Global Food Security 33 (2022) 100625

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

Climate-related hazards and Indian food supply: Assessing the risk using recent historical data

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ARTICLE INFO

Keywords:
Climate hazards
Extreme events
Food shocks
Risk assessment
Food trade

ABSTRACT

Climate-related hazards can lead to agricultural losses and affect local and wider food supply via food trade. This study estimates the potential for adverse effects of climate hazards on food supply across Indian States and Union Territories (hereafter 'states') by quantifying climate hazard risks. Risks were estimated using the most recent data available on hazard presence, vulnerability, and volume of per capita food supply that is exposed to hazards. Historical (2000–2020) climatological and geological data sourced from meteorological stations and satellite imagery were used to estimate the state-level presence of eight climate-related hazards (droughts, forest fires, floods, extreme rainfall, landslides, cyclones, extreme temperatures, sea level rise). For each state and hazard type, we distinguished between risk to food supply produced in the state and the risk to food supply imported from other states. The source of food supply was estimated from a supply and demand balance model for 30 major food items that uses government data from 2011–12. We found that climate hazard risks to food supply vary across states and by hazard type. The largest climate hazard risks to state food supply are in Bihar, Madhya Pradesh, and Assam, where the majority of risk is to locally produced supply. Food supply in each state is at risk to all eight climate hazards via food imports from other Indian states. For 14 states, the climate hazard risk is greater for imported food supply than for locally produced supply. Just five states contribute to more than half of the climate hazard risk in interstate food trade. The findings indicate that climate-related hazards in Indian states could have potentially adverse effects on national food supply, affecting both local production and interstate trade. For policy-makers, these climate hazard risks identify potential priorities for enhancing food system resilience to mitigate impacts on local and national food security.

Financial support

This study forms part of the Sustainable and Healthy Food Systems (SHEFS) programme supported by the Wellcome Trust's Our Planet, Our Health programme [grant number: 205200/Z/16/Z]. G.A. would like to thank CGIAR Research Program (CRP) on Climate Change, Agriculture and Food Security (CCAFS) and CGIAR Research Program (CRP) on Water, Land and Ecosystems (WLE), which is carried out with support from the CGIAR Trust Fund and through bilateral funding agreements for the funding support.

1. Introduction

Agricultural production is vulnerable to the impacts of climate-related hazards due to its dependence on the climate and weather. Over a quarter of the economic impact caused by disasters in low- and lower-middle-income countries (LICs and LMICs) is to the agricultural sector (FAO, 2021). Climate-related hazards, including floods, droughts, cyclones and temperature extremes, threaten each dimension of food and nutrition security (Vermeulen et al., 2012; Campbell et al., 2016). These climate hazards can reduce food availability by damaging crop or livestock production. This affects food supply in the local area, but can also have implications for food supply in other regions if the area exports food. Climate hazards can affect food access and affordability by

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https://doi.org/10.1016/j.gfs.2022.100625
Received 27 August 2021; Received in revised form 11 January 2022; Accepted 1 March 2022
Available online 21 March 2022
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reducing incomes in agriculture-dependent households, and by increasing the volatility and level of food prices (Hertel, 2016; Lloyd et al., 2018). Recent changes in climate have increased the exposure of agriculture to climate hazards (Zhu and Troy, 2018), hence there is a pressing need to implement policies that reduce the impact of climate hazards on food supply and thus improve resilience within agri-food systems. A greater understanding of the potential for climate hazards to cause adverse effects on food supply quantity could help prioritise policy options to mitigate impacts on food availability; one dimension of food security.

Due to its partly tropical location and large coastline, India experiences a high frequency and intensity of climate-related hazards (Disaster,; Shukla et al., 2019). An estimated 82% of the Indian population live in areas that are exposed to at least one climate-related hazard (Disaster), including droughts, floods, cyclones, landslides, sea-level rise, forest fires, extreme temperatures and extreme rainfall. The coastal regions are more prone to cyclones and sea-level rise (Kay et al., 2015), whereas the North Western region is more prone to droughts and extreme temperatures (Amrit et al., 2018). A disaster in one region could have implications for national food supply, particularly if the affected region is a major food producing region. For example, the Northern region produces 61% of the cereals that are traded across India for national food consumption (Harris et al., 2020). Information on where each state sources food is therefore critical to characterize climate risks to food security and to inform adaption strategies.

Studies have quantified relationships between Indian agriculture and climate hazards, highlighting that Indian agriculture is the most vulnerable sector to climate hazards (Amarnath et al., 2017), and that the risks to cereal production have increased in recent decades (Sharma et al., 2020). However, to-date the relationships between these climate hazards and Indian food supply quantity have not been estimated. We combined state-level data on climate hazard presence from 2000 with data on food production and interstate food trade to quantify the state-wise risk to the food supply for Indian food consumption of 30 major food items. We define food supply risk as the potential of climate hazards to cause adverse effects on the volume of food available for human consumption, and is quantified as the function of hazard presence, vulnerability and exposure, in line with the Fifth Assessment from the Intergovernmental Panel on Climate Change (IPCC) (Cardona et al., 2012; Field et al., 2014). The findings of this study may be used to inform disaster preparedness and promote appropriate climate adaptation strategies to safeguard food supply at the national level in India.

2. Methods

2.1. Estimating the production location of state-level food supply

Hereafter, 'state' refers to State and Union Territories (28 States and 6 UTs). Due to data availability, Andhra Pradesh represents the area of both Andhra Pradesh and Telangana pre-separation. To estimate the climate hazard risk to Indian food supply, we calculate the risk to food production and apportion this risk to food supply that is consumed within the state and food supply that is traded to other states. First, we estimate the source of food supply of each food item (N = 30) in each state, following methods in Harris et al. (2020) whereby interstate trade flows were modelled using existing state-level data on the supply and demand for each food item from the years 2011–12. The model equations are provided in Supplementary File with a detailed data glossary (Table S1). Briefly, for each state and food item, the total volume (tonnes/year) of food available for human consumption was estimated from agricultural production statistics, international imports, stock change and food allocated to non-food uses. The total demand (tonnes/year) was the volume of international exports and the relative food demand as estimated in the National Sample Survey (NSS); a household consumption and expenditure survey (scaled to state-level based on survey weights) (National Sample Survey Office, 2014). A supply and demand balance calculation was used to estimate the volume of interstate trade; states with total supply greater than demand were assumed to export the difference, while states with demand greater than supply were assumed to import the difference. The direction of interstate trade flows was estimated through a linear programming model that minimised transportation cost based on geographic distances. Thus, for each state the total volume of food supply was apportioned between food supply from local production and food supply imported from other states. The current analysis focused on the supply risks associated with Indian production and consumption only, as we were seeking to estimate the risks associated with climate hazards occurring in India and the respective vulnerability of food supplies in India. Therefore, we excluded the climate risk associated with food supply from international imports and the Indian food production that was exported internationally. Following steps of Harris et al. (2020), we validated the use of a linear programming model to estimate interstate food trade by assessing the association between the cost of transporting each food item with the value of the food item in each state (as estimated by NSS (National Sample Survey Office, 2014)).

We estimated the production location of food supply for 30 food items at state level, covering the food groups of cereals, pulses, fruits and vegetables, oils and sugar; equivalent to 52% of household food consumption (mean, kg/year) (National Sample Survey Office, 2014). The trade model used data from the years 2011–12, as this was the most recent time period for which all required data were available (see Supplementary File Table S1 for input data sources).

2.2. Calculation of climate hazard risk of food supply

We computed risk as a composite indicator of exposure, hazard and vulnerability, in accordance with the IPCC framework (Field et al., 2014) and as in previous studies of climate hazard risk (Cardona et al., 2012; Liu and Chen, 2021; Koks et al., 2015). Risk was calculated for both locally produced food supply (using local hazard, vulnerability and exposure scores), and risk food supply imported from other states (using hazard, vulnerability and exposure scores at export origin).

Hazard was defined as a the presence of a specified dangerous phenomenon or condition that may cause disruption (i.e. loss of food production) in each state (United Nations International Strategy for Disaster Reduction (UNISDR), 2009), and was expressed as the percentage of land area with the presence of each 8 climate hazards (droughts, floods, landslides, cyclones, forest fires, extreme rainfall, extreme temperature, sea-level rise) in each state. Different data sources from satellite imagery and meteorological stations were used to detect the areas affected by climate-related hazards between 2000–20 in grid cells across India, following methods of Amarnath et al. (2017) (Amarnath et al., 2017). Details of the data sources are given in Supplementary Table S1. To obtain a single hazard presence map for the 20-year period, each grid cell was given a normalised probability score of the hazard occurring, whereby 0 indicated no hazard was detected in the grid cell of over the study period and 1 indicates the hazard was detected every year in the whole grid cell. Sea-level rise represents the rate of sea-level rise over the 20-year period. Data was aggregated to state-level to give the percentage of land area with the presence of each hazard since 2000, thus presence is relative to annual frequency and land area affected. The island states of Lakshadweep and the Andaman & Nicobar Islands were excluded from all analysis due to the lack of necessary data.

Vulnerability was represented by the summary indicator of Human Development Index (HDI) that accounts for key dimensions of human development (including income, education and literacy), and has been found to be negatively associated with climate disaster risk (Patt et al., 2010). State-wise HDI data was from 2018 as the most recent year available. Finally, exposure was represented by volume of human food supply (total tonne, and tonne per capita).

Hazard, vulnerability and exposure values were normalised using the max-min normalisation procedure, whereby the largest value is represented by 1 and the lowest by 0. As HDI is negatively correlated with risk, the vulnerability score represents the inverse of the normalised value and the minimum value was 0.0001 as a high HDI does not indicate no vulnerability.

The climate hazard risk to each food item was estimated as follows:

$$LocR_i = H_i * V_i * E_i$$

$$ImR_i = \sum H_j * V_j * E_j$$

$$ALocR_{India} = \sum LocR_i$$

$$AImR_{India} = \sum ImR_i$$

$$R_i = LocR_i + ImR_i$$

Whereby for each state (i), the risk to locally produced food supply (*LocR*) was estimated as the function of local hazard (H), vulnerability (V) and exposure (E) scores. The risk to food supply imported from other states (*ImR*) was calculated according to food supply source, therefore represented as the sum of the function of hazard, vulnerability and exposure for each exporting state (j) for each importing state (i). Aggregated risk values for locally produced ($ALocR_{India}$) and imported supply ($AImR_{India}$) across Indian were calculated as the sum of state level risk values. The combined climate hazard risk was estimated as the sum of the eight climate hazard risks.

The results reported in the paper focus on per capita supply risks as the overall food supply risks were strongly linked to the size and population of the state. The risks to overall food supply can be found in the Supplementary File. For each state, we quantified the climate hazard risk to locally produced food supply, domestically imported food supply, total food supply and domestic food exports.

3. Results

3.1. Overview of indian food supply

A total of 309 Million Tonnes (MT) of food supply was included in this analysis, of which 70.3% (216.9 MT) was produced and consumed in the same state (local supply), and 29.7% (91.7 MT) was traded and consumed in a different state to which it was produced (imported supply).

Cereals were the predominant food supply group (Table 1), supplying 131.3 MT (42.5% of total food), followed by vegetables (including potatoes) (96.7 MT, 31.3%), fruits (48.0 MT, 15.5%), sugar (23.7 MT, 7.7%), pulses (7.7 MT, 2.75%), and rape & mustard oil (1.3 MT, 0.4%). The imported supply of a small number of foods (rape & mustard oil and pulses) was greater than the local food supply. Maps of state-wise production of food groups for food supply and the patterns of trade can be found in the Supplementary Files (Figs. S1–2).

Table 1
Overview of food group contribution to Indian food supply. MT: Million Tonnes.

	sugar	rape & mustard oil	cereals	vegetables	fruit	pulses
Total supply (mT, row %)	23.72 (7.66)	1.33 (0.43)	131.30 (42.42)	96.70 (31.24)	47.97 (15.50)	7.69 (2.49)
Local supply (MT, column %)	12.46 (52.53)	0.58 (43.66)	102.35 (77.95)	67.21 (69.50)	31.24 (65.12)	3.10 (40.30)
Imported supply (MT, column %)	11.26 (47.47)	0.75 (56.34)	28.95 (22.05)	29.49 (30.50)	16.73 (34.88)	4.59 (59.70)
N food Items in group	1	1	7	8	6	7

3.2. Overview of climate hazards

According to recent historical data (2000–20), the presence of climate hazards varies across states (Fig. 1). Droughts are the most prominent hazard, present in all states with a mean (M) 44.1% (standard deviation (SD) 21.1%) of land area experiencing droughts. The next most common hazards are forest fires (N = 33, M = 43.5%, SD = 34.1%), then cyclones (N = 32, M = 40.7%, SD = 26.5%), extreme rainfall (N = 33, M = 11.0, SD = 13.8%), floods (N = 33, M = 8.2, SD = 10.3%) and landslides (N = 33, M = 1.7, SD = 4.6%). Extreme temperatures are present in 20 states (M = 9.5, SD = 15.9%), and sea-level rise in 13 states (M = 3.2, SD = 8.5%).

3.3. Climate hazard risk to food supply across each climate hazard

The state-wise risks across each climate hazard to locally produced food supply and domestically imported food supply are shown in Fig. 2 (see Supplementary File Fig. S4 for state-wise hazard, exposure and vulnerability scores). The results are reported as per capita food supply risk; the overall food supply risk for each state and according to food group can be found in the Supplementary Files (Figs. S5–6, Table S3).

Droughts pose the greatest overall risk to per capita food supply produced locally in Indian states (*ALocR* = 6.82). This is followed by cyclones (*ALocR* = 6.06). Sea-level rise poses the lowest risk to locally produced food supply in India (*ALocR* = 0.45). The top five hazard risks to food supply produced locally by state are floods in Bihar (*LocR* = 0.91), droughts in Madhya Pradesh (*LocR* = 0.79), extreme temperature in Rajasthan (*LocR* = 0.65), droughts in Rajasthan (*LocR* = 0.59), and floods in Assam (*LocR* = 0.56) (Fig. 2).

As with locally produced food supply, droughts pose the greatest risk to domestically-traded food supply (*AR* = 5.94), followed by cyclones (*AR* = 4.40). Landslides pose the lowest risk to domestically-traded food supply (*AR* = 0.21). Through domestic food imports, all states are at risk to each climate hazard (Fig. 2). The states with the highest climate hazard risk to locally produced food supply have a comparatively lower climate hazard risk to imported food supply. The top five hazard risks to per capita food supply that is imported from others states are cyclones to Puducherry (*ImR* = 0.36), followed by droughts to Puducherry (*ImR* = 0.34), droughts to Daman and Diu (*ImR* = 0.33), droughts to Himachal Pradesh (*ImR* = 0.33), and forest fires to Manipur (*ImR* = 0.29) (Fig. 2).

3.4. Combined climate hazard risk to food supply

The combined climate hazard risk map to per capita food supply (including locally produced and imported food supply) for each state is shown in Fig. 3, along with the percentage of risk that is from imported food supply. For 14 states (42%), the climate hazard risk attributed to food imports from other states contributes to more than half of the total risk to food supply. These states, with the exception of Tamil Nadu and Puducherry, are in the lower two quartiles for total climate hazard risk to food supply. For all of the states in the highest quartile of total climate hazard risk to food supply, the climate hazard risk to food produced locally in the state is greater than the climate hazard risk to food imported from other states.

3.5. Climate hazard risk in state-level food exports

The combined climate hazard risk in interstate trade of per capita food supply is shown in Fig. 4 (see Fig. S7 for risk values across each state and hazard for food supply exports). Five states contribute to 53%

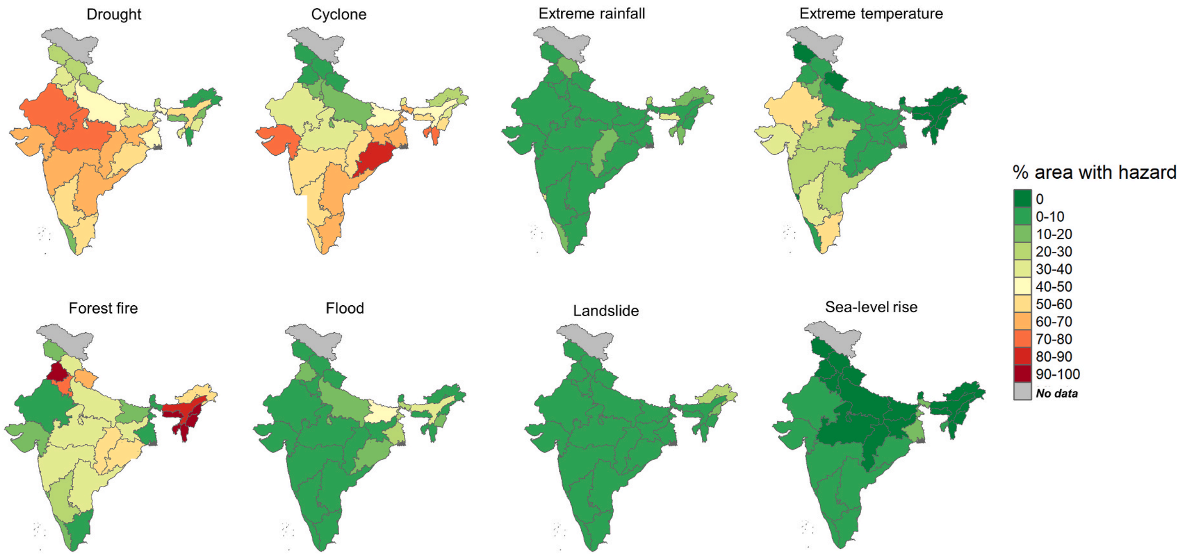

Fig. 1. Percentage land area of Indian states with the presence of each climate hazard (2000–20). Presence is relative to frequency and intensity.

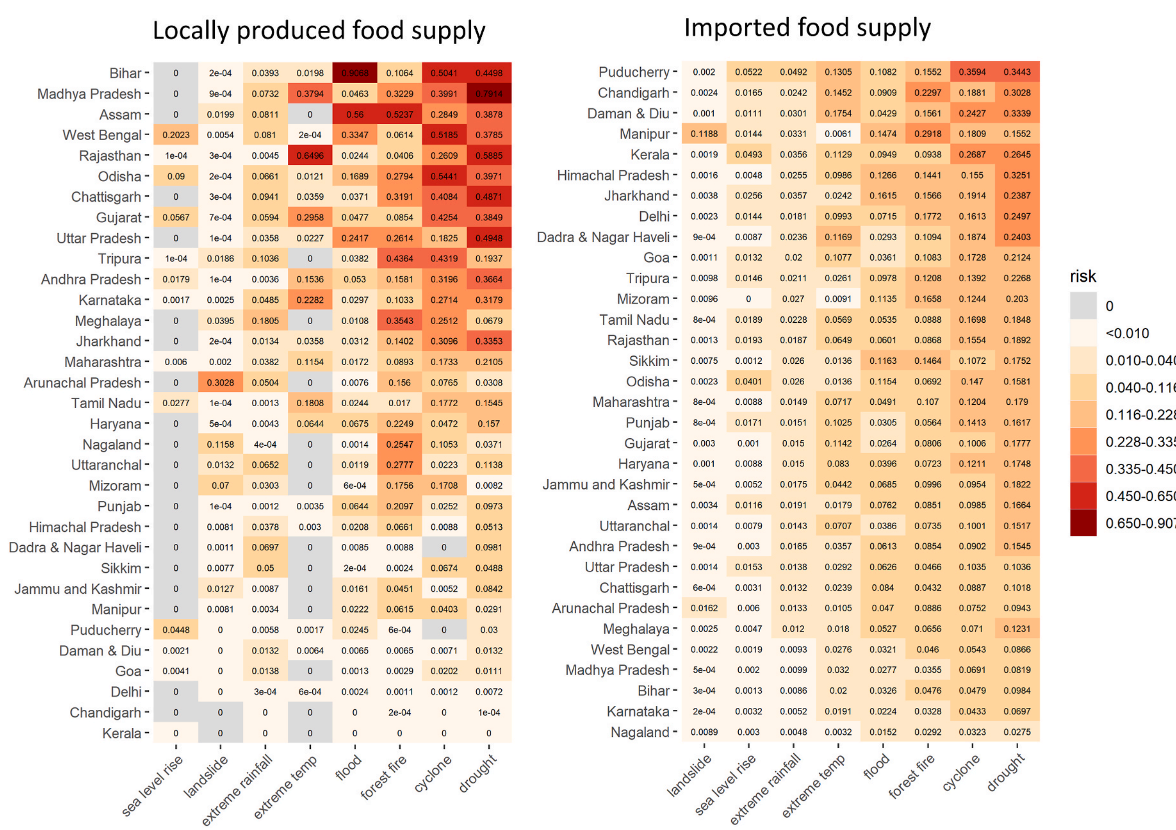

Figure 2. State-wise climate hazard risk to per capita food supply that is produced locally in the state and food supply that is imported from other Indian states (N = 33). Heatmap colour coded according to natural jenks, using the BAMMtools package in R. States are in descending order according to total risks, and hazards are ordered left to right for increasing aggregated risk across states.

of the climate hazard risk posed to interstate food trade: Uttar Pradesh ($R = 3.8$, exporting to 28 states), Madhya Pradesh ($R = 1.7$, exporting to 29 states) West Bengal ($R = 1.7$, exporting to 22 states), Gujarat ($R = 1.5$, exporting 11 states) and Andhra Pradesh ($R = 1.3$, exporting to 16 states).

4. Discussion

In this study, we quantified the climate hazard risk to food supply in Indian states by considering the risks at food supply source. Of the eight hazards assessed, our analysis suggests that droughts present a greater risk to Indian food supply than other climate hazards, whereas landslides and sea-level rise present the lowest risk. The patterns of risk across states and climate hazards varied depending on risks to food

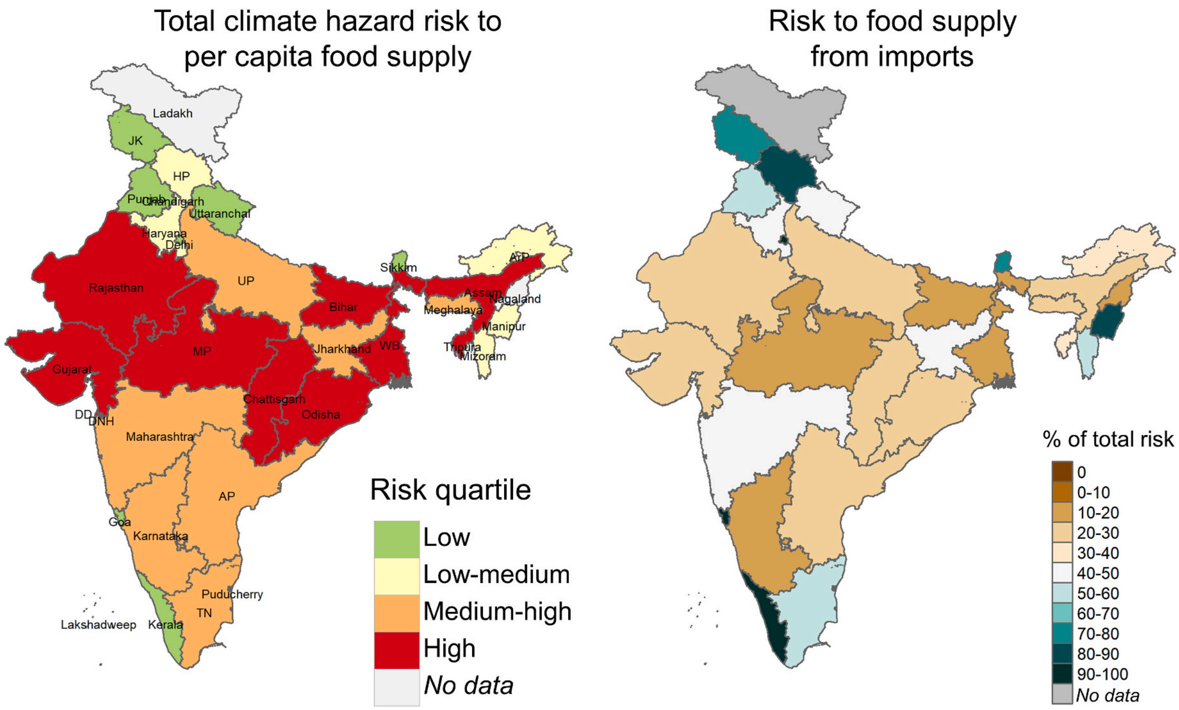

Fig. 3. Combined climate hazard risk to per capita food supply across Indian states, coloured according to risk quartile (low to high) and the % of risk attributable to imports from other states. HP: Himachal Pradesh, JK: Jammu and Kashmir, UP: Uttar Pradesh, ArP: Arunachal Pradesh, WB: West Bengal, AN: Andaman and Nicobar, AP: Andhra Pradesh, MP: Madhya Pradesh, DNH: Dadra and Nagar Haveli, DD: Daman and Diu.

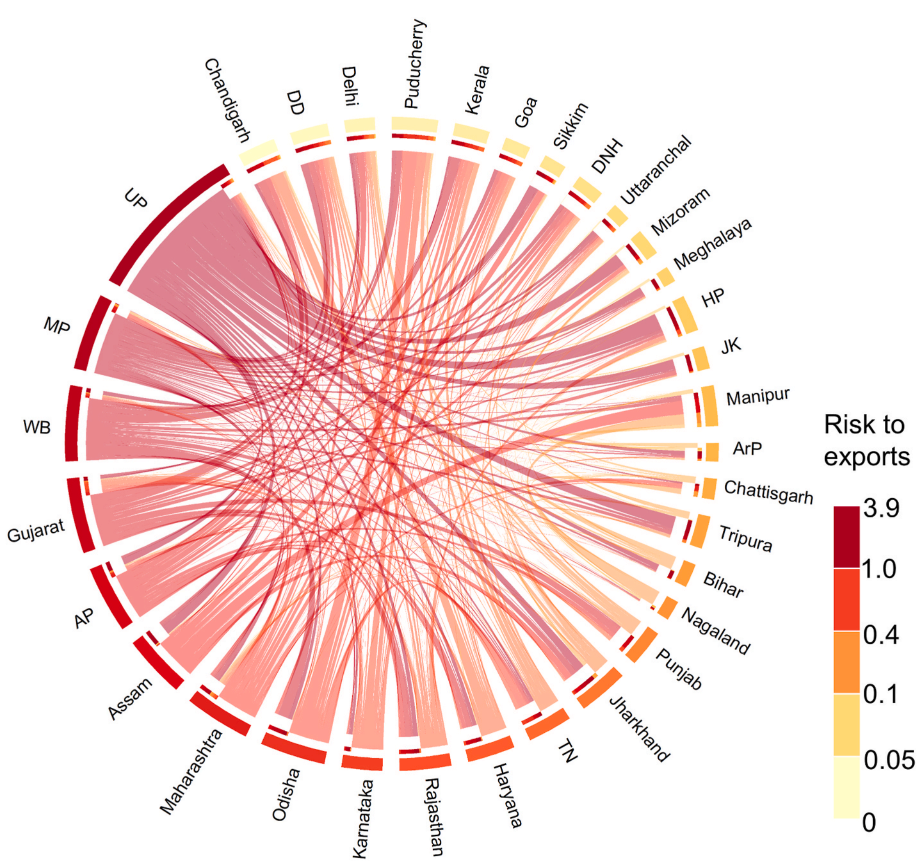

Fig. 4. Combined climate hazard risk associated with interstate trade of per capita food supply. Chords are proportional to risk and ordered anti-clockwise (starting from UP), and coloured according to the total risk to food export for each state. Chords are indented at the importing state. HP: Himachal Pradesh, JK: Jammu and Kashmir, UP: Uttar Pradesh, ArP: Arunachal Pradesh, WB: West Bengal, AN: Andaman and Nicobar, AP: Andhra Pradesh, MP: Madhya Pradesh, DNH: Dadra and Nagar Haveli, DD: Daman and Diu. Chord diagram made using the circlize package in R studio (Gu et al., 2014).

supply from local production of food supply imported from other states. The comparative risk values indicate priority states and hazards for disaster risk management.

4.1. Research in context

There have been several assessments of the impacts of multiple climate extremes and hazards on agricultural productivity in the global context (Lesk et al., 2016; Nicole et al., 2021) and in India (Sharma et al., 2020; Davis et al., 2019; Zhang et al., 2017). Additionally, previous research has explored the relationship between climate-related hazards or extremes and food security (Sam et al., 2019; Kumar and Sharma, 2013). However, to our knowledge, this is the first study to assess sub-national geographical variation in climate hazard risks to food supply from local production and food supply that is imported. This is particularly important for India given its large demographic and geographic size, diverse range of agro-ecological zones, socio-economic systems, and the presence of varied climate hazards.

Our findings demonstrate the importance of considering sub-national food trade dynamics when characterising climate-related food security risks. We found that all Indian states were exposed to all eight climate hazards through their imported food supplies. This was despite the localised nature of climate hazards, such as landslides and sea-level rise. For over one third of Indian states ($N = 14$), the risk associated with food imports was greater than the risk to local supply. However, for many of these states the total climate hazard risk to food supply was comparatively low. States with the largest contribution of imports to climate hazard risk (>90%), including Kerala, Chandigarh, Delhi, Daman and Diu, and Goa, are all relatively small states, hence do not have substantial agricultural land and thus are more likely to import food. They also have low levels of local vulnerability (Supp File Figs. S3–4); with the highest levels of development according to their HDI. Nevertheless, as they are dependent on other regions for food supply monitoring of food supply chains could still enable risk management as climate hazard risks may change.

Our findings highlight the states with food supply most at risks to climate hazards. Despite the importance of food imports for some states, the states with the highest climate hazard risk to food supply are those that depend on local production and have a high local hazard presence alongside high level of local vulnerability. This includes the states of Assam, Bihar, Madhya Pradesh and Rajasthan. In these states, increasing imports from states with a lower climate hazard risk could improve their food system resilience (He et al., 2019). Investing in transport and improving market infrastructure could encourage more food imports, however a shift in food supply source would have implications in the income of local farmers.

Finally, this study indicates the states in which a climate-related disaster could affect national food supply due to food exports. We found that five states (Uttar Pradesh, Madhya Pradesh, West Bengal, Gujarat and Andhra Pradesh) contribute to more than half of the climate hazard risk posed interstate food trade in India. This is due to their large export volumes, as well as high hazard presence and vulnerability. Exports from Uttar Pradesh alone contributed to 20% of the climate hazard risk. Therefore, droughts, forest fires or floods in Uttar Pradesh could impact food supply in 28 other states. Disruptions to important food value chains those from these key exporting states present a risk to national food security, as they can reduce food prices and have cascading impacts on non-agriculture sectors and ultimately state or national economies (Amarasinghe et al., 2020; FAO, 2015) This does not imply these states should not export, but that monitoring of supply and upscaling of disaster risk management in these states should be implemented to mitigate food security risks.

4.2. Limitations

This study provides a high-level risk assessment of how climate hazards could impact Indian food supply based on the most recent data available. It does not provide a detailed planning tool, but aims to support prioritisation efforts as the first step in risk analysis. However, there are limitations in the data and its interpretation.

Firstly, the location of food production for food supply is estimated using trade data that was calculated by modelling supply and demand balance and minimising the transport cost. We validated the model for each food item by comparing the estimated cost of transportation for the importing state, with the value of the food item in the importing state. For each food item, the value of the food item increased with the estimate cost of transportation, suggesting the assumptions of the model were representative of trade drivers in India. For processed food items we focused on the trade as edible item. We used a national-level extraction rate for processed foods (sugar, rape & mustard oil) to estimate edible portion, but there may be additional processing or variation across the country that would alter the estimated food supply volumes. Additionally, due to data and modelling constraints, we did not include the totality of food supply. We did not estimate the climate hazard risk of foreign imports due to data availability, although their contribution to the total food supply was less than 0.01% (1.2 MT/year). Furthermore, we quantified the relationships at state-level due to data availability constraints, however there will be substantial heterogeneity in experience of hazards within states, particularly for landslides and sea-level rise. Although the hazard presence score is relative to the state's land area, the risk values may overestimate the potential for adverse effects if a disaster is very localised.

This study estimated the direct risk that climate hazards in India present to the availability of food supply, but estimating the risk to food security requires further analysis. We did not estimate the climate hazard risk to food that is exported internationally. However, a climate disaster could indirectly affect food supply of households that produce food for foreign export if the harvest is lost or the market infrastructure is damaged. In addition, we did not include food that is traded through the Public Distribution System (PDS), which contributes to 10% of household food supply (mean, kg/year) (National Sample Survey Office, 2014). Through the PDS, large volumes of food are strategically moved between states. Due to data limitations, the trade model used in this study assumed that PDS stocks were nationally pooled before distribution to states, so we were unable to assess the risk to states' food supplies via the PDS. Excluding the PDS will over and underestimate the climate hazard risks for food supply in states depending on their level of contribution and procurement of PDS grains, and their local climate hazard presence compared to the states that contribute to the PDS. Additionally, the PDS provides a mechanism to adapt to a climate disaster, as it provides a buffer stock between production years, and protects the poorest households from food price spikes by setting the price of PDS grains. Further research is needed to consider the implications of the PDS for the resilience of India's food system to climate hazards. We also excluded animal-sourced food products from our study, but they contribute to 18% of household food supply (mean, kg/year) (National Sample Survey Office, 2014). There are multiple pathways that climate hazards could adversely affect animal-sourced food production, including production location, system and feed source, and thus was out of the scope of this study. Additionally, we compared the climate hazard risk to total food supply across Indian states, however different food groups are at risk to different hazards due to their location of production. For example, the food supply of vegetables is more at risk to cyclones, whereas cereals are more at risk to droughts (Supplementary File, Table S3). We used total food supply volume (tonnes), however the nutritional content of food groups are different, thus if climate hazards affect specific food groups this could differentially affect nutrient supply. A detailed comparison of the risk to food groups or items and nutrients was out of the scope of this study, but could provide more specific information for managing risks to agriculture and food systems. Finally, we did not explore how the timing of climate hazards could affect food supply and thus food security. For example, multiple climate disaster occurring simultaneously across Indian states may have a greater effect on national food supply than climate disaster occurring sequentially. Further research could explore the multiple pathways that food and nutrition security could be at risk to climate hazards in Indian states, including temporal changes in availability, affordability, and food safety.

To estimate climate hazard risk, we assessed the hazard presence in the total land area of the state rather than the cropland area, as a climate disaster could affect the food supply chain infrastructure as well as agricultural production itself. However, the areas that are exposed to hazards may not overlap with agricultural areas or food supply chains, particularly for larger states. Additionally, the vulnerability was represented by the HDI as this provides a composite indicator of known factors that are associated with vulnerability to disasters. However, other factors will determine the vulnerability of agriculture and food supply to climate hazards. For example, the adaptive capacity of farmers may vary due to participation in agricultural cooperatives or crop insurance schemes, as well as local transport and market infrastructure (Bahinipati and Venkatachalam, 2015; Parker et al., 2019). Agricultural management practices will also vary across states, such as the dependency on natural resources that could be implicated by a climate-related disasters (Taherzadeh et al., 2021). Additionally, some hazards are more damaging to agricultural productivity; across LICs and LMICs, drought is the most damaging hazard for agriculture, followed by floods (FAO, 2021). Forest fires are the least damaging (FAO, 2021). Therefore, our findings should not be taken to indicate an actual risk or likelihood of adverse impact, but as an indication of the priority states and hazards for risk management.

This study has also relied on recent historical data, and therefore the risks are likely to change as the presence and frequency of climate hazards are altered due to climate change. Additionally, the data for the supply and demand balance model were centred on the year 2011–12. Economic and population growth is changing food demand across Indian states, while climate change is disrupting agricultural production patterns. Therefore the trade patterns estimated in this study are likely to change. The risk values presented in this study should be considered as baseline estimates that will require updating when more recent data on food trade become available.

4.3. Policy implications and future directions

The impact of climate disasters on food security of a region is determined where the region sources its food from. In this study, we estimate the potential for climate disasters to adversely affect Indian food supply by quantifying the climate hazard risks. Using data on sub-national trade, we distinguish between climate hazard risks to food supply that is produced locally and climate hazard risks to food supply imported. Quantifying the differential climate risks across states and their national level implications is particularly important in India due to both central and state level policy structure (Brown et al., 2021). The comparative risk values could be used to identify hotspots of climate risks to food supply for policy interventions, and thus improve the resilience of India's food system. States with a high climate hazard risk to locally produced food supply or interstate food exports could be targeted for investments in the sustainable adaptation of agriculture, including diversification and watershed management (Taherzadeh et al., 2021). Additionally, improvements to physical, digital and institutional infrastructure could enable more efficient movement of food across India, and thus improve the resilience of the food system. The information can also be used following the early warning of a hazard, for example to prioritise areas for regional food reserves and access to food assistance (Béné, 2020), or to encourage implementation of agricultural contingency plans (Sikka et al., 2016).

Future research could enhance understanding of how sub-national hazards in India may affect food security. This study focused on the climate hazard risk to Indian food supply, but an assessment of the risk to calories or micronutrient supply could provide more nuanced understanding of the risks to nutrition-related health in India. Additionally, future research could assess how sub-national climate hazards may affect foreign exports. For example, a domestic shock in food supply could increase food prices and consequently reduce export volumes, thus providing a buffer stock for domestic food supply. However, this would reduce food supply in importing countries (Scheelbeek et al., 2020). Furthermore, our study focuses on the current climate hazard risks to food supply, but climate change is increasing the frequency, intensity and exposure to hazards (Mora et al., 2018), differentially across India (Gurditta and Singh, 2016). Research on the future climate hazard risks to food supply could inform strategies to improve food system resilience in the changing climate (Tendall et al., 2015). Moreover, there are other hazards that affect the functionality of food systems, such as the ongoing COVID-19 pandemic. As a consequence of pandemic restrictions in India, longer food supply chains were disrupted (Mahajan & Tomar, 2021) and food prices increased (Narayanan and Saha, 2020). The colliding presence of a climate hazard India could have a profound impact on the food system. Future research could explore how the Indian food system and its actors have adapted to the pandemic or to past climate disasters in order to inform effective resilience policies for national food security (FAO, 2021).

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2022.100625.

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