An assessment of the relationships between food supply and the environment in India

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ABSTRACT

Environmental changes, including increasing resource scarcity and climate change, threaten food productivity and nutrition security. Concurrently, the food system is a major driver of environmental change. To safeguard human health, food systems should be sustainable and also resilient to environmental changes. It is vital to consider the role of food trade in developing sustainable and resilient food systems, since any vulnerabilities or environmental impacts at production locations can also be transferred to locations of consumption. These issues are particularly relevant in India, where inter-state food trade is an integral part of the food system and environmental changes present an increasing risk to nutrition security.

This thesis examines relationships and inter-dependencies between food supply and environmental change in the Indian context. First, a systematic literature review explores the links between global diets and water resource use. Second, a model is built using secondary data to estimate sub-national food trade that is subsequently used in analyses to link food supply and environmental risks in India. The model is used to 1) quantify the water footprint of food items in Indian states, 2) explore the links between groundwater depletion and the consumption of cereals, 3) estimate the risk of climate hazards disrupting food supply in Indian states, and 4) evaluate policy options for increasing fruit and vegetable supply in the district of Visakhapatnam.

The findings illustrate the importance of including food trade in environmental footprint and risk assessments of food supply due to the spatial variation in environmental footprints and risks. Incorporating information on where a state sources its food supply alters the estimated water footprint of consuming food in that state. Additionally, through food imports, each state's food supply is at risk to multiple climate-related hazards beyond its administrative boundary.

For Indian policy, this thesis highlights the need to focus on reducing the water use of Indian agriculture to mitigate the risks of groundwater depletion and droughts affecting national food supply. Food trade could be part of the solution to reducing water use and improving nutrition-related health by enabling regions to optimise production based on local resources and redistributing food across the country. Continual monitoring of food supply chains will be needed as the environment continues to change.

STATEMENT OF OWN WORK

I, Francesca Harris, confirm the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

[redacted]

Francesca Harris

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PREFACE

This thesis is written in research paper style format. The supplementary material for each paper is found at the end of the thesis. Published papers have been included in the published format.

Chapter 1 provides an overview of the relationship between food supply and the environment, and the importance of considering food trade. A summary of the study context, India, is also provided.

Chapter 2 presents the research gaps the PhD addresses, and provides an overview of the PhD aims and objectives.

Chapter 3 is a published literature review in a peer-reviewed journal on studies that have explored the water footprint of diets.

Chapter 4 is a summary of the data and methods used. I describe the InFoTrade model developed in this PhD and summarise the trade-weighted water footprints estimated for Indian states. I provide an overview of the data used throughout the thesis.

Chapter 5 is a published research paper in a peer-reviewed journal. This is an analysis of the interstate trade of cereals in India, and the associated virtual water trade.

Chapter 6 is a research paper that has been submitted to a peer-reviewed journal, which quantifies the climate hazard risk associated with food supply in each Indian state.

Chapter 7 is a case study that uses the InFoTrade model to estimate the trade of fruits and vegetables in Visakhapatnam and its relationship with groundwater depletion. This chapter is in the style of a policy briefing, as it will be presented to Visakhapatnam policymakers.

Chapter 8 is discussion of the overall thesis.

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ABBREVIATIONS

AP	Andhra Pradesh
ASF	Animal sourced foods
ATREE	Ashoka Trust of Research in Ecology and the Environment
BMI	Body mass index
BWF	Blue water footprint
DALYS	Disability-adjusted life years
DGCIS	Directorate General of Commercial Intelligence and Statistics
FAO	Food and Agriculture Organisation of the United Nations
GWF	Green water footprint
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
InFoTrade	India-Food-Trade
IPCC	Intergovernmental Panel on Climate Change
HDI	Human Development Index
LCA	Life Cycle Assessment
MT	Million tonnes
NCD	Non-communicable disease
NSS	National Sample Survey
PDS	Public distribution system
RITES	Rail India Technical and Economic Service
SHEFS	Sustainable and Healthy Food Systems

SAHDI	Sustainable and Health Diets in India
UN	United Nations
UT	Union Territories
Vizag	Visakhapatnam
WF	Water footprint
WS-WF	Water scarcity weighted footprint

GLOSSARY OF KEY TERMS

Blue water footprint: water that has been sourced from surface or groundwater resources and is either evaporated, incorporated into a product or taken from one body of water and returned to another, or returned at a different time.

Climate-related hazard: the physical process or event that is driven by hydro-meteorological or oceanographic systems that could adversely affect human or natural systems.

Consumption water footprint: the water footprint associated with the consumption (i.e. use) of the product in a specified area.

Exposure: the presence of the human or natural system in the areas that could be adversely affected by a hazard.

Green water footprint: water from precipitation that is stored in the root zone of the soil and evaporated, transpired or incorporated by plants.

Groundwater: water that is below the earth's surface, either held in the soil or in pores and crevices of rocks. Groundwater can be recharged through precipitation, irrigation or active recharge. Groundwater use is defined as unsustainable when the rate of abstraction (removal) is greater than the recharge.

Groundwater depletion: continued groundwater withdrawal at a rate greater than the rate of replenishment. Term used interchangeable with groundwater overexploitation.

Production water footprint: the water footprint associated with producing a product a specified area.

Risk: the potential for a hazard to adversely affect human or natural systems.

Surface water: water which flows over or stored on the Earth's surface, contained in rivers, lakes, glaciers, snow (etc.).

Virtual water trade: the volume of water embedded in a product through the production process that is then traded through the same product. Calculated from the production water footprint at source.

Vulnerability: the susceptibility of a human or natural system in a specified area to be adversely effected by a hazard.

CHAPTER 1

BACKGROUND TO THESIS

SUMMARY OF CHAPTER

In this chapter, I provide a brief background to this thesis. I discuss how food production is linked to the environment through its dependence on natural resources and local climate. I argue that a greater understanding of food trade is crucial to linking human food supply and the environment. Finally, I introduce the study context of India, highlighting how its food and nutrition security is threatened by environmental changes and thus a greater understanding of sub-national food trade is needed.

1.1 Food and the environment

Food production is dependent on the environment, and therefore changes to the environment threaten food security (1). A pressing issue for food systems is the increasing scarcity of ecosystem resources, such as land and water (Figure 1). The number of people living in areas that have insufficient water available locally to satisfy food supply needs has increased from 360 million people in 1905 to 2.2 billion (34% of the global population) in 2005 (2). Without improvements in agricultural efficiency, this number would be nearly twice as large (2). Population growth and rising incomes are increasing the demand and competition for these ecosystem resources (3), while climate change is predicted to disrupt water availability (4). Consequently, by 2050, more than half of the global population could live in areas that suffer water scarcity (5). Of particular concern is the availability of groundwater, which is the water stored beneath the surface in soil or aquifers (6). This accounts for more than half of all irrigation water used to grow food (7), but is depleting in major food production regions including in India, the USA and China (8). Continued depletion of groundwater and other ecosystem resources could result in increased global food and nutrition insecurity, unless agriculture adapts (9).

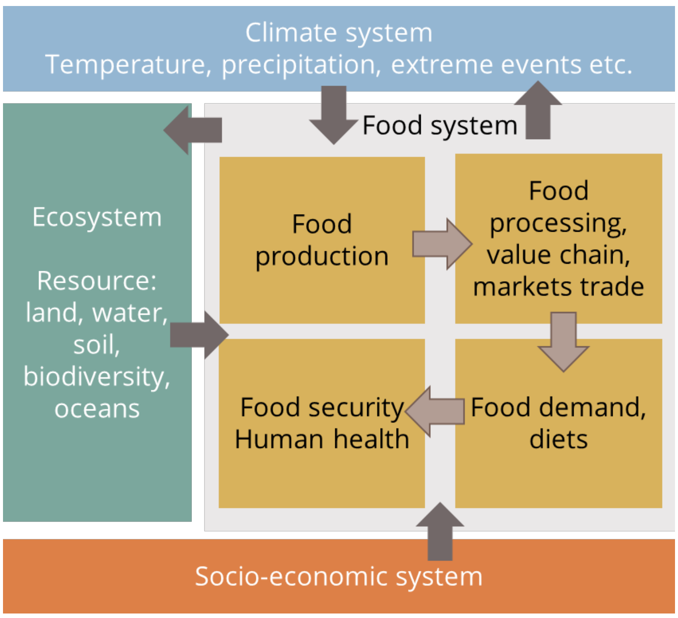

Figure 1 Relationships between climate systems, ecosystems, food systems, and socioeconomic systems discussed in this thesis. Adapted from Mbow et al., 2019 (1).

Food production is also highly likely to be impacted by the changing climate (Figure 1). Driven by increases in anthropogenic greenhouse gas emissions, of which the food system accounts for 21 – 37%, global mean temperature is rising (1). This is altering rainfall patterns and increasing the intensity and frequency of extreme weather events (10). In the last 50 years, the annual occurrence of disasters, including extreme weather events, has increased more than three-fold (11). These extreme weather events have led to crop losses: between 1964 – 2007, drought and extreme heat reduced global cereal production by 9 – 10% (12). If climate change continues on current trajectories, declines in crop yields and suitability are likely to impact nutrition-related health through reduced dietary diversity (13), with some estimates suggesting more than half a million additional deaths by 2050 (14). To mitigate these impacts, a greater understanding of how the food system is linked to the climate system is needed.

1.2 The relevance of food trade

The relationship between human diets and the environmental system is dependent on food trade, here defined as the movement of food between production and consumption location (Figure 1). Food trade links food consumers to environments in geographically disparate regions, thus environmental changes in the exporting region could threaten food security in the importing region (15). For example, the United Kingdom imports fruit and vegetables from water scarce and climate vulnerable regions, despite a relatively low local threat (16, 17). Globally, 90% of countries import most of their staple crops from countries that have depleting groundwater reserves (18). Thus, food trade has the capacity to exacerbate the impacts of environmental change on food security. Nevertheless, food trade has many benefits, such as increased incomes for food exporters (19) and greater access to nutrients for importers (20-22). Without food trade, 69 – 89% of the global population would not be able to satisfy their demand for major crop-based food items within a 100 km radius, as local crop yields and suitability are too low (23). Open food trade also enables food systems to reduce environmental resource requirements by optimising food production to the most climatically suitable areas, and using trade to distribute the food (24). Therefore as environmental changes continue, food trade could be part of the solution to improving food security. However, trade patterns should be monitored and managed to reduce the risk of disruptions (25).

A greater understanding of food trade is also important for sustainable food system research. Resource requirements vary depending on production location as local climates and ecosystems affect the inputs required and the yield (26). For example, crops use more irrigation in areas with low rainfall and high temperatures that increase evapotranspiration (26). For larger countries such as India, the USA and China, environmental footprints for the same food can vary substantially within the country due to differing ecosystems and climates (27). Due to the substantial spatial variability in climates, ecosystems and production systems, together with the long distances over which food is traded, a greater understanding of food trade is needed to accurately estimate the resource requirements or environmental footprints of diets and food systems.

1.3 Study context: India

Achieving and maintaining food and nutrition security presents a major challenge for India (28). India has the largest population of people living with food insecurity in the world, and in recent years the level has increased (29). It has the highest prevalence of childhood acute malnutrition (wasting) of all countries with data available, at 17% (30). Concurrently, rapid urbanisation and rising incomes are increasing the availability of ultra-processed foods, including refined carbohydrates, sugars, refined oils and fats (31, 32). This is driving the consumption of unhealthy diets and leading to a greater prevalence of nutrition-related chronic disease. Between 1990 – 2016, the all-age India death rate for diabetes increased by 130%, and by 50% for ischaemic heart disease (33). Unhealthy diets are now responsible for 9% of disability-adjusted life years (DALYs) lost in India, although undernutrition remains the highest contributor at 15% of all DALYs lost (33). Therefore, to tackle this double burden of malnutrition, food policies in India will need to deliver increased availability, diversity and quality of food (28).

Environmental changes, including climate and ecosystem changes, could threaten India's agricultural productivity and therefore its ability to deliver a healthy diet for its population. In particular, groundwater is depleting at rapid rates in the major food producing regions (34). If this continues, groundwater depletion will reduce the winter cropped area by 20%, and up to 68% in regions with depleted resources (35). The drivers of groundwater depletion in India are complex but have been extensively documented, and are discussed briefly here. The Green Revolution encouraged the use of high yielding cereals, irrigation and fertilisers, in support of improving national food security and rural livelihoods (36-39). Some states had a comparative advantage due to their wealth and suitability for cereal crop cultivation (40). Specifically, agricultural productivity grew in Punjab and Haryana in the Northern region, and Tamil Nadu and Andhra Pradesh in the South, whereas states in the Eastern region such as Bihar and Orissa (Odisha) lagged behind due to poor technology and lack of infrastructure. The food supply for the country therefore became more dependent on the high-yielding areas for staple grains (41). Additionally, to improve food security, the government set up the Public Distribution System (PDS) that gives farmers a minimum support price for food grains, and distributes these to low-income consumers at a fair price. The PDS contributed to the dependency on high yielding rice and wheat for national food supply, however these cereals are more resource intensive to produce than other grains such as sorghum and millet (41, 42). To maintain production and satisfy the water demand, the government provided electricity subsidies for farmers that further encouraged groundwater pumping in major food producing regions (37). Consequently, much of this groundwater use in these major food producing regions, such as Punjab and Haryana, has exceeded levels of groundwater recharge and thus become unsustainable. Unsustainable groundwater use supports a significant volume of food production; equivalent to sufficient calories that would feed 173 million people in India (38).

On top of groundwater depletion, Indian agriculture is exposed to climate-related hazards. States are differentially affected by climate hazards due to geographical vulnerabilities; for example the coastal states in the Eastern region are more prone to cyclones (43), whereas extreme temperatures are a concern for arid states in the

Northwest (44). Climate change is increasing the frequency and intensity of these climate-related hazards (10). Extreme temperatures and alterations to rainfall patterns are already affecting farming practices, with farmers shifting production to the dry season to avoid unreliable rainfall in the monsoon season (45). By 2030, India may have to import rice to meet domestic demands due to crop losses from droughts (46).

Although many studies have quantified the relationships between these environmental changes and Indian food *production* (38, 47), their relationship with food *supply* and diets has yet to be explored. As highlighted in Section 1.2, this requires information on food trade to link location of consumption to the environmental indicators at location of production. There are some previous data on the food trade of items within India (48). This data only covers rail trade, and reports zero trade of fruits and vegetables across states which is unlikely to be accurate. Newly generated estimates of sub-national food trade could enable a greater understanding of how environmental changes in India are linked to food supply, and thus inform and highlight priority options for policy to mitigate future risks to food security.

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CHAPTER 2

THESIS OVERVIEW

SUMMARY OF CHAPTER

In this chapter, I discuss the rationale and aims of the PhD, and the overall structure of this thesis. I state my contribution to the work, the funding sources and list additional publications and outputs.

2.1 PhD Rationale

Agricultural production in India is vulnerable to multiple environmental changes, which consequently threaten future food security. A greater understanding of the relationship between environmental change and food supply can suggest appropriate policy interventions to mitigate future food insecurity. However, to accurately assess the relationship between food supply and the environment requires data on where the food was produced due to the geographical variation of environmental factors.

Firstly, this PhD will synthesis studies that have assessed dietary water use, in order to understand the methodological approaches used to quantify the relationship between food and water availability. For this thesis, the review will highlight how analyses on the water used to produced diets consider where the food has come from (i.e. food trade) to account for the spatial variability in water used by food production. To-date, there has been no detailed systematic review of studies linking diets and water use.

There are pre-existing publicly available data on the interstate trade of food items in India through rail and river shipment (1). To link food supply to geographically-explicit environmental indicators, data are needed on the totality of food trade. Therefore, the major gap addressed in this work will be to estimate Indian sub-national food trade through developing the India-Food-Trade (InFoTrade) model. The InFoTrade model is based on a modelling approach that has been used in previous studies (2, 3), but adapted to the Indian context.

Through the modelled results, it is possible to explore the relationship between food supply and various environmental indicators. Firstly, water availability presents an imminent and imposing challenge to Indian agriculture. Previous research has quantified the water used to produce food items, in particular the water used for the production of cereals as they are major driver of irrigation use in Indian agriculture (4, 5). Studies have also quantified the water use of Indian diets using the water footprint (WF) indicator (6-10). The WF is the volume of water removed from a catchment area in the production of an item that is either integrated into the product, evaporated or transpired (hence no longer available for other use) (11). To estimate the WF of food supply in India, these studies either assumed that the WF is the same throughout the country, or that consumers source food from their local state (6-10). This PhD will build on this literature linking food supply to agricultural water use in India by estimating the consumption WF of food items in Indian states, but will account for location of production using data from the InFoTrade model on interstate food trade.

In addition to quantifying the WF of food items, studies have used the virtual water trade concept to illustrate the links between agricultural water use and food supply in India (12-14). Virtual water trade is the water used in the production of an item (i.e. the WF) and thus embedded in the product as it is traded (15). Previous to this PhD, no studies had specifically linked sub-national virtual water trade or food supply to groundwater depletion in India. This PhD will investigate this gap by quantifying the virtual water trade of cereals using interstate trade data from the InFoTrade model and cereal WFs. This information will highlight the extent to which unsustainable groundwater is supporting Indian food supply.

India is also highly vulnerable to drought and other climate-related hazards. Several studies have linked Indian food production to climate hazard risk (16, 17). However, by focusing solely on the risk to local food production, these studies ignore the potential risk to food supply from interstate imports. Using existing data on climate hazard presence in Indian states and data from the InFoTrade model on the interstate trade of food items, this PhD will explore how food supply in each state is at risk to climate hazards in India. The results illustrate priorities for policy interventions to reduce risk and can be used for hazard risk management.

Finally, a greater understanding of where food comes from is of particular importance to cities, which are highly dependent on external regions for their food supply. Visakhapatnam (Vizag) district is on the east coast of India, and part of the state of Andhra Pradesh. It is a Sustainable and Healthy Food Systems (SHEFS) project site. Vizag city has committed to become a Smart City, which includes a commitment to ensure citizens have "healthy lifestyle choices" (18). Adequate consumption of fruit and vegetables is a major component of healthy lifestyles (19). This PhD will downscale the InFoTrade model to the districts of Andhra Pradesh to quantify the volume of Vizag's fruit and vegetable supply that is produced locally or imported. This case study will demonstrate the application of the trade model at different scales to provide information for local policy makers in their efforts to improve food sustainability and resilience to environmental change.

2.2 PhD Aims and Objectives

Overall Aim:
The overarching aim of this PhD is to contribute to the evidence base on sustainable food systems through characterising the relationship between food supply and the environment in India, and thereby identifying areas for policy intervention to mitigate risks to future food security.

Objective 1

Systematically synthesise the global evidence on the water use of human food consumption, in order to compare indicators, methods and approaches used.

Objective 2

Develop a new model to estimate the interstate trade of Indian food items using available secondary data.

Objective 3

Using the results from Objectives 1 and 2, quantify the trade-weighted consumption water footprints of food items in Indian states.

Objective 4

Using the results from Objectives 1 and 2, quantify the virtual water trade of cereals between Indian states, and assess its relationship with groundwater depletion.

Objective 5

Using the results from Objective 2, undertake a climate hazard risk assessment of food supply in each Indian state based on food produced in the state compared to food imported from other states.

Objective 6

Downscale the model from Objective 2 for the state of Andhra Pradesh using district-level data, in order to estimate the imports of fruits and vegetables into the district of Visakhapatnam and explore policy options for increasing fruit and vegetable supply.

2.3 Candidate's Involvement

This PhD stemmed from the Sustainable and Healthy Diets in India (SAHDI) project, which aimed to quantify the environmental impacts of diets in India and define low carbon and water footprint diets that would also improve nutrition-related health. I was employed as a Research Assistant on the project, after completing an MSc in Nutrition for Global Health summer project (later published (6)) on the water footprint of Indian diets. The SAHDI project demonstrated the need to explore diets and water use in India further, hence the PhD idea was created through discussions with the project team – Rosemary Green, Edward Joy and Alan Dangour – who later became my supervisory team. I independently formulated the analysis plan, but with constant support from my supervisory and advisory committee. Pauline Scheelbeek has been a constant advisor throughout. Carole Dalin provided particular support with the methods to model interstate trade, and to the paper in Chapter 5. Owen Nicholas has provided statistical advice throughout.

This thesis would not have been possible without collaboration with colleagues. I have included a description of my contribution and collaborator involvement at the beginning of each chapter in the Research Paper Coversheet or in the chapter summary where applicable.

2.4 PhD Publications and Additional Outputs

PhD published papers:

Harris, Francesca; Moss, Cami; Joy, Edward JM; Quinn, Ruth; Scheelbeek, Pauline FD; Dangour, Alan D; Green, Rosemary; (2019) The Water Footprint of Diets: A Global Systematic Review and Meta-analysis. Advances in Nutrition: An International Review Journal, 11 (2). pp. 375-386. ISSN 2161-8313 DOI: https://doi.org/10.1093/advances/nmz091

Harris, Francesca; Dalin, Carole; Cuevas, Soledad; N R, Lakshmikantha; Adhya, Tapan; Joy, Edward JM; Scheelbeek, Pauline FD; Kayatz, Benjamin; Nicholas, Owen; Shankar, Bhavani; Dangour, Alan D; Green, Rosemary; (2020) Trading water: virtual water flows through interstate cereal trade in India. Environmental Research Letters, 15 (12). p. 125005. DOI: https://doi.org/10.1088/1748-9326/abc37a

PhD prepared manuscript:

Harris, Francesca; Amaranth, Giriraj; Joy, Edward JM; Dangour, Alan D; Green, Rosemary; (submitted) India's food supply and climate hazards: assessing the resilience of the food system. Global Food Security.

PhD policy brief:

Harris, Francesca; Exploring solutions to increase Visakhapatnam's fruit and vegetable supply.

Additional outputs:

Below I highlight my additional outputs that use the research presented in this thesis.

Blog pieces:

- Changes to human diets could reduce water scarcity, 2019. SHEFS Global.

- Most of the Indian population are consuming cereal crops from regions with depleting water reserves, 2020. LSHTM CCCPH.

Posters of research in this thesis:

- The water footprints of human diets – review. Livestock, Environment and People Conference, 2018. *Winner of poster competition.*
- Trading water: exploring the interstate trade of cereals in India. LSHTM Virtual Poster Day, 2020. *Winner of poster competition.*

Relevant conference talks:

- The water footprint of human diets: a systematic review and meta-analysis. Workshop for WASAG working group, June 2020 *(invited)*
- Trading water – exploring the water use of cereals
    - Global Food Security, Cambridge, April 2019 *(abstract submission)*
    - ANH Academy Week, Hyderabad, June 2019 *(abstract submission)*
    - Water Futures Conference, September 2019, Bangalore *(abstract submission)*
    - Webinar: "Virtual Water: The Issues and Policy Implications in India", 2021 *(invited)*
- Sustainable diets; nutrition, health and the environment. IUNS, Buenos Aires, October 2017 *(invited)*
- Sustainable diets in India, ICSS, September 2017 *(invited)*

Additional publications:

These are additional publications to which I have contributed as a co-author during my time registered as a PhD student:

2021

Brown, Kerry Ann; Srinivasapura Venkateshmurthy, Nikhil; Law, Cherry; **Harris, Francesca**; Kadiyala, Suneetha; Shankar, Bhavani; Mohan, Sailesh; Prabhakaran, Dorairaj and Knai, Cécile; (2021) Moving towards sustainable food systems: A review of Indian food policy budgets. Global Food Security 28: 100462. DOI: https://doi.org/10.1016/j.gfs.2020.100462

Shah, Mihir; PS, Vijayshankar; **Harris, Francesca;** (2021) Water and Agricultural Transformation in India, Symbiotic Relationship - I. Economic & Political Weekly, 56. https://www.epw.in/journal/2021/29/special-articles/water-and-agricultural-transformation-india.html

Shah, Mihir; PS, Vijayshankar; **Harris, Francesca;** (2021) Water and Agricultural Transformation in India, Symbiotic Relationship - II. Economic & Political Weekly, 56. https://www.epw.in/journal/2021/30/special-articles/water-and-agricultural-transformation-india.html

2020

Brown, Kerry Ann; **Harris, Francesca**; Potter, Christina; Knai, Cécile; (2020) The future of environmental sustainability labelling on food products. Lancet Planetary Health, 4 (4). e137-e138. ISSN 2542-5196. DOI: https://doi.org/10.1016/S2542-5196(20)30074-7

Choudhury, Samira; Shankar, Bhavani; Aleksandrowicz, Lukasz; Tak, Mehroosh; Green, Rosemary; **Harris, Francesca**; Scheelbeek, Pauline; Dangour, Alan; (2020) What underlies inadequate and unequal fruit and vegetable consumption in India? An exploratory analysis. Global Food Security, 24. 100332-. ISSN 2211-9124. DOI: https://doi.org/10.1016/j.gfs.2019.100332

González-García, Sara; Green, Rosemary F; Scheelbeek, Pauline F; **Harris, Francesca**; Dangour, Alan D; (2020) Dietary recommendations in Spain – affordability and environmental sustainability? Journal of Cleaner Production, 254. p. 120125. ISSN 0959-6526. DOI: https://doi.org/10.1016/j.jclepro.2020.120125

Kluczkovski, Alana; Lait, Rebecca; Martins, Carla A.; Reynolds, Christian; Smith, Pete; Woffenden, Zoe; Lynch, John; Frankowski, Angelina; **Harris, Francesca**; Johnson, David; Halford, Jason C.G; Cook, Joanne; Tereza da Silva, Jacqueline; Schmidt Rivera, Ximena; Huppert, Julian L.; Lord, Mellissa; Mclaughlin, John; Bridle, Sarah (2021), Learning in lockdown: Using the COVID-19 crisis to teach children about food and climate change. Nutr Bull. 46: 206-215. DOI: https://doi.org/10.1111/nbu.12489

2019

Alae-Carew, Carmelia; Bird, Frances A; Choudhury, Samira; **Harris, Francesca;** Aleksandrowicz, Lukasz; Milner, James; Joy, Edward JM; Agrawal, Sutapa; Dangour, Alan D; Green, Rosemary; (2019) Future diets in India: A systematic review of food consumption projection studies. Global Food Security, 23. pp. 182-190. ISSN 2211-9124. DOI: https://doi.org/10.1016/j.gfs.2019.05.006

Aleksandrowicz, Lukasz; Green, Rosemary; Joy, Edward JM; **Harris, Francesca**; Hillier, Jon; Vetter, Sylvia H; Smith, Pete; Kulkarni, Bharati; Dangour, Alan D; Haines, Andy; (2019) Environmental impacts of dietary shifts in India: A modelling study using nationally-representative data. Environnent International, 126. pp. 207-215. ISSN 0160-4120. DOI: https://doi.org/10.1016/j.envint.2019.02.004

Kayatz, Benjamin; **Harris, Francesca**; Hillier, Jon; Adhya, Tapan; Dalin, Carole; Nayak, Dali; Green, Rosemary F; Smith, Pete; Dangour, Alan D; (2019) "More crop per drop": Exploring India's cereal water use since 2005. Science of The Total Environment, 673. pp. 207-217. ISSN 0048-9697. DOI: https://doi.org/10.1016/j.scitotenv.2019.03.304

Moss, Cami; Lukac, Martin; **Harris, Francesca;** Outhwaite, Charlotte L; Scheelbeek, Pauline FD; Green, Rosemary; Dangour, Alan D; (2019) The effects of crop diversity and crop species on biological diversity in agricultural landscapes: a systematic review protocol. Wellcome Open Research, 4. p. 101. DOI: https://doi.org/10.12688/wellcomeopenres.15343.1

Tobi, Rebecca CA; **Harris, Francesca**; Rana, Ritu; Brown, Kerry A; Quaife, Matthew; Green, Rosemary; (2019) Sustainable Diet Dimensions. Comparing Consumer Preference for Nutrition, Environmental and Social Responsibility Food Labelling: A Systematic Review. Sustainability, 11 (23). p. 6575. DOI: https://doi.org/10.3390/su11236575

2018

Green, Rosemary F; Joy, Edward JM; **Harris, Francesca**; Agrawal, Sutapa; Aleksandrowicz, Lukasz; Hillier, Jon; Macdiarmid, Jennie I; Milner, James; Vetter, Sylvia H; Smith, Pete; Haines, Andy; Dangour, Alan D (2018) Greenhouse gas emissions and water footprints of typical dietary patterns in India. The Science of the Total Environment, 643. pp. 1411-1418. ISSN 0048-9697. DOI: https://doi.org/10.1016/j.scitotenv.2018.06.258

Lindgren, Elisabet; **Harris, Francesca**; Dangour, Alan D; Gasparatos, Alexandros; Hiramatsu, Michikazu; Javadi, Firouzeh; Loken, Brent; Murakami, Takahiro; Scheelbeek, Pauline; Haines, Andy; (2018) Sustainable food systems-a health perspective. Sustainability Science, 13 (6). pp. 1505-1517. ISSN 1862-4057. DOI: https://doi.org/10.1007/s11625-018-0586-x

Scheelbeek, Pauline FD; Bird, Frances A; Tuomisto, Hanna L; Green, Rosemary; **Harris, Francesca B**; Joy, Edward JM; Chalabi, Zaid; Allen, Elizabeth; Haines, Andy; Dangour, Alan D; (2018) Effect of environmental changes on vegetable and legume yields and nutritional quality. Proceedings of the National Academy of Sciences of the United States of America, 115 (26). pp. 6804-6809. ISSN 0027-8424. DOI: https://doi.org/10.1073/pnas.1800442115

2017

Haines, Andy; **Harris, Francesca**; Kasuga, Fumiko; Machalaba, Catherine; (2017) Future Earth--linking research on health and environmental sustainability. BMJ (Clinical research ed), 357. j2358-. ISSN 0959-8138. DOI: https://doi.org/10.1136/bmj.j2358

Milner, James; Joy, Edward JM; Green, Rosemary; **Harris, Francesca**; Aleksandrowicz, Lukasz; Agrawal, Sutapa; Smith, Pete; Haines, Andy; Dangour, Alan D; (2017) Projected health effects of realistic dietary changes to address freshwater constraints in India: a modelling study. The Lancet Planetary Health, 1 (1). e26-e32. ISSN 2542-5196. DOI: https://doi.org/10.1016/S2542-5196(17)30001-3

2.5 PhD Timeframe

The PhD took place from April 2017 to July 2021.

2.6 Funding

The PhD was undertaken as staff registered. Admission fees for enrolment were self-funded. My salary as Research Assistant was funded the Wellcome Trust's Our Planet, Our Health programme, on the SAHDI (grant number 103932) and SHEFS projects (grant number 205200/Z/16/Z).

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CHAPTER 3

THE WATER FOOTPRINT OF DIETS: A GLOBAL SYSTEMATIC REVIEW AND META-ANALYSIS

SUMMARY OF CHAPTER

In this chapter, I present a published literature review that synthesised the global evidence on the water use of human diets. I systematically searched the literature for studies that included the concepts of "diets" and "water use". The methods of the included studies were reported and a meta-analysis was carried out to assess the differences in dietary water footprints between diet patterns. The main report includes 41 studies that quantified dietary water using the water footprint indicator, but an additional 14 studies were found that used a different indicator. The methods of these studies were also reviewed for this PhD and their information can be found in Appendix 2.

A full summary of this chapter is presented in the Abstract.

I have inserted the published version. Where supplementary files are referred to in the paper, these can be found in Appendix 2.

RESEARCH PAPER COVER SHEET

SECTION A – Student Details

Student ID Number	1407177	**Title**	Miss
First Name(s)	Francesca Bianca		
Surname/Family Name	Harris		
Thesis Title	An assessment of the relationships between food supply and the environment in India		
Primary Supervisor	Dr Rosemary Green		

If the Research Paper has previously been published please complete Section B, if not please move to Section C.

SECTION B – Paper already published

Where was the work published?	Advances in Nutrition		
When was the work published?	6th September 2019		
If the work was published prior to registration for your research degree, give a brief rationale for its inclusion			
Have you retained the copyright for the work?*	**Yes**	Was the work subject to academic peer review?	**Yes**

*If yes, please attach evidence of retention. If no, or if the work is being included in its published format, please attach evidence of permission from the copyright holder (publisher or other author) to include this work.

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	I proposed the idea for this review early in the PhD, and consulted with my supervisory team on the aims and objectives. I carried out the search, screening and data extraction for the review, with assistance from Cami Moss who was the second reviewer (double screened and double extracted data for 30% of sample). I led the analysis of the review, and consulted with the co-authors during the process. I produced a complete first draft of the paper for co-author review. All authors provided valuable comments on the language,

	objectives and structure of the review, which were incorporated into the final manuscript. I produced all figures, tables and supplementary material. I led the submission process and responded to reviewer comments after consulting with the co-authors.

SECTION E

Student Signature	Francesca Harris
Date	27th May 2021

Supervisor Signature	Rosemary Green
Date	9th June 2021

The Water Footprint of Diets: A Global Systematic Review and Meta-analysis

Francesca Harris,[1,2,3] Cami Moss,[1,2,3] Edward JM Joy,[1,2,3] Ruth Quinn,[4] Pauline FD Scheelbeek,[1,2,3] Alan D Dangour,[1,2,3] and Rosemary Green[1,2,3]

[1] Department of Population Health, London School of Hygiene and Tropical Medicine, London, United Kingdom; [2] Leverhulme Centre for Integrative Research on Agriculture and Health, London, United Kingdom; [3] Centre on Climate Change and Planetary Health, London School of Hygiene and Tropical Medicine, United Kingdom; and [4] The School of Biological Sciences, University of Aberdeen, Aberdeen, United Kingdom

ABSTRACT

Agricultural water requirements differ between foods. Population-level dietary preferences are therefore a major determinant of agricultural water use. The "water footprint" (WF) represents the volume of water consumed in the production of food items, separated by water source; blue WF represents ground and surface water use, and green WF represents rain water use. We systematically searched for published studies using the WF to assess the water use of diets. We used the available evidence to quantify the WF of diets in different countries, and grouped diets in patterns according to study definition. "Average" patterns equated to those currently consumed, whereas "healthy" patterns included those recommended in national dietary guidelines. We searched 7 online databases and identified 41 eligible studies that reported the dietary green WF, blue WF, or total WF (green plus blue) (1964 estimates for 176 countries). The available evidence suggests that, on average, European (170 estimates) and Oceanian (18 estimates) dietary patterns have the highest green WFs (median per capita: 2999 L/d and 2924 L/d, respectively), whereas Asian dietary patterns (98 estimates) have the highest blue WFs (median: 382 L/d per capita). Foods of animal origin are major contributors to the green WFs of diets, whereas cereals, fruits, nuts, and oils are major contributors to the blue WF of diets. "Healthy" dietary patterns (425 estimates) had green WFs that were 5.9% (95% CI: −7.7, −4.0) lower than those of "average" dietary patterns, but they did not differ in their blue WFs. Our review suggests that changes toward healthier diets could reduce total water use of agriculture, but would not affect blue water use. Rapid dietary change and increasing water security concerns underscore the need for a better understanding of the amount and type of water used in food production to make informed policy decisions. *Adv Nutr* 2019;00:1–12.

Keywords: food consumption, planetary health, sustainable diets, water use; environmental footprint

Introduction

Food security depends on the availability of freshwater resources for agricultural production. Globally, ∼70% of freshwater is used annually for agricultural (food and nonfood) production. Climate change is projected to alter rainfall patterns and increase the occurrence of extreme weather events including more frequent droughts and floods (1). A growing human population and rapidly changing diets, including greater consumption of animal source foods (ASFs), has resulted in increasing global water use in agriculture (2). Identifying sustainable diets that promote health and minimize environmental impacts is increasingly important, and in this context, understanding the impact of food production and population-level dietary patterns on water use is critical for sustainable water management.

A growing body of literature suggests that in general a reduction in ASFs in the diet, particularly beef, poultry, and pork meat, corresponds with reduced environmental impacts and resource requirements (3–6). However, reducing ASF content of diets does not always correspond with lower water use, especially if ASF items are replaced with foods such as fruits and pulses that can be more dependent on irrigation (7). Additionally, there is large variability globally in the amount and type of water used in food production due to environmental and agricultural management factors (8). The most commonly used metric for assessing water use is the "water footprint" (WF), which quantifies the volume

This study forms part of the Sustainable and Healthy Food Systems (SHEFS) program supported by the Wellcome Trust's Our Planet, Our Health program (grant number: 205200/Z/16/Z).
Author disclosures: FH, CM, EJMJ, RQ, PFDS, ADD, and RG, no conflicts of interest.
Supplemental Tables 1–9 are available from the "Supplementary data" link in the online posting of the article and from the same link in the online table of contents at https://academic.oup.com/advances/.
Address correspondence to FH (e-mail: Francesca.Harris@lshtm.ac.uk).
Abbreviations used: ASF, animal source food; FBS, food balance sheet; WF, water footprint.

 Adv Nutr 2019;00:1–12; doi: https://doi.org/10.1093/advances/nmz091.

of water consumed during the production of an item (in liters per kilogram) and can be separated into the blue WF (representing the use of groundwater and surface water) and the green WF (representing the use of rainfall) (9). Crop WFs are primarily driven by evapotranspiration occurring in the field in which the crop is grown, whereas the WF of ASFs includes the evapotranspiration of feed crops and grazing lands as well as the animals' drinking and service water needs. A high blue WF means that large volumes of irrigation water are used during crop production. This can be a concern in areas where surface water and groundwater reserves are being unsustainably exploited (10). A high green or total (green + blue) WF can indicate that crops have low yields or are inefficient in their water use. A low green and high blue WF suggests rainwater is being inefficiently used, which can lead to surface water and groundwater overexploitation. A previous systematic review assessed the water use of dietary patterns, but did not distinguish between green and blue water use nor did it consider spatial heterogeneity in WFs (5).

The aim of this systematic review was to collate and synthesize the available data on the global water use of human diets. First, we identified the available literature assessing the relation between diets and water use through the WF, outlining the different data sources and models used. Second, we explored heterogeneity in dietary WFs across the world, considering both blue and green water use. Finally, we identified the food groups that are most important in determining dietary WF, and using data from identified studies, we estimated the WFs of different dietary patterns.

Methods

Study selection and search strategy

We conducted this systematic review in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (11). Included studies assessed human (population) diets (intervention) and their WF (outcome), published in English from 2000 up to the date of the search (7 February 2018) (including dietary WF estimates from 1995 onwards). We searched 7 online databases covering the fields of environment, social science, public health, nutrition, and agriculture: Web of Science Core Collection, Scopus, OvidSP MEDLINE, EconLit, OvidSP AGRIS, EBSCO GreenFILE, and OvidSP CAB Abstracts. References of previous reviews (5, 6) were hand-searched for additional articles.

The search was conducted with predefined search terms that included the concepts "diets" and "water footprint" (see **Supplemental Table 1** for all database-specific searches). After duplicates were removed, potentially relevant studies were assessed for inclusion by 2 independent researchers (FH, CM), and discrepancies were discussed and agreed by consensus. Eligible study designs included observational and modeling studies that quantified WFs from the perspective of dietary intake or food availability (known as the "bottom-up approach" in WF accounting) (12). Hence, we included studies that quantified diets through dietary intake surveys, food consumption and expenditure surveys, modeled dietary scenarios, and national food supply or availability accounts (amount of food available from production and imports after loss, exports, and other uses). Studies that only quantified future or projected dietary WFs were excluded.

Data extraction and quality assessment

Data extraction from eligible studies included reference information, study setting, data sources of diets and water use, modeling assumptions used to link diets and WF, WF of the diet(s) with units (green, blue, and total), information on dietary pattern(s), and the top 2 food groups or food items contributing to the dietary WF. Most studies provided multiple dietary WF estimates, for example, for different dietary patterns, countries, or timescales. Only dietary WF estimates from recent past (since 1995) or current diets were extracted. If exact dietary WFs were not available through the published article or supplementary files but were presented graphically, precise estimates were requested from the study's corresponding author. We wrote to 13 authors, of whom 7 responded and sent additional data. To estimate the contribution of food groups in the diet, percentages were calculated where possible for inclusion in analysis.

The majority of studies included in the review were modeling studies (i.e., combining data from primary or secondary data sources), so we appraised study quality following an adjusted appraisal tool based on the Critical Appraisal Skills Programme (CASP) Randomized Controlled Trials Checklist (13) and the Questionnaire to Assess Relevance and Credibility of Modelling Studies (14). Our adjusted appraisal tool included 10 criteria, with studies scoring either "0" for not fulfilled, "1" for fulfilled, or "NA" if not applicable. Each study included in the review was graded based on its score and converted to a percentage, with <50% as low, 50–70% as medium, and >70% as high. This information was used to perform a sensitivity analysis removing studies of low quality. Data extraction and quality assessment were carried out by 2 independent researchers (FH, CM), and discrepancies resolved by consensus.

Analysis

We tabulated information on the following features of included studies: location of study, scale (global, multicountry, national, subnational), WF assessed (green, blue, or total), data source for diets and WFs, and model assumptions used to link diet and water data. Green, blue, and total dietary WFs were standardized (to liters per day per capita). Subnational, national, and regional dietary WF estimates were categorized by continent and summary statistics calculated. National mean green, blue, and total WFs were calculated from national and subnational diet WF estimates and mapped using ArcGIS Desktop (Version 10.5; Environmental Systems Research Institute, Inc). Values were separated into 5 categories using Jenks optimization, defined by minimizing the within-category deviation from the mean, and maximizing the between-category deviation (15).

We explored the contribution of different food items to dietary WFs of each dietary pattern. Due to heterogeneity in study reporting and food groups assessed, we could not carry out a meta-analysis to explore the contribution of different food groups to the dietary WF. For example, studies reported food intake or availability in weighed amount (i.e., grams per day) or equivalent calories (i.e., kilocalories per day) and therefore could not be grouped. Additionally, some studies reported intake or availability based on specific food items (e.g., eggs or beef), whereas others reported in broad categories (e.g., ASFs). Therefore, we presented the top 2 contributing food groups or items to the dietary WF as stated in included studies. If available, percentage contributions were calculated, and, when multiple dietary WFs were estimated by the study, we recorded the range.

To assess the effect of diet pattern on the WF, we adopted a 1-step individual observation meta-analysis method using dietary WF estimates and diet pattern (16). Studies were only included in the meta-analysis if they provided an exact estimate of dietary WF that could be standardized to liters per day per capita. Meta-analysis was carried out using mixed effects regression models with study identifier as a random effect to account for multiple estimates from the same study. Dietary WFs were not normally distributed and therefore all regression analyses were carried out using log-transformed values.

Dietary patterns evaluated in included papers were grouped into 4 major categories as follows (**Supplemental Table 2** gives full details of categorization):

1) "Average" dietary patterns were those identified as current, baseline, or average intake in the included study. This category was used as the reference diet in statistical analysis.
2) "Healthy" dietary patterns were identified as such in the included study, therefore providing additional nutritional benefits when compared with average diets. These were typically national dietary guidelines [e.g., German Nutrition Society (17) or US Department of Agriculture (18)], or other food or nutrient-based guidelines [e.g., WHO (19)].
3) "Reduced animal source foods" included dietary patterns with lower consumption of ASFs than the average [e.g., those identified as vegetarian, or with step decreases in ASF content (e.g., −10%, −25%, etc.)].
4) "No animal source foods" meant no animal products consumed (e.g., those identified as vegan).

A few studies ($n = 5$) reported "other" dietary patterns, which included a small set of highly heterogeneous patterns including diets consumed by tourists and scenario diets that minimized WFs. These estimates were excluded from the meta-analysis.

Several models were used to quantify differences in dietary water use of each dietary pattern compared with the "average" dietary pattern. The WF values were log-transformed and regression coefficients were exponentiated, giving the proportional difference in dietary pattern relative to the average. The baseline model included dietary pattern, WF, and study identifier as a random effect. The location-adjusted model also included study location as a covariate. The fully adjusted model also adjusted for study scale, source of diet data, and source of WF data. Sensitivity analysis was performed by rerunning the analysis excluding studies graded as low quality ($n = 2$) and excluding studies contributing a large number of estimates (>500) ($n = 2$). It was not possible to test for publication bias, because SEs for the differences between the WFs of dietary patterns were not provided. All statistical analyses were conducted using STATA (v.15; StataCorp LP).

Results

Of 6268 unique studies identified in the initial search, a total of 41 studies were identified as relevant and included in this review (**Figure 1**). An additional 14 studies assessed dietary water use through metrics other than the WF, and were not included in this review (**Supplemental Table 3**).

Study methods, context, and quality

The included studies used a variety of data sources and methods (**Figure 2**; full details of each study are provided in **Supplemental Table 4**). Current dietary patterns were analyzed in 32 studies, and 66% ($n = 21$) of these used data on national food availability from UN FAO food balance sheets (FBSs) to derive dietary patterns. Most studies ($n = 36$) obtained WF data from the WaterStat database. Over half of the studies ($n = 23$) assessed dietary WFs at the national level. China ($n = 8$) (20–27) and the United States ($n = 7$) (28–34) had the highest number of subnational studies. A total of 17 studies assessed dietary WFs in Europe, either at regional (35–39), national (28, 40–45), or subnational levels (46–50). Only 4 studies reported WFs of diets in low- or middle-income countries, namely Uzbekistan, India, Tanzania, and Uganda (51–54). One study quantified the dietary WFs for South Korea (55). Two large studies estimated national-level dietary WFs globally (176 countries) (56, 57). Three studies quantified regional or global average dietary WFs (58–60). A third of the studies assumed food was produced and consumed in the same area, and therefore the WFs of crop and livestock items were taken from that area ($n = 16$). Five studies accounted for food imports in their estimates of dietary WFs, but applied a global average WF value to imported items. Only 4 studies included models of food trade with weighted WFs based on countries of origin (20, 28, 40, 41).

Of the 41 studies, 17 (41%) were graded as high quality and 9 (22%) as low quality (Figure 2, **Supplemental Table 5**). Only 4 studies provided a measure of uncertainty or variance for dietary WF estimates (24, 34, 52, 59). The quality of estimates included in regression analysis was high because the majority of estimates came from 3 high-quality studies (37, 56, 57).

Geographical variability in the WFs of current diets

The WF of "average" dietary patterns varied depending on country and region (**Table 1**, **Figure 3**). Regionally, the

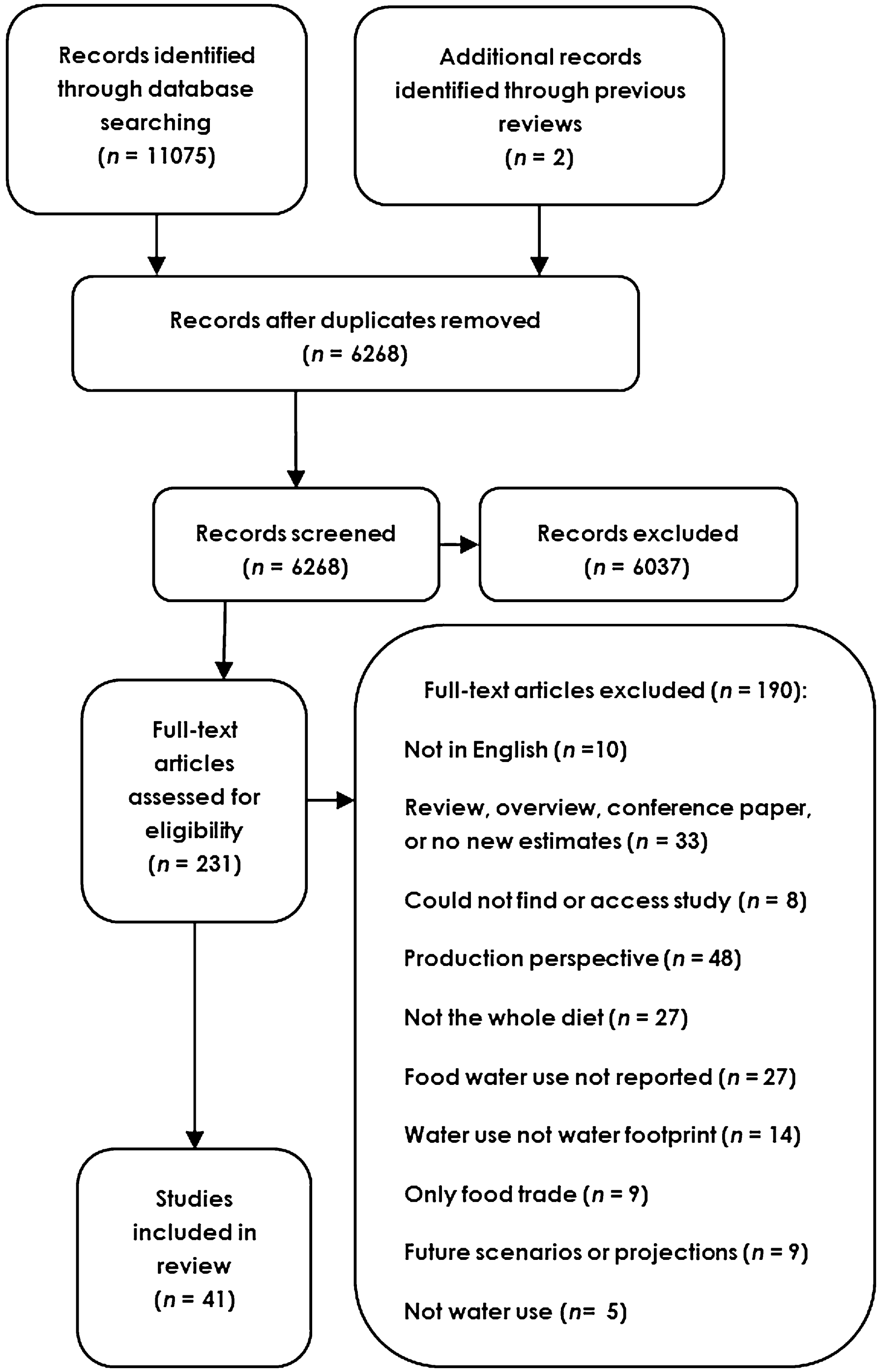

FIGURE 1 Flowchart, indicating identification and selection of studies.

total and green dietary WFs of "average" dietary patterns were greatest in Europe and Oceania. North American and Asian dietary patterns had the lowest total and green WFs. African diets had the lowest per capita median dietary blue WF, of 163 L/d (IQR: 118–267 L/d), whereas the WFs of dietary patterns in Asia were nearly double this at 382 L/d (IQR: 239–663 L/d). "Average" dietary patterns in Asia also had the greatest blue WF as a percentage of total dietary WF. "Average" dietary patterns in Egypt and Uzbekistan were more dependent on blue than green water, with blue WF representing 54% and 52% of total WF, respectively. In all other countries, "average" dietary patterns were more dependent on green than blue water. The lowest dependency on blue water was in Chad and Eritrea, where only 2% of the total dietary WF was blue.

FIGURE 2 Characteristics of included studies: context, dietary and water use data, and quality (n studies = 41).

TABLE 1 Summary of green, blue, and total WFs of the "average" dietary patterns in each continent[1]

Continent	Green[2] WF		Blue[3] WF		Total[4] WF	
	Median (IQR), L/d per capita	*n* Estimates	Median (IQR), L/d per capita	*n* Estimates	Median (IQR), L/d per capita	*n* Estimates
Africa	2681 (2324–3159)	97	163 (118–267)	98	2846 (2489–3471)	98
Asia	2321 (1762–2779)	96	382 (239–663)	98	2862 (2238–3541)	100
Europe	2999 (2604–3642)	152	241 (159–366)	153	3227 (2873–3792)	170
North America	2370 (2108–2949)	51	220 (144–300)	54	2617 (2252–3214)	51
Oceania	2924 (2361–3402)	18	230 (220–322)	18	3226 (2579–3632)	18
South America	2735 (2013–3574)	25	202 (152–296)	26	2932 (2322–3730)	25

[1]WF, water footprint.
[2]Volume of rainfall water consumed in the production of the diet.
[3]Volume of ground and surface water consumed in the production of the diet.
[4]Green and blue WFs combined.

Major foods contributing to the dietary WF

Data on the contribution of foods to WF were available in 30 studies (**Supplemental Table 6**). Here, food and food groups refer to both commodities as defined in FAO FBSs, as well as food ready for human consumption (see Supplemental Table 6). ASFs, particularly meats, were the major component of total and green dietary WFs of "average" dietary patterns. Cereals were the second most important foods for total and green dietary WFs. Plant-based foods, including cereals, nuts, and sugar, were the major components of blue WFs of "average" dietary patterns, although ASFs were still in the top 2 contributing foods in 5 out of the 10 studies. Switching to healthier diets changes the contribution of foods to the dietary WF. Plant-based foods feature as major contributors to total and green dietary WFs in 6 of 8 studies. Plant-based foods still dominated the blue WFs of healthy diets, with the inclusion of fruits as a major contributor.

The contribution of food groups to dietary WFs in "reduced ASF" or "no ASF" dietary patterns was only reported in 8 studies. In "reduced ASF" patterns, meat was usually reduced first before other animal products. Therefore, in the "reduced ASF" dietary patterns, the contribution to dietary WF of items such as milk increases relative to that of meat. Additionally, products such as tea and coffee become major contributors to the total dietary WF. Only 1 study reported the contribution of food to the dietary WF for the "no ASF" pattern; fruits and vegetables accounted for 34% of the dietary blue WF of this pattern in the United States (31).

Meta-analysis of dietary patterns and water use

In total, 1964 individual dietary WF estimates from 36 studies were available for inclusion in the meta-analysis to determine the WF of different dietary patterns (**Figure 4**, **Supplemental Tables 7–9**). Five studies reporting 28 estimates were excluded from the meta-analysis, because it was not possible to convert reported dietary WF estimates to liters per day per capita (22, 32, 33, 35, 54). Compared with "average" dietary patterns, "healthy" dietary patterns, "reduced ASF" dietary patterns, and "no ASF" dietary patterns had significantly lower total and green WFs (Figure 4). Adjusting for study location and other characteristics improved the precision of the models, suggesting there is some variability in the size of relation depending on study context. The WF of the "no ASF" pattern differed most markedly from the "average" pattern, with the total WF 25.2% lower after adjusting (95% CI: −27.1, −23.1; $P < 0.001$) and green WF 26.1% lower after adjusting (95% CI: −28.1, −24.1; $P < 0.001$). The healthier patterns had a slightly lower total WF (adjusted percentage difference: −6.0%; 95% CI: −7.9, −4.2; $P < 0.001$) and green WF (adjusted percentage difference: −5.9%; 95% CI: −7.7, −4.0; $P < 0.001$) than that of "average" dietary patterns. We found no evidence of a difference between the blue WF of "healthy" and "average" dietary patterns, even after adjusting for study location and characteristics. In the fully adjusted model there was evidence that "no ASF" and "reduced ASF" dietary patterns had lower blue WFs compared with the "average" dietary pattern (adjusted percentage difference: −11.6%; 95% CI: −14.5, −8.6; $P < 0.001$, and −5.6%; 95% CI: −7.6, 3.4; $P < 0.001$, respectively). However, this varied from the unadjusted model suggesting the relation is dependent on study location.

Findings from sensitivity analysis that excluded studies of low quality did not differ from the original analysis. Sensitivity analysis that excluded the 2 large studies that each provided >500 dietary WF estimates, reduced the robustness of the findings largely due to reduced data availability (Supplemental Tables 7–9).

Discussion

Summary of findings

This systematic review reports the available published evidence assessing the relation between human diets and the water used in their production. The average WF of diets ranged from 616 to 8075 L/d per capita for green water, 40 to 2450 L/d per capita for blue water, and 688 to 8341 L/d per capita for the total water use. Our review identified large geographical differences in the water use of diets: green WFs of diets were greatest in Europe, whereas blue WFs of diets were greatest in Asia. ASFs were major contributors to green and total WFs, whereas plant-based foods were more dominant in the dietary blue WFs. Our new analysis, including data from 36 studies, suggests that switching from current "average"' dietary patterns to "healthier" diets would result in decreased green WFs, but might not reduce blue

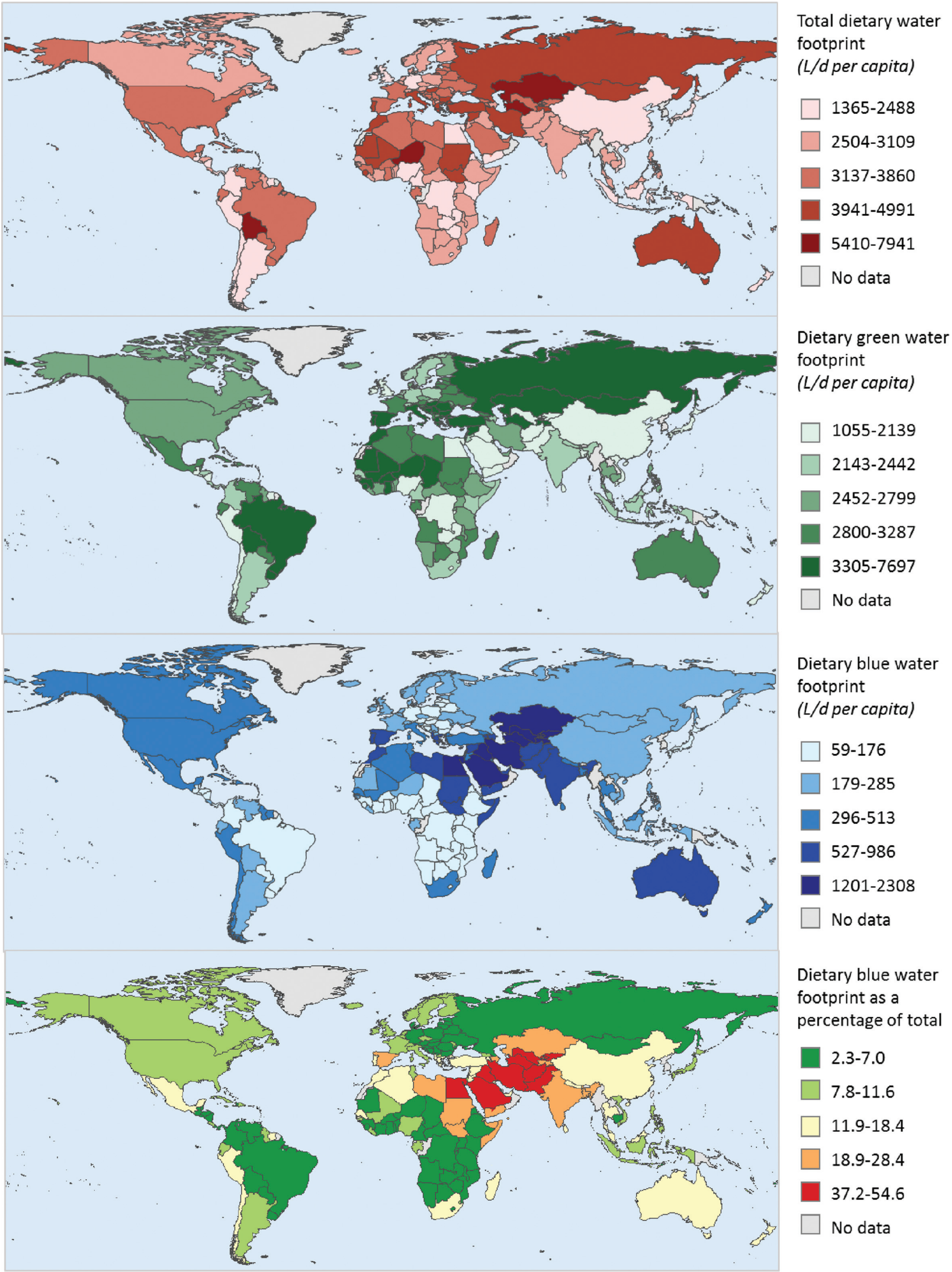

FIGURE 3 National dietary total, green, and blue dietary WFs, and blue WFs as a percentage of the total WF. Values are the mean for the respective country including national and subnational estimates. Categories are defined by natural breaks (15). WF, water footprint.

WFs. Compared with "average" dietary patterns, reducing the ASF content of diets would reduce green WFs, and in most cases blue WFs.

Research in context

To our knowledge, this is the first global systematic review of the WFs of diets. We included 41 relevant articles that reported 1964 WF estimates from 176 countries and were

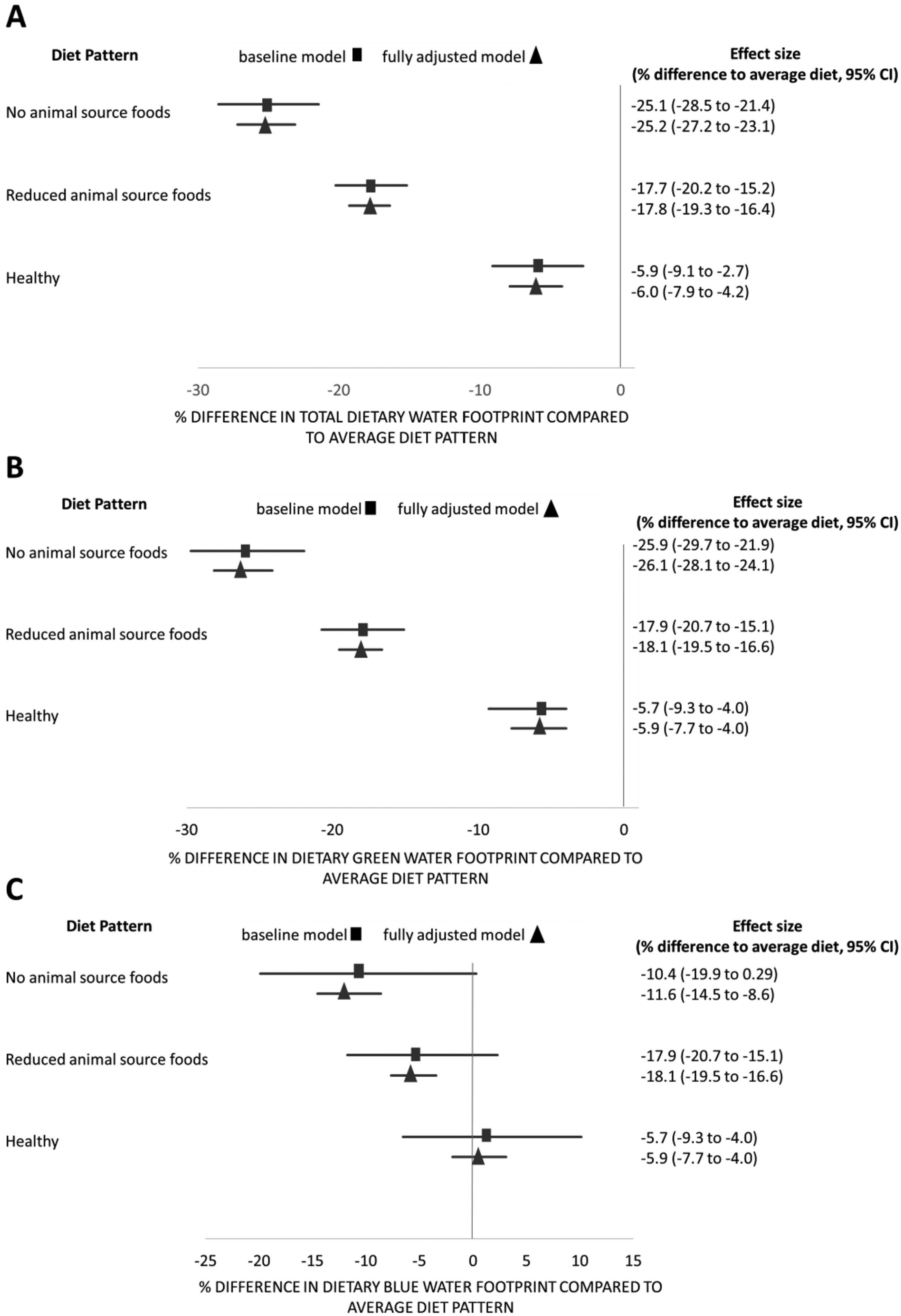

FIGURE 4 Forest plots with coefficient estimates from the mixed effects regression of diet pattern and (A) total WF, (B) green WF, and (C) blue WF. Values represent the percentage differences (95% CI) in dietary WF for each of the 3 dietary patterns compared with the average dietary pattern; *n* studies = 32 (total), 20 (green), and 24 (blue); *n* estimates = 1933 (total), 1834 (green), and 1895 (blue). In all graphs the 0 line represents the "average" dietary pattern. Study identifier was used as a random effect, and the fully adjusted model included study location, scale, and source of WF data. WF, water footprint.

able to compare the blue, green, and total WFs of different dietary patterns. By combining estimates from multiple studies, we assessed the spatial variability in dietary WFs and provided summary estimates by continent. Considerable heterogeneity exists in the total water use of diets and in the relative proportions of green and blue WFs to total WFs. Some of this variation can be attributed to local climate and agricultural management factors. For example, dietary blue WFs were much greater in areas such as the Middle East where there is limited rainfall and a greater need for irrigation. Additionally, our review highlighted that differences in composition of the diet could explain some of this variation. ASFs were the main contributor to the total WF of diets, and total dietary WF was greater in areas with high ASF consumption, such as Europe and Oceania, compared with the global average (61).

Concurrently, our study demonstrated that switching to diets with "no ASF" from current "average" dietary patterns would decrease total WF by 25% and blue WF by 12%. The total WFs of "reduced ASF" dietary patterns were also lower than "average" patterns. Dairy products typically have a lower WF than meat (33), and the reduced ASF patterns often substituted the meat with dairy products, oil crops, and pulses. One previous review that assessed dietary WFs in 8 mostly high-income countries, also reported that vegetarian diets had lower total WFs compared with current habits, and that changing to healthier dietary patterns would result in a median reduction in total dietary WF of 18% (5). Our new analysis includes data from 176 countries and is therefore more representative of global food systems. Our estimate of the potential for healthier dietary patterns to reduce total WF was lower (−6.0%; 95% CI: −7.9, −4.2), perhaps reflecting the greater diversity in current "average" diets. For example, particularly in low-income settings, diets might need to increase their ASF content to achieve nutritional adequacy, thereby concomitantly increasing the dietary WF (61, 62). Our study shows that "healthier" diets have blue WFs similar to "current" dietary patterns. Plant-based foods that are important components of healthy diets, such as fruits, oils, and nuts, were major contributors to dietary blue WFs (63). Production of these crops, and therefore healthy diets, could be sensitive to declining groundwater or surface water availability where this might limit irrigation (64).

Strengths and limitations

By pulling together the available evidence on dietary WFs, this review adds to the growing literature on the environmental impacts of human diets, and the potential for dietary change to reduce this impact. We systematically sought and reviewed the available evidence from 7 databases and identified significantly more studies than previous reviews (4, 5). We prespecified inclusion criteria, and 2 independent reviewers assessed each publication for relevance. We included studies that modeled diets, but did not include studies that assessed the WFs of diets projected into the future, due to the associated uncertainties of such projections (65, 66). Several indicators have been applied to assess the relation between diets and water use. The available evidence base is dominated by the WF and this review did not incorporate findings that used alternative metrics of water use.

Dietary WF assessments predominantly rely on 2 major open data sources [FAOSTAT FBSs (67) and WaterStat (33, 68)] that both have limitations. The FBSs report data on per capita food availability at the national level, and although these data are frequently used as a proxy for individual dietary intake, they typically overestimate actual dietary intake (69) and can therefore overestimate dietary WFs. Data from WaterStat are relatively outdated (1996–2005), and make use of globally gridded databases that might not adequately account for variation. For example, the database on ASFs relies on estimates aggregated to geoeconomic region such as Asia or member countries of the Organization for Economic Cooperation and Development (OECD) (33). To accurately estimate dietary WFs an understanding of where the food is produced and consumed is needed, and yet a third of studies ($n = 16$) did not incorporate any information on food trade in their models. Our analysis used location of where the diet would be consumed, rather than location of crop production, to estimate spatial variability in WFs, and we recognize that this will have underestimated the variability in WF. Furthermore, because the available published literature has mainly focused on high-income settings, there is limited representation of production systems in low- and middle-income countries, which might have different WFs. For example, the type of livestock system can affect both the type and amount of water used by the feed products, and therefore the associated WF of the ASF (70). These differences have not been explored here.

Poor reporting of methods, modeling approaches, and data sources were all common in the included studies, and there was a lack of uncertainty estimates. Sensitivity analysis removing studies of low quality did not lead to any differences in the interpretation of our regression results. The challenge of diverse reporting standards across academic disciplines and subsequent synthesis has been identified in previous interdisciplinary reviews (3). Finally, our meta-analysis was particularly dependent on 2 large studies from the same author group (56, 57), and as highlighted above, the majority of studies were focused on high-income settings. This identifies the need for more evidence on dietary WFs to be generated by academic groups around the world.

Policy relevance and further research needs

By synthesizing the available literature, we provide estimates for the WFs of human diets for each continent. This is important for food security and environmental sustainability, because considerable spatial heterogeneity exists, which indicates both solutions and risks. For example, dietary blue WFs in Asia were found to be particularly high. Water scarcity in this region is a concern because groundwater resources are depleting in some areas, and climate change could disrupt normal patterns of rainfall and irrigation water supply (10, 71, 72). Changing dietary habits in Asia therefore could be insufficient to reduce local water use, unless coinciding with improved water management in agriculture (7, 73). Instead, improvements to nutritional status could be achieved through switching to more nutrient-dense and water-efficient crops. For example, it has been shown that cereals such as maize, millet, and sorghum could be grown instead of rice and wheat in India (74, 75). Countries could also import food from water-abundant regions.

Our findings also demonstrate that changes to current dietary patterns could be beneficial for both health and water sustainability. Healthy diets have a lower total WF compared with current patterns, and reducing ASFs could further decrease this. However, the evidence for blue WFs was not well defined. Fruit, nuts, and vegetables were major components of dietary blue WFs, particularly in healthy patterns. Literature on sustainable diets has generally focused on the importance of reducing ASFs to reduce environmental impacts (63). Future research needs to consider fruits, vegetables, and nuts in more detail, particularly because an increase in production is required to meet healthy dietary guidelines globally (76).

To understand the full impact of consumers on water resources, water use must be linked to local water availability, particularly in areas where water demand is growing and climate change threatens supply. Some studies are now using a water scarcity–weighted footprint metric for this purpose (41, 77), but such studies remain relatively rare. Additionally, food trade must be considered in future research, because it affects dietary WF calculations and could offer potential solutions to reduce local WFs in areas of water scarcity. Development of new technologies to record food supply chains will enable more accurate assessments of WFs in the future, and will help to inform policy and consumer decisions.

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CHAPTER 4

METHODS AND DATA

SUMMARY OF CHAPTER

This chapter provides a summary of the India-Food-Trade (InFoTrade) model developed in this PhD and used for the analyses in Chapters 5 - 7. I also detail the methods used to estimate Indian state-level trade-weighted consumption water footprints of food items, which are an additional output of this PhD but not included in the research papers. Finally, this chapter ends with a data glossary for all of the thesis.

Where Appendix are referred to, these can found in Appendix 3.

4.1 Background on modelling food trade

Food trade - that is the movement of food between location of production to location of consumption - is often analysed at international level and has provided valuable evidence on vulnerabilities of global food supply to environmental change (1). Harmonised data are available on the import and export of commodities to and from countries (2). However, data on the sub-national movement of food are collected less frequently but in large countries this may constitute a large proportion of total food trade (3). Therefore, models are used to estimate sub-national food trade when there are no primary data available. For example, it is possible to estimate trade using data on the supply and demand of food items for each sub-national region, and calculate the direction of trade flows based on minimising the cost of transportation. This type of model has been used to estimate sub-national food trade in China (4) and the United States of America (5). It has been shown to produce results that are comparable to actual data on trade flows where these are available (6). Other modelling approaches to estimate trade include the gravity model (7), however this model requires actual trade data that do not exist for food trade in India. Therefore, for the purpose of this PhD I build on existing research to estimate trade flows for the Indian context and develop the India-Food-Trade (InFoTrade) model.

4.2 Description of InFoTrade model

First I estimated the supply and demand balance for each State and Union Territory (UT) (hereafter 'state') and food item. For each state (i) and food item (f), the available supply of food ($S_{i,f}$) in tonnes includes local production ($P_{i,f}$) and foreign imports ($FI_{i,f}$), change in stock ($\Delta St_{i,f}$), minus waste and non-food uses of the food item ($OU_{i,f}$) (feed, seed, processed and other) (Equation 1, with definition of these quantities and their data sources given in Table 4.2 in the Data Glossary):

$$S_{i,f} = P_{i,f} + FI_{i,f} + \Delta St_{i,f} - OU_{i,f} \tag{1}$$

The volume of supply for non-food uses ($OU_{i,f}$) in the state is calculated using the proportion of supply diverted to non-food use according to national-levels (α_f) (Equation 2).

$$OU_{i,f} = \alpha_f * (P_{i,f} + FI_{i,f} + \Delta St_{i,f}) \tag{2}$$

The state's demand for each food item includes food for human consumption and foreign exports ($FE_{i,f}$) (Equation 3).

$$D_{i,f} = C_{i,f} + FE_{i,f} \tag{3}$$

The difference between supply and demand in each state is used to estimate the volume (tonnes/year) imported or exported. States with supply greater than demand are assumed to export the excess supply, and states with demand greater than supply are assumed to import the unmet demand.

The state trading pairs to use excess supply or satisfy unmet demand are modelled using linear programming. The function of the model is to minimize the total transportation cost (Equation 4).

$$TC_f = \sum_{i,j,f} \left(t_{i,j,f} \cdot tc_{i,j,cat}\right) \tag{4}$$

The model constraints are:

- Supply of each food item equals demand in each state (Equation 5).
- Trade flows are only positive (Equation 6).
- Net export of the commodity is bounded by local production or foreign import (if any) (Equation 7).

$$\forall \epsilon \; [1:35]: P_{i,f} + FI_{i,f} + \Delta St_{i,f} - OU_{i,f} + \sum_{j \neq i, j=1:35} (t_{j,i,f} - t_{i,j,f}) = C_{i,f} + FE_{i,f} \tag{5}$$

$$\forall (i,j): t_{i,j,f} \geq 0; \; \forall i : t_{i,i,f} = 0 \tag{6}$$

$$\sum_{j \neq i, j=1:35} (t_{i,j,f} - t_{j,i,f}) <= \max\,(0, St_{i,f} FI_{i,f)} \tag{7}$$

The assumptions of the InFoTrade model are as follows:

- $t_{i,j,f}$ is the unknown interstate trade matrix for the food item f, in tonnes,
- $tc_{i,j,cat}$ is the interstate transportation cost matrix for each food group category, in Rupees/tonne,
- TC_f is the total transportation cost of interstate trade of the food item f, in Rupees.
- i refers to the exporting state, while j refers to the importing state [N= 35, pre-separation of Andhra Pradesh],
- $P_{i,f},\ FI_{i,f},\ FE_{i,f},\ \Delta OU_{i,f}\ and\ \Delta St_{i,f}$ are state i's production, foreign import, foreign export, non-food uses and net change in stock of food item f, in tonnes.
- $C_{i,f}$ is the state i's total annual demand for food item f, in tonnes.

The transport costs matrix is calculated using distance per mode between each state and transportation costs in Rupees/Km/tonne (available for the food categories of grains, sugar, fruits and vegetables and livestock) (8). Transport costs (tc) are calculated for each food category (cat) as follows (Equations 8-12):

$$tc_{i,j,cat}^{road} = dist_{i,j}^{road} \sum_k tc_{India,cat_k}^{road}\, I_k(dist_{i,j}^{road}) \tag{8}$$

$$I_k\left(dist_{i,j}^{road}\right) = 1\ if\ dist_{i,j}^{road}\ \in (min_k, max_k) \tag{9}$$

$$I_k\left(dist_{i,j}^{road}\right) = 0\ if\ dist_{i,j}^{road} < min_k\ or\ dist_{i,j}^{road} >\ max_k \tag{10}$$

$$tc_{i,j,cat}^{rail} = tc_{India,cat}^{rail} * dist_{i,j}^{rail} \tag{11}$$

$$tc_{i=is,j=is,,}^{ship} =\ tc_{India}^{ship} * dist_{i=is\ or\ isport,j=is\ or\ isport}^{ship} \tag{12}$$

Where tc_{India,cat_k}^{road} represents the average cost of road transport, weighted according to road type travelled for the food category (cat) in Rupees/Km/Tonne in India. The road transport cost matrix, $tc_{i,j,cat}^{road}$, is estimated through road distance and the average road transport cost. Road transport costs are non-linear for distance, as capacity and time costs per Km decrease with distance travelled. Therefore, distance category is represented by k (8), and $I_k\left(dist_{i,j}^{road}\right)$, and is an indicative function that takes the value of

1 if the distance is in category k and the value of 0 if the distance is in any other category. The average cost of rail transport, $tc^{rail}_{India,cat}$ is weighted according to rail type travelled for the food category in India in Rupees/Km/tonne (8). The transport cost to and from the island UTs (Lakshadweep and Andaman and Nicobar Islands), $tc^{ship}_{i=is,j=is}$, are estimated using the cost of shipment in Rupees/Km/tonne, tc^{ship}_{India}, and the shipping distance ($dist^{ship}_{i=is\ or\ isport,j=is\ or\ isport}$), and the cost of rail or road transport between the state of their mainland port and other states. For all other states, it is assumed that food is traded via land transport.

The transportation costs matrices to be minimised for each food category are estimated as (Equation 13):

$$tc_{i,j,cat} = \left(tc^{road}_{i,j,cat} * \ prop^{road}_{cat}\right) + \left(tc^{rail}_{i,j,cat} * prop^{rail}_{cat}\right) + \ tc^{ship}_{i=is,j=is,} \quad (13)$$

Where $prop^{road}_{cat}$ and $prop^{rail}_{cat}$ are the proportion of each food category transported by road and rail in India respectively.

For processed food products (oils and sugar), I estimated trade flows as raw materials as this aligned with the data on foreign import and export volumes. I then converted trade flows and food consumption to tonnes of extracted (i.e. edible) product, using the extraction rate ($ex_{india,f}$), as follows (Equations 14 and 15):

$$t^{\,edible}_{i,j,f} = t_{i,j,f} \ * ex_{india,f} \quad (14)$$

$$C^{\,edible}_{i,j,f} = C_{i,f} * ex_{india,f} \quad (15)$$

The interstate trade was estimated using the InFoTrade model for 41 food items, covering the groups of cereals, pulses, fruits, vegetables, animal-sourced food products, sugar and rape & mustard oil. The food items to be modelled were selected based on the availability of data across sources and to represent multiple food groups. The model was estimated using data from the year 2011-12 as this was the most recent time period for which all of the data were available.

4.3 Validation of the modelled results using consumer value

The InFoTrade model assumes that trade is determined by minimising the cost of transporting the product. If true, the transport costs should be represented in the cost the consumer pays for the product; items that travel further will cost more and vice versa. Data are available on the value (price paid by household/amount bought) of products from the Indian National Sample Survey (9), and these data were used to validate the trade model results.

The relationship between cost of transport and consumer value of the food item was assessed through linear regression (see Appendix 3 for scatter plots). I used a mixed effects linear regression model for each food group, with the food item as the random effect. The model was weighted by the consumption volume in the state ($C_{i,f}$). The results are presented in Table 4.1. For all food groups assessed, except for milk, the value of the food item had a positive relationship with the cost of transport. The effect size was positive but not significant for meat (5.64, -2.63 to 13.90, P = 0.181) and pulses (1.97, 95% CI 1.97 to -2.47, P = 0.384). The value of milk was found to decrease with increasing transportation costs (-2.59, 95% CI -4.53 to -0.4, P = 0.011). This suggests that the modelling approach was not valid to estimate the trade of milk.

Table 4.1 Mixed effect linear regression results comparing the transport cost for food groups against the value in the importing state, weighted by the consumption volume. Food item included as random effect. See Appendix 3 for full regression results.

FOOD GROUP	COEFFICIENT	LOW 95% CI	HIGH 95% CI	P	N	N FOOD ITEMS
Cereals	3.32	1.27	5.36	0.001	245	7
Eggs	5.68	2.69	8.66	<0.001	35	1
Fruits	3.15	0.28	6.02	0.032	245	7
Meat	5.64	-2.63	13.90	0.181	140	4
Milk	-2.59	-4.53	-0.64	0.011	35	1
Rape & mustard oil	5.10	2.01	8.20	0.002	33	1
Pulses	1.97	-2.47	6.41	0.384	210	6
Sugar	11.45	3.89	19.01	0.004	35	1
Vegetables	2.47	0.97	3.97	0.001	280	8

4.4 Trade-weighted consumption water footprints of food items

Trade-weighted consumption water footprints (WF) of food items were calculated for Indian states, weighted according to the volume of each food item consumed from local production, imported from other states, or imported from other countries. The term consumption WF is used to represent the WF that would be associated with consuming the food item in that state accounting for food trade, whereas the production WF is the WF associated with producing the food item in that state or country. I estimated consumption WFs for crop and animal-sourced food items in Indian states using data on local production, foreign imports, interstate trade, state-level consumption, state-level WFs, and country WFs (data sources given in Table 4.2 in the Data Glossary). I estimated both the blue WF, which is the water sourced from ground and surface water sources, and the green WF, which is the water sourced through rainfall or evapotranspiration (10) .

The water footprint of crop food items

First, I estimated the WF of local supply for each crop food item (c) in each state (j) (Equations 16-18):

$$PWU_{i,c} = Pwf_{i,c} * P_{i,c} \tag{16}$$

$$FIWU_{i,c} = FIwf_c * FI_{i,c} \tag{17}$$

$$Swf_{i,c} = \frac{PWU_{i,c} + FIWU_{i,c}}{P_{i,c} + FI_{i,c}} \tag{18}$$

Where $PWU_{i,c}$ is the water use of local production, $Pwf_{i,c}$ is the production WF for each crop food item in the respective state. $FIWU_{i,c}$ is the water use of foreign imports, calculated using the weighted average of production WFs in the origin country of imports ($FIwf_c$). Original country of production (as opposed to the most recent country of export as reported in the publicly available Food Balance Sheet data) of foreign imports was estimated using methods from Kastner et al. 2014 (11), but with updated data representing a more recent time frame. The water use of local production and foreign imports for each commodity were combined to calculate the WF of supply for the food crop item in each state ($Swf_{i,c}$ m^3/tonne).

To obtain the water use of locally produced supply in each state ($locCWU_{i,c}$ in m^3), the WF of local supply was multiplied by the corresponding tonnes of food consumed from local supply ($locC_{i,c}$) (Equation 19):

$$locCWU_{i,c} = Swf_{i,c} * locC_{i,c} \tag{19}$$

To obtain the WF of food imported from other states ($imCWU_{j,c}$ in m^3) the volume of imports for each state ($imC_{j,c}$) was multiplied by the WF of supply from the corresponding exporting state. These were summed across exporting partners to obtain the total volume of water imported (Equation 20).

$$imCWU_{j,c} = \sum Swf_{i,c} * imC_{j,c} \tag{20}$$

Finally, I estimated the consumption WFs of food items in each state as follows (Equations 21 and 22):

$$CWU_{j,c} = imCWU_{j,c} + locCWU_{i,c} \tag{21}$$

$$Cwf_{j,c} = \frac{CWU_{j,c}}{C_{j,c}} \tag{22}$$

Whereby the consumption water use from local supply was combined with the consumption water use of imports. To obtain the water footprint, this was divided by the total food consumption estimated in the state.

The water footprint of animal-sourced food items

There are no state-level data available on the WF of animal-sourced food (ASF) items in India. Therefore to estimate the trade-weighted consumption WF of ASF items I first estimated the production WFs of ASF items in each state following methods of Mekonnen and Hoekstra (2012) (12), where the total WF is calculated from the WF of animal feed and water required for drinking and services. There are no state-level data on the volume and composition of feed required for livestock or poultry production. Therefore to obtain state-level volumes and composition of feed, I used data on the proportion of each animal production system in each state, and the volume and composition of feed used in each animal production system (data sources given in Table 4.2 in the Data Glossary).

The total volume of feed required for each animal in each state (i), was estimated by feed conversation efficiency (FCE), which is the ratio of the volume of feed ($VolFeed$, tonnes/animal) to the volume of product output (PO, in tonne/year/animal for eggs and milk, or tonnes/lifetime/animal for meat) for each ASF item (N = 7; milk, eggs, beef, pork, poultry meat, goat meat, sheep meat). The feed conversion efficiency for the production system (ps) and ASF item (a) was calculated as follows (Equation 23):

$$FCE_{ps,a} = \frac{VolFeed_{ps,a}}{PO_{ps,a}} \quad (23)$$

The production system feed conversation efficiency was converted to state level using the proportion of area allocated to each production system in each state (Equation 24):

$$FCE_{i,a} = \sum FCE_{ps,a} * pPS_{i,a} \quad (24)$$

The total volume of feed (tonnes) was estimated using the state-level feed conversion efficiency, and the state level product output for each ASF item (Equation 25):

$$VolFeed_{i,a} = FCE_{i,a} * PO_{i,a} \quad (25)$$

Feed is made up of grazing, occasional feeds, stover and grains. The proportion of each feed ingredient in the total feed is available for each animal production system ($propFeed_{ing,ps,a}$), and was used to estimate the total volume of each feed ingredient for each state and animal ($VolFeed_{ing,i,a}$) as follows (Equations 26 and 27):

$$pFeed_{ing,i,a} = pFeed_{ing,ps,a} * pPS_{i,a} \quad (26)$$

$$VolFeed_{ing,i,a} = pFeed_{ing,i,a} * VolFeed_{i,a} \quad (27)$$

The WF of grazing in India was taken from Mekonnen and Hoesktra (2012) (12). For stover and occasional feed the WF was assumed to be zero, as their WF is accounted for in the by-product of the grain commodity. The WF of grains was estimated from the WF of feed grain ingredients (N=13) using their production WFs in each state. I assumed that the feed grain ingredients were obtained locally, unless the crop was also included in the crop food item trade model (N=5). For these feed grain ingredients, the interstate feed trade was estimated using the volume of the crop taken from production for feed (supply) and the total feed volume required for ASF items (demand). Trading pairs for the feed grain item were estimated by minimising the cost of transport, assuming the cost of transport (Rupee/Km/Tonne) as the cost for food grains (8). The blue and green WF of feed (m^3/tonne) were estimated as weighted average of the WFs of feed grain ingredients (ing) from imports ($Feedwf_{ing,i,a,import}$), the WF of feed grains from local production ($Feedwf_{ing,i,a,local}$) and the WF of grazing ($grazingwf$), based on their volume in feed ($VolFeed$) for each animal and state (Equation 28):

$$Feedwf_{i,a} = \frac{(\sum(Feedwf_{ing,i,a,import} * VolFeed_{ing,i,a,import}) + \sum(Feedwf_{ing,i,a,local} * VolFeed_{ing,i,a,local}) + (grazingwf * VolFeed_{ing,i,a,grazing}))}{\sum VolFeed_{i,a}} \quad (28)$$

The green WF of the ASF item (m^3/tonne) produced in a state ($Pgwf_{i,a}$) was estimated as (Equation 29):

$$Pgwf_{i,a} = \frac{Feedgwf_{i,a} * VolFeed_{i,a}}{PO_{i,a}} \quad (29)$$

The blue WF of the ASF item ($Pbwf_{i,a}$) includes the water used for drinking and service needs of the animal (DS), the water used for mixing, and the WF of the feed ingredients (Equations 30 and 31):

$$Pbwf_{i,a} = \frac{(Feedbwf_{i,a} * VolFeed_{i,a}) + DS + mixing}{PO_{i,a}} \quad (30)$$

$$mixing = 0.5 * (prop_{grains,i,a} * VolFeed_{i,a}) \quad (31)$$

Finally, as for crop food items, the consumption WF of ASF items in each state was weighted according to the volume consumed from local production, imported from other states, or imported from other countries.

4.5 Comparison of trade-weighted consumption water footprints across food items

The trade-weighted consumption WFs of the food items are summarised in Figures 4.1 and 4.2. According to the median values, the green WFs of meat products were the largest, ranging between 20,047L/kg (IQR: 3,011) for sheep & goat meat, and 10,753 L/kg (IQR:

2,576) for beef & buffalo meat. The median green WFs of fruits and vegetables were generally lower than other food items, ranging between 76 L/kg (IQR: 34) for cabbage and 1,376 L/kg (IQR: 183) for mango.

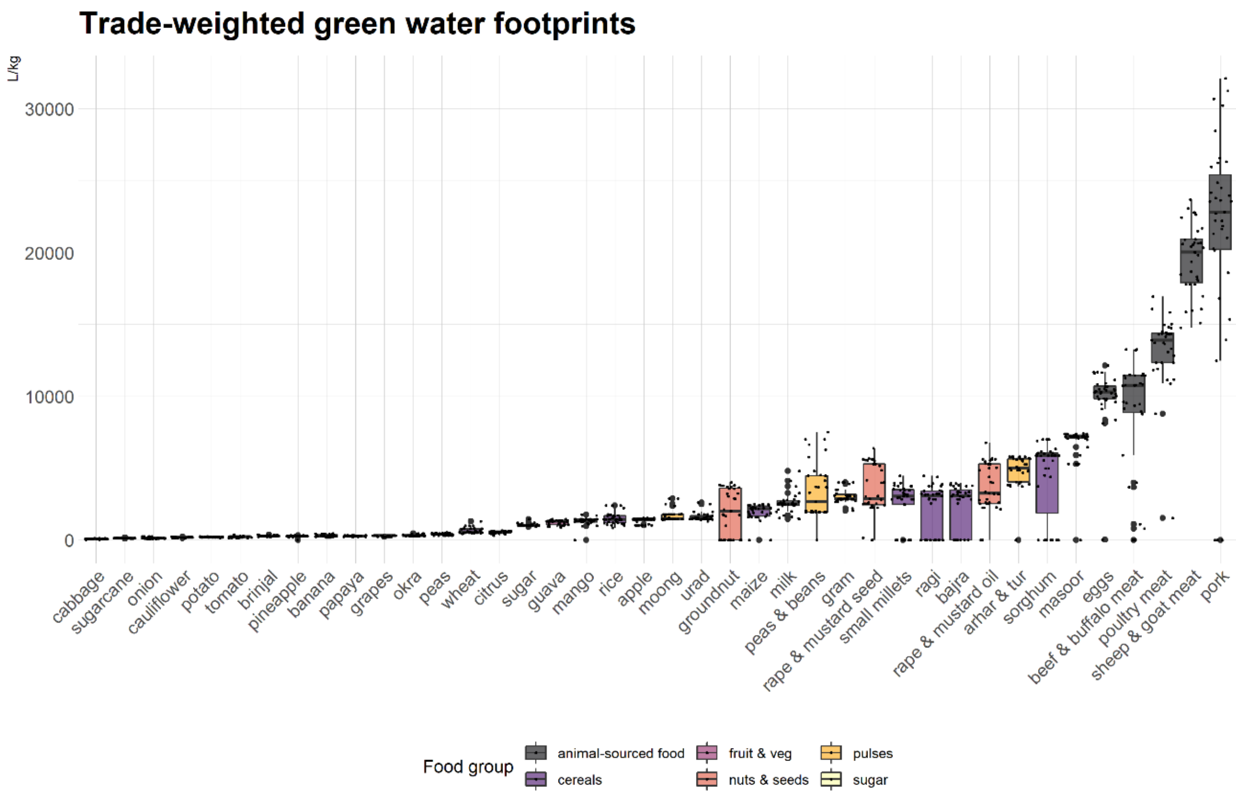

Figure 4.1 The trade-weighted green water footprints (L/kg) of consumption of Indian food items estimated in this thesis, ordered by median value.

A similar pattern was observed for the blue WF, whereby poultry meat had the largest median blue WF (2,181 L/kg, IQR: 974). However, beef and buffalo meat had very low median blue WFs (1 L/kg, IQR: 1), as the majority of their feed came from grazing, stover and occasional grains that are not irrigated in India. Rape & mustard seed oil had a comparatively large median blue WF with a large range; 1,431 L/kg (IQR: 2,733). Wheat (905 L/kg (IQR: 441)) and sugar (1,170 L/kg (IQR: 47)) also had large median blue WFs, with less variability between states. Some fruits, including mango (406 L/kg (IQR: 413)) and guava (543 L/kg (IQR: 503) also had relatively high median blue WFs. For ragi, small millet, grapes, tomatoes and pineapple, the median blue WFs were less than 1 L/kg.

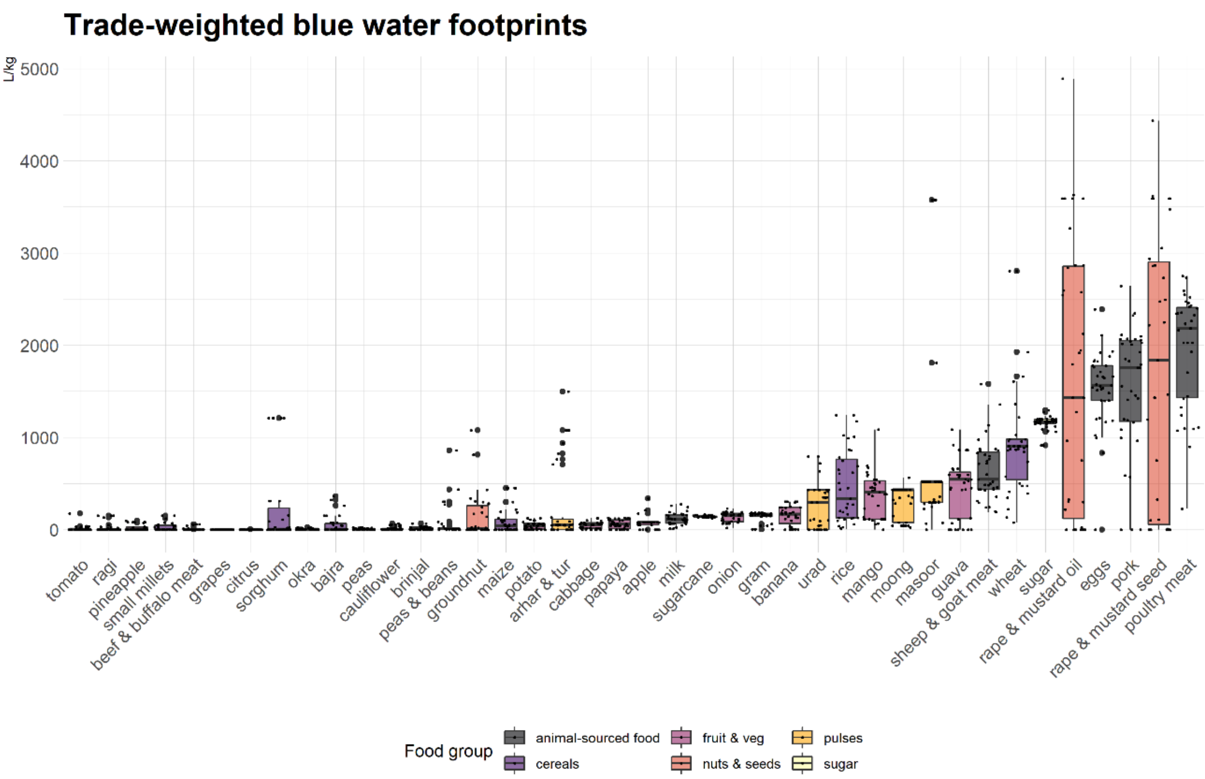

Figure 4.2 The trade-weighted blue water footprint (L/kg) of Indian food items estimated in this thesis, ordered by median value.

4.6 Comparison of trade-weighted consumption water footprints across states

Variability in the trade-weighted consumption WFs was also observed across states, as shown in Figures 4.3. To ensure differences represent spatial variability rather than differences in the pattern of food items consumed in the state, state-level median values were estimated based on the food items produced in all states (N=18). The median green WFs of the food items in each state ranged between 309 L/kg (IQR: 1,672) in Tripura to 1,281 L/kg (IQR: 2793) in Karnataka. The median blue WF of the food items in each state ranged between 0 L/kg (IQR: 17) in Mizoram, to 159 L/kg (IQR: 330) in Punjab.

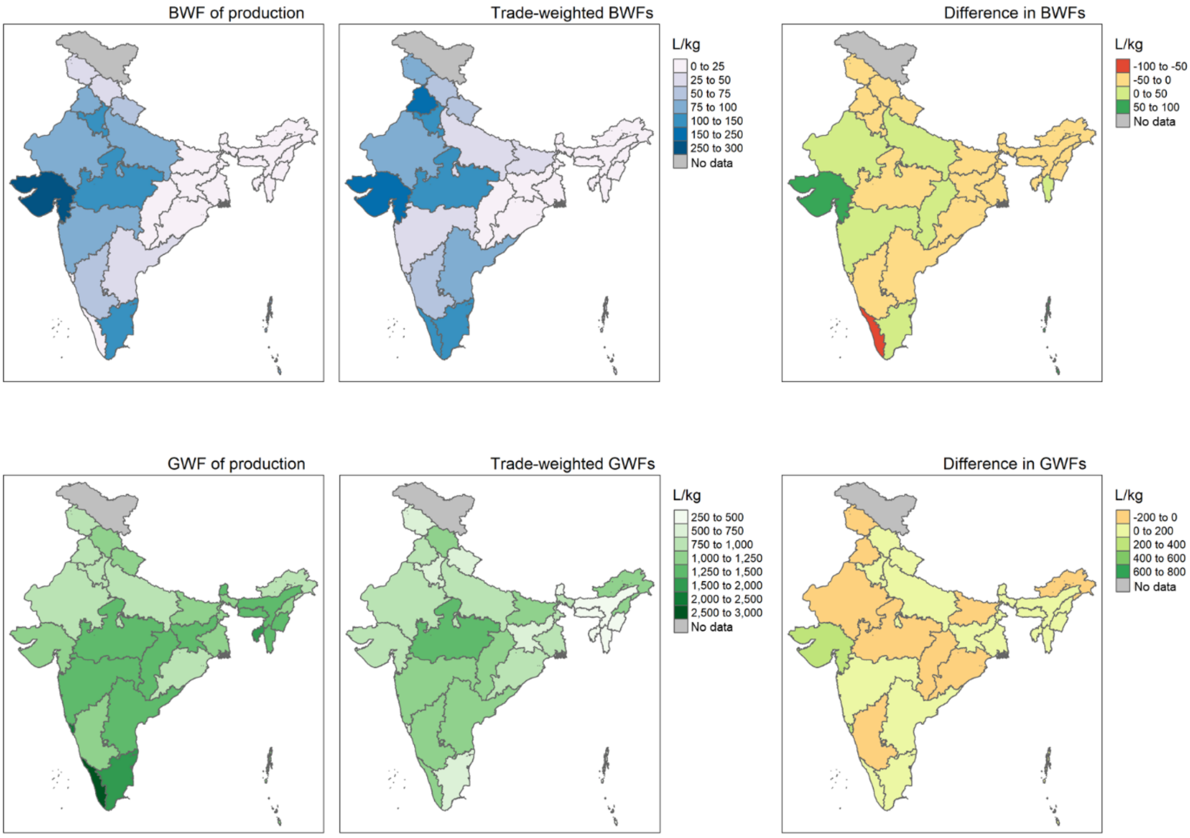

Figure 4.3 Median production water footprints of food items in Indian states compared to the median of trade-weighted consumption water footprints calculated in this thesis. Difference is median of the production water footprint minus the trade-weighted water footprint. Food items included in the state median calculations are produced in each state of India for direct comparison (N=18). BWF; blue water footprint, GWF; green water footprint.

The median trade-weighted consumption WFs were different to the median production WFs in each state (Figure 4.3). The values of the median difference between production WFs and trade-weighted consumption WFs ranged between -80 to 760 L/kg for green WFs and -82 to 76 L/kg for blue WFs. Although the direction of differences varied, there were some trends. States in the west of India generally had higher trade-weighted consumption blue WFs due to higher local production blue WF in the region (Figure 4.3). Whereas states in the east, particularly the North-Eastern region, had lower trade-weighted consumption blue WFs driven by lower production blue WFs in the region. For states with higher production WFs, such as production blue WFs in Gujarat and production green WFs in Kerala, the corresponding trade-weighted consumption WFs were lower than the production WFs. For 26 states (74%), the production green WFs were larger than the trade-weighted consumption green WFs. For 25 states (71%), the production blue WF were larger than the trade-weighted consumption blue WFs. This indicates that WF assessments of Indian food supply could overestimate the water used to produce food if sub-national food trade is not considered. However, these are only descriptive results; further analysis is needed to explore the relationships between trade and water footprint in detail.

4.7 Data Glossary

Table 4.2 lists the variables used for the analysis of this PhD, including their code as noted in equations (if applicable) and their source.

Table 4.2 Data glossary for this thesis.

Variable	Code	Source
	INTERSTATE INFOTRADE MODEL	
Production of commodity in each state (tonne/year)	$P_{i,f}$	Obtained from Directorate of Economics and Statistics, Ministry of Agriculture and Farmer's Welfare, and Agriculture Statistics at a Glance Year Book, 2014 (13)
Volume of foreign imports and export (tonne/year) to ports in India for each food item	$FI_{i,f}$ $FE_{i,f}$	The total volume of foreign trade in India was taken from Kastner et al. (2014), which provides a detailed global matrix of estimated location of production (tonne/year) (11). Foreign exports and imports were distributed between states based port and commodity specific estimates from Directorate General of Commercial Intelligence and Statistics (DGCIS), Government of India, downloaded from the AgriExchange website (14). The total volume of foreign trade did not match between the two data sources; therefore, I used the volume from Kastner et al. (2014) and scaled to the port-specific values.
Net change in stock (tonne/year)	$\Delta St_{i,f}$	India-specific figures in United Nations Food and Agricultural Organisation (FAO) Food Balance Sheets (2010-13) (15). For rice and wheat, the stock is taken from the Department of Food and Public Distribution estimates for the contribution of each state to the Public Distribution System (16).

Proportional of total supply going to waste, feed, seed and other non-food uses	α_f	India-specific figures from FAO Food Balance Sheets (2010-13) (15).
Extraction rate of edible product from raw	$ex_{india,f}$	For the processed products of oils and sugar, extraction rates were used to convert between primary/raw product and edible product (17).
Food available for consumption of each food item in each state (tonne/year)	$C_{i,f}$	Volume of food available for consumption in each state, calculated using proportional consumption of the national demand relative to state weighted values from the NSS 68th Round (2011-12) (9). Total of consumption is equal to the food supply remaining after non-food uses have been removed. The NSS database is assumed nationally representative.
Transportation costs of food categories by rail (Rupees/Km/tonne)	$tc^{rail}_{India,cat}$	Cost of railway transport for food categories reported in the Rail India Technical and Economic Service (RITES) Planning Commission Report of India (8, 18).
Railway distance between state capitals (Km)	$dist^{rail}_{i,j}$	The shortest path of goods rail transport between train stations of state capitals between each state importing and exporting pair, as reported by the Government of India Centre for Railway Information Systems (19).
Transportation costs of food categories by road (Rupees/Km/tonne)	tc^{road}_{India,cat_k}	Cost of road transport for food categories reported in the RITES Planning Commission Report of India (8, 18). Costs vary depending on distance category k.
Road distance between state capitals (Km)	$dist^{road}_{i,j}$	Minimum road distance between state capitals for each state importing and exporting pair, obtained from Google Maps (20)
Transportation costs of shipping commodities for island UTs (Rupees/Km/tonne)	tc^{ship}_{India}	Cost of shipping (Rupees/km/tonne) reported in the RITES Planning Commission Report of India (8). Shipping cost were not category specific.
Shipping distances between island states and mainland ports (Km)	$dist^{ship}_{i=is\ or\ isport,\ j=is\ or\ isport}$	For island Union Territories (is) Andaman and Nicobar Islands and Lakshadweep with no road or rail transport available, distance between the major island port and major mainland ports were taken from Google Maps (20).
Weights for food group transported by road vs rail	$prop^{road}$ $prop^{rail}$	Weighted proportion of food category transported by road and rail in India, as stated in the RITES Planning Commission Report of India (18).
WATER FOOTPRINTS OF CROP FOOD ITEMS		
Water footprints of production of crop	$Pwf_{i,c}$	For cereals, the green and blue production WFs were taken from Kayatz et al. (2019), representing the

items in Indian states		years 2005-2014 (21). For other crop items, the green and blue WFs were taken from (10).
Water footprint of production of crops from foreign countries	$FIwf_c$	The production WFs of crop food items produced in other countries were taken from Mekonnen and Hoekstra (2011) (10).
WATER FOOTPRINTS OF ANIMAL-SOURCED FOOD ITEMS		
Volume of feed for the animal production systems	$VolFeed_{ps,a,}$	Total feed allocated to each animal according to animal production systems in India (22).
Product output for the animal in each state	$PO_{i,a}$	Annual product output (tonne) per animal in each state from 19th Livestock Census (23)
Proportion of production system in each state	$pPS_{i,a}$	Proportion production of system for each animal in each state estimated from gridded ruminant maps (24), gridded pig and poultry system maps (25), and state boundaries (26)
Proportion of each feed ingredient in total feed according to production system	$pFeed_{ing,ps,a}$	Feed composition including volume of grazing, occasional, stover and grains (N=13) available for each animal production systems in India (22).
CHAPTER 5		
Stage of groundwater depletion		State-level values for the stage of groundwater depletion taken from the Central Groundwater Board report (27).
Irrigation source		Proportion of irrigation from ground- or surface-water sources in each state (28).
CHAPTER 6		
Climate hazard exposure		State-level estimates on the area exposed to eight climate-related hazards (droughts, floods, landslides, cyclones, forest fires, extreme rainfall, extreme temperature, sea-level rise) in Indian states, estimated following methods from Amarnath et al. (2017) but updated for more recent data (29).
CHAPTER 7		
District-level horticulture production		District-level data on horticulture production for districts in Andhra Pradesh and Telangana taken from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) database (30).
District-level data on fruit and vegetable demand and foreign trade; and road and rail distance between districts and states.		District-level data for the districts in Andhra Pradesh and Telangana from the same databases at the interstate trade model as stated previously in this table.

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CHAPTER 5

TRADING WATER: VIRTUAL WATER FLOWS THROUGH INTERSTATE CEREAL TRADE IN INDIA

SUMMARY OF CHAPTER

This chapter includes a research paper in which I estimated the interstate virtual water trade of cereals in India. The interstate trade of cereals was estimated using the InFoTrade model detailed in Chapter 4. This data was combined with state-wise data on cereal water footprints and irrigation source to estimate virtual water trade. The relationship between virtual water trade and status of groundwater depletion in Indian states was assessed. Finally, I estimated the theoretical water savings enabled through interstate cereal trade in India.

A full summary of this chapter is presented in the Abstract.

I have inserted the published version. Where supplementary files are referred to in the paper, these can be found in Appendix 4.

RESEARCH PAPER COVER SHEET

SECTION A – Student Details

Student ID Number	1407177	**Title**	Miss
First Name(s)	Francesca Bianca		
Surname/Family Name	Harris		
Thesis Title	An assessment of the relationships between food supply and the environment in India		
Primary Supervisor	Dr Rosemary Green		

If the Research Paper has previously been published, please complete Section B, if not please move to Section C.

SECTION B – Paper already published

Where was the work published?	Environmental Research Letters		
When was the work published?	1st December 2020		
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SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	Carole Dalin, my PhD advisor, proposed the idea of using a linear optimisation model to estimate interstate trade, having used this method to estimate sub-national trade flows in China. I collated the data and drafted the code for the model. This was later checked by my PhD advisor, Owen Nicholas. I consulted the co-authors through the analysis, all of whom provided suggestions on the direction of analysis. In particular, Soledad Cuevas provided detailed comments and suggestions on the steps to estimate trade. I produced a complete first draft of the paper for co-author review. All authors provided input on language which was incorporated into the final manuscript. I produced all figures, tables and supplementary material. I led the submission process, and with the support from co-authors when responding to reviewer comments.

SECTION E

Student Signature	Francesca Harris
Date	27th May 2021

Supervisor Signature	Rosemary Green
Date	9th June 2021

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Trading water: virtual water flows through interstate cereal trade in India

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Supplementary material for this article is available online

Abstract

Cereals are an important component of the Indian diet, providing 47% of the daily dietary energy intake. Dwindling groundwater reserves in India especially in major cereal-growing regions are an increasing challenge to national food supply. An improved understanding of interstate cereal trade can help to identify potential risks to national food security. Here, we quantify the trade between Indian states of five major cereals and the associated trade in virtual (or embedded) water. To do this, we modelled interstate trade of cereals using Indian government data on supply and demand; calculated virtual water use of domestic cereal production using state- and product-specific water footprints and state-level data on irrigation source; and incorporated virtual water used in the production of internationally-imported cereals using country-specific water footprints. We estimate that 40% (94 million tonnes) of total cereal food supply was traded between Indian states in 2011–12, corresponding to a trade of 54.0 km^3 of embedded blue water, and 99.4 km^3 of embedded green water. Of the cereals traded within India, 41% were produced in states with over-exploited groundwater reserves (defined according to the Central Ground Water Board) and a further 21% in states with critically depleting groundwater reserves. Our analysis indicates a high dependency of Indian cereal consumption on production in states with stressed groundwater reserves. Substantial changes in agricultural practices and land use may be required to secure future production, trade and availability of cereals in India. Diversifying production systems could increase the resilience of India's food system.

1. Introduction

Rising global population and economic growth are increasing pressure on global water resources [1]. An estimated four billion people experience severe water scarcity for at least one month of the year, where the water demand exceeds that available for use locally [2]. The agricultural sector dominates human water use and is particularly vulnerable to water scarcity [3, 4]. Currently, 20% of global irrigation is dependent on groundwater abstraction from depleting aquifers [5], and the greater frequency of extreme weather events is threatening agricultural productivity [6, 7]. Understanding the trade of food, and its embedded or virtual water, can illustrate linkages between food consumers and water resources, and identify when changes in the availability of water might affect the availability of food [8–11].

Indian agriculture plays a major role in national and global food security, and is a source of employment for over half of the Indian workforce [12]. Indian population growth is leading to increased demand for food and water [13]. Greater use of improved crop varieties, irrigation and fertilisers have contributed to substantial improvements in crop yields in India [14]. However, in the major food-producing states of Punjab, Haryana and Uttar Pradesh in the north, and Tamil Nadu and Karnataka in the south, groundwater resources are rapidly depleting [15]. Recent shifts to greater food production in the dry season to avoid unreliable rainfall in the wet season may further increase dependency on ground- and surface-water for agricultural irrigation [16]. Cereals are an important component of the Indian food system, comprising 45% of all agricultural production [17], and contributing to 47% of the total daily dietary energy intake. India is self-sufficient in cereals [18], importing only 0.01% of national cereal supply from other countries, and is a major exporter of rice and wheat globally [19].

This study aims to quantify the interstate and international trade of cereals in India, and the associated trade of embedded or virtual water. We extend previous estimates of virtual water trade in India that have either focused only on international trade [20, 21]; estimated the embedded water in food grains transported by railways [22] (20% of all food grain transport [23]); focused only on trade through the Indian Public Distribution System (PDS—a large-scale Government programme that procures and redistributes cereals at fair priced shops) that contributes to 35% of all cereal consumption [24]; or have not accounted for the PDS [25]. Our study explores the totality of the virtual water trade associated with cereals in India by developing a model to predict interstate cereal trade flows through both road and rail transport, and fully incorporating both the PDS and international trade. The primary objective of this study is to enhance understanding of the dependency of the Indian food system on water resources.

2. Methods

2.1. Estimating supply and demand of cereals in each state

There are currently no comprehensive data available on interstate cereal trade in India (hereafter, 'state' refers to State and Union Territories [$N = 35$]). We quantify the trade of cereals through the PDS and non-PDS cereals separately.

For each of the five major cereals consumed in India (wheat, rice, maize, millet and sorghum; 99% of total cereals available for human consumption [19]), state-level data were collated on production, foreign imports and exports, PDS procurement, stocks, non-food uses and amounts available for food consumption. The supply by states of each cereal includes local production and foreign import, plus net change in stock (i.e. cereals stored between production and retail), waste and non-food uses of cereals (feed, seed, processed and other). The demand by states for each cereal includes food consumption and foreign export. We estimated interstate cereal trade by modelling non-PDS cereal supply and demand balance, where excess supply from a state meets unmet demand in other states, and used data on PDS procurement and consumption to estimate PDS trade.

Analysis was focused on the years 2011–12 as this is the most recent time period for which all required data were available. Data were collated from various sources as follows (full details in supplemental table S3, which is available online at https://stacks.iop.org/ERL/15/125005/mmedia): state cereal production was derived from Government production statistics; the proportion of cereal supply wasted and allocated to non-food uses were taken from India-specific data from the Food and Agricultural Organisation (FAO) Food Balance Sheets [19]; and data on PDS procurement were used to estimate the amount of rice and wheat exported through the PDS [26]. The total volume of foreign imports and exports for India was estimated following methods from Kastner *et al*, whereby global data on bilateral trade flows is integrated with country-level production estimates to account for the origin of production and final destination of commodities rather than representing port stops [27]. There are no data available on production by states for international export or on the consumption of foreign cereals. Therefore, to link international trade with domestic trade we used data from the Agricultural & Processed Food Products Export Development Authority, Ministry of Commerce & Industry [28] that specifies port of entry and exit for commodities. Total volume amounts of foreign imports and exports estimated following methods of Kastner *et al* [27] were allocated proportionally to port states ($N = 13$) based on these port import and export quantities. Foreign imports were integrated into the port state's supply of cereals, and foreign exports were to the port state's demand along with food consumption. The quantity of cereals required for food consumption was estimated from the 68th Round of the Indian National Sample Survey (NSS) conducted in 2011–12 [24]. The NSS is a nationally representative household consumption and expenditure survey conducted by the Government of India, that does not include food eaten outside the home and therefore underestimates consumption. Hence, we calculated consumption using the availability of each cereal after removal of non-food uses and foreign export from the supply in each state, and estimated the consumption by dividing the total availability for food at national level by the proportional consumption for each state according to NSS.

The supply and demand accounts were used to identify states with excess cereals for interstate trade and states with unmet demand. For each cereal, states with supply greater than their own demand were designated as cereal exporters, while states with demand greater than their supply were designated as importers.

2.2. Quantifying domestic and foreign cereal trade in India

The direction and volume of non-PDS cereal trade flows were estimated through a linear programming model that minimised the overall cost of transportation [23, 29–31]. Previous analysis on intra-national trade flows suggests that models that minimise the cost of transport provide estimates are comparable to primary data [32]. The methods are briefly described below (see supplemental file for equations and a full list of data sources).

The cost of transportation between states was calculated based on the rail and road distance to each respective state capital, multiplied by the cost of transportation per km per tonne of cereals for each mode. Minimum road distance was estimated using map data from Google [33], and minimum rail distance for commodity transport was taken from the Indian Government Centre for Railway Information Systems online tool [34]. Using data from the Indian Government Planning Commission on the cost of transportation per km per tonne of cereals (as the food group) [35], we calculated the associated transportation cost matrix for each mode. The relationship between transportation cost and distance travelled is non-linear, as it is assumed longer routes will have reduced time and capacity costs relative to shorter distances. The transportation cost to and from the island states (Lakshadweep and Andaman and Nicobar Islands) includes the cost of shipment to their nearest mainland ports according to the shipping distance and cost per km per tonne for shipment [35], and the cost of rail or road transport between the state of their mainland port and other states. A combined cost of transportation matrix for cereals between Indian states was estimated using the proportion of cereals (as the food group) transported by road or rail in India [35], and subsequently used as the cost to be minimised in the linear programming model.

An optimisation model was constructed with the objective function to minimise transportation costs, while allocating the excess supply from states to those with unmet demand for each cereal. The constraints for the model were as follows:

- Supply of each commodity equals demand in each state.
- Trade flows are only positive.
- Foreign imports are added to the port states' total supply, while foreign exports are added to the port states' demand.
- Net export of the commodity is bounded by local production or foreign import (if any).

The model was run independently for each cereal, giving an output of total tonnes of each cereal traded annually between every combination of two states.

To validate the approach of minimising transportation costs to estimate non-PDS trade, we used a mixed effects linear regression model to assess the association of our calculated cost of transportation (Rupees kg^{-1}) for importing each cereal with the value of the corresponding cereal to the consumer in the importing state (Rupees kg^{-1} — using data from the NSS). The cost of transportation was weighted according to import volume from each exporting states, as calculated by the trade model.

We considered separately the trade of cereals through the government PDS programme that procures rice, wheat and other crops at a minimum support price and sells these at a reduced rate in fair price shops. The PDS does not distribute based on minimising the cost of transportation [36, 37], hence we did not use the optimisation model to estimate PDS trade. Data is available on the volume of rice and wheat procured by the central Indian government for the PDS [26]. We calculated the volume of PDS exports for each state based on the known contribution to the central pool after the removal of waste (according to national average proportions). We assumed that states import PDS cereals from this central pool proportionally to their estimated PDS consumption in the NSS [24]. For states with a decentralised PDS ($N = 13$) (i.e. they satisfy their own PDS demand, but still contribute to central pool), PDS consumption was calculated according to proportional PDS rice and wheat consumption compared to non-PDS rice and wheat consumption in the NSS. Total PDS production in India reflects the total procurement of PDS cereals and the estimated local PDS consumption in decentralised states.

We evaluated the association of common drivers of trade (e.g. distance, GDP) with interstate trade patterns for non-PDS and PDS cereals through a gravity model (see supplemental file section 1.4 for full details on the gravity model methods). We compared whether our model outputs on estimated trade flows were consistent with existing gravity models of interstate trade flows on the rail trade of agricultural commodities [38], and the trade of manufacturing goods [39].

Data matching and cleaning was carried out in MS Excel and R Studio (R Version 3.6.1). The linear programming model was run in R Studio using integer programming for solving transportation problems (available through the lpSolve package in R, see supplemental file section 1.2.2 for code) [40]. Interstate trade matrices for each cereal are available at Harris *et al* [41].

2.3. Quantifying virtual water trade

State-level blue and green water footprints (WFs) were used to calculate virtual water trade (see supplemental file section 1.5 for detailed equations). The green WF refers to the volume (m^3/tonne) of precipitation water that is consumed during crop production, either from evapotranspiration, transpiration, or incorporated into the final crop product [42]. The blue WF refers to the volume (m^3/tonne) of water withdrawn from ground- and surface-water sources and consumed during crop production, or incorporated into the final crop product [42]. The state-level WFs of domestic cereal production were taken from published data covering the years 2005–14 [16] that were estimated using an online WF assessment tool [43] and government production and irrigation statistics. These WF estimates are slightly lower than published data from earlier years (1996–2005) [42], due to improved yields and a small decrease in reference evapotranspiration. Full methods and comparison to other WFs can be found in Kayatz *et al* [43].

The WFs of foreign imports were weighted according to import volume from each country of origin. WF values of foreign cereals were only available from the years 1996–2005 [42], however foreign imports contribute very little (<0.01%) to the total supply so this will not substantially affect our virtual water trade estimates. Virtual water trade was calculated as the product of cereal export and associated cereal WF in the exporting state (in m^3/tonne). For port states exporting both domestic and foreign cereals, the WFs of cereal exports were weighted based on the amount of domestic and foreign cereals in the port state's supply.

We further explored the ground- and surface- virtual water trade of domestically produced cereals. State-level blue WFs were proportionally weighted according to state-level data on the area irrigated by ground- and surface-water [44, 45]. Ground- and surface-water trade was only estimated for domestically produced cereals as the required data were not available for foreign imports. We matched cereal exports to the groundwater status of the exporting state in 2011–12 as defined by the Central Ground Water Board [46] that categorised states as safe, semi-critical, critical and over-exploited according to ratio of groundwater use to groundwater availability [47]. To illustrate interstate trade patterns we constructed chord diagrams using the 'circlize package' in R that displays trade pairs in a circle format using chords that are proportionally sized to the volume of trade between trading pairs [48].

Finally, we calculated theoretical green, ground- and surface-water savings due to interstate cereal trade. A trade relationship is considered to lead to water savings when crops are exported from a relatively more water-productive state (i.e. where the crop has a lower WF) to a less water-productive state [29]. Trade flows in the opposite direction are considered to lead to negative water savings, i.e. water losses. In other words, water savings represent the difference between water that would be used to produce cereals for food consumption in a no-trade situation and the water currently used. The practical meaning of this needs to be carefully considered as the quantity of the crop imported by a state cannot always be produced locally. Water savings were calculated for each cereal and each trading pair of states. National water savings represent the sum of savings for all the interstate trade links.

2.4. Sensitivity analysis

We explored the sensitivity of our model and virtual water trade estimates to the input data. To illustrate the sensitivity to assumptions on cereal transport modes and costs, we estimated the trade patterns of non-PDS cereals that would occur if transport between states was conducted only by rail or only by road. We also carried out a sensitivity analysis to explore the assumption that the PDS does not trade cereals across states in a way that would minimise the cost of transportation. We used a linear programming model that minimised the cost of transportation that would be required to balance supply and demand of PDS rice and wheat across Indian states (as for non-PDS cereals). Finally, sensitivity analysis was carried out using annual average production, foreign trade quantities and allocation of cereals to non-food uses for the years 2010 to 2013. We compared these trade patterns and results with the 2011–12 model, in order to test the robustness of our conclusions to annual fluctuations in cereal supply.

3. Results

3.1. Overview of cereal production, consumption and foreign trade

We first present for the study period (2011–2012) an overview of cereal production, consumption, and foreign trade and the associated embedded water. The annual cereal production in India for 2011–12 was 249.9 million tonnes (Mt), of which 42% was rice, 41% wheat, 8% maize, 6% millet and 3% sorghum (table 1) [17]. The volume of embedded water in these cereals amounted to 292.3 km^3 of green water, and 145.3 km^3 of blue water. After accounting for the non-food uses of cereals (feed, seed, processing), waste, and foreign export, 201.2 Mt of cereals remained in India for human food consumption (81% of total production). The embedded water use of cereal consumption was estimated as 237.3 km^3 of green water

Table 1. Estimated production, consumption and foreign trade of cereals in India and the associated embedded water, for the period 2011–12. PDS: Public Distribution System.

Variable	Total volume (Mt)	Embedded green water (km^3)	Embedded blue water (km^3)
Total cereal production	249.9	292.3	145.3
Cereal production for the PDS	74.2	71.3	48.5
Total cereal allocated to food consumption	201.2	237.2	123.9
Cereal consumption through the PDS	71.4	68.6	46.7
Foreign import	<0.1	<0.1	<0.01
Foreign export	9.7	9.9	4.5

and 123.9 km^3 of blue water. Foreign imports made a very small contribution to total cereal supply and nearly 10 Mt of cereals (with an associated 14.4 km^3 of embedded water) were exported.

3.2. Interstate trade of cereals and the associated virtual water trade

We estimated that 93.8 Mt of domestic- and foreign-produced cereals were traded for food consumption between Indian states during 2011–12 (40% of the total food supply of cereals in India). The main cereal traded was rice (45.5 Mt, 48% of cereal trade), followed by wheat (40.0 Mt, 43% of cereal trade). The total water embedded in interstate cereal trade was equal to 153.4 km^3 (figure 1), of which 35% (54.0 km^3) was blue water, and 65% (99.4 km^3) was green water (see supplemental files, figure S3 for trade patterns in Mt and virtual water trade flows separated out by PDS and non-PDS trade, and type of water).

There were regional and state-level differences in the contribution to interstate imports and exports. The Northern region accounted for 61% of all cereal interstate exports (56.9 Mt), equivalent to 83.8 km^3 of embedded water. The Western region exported the least amount of cereals: 1.0 Mt (1%), equivalent to 1.7 km^3 of water. There were 5 states that imported but did not export cereals to other states: Chandigarh, Delhi, Lakshadweep, Manipur, and Mizoram. States that imported the largest amount of water through cereal trade were Maharashtra (28.4 km^3; 11.5 Mt), and Uttar Pradesh (24.8 km^3; 7.1 Mt).

Trade patterns varied between PDS and non-PDS cereals. The majority (58%; 58.0 Mt) of interstate cereal trade occurred through the PDS. The total volume of embedded water traded through PDS rice and wheat amounted to 54.3 km^3 of green water and 36.7 km^3 of blue water. As the main PDS contributors, the states exporting the most water through the PDS were Punjab (20.9 km^3), Andhra Pradesh (12.6 km^3), and Madhya Pradesh (9.9 km^3).

In addition, 35.8 Mt of non-PDS cereals were traded between states, corresponding to 45.1 km^3 of green water and 17.3 km^3 of blue water. The Northern region accounted for 78% of these blue water exports and 67% of the green water exports.

3.3. Virtual water trade of domestically produced cereals according to groundwater status in the exporting state

We explored the patterns of trade and the embedded ground- and surface-water of domestically produced cereals according to status of groundwater depletion in the exporting state. Nearly all (99.9%) of the cereals traded between Indian states were produced domestically. The embedded water in interstate trade of domestically produced cereals was equal to 32.3 km^3 of groundwater and 21.7 km^3 of surface water (table 2, figure 2, see supplemental file figure S4 for results separated out by PDS/non-PDS trade).

States defined as over-exploited in their groundwater reserves according to the Central Groundwater Water Board of the Government of India [46] ($N = 4$) produced and exported 41% (38.6 Mt) of the domestically produced cereals in interstate trade (table 2), equivalent to 39% (12.7 km^3) of the total groundwater embedded in interstate cereal trade. A further 21% (19.6 Mt) of domestically produced cereals were exported from states with semi-critical to critical groundwater status ($N = 6$), equivalent to 10.4 km^3 (32%) of groundwater. States with over-exploited groundwater resources imported 4% of cereals (3.8 Mt), equivalent to 1.4 km^3 of groundwater.

States with safe groundwater reserves ($N = 25$) exported 35.5 Mt (38%) of domestically produced cereals, equivalent to 9.2 km^3 (28%) of the embedded groundwater traded between states, and imported 63.8 Mt (68%) of cereals, equivalent to 22.7 km^3 (70%) of groundwater. These states were the main contributors to virtual surface water exports through domestically produced cereals (12.7 km^3; 59%).

PDS trade was more dependent on over-exploited groundwater than non-PDS cereal trade; 47% of PDS cereal exports (27.2 Mt) came from states with over-exploited groundwater resources compared to 32% of non-PDS cereal exports (11.4 Mt). States with groundwater resources defined as safe imported 63% of PDS cereals (36.6 Mt) and 76% of non-PDS cereals (27.2 Mt).

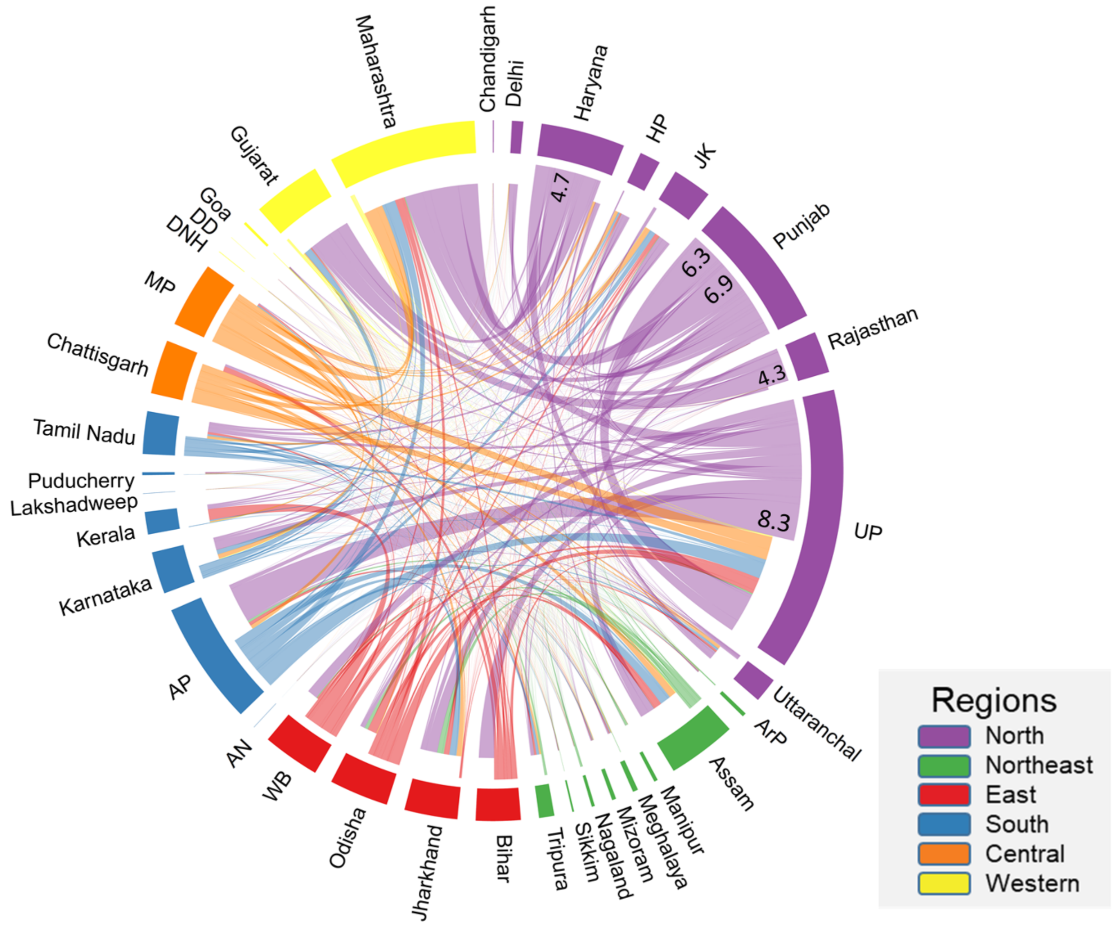

Figure 1. Total virtual water embedded in interstate trade of cereals in India during 2011–12, in cubic kilometres per year. Chords link exporting and importing states, and are coloured according to region of the exporting state (see supplemental file figure S1 for map of Indian states and regions). Chords are indented for importing state. Some states are abbreviated for figure clarity: 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.

3.4. Water savings induced through trade

Trade-induced water savings in India during 2011–12 amounted to 28.8 km^3 of green water and 4.5 km^3 of surface water. However, there was a theoretical loss of groundwater resources due to trade of 2.0 km^3. For 27 states, cereal trade was groundwater-inefficient, i.e. these states had a lower groundwater WF per tonne than the states from which they imported (see supplemental figure S5 for water saving by state).

3.5. Validation of the model and sensitivity analysis results

3.5.1. Validation of the cost of transportation data

We found strong evidence that the cost of transportation as estimated in this study was associated with the unit value paid by the consumer, validating our use of a minimal cost optimisation model for this analysis (see supplemental file figure S6 for scatter plot). For every 1 Rupee kg^{-1} increase in the cost of transportation, the price of cereal for the consumer increased by 4.92 Rupees kg^{-1} (95% CI 1.58 to 8.06, $P < 0.01$, $N = 114$).

3.5.2. Comparison of the trade model to existing literature

We used a gravity model to compare the modelled cereal trade flows with existing data on rail trade flows of agricultural products from 2005–14 [38], and the trade of manufacturing goods from 2015–16 [39]. The gravity model analysis of non-PDS cereals demonstrated that non-PDS cereal trade was primarily driven by distance; consistent with existing evidence on international trade flows [49] and interstate trade flows of manufacturing goods in India [39]. The gravity model including PDS and non-PDS cereal trade identified that distance was not a barrier to trade; consistent with the fact that PDS does not distribute cereals based on minimising the cost of transportation, and in line with existing evidence on agricultural rail trade in India that included PDS cereals [38]. The good alignment of our findings from gravity models with the existing evidence base supports the validity of our approach to model interstate cereal trade in India and also suggests that our results are reflective of interstate trade patterns from a broader

Table 2. Trade of domestically produced cereals and the embedded surface water and groundwater, according to groundwater status in the exporting or importing state. Groundwater status defined according to the Central Groundwater Board estimates from 2011. PDS: Public Distribution System. Row percentages may not total 100% due to rounding.

Variable	Status of groundwater in states		
	Safe ($N = 25$)	Semi-critical to critical ($N = 6$)	Over-exploited ($N = 4$)
Total state exports of domestically produced cereals (Mt, % of row total)	35.5 (38%)	19.6 (21%)	38.6 (41%)
PDS exports (Mt, % of row total)	24.4 (42%)	6.4 (11%)	27.2 (47%)
Non-PDS cereal exports (Mt, % of row total)	11.2 (31%)	13.2 (37%)	11.4 (32%)
Embedded groundwater in state exports of domestically produced cereals (km^3, % of row total)	9.2 (28%)	10.4 (32%)	12.7 (39%)
Embedded surface water in state exports of domestically produced cereals (km^3, % of row total)	12.7 (59%)	3.1 (14%)	5.9 (27%)
Total state imports of domestically produced cereals (Mt, % of row total)	63.8 (68%)	26.2 (28%)	3.8 (4%)
PDS imports (Mt, % of row total)	36.6 (63%)	19.5 (34%)	2.0 (3%)
Non-PDS cereal imports (Mt, % of row total)	27.2 (76%)	6.7 (19%)	1.8 (5%)
Embedded groundwater in state imports of domestically produced cereals (km^3, % of row total)	22.7 (70%)	8.2 (25%)	1.4 (4%)
Embedded surface water in state imports of domestically produced cereals (km^3, % of row total)	15.1 (70%)	5.9 (27%)	0.7 (3%)

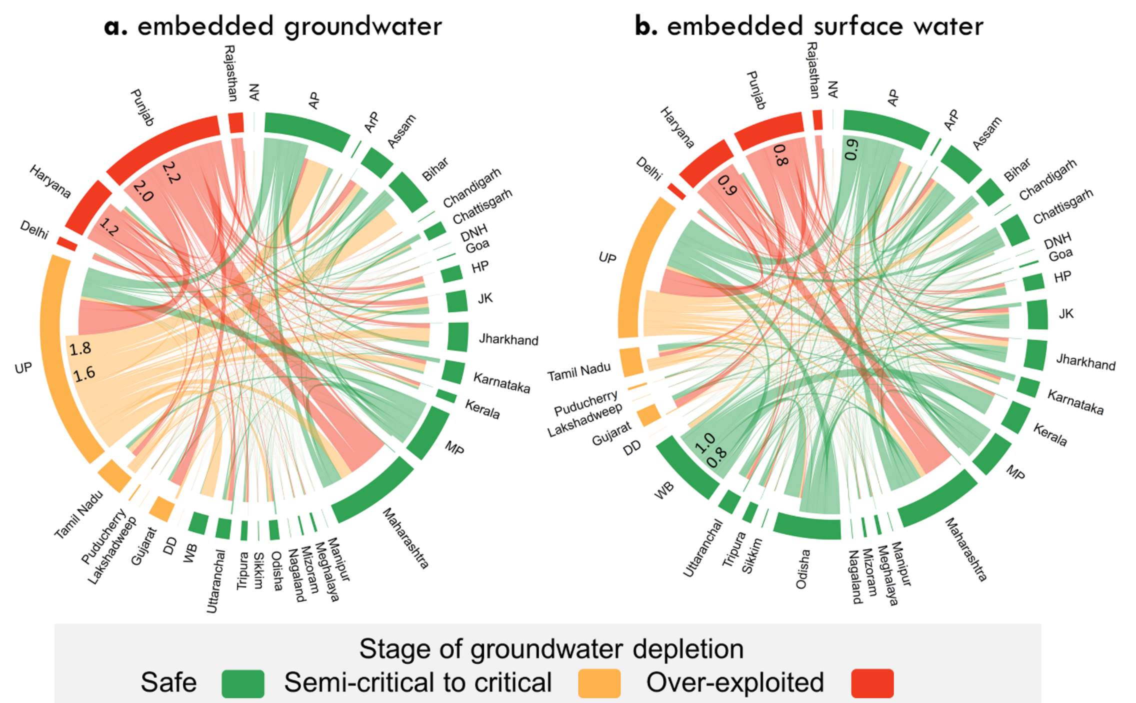

Figure 2. The ground- and surface-water embedded in the interstate trade of cereals in India during 2011–12, in cubic kilometres per year. Chord colour corresponds to the stage of groundwater depletion in the exporting state in 2011, as defined by the Central Groundwater Board of India [46]. Chords are indented for importing state. Some states are abbreviated for figure clarity. AN: Andaman and Nicobar, AP: Andhra Pradesh, ArP: Arunachal Pradesh, DNH: Dadra and Nagar Haveli, HP: Himachal Pradesh, JK: Jammu and Kashmir, MP: Madhya Pradesh, DD: Daman and Diu, UP: Uttar Pradesh, WB: West Bengal.

time frame (see supplemental file, section 2.4 for full results).

3.5.3. Sensitivity analysis using varying cost of transportation
We explored the sensitivity of the estimated non-PDS cereal trade flows to the cost of transportation data by comparing our modelled results to cereal trade conducted only by rail or by road. Trade patterns were similar under each mode, with the Northern region again dominating cereal exports (supplemental file figure S7). Compared to the combined transport mode model, the volumes of cereal traded varied for 114 (11%) trading pairs under road transport and 131 (19%) trading pairs under rail transport. This equates to 4.0 Mt (11%) and 14.9 Mt (41%) of cereals traded differently under road transport and rail transport respectively, identifying that our modelled trade flows were sensitive to assumptions on mode of transport.

3.5.4. Sensitivity analysis of cereal trade through the Public Distribution System
We modelled PDS trade based on minimising the cost of transportation to compare with our main results. We found that interstate trade of PDS cereals was reduced by 9% to 53 Mt, as more cereals remained in the state where they were produced to minimise the cost of transport (see supplemental file figure S8 and table S5). Additionally, there was a slight shift in the proportion of cereals exported from states according to groundwater status: 52% (27.6 Mt) of cereals were exported from states defined as over-exploited in their groundwater reserves, compared to 47% (27.2 Mt) in the central pool model.

3.5.5. Sensitivity analysis using supply data from a different time frame
To test the sensitivity of our findings to the input data on cereal supply (production, international trade and stock), we quantified the virtual water trade network using yearly average production, stock and international trade data over the period 2010–13. Trade patterns obtained from the 2010–13 data were similar to the 2011–12 estimates, such that the Northern region dominated exports and the Western region imported the most (see supplemental file, section 2.3 figures S9 and S10 for chord diagram using 2010–13 data, and table S6 for comparison of key variables using 2010–13 and 2011–12 data). The largest differences in regional trade patterns of non-PDS cereals were imports in the Northeast region, and exports from the Western region. Imports in the Northeast were greater using 2010–13 average at 2.8 Mt compared to 0.6 Mt in 2011–12, and the Western exports were greater using 2010–13 average at 1.6 Mt compared to 0.5 Mt in 2011–12.

The total volume of virtual water traded between Indian states through cereals was estimated to be 152 km^3 using the 2010–13 average, which is 1.0% lower than our estimate from 2011–12. The estimated volumes of ground-and surface-water embedded in the trade of domestically produced cereals were 32.5 km^3 and 22.1 km^3 respectively, which are marginally larger (by 0.8% and 1.8%, respectively) than the values calculated for 2011–12. As trade patterns varied slightly using the 2010–2013 average, so did the theoretical water savings induced by trade at national level. However, water savings followed the same pattern, such that green water savings were the greatest (35.4 km^3 $year^{-1}$), followed by surface water savings (1.92 km^3 $year^{-1}$), and there was a loss of groundwater resources (−3.18 km^3 $year^{-1}$).

4. Discussion

4.1. Summary
We built a supply and demand balance model that minimised transportation cost and combined with existing data to explore interstate trade of cereals for human food consumption and the associated virtual water flows in India. We estimate that 93.8 Mt of domestic- and foreign-produced cereals were traded for food consumption between states in 2011–12 with an associated total virtual water flow of 153.4 km^3. States with over-exploited groundwater (as defined by the Central Groundwater Water Board of the Government of India) produced 41% of the interstate exports of cereals, and a further 21% was produced and exported from states with semi-critical or critical groundwater reserves. Through the interstate trade of cereals, 31 out of 35 Indian states rely at least in part on cereals produced in states with over-exploited groundwater, equating to 917 million people, or 76% of the Indian population. Our analysis of trade-induced water savings demonstrates that Indian interstate trade encourages the production of crops that use less rainwater and surface water in their production, but leads to slightly more groundwater use per year: 2.0 km^3, equivalent to 2% of the total groundwater used for cereal production. Changes in production and interstate trade patterns, in irrigation methods and in the type of cereal consumed appear necessary to improve the resilience of India's food system.

4.2. Research in context
There are many studies that explore the impact of food consumption on water use at the national level [50]. However, water requirements vary between crops, and are affected by local agricultural and climatic factors; hence in a country the size of India, estimating the embedded water in food consumption and assessing the associated resilience of the food supply, requires subnational information linking locations of consumption and production. The blue water use of cereal consumption in 2011–12 varies by more than 1000% for some states if local WFs are used

rather than trade-weighted WFs (supplemental file, table S7), demonstrating the value of understanding patterns of within-country trade when assessing the environmental impacts of food systems [9].

Our findings have particular relevance for Indian water management policies that aim to address the unequal distribution of water resources. The National River Interlinking project, a major infrastructure scheme supported by the Indian Government, aims to transfer water from water-abundant to water-scarce regions. It has been estimated that once this project is completed a total of 175 km^3 $year^{-1}$ will be transferred from the Eastern region where groundwater reserves are not stressed, to the major food producing regions in the North [51]. Consistent with previous assessments, we show that virtual water currently moves in the opposite direction through trade of food crops, from north to east. Our estimate for the total water transferred through cereal trade is slightly less than the estimated water flow through canals and rivers in the interlinking project at 153 km^3 $year^{-1}$. This is higher than previous estimates, as we have accounted for both PDS and non-PDS cereal trade, and incorporated internationally imported cereals. Our findings reiterate the substantial potential for balancing water resources through the trade of crops in India, either in addition to or in place of large-scale infrastructure projects.

The patterns of interstate cereal trade in India emphasise the large dependency of agriculture on groundwater irrigation in groundwater-scarce states. Similar relationships have been found for intra-national trade in the United States of America [52]. Water policy is currently set at state level in India [53]. Our analysis suggests that a national-level perspective on water resource use is needed to understand supply risks and opportunities for effective integrated water resource management. Electricity subsidies for agriculture provided by state governments have encouraged farmers to extract groundwater at increasing depths [54, 55]. We found that the interstate trade of cereals is associated with slightly more groundwater use than there would be without such trade. It is possible that interstate cereal trade encourages continued production of cereals irrigated with groundwater for export. This may discourage agricultural improvements in importing states; Eastern states which are safe in their groundwater reserves and net importers, also have the highest yield gaps and therefore the greatest unmet potential to increase production [56, 57]. Adapting the agricultural subsidy system, for example by changing tariffs on electricity in the Eastern region [54], could help diversify cereal production locations in India, while interstate trade can be used to fulfil demand. Furthermore, diversifying the type of cereal produced could also reduce water use. Agricultural policies from the Green Revolution in India encouraged production of high-yielding rice and wheat and reduced emphasis on traditional cereal crops such as sorghum and millet [58]. Compared to rice and wheat these traditional cereal crops require less irrigation per tonne of production, are more drought resistant, and have greater nutritional quality. Therefore planting sorghum and millet in water scarce regions could reduce the total water used in Indian agriculture, improve resilience against future water shortages and lead to nutritional benefits [59, 60]. Other states could substitute some of the supply gaps in rice and wheat that can subsequently be traded to satisfy demand. Water availability is only one determinant of production diversity in India, and other factors including agro-ecological suitability, adaptability of production systems and infrastructure capacity, and the willingness of consumers to change consumption patterns of cereals should also be considered.

4.3. Limitations

Our study aimed to quantify interstate cereal trade in India and the associated virtual water trade. As with all modelled analyses, the results should be taken as representative of the likely reality. An important assumption of the trade model is that states will only export cereals if they have met their own consumption needs and, conversely, states will only import cereals if they have insufficient supply. This is a common assumption in supply and demand balance models, and has been used in previous sub-national trade analyses [32]. However, it has likely underestimated interstate trade. Additionally, we assumed that foreign products would be consumed by the port state before exporting to other states as international trade would be organised to limit the distance to markets in India, but this may not always be the case. Furthermore, we incorporated foreign exports as part of the port state's demand, hence this must be imported from other states if it cannot be met by the port state's supply. This would have accounted for some international trade occurring via ports in other states, but we may have underestimated the foreign export from certain states that have specialised production of higher quality cereals for export. Finally, the objective of the model was to minimise the cost of transportation, and because of the absence of data, transportation costs were necessarily estimated based on distance between state capitals as sites of the central cereal trade markets. While our model outputs suggested that adjacent states were more likely to trade than more distant states (supplemental file table S4), which is highly plausible, our approach will undoubtedly have affected estimates for transportation cost, particularly in larger states. Additionally, our transportation costs were estimated by the proportion of road and rail transport at national level, but this may vary for some states pairs. Our sensitivity analysis using just road or just rail transport indicated this assumption could affect trade flow estimates. Furthermore, the transportation costs were not disaggregated by cereal type, as data were only available for the cereal food group. Although transport logistics, such as storage, are likely to be similar across the cereal types, transportation costs or modes may vary due to differences in infrastructural capacity in the producing regions [61]. Despite these limitations, our cereal transportation cost estimates were found to be correlated to a higher unit value paid by consumers for the cereals. The large effect of transportation costs on unit value (4.92 Rupees kg^{-1} increase in price for 1 Rupee kg^{-1} in transportation cost), suggests the existence of additional costs along the supply chain, such as storage, intermediation or marketing costs. Additionally, cereal unit value differentials across Indian states are driven by difference in quality, as well transport costs [62]. It was not possible to disaggregate cereal trade by quality due to lack of data.

Using data on central procurement of cereals and estimates on PDS consumption from NSS data we proportionally allocated rice and wheat based on states' demand and supply. In our model, states with an established decentralised system first satisfied their own PDS demand before exporting excess supply. It is possible that if all states do the same to minimise transportation costs the amount of interstate trade would decrease. Our sensitivity analysis exploring PDS trade suggests that minimising transportation costs would only reduce PDS trade by 9%, and mainly reduce exports from states with safe groundwater reserves. Therefore, while the assumption that PDS cereals are distributed from a central pool may overestimate trade pairs, it does not affect our conclusion that PDS trade is heavily dependent on exports from states with unsustainable groundwater use.

There are some limitations to the data. Our analysis has focused around a short time frame of 2011–12 as this was the most recent year for which all required data were available. While some factors that drive trade are relatively fixed including distance or agricultural land area for each state, other factors including rainfall patterns, cereals price and demand will vary over time. The quantity of cereals exported from some regions varied using 2010–13 yearly average supply estimates, which was possibly related to the droughts in 2010 that would have disrupted agricultural production in rainfall dependant states [63]. There were no major droughts or other extreme weather events in 2011–12 in India, hence this time period may be more reflective of normal trade patterns [13, 16, 63]. However, despite small differences in trade flows, the major trade pattern did not differ substantially between the two time periods and virtual water trade flows were comparable, supporting the robustness of our findings (supplemental file section 2.7, table S6). Nevertheless, the current and future status of Indian agriculture and water availability may be different to our study timeframe. Our estimated cereal consumption levels may not reflect recent years due to population growth and changes in cereal consumption patterns, but there are no recent data on cereal consumption at state-level that would allow us to explore this further. There have been no large changes to groundwater status in Indian states since the time period studied [64], but increased frequency of extreme weather events and changing precipitation patterns are altering agricultural practices [65, 66], which could affect water use. Continued monitoring of virtual water use and trade in India is warranted.

Our estimated total mass of cereals available for consumption at national level (Mt) was 9% and 29% higher than the equivalent values FAO's Food Balance Sheets [19] and NSS [24], respectively (supplemental file table S1). Differences were lower for rice and wheat compared to other cereals. These discrepancies may be due to inaccurate estimates of the waste and non-food uses of cereals, for example it is possible that we underestimated leakage (waste) from the PDS, which may be up to 40% in some areas [67], hence we may have overestimated the consumption of PDS cereals. Neither NSS nor FAO's Food Balance Sheets accurately assess total dietary consumption so discrepancies with the consumption values calculated in this study are expected. NSS underestimates food eaten outside the home and the consumption of processed foods, therefore it is possible that our estimates for state-level consumption may not accurately reflect the pattern of cereal consumption. However, the proportion of meals eaten outside the home does not vary appreciably across income levels or states [68], hence the consumption values estimated in our state are still reliable.

Finally, the objective of this study was to quantify the virtual water trade of cereals associated with human food consumption to illustrate relationships between food security and water resources, but cereals are only one (albeit the largest) food group. The virtual water trade of other crops, such as fruits, vegetables, and pulses, may be different. Additionally, cereals are also traded for feed for animal-sourced food, which was not included in our trade estimates. This will have underestimated the cereal trade, particularly for maize as 37% of production is used for feed in India according to India-specific data from FAO Food Balance Sheets [19]. We do not explore the drivers of virtual water trade, such as arable land availability [69–71], or assess how food trade is associated with other environmental issues that could affect future food production, such as climate change. However, our analysis provides novel data on trade patterns in India that can be used in future research to develop policy relevant scenarios to mitigate future food insecurity risks.

4.4. Policy implication and future directions

There is substantial interstate trade of cereals in India, but the dominance of rice and wheat as traded crops, and the Northern states as exporting region, potentially increases the vulnerability of India's food system to changing water availability. Increasing the diversity of crop production could mitigate this risk and simultaneously enhance the diversity of food consumption, which is important for nutritional security. The Indian Central Goods and Service Tax came into effect during 2017, and seeks to streamline the trade of goods and services between states by reducing processing and travel time [72]. This new legislation provides a more accessible market for producers with associated economic benefits, and offers an opportunity to improve the sustainability of the Indian food system through diversification of food supply for consumers [73, 74]. However, it also increases the urgency for interventions to reduce groundwater use and limit food production in over-exploited areas to maintain water security. Recent developments in India such as the Food Smart City initiative could improve the availability of data on food trade and enable states to track risks to their food supply chain [75].

In the context of sustainability research, our study demonstrates the importance of considering trade when quantifying the environmental resource use of food systems. By collating available data on production, consumption and transport, we have explored both the international and sub-national virtual water trade of cereals in India. Our findings are novel for India, where interstate trade is not well understood, and we provide a modelling approach that can be replicated in other settings.

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Conflict of interest

The authors declare no competing interests.

Author Correspondence and Contributions Statement

The authors confirm contributions to the paper as follows: study conception and design: FH, CD, SC, RG, EJMJ, PFDS, BS, BK; analysis and interpretation of results: FH, CD, SC, RG, EJMJ, ON, ADD, LNR; draft manuscript preparation: FH, CD, SC, LNR, TA, EJMJ, PFDS, BK, ON, BS, ADD, RG. Please contact FH for correspondence and requests for materials.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.17037/DATA.00001870.

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CHAPTER 6

INDIA'S FOOD SYSTEM AND CLIMATE HAZARDS: ASSESSING THE RESILIENCE OF THE FOOD SUPPLY

SUMMARY OF CHAPTER

This chapter presents a research paper that quantifies the climate hazard risks posed to Indian food supply. Using the InFoTrade model described in Chapter 4, I estimated the source of food supply (locally produced or imported from other states) of 30 food items for each Indian state. This information on source of food supply was combined with state-wise data on the presence of eight climate hazard and state-wise vulnerability to estimate the climate hazard risk. The risk values were compared across states, climate hazard type, and source of food supply. Finally, the climate hazard risks in Indian interstate food trade were investigated.

A full summary of this chapter is presented in the Abstract.

The paper has been submitted for peer-review. I have included the text and figures of the submitted version but formatted to align with the thesis format. Where supplementary files are referred to in the paper, these can be found in Appendix 5.

RESEARCH PAPER COVER SHEET

SECTION A – Student Details

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First Name(s)	Francesca Bianca		
Surname/Family Name	Harris		
Thesis Title	An assessment of the relationships between food supply and the environment in India		
Primary Supervisor	Dr Rosemary Green		

SECTION C – Prepared for publication, but not yet published

Where is the work intended to be published?	Global Food Security
Please list the paper's authors in the intended authorship order:	Francesca Harris, Giriraj Amarnath, Edward Joy, Alan Dangour, Rosemary Green
Stage of publication	**Submitted**

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	Through conversations with my supervisors we developed the idea for the paper. I sought the data, and contacted Giriraj Amarnath who had published a study on climate-hazards in India. I discussed the idea for the paper with Giriraj and he shared the climate-hazard data for the study. I carried out all the analysis in the paper and consulted with my supervisors along the way. I produced the first draft for comments from the authors, who provided feedback on the analysis and text. I made all figures in the final manuscript.

SECTION E

Student Signature	Francesca Harris
Date	27th May 2021

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Date	9th June 2021

Abstract

Climate 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. Data on presence of eight climate hazards (droughts, forest fires, floods, extreme rainfall, landslides, cyclones, extreme temperatures, sea level rise) were taken from satellite imagery. 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. We found that climate hazard risks to food supply vary across states and 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 from all eight climate hazards via food imports. For 14 states, the climate hazard risk to imported food supply is greater than the climate hazard risk to 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 through both impacts on local production and interstate trade. For state and national governments, these climate hazard risks identify potential priorities for enhancing food system resilience to mitigate impacts on local and national food security.

6.1 Introduction

Agricultural production is vulnerable to the impacts of natural hazards due to its dependence on the climate and weather. Over a quarter of the impact caused by disasters in low- and lower-middle-income countries (LMICs) is to the agricultural sector (1). Climate-related hazards, including floods, droughts, cyclones and temperature extremes, threaten each dimension of food and nutrition security (2, 3). Climate hazards can reduce food availability by damaging crop or livestock production. Climate hazards can affect food access and affordability by reducing incomes in agriculture-dependent households, and by increasing the volatility of food prices (4, 5). Recent changes in climate have increased the exposure of agriculture to climate hazards (6), hence there is an urgent 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 could help prioritise policy options to mitigate impacts on food security.

Due to its tropical location and large coastline, India experiences a high frequency and intensity of climate-related hazards (7, 8). An estimated 82% of the Indian population live in areas that are exposed to at least one hazard (7), 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 (9), whereas the North Western region is more prone to droughts and extreme temperatures (10). 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 (11). Information on where each state sources food is therefore critical to characterize climate risks to food security and to inform adaption strategies.

Studies have previously identified the exposure of Indian agricultural production to climate hazards (12) and the associated risk in agriculture (13), however to date the relationships between these climate hazards and Indian food supply have not been quantified. We combined state-level data on climate hazards, food production and interstate food trade to quantify the state-wise risk to the food supply of 30 major food items. We define food supply risk as the potential of climate hazards to cause adverse effects on food supply, 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) (14, 15). The findings of this study may be used to inform disaster preparedness and promote appropriate climate adaptation strategies to safeguard food security at the state and national levels in India.

6.2 Methods

6.2.1 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 source of food supply of each food item (N = 30) in each state, we followed 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. The model equations and details of input data sources are provided in Supplementary File. Briefly, for each state and food item, the total volume (tonnes/year) of food available for human consumption was estimated from production, foreign import, stock change and food allocated to non-food uses. The total demand (tonnes/year) was the volume of foreign exports and the relative food consumption demand as estimated in the National Sample Survey (NSS); a household consumption and expenditure survey (scaled to state-level based on survey weights) (16). A supply and demand balance calculation was used to estimate the volume of 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 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 domestic production only, as we were interested in the risks associated with climate hazards in India. Therefore, we excluded the climate risk associated with food supply from foreign imports and the Indian food production that was exported internationally. Following steps of Harris et al. (2020), we validated the trade flows by assessing the association with the total cost of transport for importing the food item in each state with the economic value of the product in each state (as estimated by NSS (16)).

We estimated the production location of food supply for 30 food items in each state, covering the food groups of cereals, pulses, fruits and vegetables, oils and sugar; equivalent to 52% of household food consumption (mean, kg/year) (16). 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. The major features of crop production, trade and consumption patterns are likely to remain quite consistent over time since they are driven by factors such as the location of major conurbations and agricultural land area.

6.2.2 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 (15) and as in previous studies of climate hazard risk (14, 17, 18). Risk was calculated for both locally produced food supply (using local hazard, vulnerability and exposure scores), and risk to imported food supply (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 (19), 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 were used to map the severity and extent of each hazard across India since 2000, following methods of Amarnath et al., 2017 (12). Details of the data sources are given in Supplementary Table 1. The island states of Lakshadweep and the Andaman & Nicobar Islands were excluded from all analysis due to the lack of necessary data. Data was aggregated to state using the percentage of geographical area with the presence of each hazard.

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 (20). 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 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.

6.3 Results

6.3.1 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 6.1), 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 illustrating state-wise production of food groups for food supply and the patterns of trade can be found in the Supplementary Files (Figure S1-2).

Table 6.1 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

6.3.2 Overview of climate hazards

The presence of climate hazard varies across states (Figure 6.1). Droughts are the most prominent hazard, present in all states with a mean (M) 44.1% (standard deviation (SD) 21.1%) of land area. 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%).

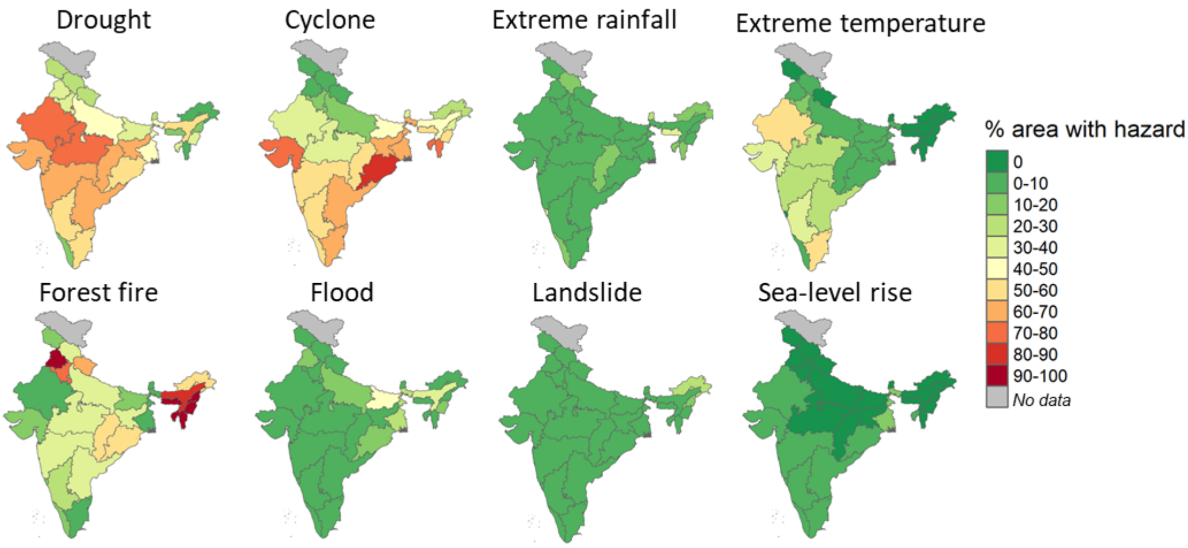

Figure 6.1 Percentage land area of Indian states with the presence of each climate hazard

6.3.3 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 Figure 6.2 (see Supplementary File Figure 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 can be found in the Supplementary Files (Figure S5-6).

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) (Figure 6.2).

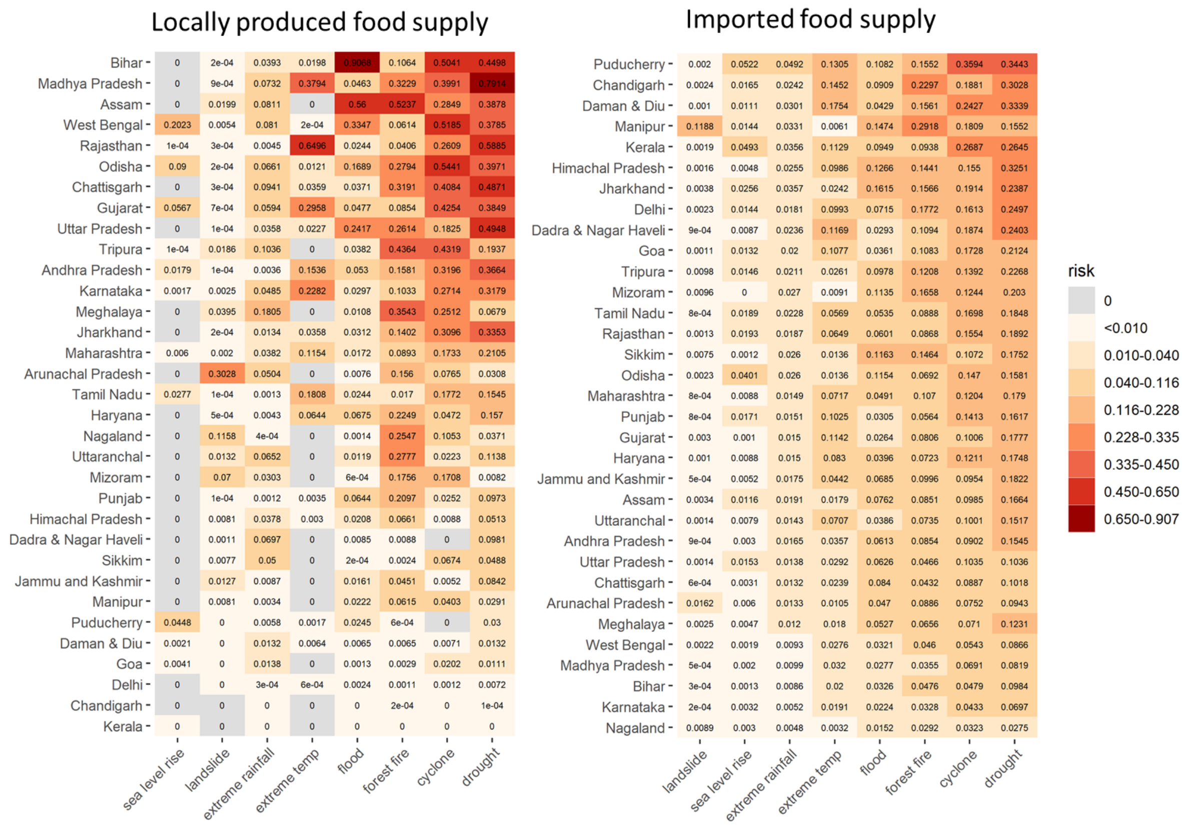

Figure 6.2 State-wise climate hazard risk to per capita food supply that is produced locally in the state and food supply that is imported from other Indian states (N=33). Heatmap colour coded according to natural jenks, using the BAMMtools package in R. States are in descending order according to total risks, and hazards are ordered left to right for increasing aggregated risk across states.

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 (Figure 6.2). 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) (Figure 6.2).

6.3.4 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 Figure 6.3, 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.

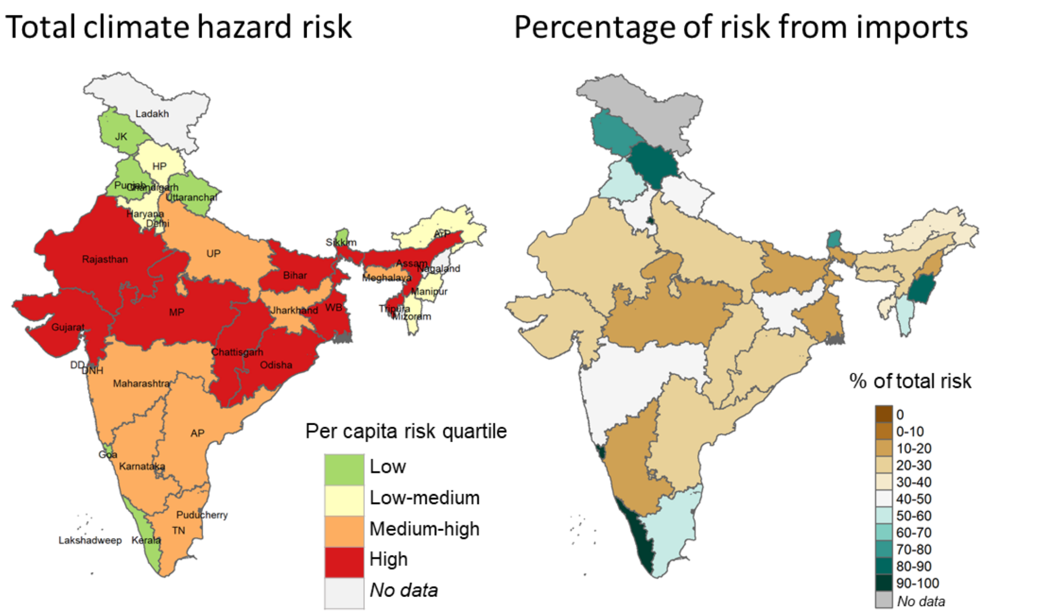

Figure 6.3 Combined climate hazard risk to per capita food supply across Indian states, coloured according to risk quartile (low to high) and the percentage of total risk attributable to imports from other states. HP: Himachal Pradesh, JK: Jammu and Kashmir, UP: Uttar Pradesh, ArP: Arunachal Pradesh, WB: West Bengal, AN: Andaman and Nicobar, AP: Andhra Pradesh, MP: Madhya Pradesh, DNH: Dadra and Nagar Haveli, DD: Daman and Diu.

6.3.5 Climate hazard risk in state-level food exports

The combined climate-hazard risk in interstate trade of per capita food supply is shown in Figure 6.4 (see Figure S7 for risk values across each state and hazard for food supply exports). Five states contribute to 53% 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).

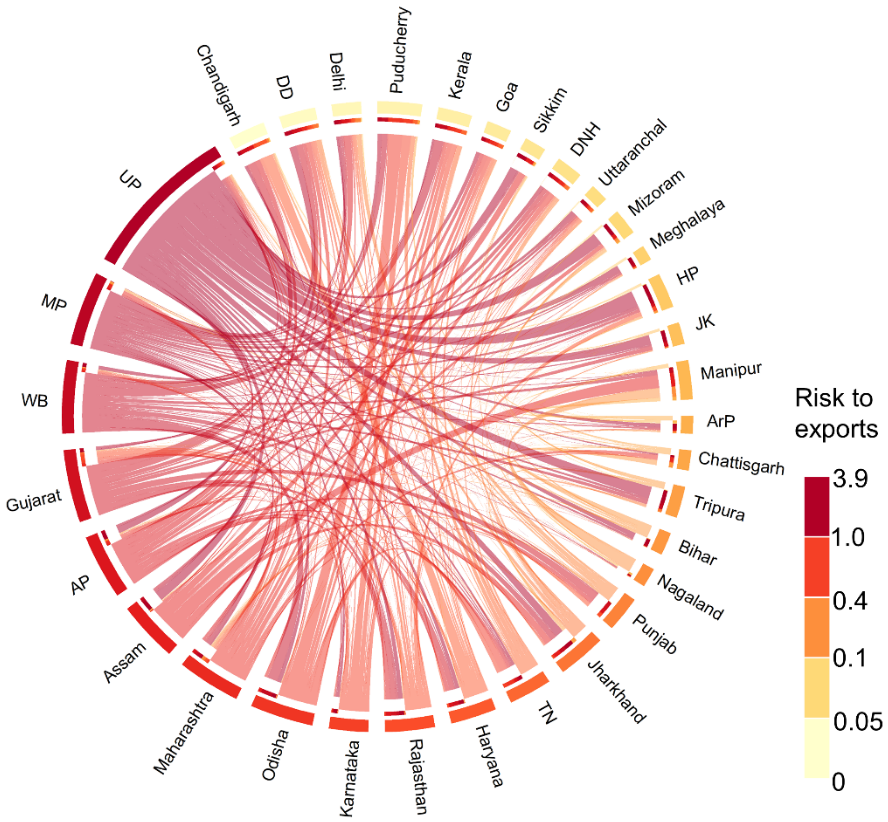

Figure 6.4 Combined climate hazard risk associated with interstate trade of per capita food supply. Chords are proportional to risk to exports and ordered anti-clockwise (starting from UP), and coloured according to order of risk to exports. Chords are indented at the importing state. HP: Himachal Pradesh, 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 (21).

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

6.4.1 Research in context

There have been several assessments of the impacts of multiple climate extremes and hazards on agricultural productivity in the global context (22, 23) and in India (13, 24, 25). Previous research has also explored the relationship between climate-related hazards or extremes and food security (26, 27). 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 Figure 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 (28). 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. 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 food supply chains from these key exporting states could affect national food security by reducing food prices, and have cascading impacts on non-agriculture sectors and ultimately state or national economies (29, 30) 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.

6.4.2 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). We did not include food that is traded through the Public Distribution System (PDS), which manages food surplus and trades crops across Indian states, hence has a different relationship to food supply risk than privately traded food. On average, the PDS contributes to 10% of household consumption (mean, kg/year) (16). Additionally, animal-sourced food products have been excluded but contribute to 18% of household food consumption (mean, kg/year) (16). The relationship between climate hazard risk of animal-sourced food products is different to agricultural crop productivity as it includes the risk for the animal and the feed products, and thus was out of the scope of this study.

To estimate climate hazard risk, we used the presence of each hazard as a composite indicator of frequency and intensity, and the volume of food produced at state level. However, these may not overlap, 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 be important for vulnerability of agriculture and food supply to climate-hazards, such adaptive capacity of farmers (31, 32). Agricultural management practices will also vary across states, such as the dependency on natural resources that could be implicated by a climate-related disasters (33). Additionally, some hazards are more damaging to agricultural productivity; across LMICs, drought is the most damaging hazard for agriculture, followed by floods (1). Forest fires are the least damaging (1). 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.

Finally, we have used the most recent data available to inform the estimation of risk. However, the data for the supply and demand balance model were centred on the year 2011-12, and thus food supply source may have changed. The risks values presented in this study should be considered as baseline estimates that will require updating when more recent data on national-level on food consumption become available.

6.4.3 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 (34). 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 (33). 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 (35), or to encourage implementation of agricultural contingency plans (36).

Future research could enhance understanding of how sub-national hazards in India may affect food security. For example, future research could assess how sub-national climate hazard risks in India are linked to foreign exports and thus food security in other countries (37). Additionally, our study focuses on the current climate hazard risks to food supply, but climate change is increasing the frequency, intensity and exposure to hazards (38), differentially across India (39). Research on the future climate hazard risks to food supply could inform strategies to improve food system resilience in the changing climate (40). 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 (41) and food prices increased (42). The colliding presence of a natural disaster 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 (1).

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CHAPTER 7

EXPLORING SOLUTIONS TO INCREASE VISAKHAPATNAM FRUIT AND VEGETABLE SUPPLY

SUMMARY OF CHAPTER

In this chapter, I present a case study that demonstrates how the InFoTrade model developed in Chapter 4 can be applied to a local context.

Visakhapatnam (Vizag) is an urban district in the state of Andhra Pradesh on the east coast of India. Vizag's policy makers have committed to transforming Vizag into a "healthy and liveable city" through the Smart City Initiative of India. Increasing the availability of fruits and vegetables in Vizag is one way by which this goal could be achieved. In this case study, I explore two options for increasing fruit and vegetable supply: increasing local production and increasing imports. I assess the current status of fruit and vegetable production in Vizag and, using local yields, quantify the additional land that would be required to produce fruits and vegetables locally in order to meet nutritional needs. Using the InFoTrade model with additional localised data for districts of Andhra Pradesh and Telangana, I estimate the trade of eight vegetables and seven fruits. I explore the origin of fruit and vegetable imports into Vizag to assess if increasing imports could be a sustainable option. Finally, I compare the policy implications of both interventions to support local decision makers.

Note: The case study will not be published in a peer-reviewed journal, but is being presented to local policy makers through partners at the Centre for Chronic Disease Control, India. It is therefore presented in the style of a policy briefing.

Contribution: I formed the idea for this case study in discussion with my supervisors early on in the PhD. I carried out the analysis, and consulted with Owen Nicholas on the food trade model. I completed the first draft, and Anjali Rao, Sukhwinder Singh and Nikhil SV, Rosemary Green and Edward joy provided comments. I created all the figures in the chapter.

Case Study:

Exploring solutions to increase Visakhapatnam's fruit and vegetable supply

Written by Francesca Harris, Nikhil SV, Sukhwinder Singh, Anjali Rao, Alan Dangour, Edward Joy & Rosemary Green.

PHOTO: Vegetables on sale at Ritu Bazaar, Visakhapatnam.

The problem

Visakhapatnam (Vizag) has committed to the Smart City Initiative of India. Through this, Vizag city aims to “transform into a healthy and liveable city by ensuring its citizens have healthy lifestyle choices” (1). Providing evidence on the status of fruits and vegetable supply and consumption in Vizag can illustrate policy options to improve local nutrition and inform city-level planning for food sustainability.

Why fruits and vegetables?

- Low intake of fruits and vegetables is a leading cause of death and disability, as they are rich in important nutrients that reduce nutritional deficiencies and protect against non-communicable diseases (NCDs) (2).
- 98.4% of Indians are consuming less than the recommended 5 servings of fruits and vegetables per day (3).
- Vizag has a high prevalence of child undernutrition: 31% of children are chronically undernourished and thus have stunted growth (4, 5).
- Vizag also has a growing population who are overweight; 24% of women are overweight or obese (body mass index (BMI) ≥ 25.0 kg/m2), and more than half have a high waist-to-hip ratio (58%) (4). High BMI and waist-to-hip ratio are markers of NCD risk.
- Increased availability and affordability of fruits and vegetables in Vizag would help tackle both forms of malnutrition.

What should fruit and vegetable supply in Vizag be?

- The recent EAT-Lancet Commission stated the optimal diet for health should include ~200 g/person/day of fruits, and ~300 g/person/day of vegetables (6).
- However, this supply should also be sustainable and with minimal risk of environmental changes disrupting supply chains.
- The level of groundwater in Vizag is defined as safe according to the Central Ground Water Board (2017). Therefore, a lack of groundwater to irrigate horticulture is not a priority concern for Vizag.
- However, groundwater depletion could be a concern for Vizag’s fruit and vegetable supply that is imported from other states in India. Andhra Pradesh is importing cereals for food supply that have been produced in states with groundwater levels defined as over-exploited (7).
- Increasing the supply of fruits and vegetables must not come at the cost of increasing groundwater depletion in other states.

Objective

The objective of this report is to explore how the supply of fruits and vegetables in Visakhapatnam (Vizag) district could be increased to meet the nutritional demand. We ask the following questions:

- Does Vizag **produce enough fruits and vegetables** for its population to consume the recommended intakes of a healthy diet, and if not what is the **nutritional supply gap**?
- What would be the **land area required** to produce the nutritional supply of fruits and vegetables based on the current yields in Vizag, and therefore how could expansion of horticultural land area contribute to increasing local fruit and vegetable supply?
- Where does Vizag **import fruits and vegetables** from, and **are these imports groundwater sustainable** for increasing fruit and vegetable supply?

Fruit and vegetable production and the nutritional demand gap

The production of fruits and vegetables in Vizag for 2007-2016 is shown in Figure 1. Vegetable production includes 23 varieties (excluding potatoes), and fruit production includes 14. The average (mean) annual production of vegetables is 263 thousand tonnes, ranging between 196 thousand tonnes in 2015 and 307 thousand tonnes in 2013. The largest contributors to vegetable production are tomato (average 64 thousand tonnes, 25% of total vegetable production) and brinjal (average 50 thousand tonnes, 18% of total vegetable production). The average annual production of fruits is 224 thousand tonnes, with a range between 161 thousand tonnes in 2015 and 353 thousand tonnes in 2016. The largest contributors to fruit production are mango (average 130 thousand tonnes, 58% of total fruit production) and bananas (average 60 thousand tonnes, 27% of total fruit production).

To satisfy the EAT-Lancet recommendation of 300 g/person/day of vegetables and 200 g/person/day of fruits in Vizag, this would require 470 thousand tonnes of vegetables and 313 thousand tonnes of fruits to be available each year (population according to 2011 Census). The average nutritional supply gap (i.e. the difference between the supply required for EAT-Lancet recommendations and local production) was 207 thousand tonnes for vegetables (44% less than the supply required), and 89 thousand tonnes (29% less than the supply required) for fruits.

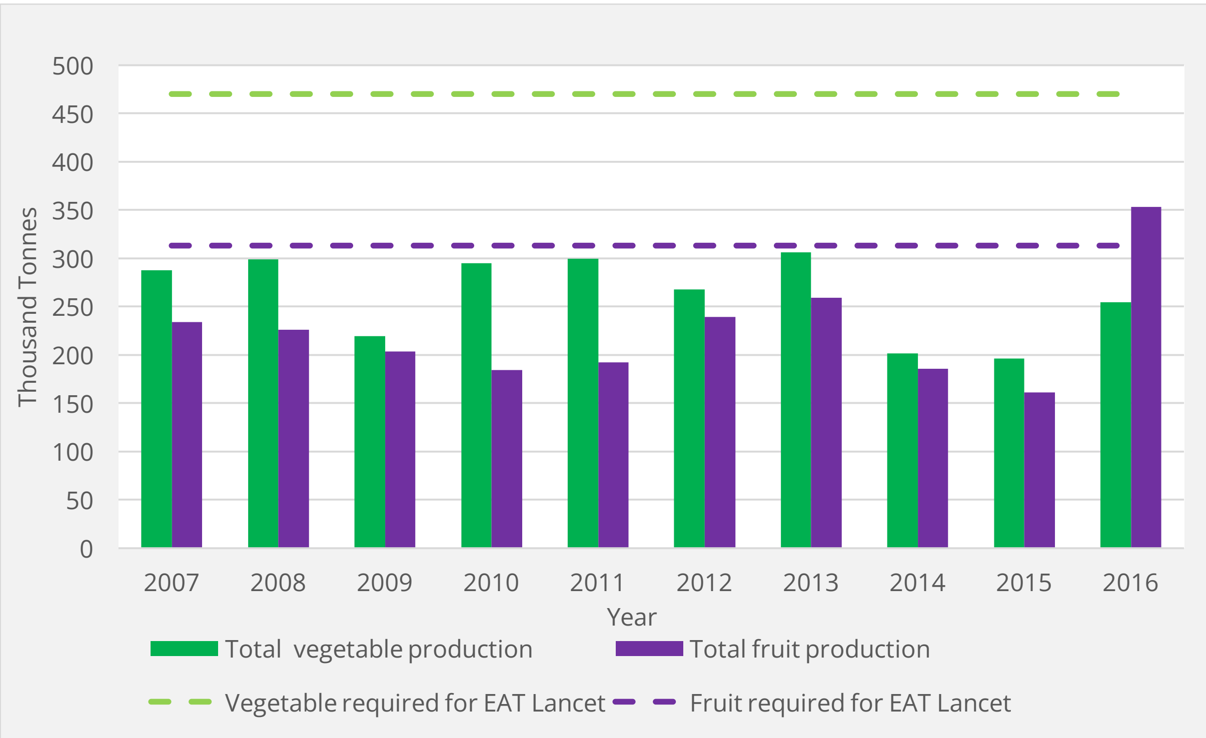

Figure 1: Fruit and vegetable production in Vizag compared to EAT-Lancet recommended intakes. Annual production for the Vizag district taken from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Database (8).

Land needed to fill nutritional supply gap

We estimated the land required to produce the EAT-Lancet recommended supply of fruits and vegetables for Vizag within the local area (Figure 2). Based on the local yields (10-year average), a total of 28.2 thousand hectares of land would be required to produce the EAT-Lancet recommended supply of vegetables for Vizag, and a total of 25.0 thousand hectares would be required for the EAT-Lancet recommended supply of fruit. The average land area currently allocated to vegetable production in Vizag is 15.9 thousand hectares. The EAT-Lancet recommended supply of vegetables would therefore require an extra 12.4 thousand hectares, or a 78% increase. The average land area currently allocated to fruit production in Vizag is 17.7 thousand hectares. The EAT-Lancet recommended supply of fruits would therefore require an extra 7 thousand hectares, or a 40% increase.

The total extra land needed in Vizag to meet the EAT-Lancet recommendations for fruits and vegetables is 19.7 thousand hectares, which is equivalent to 6% of the total agricultural land area in Vizag.

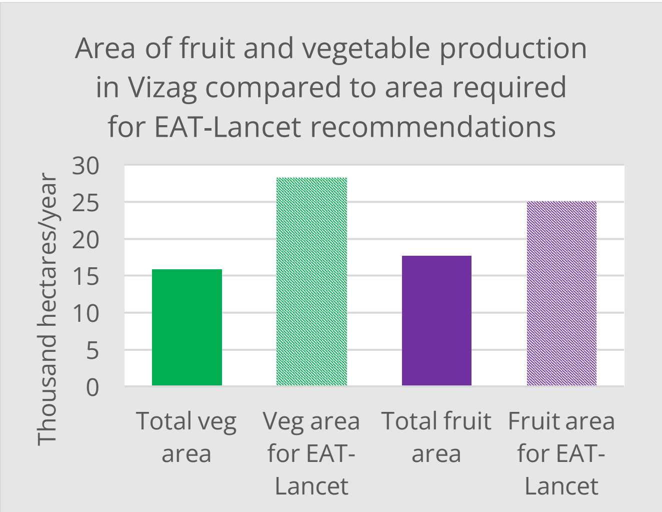

Figure 2: Average annual land area allocated to fruits and vegetables in Vizag (2007-2016 (8)), compared to the area that would be required to produce the EAT-Lancet recommended intake. Area for recommended amount is estimated using 10-year average yields in Vizag and estimated production for 200 g/person/day of fruits and 300 g/person/day of vegetables. Average (mean) of annual figures presented to balance inter-annual fluctuations.

The origin of fruit and vegetable imports

Importing fruits and vegetables into Vizag could contribute to meeting the nutritional demand, providing that their production is not at risk from groundwater shortages. We explored the origin of fruit and vegetable imports into Vizag and their relationship with groundwater availability at location of production. No administrative data are collected on Vizag fruit and vegetable imports that consider the location of production, therefore we used a model to estimate imports of major fruits (N=8) and vegetables (N=7) into Vizag district. See Box 1 for a summary of methods.

All of the fruits and vegetables imported into Vizag for its own food supply were produced domestically in India (although some fruits and vegetables produced in Vizag were exported to other countries). The volume and source of supply for the major fruits and vegetables is shown in Figure 3. The supply of ladies finger, papaya, mango, peas and brinjal was solely dependent on local production in Vizag, hence there are no imports. Conversely, Vizag relied solely on imports for apple, pineapple and cauliflower supply, and mainly on imports for citrus fruits (98%). The other fruits and vegetables were both produced locally and imported. The supply of vegetables was more dependent on local production than imports; 17% (53.6 thousand tonnes) of the total supply of vegetables was imported. Conversely, 57% (161 thousand tonnes) of fruit supply came from domestic imports. The main imported fruit was banana, of which 93 thousand tonnes was imported (69% of supply).

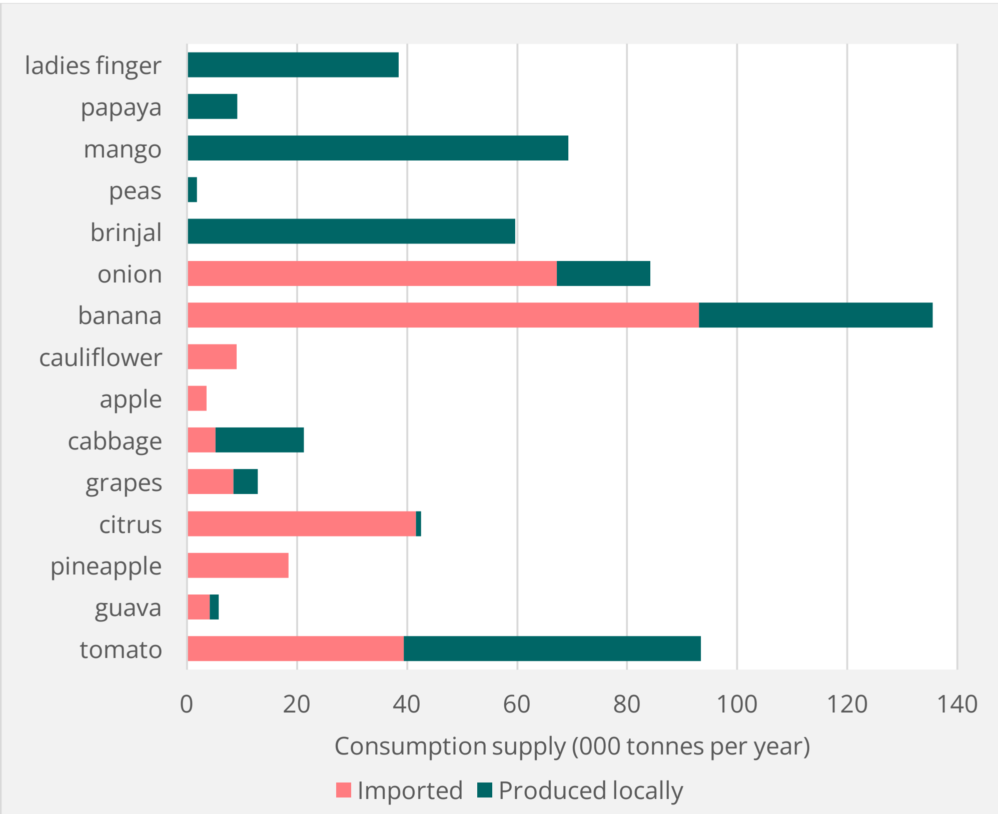

Figure 3 Volume (thousand tonnes) and source of supply of major fruits and vegetables in Vizag. Trade data is modelled for the year 2011-12.

The origin of Vizag's fruit and vegetable imports is shown in Figure 4. Other districts in Andhra Pradesh or Telangana contributed to 39% (97.4 thousand tonnes) of fruits and vegetables imports to Vizag. These were mainly from West Godavari, which supplies 53.5 thousand tonnes of bananas to Vizag. Vizag imported 70 thousand tonnes of fruits and vegetables from Karnataka; namely onions (67.1 tonnes thousand tonnes) and guava (2 thousand tonnes). The longest supply chain was for apples, which come from Jammu and Kashmir.

The majority (67%) of fruits and vegetables imported into Vizag were produced in areas classified as safe in their groundwater reserves. The remainder (33%, 82.6 thousand tonnes) were produced in regions classified as semi-critical; namely citrus fruits from Nalgonda (42 thousand tonnes) and bananas from Tamil Nadu (40 thousand tonnes). Citrus fruits from Nalgonda accounted for 98% of Vizag's total citrus supply, and bananas from Tamil Nadu accounted for 30% of Vizag's total banana supply.

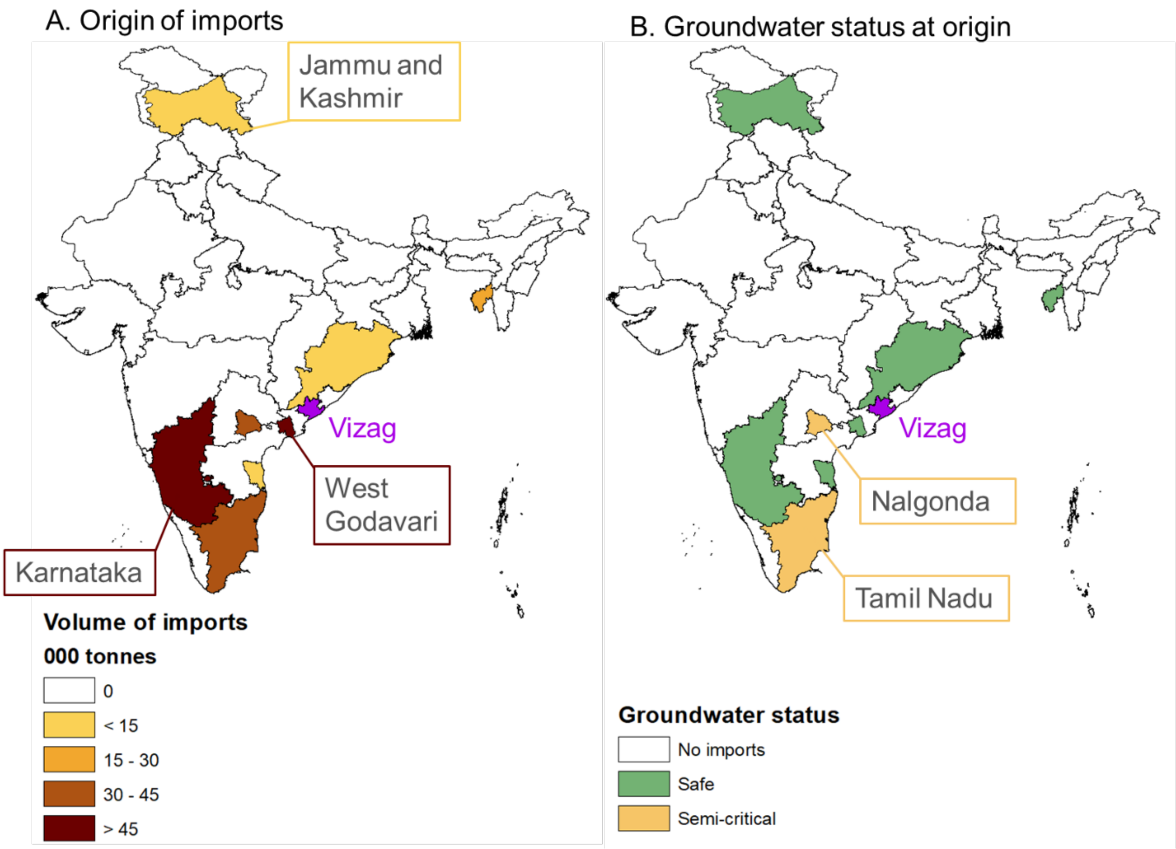

Figure 4 Import origin of fruits and vegetables imported into Vizag during the study period (2011-12), according to volume (tonnes) (A), and groundwater status according to Central Ground Water Board, 2017 (B).

BOX 1: Summary of methods to estimate trade

- We follow methods of Harris et al. 2020, using district-level data for Andhra Pradesh (N=23, pre-separation into Telangana and Andhra Pradesh), and state-level data for other Indian states (N=34).
- Briefly, data was collated for each state or district on production (9), foreign imports, foreign exports (5, 10), stocks, non-food uses (11) and food available for consumption (12).
- For each district or state, supply of each fruit or vegetable item includes local production and foreign imports, minus stock and non-food uses of crops (waste, feed, seed, processed and other). The demand for each item includes food consumption and foreign exports. Foreign imports were included in local supply of the item, while foreign exports were included in the demand.
- The differences between supply and demand volumes were used to indicate which districts or states had excess supply of each item for trade and which had unmet demand.
- To estimate trading pairs, we use a linear programming model that minimises the total cost of transporting each item between districts and states. The distance between each pair of districts or states was obtained for both road and rail routes. The cost of transportation (tonne per km) was taken from Indian government data (13, 14).

Research limitations

We did not account for waste as there is no local data on the volume of fruit and vegetable weight. Therefore, the estimated nutritional demand gap of fruits and vegetables is lower than the actual amount that would need to be produced if waste were accounted for. The nutritional demand is based on the recommended fruit and vegetable intake for adults, and thus will overestimate the population recommendation because it does not consider the lower nutritional recommendation for children. Additionally, the trade pattern is modelled data, hence further research is needed to understand if this reflects actual supply chains. We only modelled the trade flows of 15 fruit and vegetables hence do not consider the totality of fruit and vegetable trade. However, this research indicates relationships of Vizag with other states through imports of major fruits and vegetables.

Conclusions & Recommendations

Vizag does not produce enough fruits and vegetables to meet the nutritionally recommended supply of its population

The annual production of fruits and vegetables in Vizag is below the EAT-Lancet recommendations for nutritionally adequate diets. For vegetables, it is lower by 207 thousand tonnes (-44%), and fruits by 89 thousand tonnes (-29%). To increase the availability of fruits and vegetables, Vizag could either increase its local production, or increase its imports. Table 1 summarises the research findings, advantages, disadvantages and policy recommendations under these two options.

Table 1: Research findings and policy recommendations for increasing Vizag's fruit and vegetable supply

	INCREASING FRUIT AND VEGETABLE SUPPLY THROUGH INCREASING LOCAL PRODUCTION	**INCREASING FRUIT AND VEGETABLE SUPPLY THROUGH INCREASING IMPORTS**
EVIDENCE FROM THIS RESEARCH	- Would require **land expansion of fruit and vegetable production by 20 thousand hectares** based on local yields. As an indication of scale, this is similar to the land area allocated to pulses; 21.7 thousand hectares. - **Fruit production is increasing**, but 26% (53 thousand tonnes) was **exported** to other Indian states	- Fruit supply in Vizag is more dependent on imports (57%) than local production. Conversely, vegetable supply is more dependent on local production (83%). - Current fruit and vegetable supply chains are **safe from groundwater depletion**, except for citrus fruits and bananas. - **Districts close to Vizag** (in AP & Telangana) provide 40% of Vizag's fruit and vegetable imports.
ADVANTAGES	- **Improving self-sufficiency** of food supply can **reduce exposure to external shocks**, including environmental or unexpected shocks such as pandemics. Longer supply chains were the most disrupted due to the lockdown measures of the COVID-19 pandemic (15).	- If there is no change in trading partners, the majority (66%) of imports are not contributing to groundwater depletion and supply is from nearby areas. - Price of fruits and vegetables may be lower for consumers if imported from areas that are **optimal for production.**
DISADVANTAGES	- If **forests** are cleared for production, **local biodiversity** could decrease. - Replacing cereal crops with fruits and vegetables could **reduce farmers' income**, depending on existing production and land suitability. - Vizag population **may not consume** the additional fruits and vegetables produced because exporting them is profitable (as indicated from current fruit exports).	- Increased imports could make Vizag more vulnerable to **external shocks** - If supply chains get longer, this could **increase the cost to the consumer**; imported apples travel the furthest to Vizag and are the most expensive fruit for consumers (16). Longer supply chains would also increase **transport-related greenhouse gas emission**s (17).
POLICY RECOMMENDATIONS	- Provide **incentives for farmers** to sustainably increase the production (land expansion or improving yields) of fruits and vegetables in Vizag. - Provide **incentives for citizens** to increase production of fruits and vegetables, for example through community gardens. - **Increase fruit and vegetable demand** by increasing density of markets; campaigns to incentivise consumption of locally grown vegetables; public procurement of Vizag fruits and vegetables for public institutions. - Further research could assess the suitability of land, the impact on farmers' income and the barriers to increasing consumption.	- Inclusion of fruit and vegetable **import and export tracking** based on latest available data by the Smart Cities project. - Reduce supply of fruits and vegetables from areas with **semi-critical groundwater levels**; citrus from Nalgonda and bananas from Tamil Nadu. - Further research could assess current supply chains and price differences between locally produced and imported fruit and vegetables for consumers.

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CHAPTER 8

DISCUSSION

SUMMARY OF CHAPTER

In this chapter, I summarise the findings under each thesis objective and propose how they contribute to the thesis and the research field. I discuss the implication of the thesis findings for policy and future research in India. I provide an overview of my research journey through the PhD, which has informed the final content of the thesis. I discuss the contributions of the research to the wider scientific literature, and by reflecting on the thesis limitations, I introduce areas for future research.

8.1 PhD Summary

Driven by concerns of climate and other environmental changes, there is a growing body of evidence on the links between food systems and the environment (1). Trade increases the interconnectivity of food systems across geographical spaces, and thus the complexity of the relationship between human diets the environment. In this thesis, I use modelled data on sub-national food trade to characterise the relationship between Indian food supply and water use, groundwater depletion and climate hazard risks. The research contributes to the field of sustainable food systems by demonstrating that including data on sub-national food trade in environmental footprint and risk assessments can advance understanding of the relationships between food and the environment. Below, I summarise the PhD findings under each objective, highlighting their contribution to the thesis argument and to the wider research field.

Objective 1: Systematically synthesise the global evidence on the water use of human food consumption, in order to compare indicators, methods and approaches used.

This objective was achieved in Chapter 3, which presented a systematic review on dietary water footprints (WFs) published in the journal Advances in Nutrition. Through searching seven databases and screening 6268 papers, I found 41 studies that assessed the water use of human diets using the WF indicator. There were an additional 14 studies found that quantified dietary water use with other water use indicators (Appendix 2).

This review contributed to this PhD by identifying a research gap to be explored in my thesis. Food trade is infrequently considered in assessments of the water use of human food consumption; instead it is often assumed that all foods are produced in the same location where they are consumed. Of the studies included in the review, four accounted for international food trade using data from the United Nations Food and Agricultural Organisation (FAO) Trade database or used country-specific trade statistics if available (2-5). However, none of the included studies incorporated sub-national food trade in their dietary water use assessments (including non-WF studies).

Beyond the thesis, this systematic review contributes to the research field as the first systematic review to focus solely on dietary water use, considering blue and green WF separately. Through a meta-analysis, I found that healthier diets had lower green WFs than current patterns, but were not lower in their blue WFs. This novel summary finding added nuance to the previous understanding that healthier diets have lower environmental impacts (generally measured by greenhouse gas emissions) than current dietary patterns (6).

The research under this objective was presented as a poster at the Oxford Livestock Environment and People Conference in 2018, winning the prize for the best poster. It was also presented at an international workshop in 2020 for the Water Scarcity in Agriculture (WASAG) Water-Nutrition Working Group. This presentation is published on the International Food Policy Research Institute webpage. It has been cited more than 30 times by October 2021, including in a perspective article from leading water security researchers (7).

Objective 2: Develop a new model to estimate the interstate trade of Indian food items using available secondary data.

The model under this objective (InFoTrade model) was described in Chapter 4. Briefly, the InFoTrade model used state-wise data on the supply and demand of food items and the international trade at ports. This predicted the states that had excess food supply and thus would export to other states, and the states that had unmet demand to be imported. The direction of these trade volumes was determined using a linear programming model that minimised the cost of transporting each food item across India. The InFoTrade model was used to estimate the interstate trade of 41 food items, covering the groups of cereals, fruits, vegetables, pulses, oils, sugar, meats, eggs and milk.

The InFoTrade model provided the sub-national trade data that were used in subsequent analyses of this thesis, in order to quantify the relationship between food supply and the environment in India.

Beyond this thesis, the InFoTrade model provides a methodological contribution to the research literature. The modelling framework and validation procedure can be used in other contexts to estimate sub-national trade flows where sub-national trade data are not available.

Objective 3: Using the results from Objectives 1 and 2, quantify the trade-weighted consumption water footprints of food items in Indian states.

The process to estimate the blue and green WF of food items was detailed in Chapter 4. For 40 food items, I estimated the trade-weighted WFs in each of the 35 Indian states (pre-Andhra Pradesh separation), using available data on crop WFs for Indian states (8), and the outputs of the InFoTrade model.

These estimates contribute to the thesis by demonstrating that trade-weighted consumption WFs of food items vary from the production WFs of food items, and thus accounting for food trade improves the accuracy of WF assessments of food supply. The differences in the median trade-weighted consumption WFs to the production WFs varied between -80 to 760 L/kg for green WFs and -82 to 76 L/kg for blue WFs.

These novel WF estimates provide data for the research field that will be used to estimate environmental footprints of food consumption in two Indian states by the Sustainable and Healthy Food Systems (SHEFS) project. The research was presented as an oral presentation at the Livestock Environment and People Conference, Oxford (2018).

Objective 4: Using the results from Objectives 1 and 2, quantify the virtual water trade of cereals between Indian states, and assess its relationship with groundwater depletion.

In Chapter 5, this objective was achieved by using the InFoTrade model and data on the trade of cereals through the Public Distribution System (PDS) to quantify the volume of cereals traded between each state. State-wise cereal production WFs were used to estimate the virtual green (rainfall), ground and surface water traded between Indian states. This study was published in the journal of Environmental Research Letters.

This analysis contributes to this thesis by demonstrating that, through sub-national trade, concerns for water availability in one state can have implications on food supply in others. Despite only four Indian states experiencing groundwater depletion, cereal supply in 31 states was partly dependant on this depleting water through sub-national cereal trade. This suggested that further research in this thesis should quantify other environmental risks to Indian food supply.

As a contribution to the research field, this study provides novel estimates for the volume of virtual water transported across India through cereal trade. I found that current virtual water trade was enabling lower use of green and surface water in cereal production for food supply, but was not reducing dependence on groundwater reserves. Thus, I demonstrate that a greater understanding of sub-national food trade can illustrate relationships between water and food.

I have presented the research under this objective at three conferences through abstract submission (Global Food Security (2019), Agriculture, Nutrition and Health Academy Week (2019), Water Future Conference (2019)). I was an invited speaker at a webinar on "Virtual Water: The Issues and Policy Implications in India", hosted by Partners of Prosperity in association with Manav Rachna International Institute of Research and Studies (2021). The research was cited in a paper on 'Water in Agriculture' as part of the UN Food and Agricultural Organisation's National Dialogues for Indian Agriculture Towards 2030. It was reported in several national media articles, indicating that the findings are of interest beyond the academic community:

- How selling cereals is actually exporting water, 30th June 2019, KV Kurmanath, The Hindu BusinessLine,
- States with stressed groundwater trade most cereals, finds study, 5th December 2020, Jacob Koshy, The Hindu (National, with subsequent copies on several online news outlets),
- States with stressed groundwater trade most cereals, 5th December 2020, Ayushi Kedia, Maverick Times,

- India's food supply runs on water misuse, 4th January 2021, Shijith Kunhitty. Mint,
- Cereals drain India dry, 20th Jan 2021, Aarti Kelkar Khambete, India Water Portal,
- Groundwater Reserves A Concern In India's Cereal-Growing Regions, 17th Feb 2021, Outlook Krishi.

Objective 5: Using the results from Objective 2, undertake a climate hazard risk assessment of food supply in each Indian state based on food produced in the state compared to food imported from other states.

The research under this objective was presented in Chapter 6. Using the InFoTrade model, I estimated where the food supply of 30 food items was produced for each Indian state (locally produced supply vs domestically imported food). I used a composite indicator of hazard presence, exposure and vulnerability at the location of production to estimate the climate hazard risk to food supply for Indian states.

This study contributes to the thesis by highlighting that, along with groundwater depletion, sub-national food trade in India exposed consumers to geographically disparate climate-hazards. Each state was at risk from each climate-related hazard through its food imports even if not through its domestic production; this included sea level rise and extreme temperatures that are geographically specific. The findings can be used by state-level governments in disaster risk management.

This chapter illustrates a novel approach to quantify the climate-hazard risks to national food supply that integrates data on sub-national food trade, climate hazards and vulnerability. The research paper has been submitted (August 2021) to the journal Global Food Security to be peer-reviewed for publication.

Objective 6: Downscale the model from Objective 2 for the state of Andhra Pradesh using district-level data, in order to estimate the imports of fruits and vegetables into the district of Visakhapatnam and explore policy options for increasing fruit and vegetable supply.

The case study under this objective was presented in Chapter 7. This case study explores two options for increasing the availability of fruits and vegetables in the Vizag district; by increasing local production or by increasing imports.

This research contributes to this thesis by demonstrating how data on sub-national food trade can be used to inform policy options for local governments to improve food system sustainability. I found that none of the fruit and vegetables imported into Vizag are produced in areas with over-exploited groundwater; the majority (66%) are produced in areas that are currently safe in their groundwater reserves. Therefore, increasing fruit and vegetable imports from current export partners is a viable option for increasing fruit and vegetable supply for the district if considering groundwater depletion risk.

This case study also presents a methodological contribution to the literature, by highlighting how publicly available district and state-level data can be combined to estimate sub-national food trade and thus import dependency of a specific region.

Although the COVID-19 pandemic has delayed plans, the results will be presented to policy makers in Vizag, including the agriculture department and the Smart City initiative.

8.2 Implications of research findings for India

The aim of this thesis was to quantify the relationships between food supply and the environment in India to inform policy options that could mitigate future food insecurity risks. These relationships have been reported through the thesis chapters along with specific policy options, and therefore will not be repeated here. However, I will discuss some overarching insights and policy options that are relevant across the chapters, and introduce areas for future research.

This thesis emphasised that a pressing challenge for Indian food supply is water availability. Chapter 5 illustrated that the food supply of cereals in India is highly dependent on over-exploited groundwater resources in some producing regions. Most states (31 out of 35) are importing cereals that have been produced with over-exploited groundwater; this equates to 76% of the Indian population. This highlighted that interventions are needed to reduce water use, particularly groundwater, in the regions that are currently exporting cereals to minimise future risks to national food security.

In addition to groundwater depletion, droughts are a concern for national food supply. Chapter 6 found that droughts present the largest climate hazard risk to food supply for most states. Droughts in Uttar Pradesh are a particularly high risk to national food supply, as Uttar Pradesh is exporting foods to 30 other states. Reducing the blue WF (L/kg) of food items could be an important solution for reducing the risk of drought for food supply in addition to the risks to groundwater depletion described above (9). The systematic review (Chapter 3) found that the median blue WF of Asian diets was the highest across continents. This is partly due to low yields, therefore interventions to increase yields for both crop and livestock production could reduce blue WFs per kg of food produced.

An alternative solution to improving the resilience of India's food system to water-related risks would be to consider how food production is distributed across India. Some states are comparatively less vulnerable to groundwater depletion or droughts, as shown in Figure 8.1. For example, states in the Eastern region have safe groundwater resources and a lower drought risk. This region has abundant water resources, such that the government is investing in reservoirs and canals to transfer 176 km^3 of water from the Eastern region to the major food producing regions (10). The Eastern region also has the greatest yield gaps across India, hence food production could increase without the need for additional land. Therefore sustainably increasing food production in these regions and using trade to export goods to other states could present an opportunity to improve national food security by reducing water-related risks (11). However, further research is required to determine agro-ecological suitability as well as the potential impact on farmers.

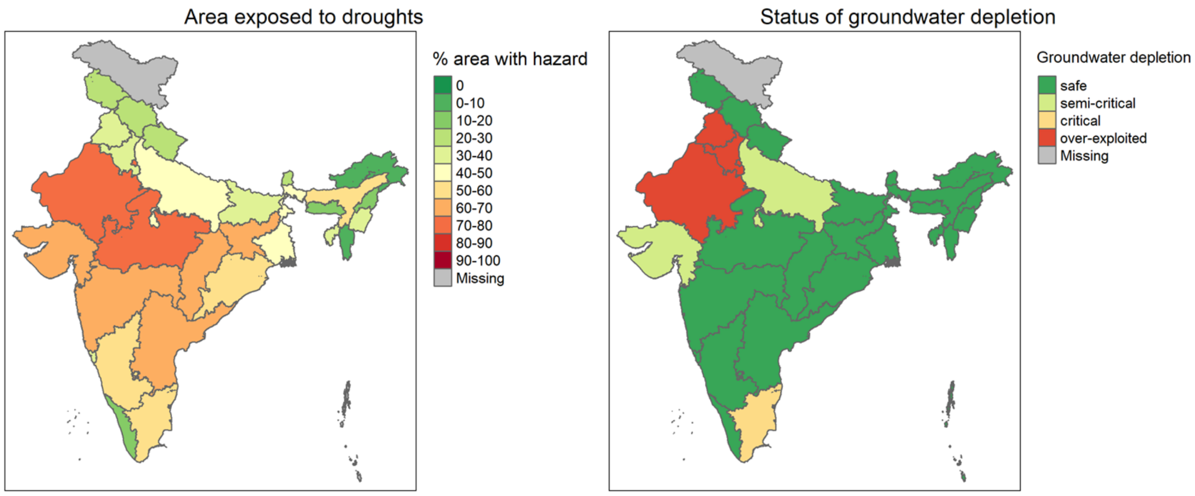

Figure 8.1 State-wise area exposed to droughts (12) and stage of groundwater depletion according to the Central Ground Water Board (13).

Current challenges of water availability in India will be exacerbated by increasing agricultural demand. Rising incomes and urbanisation are altering dietary patterns; traditional diets are being replaced with more Westernised patterns, with high sugar, fat and salt (14). In other emerging economies undergoing this nutrition transition, dietary changes also include increased consumption of red meat and dairy (15) – foods with high environmental footprints. The majority of Indians consume a lacto-ovo-vegetarian diet (16), therefore red meat consumption is not increasing substantially in India (15). Nevertheless, the consumption of dairy products is increasing with incomes (17, 18) which could lead to more water demand. The consumption of poultry meat is also increasing (19), which has a particularly high blue WF in India due to its poor feed conversion efficiency (Chapter 4). Therefore, this nutrition transition in India could increase the agricultural water demand. Improvements to the efficiency of water use in agriculture will be insufficient to satisfy this increasing water demand, and thus water scarcity could worsen (20).

Consequently, the population-wide adoption of diets that use less water could prevent water scarcity by reducing agricultural water demand. Low water use diets in India consistent mainly of vegetables, fruits and whole grains, and small amounts of animal-sourced foods (ASFs) and nuts (21, 22). These diets could also have a higher nutritional value as compared to current patterns, and thus their adoption could also improve nutrition-related health (21, 22). However, the production of low water use foods for the diets depends on farmers to change their cropping pattern (21). Further research is required to understand the feasibility of changing cropping patterns, but nevertheless there is potential for crop shifts to reduce water use. In addition, strategies that involve changing cropping patterns to meet nutritional needs assume that trade will deliver the food accordingly. Research on international food trade suggests that this may happen for some contexts, but not all (23). Policy interventions are thus needed to help trade patterns adapt to changing dietary choices. To the author's knowledge, there are no studies on the relationship between sub-national trade and nutritional outcomes. The interstate trade data estimated in this thesis suggests, descriptively, that sub-national Indian trade may not be supportive of delivering healthy and nutritious diets in India. States with higher levels of income and prevalence of non-communicable diseases, such as Kerala, are major food importers. Whereas, states with lower levels of income and high levels of undernutrition, such as Bihar, are less dependent on imports. It is possible that barriers to interstate trade, such as differences in taxes across states (24, 25), do not support food security in some states as they modify food prices (26). Interstate trade of goods in India has recently become easier through the Central Goods and Service Tax of 2017 and the Indian Agricultural Acts of 2020, which may alter the relationships found in this thesis. Further research is needed to explore the drivers of sub-national food trade flows in India and possible policy levers to manage trade patterns for optimal nutrition and environmental resource use.

Finally, through collating the most recent data available on environmental indicators and food supply, this research has highlighted relationships between food and the environment at a sub-national level in India. However, climate change is likely to alter environmental risks and consequently food trade patterns. The availability of groundwater resources will change as increased temperatures affect snow-melt from the Himalayas (27, 28). Each of the climate hazards presented in Chapter 6 will increase in intensity and frequency, as well as spatial distribution across India (29, 30). As agricultural suitability and resource availability change, states are likely to both import and export different crops. Further research could explore the implications of the changing climate on agricultural productivity across Indian states and use the modelling approach of this thesis to predict changes to interstate food trade. Additionally, scenarios for agriculture, nutrition and the environment could be explored, such as Shared Socio-economic Pathways (31), thus developing a greater understanding of how policy can be used to foster sustainable and resilient food systems in India.

8.3 The research journey

In this section, I provide an account of the research journey of this PhD to justify the research undertaken.

When I started this PhD in 2017, I had recently published a paper on WF of diets in India (32), which formed part of the Wellcome funded Sustainable and Healthy Diets in India (SAHDI) project. The study used individual food consumption data for over 7000 Indian adults (33), and assessed the spatial and socio-demographic variability in dietary WFs. This was the first study to explore the WF of different diets in India, hence it addressed an important research gap. For example, we found that urban dwellers had a higher dietary WF than rural dwellers. We also found that the blue WF of diets in India was comparatively higher than other countries, largely driven by the high blue WF of wheat. However, the dietary data were quite old (1995-2006), and the sample population spanned five Indian states hence was not geographically representative of India. Additionally, when assigning WFs to food items, we assumed that food was produced and consumed in the same state. In this context, the original aim of my PhD was to build on this work but use geographically representative dietary data. I planned to develop dietary change scenarios that could be nutritionally beneficial and sustainable for water in India, and consider where the food items had been produced. Given the lack of sub-national trade data, I sought a modelling approach that would allow me to estimate sub-national trade flows. My PhD advisor, Carole Dalin, modelled sub-national trade flows in China (34), hence we had assumed it would be simple to apply this model to the Indian context.

Concurrently, my SAHDI project colleague Benjamin Kayatz was estimating new WF data for crop items in India. The estimates were first developed for cereals, hence it was decided that a simple analysis could be carried out using the modelled interstate trade flows and the new cereal WFs. Once I had developed the model and produced initial results on the virtual water trade of cereals, I presented the research at two conferences, one in the UK and one in India, and the feedback suggested this was an important and novel piece of research. Therefore, I chose to focus my initial paper on cereals, and explore the water use associated with all food groups in the dietary scenario analysis for my second research paper.

I was then fortunate enough to spend four months visiting the Ashoka Trust in Research in Ecology and the Environment (ATREE) in Bengaluru with the SHEFS project (July 2019-October 2019). Here, I discussed my work and PhD plans with senior environmental science researchers. When I introduced the idea of developing dietary scenarios, this was met with concern over their applicability. In particular, how these dietary scenarios relate to actual "on the ground experience", and if they are useful for the change makers i.e. the farmers. I was also conscious of my position as a white, British researcher, and agreed that the research must aim to be useful for those who need to know it. I continued to listen to the advice of colleagues, who suggested that virtual water trade would be of significant interest to local policy makers. I planned to carry out expert interviews to gain contextual insight for the development of scenarios.

Subsequently, I was confronted by a barrier in my plans for dietary scenario analysis in terms of the validity of the trade model. The validation analysis of the InFoTrade model for milk found the value of milk was negatively associated with the cost of transport. Therefore, the model was not suitable to estimate milk trade and I could not include milk in the dietary scenario analysis. Milk is an important food item for nutrition in India (35), but also has a high green WF (32), therefore excluding it from the dietary scenarios would affect the legitimacy of the proposed water sustainable diets. Further research was needed to understand the drivers of ASF trade in India, and thus determine a more suitable modelling approach. Therefore, considering the scope and timeframe of this PhD, I decided that I would focus on crop food items in subsequent analysis.

Then, the COVID-19 pandemic started, and it was clear that a greater understanding of the water sustainability of diets would not be a priority for Indian researchers or policy-makers. The option to carry out expert interviews was no longer appropriate in the near term. I explored many different research questions that would use the data I had developed on the interstate trade of food items. The pandemic disrupted food chains across the world (36), highlighting the fragility of food trade. Therefore, I considered that assessing the risk of environmental shocks disrupting food trade would be of research and policy interest in India. Thus, the final paper of this thesis (Chapter 6) has a different research theme to the PhD, which originally focused on water sustainability. Nevertheless, there are threads that pull the research together, which I discuss in this final chapter.

8.4 Research contribution

In this section, I propose how the research presented in this thesis provides methodological and empirical contributions to advancing scientific understanding of the relationships between food and the environment.

The first contribution of this thesis to the literature is the methodological contribution of the trade model. Although the InFoTrade model is similar to previous models (34, 37), it differs by relying solely on publicly available data. It is likely that previous dietary WF assessments exclude sub-national trade because context-specific data is not available. Household consumption and expenditure surveys, which were used as the basis for the model in this thesis, are collected in 120 countries (38). Therefore, this thesis presents a simple modelling framework that can be repeated in these contexts where no trade data are available. However, the simplicity is also a potential disadvantage in terms of validity. There are no data on interstate trade of food items in India that could be used to directly assess the validity of the model. I developed a validation procedure that assessed if assumptions of the model were met, namely that transport costs are reflected in primary data from the household consumption and expenditure survey. This validation procedure could also be repeated for other contexts to assess suitability of the modelling approach. Thus, the modelling framework of this thesis could be used to improve the accuracy of estimates on dietary WFs or other spatially-explicit environmental footprints.

The second research contribution of this PhD are the trade-weighted WFs of food items in Indian states. The InFoTrade model enabled me to estimate the trade-weighted consumption WF of 40 food items across Indian states. This was the first time trade-weighted consumption WFs had been estimated for Indian states. I also updated state-level production WFs of ASFs in India, using the most recent data available on livestock feed intake and production systems across states. Although I used the most recent data, the data are still relatively old and thus may not accurately reflect current estimates. The WF of production for crop items reflects the years 1996-2005. The feed intake data reflects the year 2000, and is therefore unlikely to be accurate for India as commercial farming has increased, especially for poultry products (39). Nevertheless, these are still novel WF estimates for India that contribute empirically to research.

This thesis also contributes to the literature by demonstrating the importance of including trade data to accurately assess the environmental footprint of food systems. This was highlighted by differences in the estimated trade-weighted consumption WFs and the production WFs across Indian states. For all food items and states, the production WFs differed to the trade-weighted consumption WF. In Chapter 4, a descriptive analysis found that for more than two thirds of states, the median production WFs of food items were larger than the median consumption WFs for both green and blue WFs. This indicates that sub-national trade in India enables more efficient water use in Indian agriculture. In Chapter 5, the water saving analysis corroborated this finding; cereal trade enables more efficient use of green and surface water in cereal production for food supply. Therefore, if studies do not consider sub-national food trade, this could overestimate the total WF of diets. The studies included in the review (Chapter 3) and more recent global studies have only considered the potential for dietary changes to reduce water use at the national level (40). However, aggregating dietary WFs to national-level could mean dietary WFs are incorrect, and in the worst case inform sustainable diet recommendations that unintentionally lead to more water use (41). This is important for current food policy, as there has been increasing interest in the potential for environmental footprint labelling to drive sustainable dietary choices (42). Before such a policy can be implemented, relevant stakeholders could consider how food trade and geographical variation in WFs and other spatially-explicit environmental impacts can be considered in labels (42).

Finally, this thesis contributes to the literature by demonstrating a greater understanding of sub-national food trade can illustrate environmental risks to food supply. In Chapter 5 and 7, I found that groundwater depletion is not solely a concern for the affected states, but also many other states (and districts) across the country. This suggested that further research was needed on how food supply is linked to other environmental risks. The study in Chapter 6 combined data state-wise data on food trade, food supply, vulnerability and hazard presence to estimate the climate hazard risk to food supply. Along with groundwater depletion, I found that local climate hazard risks are not solely a concern for the affected states, but are a risk to food supply across the country through food imports. In combination, these findings contribute to the literature by emphasising environmental risks assessments that consider sub-national food trade will reveal variations in food supply risks masked at the national-level.

8.5 Reflections and areas for future research

In this section, I reflect on the research carried out in this thesis and its limitations, and thus introduce areas for future study.

My selection of the WF indicator to link water resources and food in Chapters 3-5 could be questioned as alternative indicators of water use are available. The WF provides a volumetric representation of water consumption to inform water management; assuming that water is a depleting global resource and thus water use should be reduced in any given context (43). However, some areas have abundant water supply while others suffer with water scarcity, hence the same volume of water used in each location has different consequences to local water users (44). The water scarcity weighted footprint (WS-WF) is an alternative indicator that incorporates the relative local water availability by weighting the blue WF with the corresponding local blue water scarcity (45). There is debate on the value of the WF compared to the WS-WF (43, 44, 46, 47), therefore it is important to note the consequences of having used the WF for the conclusions of my thesis.

For example, in Chapter 5 I found that virtual water is transferred from states with depleting groundwater reserves to states with safe groundwater reserves through cereal trade. However, some states with depleting groundwater reserves, such as Punjab, actually have relatively high surface water availability (48). Use of the WS-WF indicator may have altered my conclusion on how cereal trade relates to water availability as the WS-WF includes both ground and surface water availability. Furthermore, I used the indicator 'stage of groundwater depletion' as a categorical indicator while the WS-WF is a continuous variable and thus could be more informative in cross-state comparisons of water scarcity. Future research using the WS-WF to assess the relationships between food supply and water use across India could potentially highlight priorities for water management to reduce water scarcity.

Additionally, I included green water use in my WF analysis, but green water is not included in the WS-WF indicator. Green water is sourced from precipitation on land area, therefore the green WF is correlated with indicators of land use (49). The WS-WF is used in Life Cycle Assessments (LCAs) with other environmental indicators, hence including green water could lead to double counting of potential environmental impacts. In this thesis, I did not undertake an LCA so there is no risk of double counting. However, the green WF should be interpreted with caution, as in the absence of human intervention (i.e. agriculture) green water would still be used by natural vegetation (44). The blue WF, in contrast, is driven by human intervention. The net difference in the green WF of food production and the green WF of natural vegetation would be a more comparable indicator to the blue WF and would have lower values than the green WFs estimated in this thesis, however these data are not available. Additionally, a large green WF does not necessarily indicate that intervention is needed. For example, ASFs often have a particularly high green WF due to the poor conversion of feed to food product, as shown in Chapter 3 and 4. Yet some rangelands are not suitable for crop production, hence there is no competing use for the feed's green WF and a low opportunity cost to produce these ASFs, regardless of their high green WF (50, 51). While it is recommended that green water use is included in water use assessments due to its dominant contribution to food production (43, 52), further research could help to unpick the nuances of green water use and its relationship with land use.

Reflecting on the research presented in this thesis, there is not a complete coherence between the methodological gap identified and the subsequent research carried out. In Chapter 3, I identified a methodological gap in the literature on the water use of human food consumption, namely that studies infrequently consider food trade. The systematic review on dietary WFs identified that 33% of studies did not consider food trade at all, and none of the included studies had considered sub-national food trade. This gap was something I aimed to fill in my PhD, but unfortunately I did not apply the trade-weighted consumption WFs from Chapter 4 to estimate the WF of current diets in India, and therefore did not fill the gap. Research is underway to include the trade-weighted WFs detailed in Chapter 4 to assess diets in two Indian states, and the WF estimates can be applied for other research studies. However, it is important to recognise that the PhD did not fully address the gap identified. Additionally, the review focused solely on studies that estimated the WF of current diets; studies that only considered future dietary WFs or explored the WF of single food items were excluded. Sub-national food trade has been considered in the WF of future diets in China (34), and in the WF of soy and sugarcane in Brazil (37). Therefore, although the systematic review of this thesis highlighted a gap, it was not a complete gap in the literature.

Another limitation of the work presented in this thesis is it relies on single modelling approach to estimate the food trade of food items in India. The limitations of the InFoTrade model have been detailed in Chapter 5 and 6 and thus will not be repeated.

Nevertheless, it is important to state this as a limitation of the thesis as a whole; as the relationships found are not actual but modelled relationships representative of reality. Although the validation procedure suggested it was a suitable trade model for most food items (40 out of 41), the trade of food items will vary depending on supply chain requirements and processes. For example, some fruit and vegetables require a cold chain (43). Additionally, informal trading is common in India, particularly for livestock products (44). This implies that the markets for cross-state trading are not yet established, hence may not be optimised for reducing costs as the InFoTrade model assumes. Further research could develop a model for each food item or group by incorporating constraints to account for different supply chain requirements and cultural drivers of food trade.

This thesis is also limited by focusing on quantifying the current relationships between food and environment, rather than solutions to reduce environment footprints or risks. Further research could use the trade model presented in this thesis to explore solutions to improve environmental sustainability. For example, it could be easily used to assess how diversifying sub-national trade partners affect the environmental risks associated with food imports. Diversifying trading partners could be added as a constraint to the model, and the results could be compared with the data presented in this thesis. However, the food trade model cannot be used to assess solutions to reduce the environmental footprint of food systems. The model is dependent on balancing supply and demand, therefore if the input data on production is changed for one state, the modeller must assign this additional volume to either another state or to national level. In other words, the model does not implicitly consider feedback mechanisms, and thus is limited in is use to assess solutions. Alternative models, such as system dynamics or agent-based modelling, allow for feedback and therefore can explore solutions by assessing how changes in one part of the food system may influence others.

Additionally, there remain many unanswered questions around how food trade can be part of the solution to improving food system sustainability. As demonstrated in Chapter 6, there is a conflict between those who benefit from food trade due to reducing the environmental risks associated with local food supply, as compared to those who increase their risk to external environmental shocks through imports (45, 46). Further research is needed to understand how trade can be used both at national and sub-national scales to improve the resilience of the entire food system in an equitable manner. For now, the policy focus could remain on reducing the environmental risks to and impacts of food production at the source (47).

8.6 Conclusion

Through developing a greater understanding of sub-national food trade, this thesis assessed relationships between Indian food supply and the environment. For India, the research illustrates Indian food supply is highly interconnected across States and Union Territories. This thesis found that a substantial volume of food is traded sub-nationally in India; 40% of cereal food supply (Chapter 5), and between 30-60% of food supply for other crop food groups (Chapter 6). Environmental changes pose a risk to national food supply through sub-national food trade; 31 states are importing food that has been produced with unsustainable groundwater, while 30 states are importing food with a high drought risk. Agricultural diversification, including crop type and location of production, is an important solution for improving the sustainability of India's food system (48). Under diversification, food trade will play an essential role in distributing food across the country, and therefore future research is needed on the drivers of sub-national food flows and the policy levers to ensure equitable food distribution. To support this, continued monitoring of sub-national food supply chains is needed.

This thesis also advances scientific understanding of sustainable food systems. Firstly, I demonstrate that incorporating data on sub-national trade in larger countries improves the accuracy of WF assessments. Additionally, including data on sub-national trade in environmental risk assessments of food supply demonstrates substantial risks associated with domestic food imports. Future research could apply the modelling framework developed in this thesis to quantify sub-national food trade in other contexts and advance understanding of the relationship between food supply and the environment.

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APPENDIX

Appendix contents

Note:

Appendix files associated with published papers have been included in the published format.

APPENDIX 1 - Chapter 2: Thesis Overview Ethical Approval

London School of Hygiene & Tropical Medicine
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Observational / Interventions Research Ethics Committee

Miss Francesca Harris
LSHTM

19 October 2017

Dear Miss Francesca Harris

Study Title: The role of sustainable diets for water security in India

LSHTM Ethics Ref: 14331

Thank you for your application for the above research project which has now been considered by the Observational Committee via Chair's Action.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation, subject to the conditions specified below.

Conditions of the favourable opinion

Approval is dependent on local ethical approval having been received, where relevant.

Approved documents

The final list of documents reviewed and approved is as follows:

Document Type	File Name	Date	Version
Protocol / Proposal	Ethics-protocol_29.09	02/10/2017	2
Investigator CV	CV Francesca Harris LSHTM Format	02/10/2017	1
Investigator CV	CV Rosie Green LSHTM Format	02/10/2017	1
Local Approval	attachmentEntry-8782	03/10/2017	1
Protocol / Proposal	03.10_Water-diet-review-protocol	03/10/2017	1
Investigator CV	Edward Joy_CV_2_page_170919	04/10/2017	1
Investigator CV	Dangour CV July 2017	04/10/2017	1
Investigator CV	CV Pauline Scheelbeek - Sep 2017	04/10/2017	1

After ethical review

The Chief Investigator (CI) or delegate is responsible for informing the ethics committee of any subsequent changes to the application. These must be submitted to the committee for review using an Amendment form. Amendments must not be initiated before receipt of written favourable opinion from the committee.

The CI or delegate is also required to notify the ethics committee of any protocol violations and/or Suspected Unexpected Serious Adverse Reactions (SUSARs) which occur during the project by submitting a Serious Adverse Event form.

An annual report should be submitted to the committee using an Annual Report form on the anniversary of the approval of the study during the lifetime of the study.

At the end of the study, the CI or delegate must notify the committee using the End of Study form.

All aforementioned forms are available on the ethics online applications website and can only be submitted to the committee via the website at: http://leo.lshtm.ac.uk.

Further information is available at: www.lshtm.ac.uk/ethics.

Yours sincerely,

[redacted]

Professor John DH Porter
Chair

APPENDIX 2 - Chapter 3: Literature Review

Supplemental Table 1 Database specific search strategies used find relevant articles for inclusion in the systematic review.

Web of science		
Set	***Search***	**Hits (07/02/18)**
# 5	#4 AND #3	3,809
# 4	TS=(diet* OR ((food) NEAR/1 (consumption OR choice* OR secur* OR guideline OR recommendation)))	715,996
# 3	#2 OR #1	121,214
# 2	TS = ((water OR fresh-water OR freshwater OR groundwater OR ground-water OR blue-water OR green-water) NEAR/1 (footprint* OR overconsumpt* OR over-consumpt* OR consumption OR sustainability OR efficien* OR conservation OR saving* OR reduc* OR usage OR resourc* OR security OR availab* OR scarc*))	120,0986
# 1	TS= ("virtual water" OR waterfootprint)	854
Ovid Medline		
Set	***Search***	**Hits (07/02/18)**
1	((water or fresh-water or freshwater or groundwater or ground-water or blue-water or green-water) adj1 (footprint* or overconsump* or over-consump* or consump* or sustainab* or efficien* or conserv* or saving* or reduc* or usage or resourc* or security or availab* or scarc*)). ab, ti.	12550
2	("virtual water" or waterfootprint).ab,ti.	120
3	1 or 2	12616
4	diet*.mp. or (food adj1 (consumption or choice* or secur* or guideline* or recommendation*)).ab,ti.	603894
5	3 and 4	1214
6	Limit 5 to yr="2000-Current"	748
Agris OVID		
Set	***Search***	**Hits (07/02/18)**
1	((water or fresh-water or freshwater or groundwater or ground-water or blue-water or green-water) adj1 (footprint* or overconsump* or over-consump* or consump* or sustainab* or efficien* or conserv* or saving* or usage or resourc* or security or availab* or scarc*)).ab,ti. (26595)	**26595**
2	("virtual water" or waterfootprint).ab,ti.	**154**
3	1 or 2	**26625**
4	((diet or food) adj1 (consum* or choic* or secur* or guideline* or recommendation*)).ab,ti.	16747
EconLit OVID		
Set	***Search***	**Hits (07/02/18)**
5	3 and 4	457
# ▲	Searches	Results
1	((water or fresh-water or freshwater or groundwater or ground-water or blue-water or green-water) adj1 (footprint* or overconsumpt* or over-consumpt* or consumption or sustainability or efficien* or conservation or saving* or reduc* or usage or resourc* or security or availab* or scarc*)).ab,ti.	2803
2	("virtual water" or waterfootprint).ab,ti.	67
3	1 or 2	2813

4	diet*.mp. or (food adj1 (consumption or choice* or secur* or guideline or recommendation)).ab,ti. [mp=heading words, abstract, title, country as subject]	5047
5	3 and 4	78
CAB Abstracts		
Set	***Search***	**Hits (07/02/18)**
1	((water or fresh-water or freshwater or groundwater or ground-water or blue-water or green-water) adj1 (footprint* or overconsump* or over-consump* or consump* or sustainab* or efficien* or conserv* or saving* or usage or resourc* or security or availab* or scarc*)).ab,ti. (26595)	**83145**
2	("virtual water" or waterfootprint).ab,ti.	**495**
3	1 or 2	**83219**
4	((diet or food) adj1 (consum* or choic* or secur* or guideline* or recommendation*)).ab,ti. ()	50894
5	3 and 4	1675
SCOPUS		
	Search	
	TITLE-ABS-KEY(((virtual water) OR waterfootprint OR ((water OR fresh-water OR freshwater OR groundwater OR ground-water OR blue-water OR green-water) W/1 (footprint* OR overconsumpt* OR over-consumpt* OR consumption OR sustainability OR efficien* OR conservation OR saving* OR reduc* OR usage OR resourc* OR security OR availab* OR scarc*))) AND (diet* OR (food W/1 (consumption OR choice* OR secur* OR guideline OR recommend*))))	**Total hits (07/02/18) – 4238**
GREENFILE		
	Search	**Hits (07/02/18)**
	((water or fresh-water or freshwater or groundwater or ground-water or blue-water or green-water) N1 (footprint* or overconsumpt* or over-consumpt* or consumption or sustainability or efficien* or conservation or saving* or reduc* or usage or resourc* or security or availab* or scarc*)) OR ("virtual-water" or waterfootprint) – AB	
	AND	
	diet* or (food N1 (consumption or choice* or secur* or guideline or recommendation)) - AB	
	From 2000	**292**

APPENDIX

Supplemental Table 2 Characteristics and results of included studies

Study (Supplemental Reference)	General study aims	Scale of estimate(s)	Location of estimate(s)	Dietary data source and scenarios (if any)	Water assessment method and data source	Indicator terms used	Findings relevant to this review	Assumptions about imported food	Quality level
Birney, C. I et al. 2017 (1)	Quantify environmental impacts of diets in USA (2010) including food loss and waste, and assess changes if diets shifted to those recommended.	National	USA	Uses the Economic Research Service (ERS) Loss-Adjusted Food Availability (LAFA) dataset for food consumption, and the US Department of Agriculture (USDA) dietary guidelines as a scenario	Green and blue water footprints using data from WaterStat and Tom et al., 2016 (2)	Green and blue water footprints	Blue and green water footprints of current dietary patterns are 756400 L/year per capita and 101800 L/year per capita respectively. Shifting to USDA guidelines results in green WFs 699700 L/year per capita, blue WF 114000 L/year per capita. The amount of food is only available in kcal/d per capita so couldn't include in quantitative analysis.	Food produced/ consumed in the same area, and global average water footprints applied if USA was not available.	high
Blas, A. et al. 2016 (3)	Composed seasonal menus of the recommended Mediterranean and the USDA diets, and compared WFs of each if produced in Spain vs USA.	National	Spain, USA	Scenario diets; Mediterranean Diet Foundation, US Department of Agriculture	Water Footprint Assessment Method, WaterStat database	Green, blue and grey water footprints	Mediterranean dietary pattern has lower WF in both countries, compared to the USDA. The WF of Mediterranean diet in Spain is 5276 L/d per capita, switching to USDA would increase this to 6870 L/d per capita - mainly due to increased green water use. The USDA WF in the US is 5632 L/d per capita, switching to the Mediterranean would result in a decreased WF of 4003 L/d per capita.	Considers imports, but only for some products and assuming weighted average from import countries (FAOStat trade matrix (4))	high
Capone, R. 2012 (5)	Compares water footprints, carbon footprints and ecological footprints between the three	National	Italy, Bosnia, Serbia	FAO Food balance Sheets, food available for supply	Water Footprint Assessment Method, WaterStat database	Green, blue and grey water footprints	The total green and blue water footprints of food supply were similar in Bosnia and Italy (1686.01 Million m^3 and 1683.4 Million m^3 respectively), and highest in Serbia. Meat is	Considers imports, weighted based on origin (data source not clear).	medium

	different countries based on 2006.						the highest contributor to the water footprint in all three countries.		
Damerau, K. et al. 2016 (6)	Investigates current (2011) and future environmental impacts (2050), based on changes to food preferences and fuel use. Explores dietary change scenarios by increase protein to match demand and substituting items.	Multi-country	Regions; Asia, Latin America, Middle East, OECD, Eastern Europe and Soviet Union	FAO Food Balance Sheets; food available for supply. Dietary change scenarios were; increasing protein supply to match the level in OECD countries, swapping certain foods while maintaining macro-nutrient share, and decreasing carbohydrate in the diet while substituting with fat.	Water Footprint Assessment Method, WaterStat database	Blue water footprints, Water intensity	Blue water footprints are lowest in the Middle East and Africa (481 L/d per capita), and highest in the Eastern European and Soviet Union (992 L/d per capita) and Asia (751 L/d per capita). In all regions, altering the macro-nutrient content of the diet (to more protein) and replacing certain foods (for example cereals, dairy) with less water demanding products (e.g. tubers, eggs), results in reduced blue water footprint.	Food produced/ consumed in the same area	high
Davis, K. F. et al. 2016 (7)	Explores environmental impacts current and future diet (2050) and assesses the potential of dietary change scenarios.	Global	Global	FAO Food balance Sheets, food available for supply	Water Footprint Assessment Method, WaterStat database	Total water footprint (green and blue)	776 m^3/y is required to support an average global diet (circa 2009). Animal products contribute to 43% of this.	Food produced/ consumed in the same area	high
Djanibekov, N. et al. 2013 (8)	Quantified the national water footprints of food consumption in Uzbekistan (2009) and projects income driven changes to the population's diet and resulting water footprints to 2034.	National	Uzbekistan	FAO Food balance Sheets, food available for supply	Water Footprint Assessment Method, WaterStat database	Total water footprint (green and blue)	The total water footprint of food consumption in Uzbekistan 1097 m^3/y per capita	Not clear	high
Gephart, J. A. et al. 2016 (9)	Minimise water, nitrogen, carbon and land footprints of diets based on nutritional and population data from the United States.	National	USA	Scenario of minimising environmental impacts while achieving nutritional needs. Food products and groups based on the USDA Dietary Guidelines and the Harvard University Healthy Eating Plate. Scenarios were calculated first with no constraint on the serving number, and second with	Water Footprint Assessment Method, WaterStat database, plus an additional estimation of the water footprint of seafood based on	Total water footprint (green and blue)	Diets that were optimised for nutrition and water with no constraint of serving number could achieve a total water footprint of 0.62 m^3/d per capita. However, when the 26 serving constraint was added this increased to 2.26 m^3/d per capita. If diets are optimised	Food produced/ consumed in the same area	medium

				constraints of maximum of 26 servings of each specific food item.	Gephart et al., 2014. (10)		to all environmental impacts and nutrient constraints, the water footprint is 2.46 m^3/d per capita.		
Goldstein, B. et al. 2017 (11)	Applies Life Cycle Assessment (LCA) methodology to assess the potential for a plant-based burger to reduce the environmental impacts of food demand in the United States through vegetarian and vegan diets.	National	USA	USDA loss-adjusted-food-availability estimates (2010) for the average diet, and the vegetarian and vegan diets are based on the USDA's 2010 dietary guidelines.	Ecoinvent 3.2 database	Blue water footprint	The mean US diet has a blue water footprint of 294 m^3/y per capita. Vegetarian and vegan diets would reduce this by 62% and 70% respectively (when diets remain iso-caloric). Substituting ground beef for a plant based burger at 10%. 25% and 50% would also reduce water use by 6 (2.1%), 15 (5.2%) and 31 (10.4%) m^3/y per capita.	Not clear	medium
Hadjikakou, M. et al (12)	Compares the water footprints (direct and indirect) of five different tourist groups travelling from the UK to the Eastern Mediterranean (Cyprus, Turkey, Greece, Syria).	Population group – tourists	Eastern Mediterranean	Scenario diets based on different types of holiday; Luxury golf holiday; meat-rich diet, walking/hiking holiday; vegan diet, budget beach holiday; western diet, relaxing beach holiday; holiday diet, backpacking; local diet.	Water Footprint Assessment Method, WaterStat database	Green and blue water footprints, virtual water content	Diets are the largest component of tourist's water use. Meat contributes to over 75% of the water use for all diets, except the vegan one. However, fruit and vegetables in the vegan diet had a particular high water footprint.	Considers import quantity through FAOStat trade balance sheets (4), WF value assumed to be the same as local.	high
Hai-yang, S. 2015 (13)	Assesses the virtual water content of food consumption in the Gansu province, China (1992-2005), and quantifies the water saving potential of diet changes; reducing meat and increasing vegetables.	Sub-national	China (Gansu)	Gansu Province Statistical Yearbook for average consumption and three scenarios of changing meat and vegetable products.	Water Footprint Assessment Method, WaterStat database	Total water footprint (green and blue)	The average water footprint of an individual in the Gansu province is 698m^3/y per capita. This decreases with reduction in meat; for an iso-caloric diet, the total water footprint is 635m^3/y per capita with 50% reduction in meat and a 400% increase in vegetables.	Not clear	low
Harris, F. et al. 2017 (14)	Quantifies the green and blue water footprints of diets in India, comparing the	National/Sub-National	India	Dietary data from food frequency questionnaire in India (15) (n=6775)	Water Footprint Assessment Method, WaterStat	Green and blue water footprints	An Indian diet has an average (SD) green water footprint of 2531 (885) L/d per capita, and blue of 737	Food produced/ consumed in the same area	high

	blue water footprint between different socio-demographic groups				database, with additional adjustments of animal source foods based on the spatial variability in the water footprint of feed.		(263) L/d per capita. The blue water footprint is lowest in the Southern region, and highest for urban and wealthier populations.		
Hess, T. et al. 2015 (16)	Calculates the water footprint and blue water scarcity footprint of UK food consumption (2005), and assesses alternative future scenarios dietary scenarios and their effect on global water scarcity.	National	UK	UK food consumption obtained from Audsley et al., 2009 (17)	Blue and green water footprints obtained using Water Footprint Assessment Method, WaterStat database. Virtual blue water scarcity calculated using country specific estimates of Water Stress Index (18)	Blue and green virtual water consumption; Water scarcity footprint	The average total dietary water footprint in the UK 2400L/d per capita, of which 160L/d per capita is blue.	Considers import quantity and water footprint in country of origin, using UK trade data from HM Revenue and Customs, 2013 (19) and INTRACEN, 2013(20).	medium
Jalava, M. et al. 2016 (21)	Quantifies water footprints of national diets globally (2009-2011), and assesses the potential to reduce water use and scarcity by changing diets (recommended and reducing animal source foods) and reducing food loss and waste.	Global/National	Global	Current food consumption based on Food and Agricultural Organisation Food Balance Sheets. Scenarios were changing diets based on WHO recommendations (22), and four diet scenarios with 50%, 25%, 12.5%, and 0% cap on animal based protein, of which one third can be from meat.	Water Footprint Assessment Method, WaterStat database	Green and blue water footprints and water saving	Shifting global diets to those recommended would decreased the blue and green water footprints by 6% and 7% respectively. Reducing animal source foods by 25% would decrease this further; - 11% for blue, -18% for green.	Considers import quantity from FAO trade data (4), uses global average water use values	high
Jalava, M. et al. 2014 (23)	Compares the water footprint of current national diets globally (2007-2009) to diets that follow recommendations and four scenarios of reducing animal sources foods.	Global/National	Global	Current food consumption based on Food and Agricultural Organisation Food Balance Sheets. Scenarios were changing diets based on WHO recommendations(22), and four diet scenarios reducing animal sources foods to 50%, 25%, 12.5% and 0% of the total protein intake.	Water Footprint Assessment Method, WaterStat database	Green and blue water footprints	In regions of the world consuming diets that are excess in energy, the blue water footprint is 360L/d per capita and green 2563L/d per capita. This could be reduced by 6% for green and blue if following the recommended diet, or 19% (blue) and 22% (green) if no animal source protein. In regions of the world that	Considers imports from FAO trade data (4), using water footprint of weighted average of all global exports	high

							need to increase energy intake of the diet, the green water footprint was 1943L/d per capita and blue 442L/d per capita. Switching to the recommended diet would increase the green and blue water footprints by 7%, but reducing animal source foods to 0% decreases the blue water footprint by 8% and green by 17%.		
Kang, J. F. et al. 2017 (24)	Calculates the water footprint of food consumption in rural and urban Xiamen, China, and uses decomposition analysis to assess the driving forces in water footprint change (2001-2012).	Sub-national	China (Xiamen)	Food consumption data from the Yearbook of Xiamen Special Economic Zone (2002-2013)	Followed the Water Footprint Assessment method, using CROPWAT software (25) for local crops and Hoekstra and Chapagain (26) for imported foods and livestock.	Total water footprint (green and blue), virtual water content	The total water footprint of food consumption in Xiamen in 2001 was 725 Million m^3/y compared to 1369 Million m^3/y in 2012. For Xiamen city specifically, the food consumption water footprints were 524 Million m^3/year in 2001 compared to 1199 Million m^3/y in 2012. Values could not be converted to per capita for the analysis.	Considers imports in the virtual water content of crops, although methods are not clear.	medium
Kummu, M. et al. 2012 (27)	Estimates the water use for domestic food supply and corresponding food loss and waste for all countries globally.	Global/ Multi-country	Regions: Africa, Europe, Industrialised Asia, Latin America, North Africa & Western-Central Asia, South & Southeast Asia, Global	FAO Food balance Sheets, food available for supply but with additional adjustments for food waste.	Water Footprint Assessment Method, WaterStat database	Blue water footprint	The global average blue water footprint of food supply is 111 m^3/y per capita. It is highest in North Africa & West-Central Asia 258 m^3/y per capita, and lowest in Sub-Saharan Africa at 52 m^3/y per capita.	Considers import quantity, using weighted average of all global exports for water footprint	high
Li, J. 2017 (28)	Assesses the direct and indirect water footprints of tourists in the Beijing-Tianjin-Hebei metropolitan region of China.	Population group – tourists	China	Four scenario diets for different tourist groups (for each Western and Asian); high end, economy, family travel and backpacker.	Water Footprint Assessment Method, WaterStat database	Total water footprint	Western high end tourists have the highest dietary water footprint at 8520 L/d per capita, compared to an Asian backpacker tourist with only 2797 L/d per capita. Included in the analysis as food groups converted from kcal to kg/y per capita based on	Not clear	medium

							conversion rates given by author.		
Lyakurwa, F. S. 2014 (29)	Assesses the water footprint of food consumption in Tanzania, linking the water footprints with energy values of food, and calculates the water savings of different dietary scenarios (reducing animal source foods).	National	Tanzania	FAO Food balance Sheets, food available for supply	Water Footprint Assessment Method, WaterStat database	Water footprint (water saving)	The water saving of dietary scenarios ranges between 688 Million m^3 if 100% of animal products are replaced with vegetable products, compared to 28 Million m^3 if 25% of wheat and rice consumption is replaced with fruits. Baseline dietary water footprint was not available.	Considers import quantity, using FAO food balance sheets. Water use data not clear.	low
Marrin, D.L. 2016 (30)	Estimates the local blue water used for animal and plant-based food, and compares the potential for dietary shifts and reducing food waste of local residents to reduce local blue water use.	Sub-national	USA (California)	Not clear	Obtained from a report undertaken by the Pacific Institute (31)	blue water footprint	Animal based foods consume an average of 7 billion m^3/y compared to 3.1 billion m^3/y in California. Adopting one vegan day per week could decrease the local blue water footprint by 6%, compared to 14% for one vegan meal per day.	Food produced/ consumed in the same area	low
Martin, M. and Danielsson, L. 2016 (32)	Uses life cycle assessment methodology to calculate the environmental impacts of food consumption in the European Union (2010), and compares policy options for reducing them to 2030 and 2050.	Multi-country	EU27	FAO Food balance Sheets, food available for supply	Ivanova et al., 2015.(33) and the Ecoinvent database (34)	blue water footprint	In 2010, the blue water footprint of EU food consumption as 98700 Million m^3 (including waste figures).	Not clear	low
Mekonnen, M. M. and Hoekstra, A. Y. 2012 (35)	Quantifies the water footprints of animal products globally, and includes an estimate for the water saving if the average American switched to vegetarian or vegan diets.	National	USA	Scenario: replacing all meat with an equivalent amount of crop products (pulses and nuts)	Water Footprint Assessment Method, WaterStat database	Water footprint (water saving)	Meat contributes to 37% of the total dietary water footprint of an American. Replacing all meat with plant products decreases the water footprint by 30%.	Not clear	low

Mukuve, F. M. and Fenner. R.A. 2015 (36)	Calculates the current (2012) water resource use of food consumption in Uganda, and assesses the potential water resource use to achieve food security (in 2012, and 2050).	National	Uganda	FAO Food balance Sheets, food available for supply (1900 kcal/d per capita), and a scenario for increasing Uganda food consumption to FAO's recommended daily calorie intake level of 3000 kcal/d per capita (37).	Based on diet for Sub-Saharan Africa from Rockström, 2003 (38).	Total water footprint (green and blue)	The current diet results in the water consumption of 690 m^3/y per capita, compared to 1300 m^3/y per capita if daily calorie needs are met.	Not clear	low
Ruiter de, H. 2012 (39)	Assesses the potential to reduce water use by quantifying the water use of the food production system at different levels (e.g. crop, agricultural and cultural).	National	The Netherlands, Spain	Scenario diet to match minimum food requirements in The Netherlands and Spain, and a more culturally acceptable diet in The Netherlands.	Calculated water requirements and Water Footprint Assessment Method, WaterStat database	Total water footprint (green and blue), water requirements.	The minimum amount of water required to produce a diet (consisting of sugar beet, rapeseed and oats) is 295 L/d in the Dutch system, however the location of production matters where it would be 686 L/day per capita. If diets consist of the four most eaten foods in The Netherlands, the water requirements increase to 1413 L/day per capita.	Food produced/ consumed in the same area	low
Saez-Almendros, S. et al. 2013 (40)	Compares the environmental impacts of the current Spanish diet to the Mediterranean Diet Pattern and an average USA (Western) diet.	National	Spain	For current consumption, uses FAO Food Balance Sheets (2007) and the Household Consumption Surveys of the Spanish Ministry of Agriculture, Food and Environment (6000 households). Scenarios are Western (USA - FAO FBS) diet, and a diet based on the Mediterranean Diet Pattern Pyramid.	Various sources: Water Footprint Assessment Method, WaterStat database., Eurostat database, Garrido et al., 2012 (41). Gazulla et al., 2010 (42).	Total water footprint (green and blue)	The average diet of a Spanish citizen has a total water footprint of is 19.7 km^3/y if FBS are used to quantify consumption, compared to 13.4 km^3/y with household consumption surveys. The MDP has a water footprint lower at 13.3 km^3/y, but the WDP is highest at 22.0 km^3/y.	Food produced/ consumed in the same area	high
Song, G et al. 2015 (43)	Quantifies the environmental impacts of food consumption and waste of a household in China.	National	China	Chinese Health and Nutrition Survey database (2004-2009)	DEFP database from the Barilla foundation	Total water footprint (green and blue)	The average household in China has a dietary water footprint of 2436 m^3/y, which equates to 673 m^3/y per capita.	Not clear	medium

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Sun, S et al. 2015 (44)	Calculates the water and energy conversion efficiencies of different crops in China, and assesses water saving potential through changing food consumption in China.	National	China	Chinese statistical year book (2011) (45) and China Agriculture Statistical Report (2011) (46) for current consumption, and scenario diets based on lower and upper limits from the Dietary Guidelines for Chinese Residents, 2011 (47).	Water Footprint Assessment Method, WaterStat database	green and blue water footprints	If diets in China were adjusted to healthy dietary guidelines, this could achieve a green water saving of between -59.79 Gm^3 (for lower limit of animal source foods), while the blue water footprint could decrease by 4.64 Gm^3. If diets were shifted to the upper limit of animal source foods in the dietary guidelines, this would increase water use by 0.11 Gm^3.	Food produced/ consumed in the same area	low
Thaler, S. et al. 2014 (48)	Undertakes an environmental impact assessment of food consumption in Austria (2001-2006)	National	Austria	Statistik Austria, 2007 (49)	Used the Water Footprint Assessment but calculated based on available data in Austria.	green and blue water footprints	The green water footprint was 3.9 m^3/d per capita, and blue was 0.04 m^3/d per capita. Animal source foods are responsible for 87% of the total water footprint.	Considers import quantity from Statistik Austria 2007 supply balance accounts, using global average water footprints	high
Tom, M. S. et al. 2016 (2)	Compares the potential to reduce environmental impacts of USA food consumption through different dietary strategies.	National	USA	Calculated based on US Department of Agriculture and US Department of Health and Human Services 2010 data, and total energy intake based on calculated requirements from the National Health and Nutrition Examination Survey. The three dietary scenarios include 1) reducing calories to sufficient level, 2) changing food mix to patterns recommended by the USDA Dietary Guidelines, without reducing Caloric intake, and 3) reducing Caloric intake levels and shifting food mix to meet USDA Dietary Guidelines.	Water Footprint Assessment Method, WaterStat database	blue water footprints	Compared to current average intake, shifting to healthier diets in the USA would result in an increased blue water footprint by around 16%. Reducing caloric level to proposed level for normal weight would decrease the blue water footprint by around 9%. Combination of both changing the food mix and reducing calories increases the water footprint by 10%.	Food produced/ consumed in the same area	medium
Vanham, D. 2013 (50)	Analysis the water footprint of current diets in Austria and compares to healthier and vegetarian diets.	National	Austria	Current food intake based on FAO FBS, with conversion factors applied to account for waste and other uses (Statistics Austria data, Zessner et al., 2011 (51)	Water Footprint Assessment Method, WaterStat database	green and blue water footprints	The green water footprint was 3108 L/d per capita, and the blue was 181 L/d per capita. Dietary scenarios could not be used as they contain grey water.	Not clear	high

Vanham, D. et al. 2014 (52)	Compares the water footprint of the average diet in the EU28 (EU27+Croatia), to a healthy diet, vegetarian and combined diet.	Multi-country	EU28	For current consumption, uses FAO Food Balance Sheets (1996-2005), with additional conversion factors for waste and other uses (51, 53) Recommended diet based on the German Nutrition Society recommendation; healthy, vegetarian, combined.	Water Footprint Assessment Method, WaterStat database	green and blue water footprints	The water footprint of the reference diets in the EU28 had a green water footprint of 3572 L/d per capita, and a blue of 299 L/d per capita. Healthier diets had lower water footprints than the reference, but vegetarian diets had the lowest green and blue water footprints (2187 and 206 L/d per capita respectively).	Not clear	medium
Vanham, D. and Bidoglio, G. 2014 (54)	Assesses the agricultural water footprints in 365 European river basins, and compares this to two dietary scenarios; healthy and vegetarian.	Multi-country/National	Europe	FAO Food Balance Sheets, food available for supply for current consumption. Healthy dietary scenarios were based on regional FBDG for the 40 nations separately.	Water Footprint Assessment Method, WaterStat database	green and blue water footprints	If diets were to shift to healthier patterns, this would decrease the water footprints in most river basins (max -32%), however it increased in some areas such as northern and eastern Europe.	Not clear	medium
Vanham, D. and Bidoglio. D. 2014 (55)	Quantifies the water footprint of Milan, including agricultural, industrial and domestic use.	Sub-national	Italy (Milan)	FAO Food balance Sheets, food available for supply for current consumption, as well as Mediterranean dietary guideline (56) for a healthy diet and vegetarian diet.	Water Footprint Assessment Method, WaterStat database	green and blue water footprints	The current diets in Milan have a green water footprint of 4714 L/d per capita and a blue of 441 L/d per capita. By switching to healthier diets this could be reduced to; green 3196 L/d per capita, blue 321 L/d per capita. This is even more for vegetarian diets; green: 2592 L/d per capita, blue: 280 L/d per capita	Not clear	medium
Vanham, D. et al. 2015 (57)	Calculates the water and nitrogen use of EU food consumption and waste.	Multi-country	EU	FAO Food Balance Sheets, food available for supply for current consumption, with correction factors applied for waste and other uses.	Water Footprint Assessment Method, WaterStat database	green and blue water footprints	The green water footprint of EU food consumption was calculated at 3383 L/d per capita, and the blue was 270 L/d per capita.	Food produced/ consumed in the same area	high

Vanham, D. et al. 2016.(58)	Estimates the water footprints associated with food consumption in 13 Mediterranean cities (1995-2005) and assesses the potential for different dietary strategies to reduce this (healthy with meat, healthy pescatarian, healthy vegetarian).	Sub-national	Croatia (Dubrovnick), France (Lyon), Greece (Athens), Israel (Jerusalem), Italy (Genova, Pisa, Bolgona, Reggio), Slovenia (Ljublijana), Spain (Manresa, Zaragoza), Turkey (Istanbul, Ankara)	FAO FBS with correction factors (using national surveys for each country), and scenarios for reducing water footprints. Healthy meat patterns all based on the Mediterranean diet (56).	Water Footprint Assessment Method, WaterStat database	green and blue water footprints	The total water footprints of current food consumption ranged from 3277 L/d per capita in Ljubljana, to 5789 L/d per capita. in Jerusalem. Switching to a healthy diet could reduce this in all cities, with the healthy vegetarian diets having the lowest total water footprints (2211 L/d per capita in Ljubljana).	Not clear	high
Vanham, D. et al. 2017.(59)	Quantifies the water footprint the direct and indirect water footprints in Hong Kong (1995-2005) and compares the water footprint of different dietary scenarios (current, healthy, pescatarian, and vegetarian).	Sub-national	China (Hong Kong)	FAO FBS with correction factors (for food use and waste), and dietary scenarios based on recommendations from the Chinese Nutrition Society (47), with adjustments for calorie requirements based on the population distribution. Pescatarian was healthy but with all meats/animal fats substituted for plant products, vegetarian is healthy but with all fish and meats substituted for plant products.	Water Footprint Assessment Method, WaterStat database	green and blue water footprints	The total water footprint of diets in Hong Kong was 4727 L/d per capita, of which the blue water footprint was 634 L/d per capita. With healthy dietary shifts, this total water use was reduced by 40%. The largest reduction was achieved from switching to healthy vegetarian diets; a green water footprint of 1832 L/d per capita and a blue of 392 L/d per capita	Considers import quantity and source (FAO trade matrix)(4).	high
Vanham, D et al. 2017 (60).	Calculates the water footprint of food consumption (1995-2005) in different Nordic cities, and assesses the potential for different dietary strategies (healthy, pescatarian, vegetarian) to reduce this.	Sub-national	Sweden (Stockholm, Malmo, Eslov, Helsingborg, Kristianstad), Denmark (Copenhagen), Finland (Helsinki), Norway (Oslo), Iceland (Reykjavik)	FAO FBS with additional calculations using national dietary of food surveys for each country. For the Healthy dietary scenarios, used new Nordic Nutrition Recommendations (NNR) of 2012 (Nordic Council of Ministers, 2012), healthy pescatarian based on the NNR, and healthy veg based on NNR	Water Footprint Assessment Method, WaterStat database	green and blue water footprints	The water footprints vary between 3552 L/d per capita in Denmark to 2865 L/d per capita in Helsinki. Switching to healthy diets reduced the water footprint for all cities. The greatest reduction can be achieved by switching to healthy vegetarian diets (between -35% to -44%).	Not clear	medium
Vanham, D. et al. 2013 (61)	Compares the water footprints of food consumption (1995-2005) between the North, West, South and Eastern EU zones, and calculates the water footprint for healthy	Multi-country	EU - East, North, South, West	FAO FBS with correction factors for current consumption. Healthy dietary scenario is based on regional dietary guidelines (e.g. German Nutrition Society, Mediterranean dietary guidelines).	Water Footprint Assessment Method, WaterStat database	green and blue water footprints	The water footprints of current diets are 5364 L/d per capita (South), 3635 L/d per capita (East), 3421 L/d per capita (West) and 2889 L/d per capita(North). Diets in the South had the highest blue water footprint at 618 L/d per capita. Switching to	Food produced/ consumed in the same area	high

	and vegetarian diets in each region.						healthy diets would reduce this between -30 to -3%. Vegetarian diets would reduce total water footprints to between -41% to -27% (depending on region).		
Vanham, D et al. 2016 (62)	Assess the water footprint associated with direct use and food consumption (1995-2005) in Dutch cities with different levels of urbanisation, and compares current dietary water footprint to healthy, pescatarian and vegetarian diets.	Sub-national	The Netherlands (Amsterdam, Dordrecht, Rotterdam, Einhoven, Maastricht, Nieuwegin, Venlo)	FAO FBS, and Dutch National Food Consumption Survey (DNFCS) 2016. The DNFCS was used to distinguish food consumption by urbanisation level. Ref year for FBS 1996-2005. Healthy diets based on Dutch Food Based Dietary Guidelines, pescatarian is the same as healthy but with all meat products replaced with plant products, and vegetarian is all the meat and fish products replaced with plant products.	Water Footprint Assessment Method, WaterStat database	total (green and blue water footprints combined)	The total water footprint of current diets ranged from 3126L/d per capita in strongly urbanised cities to 3245 L/d per capita in extremely urbanised cities. All dietary scenarios explored reduced the water footprint of food consumption, but the lowest values were achieved for vegetarian diets; between 1860L/d per capita for Nieuwegin to 1883L/d per capita for Amsterdam.	Food produced/ consumed in the same area	medium
Yoo, S. H.et al. 2016 (63)	Observed the trends in water footprints over 25 years in South Korea (from 1985 to 2010), future food production and consumption scenarios were explored in 2015 and 2020 for the targets of food self-sufficiency.	National	South Korea	Korea Rural Economic Institute (KREI) (2011) Food balance sheet. Korea Rural Economic Institute, Seoul (in Korean)	Various National databases; Yoo et al., 2014a (64). Yoo et al., 2014b (65), Lee et al., 2015 (66).	green and blue water footprints	The water footprint of food consumption has increased in South Korea from 758.9 m^3/y per capita (1995) to 822.9 m^3/y per capita (2010. In 2010, the green water footprint was 754 m^3/y per capita and the blue was 68.9 m^3/y per capita. Cereals and meats accounted for 18.3 and 38.6 % of the total water footprint of food consumption in 2010.	Not clear	medium

Yuan, Q. et al. 2016 (67)	Assesses the water footprint of food consumption in the Heilongjiang northernmost province of China, comparing the differences between rural and urban households.	Sub-national	China (Heilongjiang)	China Health and Nutrition Survey	Water Footprint Assessment Method, WaterStat database	green and blue water footprints	The average total dietary water footprint in the region was 1.47m^3/d per capita. This was higher in the urban region compared to rural. The green water footprint in the urban area was 1.64 m^3/d per capita, and blue 0.32 m^3/d per capita, in the rural the green was 1.14 m^3/d per capita and the blue was 0.26 m^3/d per capita.	Not clear	low
Zhuo, L. et al. 2016 (68)	Quantifies the consumptive water use and virtual water trade in China from 1978-2008, and considers water use under future scenarios (to 2030 and 2050).	National	China	FAO Food Balance Sheets; food available for supply.	Water Footprint Assessment Method, WaterStat database	total (green and blue water footprints combined)	The total water footprint of Chinese food consumption in 2005 was 927 m^3/y per capita (baseline scenario for the analysis).	Considers import quantity through the difference between production and consumption, and applies global average WFs for the crops.	medium

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Supplemental Table 3 Quality scores of included studies

Study (Supplemental Ref.)	**Was the baseline diet source stated?**	**Is there a clear description of the baseline diet pattern?**	**Is the full diet assessed?**	**Is there a clear description of the water use assessed?**	**Is the water use data source clearly stated?**	**Is there a clear description of the study area/ population?**	**Is there a description of methods used to link consumption-water (e.g. consideration of trade or other factors)?**	**Are the assumptions/ limitations stated?**	**Are there confidence limits around the estimated dietary water use?**	**For studies assessing scenarios, is there a clear justification/ description of the scenario diet?**	**%**	**quality - >50% = low, 50-70% = medium, >70%= high**
Birney, C. I et al. 2017 (1)	1	1	0	1	1	1	1	1	0	1	80	high
Blas, A. et al. 2016 (3)	1	1	0	1	1	1	1	1	0	1	80	high
Capone, R. 2012 (5)	1	1	0	1	1	1	0	0	0	NA	55.6	medium
Damerau, K. et al. 2016 (6)	1	0	1	1	1	1	1	1	0	1	80	high
Davis, K. F. et al. 2016 (7)	1	1	1	1	1	0	0	1	1	NA	77.8	high
Djanibekov, N. et al. 2013 (8)	1	1	1	1	1	1	0	1	0	NA	77.8	high
Gephart, J. A. et al. 2016 (9)	1	1	0	1	1	0	0	1	0	1	60	medium
Goldstein, B. et al. 2017 (11)	1	1	1	1	0	0	1	1	0	1	70	medium
Hadjikakou, M. et al (12)	1	0	1	1	1	1	1	1	0	NA	77.8	high
Hai-yang, S. 2015 (13)	1	0	1	0	0	1	0	0	0	0	30	low
Harris, F. et al. 2017 (14)	1	1	1	1	1	1	1	1	1	NA	100	high
Hess, T. et al. 2015 (16)	1	0	1	1	1	0	1	1	0	NA	66.7	medium
Jalava, M. et al. 2016 (21)	1	1	1	1	1	1	1	1	0	1	90	high
Jalava, M. et al. 2014 (23)	1	1	1	1	1	0	1	1	0	1	80	high
Kang, J. F. et al. 2017 (24)	1	0	1	1	1	1	1	0	0	NA	66.7	medium

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Kummu, M. et al. 2012 (27)	1	0	1	1	1	1	1	1	0	NA	77.8	high
Li, J. 2017 (28)	0	1	1	0	1	0	0	1	0	1	50	medium
Lyakurwa, F. S. 2014 (29)	0	0	1	1	1	0	0	0	0	0	30	low
Marrin, D.L. 2016 (30)	0	0	0	1	0	0	1	0	0	NA	22.2	low
Martin, M. and Danielsson, L.. 2016 (32)	1	1	0	1	1	0	0	0	0	NA	44.4	low
Mekonnen, M. M. and Hoekstra, A. Y. 2012 (35)	0	0	0	1	1	0	0	0	0	0	20	low
Mukuve, F. M. and Fenner. R.A. 2015 (36)	0	0	1	0	1	0	0	0	0	1	30	low
Ruiter de, H. 2012 (39)	1	0	0	0	1	0	0	1	0	1	40	low
Saez-Almendros, S. et al. 2013 (40)	1	0	1	1	1	1	1	1	0	1	80	high
Song, G et al. 2015 (43)	1	1	1	0	1	1	0	0	1	NA	66.7	medium
Sun, S et al. 2015 (44)	1	0	0	0	1	1	0	0	0	NA	33.3	low
Thaler, S. et al. 2014 (48)	1	1	0	1	1	1	1	1	0	NA	77.8	high
Tom, M. S. et al. 2016 (2)	1	0	1	1	1	0	0	1	1	NA	66.7	medium
Vanham, D. 2013 (50)	1	1	1	1	1	1	1	0	0	1	80	high
Vanham, D. et al. 2014 (52)	1	1	1	1	1	0	0	0	0	1	60	medium
Vanham, D. and Bidoglio, G. 2014 (54)	1	0	1	1	1	0	0	0	0	1	50	medium
Vanham, D. and Bidoglio. D. 2014 (55)	1	0	1	1	1	0	0	1	0	1	60	medium
Vanham, D. et al. 2015 (57)	1	1	1	1	1	1	0	1	0	NA	77.8	high
Vanham, D. et al. 2016.(58)	1	1	1	1	1	1	0	1	0	1	80	high
Vanham, D. et al. 2017.(59)	1	1	1	1	1	1	1	1	0	1	90	high
Vanham, D et al. 2017 (60).	1	1	1	1	1	1	0	0	0	1	70	medium

Vanham, D. et al. 2013 (61)	1	1	1	1	1	1	0	1	0	1	80	high
Vanham, D et al. 2016 (62)	1	0	1	1	1	1	0	0	0	1	60	medium
Yoo, S. H.et al. 2016 (63)	1	1	1	1	1	1	0	0	0	NA	66.7	medium
Yuan, Q. et al. 2016 (67)	1	0	0	1	0	0	0	0	0	NA	22.2	low
Zhuo, L. et al. 2016 (68)	1	0	0	1	1	1	1	1	0	NA	66.7	medium

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Supplemental Table 4 Major food groups contributing to each dietary WF for the corresponding patterns. N studies = 30. Light colours boxes indicate information was not available.

KEY	mixed animal source and plant based foods	fruits and vegetables	animal source foods	grains, cereals, potatos	other plant based foods

			Main food groups contributing to the dietary water footprint (%)*					
Study (Supplemental Ref.)	Country/Region	Diet pattern	Blue		Green		Total	
Birney et al. 2017 (1)	USA	average	meat, poultry, eggs (24%)	grains (13%)	meat, poultry, eggs (49%)	dairy (15%)		
Capone 2012 (5)	Italy, Bosnia, Serbia	average					meat (beef) (32-42%)	dairy (milk) (10-22%)
Davis et al. 2016 (7)	Global (245 countries)	average					grains (30%)	beef meat (12%)
Djanibekov et al. 2013 (8)	Uzbekistan	average					meat (42%)	wheat (16%)
Goldstein et al. 2017 (11)	USA	average	protein (74%)	grain (10-11%)				
Hai-yang 2015 (13)	China	average					fruits (12-16%(	eggs (8-12%)
Harris et al. 2017 (14)	India	average	wheat (0-88%)	rice (0-85%)	meat and fish (0-80%)	rice (0-70%)		
Hess et al. 2015 (16)	UK	average	milk (18%)	rice (12%)				
Marrin 2016 (30)	USA	average	plant based foods (55%)					
Mekonnen and Hoekstra 2012 (35)	USA	average					meat (37%)	
Song et al. 2015 (43)	China	average					pork meat (22%)	rice (22%)
Thaler et al. 2014 (48)	Austria	average	plant based foods (75%)		animal source foods (83%)			
Vanham et al 2016 (58)	Mediterranean (8 countries)	average					meat	
Vanham et al. 2013 (52)	EU (28 countries)	average	milk (exc butter) (13%)	pigmeat (12%)	milk (exc butter) (13%)	bovine meat (12%)		
Vanham et al. 2013 (61)	EU (28 countries)	average					meat	milk and milk products
Vanham and Bidoglio 2014 (55)	Italy	average					meat	crop oils
Vanham et al. 2015 (57)	EU (28 countries)	average	meat (30%)	sugar (11%)	meat (37%)	cereals (10%)		
Vanham et al. 2016 (62)	The Netherlands	average					meat (29-31%)	milk and milk products
Vanham et al. 2016 (58)	China	average	tree nuts (25%)	freshwater fish (11%)	meat	cereals		
Vanham et al. 2017(60)	Nordic region (5 countries)	average					meat (32%)	milk and milk products (19%)
Vanham 2013 (50)	Austria	average					meat	milk and milk products
Yoo et al. 2016 (63)	South Korea	average	cereals (65-75%)	tree nuts, oil crops and sugars (9-15%)	meats (35-42%)	oils and fats (18-25%)		
Yuan et al. 2016 (67)	China	average					animal source foods	

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Zhuo et al. 2016 (68)	China	average					animal products (44%)	cereals (32%)
Birney et al. 2017 (1)	USA	healthy	fruit (27%)	meat, poultry, eggs (16%)	meat, poultry, eggs (39%)	dairy (27%)		
Blas et al. 2016 (3)	USA, Spain	healthy	olive oil (24-29%)	soy milk (21%)	olive oil (22%)	beef meat (7-19%)		
Saez-Almendros et al. 2013 (40)	Spain	healthy					vegetables (34%)	cereals (17%)
Vanham et al. 2013 (52)	EU (28 countries)	healthy	meat	fruit				
Vanham et al. 2013(61)	EU (28 countries)	healthy					meat	milk and milk products
Vanham and Bidoglio 2014 (55)	Italy	healthy					meat	cereals
Vanham et al. 2016 (58)	The Netherlands	healthy					stimulants	milk and milk products
Vanham et al.2017 (59)	China	healthy	tree nuts	cereals	cereals	meat		
Vanham et al. 2017 (60)	Nordic region (5 countries)	healthy					meat (31%)	stimulants (32%)
Vanham 2013 (50)	Austria	healthy					meat	milk and milk products
Goldstein et al. (11)	USA	reduced ASF	fruits and vegetables (18%)	proteins (21%)				
Vanham et al. 2013 (52)	EU (28 countries)	reduced ASF	milk and milk products	fruit				
Vanham et al. 2013 (61)	EU (28 countries)	reduced ASF					milk and milk products	stimulants
Vanham and Bidoglio 2014 (55)	Italy	reduced ASF					cereals	crop oils
Vanham et al. 2016 (58)	The Netherlands	reduced ASF					stimulants	milk and milk products
Vanham et al. 2017 (59)	China	reduced ASF	tree nuts	cereals	cereals	fruit		
Vanham et al. 2017 (60)	Nordic region (5 countries)	reduced ASF					stimulants (29-31%0	pulses, nuts and oil crops (14-24%
Vanham 2013 (50)	Austria	reduced ASF					milk and milk products	cereals
Goldstein et al. 2017 (11)	USA	no ASF	fruits and vegetables (34%)	grains (25%)				

* Top two items based on food groups reported in the study. If available percentages are reported. For studies that estimated multiple dietary water footprints, ranges in percentage contribution are presented. If percentage contributions could not be calculated (e.g. because data was displayed graphically), food groups are listed; only food groups that are clear major contributors across all diets are presented

Supplemental Table 5 Categories of dietary patterns used in the meta-analysis

	Categories used in meta-analysis				
	Average	**Healthy**	**Reduced animal source foods**	**No animal source foods**	**Other**
Name of dietary pattern in included studies[1]	Reference	National dietary guidelines (USDA, German Nutrition Society)	meat 75%, vegetables 200%	Vegan	Tourist; meat rich, western, holiday diet.
	Current	Current + additional protein to meet demand	meat 30%, vegetable 260%	Recommended diet with 0% protein from animal sources	FAO recommended calorie level for food security
	Total	Replaced foods + additional protein	meat 50%, vegetables 400%		minimum food requirement
	Baseline	Macro-nutrient shift + additional protein and replaced foods	vegetarian		adjusted to match culturally appropriate foods
		Minimum optimised for carbon +nutrient requirements	healthy pescatarian		western pattern
		Minimum optimised for nitrogen + nutrient requirements	healthy vegetarian		European high end tourist
		Minimum optimised for water + nutrient requirements			European tourist, economy tour
		Minimum optimised for land + nutrient requirements			European, family travel
		Minimum optimised for combined environmental impacts + nutrient requirements			European, backpacker/eco tour
		Dietary guidelines but with lower limit of animal products, higher crops			Asian, high end tourist
		Dietary guidelines but with upper limit of animal products, lower crops			Asian, economy tour
		Average with reduced kcal			Asian, family travel
		Dietary guideline but no change in kcal			Asian, backpacker/eco tour
		Dietary guideline + energy reduction			
		Combination of healthy and vegetarian			
		Turkish food based dietary guidelines			
		WHO recommended guidelines			
		Mediterranean dietary pattern			

[1]Values represent terminology used in the included study

Supplemental Table 6 Results from the meta-analysis on the effect of diet pattern on dietary total water footprint

	Model	Diet pattern	Coefficient (log)	*P* value	Lower 95% Confidence Limit (log)	Upper 95% Confidence Limit (log)	Coefficient (after exponentiation)	Lower 95% Confidence Limit (after exponentiation)	Upper 95% Confidence Limit (after exponentiation)	*N* estimates	*N* studies
all studies	simple	no animal source foods	-0.2886818	<0.001	-0.3361521	-0.2412115	-25.0749421	-28.54855801	-21.43245615	1933	32
		reduced animal source foods	-0.1952873	<0.001	-0.2259367	-0.1646379	-17.74017084	-20.22314012	-15.1799218	1933	32
		healthy	-0.0612204	<0.001	-0.0954	-0.0270409	-5.938409482	-9.099074197	-2.667856814	1933	32
	adjusted for location	no animal source foods	-0.2896898	<0.001	-0.3169606	-0.262419	-25.15042851	-27.16405481	-23.08113339	1933	32
		reduced animal source foods	-0.1959683	<0.001	-0.2135844	-0.1783522	-17.79617071	-19.23160113	-16.33522957	1933	32
		healthy	-0.061654	<0.001	-0.0813029	-0.0420051	-5.979185746	-7.808559872	-4.113510965	1933	32
	fully adjusted	no animal source foods	-0.2900833	<0.001	-0.3173443	-0.2628223	-25.17987602	-27.1919966	-23.11214851	1933	32
		reduced animal source foods	-0.1963015	<0.001	-0.2139077	-0.1786952	-17.82355647	-19.25770933	-16.36392167	1933	32
		healthy	-0.0622541	<0.001	-0.0818882	-0.0426201	-6.035590711	-7.862503734	-4.172463026	1933	32
excluding studies with >500 estimates	simple	no animal source foods	0.3701012	0.193	-0.1873707	0.927573	44.78811328	-17.08636814	152.8365382	337	30
		reduced animal source foods	-0.4252939	<0.001	-0.4867404	-0.3638475	-34.64223296	-38.53734307	-30.50028263	337	30
		healthy	-0.1940069	<0.001	-0.2588426	-0.1291712	-17.6347779	-22.80554825	-12.11765019	337	30
	adjusted for location	no animal source foods	0.3194119	0.151	-0.1162489	0.7550727	37.63181136	-10.97463884	112.7766206	337	30
		reduced animal source foods	-0.4287764	<0.001	-0.4728375	-0.3847153	-34.86944552	-37.6768662	-31.93556119	337	30
		healthy	-0.1964706	<0.001	-0.2429688	-0.1499725	-17.83745133	-21.57040166	-13.92683538	337	30

		no animal source foods	0.3253053	0.157	-0.1253653	0.7759758	38.4453255	-11.78254147	117.2711225	337	30
		reduced animal source foods	-0.4301385	<0.001	-0.4740442	-0.3862327	-34.95809945	-37.75202616	-32.03876385	337	30
	fully adjusted	healthy	-0.198678	<0.001	-0.2449476	-0.1524084	-18.01861691	-21.7254447	-14.13624584	337	30
excluding studies of low quality		no animal source foods	-0.2884263	<0.001	-0.3357722	-0.2410804	-25.0557963	-28.52140845	-21.42215527	1918	27
		reduced animal source foods	-0.1957239	<0.001	-0.2263218	-0.1651259	-17.77607764	-20.25385627	-15.2213039	1918	27
	simple	healthy	-0.0616445	<0.001	-0.0957599	-0.0275291	-5.978292544	-9.131783553	-2.715362769	1918	27
		no animal source foods	-0.2904166	<0.001	-0.3172949	-0.2635383	-25.20480941	-27.18839979	-23.16718051	1918	27
		reduced animal source foods	-0.1965849	<0.001	-0.2139658	-0.1792039	-17.84684197	-19.26240032	-16.40645652	1918	27
	adjusted for location	healthy	-0.062207	<0.001	-0.0815944	-0.0428195	-6.031164883	-7.835429761	-4.191569132	1918	27
		no animal source foods	-0.2914613	<0.001	-0.318352	-0.2645705	-25.28290714	-27.26532827	-23.24644643	1918	27
		reduced animal source foods	-0.1970267	<0.001	-0.2144106	-0.1796428	-17.88312922	-19.29830442	-16.44313768	1918	27
	fully adjusted	healthy	-0.0626953	<0.001	-0.0820832	-0.0433075	-6.077038664	-7.880468794	-4.23831224	1918	27

Supplemental Table 7 Results from the meta-analysis on the effect of diet pattern on dietary green water footprint

	Model	Diet pattern	Coefficient (log)	*P* value	Lower 95% Confidence Limit (log)	Upper 95% Confidence Limit (log)	Coefficient (after exponentiation)	Lower 95% Confidence Limit (after exponentiation)	Upper 95% Confidence Limit(after exponentiation)	*N* estimates	*N* studies
all studies	simple	no animal source foods	-0.300076	<0.001	-0.3525648	-0.2475873	-25.92380794	-29.71169785	-21.93179357	1834	20
		reduced animal source foods	-0.1977656	<0.001	-0.2322	-0.1633312	-17.94378296	-20.72124501	-15.06901496	1834	20
		healthy	-0.0591573	0.002	-0.0974991	-0.0208155	-5.744150696	-9.289684205	-2.060035286	1834	20
	adjusted for location	no animal source foods	-0.302352	<0.001	-0.3295288	-0.2751753	-26.09221363	-28.07374299	-24.05610181	1834	20
		reduced animal source foods	-0.199059	<0.001	-0.2168913	-0.1812267	-18.04984587	-19.49825301	-16.57537864	1834	20
		healthy	-0.0601711	<0.001	-0.0800315	-0.0403107	-5.839658854	-7.691273132	-3.950903176	1834	20
	fully adjusted	no animal source foods	-0.3030494	<0.001	-0.3302222	-0.2758767	-26.14373895	-28.12359937	-24.10935018	1834	20
		reduced animal source foods	-0.1993074	<0.001	-0.2171266	-0.1814882	-18.07019976	-19.51719284	-16.59719132	1834	20
		healthy	-0.0604242	<0.001	-0.0802695	-0.0405789	-5.863487821	-7.713239995	-3.976660089	1834	20
excluding studies with >500 estimates	simple	no animal source foods	0.2950423	0.512	-0.5877966	1.177881	34.31831741	-44.44499639	224.7485485	238	18
		reduced animal source foods	-0.431837	<0.001	-0.4977598	-0.3659141	-35.06847936	-39.21090672	-30.64376243	238	18
		healthy	-0.1940312	<0.001	-0.2617137	-0.1263487	-17.63677935	-23.02686337	-11.86925187	238	18
	adjusted for location	no animal source foods	-0.1812176	0.146	-0.4252626	0.0628273	-16.57461947	-34.64018723	6.484292498	238	18
		reduced animal source foods	-0.4364895	<0.001	-0.4727384	-0.4002405	-35.3698716	-37.67068967	-32.98411466	238	18
		healthy	-0.1907013	<0.001	-0.2277151	-0.1536875	-17.36206092	-20.3648892	-14.24600396	238	18
	fully adjusted	no animal source foods	-0.1849332	0.127	-0.4223726	0.0525062	-16.88401965	-34.45102416	5.390909629	238	18

		reduced animal source foods	-0.4413345	<0.001	-0.4767762	-0.4058928	-35.68224723	-37.92185554	-33.36184003	238	18
		healthy	-0.197003	<0.001	-0.2333041	-0.1607018	-17.88118303	-20.80872838	-14.84540357	238	18
excluding studies of low quality	simple	no animal source foods	-0.298768	<0.001	-0.3512166	-0.2463194	-25.82685288	-29.61687125	-21.83274812	1828	18
		reduced animal source foods	-0.1975808	<0.001	-0.2319779	-0.1631836	-17.92861757	-20.70363524	-15.05647822	1828	18
		healthy	-0.0579475	0.003	-0.096276	-0.0196191	-5.630050964	-9.17866854	-1.94278979	1828	18
	adjusted for location	no animal source foods	-0.3022482	<0.001	-0.3294116	-0.2750848	-26.0845416	-28.06531274	-24.04922858	1828	18
		reduced animal source foods	-0.1991499	<0.001	-0.2169821	-0.1813176	-18.0572948	-19.50556223	-16.58296159	1828	18
		healthy	-0.05999	<0.001	-0.0798699	-0.0401101	-5.822604872	-7.676354836	-3.931633794	1828	18
	fully adjusted	no animal source foods	-0.304015	<0.001	-0.3312219	-0.2768082	-26.21502014	-28.1954183	-24.18000941	1828	18
		reduced animal source foods	-0.2002667	<0.001	-0.2181066	-0.1824268	-18.14875733	-19.59602735	-16.67543647	1828	18
		healthy	-0.0611185	<0.001	-0.0810019	-0.041235	-5.928824117	-7.780806072	-4.03964034	1828	18

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Supplemental Table 8 Results from the meta-analysis on the effect of diet pattern on dietary blue water footprint

	Model	Diet pattern	Coefficient (log)	*P* value	Lower 95% Confidence Limit (log)	Upper 95% Confidence Limit (log)	Coefficient (after exponentiation)	Lower 95% Confidence Limit (after exponentiation)	Upper 95% Confidence Limit(after exponentiation)	*N* estimates	*N* studies
all studies	simple	no animal source foods	-0.1093409	0.056	-0.2216032	0.0029215	-10.35752258	-19.87667694	0.292577174	1865	24
		reduced animal source foods	-0.051027	0.175	-0.1247483	0.0226942	-4.974698665	-11.7280945	2.295367248	1865	24
		healthy	0.0147133	0.725	-0.0672679	0.0966945	1.482207342	-6.50553039	10.15238067	1865	24
	adjusted for location	no animal source foods	-0.1219144	<0.001	-0.1556638	-0.0881651	-11.47758596	-14.41531223	-8.439030292	1865	24
		reduced animal source foods	-0.0568063	<0.001	-0.0789815	-0.0346311	-5.522294504	-7.594298066	-3.403830619	1865	24
		healthy	0.0057747	0.647	-0.0189472	0.0304965	0.579140572	-1.876883012	3.096628166	1865	24
	fully adjusted	no animal source foods	-0.123339	<0.001	-0.1570884	-0.0895896	-11.6036052	-14.53714937	-8.569366039	1865	24
		reduced animal source foods	-0.0570722	<0.001	-0.0792389	-0.0349055	-5.547412786	-7.618080233	-3.430332972	1865	24
		healthy	0.0057142	0.65	-0.0189944	0.0304228	0.573055718	-1.881514314	3.089030225	1865	24
excluding studies with >500 estimates	simple	no animal source foods	0.8787103	0.079	-0.100145	1.857566	140.7792373	-9.529377388	540.8120409	269	22
		reduced animal source foods	-0.2133064	0.027	-0.4025342	-0.0240786	-19.20914439	-33.13765284	-2.379102328	269	22
		healthy	-0.0430928	0.661	-0.2356312	0.1494456	-4.217749999	-20.99280012	16.11903003	269	22

	adjusted for location	no animal source foods	0.2107932	0.153	-0.0781573	0.4997438	23.46570016	-7.518105892	64.82989224	269	22
		reduced animal source foods	-0.242439	<0.001	-0.288389	-0.196489	-21.52883865	-25.05300083	-17.8389631	269	22
		healthy	-0.0913167	<0.001	-0.1388692	-0.0437643	-8.727139603	-12.96581383	-4.28204619	269	22
	fully adjusted	no animal source foods	0.1323361	0.396	-0.1733928	0.4380651	14.14919102	-15.91927191	54.970579	269	22
		reduced animal source foods	-0.2409706	<0.001	-0.2870562	-0.194885	-21.41352695	-24.95304487	-17.70707105	269	22
		healthy	-0.0872722	<0.001	-0.1348308	-0.0397136	-8.357238992	-12.61362431	-3.893535134	269	22
excluding studies of low quality	simple	no animal source foods	-0.1087077	0.058	-0.2211224	0.0037071	-10.30074299	-19.83814438	0.371397979	1859	22
		reduced animal source foods	-0.0505226	0.18	-0.1243716	0.0233264	-4.926755812	-11.69483621	2.360058826	1859	22
		healthy	0.0168003	0.689	-0.0654221	0.0990227	1.694221868	-6.332798933	10.40913621	1859	22
	adjusted for location	no animal source foods	-0.1217487	<0.001	-0.1555261	-0.0879713	-11.46291658	-14.4035264	-8.421284056	1859	22
		reduced animal source foods	-0.0566116	<0.001	-0.0788115	-0.0344116	-5.503897904	-7.578587761	-3.382625433	1859	22
		healthy	0.0062309	0.622	-0.0185462	0.0310079	0.625035244	-1.837527752	3.149365265	1859	22
	fully adjusted	no animal source foods	-0.1231555	<0.001	-0.1569442	-0.0893668	-11.58738297	-14.52482474	-8.548993025	1859	22
		reduced animal source foods	-0.0568623	<0.001	-0.0790602	-0.0346643	-5.527585107	-7.601570108	-3.407037559	1859	22
		healthy	0.0062815	0.619	-0.0184878	0.0310507	0.630126999	-1.831794896	3.153780153	1859	22

Supplemental Table 9 Studies assessing dietary water use through other metrics (not the water footprint) and therefore were not included in the review

Authors, year (Supp. Ref.)	General study aims	Scale of estimate(s)	Location of estimate(s)	Dietary data source and scenarios (if any)	Water assessment method and data source	Indicator terms used	Findings relevant to this review	Assumptions about imported food
Amarasinghe, U. A. et al. 2007 (69)	Quantify current (2000) and future (2025 and 2050) water use of food consumption in India.	National	India	FAO Food Balance Sheets, food available for supply and data from the National Sample Survey of India.	Calculated from national data	Consumptive water use	Consumptive water use at 567.2 km^3/year for the country. The irrigated crops account for 54% of the total consumptive water use.	Food produced/ consumed in the same area
Chahed, J. et al.2015 (70)	Assess the water equivalent of food stuffs production, trade and demand in Tunisia.	National	Tunisia	Not clear	Modelled based on water use data.	Virtual water content. Food demand water equivalent	The water equivalent of food demand has increased from 1000 m^3/year per capita in the early 1970s to more than 1500 m^3/year per capita in the last 2000s.	Not clear
Chahed, J. et al. 2008 (71)	Assesses the water supply and demand in Tunisia (1990-1997)	National	Tunisia	Not clear	Modelled based on water use data.	Equivalent water for food demand	The equivalent-water for food requirement (11.8 billion m^3/year) is about 1300 m^3/year per capita.	Not clear
Du, B. et al. 2015 (72)	Assesses the direct and indirect water requirements for food consumption from 1995 to 2010 at the household level in the Inner Mongolia Autonomous Region of China.	Sub-national	Hulun Buir, Xilin Gol, and Ordos districts, Northern China.	Food consumption data collected from 209 households in three sub-regions of area.	Based on other sources: Gerbens-Leenes, P.W. and Nonhebel, S. (73);. Li, L. and Wu, X. (74) , Xu, Z.. et al. (75)	Virtual water content	In 1995, the respective virtual water contents of food consumption for Hulun Buir, Xilin Gol and Ordos were; 1758.8 m^3/year per capita, 2377.6 m^3/year per capita and 1838.5 m^3/year per capita, compared to 2307.3 m^3/year per capita, 2054.3 m^3/year per capita and 1553.8 m^3/year per capita in 2010. The virtual water content decreased in the Xilin Gol and Ordos due to decreasing consumption of meat and increasing fruit and vegetables.	Not clear
Gerten, D. et al. 2011 (76)	Assesses global blue and green water availability and corresponding water requirements of current (average between 1972 to 2000) and future (2070-99) food production.	Global/National	Global (all countries)	Scenario diet of 3000 kcal, with 20% animal and 80% vegetal products.	Calculated using the Lund–Potsdam–Jena managed Land (LPJmL) model, that simulates plant growth, production and phenology.	Green and blue water requirements	The global average requirement is 1095 m^3/year per capita, but this varies depending on location; with the lowest in Europe, North America and China. The higher values were in North and East Africa and south-western Asia, countries requiring >2500 m^3/year per capita.	Food produced/ consumed in the same area

Goldstein, B. et al. 2016 (77)	Applies Life Cycle Assessment (LCA) methodology to compare vegetarian and vegan diets to the average Danish diet.	National	Denmark	Average Danish diet from Danish consumption surveys from 2003 to 2008(78). Vegetarian diets were based on the Vegetarian food guide pyramid (Loma Linda University – School of Public Health, 2008. The Vegetarian Food Pyramid (79)).	Taken from the LCA Ecoinvent 3.1 database (consequential modelling) (34).	Water scarcity index	The water scarcity index of the average diet was 0.803 m^3/d per capita, compared to 1.116 m^3/d per capita for vegetarian and 1.117 m^3/d per capita for vegan diets.	Not clear
Kummu, M. et al. 2014 (80)	Compares the effects of hydro climatic variability on the global green and blue water availability and requirements for food production (per food production units) (1977-2006).	Global/Multi-country	Food production units globally	Scenario diet of 3000 kcal/d per capita, with 20% animal and 80% vegetal products.	Calculated using the Lund–Potsdam–Jena managed Land (LPJmL) model that simulates plant growth, production and phenology.	Green and blue water requirements, green and blue water scarcity (based ratio of availability and requirements).	Green and blue water requirements of a reference diet is lowest in in western Europe and some of North America (<650 m^3/year per capita). The requirements are highest (>1300 m^3/year per capita) in northern parts of Latin America, Africa and Southern Asia. Green-blue water scarcity (when requirements are greater than availability) was experienced by 34% of the global population (year 2000). This is mostly found in the Middle East to South Asia.	Food produced/ consumed in the same area
Liu, J. and Savenije, H. H. G. 2008 (81)	Calculates the per capita water requirements for food in China from 1961 to 2003.	National	China	FAO Food balance Sheets, and two scenarios - basic (assuming energy requirements are met by wheat only), and subsistence (based on recommended food intake from the Chinese Nutrition Society (47))	Various sources: Liu, J. and Zehnder, A. et al. (82) Zimmer, D. and Renault, D. (83), and Hoekstra and Chapagain (26).	water requirement, virtual water content	The total water requirement of food was 1127km^3/year for China. The per capita water requirement in 2003 was roughly 860 m^3/year per capita according to FAO food supply accounts, compared to 300 m^3/year per capita for the basic diet, and between 505-730 m^3/year per capita for the subsistence diet (depending on upper and lower boundaries of the recommended daily intake of food).	Food produced/ consumed in the same area
Marlow, H. J. et al. 2015 (84)	Compares the environmental impacts of two dietary patterns in California: higher and lower animal products.	Sub-national	USA (California)	Adventist Health Study (n=34198). Two dietary groups were defined based on their consumption of meat (lower consumption <1 serving of meat/week).	Cost and Return Studies (CRS) published by the University of California Cooperative Extension Service and the University of California Davis Department of Agriculture and Resource Economics	Irrigation rate, irrigation use	The higher animal product diet required 13,545L of water, compared to 3292L for the lower animal product diet (per week).	Food produced/ consumed in the same area
Notarnicola, B. et al. 2017 (85)	Carries out a full life cycle assessment of the average food consumption of a citizen in the European Union 27 Countries.	Multi-country	EU27	Eurostat and FAO databases to develop a "food basket" of representative food products consumed by the average EU27 citizen.	Not clear	Water resources depletion	An average EU citizen incurs 44 m^3/year per capita of water depletion. This could be reduced if animal source food consumption in the diet was reduced by 25 and 50% (estimates in graph).	Considers import quantity and source from the Eurostat international

								trade database (2010).
Porkka, M. et al. 2016 (86)	Historical analysis assessing green and blue water requirements globally in each food production unit (from 1905 to 2005).	Global/Multi-country	Food production units globally	Scenario diet of 3000 kcal/d per capita, with 20% animal and 80% vegetal products.	Calculated using the Lund–Potsdam–Jena managed Land (LPJmL) model, that simulates plant growth, production and phenology.	Green and blue water requirements, green and blue water scarcity (based ratio of availability and requirements).	The green-blue water requirements of diets have been decreasing worldwide due to increase in yields. Green-blue water requirements were highest in Central and Southern Africa, Central America and South Asia. By 2005, green-blue water scarcity in terms of available supply to dietary requirements effected 34% of the population.	Food produced/ consumed in the same area
Renault, D. and Wallender, W. W. 2000(87)	Assesses the nutritional water productivity of different crops and animal products, and applies this to the average diet in the USA (1995), comparing different dietary changes.	Sub-national	USA	FAO Food Balance Sheets, and six scenarios for change the water requirements - animal products reduced by 25%, replaced with veg 50% beef replaced with poultry and adjustment of veg 50% red meat replaced with veg Animal products reduced by 50% and replaced with "Vegetarian Survival" - only four products, used to achieve necessary nutrition targets balanced	Calculated (using US statistics and the FAO CROWAT data for reference evapotranspiration(25))	water requirement, water productivity, nutritional water productivity	The average diet of a USA citizen has a water requirement of 5.4 m^3/d. The water productivity increases as the amount of animal source foods decreases. A diet based on survival only (i.e. only using four nutrient rich products), can a water requirement of only 1.0m3 of water per day.	Food produced/ consumed in the same area
Rockström, J. et al. 2007 (88)	Calculates the additional water required to satisfy global hunger targets of the Millennium Development Goals in 92 developing countries.	Multi-country	Developing countries	Current levels based on FAO food balance sheets, but the scenario of a target diet is based on 3000kcal/d per capita with 20% animal and 80% vegetal.	Calculated based on FAO/UN databases.	water productivity, water requirements	To produce a balanced diet, an average pf 1300 m^3/year per capita is needed of freshwater. If water productivity does not improve, and additional 2200km^3/year of vapour flow is needed to halve hunger by 2015 (from 2002 levels).	Not clear
Singh, A. K. et al. 2007 (89)	Assesses the irrigation water requirement in a community of the Mahi (river) command area, and uses linear programme model to reduce the demand while ensuring the minimum requirement for food is met.	Sub-national	Baswara District, Rajasthan, India	Scenario of food requirements based on maize, gram, mustard, wheat and vegetables.	Data collected on irrigation use and environmental conditions in the area.	irrigation water requirement	1420.3 ha m of irrigation water (40% of available water) is required to produce the minimum food required.	Food produced/ consumed in the same area

APPENDIX

Appendix 1 References

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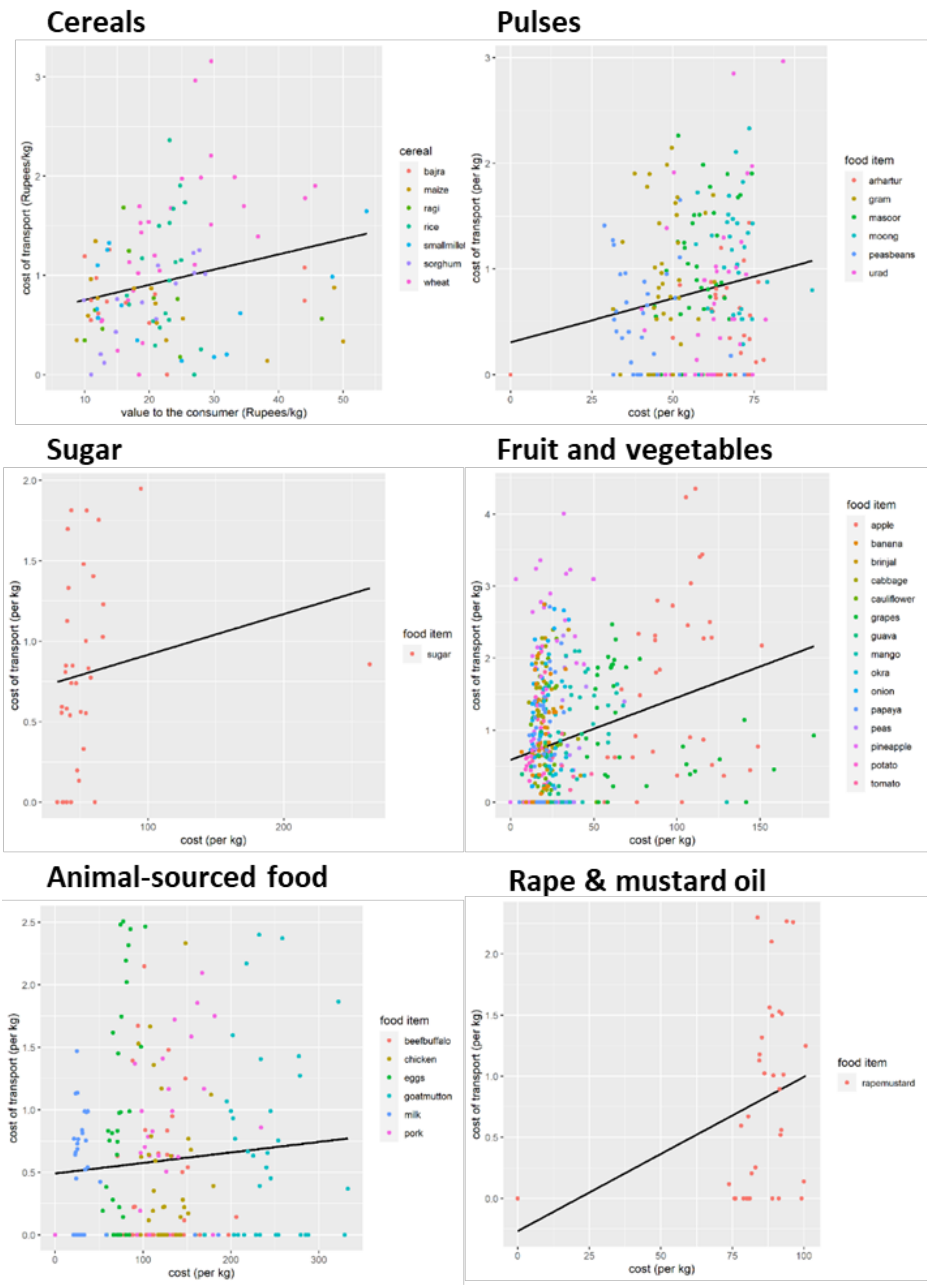
APPENDIX 3 - Chapter 4: Methods and Data



Appendix Figure 3.1 Cost of transport plotted against the cost of the product for the consumer for each food item and food group. Line represents basic linear regression relationship.

APPENDIX

Appendix Table 3.1 Results of the regression analysis assessing the association between transportation cost as calculated in the InFoTrade model and value to the consumer from the National Sample Survey. Results are shown for each food group and for both the mixed effect model and the mixed effect model weighted by the volume of food consumption in the state. Food item included as a random effect.

FOOD GROUP	MODEL	COEFFICIENT	LOW CI	HIGH CI	P	N
CEREALS	Mixed	7.43	5.06	9.80	<0.001	245
CEREALS	Mixed weighted by consumption	3.32	1.27	5.36	0.001	245
PULSES	Mixed	6.19	3.83	8.56	<0.001	210
PULSES	Mixed weighted by consumption	1.97	-2.47	6.41	0.384	210
RAPE & MUSTARD OIL	Mixed	5.85	-3.00	14.70	0.195	70
RAPE & MUSTARD OIL	Mixed weighted by consumption	5.10	2.01	8.20	0.002	33
SUGAR	Mixed	10.63	-12.01	33.27	0.346	35
SUGAR	Mixed weighted by consumption	11.45	3.89	19.01	0.004	35
FRUIT & VEGETABLES	Mixed	2.50	0.98	4.02	0.001	525
FRUIT & VEGETABLES	Mixed weighted by consumption	2.77	1.32	4.23	<0.001	525
ANIMAL PRODUCTS	Mixed	6.88	-0.39	14.16	0.064	210
ANIMAL PRODUCTS	Mixed weighted by consumption	-1.62	-3.72	0.48	0.131	210
EGGS	Mixed	6.31	2.76	9.85	0.001	35
EGGS	Mixed weighted by consumption	5.68	2.69	8.66	<0.001	35
MILK	Mixed	-21.19	-47.51	5.13	0.111	35
MILK	Mixed weighted by consumption	-2.59	-4.53	-0.64	0.011	35
MEAT	Mixed	10.71	0.50	20.91	0.04	140
MEAT	Mixed weighted by consumption	5.64	-2.63	13.90	0.181	140
FRUIT	Mixed	2.28	-0.46	5.01	0.102	245
FRUIT	Mixed weighted by consumption	3.15	0.28	6.02	0.032	245
VEGETABLES	Mixed	2.72	1.58	3.86	<0.001	280
VEGETABLES	Mixed weighted by consumption	2.47	0.97	3.97	0.001	280

APPENDIX 4 - Chapter 5: Trading water: virtual water flows through interstate cereal trade in India

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Supplementary information.

This supplementary file provides further information on the data and model used for the analysis, and additional figures and results as referred to in the main manuscript.

Contents

1. Data and Methods

1.1 Calculating food supply and demand balances of cereals in each state

For each of the five major cereals (c) (wheat, rice, maize, sorghum, and millets; with millets including ragi, bajra and small millet), state-level data was collated on production (P), foreign imports (FI), foreign exports (FE), stocks (St), non-food uses (OU) and food available for consumption (C). Hereafter, state refers to both State and Union Territories (N=35, with Andhra Pradesh as the State pre-separation into Andhra Pradesh and Telangana). The most recent nationally representative data available on cereal consumption in India is from the years 2011-12 hence all other data sources were focused on this period. Given potential annual fluctuations, we also carried out sensitivity analysis to compare the resulting trade flows using three-year average from 2010-13.

For each state (i) and cereal (c), available supply of food) includes local production ($P_{i,c}$) and foreign imports ($FI_{i,c}$), change in stock ($\Delta St_{i,c}$), minus non-food uses of cereals ($OU_{i,c}$) (waste, feed, seed, processed and other) (equation 1, with definition of these quantities given in the glossary).

$$S_{i,c} = P_{i,c} + FI_{i,c} + \Delta St_{i,c} - OU_{i,c} \tag{32}$$

The amount of supply for non-food uses ($OU_{i,c}$) in the state was calculated using the proportion of supply diverted to non-food use according to national-levels (α_c) (equation 2).

$$OU_{i,c} = \alpha_c * (P_{i,c} + FI_{i,c} + \Delta St_{i,c}) \tag{33}$$

The state demand for cereals includes cereals for food consumption in rural (rur) and urban (urb) populations and foreign exports ($FE_{i,c}$) (equation 3). The supply and demand accounts were used to indicate which states had excess cereals for interstate trade and which had unmet need.

$$D_{i,c} = C_{i,c}^{urb} + C_{i,c}^{rur} + FE_{i,c} \tag{34}$$

Various data sources were used to estimate supply and demand for each state (see section 1.6 for glossary). State cereal production was taken from Indian Government production statistics (1), while non-food uses for each cereal are fixed percentages from Indian specific data in the Food Balance Sheets of the UN Food and Agricultural Organisation (FAO) (2). Stock for millets, sorghum and maize is also taken from Indian specific data in the FAO Food Balance Sheets, while stock estimates for rice and wheat is taken from data published by the Department of Food & Public Distribution, Government of India, on the Public Distribution System (PDS) (see Section 1.3 for further details).

The total amount of cereals contributing to foreign imports and export in India were estimated following methods from Kastner et al. (2014) (3), with data updated for more recent years. This provides a detailed trade matrix linking Indian imports to country of production and Indian exports to final country destination. Data is available from Directorate General of Commercial Intelligence and Statistics (DGCIS), Government of India, on the tonnes of foreign imports and exports of cereals occurring at port states (4), however the amount of foreign trade was different in these data sources. Therefore, we used national foreign exports and import amounts calculated following methods from Kastner et al. (2014) using updated data for more recent years, and assigned to port states based on DGCIS.

The consumption of cereals varies considerable throughout India, both due to differences in local production as well as consumer preference. To incorporate state variation in cereal demand we used the 68th Round of the Indian National Sample Survey (NSS), carried out in 2011-12 (5).

We could not use values for state-level consumption from the NSS, as it is a nationally representative household consumption and expenditure survey, hence does not capture food eaten outside the home and due to measurement techniques does not reflect actual consumption (6). Instead, we take our calculated supply of each cereal available for food at national level and allocate to each state based on proportional consumption in NSS (tonne/year).

Discrepancies between the total food available in India in NSS compared to the total food supply calculated in this study are shown in Table S1, along with data from the FAO Food Balance Sheets. FAO Food Balance Sheet quantify the food available for food consumption at national-level and tend to overestimate consumption compared to sub-national surveys (6).

Table S1 Consumption of cereals at the national level in Million Tonnes (Mt) per year for 2011-12, calculated in this study, recorded in household expenditure surveys, National Sample Survey (NSS), and food balance sheets (FAO). PDS: Public Distribution System.

	Calculated in this study (Mt)	NSS (Mt, *% difference to calculated)*	FAO Food Balance Sheets (Mt, *% difference to calculated)*
Total rice (PDS and non PDS)	85.2	75.9 *(-10.9%)*	86.5 *(+1.48%)*
Total wheat (PDS and non PDS)	92.4	58.7 *(-36.5%)*	71.9 *(-22.2%)*
Maize	5.99	1.35 *(-77.5%)*	7.94 *(+32.7%)*
Millets	12.5	3.67 *(-70.7%)*	10.9 *(-13.0%)*
Sorghum	5.08	2.44 *(-52.0%)*	6.22 *(+22.5%)*
Total	201	142 (-29.4%)	183.4 (-8.8%)

1.2 Modelling interstate non-PDS cereal trade volumes and direction

1.2.1 Theory and linear programming model equations

There are no data available on interstate trade of cereals in India that include volumes transported by road and rail. Data is available on the volume of cereals transported by rail, however this only accounts for 20% of the total cereal trade (7, 8). Consequently, we modelled interstate cereal trade flows using an allocation problem approach. This assumes that a state must satisfy its own demand before it can export its supply. Therefore, when supply is greater than demand the region is net exporter, but if the demand is greater than supply the region is a net importer. The supply and demand pairs are then calculated through a least-cost allocation. This modelling approach has been validated against actual data on inter-regional trade in the United States of America (9), and has been used to explore intra-national trade flows in India (7) and China (10).

The distances between each state capital in exporter (i)-importing (j) pair was obtained for both road and rail routes (equations 3 to 6). The road transportation costs reflect not only distance but fixed costs and capacity. That is, longer distances have lower costs per km because the loading time as a proportion of total travel is less, and because longer routes, on average, include faster, highway roads. In order to reflect this non-linearity, road distances are split into 6 categories, and each is assigned an average transportation cost per km/tonne. These parameters are provided by the Indian government based on their own calculations (7, 8). The island states (is) of Andaman and Nicobar Islands, and Lakshadweep, have an additional transportation cost calculated using the average cost of shipping commodities in India, multiplied by distance to their major mainland ports ($isport$) (equation 8).

Transportation costs (tc) were calculated as follows:

$$tc_{i,j}^{road} = dist_{i,j} \sum_{k} tc_{India_k}^{road} \, I_k(dist_{i,j}) \tag{35}$$

$$I_k\left(dist_{i,j}\right) = 1 \; if \; dist \; \in (min_k, max_k) \tag{36}$$

$$I_k\left(dist_{i,j}\right) = 0 \; if \; dist_{i,j} < min_k \; or \; dist_{i,j} > \; max_k \tag{37}$$

$$tc_{i,j}^{rail} = tc_{India}^{rail} * dist_{i,j}^{rail} \tag{38}$$

$$tc_{i=is,j=is,}^{ship} = \; tc_{India}^{ship} * dist_{i=is \; or \; isport, j=is \; or \; isport}^{ship} \tag{39}$$

Where:

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$tc_{India_k}^{road}$ represents the weighted average cost of road transportation in Rupees/Km/Tonne for distance category k (7), and $I_k(dist_{i,j})$ is an indicative function that takes value 1 if the distance is in category k and value 0 if the distance is in any other category. tc_{India}^{rail} and represent the weighted average cost of rail of food grains in India in Rupees/Km/Tonne (7).

The transportation costs matrix to be minimised was estimated as:

$$tc_{i,j} = \left(tc_{i,j}^{road} * prop^{road}\right) + \left(tc_{i,j}^{rail} * prop^{rail}\right) + tc_{i=is,j=is,}^{ship} \tag{40}$$

Where $prop^{road}$ and $prop^{rail}$ are the proportion of food grains transported by road and rail in India respectively, as estimated by the RITES Ltd. Planning Commission report (7).

The transportation cost matrix was used as the function in the optimisation model, in which the following constraints were applied:

- Supply of each commodity equals demand in each state.
- Trade flows are only positive.
- Foreign imports are added to the states total supply, while foreign exports are added to the states demand.
- Net export of the commodity is bounded by local production or foreign import (if any).

Minimize:

$$TC_c = \sum_{i,j,c} \left(t_{i,j,c} \cdot tc_{i,j}\right) \tag{41}$$

Subject to:

$$\forall \epsilon\ [1:35]: P_{i,c} + FI_{i,c} - + \Delta St_{i,c} - OU_{i,c} + \sum_{j \neq i, j=1:35} (t_{j,i,c} - t_{i,j,c}) = C_{i,c}^{urb} + C_{i,c}^{rur} + FE_{i,c} \tag{42}$$

$$\forall (i,j): t_{i,j,c} \geq 0;\ \forall i : t_{i,i,c} = 0 \tag{43}$$

$$\sum_{j \neq i, j=1:35} (t_{i,j,c} - t_{j,i,c}) <= \max\,(0, St_{i,c}FI_{i,c}) \tag{44}$$

Assumptions of the model

- $t_{i,j,c}$ $(tonne_{crop})$ is the unknown interstate trade matrix for commodity c,
- tc is the interstate transport cost matrix for cereal commodities,
- TC_c is the total cost of interstate trade of commodity c,
- i refers to the exporting state/UT, while j refers to the importing state/UT [N = 35],
- $P_{i,c}$, $FI_{i,c}$, $FE_{i,c}$, $\Delta OU_{i,c}$ and $\Delta St_{i,c}$ $(tonne_{crop})$ are state i's production, foreign import, foreign export, other uses and net change in stock of commodity c,
- $C_{i,c}^{urb}$ and $C_{i,c}^{rur}$ $(tonne_{crop})$ are state i's consumers demand for commodity c, for urban and rural populations respectively (total, not per capita).

1.2.2 R Code

Here we outline the R code for the optimisation model used to calculate the interstate trade flows of non-PDS cereal trade in India. File names will vary depending on user, as will state names or numbers for different contexts.

Load package:

```
library(lpSolve)
```

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 # a function was created for the trade model, which was then applied to each cereal. costfile is the transport cost matrix, fbsfile contains food supply and demand data (food balance sheet), and commodity is the name of the commodity for which the model is being executed. Where variables indicate state, this are specific to Indian context (N=35).

```
trade_model <- function(costfile, fbsfile, commodity) {
 statelist<-c(
  "Andaman and Nicobar", "Andhra Pradesh", "Arunachal Pradesh”, "Assam",
  "Bihar", "Chandigarh", "Chattisgarh”, “Dadra and Nagar Haveli",
  "Daman and Diu”, "Delhi", "Goa”, “Gujarat”, “Haryana",
  "Himachal Pradesh", "Jammu and Kashmir”, “Jharkhand”, “Karnataka",
  "Kerala", "Lakshadweep”, “Madhya Pradesh", "Maharashtra”, “Manipur",
  "Meghalaya”, “Mizoram”, “Nagaland", "Odisha", "Puducherry", "Punjab",
  "Rajasthan”, "Sikkim", "Tamil Nadu", "Tripura”, "Uttar Pradesh",
  "Uttaranchal", "West Bengal")
 state_num<-c(seq(1:35))
 variables_names <-c("un.demand", "ex.supply", "consum.total_tonne", "other.uses_tonne", "total.supply.trade",
           "P_tonne", "FI_tonne", "supply", "F_tonne", "W_tonne", "Se_tonne", "O_tonne",
           "consum.rural_tonne", "consum.urban_tonne", "FE_tonne")
```

 # load transportation cost matrix

```
 A <- read.csv(costfile)
 cost <- as.matrix(A, header = TRUE)
 rownames(cost) <- state_num
 colnames(cost) <- state_num
 diag(cost) <- 0
```

 # the next section of the code includes the calculations to estimate supply and demand for each Indian state, hence these are specific to the data available for this study.

```
 fbs <- read.csv(fbsfile)
 supply1 <- c(fbs$P_tonne+fbs$FI_tonne)
 S_tonne <-c(fbs$S_perc*supply1/100)
 supply <- c(supply1 + S_tonne)
 F_tonne <- c(supply/100 * fbs$F_perc)
 W_tonne <- c(supply/100 * fbs$W_perc)
 Se_tonne <- c(supply/100 * fbs$Se_perc)
```

```
O_tonne <- c(supply/100 * fbs$O_perc)

other.uses_tonne <-c(F_tonne + W_tonne + Se_tonne + O_tonne)

total.supply.food <- c(supply - other.uses_tonne - fbs$FE_tonne)

consum.h.total<- c(fbs$consum.h.rural_kg + fbs$consum.h.urban_kg)

consum.urban_p <- c(fbs$consum.h.urban_kg/(consum.h.total[36]))

consum.rural_p <- c(fbs$consum.h.rural_kg/(consum.h.total[36]))

consum.urban_tonne <- c(consum.urban_p*total.supply.food[36])

consum.rural_tonne<- c(consum.rural_p*total.supply.food[36])

consum.total_tonne<- c(consum.rural_tonne + consum.urban_tonne)

total.supply.trade <-c(supply - other.uses_tonne)

total.demand <-(consum.total_tonne + fbs$FE_tonne)


# calculation of excess supply and unmet demand, to be used as constraints in the optimisation

ex.supply <- c(total.supply.trade - total.demand)

ex.supply[ex.supply <= 0] = 0

un.demand <- c(total.demand - total.supply.trade)

un.demand[un.demand <= 0] = 0

ex.supply.states<-ex.supply[1:35]

un.demand.states<-un.demand[1:35]


# executing the optimisation model for minimising transport cost

obj.fun <- matrix(cost)

m <- 35

n <- 35

constr <- matrix(0, n+m, n*m)

for(i in 1:m){

  for(j in 1:n){

    constr[i, n*(i-1) + j] <- 1

    constr[m+j, n*(i-1) + j] <- 1

  }

}

constr.dir <- c(rep("<=", m), rep(">=", n))

rhs <- c(ex.supply.states, un.demand.states)

prod.trans <- lp ("min", obj.fun, constr, constr.dir, rhs,
```

```
            compute.sens = TRUE)

  sol<-matrix (prod.trans$solution, m, n, byrow=TRUE)

colnames(sol) <-statelist

  rownames(sol) <-statelist

 # exporting the results

  write.csv(sol, file = paste0("sol_11-12", commodity, costfile))

  fbs_variables <-data.frame(un.demand, ex.supply, consum.total_tonne, other.uses_tonne, total.supply.trade,

                fbs$P_tonne, fbs$FI_tonne, supply, F_tonne, W_tonne, Se_tonne, O_tonne,

                consum.rural_tonne, consum.urban_tonne, fbs$FE_tonne)

  write.csv(fbs_variables, paste0("fbs_variables", commodity, ".csv"))

}
```

1.3 Calculating trade flows in the public distribution system

The Public Distribution System (PDS) is a government subsidies food grain programme, that procures rice, wheat and other crops at a minimum support price and sells these at a reduced rate in fair price shops. It has been shown that the PDS is not distributed based on minimising transport (11, 12), hence it would be inappropriate to model as such. Instead, grains are centrally procured then redistributed, except for states with decentralised PDS where they first supply their own demand before exporting (Table S1). Data is available from the Food Cooperation of India on the procurement of PDS rice and wheat for each state for the central pool, and PDS consumption is estimated in NSS. The total PDS rice and wheat procured was subtracted from local production in each state, and total PDS supply calculated by removing the estimated proportion of waste for each cereal (2). This PDS supply was redistributed proportionally to other states according to the reported consumption patterns in NSS (5). For states with a decentralised system, they supply their own PDS consumption first before contributing to the central pool (Table S2) (13). Hence their PDS consumption was estimated by combining PDS consumption of rice and wheat with non-PDS consumption of each ($C_{i,c}^{urb}$ and $C_{i,c}^{rur}$) according to the NSS, and including in their food demand. This approach to trade is likely to overestimate trading pairs and the amount of interstate trade; as it is likely that some of the PDS cereals are distributed more efficiently. We therefore carry out a sensitivity analysis that uses a linear programming model that minimises the cost of transportation that would be required to balance supply and demand of PDS rice and wheat across Indian states (as for non-PDS cereals).

Table S2 States and Union Territories in India with a decentralised public distribution system (13)

State or Union Territory	Cereal
Andaman &Nicobar Islands	Rice
Bihar	Rice/Wheat
Chhattisgarh	Rice/Wheat
Gujarat	Wheat
Karnataka	Rice
Kerala	Rice
Madhya Pradesh	Rice/Wheat
Odisha	Rice
Tamil Nadu	Rice
Uttarakhand	Rice/Wheat
West Bengal	Rice/Wheat
Punjab	Wheat
Rajasthan	Wheat

Andhra Pradesh	Rice

1.4 Comparison of interstate trade flows with existing literature

To explore how our modelled data compares to existing knowledge of domestic trade in India, we used the resulting trade flows to estimate a gravity equation. The gravity model uses data on trade flows to explore the effect of different factors (e.g. distance, economic size) in driving trade. Two gravity equations have been estimated for interstate trade flows in India. Khanal (2016) estimated a gravity model for the rail trade of agricultural commodities (14), and The Economic Survey 2016-17 of India estimated a gravity model for the interstate trade of manufactured goods (15). These models explore different trade relationships and quantities to our study; hence we cannot directly compare the model outputs. Instead, we compare relationships found from our model outputs for 2011-12 for non-PDS trade only (i.e. the results from the linear programming model), and for all cereal trade (including non-PDS and PDS), with the relationships of existing gravity models.

Our analysis focuses on cereal trade for a relatively small number of trading pairs so there are a large number of zero values that can bias the results. Consequently we used the Pseudo Maximum Likelihood Method (PPML) as Khanal (2016), which can provide consistent coefficient results despite zero values (16). We included variables that were identified to be significantly associated with interstate trade in India in the previous models. The gravity equation was formulated as follows:

$$\log(t_{i,j}) = logGDP_i + logGDP_j + logdist_{i,j} + adj_{i,j} + F_i + F_j \tag{45}$$

Where GDP_i and GDP_j are the state gross domestic products for agriculture and allied sectors in the exporter and importing states, $dist_{i,j}$ is the distance between each state, calculated as the distance between state capitals, and $adj_{i,j}$ is a dummy variable indicating if states share a common border. F_i and F_j represent fixed effects for each exporter and importer.

The gravity model was built in STATA IC 16 (Version 1).

1.5 Calculating the embedded water in cereal production, consumption and trade

In order to calculate the WF of cereal production, foreign and domestic trade, we carried out the following steps for each cereal (c) and state (i, j):

$$PWU_{i,j,c} = Pwf_{i,j,c} * P_{i,c} \tag{46}$$

$$FIWU_{i,c} = FIwf_c * FI_{i,c} \tag{47}$$

$$Swf_{i,c} = \frac{PWU_{i,c} + FIWU_{i,c}}{P_{i,c} + FI_{i,c}} \tag{48}$$

$$PDSWU_{i,j,c} = Pwf_{i,j,c} * PDS_{i,c} \tag{49}$$

Where $PWU_{i,c}$ is the water use of local production, $Pwf_{i,c}$ are the water footprints of local production for each cereal. $FIWU_{i,c}$ is the water use of foreign imports, calculated using the weighted average WFs of imports ($FIwf_c$) according to country of origin. These were combined to calculate the WF of cereal supply ($Swf_{i,c}$, m^3/tonne) in each state. Finally, the water use associated with PDS ($PDSWU_{i,j,c}$) is calculated using the local water footprint in the state in which the PDS is procured, multiplied the total procurement ($PDS_{i,c}$, tonnes).

We calculated the virtual water associated with interstate trade as follows:

$$tWU_{i,j,c} = (Swf_{i,c} * t_{i,j,c}) + PDSWU_{i,j,c} \quad (50)$$

Where the WF of supply (m^3/tonne) the exporting state is multiplied by the volume of each cereal (c) exported from state ($t_{i,j,c}$) to obtain the virtual water trade of non-PDS trade: $tWU_{i,j,c}$, and the water uses associated with PDS trade is added.

These values were used to obtain the water use of cereal consumption at national level ($IndiaCWU$):

$$Cwf_{c,j} = \frac{tWU_{i,j,c} + PWU_{i,j,c} + FIWU_{i,j,c}}{t_{i,j,c} + P_{i,j,c} + FI_{i,j,c}} \quad (51)$$

$$IndiaCWU_c = \sum Cwf_{c,j} * C_{c,j} \quad (52)$$

The WF of demand for each cereal in each state (Cwf, in m^3/tonne) is calculated relative to local supply and imports, multiplied by total cereal consumption (C, in tonnes) in the corresponding state and summed across the 35 states to obtain the total water use of cereal consumption at national-level, $IndiaCWU_c$.

We calculated theoretical water savings or losses from trade. For the savings in local water use in each state, we focus on the green, ground- and surface-water used in domestic production. Water savings occur when a state imports products that have a lower WF (i.e. higher water efficiency) than their own, whereas losses occur when the state imports products with a higher WF (i.e. lower water efficiency) than their own. Local water savings were calculated for each trading pair and commodity ($locWS_{i,j,c}$) as follows:

$$locWS_{i,j,c} = t_{i,j,c}^{dom} * (Pwf_{j,c} - Pwf_{i,c}) \quad (53)$$

Where $t_{i,j,c}^{dom}$ is the volume of domestically produced cereals (PDS and non-PDS) in tonnes/year traded between the respective state pair, $Pwf_{j,c}$ and $Pwf_{i,c}$ and the respective WFs of local production in the importing and exporting state.

1.6 Glossary

Table S3 Variables and data sources used to calculate cereal supply and demand balances and trade flows for each State and Union Territories in India

Variable	Code	Source
Variables for calculating state supply and demand balances		
Production of commodity in each state (tonne/year, 2010-13).	$P_{i,c}$	Obtained from Directorate of Economics and Statistics, Ministry of Agriculture and Farmer's Welfare, and Agriculture Statistics at a Glance Year Book, 2014 (1)
Volume of foreign imports and export (tonne/year) to ports in India for each commodity (2010-13).	$FI_{i,c}$ $FE_{i,c}$	The total volume of foreign trade in India was taken from Kastner et al. (2014), which provides a detailed global matrix of estimated location of production (tonne/year) (3). Foreign exports are imports were distributed between states/UTs based port and commodity specific estimates from Directorate General of Commercial Intelligence and Statistics (DGCIS), Government of India, downloaded from the AgriExchange website (4). The total volume of foreign trade did not match between the two data sources; therefore, we used the volume from Kastner et al. (2014) and scaled to the port-specific values.
Net change in stock (tonne/year) (2010-13)	$\Delta St_{i,c}$	India-specific figures in UN Food and Agricultural Organisation (FAO) Food Balance Sheets (2010-13) (2). For rice and wheat, stock contribution of each state is obtained from Department of Food & Public Distribution, Annual Report (2013-14) (tonne/year) (17).
Proportional of total supply going to waste, feed, seed and other uses for each year (2010-13).	α_c	India-specific figures from UN Food and Agricultural Organisation (FAO) Food Balance Sheets (2010-13) (2).

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Demand (food available for consumption) of each cereal in each state (tonne/year) (2011-12)	$C_{i,c}^{urb}$ $C_{i,c}^{rur}$	National-level demand based on food supply available after non-food uses have been removed. State-level values were calculated using proportional consumption of the national demand relative to NSS 68th Round (2011-12) (5). The NSS database is assumed nationally representative.
Variables for calculating trade flows		
Matrix of transportation costs of cereals by road (Rupees/tonne)	$tc_{i,j}^{road}$	Obtained for each state importing and exporting pair using the minimum road distance between state capitals from Google Maps (18), multiplied by cumulative distance of road transport (Rs./km/tonne) from RITES Planning Commission Report of India (7).
Matrix of transportation costs of cereals by rail (Rupees/tonne)	$tc_{i,j}^{rail}$	Obtained for each state importing and exporting pair using the shortest path of goods rail transport between train stations of state capitals, as reported by the Govt. of India Centre for Railway Information Systems (19). Values were multiplied by the cost of railway transport for food grains (Rs./km/tonne) reported in the RITES Planning Commission Report of India (7, 8).
Transportation costs of cereals by shipping for island Union Territories	$tc_{i=is,j=is}^{shipping}$	For island states (is) Andaman and Nicobar Islands and Lakshadweep with no road or rail transport to other states available, distance between the main island port and major mainland ports were taken from Google Maps and multiplied by the costs of shipping (Rupees/km/tonne) reported in the RITES Planning Commission Report of India (7). For all other states trade was assumed to occur via land.
Weights for cereal transported by road vs rail	$prop^{road}$ $prop^{rail}$	Weighted proportion of cereals transported by road and rail in India, estimated in the RITES Planning Commission Report of India (8).
Distance between state capitals	$dist_{i,j}$	Minimum road distance between state capitals according to Google Maps (18)
State-wise GDP from Agriculture and Allied Sectors (2011-12) at constant price (2004-5) (Lakhs Rupees)	$GDP_{i,j}$	Taken from Directorate of Economics & Statistics of respective State Governments (20). Data was not available for the Union Territories; Lakshadweep, Daman and Diu, and Dadra and Nagar Haveli, so trade flows to and from these states were excluded from the gravity model.
Adjoining state dummy	$adj_{i,j}$	Dummy variable of 1 if states share a border of 0 if not.

APPENDIX

2. Results

2.1 Interstate trade of cereals during 2011-12 and associated virtual water

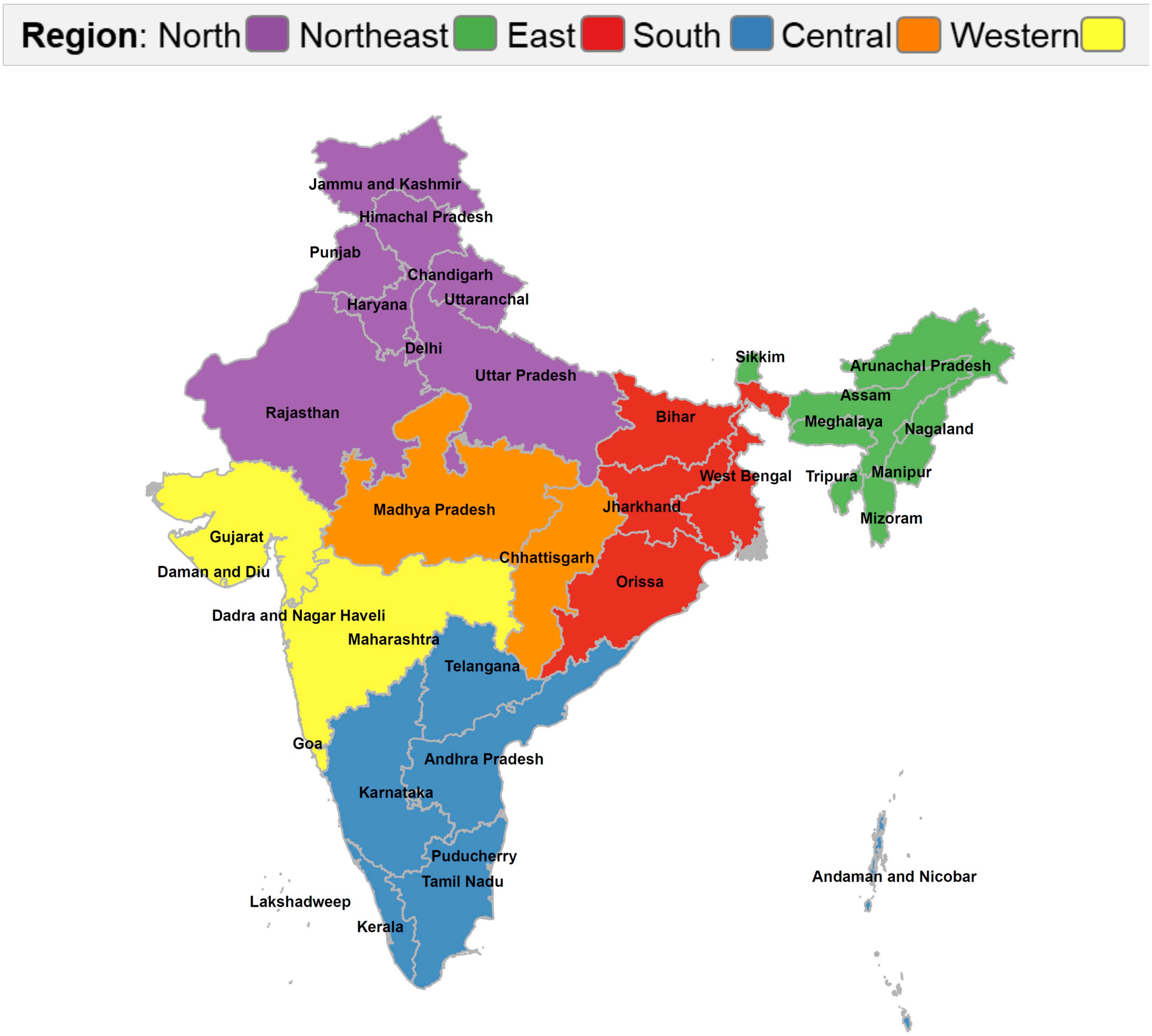

Figure S1 Map of Indian states, colour coded by region. Maps for Indian administrative boundaries available from DIVA-GIS (21)

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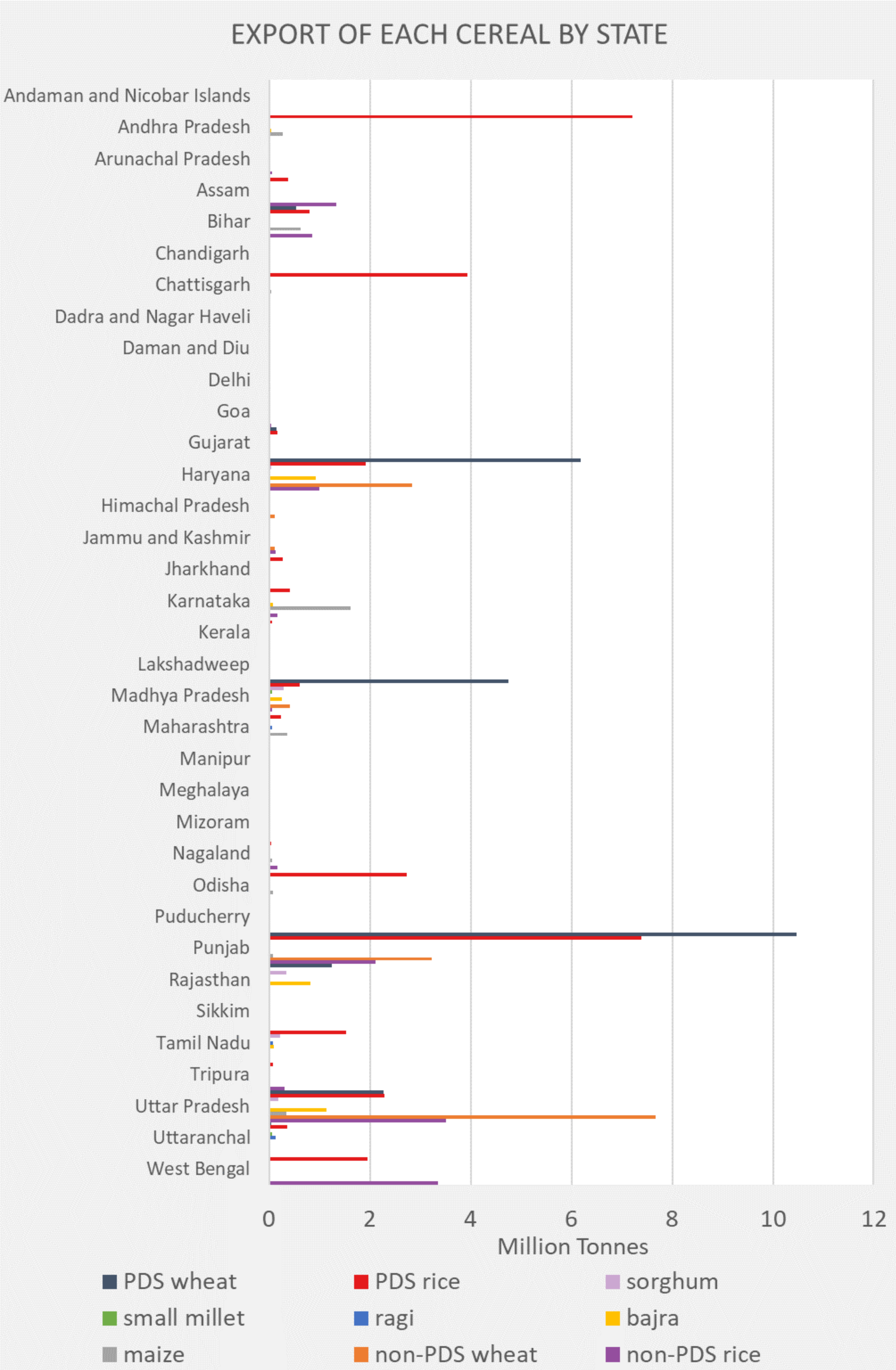

Figure S2 Total tonnes of each cereal exported from Indian states for the period 2011-12. Millet includes bajra, ragi and small millets.

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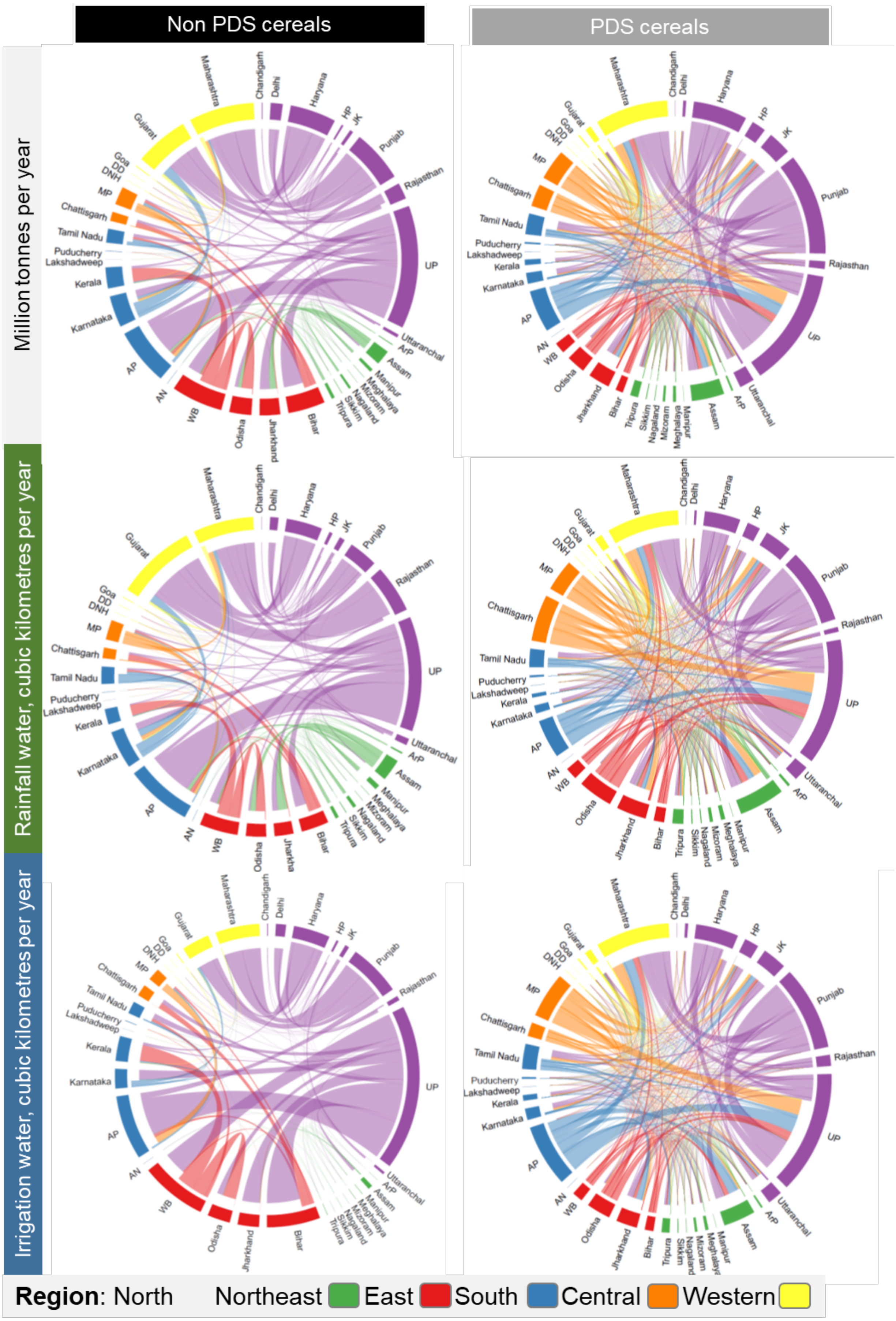

Figure S3 Interstate trade of all cereals and the embedded water, for the period 2011-12. Colours of chord corresponding to the region of export. Chords are indented for importing state. HP: Himachal Pradesh, JK: Jammu and Kashmir, UP: Uttar Pradesh, ArP: Arunachal Pradesh, WB: West Bengal, AN: Andaman and Nicobar, AP: Andhra Pradesh, MP: Madhya Pradesh, DNH: Dadra and Nagar Haveli, DD: Daman and Diu.

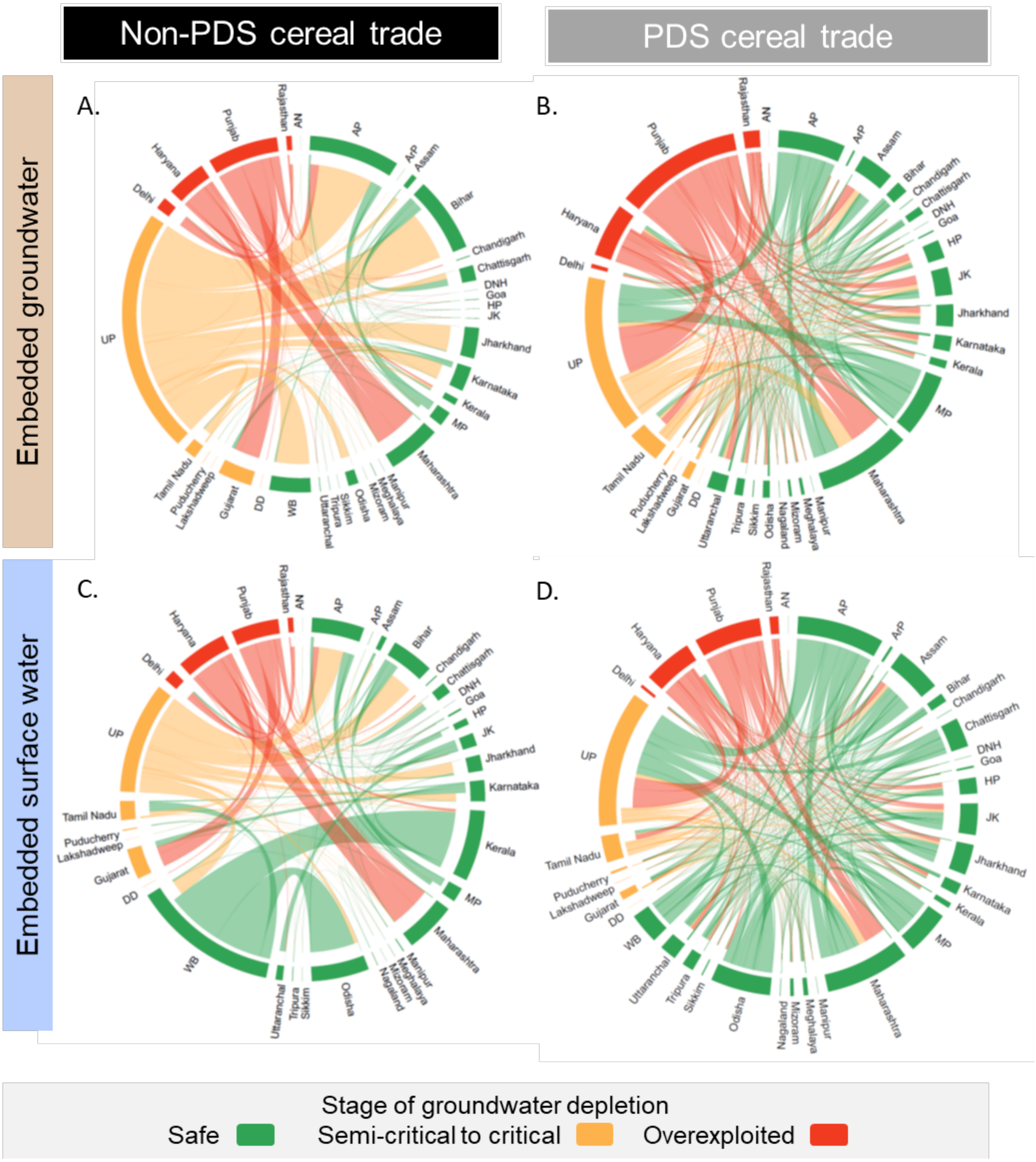

Figure S4 The ground and surface water exported through the interstate trade of cereals in India, using data from 2011-12. A and C: additional cereal trade not included in the Public Distribution System. B and D: cereals traded through the Public Distribution System (PDS). Chord colour corresponds to the stage of groundwater depletion in the exporting state, as defined by the Central Groundwater Board of India (22). Chords are indented for importing state. AN: Andaman and Nicobar, AP: Andhra Pradesh, ArP: Arunachal Pradesh, DNH: Dadra and Nagar Haveli, HP: Himachal Pradesh, JK: Jammu and Kashmir, MP: Madhya Pradesh, DD: Daman and Diu, UP: Uttar Pradesh, WB: West Bengal.

APPENDIX

2.2 Theoretical trade-induced water savings for each state

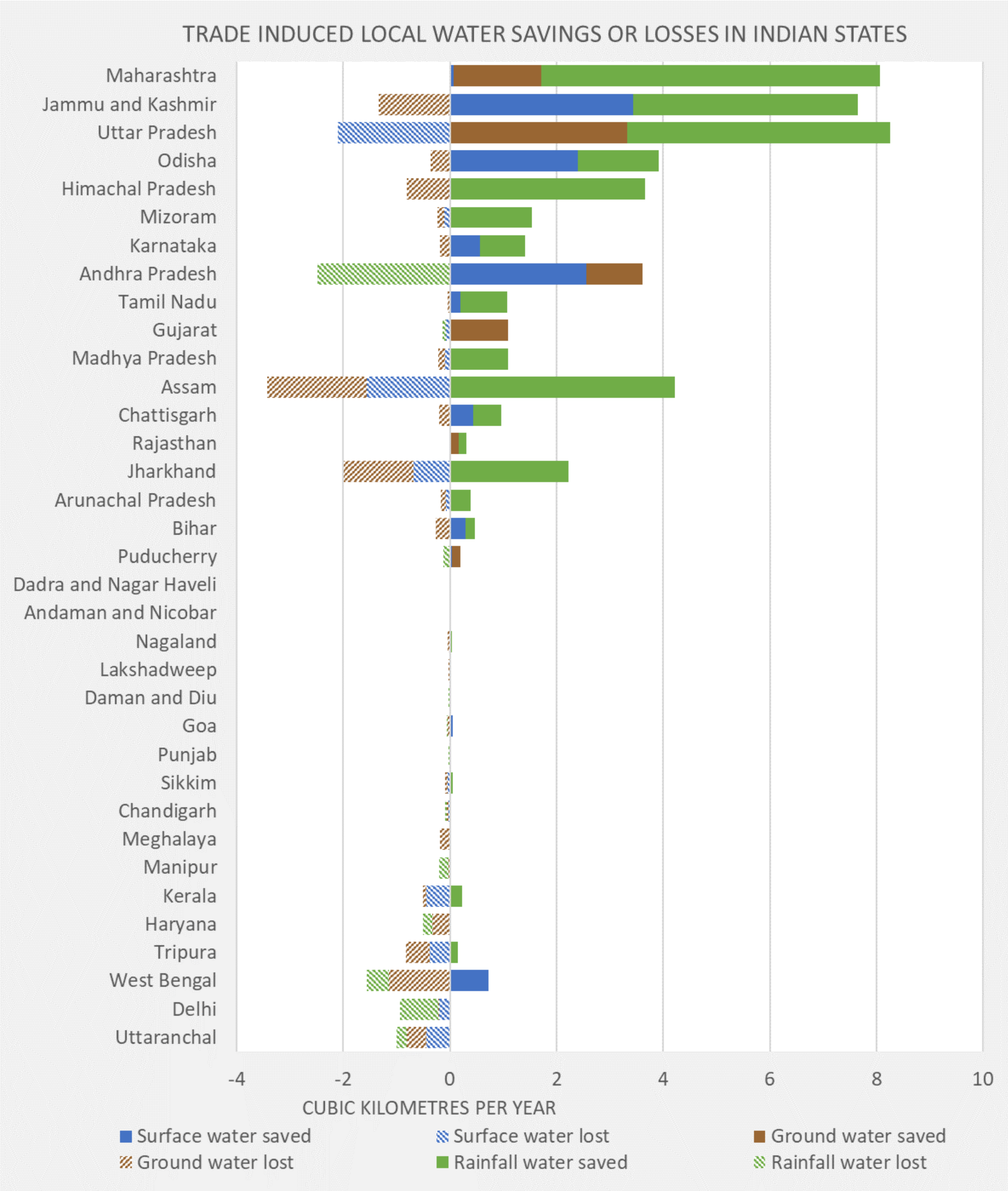

Figure S5 Theoretical local rain-, ground- and surface-water savings and losses induced through intestate trade of domestic cereals in India during 2011-12. States are in descending order according to total water saved.

APPENDIX

2.3 Comparison of the price of cereals with the cost of transportation

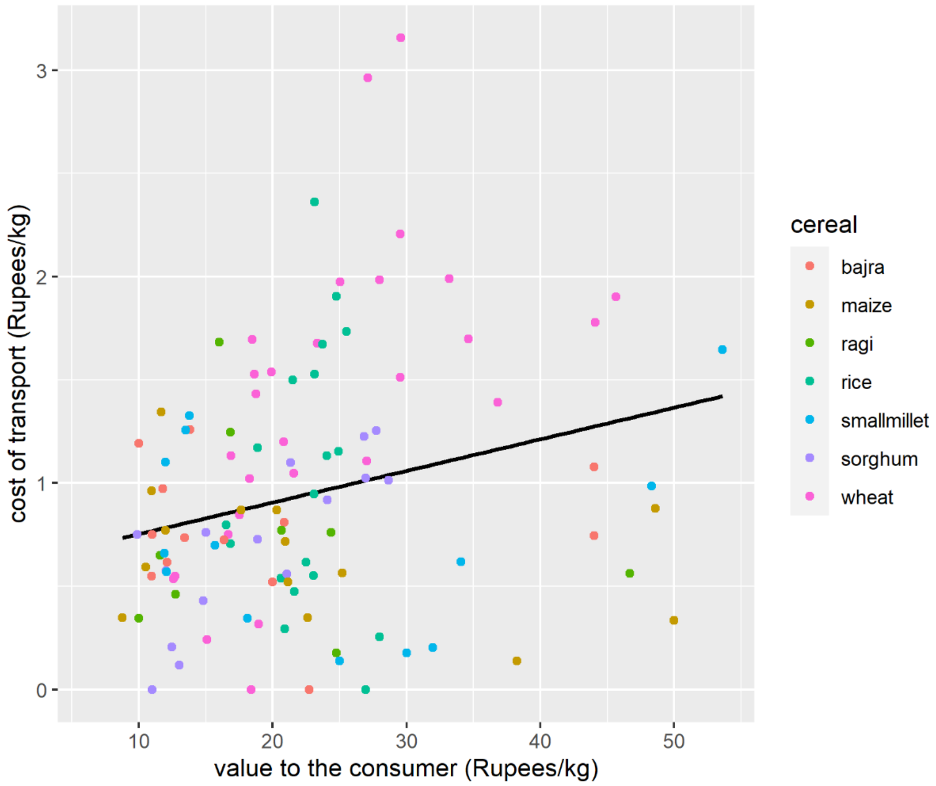

Figure S6 Cost of transportation for cereals plotted against the value to the consumer in the importing state each cereal to the consumer. Regression line represent the simple linear regression model. Mixed effect regression coefficient: 4.92 Rupees/kg (95% CI 1.58 to 8.06, P<0.01, N=114, estimated using STATA IC 16 (version 11)).

2.4 The gravity equation estimated from predicted trade flows

The results from the gravity equations of non-PDS cereal trade only and all cereal trade using data from 2011-12 are in Table S4, along with estimates extracted from published reports on gravity models of Indian interstate trade. As each model uses different trade data, and includes different variables, we do not directly compare regression coefficients but focus on the relationships and trends.

Table S4 Regression coefficients of predicted interstate trade flows in this study and extracted estimates from existing gravity models of interstate trade in India.

Variable	*Coefficients (SE) 2011-12 non-PDS trade of cereals only (Dependant variable log of flows)*	*Coefficients (SE) 2011-12 all cereal trade (Dependant variable log of flows)*	*Coefficients (SE) Khanal (2016, trade data from 2005-14) (Dependant variable log of flows)*	*Coefficients (SE) Economic Survey (2017, trade data from 2015-16) (Dependant variable log of imports)*
Log distance between states	-2.24 (0.32)***	0.101 (0.0557)*	No association[1]	-0.928 (0.169)***
Log exporter GDP	1.40 (0.395)***	-0.220 (0.0335)***	0.194 (0.226)	0.958 (0.0568)***
Log importer GDP	-0.438 (0.344)	0.149 (0.0110)***	1.109 (0.277)***	0.816 (0.0943)***
Adjoining state dummy	0.435 (0.231)*	0.0432 (0.0551)	0.300 (0.237)	0.349 (0.193)*
Observations	781	811	1036	380

*Robust standard errors in parentheses. *** p<0.01, **p<0.05, *p<0.1*

[1] Relationships reported as no association in the text, but coefficient was not reported.

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The main driver of interstate trade for non-PDS cereals as estimated in our model was distance, whereby interstate trade has a strong negative association with increasing distance. This is expected as these trade flows were estimated by minimising the cost of transportation, which is mainly driven by distance. A negative relationships between trade and distance is consistent with gravity model results from international trade flows (23) and interstate trade flows of manufacturing goods in India (15). We also found that a larger agricultural GDP of the exporting state was associated with non-PDS trade, but the agricultural GDP of the importer was not. This could be due to our assumption that only states with excess supply of cereals will export, hence those states with larger agricultural GDP (and therefore production) are more likely to be exporters.

We also present the findings from the gravity model with all cereal trade, which is more comparable to the gravity model by Khanal (2016) that focused on agricultural rail trade and included trade through the PDS. Consistent with the model by Khanal (2016), we found no association with distance and all cereal trade. We also found states with larger agricultural GDPs were more likely to import, which is consistent with Khanal’s finding that agricultural rail trade is demand led. In contrast, we found a small negative association with agricultural GDP of the exporter. This may relate to the existence of the decentralised PDS for states with a higher agricultural GDP, such Andhra Pradesh and West Bengal, therefore they will not be exporting cereals to the PDS. However, these findings on the relationships between GDP and trade are only indicative, as agricultural GDP is not entirely reflective of the size of cereal economies in each state.

The gravity model coefficients enabled us to relate the trade model results to existing evidence. The coefficients indicate our model results are not widely dissimilar to estimates using actual data on trade. We do not use the gravity model results for any further modelling.

2.5 Sensitivity analysis of transportation cost data

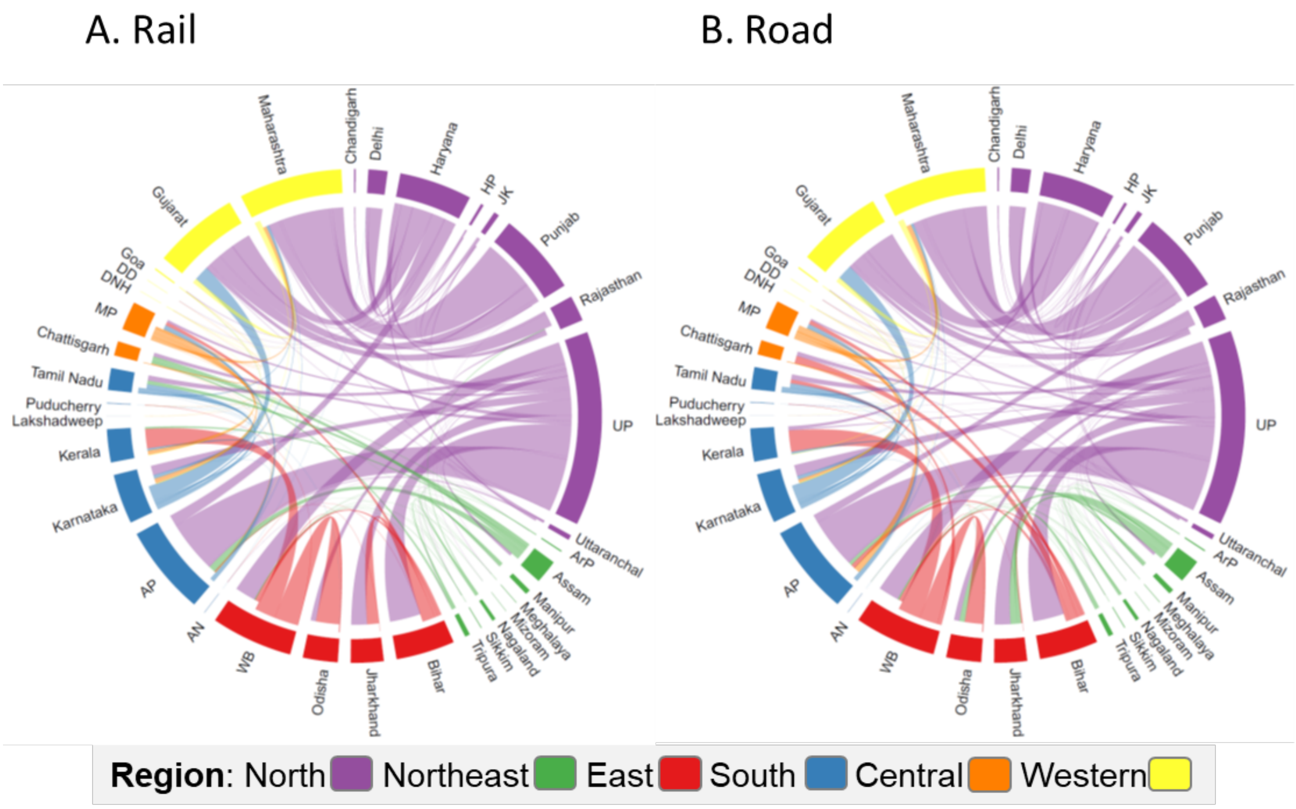

Figure S7 Patterns of interstate trade of all non-PDS cereals in Mt calculated through minimising A: the cost of rail transport, B: the cost of road transport. Chords are indented for importing state. HP: Himachal Pradesh, JK: Jammu and Kashmir, UP: Uttar Pradesh, ArP: Arunachal Pradesh, WB: West Bengal, AN: Andaman and Nicobar, AP: Andhra Pradesh, MP: Madhya Pradesh, DNH: Dadra and Nagar Haveli, DD: Daman and Diu.

APPENDIX

2.6 Sensitivity analysis of cereal trade through the Public Distribution System

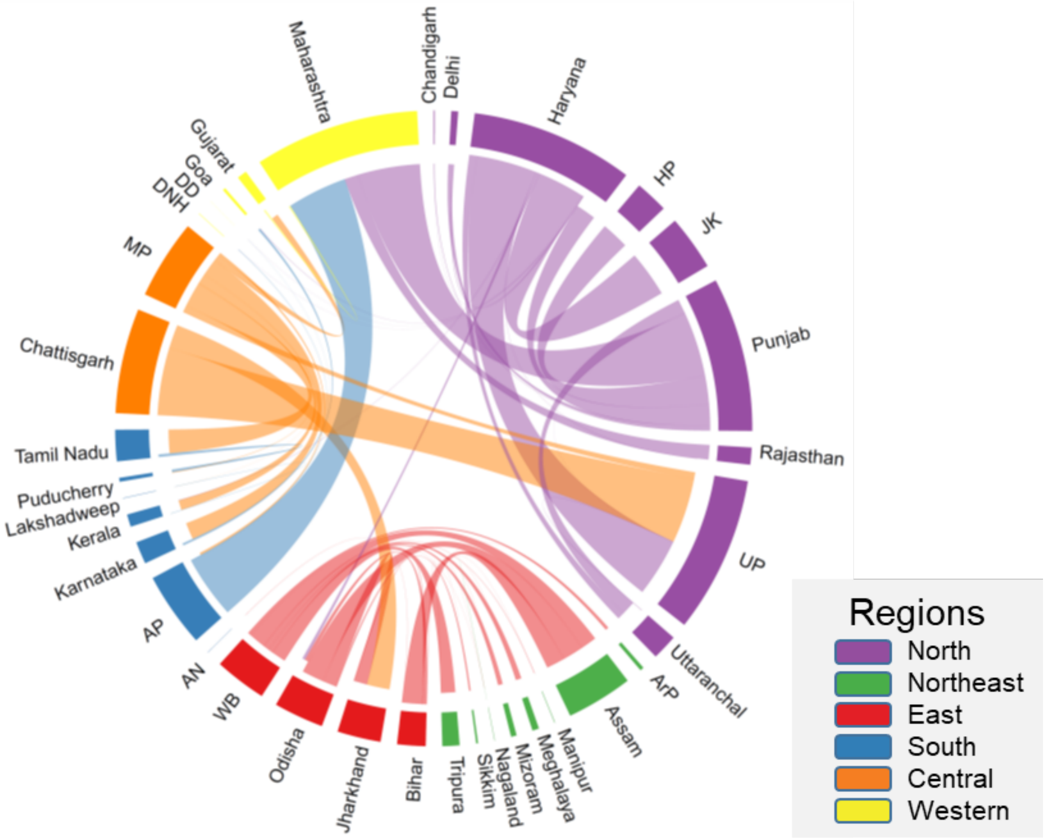

Figure S8 Modelled interstate trade of PDS cereals (Million Tonnes) based on minimising the cost of transportation. Colours of chord corresponding to the region of export. Chords are indented for importing state. HP: Himachal Pradesh, JK: Jammu and Kashmir, UP: Uttar Pradesh, ArP: Arunachal Pradesh, WB: West Bengal, AN: Andaman and Nicobar, AP: Andhra Pradesh, MP: Madhya Pradesh, DNH: Dadra and Nagar Haveli, DD: Daman and Diu.

Table S5 Trade of cereals through the Public Distribution System (PDS) and the embedded surface water and groundwater, if trade is optimised to minimise transportation cost. Groundwater status defined according to the Central Groundwater Board estimates from 2011(22). PDS: Public Distribution System. Row percentages may not total 100% due to rounding.

Variable	Status of groundwater in states		
	Safe (N=25)	Semi-critical to critical (N=6)	Over-exploited (N=4)
PDS exports (Mt, % of row total)	23.7 (44.8%)	1.68 (3.16%)	27.6 (52.1%)
Embedded groundwater in state exports of PDS cereals (km^3, % of row total)	8.13 (43.5%)	0.892 (4.78%)	9.65 (51.7%)
Embedded surface water in state exports of PDS cereals (km^3, % of row total)	9.74 (66.0%)	0.614 (4.16%)	4.41 (29.9%)
PDS imports (Mt, % of row total)	36.0 (67.8%)	14.7 (27.8%)	2.33 (4.39%)
Embedded groundwater in state imports of PDS cereals (km^3, % of row total)	12.1 (64.6%)	5.86 (31.4%)	0.746 (4.00%)
Embedded surface water in state imports of PDS cereals (km^3, % of row total)	11.0 (74.5%)	3.47 (23.5%)	1.98 (1.98%)

2.7 Results from sensitivity analysis using data from 2010-13 yearly average

Table S6 Key variables estimated in the analysis using data from 2011-12 year compared to the yearly average for 2010-13 period. Mt = Million Tonnes, PDS = Public Distribution System.

Variable (unit)	Year 2011-12	Yearly average 2010-13	Difference	Percentage Difference (2011-12 to 2010-13 average)
Summary statistics				
Total cereal production (Mt)	250	245	5.12	2.05
Blue water use of cereal production (km^3)	145	141	4.40	3.03
Green water use of cereal production (km^3)	292	290	2.36	0.808
Ground water use of Indian cereal production (km^3)	88.3	84.6	3.66	4.14
Surface water use of Indian cereal production (km^3)	57.0	56.3	0.74	1.30
Total cereal consumption (Mt)	201	192	9.19	4.57
Green water use of all cereal consumption (km^3)	237	228	9.39	3.95
Blue water use of all cereal consumption (km^3)	124	119	5.08	4.10
Total foreign export of cereals (Mt)	9.75	14.4	-4.65	-47.7
Total foreign import of cereals (Mt)	0.0175	0.0569	-0.0394	-225
Total interstate cereal trade (Mt)	93.8	93.9	-0.159	-0.170
Total embedded water in interstate cereal trade (km^3)	153	152	1.52	0.993
Public Distribution System				
Cereal production for PDS (Mt)	74.2	73.7	0.548	0.739
PDS consumption (Mt)	71.4	70.9	0.552	0.773
Total PDS exports (Mt)	58.0	58.2	-0.234	-0.404
Blue water traded through PDS (km^3)	36.7	37.4	-0.705	-1.92
Green water traded through PDS (km^3)	54.3	52.7	1.55	2.86
Groundwater traded through PDS (km^3)	21.3	21.6	-0.359	-1.69
Surface water trade through PDS (km^3)	15.4	15.8	-0.345	-2.24
Results from non-PDS cereal trade model				
Non-PDS consumption (Mt)	146	137	9.37	6.40
Total non-PDS cereal trade (Mt)	35.8	35.7	0.0751	0.0548
Blue water embedded in non-PDS trade (km^3)	17.3	17.2	0.0657	0.381
Green water embedded in non-PDS trade (km^3)	45.1	44.5	0.609	1.35
Groundwater embedded in non-PDS trade (km^3)	11.0	10.9	0.117	1.06
Surface water embedded in non-PDS trade (km^3)	6.24	6.30	-0.0514	-0.823
Central imports (Mt)	1.75	1.62	0.124	7.10
East imports (Mt)	8.77	6.16	2.61	29.8
North imports (Mt)	2.22	2.81	-0.597	-26.9
Northeast imports (Mt)	0.599	2.78	-2.18	-364
South imports (Mt)	10.4	9.28	1.07	10.4
Western imports (Mt)	12.1	13.0	-0.954	-7.91
Central exports (Mt)	1.09	0.773	0.319	29.2
East exports (Mt)	4.93	4.57	0.359	7.29
North exports (Mt)	24.7	21.6	3.169	12.8
Northeast exports (Mt)	1.99	2.78	-0.788	-39.6

South exports (Mt)	2.55	4.42	-1.87	-73.2
Western exports (Mt)	0.458	1.57	-1.12	-244
Theoretical water savings	**Year 2011-12**	**Yearly average 2010-13**	**Difference**	**Percentage Difference (2011-12 to 2010-13 average)**
Groundwater savings (km^3)	-1.97	-3.18	1.21	-61.7
Surface water savings (km^3)	4.51	1.92	2.59	57.4
Green water savings (km^3)	28.8	35.4	-6.53	-22.6

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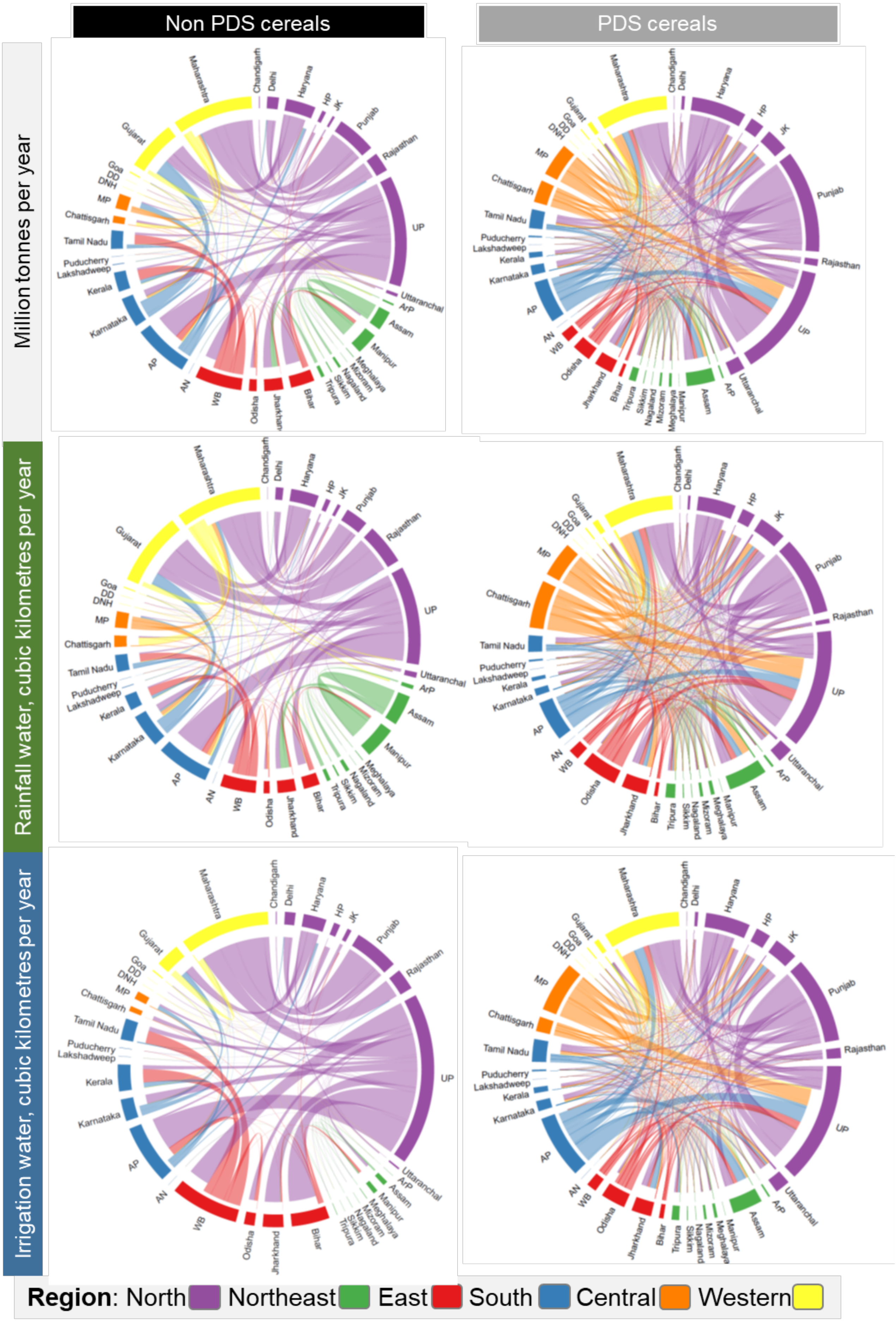

Non PDS cereals
PDS cereals
Million tonnes per year
Rainfall water, cubic kilometres per year
Irrigation water, cubic kilometres per year
Maharashtra
Chandigarh
Delhi
Haryana
HP
JK
Punjab
Rajasthan
UP
Uttaranchal
ArP
Assam
Manipur
Meghalaya
Mizoram
Nagaland
Sikkim
Tripura
Bihar
Jharkhand
Odisha
WB
AN
AP
Karnataka
Kerala
Lakshadweep
Puducherry
Tamil Nadu
Chattisgarh
MP
DNH
DD
Goa
Gujarat
Region: North Northeast East South Central Western

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Figure S9 Interstate trade of all cereals and the embedded water, using yearly average for the period 2010-13. Colours of chord corresponding to the region of export. Chords are indented for 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.

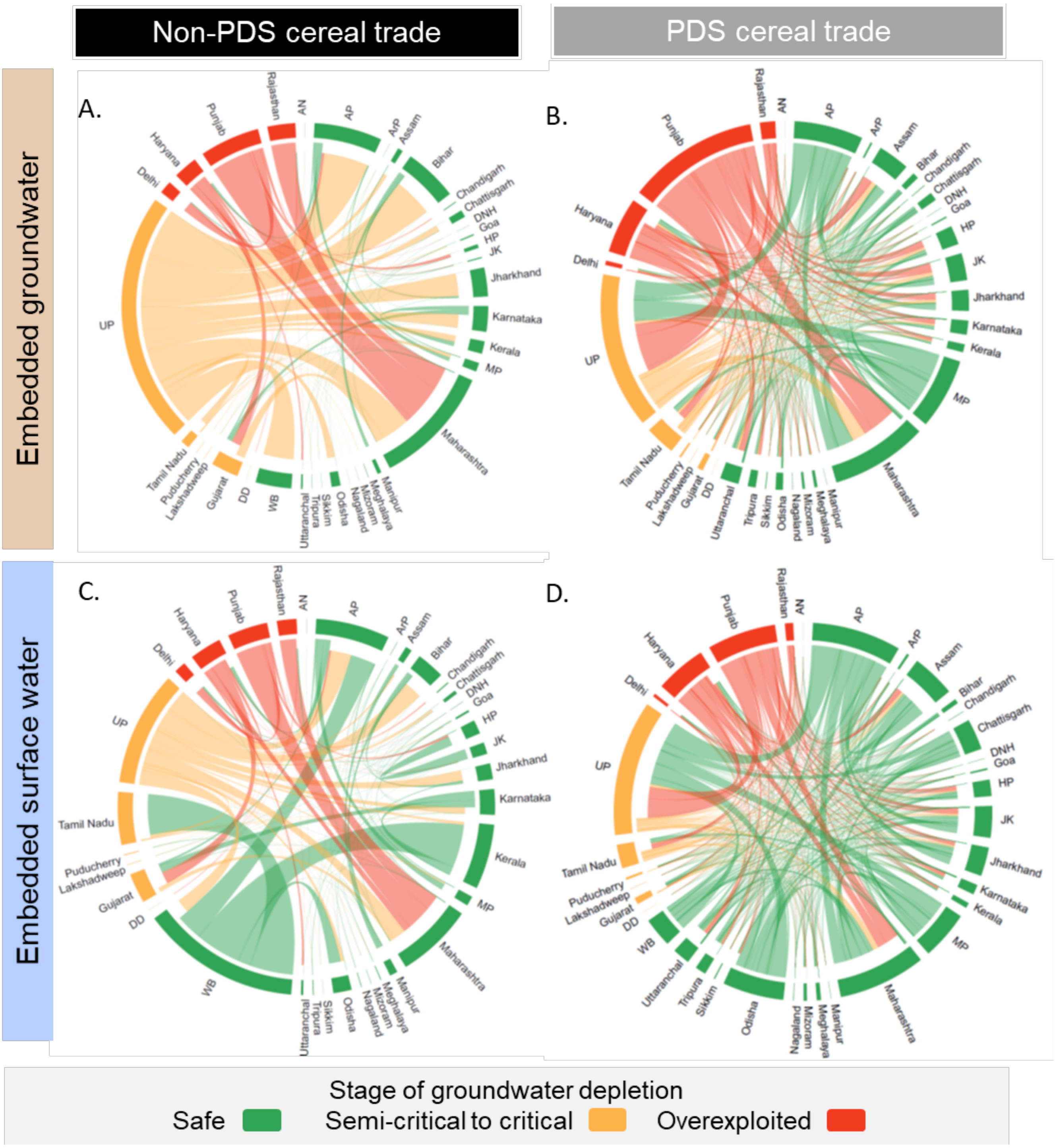

Figure S10 The ground and surface water exported through the interstate trade of cereals in India, using the yearly average between 2010-13. A and C: additional cereal trade not included in the Public Distribution System. B and D: cereals traded through the Public Distribution System (PDS). Values in Km^3/year. Chord colour corresponds to the stage of groundwater depletion in the exporting state, as defined by the Central Groundwater Board of India (22). Chords are indented for importing state. AN: Andaman and Nicobar, AP: Andhra Pradesh, ArP: Arunachal Pradesh, DNH: Dadra and Nagar Haveli, HP: Himachal Pradesh, JK: Jammu and Kashmir, MP: Madhya Pradesh, DD: Daman and Diu, UP: Uttar Pradesh, WB; West Bengal.

2.8 The water use of cereal consumption in each state

Table S7 Comparison of the estimated water use of cereal consumption in each state using consumption volumes based on the National Sample Survey (2011-12), and either local water footprints, or after accounting for trade hence using water footprints based on the origin of production.

State	Using local water footprints		After accounting for trade (i.e. estimated in this study)		Percentage difference	
	Blue water (km^3)	*Green water (km^3)*	*Blue water (km^3)*	*Green water (km^3)*	*Difference in blue water use (%)*	*Difference in green water use (%)*
Andaman and Nicobar Islands	0.0253	0.0501	0.0225	0.0420	-11.1	-16.3
Andhra Pradesh	9.66	8.95	7.29	9.09	-24.6	1.57
Arunachal Pradesh	0.0235	1.06	0.194	0.677	723	-36.4
Assam	0.321	16.0	3.74	11.8	1067	-26.3
Bihar	9.97	14.8	9.95	14.7	-0.240	-0.815
Chandigarh	0.0198	0.0668	0.0815	0.0948	312	42.0
Chhattisgarh	1.65	5.36	1.44	5.02	-12.6	-6.26
Dadra and Nagar Haveli	0.0409	0.0879	0.0352	0.0745	-14.0	-15.2
Daman and Diu	0.00820	0.0309	0.00711	0.0347	-13.4	12.4
Delhi	0.620	0.683	0.837	1.40	34.9	105
Goa	0.197	0.312	0.190	0.332	-3.69	6.44
Gujarat	5.57	15.3	4.79	16.1	-14.0	5.41
Haryana	2.07	2.64	2.40	2.82	15.9	6.55
Himachal Pradesh	0.963	7.28	1.76	3.62	82.9	-50.4
Jammu and Kashmir	5.36	10.7	3.25	6.48	-39.4	-39.1
Jharkhand	1.50	10.8	3.49	8.61	132	-20.2
Karnataka	4.48	13.3	4.11	12.4	-8.33	-6.60
Kerala	1.47	2.91	2.07	2.65	40.4	-8.94
Lakshadweep	0.0148	0.0438	0.0189	0.0348	27.5	-20.7
Madhya Pradesh	8.36	13.2	8.51	12.5	1.74	-5.48
Maharashtra	13.9	37.7	12.2	31.6	-12.2	-16.4
Manipur	0.00787	0.521	0.0401	0.687	410	31.8
Meghalaya	0.211	0.916	0.398	0.888	88.8	-3.15
Mizoram	0.0327	2.32	0.270	0.798	726	-65.7
Nagaland	0.00945	0.388	0.0471	0.352	399	-9.39
Odisha	5.47	8.81	3.79	7.98	-30.6	-9.49
Puducherry	0.454	0.260	0.259	0.375	-42.8	44.1
Punjab	1.44	2.02	1.44	2.02	0.00431	0.13
Rajasthan	7.66	24.2	7.55	24.1	-1.50	-0.34
Sikkim	0.00480	0.3036	0.0934	0.248	1845	-18.2
Tamil Nadu	5.61	7.25	5.49	6.44	-2.10	-11.2
Tripura	0.0593	2.18	0.879	2.03	1383	-7.06
Uttar Pradesh	30.7	44.1	29.4	39.2	-4.00	-11.2
Uttaranchal	0.913	3.03	1.68	3.17	84.4	4.78
West Bengal	5.94	8.89	6.17	9.02	3.82	1.40

India	125	266	124	237	-0.623	-10.9

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APPENDIX 4 - Chapter 6: India's food system and climate hazards: assessing the resilience of the food supply

Supplementary information.

Francesca Harris, Giriraj Amarnath, Edward Joy, Alan Dangour, Rosemary Green

Contents

Modelling state-wise location of food production for food supply

For each state (i) and food item (f), available supply of food ($S_{i,f}$) includes local production ($P_{i,f}$) and foreign imports ($FI_{i,f}$), change in stock ($\Delta St_{i,f}$), minus waste and non-food uses of cereals ($OU_{i,f}$) (feed, seed, processed and other) (equation 1, with definition of these quantities given in the glossary).

$$S_{i,f} = P_{i,f} + FI_{i,f} + \Delta St_{i,f} - OU_{i,f} \quad (54)$$

The amount of supply for non-food uses ($OU_{i,f}$) in the state was calculated using the proportion of supply diverted to non-food use according to national-levels (α_f) (equation 2).

$$OU_{i,f} = \alpha_f * (P_{i,f} + FI_{i,f} + \Delta St_{i,f}) \quad (55)$$

The state demand for cereals includes cereals for food consumption in rural (rur) and urban (urb) populations and foreign exports ($FE_{i,f}$) (equation 3).

$$D_{i,f} = C_{i,f}^{urb} + C_{i,f}^{rur} + FE_{i,f} \quad (56)$$

The supply and demand of each food items was balanced across states to estimate the quantity of food items exported or imported from each state. Therefore, excess supply from a state meets unmet demand in other states. The direction and volume of trade flows for each food item were estimated through a linear programming model that minimised the overall cost of transportation (1-4).

The function of the model was to minimize:

$$TC_f = \sum_{i,j,f} \left(t_{i,j,f} \cdot tc_{i,j,cat}\right) \quad (57)$$

The model constraints were:

- Supply of each food item equals demand in each state (equation 5).
- Trade flows are only positive (equation 6).
- Foreign imports are added to the states total supply, while foreign exports are added to the states demand.

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- Net export of the commodity is bounded by local production or foreign import (if any) (equation 7).

$$\forall\epsilon\ [1:35]: P_{i,f} + FI_{i,f} + \ \Delta St_{i,f} - OU_{i,f}\ + \sum_{j\neq i, j=1:35} (t_{j,i,f} - \ t_{i,j,f}) = C^{urb}_{i,f} +\ C^{rur}_{i,f} +\ FE_{i,f} \quad (58)$$

$$\forall(i,j): t_{i,j,f}\ \geq 0;\ \forall i : t_{i,i,f} = 0 \quad (59)$$

$$\sum_{j\neq i, j=1:35} (t_{i,j,f} - \ t_{j,i,f}) <= \max{(0, St_{i,f} FI_{i,f})} \quad (60)$$

The assumptions of the model were as follows:

- $t_{i,j,f}$ is the unknown interstate trade matrix for the food item f, in tonnes,
- $tc_{i,j,cat}$ is the interstate transportation cost matrix for each food category, in Rupees/tonne,
- TC_f is the total cost of interstate trade of the food item f, in Rupees.
- i refers to the exporting state, while j refers to the importing state [N= 35],
- $P_{i,f},\ FI_{i,f},\ FE_{i,f},\ \Delta OU_{i,f}\ and\ \Delta St_{i,f}$ are state i's production, foreign import, foreign export, non-food uses and net change in stock of food item f, in tonnes.
- $C^{urb}_{i,f}$ and $C^{rur}_{i,f}$ are state i's consumers demand for food item f, for urban and rural populations respectively (total, not per capita), in tonnes.

Data on transportation costs in Rupees/Km/Tonne was available for the categories of grains, sugar, fruits and vegetables and livestock as in the RITES Ltd. Planning Commission report (5). The relationship between transportation cost and road distance travelled is non-linear, as it is assumed longer routes will have reduced time and capacity costs relative to shorter distances Transportation (tc) were calculated for each these food categories (cat) as follows:

$$tc^{road}_{i,j,cat} = dist^{road}_{i,j} \sum_k tc^{road}_{India,cat_k}\ I_k(dist^{road}_{i,j}) \quad (61)$$

$$I_k\left(dist^{road}_{i,j}\right) = 1\ if\ dist^{road}_{i,j}\ \in (min_k, max_k) \quad (62)$$

$$I_k\left(dist^{road}_{i,j}\right) = 0\ if\ dist^{road}_{i,j} < min_k\ or\ dist^{road}_{i,j} >\ max_k \quad (63)$$

$$tc^{rail}_{i,j,cat} = tc^{rail}_{India,cat} * dist^{rail}_{i,j} \quad (64)$$

$$tc^{ship}_{i=is,j=is,,} =\ tc^{ship}_{India} * dist^{ship}_{i=is\ or\ isport,j=is\ or\ isport} \quad (65)$$

Where:

tc^{road}_{India,cat_k} represents the weighted average cost of road transportation for the food category (cat) in Rupees/Km/Tonne for distance category k (5), and $I_k\left(dist^{road}_{i,j}\right)$ is an indicative function that takes value 1 if the distance is in category k and value 0 if the distance is in any other category. $tc^{rail}_{India,cat}$ and represent the weighted average cost of rail of the food category in India in Rupees/Km/Tonne (5). The transportation cost to and from the island states (Lakshadweep and Andaman and Nicobar Islands) is based on the cost of shipment $tc^{ship}_{i=is,j=is,,}$, calculated from the shipping distance ($dist^{ship}_{i=is\ or\ isport,j=is\ or\ isport}$) and cost per km per tonne for shipment= tc^{ship}_{India} (5), and the cost of rail or road transport between the state of their mainland port and other states. For all other states/UTs trade is assumed to occur via land.

The transportation costs matrix to be minimised was estimated as:

$$tc_{i,j,cat} = \left(tc^{road}_{i,j,cat} *\ prop^{road}_{cat}\right) + \left(tc^{rail}_{i,j,cat} * prop^{rail}_{cat}\right) +\ tc^{ship}_{i=is,j=is,} \quad (66)$$

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Where $prop_{cat}^{road}$ and $prop_{cat}^{rail}$ are the proportion of each food category transported by road and rail in India respectively.

For processed food products (oils and sugar), we estimated trade flows as raw materials as this aligned with the data on international trade flows. We then converted trade flows and food consumption to tonnes of extracted (i.e. edible) product, using the extraction rate ($ex_{india,f}$), as follows:

$$t_{i,j,f}^{edible} = t_{i,j,f} * ex_{india,f}$$

$$C_{i,j,f}^{edible} = (C_{i,f}^{urb} + C_{i,f}^{rur}) * ex_{india,f}$$

Table S1 Data glossary; variables and data sources used in this study

Variable	Code	Source
Production of commodity in each state (tonne/year, 2011-12).	$P_{i,f}$	Obtained from Directorate of Economics and Statistics, Ministry of Agriculture and Farmer's Welfare, and Agriculture Statistics at a Glance Year Book, 2014 (6)
Volume of foreign imports and export (tonne/year) to ports in India for each food item (2011-12).	$FI_{i,f}$ $FE_{i,f}$	The total volume of foreign trade in India was taken from Kastner et al. (2014), which provides a detailed global matrix of estimated location of production (tonne/year) (7). Foreign exports are imports were distributed between states/UTs based port and commodity specific estimates from Directorate General of Commercial Intelligence and Statistics (DGCIS), Government of India, downloaded from the AgriExchange website (8). The total volume of foreign trade did not match between the two data sources; therefore, we used the volume from Kastner et al. (2014) and scaled to the port-specific values.
Net change in stock (tonne/year) (2011-12)	$\Delta St_{i,f}$	India-specific figures in UN Food and Agricultural Organisation (FAO) Food Balance Sheets (2011) (9).
Proportional of total supply going to waste, feed, seed and other non-food uses for each year (2011-12).	α_f	India-specific figures from UN Food and Agricultural Organisation (FAO) Food Balance Sheets (2011) (9).
Extraction rate of edible product from raw	$ex_{india,f}$	For the processed products of oils and sugar, extraction rates were used to convert primary/raw product to edible product, according to India specific values (10)
Demand (food available for consumption) of each food item in each state (tonne/year) (2011-12)	$C_{i,f}^{urb}$ $C_{i,f}^{rur}$	National-level demand based on food supply available after non-food uses have been removed. State-level values were calculated using proportional consumption of the national demand relative to NSS 68th Round (2011-12) (11). The NSS database is assumed nationally representative.
Transportation costs of food categories by rail (Rupees/km/tonne)	$tc_{India,cat}^{rail}$	Cost of railway transport for food categories reported in the RITES Planning Commission Report of India (2, 5). multiplied by cumulative distance of road transport (Rs./km/tonne) from RITES Planning Commission Report of India (5).
Railway distance between state capitals	$dist_{i,j}^{rail}$	The shortest path of goods rail transport between train stations of state capitals between each state importing and exporting pair, as reported by the Govt. of India Centre for Railway Information Systems (12).
Transportation costs of food categories by road (Rupees/km/tonne)	tc_{India,cat_k}^{road}	Cost of road transport for food categories reported in the RITES Planning Commission Report of India (2, 5). Costs vary depending on distance category k.
Road distance between state capitals	$dist_{i,j}^{road}$	Minimum road distance between state capitals for each state importing and exporting pair obtained from Google Maps (13)
Transportation costs of shipping commodities for island Union Territories	tc_{India}^{ship}	Cost of shipping (Rupees/km/tonne) reported in the RITES Planning Commission Report of India (5). Shipping cost is not category specific.

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Shipping distances between island states and mainland ports	$dist^{ship}_{i=is\ or\ isport,\ j=is\ or\ isport}$	For island states (is) Andaman and Nicobar Islands and Lakshadweep with no road or rail transport available, distance between the main island port and major mainland ports were taken from Google Maps(13).
Weights for food group transported by road vs rail	$prop^{road}$ $prop^{rail}$	Weighted proportion of food group transported by road and rail in India, as states in the RITES Planning Commission Report of India(2).
Floods presence		Flood hazard map is based on NASA MODIS Terra time series satellite data for the year between 2000-2020. A flood algorithm was applied to detect flood pixels on each eight-day satellite image to map the monthly, seasonal and annual flood extent over India (14).
Drought presence		Drought hazard map is based on the analysis of drought events year 2000-2020 by analysing rainfall, vegetation, soil moisture and evapotranspiration to produce a weekly integrated drought severity index (IDSI) using satellite observations from NASA MODIS surface reflectance, rainfall product from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), surface soil moisture from land surface temperature and rainfall data from the Tropical Rainfall Measuring Mission (TRMM). The weekly indexes were combined to generate annual drought frequency maps and an estimated drought area in sq. km. Sixteen years of drought frequency was normalized to calculate the hazard level (15).
Extreme temperature presence		Heat wave hazard map is based on the analysis of extreme temperature events year 2000-2015. The pixels were extracted from NASA MODIS LST 8-day weekly products to represent the extreme temperature area in sq. km based on annual frequency. Sixteen years' heat wave data was normalized to calculate the hazard. NASA MODIS Land Surface Temperature (LST) data (MOD11A2, 8-day).
Extreme rainfall presence		Extreme rainfall hazard map is based on analysis of extreme rainfall events year 1951- 2015. The extracted pixels represent the extreme rainfall area in sq. km based on annual frequency. Sixteen years' extreme rainfall frequency was normalized to calculate the hazard level. Rainfall data downloaded from Asian Precipitation - Highly Resolved Observational Data Integration Towards Evaluation of Water Resource (APHRODITE) (16) and NASA Tropical Rainfall Measuring Mission (TRMM) (17)
Landslides presence		Landslide hazard map is based on an estimate of the annual frequency of landslides triggered by precipitation. Data from the International Centre for Geohazards, Norwegian Geotechnical Institute is based on a combination of trigger and susceptibility defined by six parameters: slope factor, lithological (or geological) conditions, soil moisture condition triggered by precipitation, vegetation cover, precipitation and seismic conditions. Data from Global Risk Data Platform (18)
Sea level rise presence		Coastal hazard map was created by integrating six different parameters: (1) rate of sea-level rise; (2) coastal slope; (3) regional elevation; (4) tidal range; (5) tsunami wave arrival height and (6) coastal geomorphology. The source of elevation data is the Shuttle Radar Topography Mission (SRTM) downloaded from the Consortium for Spatial Information (CGIARCSI). Tidal gauge on sea-level rise data was downloaded from the Permanent Service for Mean Sea Level (PSMSL) and General

		Bathymetric Chart for the Oceans (GEBCO) as monthly point data. http://srtm.csi.cgiar.org/ and https://www.psmsl.org
Forest fire presence		Forest fire hazard map is based on the NASA MODIS NRT active fire products (MCD14DL) using the standard MOD14/MYD14 Fire and Thermal Anomalies product year 2001-2017. In order to account for the low to severe fire hazard areas, vector data from DIVA-GIS was added to the analysis. Each MODIS active fire location represents the centre of a 1 km pixel that is flagged by the algorithm as containing one or more fires within the pixel. Data from the NASA Fire Information for Resource Management System (FIRMS). https://firms.modaps.eosdis.nasa.gov/download/
Hazard score	H	The presence of the climate related hazard in a state, according to percentage of area exposed in each state. Values are normalised for each hazard type between 0 to 1, with 1 representing 100% of state area with the presence of the hazard and 0 representing no hazard presence in the state.
Vulnerability score	V	The vulnerability of the state in responding to the climate-hazard, represented by the Human Development Index (HDI) as a composite indicator of several factors that increase vulnerability. HDI values were normalised across states using the max-min approach, and the vulnerability score is the inverse of the normalised value. Sub-national HDI values downloaded from the Global Data Lab(19)
Exposure score	E	The volume (tonnes) of food production for food supply in the state. Values across local production and imported volume are normalised between 0 to 1 according to the max-min approach. Modelled data on source of food supply for each Indian state according to 30 major food items.

Validation of the model to estimate location of production for each food group

We follow the methods of Harris et al,. 2020 to validate our modelling approach to estimate food trade for each food item. We use a mixed effect linear regression model to assess the association between the cost of transportation (Rupees/kg) against the unit value of the food item to the consumer in the importing state (Rupees/kg – using data from the NSS). The model was weighted according to the volume of consumption. We performed a mixed effect regression analysis for each food group, with the food item as the random effect. The results are shown in Supp Table 2. For each food group, the relationship between cost of transport and cost to the consumer is positive, suggesting the modelling approach of minimising the cost of transportation is valid. For pulses, the relationship was positive but not significant. Their contribution to total supply was relatively small so we included them in the analysis.

Supp Table 2 Results of the mixed effect linear regression comparing the transport cost for food groups against the cost to the consumer in the importing state, weighted by the consumption volume. Food item in each food group included as random effect.

FOOD GROUP	COEFFICIENT	LOW 95% CI	HIGH 95% CI	P	N	N FOOD ITEMS
CEREALS	3.32	1.27	5.36	0.001	245	7
FRUIT	3.15	0.28	6.02	0.032	245	7

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RAPE & MUSTARD OIL	5.10	2.01	8.20	0.002	33	1
PULSES	1.97	-2.47	6.41	0.384	210	6
SUGAR	11.45	3.89	19.01	0.004	35	1
VEGETABLES	2.47	0.97	3.97	0.001	280	8

Overview of state-wise data on food supply (exposure) and vulnerability

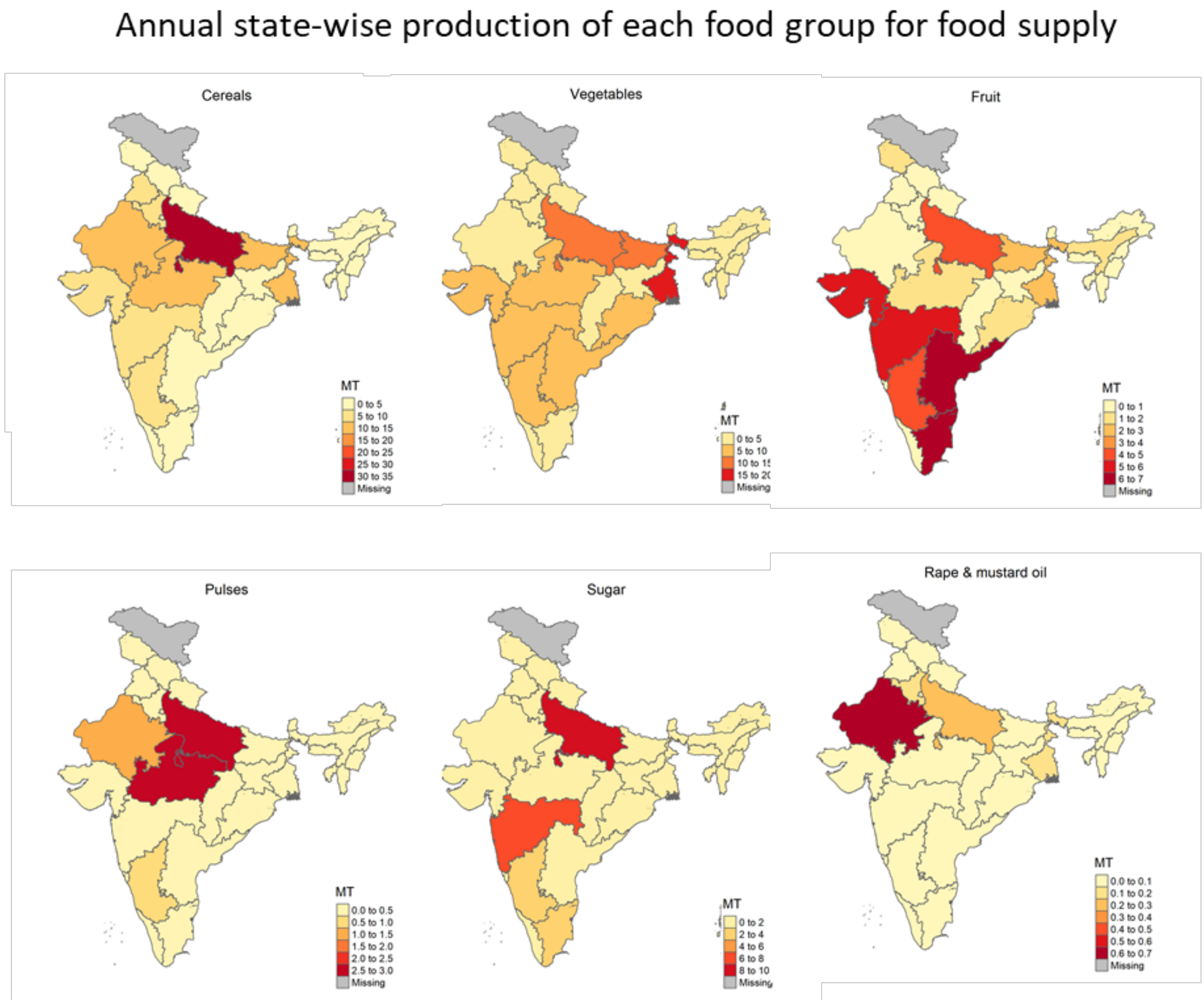

Figure S1 State-wise production of food groups for food supply as estimated in this study

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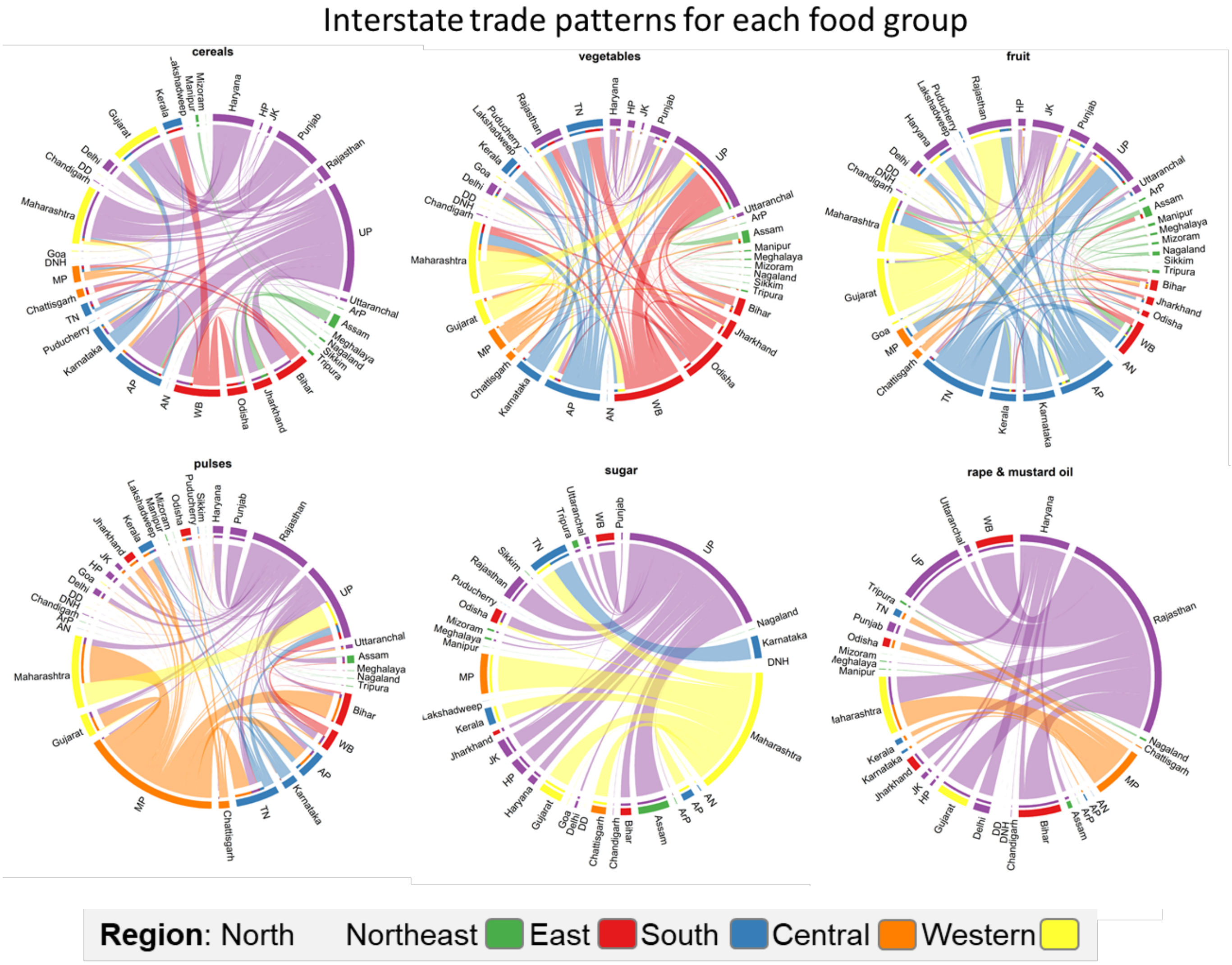

Figure S2 Interstate trade of food groups, as estimated in this study. Chords are coloured according to the region of the exporting state, and indented for the importing state. Chord size is relative to tonnes traded by year.

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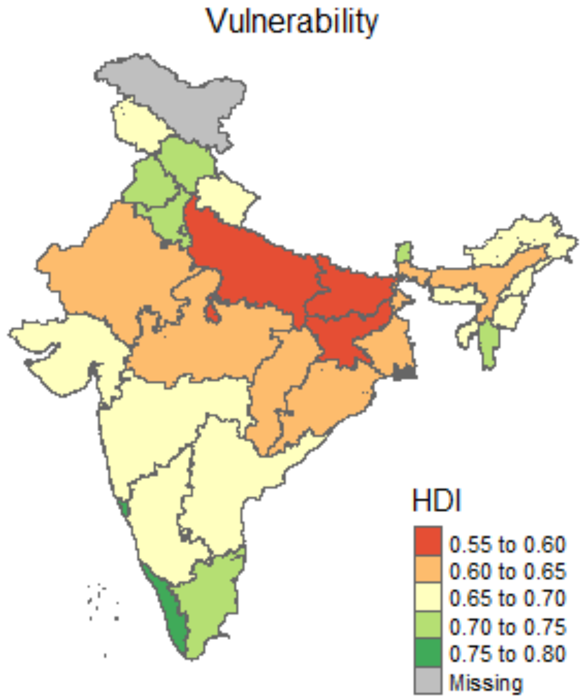

Figure S3 Human Development Index for Indian states (19). A higher value represents higher level of development. The HDI Index varies between 0.779 in Kerala, and 0.576 in Bihar.

Hazard, vulnerability and exposure scores for total food supply in each state

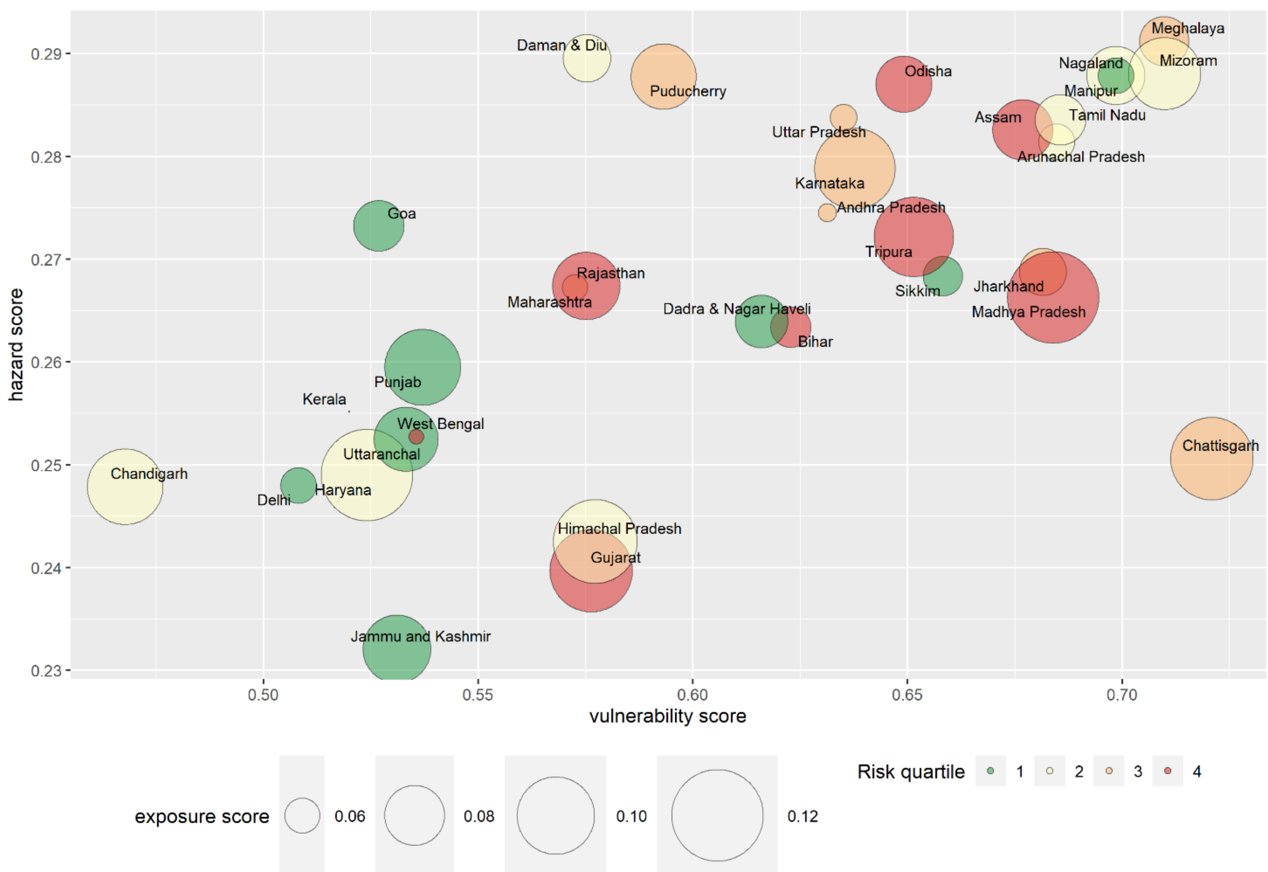

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Figure S4 Hazard, vulnerability and exposure scores for per capita food supply in each state. Bubbles are colour coded according to total food supply risk quartile. Maps illustrate the local risk per capita and the import risk per capita for each state.

Climate hazard risk results for total (Tonnes/state) food supply across states

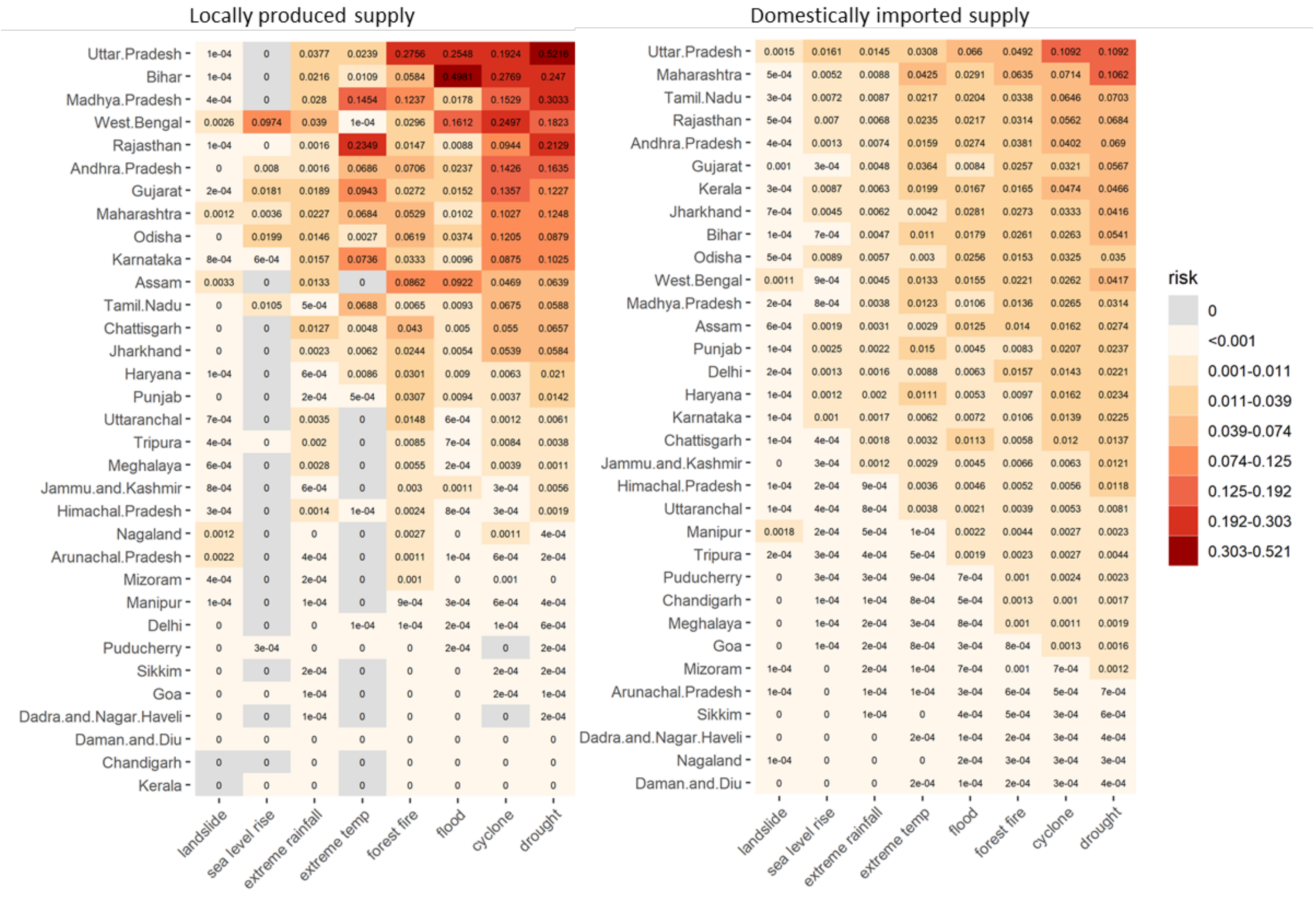

Figure S5 The overall climate-hazard risk to food supply across Indian states (N=33), according to supply that is produced locally compared to supply that is imported from other states. Heat maps are colour coded according to natural jenks of local supply for each supply level, using the BAMMtools package in R.

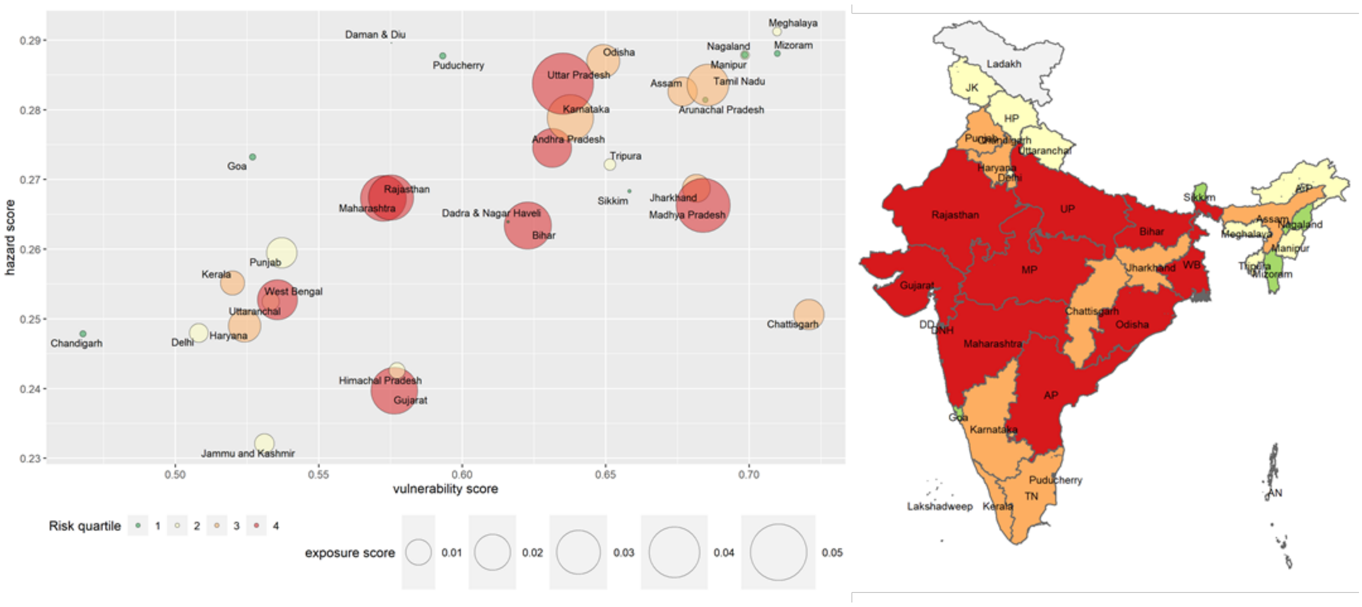

Figure S6 Hazard, vulnerability and exposure scores for food supply in each state, alongside a map of the combined climate hazard risk to overall food supply for each state. Bubbles are colour coded according to combined climate hazard risk quartile.

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Climate hazard risk in food supply exports for each state and hazard type

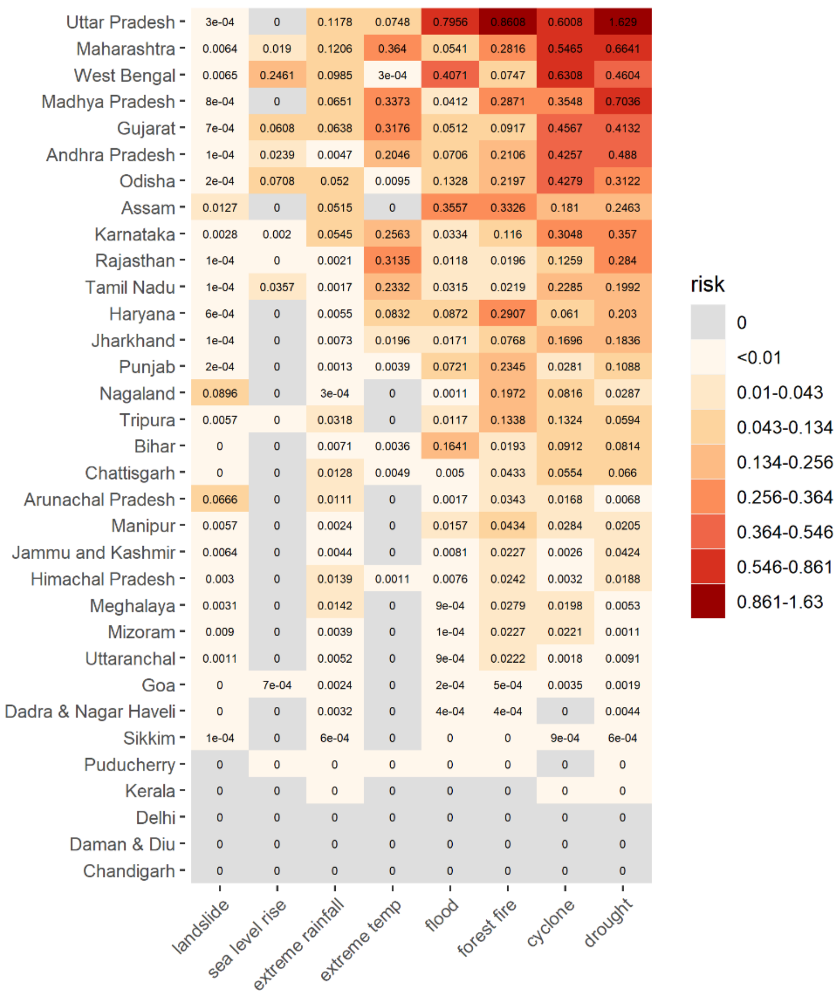

Figure S7 Climate-hazard risk to food supply exported from each Indian state included in this study (N=33). Heat map is colour coded according to natural jenks, using the BAMMtools package in R.

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