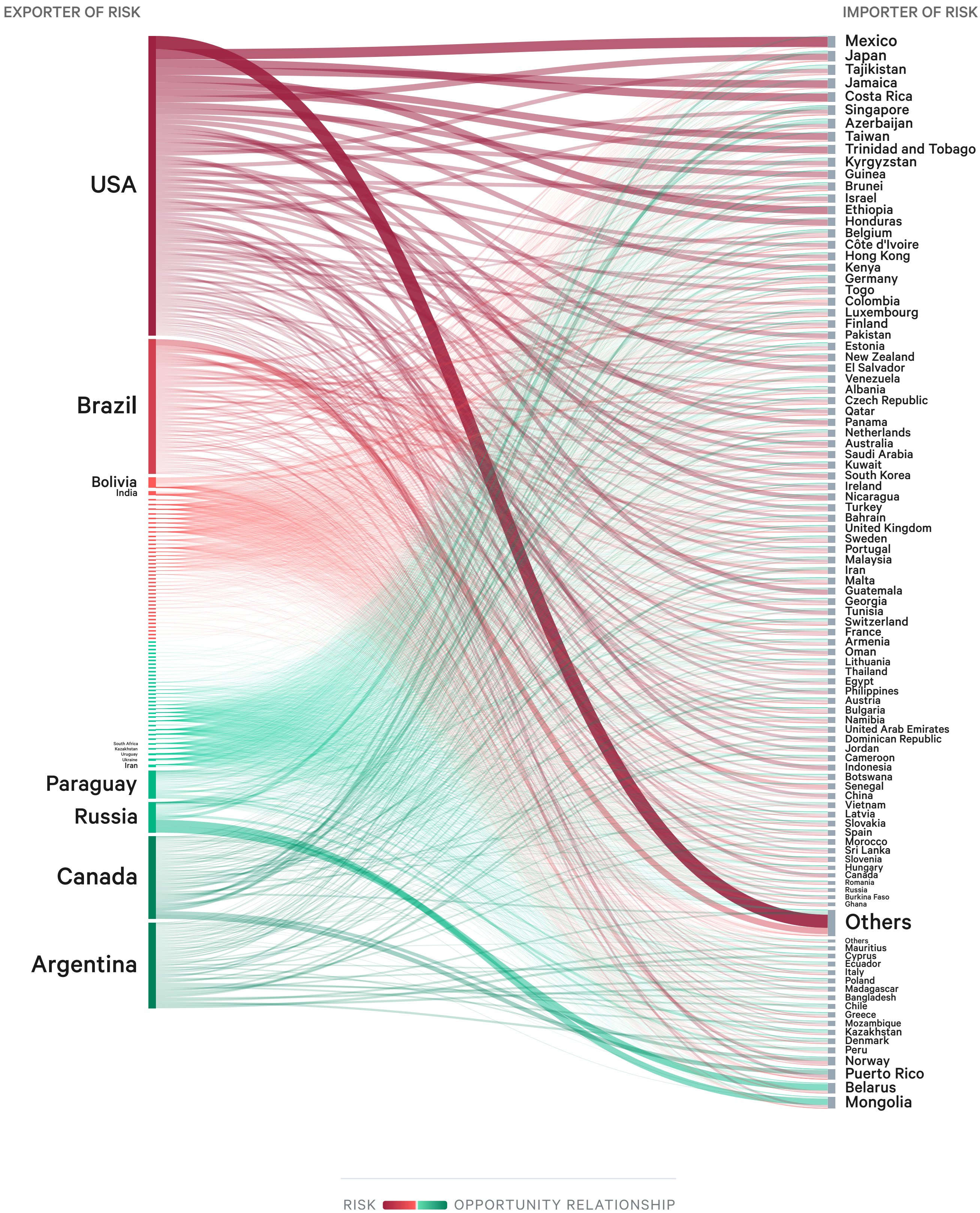


Figure 44. Risk and opportunity in bilateral trade relationships for **sugar cane**

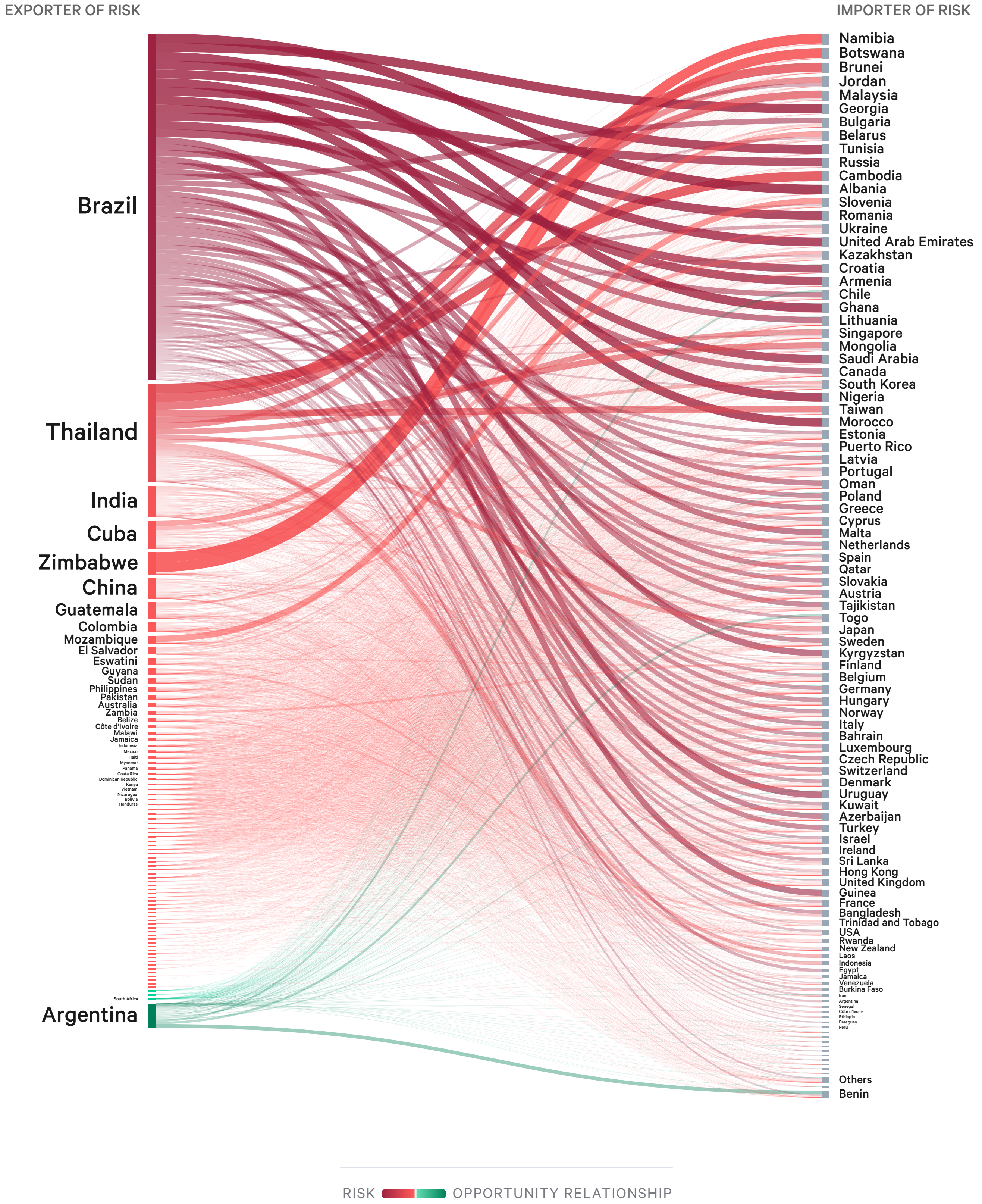


Figure 45. Risk and opportunity in bilateral trade relationships for **Arabica coffee**

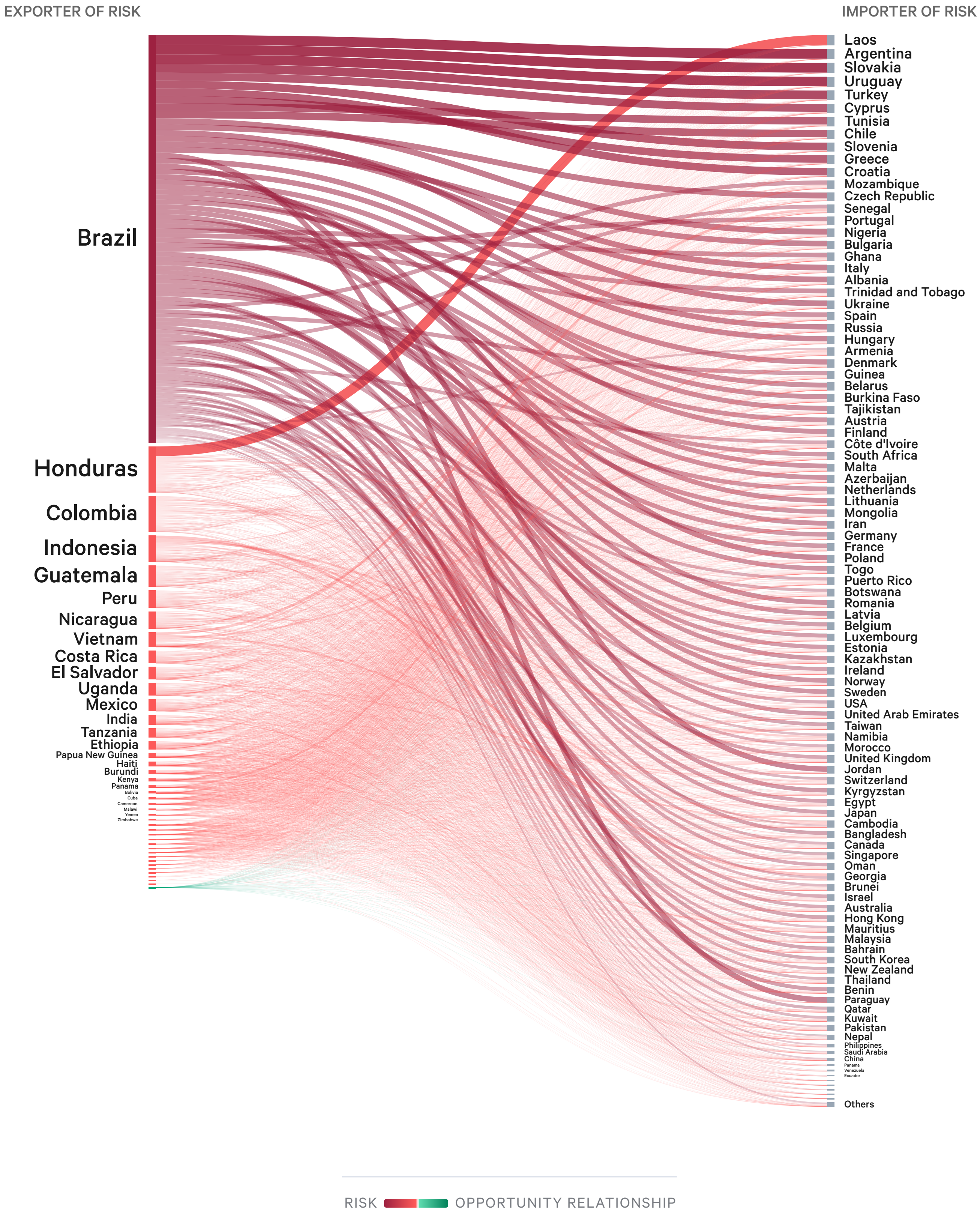
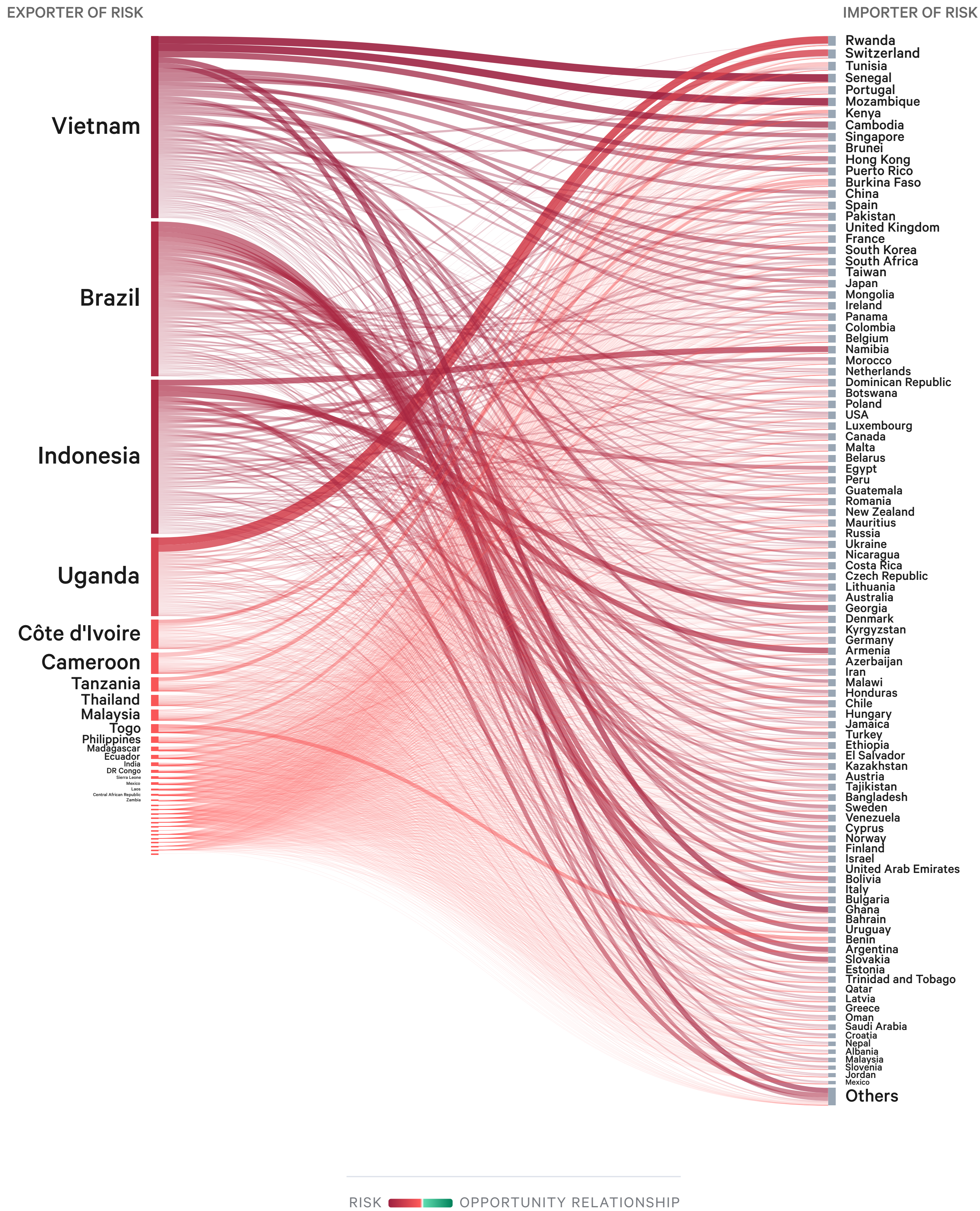


Figure 46. Risk and opportunity in bilateral trade relationships for **Robusta coffee**



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