DESIGN AND ANALYSIS OF URBAN FOOD SYSTEMS FOR MULTIPLE SUSTAINABILITY OBJECTIVES

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ABSTRACT

Globally, there is rising interest in urban food systems. The food system encompasses the linkages between food production and consumption, the institutions who govern them, and the associated multiple sustainability outcomes of environment, economy, equity, human health and well-being (UNEP 2016). Cities thus require tools necessary to evaluate their food system in light of multiple sustainability objectives.

This dissertation contributes to the literature by exploring food supply systems to cities from a trans-boundary perspective, linking multiple sustainability outcomes with actions that seek to address health and well-being within the city. We develop spatially disaggregated footprints to assess the multiple environmental impacts of water, GHG, land of both current urban food demand and future scenarios in multiple cities in India and the U.S. Key findings, organized by chapter are described below.

The developed methods include five main steps of: 1) quantifying community-wide food demand (across homes, business, and industry); 2) estimating current local production; 3) estimating origins of production serving urban demand by agri-food type, quantifying spatially informed second order impacts (energy/GHG for irrigation); 4) quantifying current in- and trans-boundary environmental impact (energy/GHG, water, and land in Chapter 3). Applied to Delhi India, the analysis finds 10% of food by mass provided by local production. Further, food was the largest contributor to the city water footprint (accounting for both green and blue water) across infrastructure sectors. Food activities also shaped both in-boundary energy and water flows, particularly with the activities of cooking, and urban agriculture respectively.

Chapter 3 uses a baseline from Chapter 2 to assess the contribution of city-scale actions to the overall food system's environmental impacts (expanding to include land, GHG/energy, water). Applied to Delhi, India, the analysis demonstrates that city-scale action can rival typical food policy interventions that occur at larger scales, although no single city-scale action can rival in all three environmental impacts. In particular,

improved food-waste management within the city (7% system-wide GHG reduction) matches the GHG impact of pre-consumer trans-boundary food waste reduction. The systems approach is particularly useful in illustrating key tradeoffs and co-benefits. For instance, multiple diet shifts that can reduce GHG emissions have trade-offs that increase water and land impacts. Improving the nutrition status for the bottom 50% of the population to the median diet is accompanied by proportionally smaller increases of water, GHG, and land impacts (4%, 9%, and 8%, systemwide): increases that can be offset through simultaneous city-scale actions, e.g., improved food-waste management.

Chapter 4 analyses the food systems of 9 different cities within a single country (India). Taking into account differences of unique economies, socio-cultural characteristics and supply chains finds variation across food systems. This work connects urban food demand of consumers and producers incorporating differences of diet and socio-economic data with supply chain data with location of production to inform food miles and environmental impacts across cities. The ratio of consumers to producers largely shapes community-wide food demand, as well as substantial differences in residential diet. Differences of residential diet result in a variation of per capita resource use of 91% (range of 600-1,148; median of 771 m^3/capita) for water, 35% for greenhouse gas (GHG) (1st and 2nd order impacts) (range of 0.29-0.45; median of 0.39 t CO_2e per capita) and 141% for land (range of 0.12-0.28; median of 0.14 ha per capita). The computation of GHG impacts includes 2nd order impacts (emissions from irrigation), which exhibit even greater variation of 1326% across city per capita consumption (range of 0.02 to 0.29; median of 0.18 t CO_2e) accounting for 6-63 % of total combined 1st and 2nd order GHGs.

Levels of under-nutrition also vary by city, with the average residential diet of all but two cities (Pondicherry and Delhi) falling below the national recommendations for caloric intake. Three cities (Ahmadabad, Rajkot, Chennai) fall below the recommended protein intake, suggesting an important role for cities in national food security agendas. Food miles vary between cities, with the range of 196 (Pondicherry) to 1,137 (Chennai) km/ton. It is interesting to note, however, that even the highest, (Chennai) is less than U.S. average of >1600 km/t. We also evaluate supply chain risk in terms of the water

scarcity of food producing regions that serve cities. The food producing locations on average, are less water scarce than the watersheds local to the urban environments, suggesting the water intensive large-scale agriculture would be best located at a distance from urban centers, away from competing demands.

Chapter 5 further expands the systems framework to the U.S. This work compares the Indian analyses of Pondicherry and Delhi with Minneapolis (Hennepin County) and New York City in the United States, illustrating the wide-spread applicability of these methods, despite differing levels of data availability and substantial differences of food system structure (i.e. differences of diets, levels of local production, processing, etc). This work combines bottom-up and top-down methods to overcome data limitations of the U.S food system, specifically with respect to community-wide flows encompassing homes, businesses, and industries as well as assessing the sensitivity of the supply chain to location of production. The baseline analysis of the four cities finds that 2^{nd} order contribution to GHG impact of per capita food demand is much lower in the U.S. than India due to a higher contribution of meat emissions to total diet and greater energy efficiency of irrigation in the U.S. The scenario analysis provides similar findings across all four cities, with diet change and food waste management as key levers to mitigate environmental impact, though with the distinction of pre-consumer food waste playing a larger role than Indian cities, while post-consumer waste management is more important in U.S cities.

Over all, the methods of this dissertation can inform policy in diverse cities despite some data limitations. This provides a timely contribution to cities eager for analysis tools that will help guide progress towards the many objectives of urban food systems.

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CHAPTER 1 | Introduction and background

INTRODUCTION

Globally, we live on an urban planet (Wigginton *et al* 2016). Currently home to over half of the global population (UN 2015) and generating over 80% of global GDP, (McKinsey Global Institute 2011) urban areas are continuing to grow at a rapid pace, expected to house over two thirds of the global population by 2050 (UN 2015).

With such high concentration of population and activity, cities are being called to take up global development mandates, such as the United Nation's Sustainable Development Goals (SDGs). These goals include 17 issues of global importance, ranging from ending hunger, combatting climate change, to caring from the environment, education, and health (United Nations 2017). Developed in 2015, as a part of the 2030 Agenda for Sustainable Development, the SDGs bring together goals for both developed and developing nations. These goals detail multiple distinct objectives for addressing human and environmental well-being, such as halting biodiversity loss, addressing land degradation and mitigating climate as well as ending hunger, promoting well-being and providing clean water (United Nations 2017).

Yet to understand the role that cities can play in these broad global agendas, cities cannot be viewed as entities bounded by their administrative boundaries. Rather cities must be viewed as complex, multi-scale, multi-sector trans-boundary systems, intricately linked with technical, social, and environmental resources, well-beyond the city boundary (McPhearson *et al* 2018, Grimm *et al* 2017, Ramaswami *et al* 2012). These linkages, are multi-directional, with rural and urban areas both contributing to, and taking from one another. The research area of sustainable urban systems has emerged to better understand the trans-boundary nature of cities and urban areas as they impact multiple sustainability goals. Recently a few frameworks have emerge that aim to capture the complexity of urban systems, such as the social-ecological-infrastructure systems (SEIS) framework (Ramaswami *et al* 2012) and the social-ecological technical system (SETS) framework (Grimm *et al* 2017). Such interdisciplinary frameworks, however, need a long time, applied to specific contexts and issues to further develop.

The focus of this dissertation is to explore food supply systems to cities from a trans-boundary perspective, linking multiple sustainability outcomes with actions that seek to address health and well-being within the city.

The urban food system indeed requires a systems perspective to understand trans-boundary linkages. For example, over 70% of global greenhouse gas (GHG) emissions are attributed to cities (only accounting for energy use), (Seto *et al* 2014) with associated climate change ramifications that are not just limited to urban areas, but extend well-beyond city boundaries. In the reverse direction, rural areas provide the majority of urban food demands, with embedded land, water, energy resources flowing from rural areas to centers of urban demand. Thus resource shortages or disruptions in rural areas can substantially affect the functioning of a city.

The method of footprinting has emerged as a tool to quantify and inform these bi-directional local to regional to global linkages with trans-boundary environmental impacts (Ramaswami *et al* 2008, Kennedy *et al* 2010). The concept of footprints initially began as an aggregate “ecological footprinting” that adds up multiple indicators, expressed as single measure of global land equivalent (Wackernagel *et al* 1999). This approach has received criticism, in that it combines into a single indicator measures that do not compare, combining disparate impacts on disparate scales, and not addressing different sectors of society contributing to the impact (Kitzes *et al* 2009, Galli *et al* 2012, 2016).

In the past decade, more nuanced conceptualization of footprinting have emerging from the field of industrial ecology, combing life-cycle assessment (LCA) with material flow analysis (MFA) and advancing methods of environmentally extended input-output

(IO)analysis (Chavez and Ramaswami 2013, Kennedy *et al* 2010). This includes footprints that characterize separate impacts, such as GHG, land and water, and also speak to different sectors of society (i.e. consumption- versus production-based footprints) (Chavez and Ramaswami 2013). Footprints disaggregated into different impact categories, (energy, GHG, water, land) provide a mechanism to explore nexus issues. Further, the United Nations promotes this multiple footprinting approach as a tool to understand the specific resource needs of cities and associated environmental impact of cities—a particular objective of multiple SDGs (i.e SDG-13 climate action) (Bringezu et al. 2017).

One system that underlies multiple SDGs is the food system. Globally, the food system has received much attention as essential to support the health of human populations, with issues ranging from under-nutrition to obesity (Godfray *et al* 2012). Yet the food system also plays a central role in sustainability agendas. For example, in terms of water, 70-85% of global water use is attributed to agricultural production, (Gleick 2003) with 38% of global land used for cultivation and pasture, (Ramankutty *et al* 2008) and 19-29% of global GHGs (Vermeulen *et al* 2012) credited to food system activities spanning production through consumption.

While these environmental impacts are well studied on national and global scales, the role cities play in shaping food system environmental outcomes remains largely unknown. This is an important gap in understanding when cities are considered such central demand centers of the food system, affecting environmental impacts well beyond city boundaries, but also as requiring a sustained supply to meet the nutritional needs of their populations. This requires increasing understanding of the food system from an urban systems perspective, forming the broad area of focus of this dissertation.

In an applied sense, an urban systems perspective is important in order to inform policies on the ground. Many cities are developing food action plans with various objectives, ranging from health and equity to environmental sustainability and resilience (City of Minneapolis 2016, City of Vancouver 2013). Further, several city-scale GHG inventories and climate action plans include the food system as an area of focus (City of Minneapolis 2013, Goldstein *et al* 2016, C40 2015). Within many cities, food policy councils being convened to address these food system actions, tend to place heavy emphasis on urban agriculture assuming it to have large environmental benefit. However, there is a lack of analytic tools that can then be used in individual cities to inform with city-scale food system actions are most effective at mitigating environmental impact.

Specifically, there is an urgent need for evaluation and analysis tools able to:

1) Quantify urban community-wide food use (a necessary prerequisite to assess potential of urban self-reliance and environmental impact);
2) Assess how city food system actions may mitigate or exacerbate environmental impacts;
3) Begin to evaluate how the multitude of urban food system objectives and actions may potentially conflict with, or complement, one another, particularly with respect to environmental sustainability efforts.

The following introductory chapter provides background to this dissertation, split into the sections of:

- Cities and greenhouse gas accounting
- Multiple objectives of city food systems
- Quantifying food flows to cities
- Environmental tradeoffs

The chapter concludes with the specific objectives of this thesis.

CITIES AND GREENHOUSE GAS ACCOUNTING

Countries globally have committed to decreasing their environmental impact through individual commitments as well as collective global agreement, such as the COP21 Paris Agreement (UNFCCC 2015). The Intergovernmental Panel on Climate Change (IPCC) reports that 25% global GHG emissions are a result of electricity and heat production, followed closely by 24% from agriculture, forestry and land and 14% from transportation (IPCC 2014). Thus, looking beyond energy and transport sectors for greenhouse gas (GHG) emission reduction strategies, the food system becomes an important sector of focus.

When the GHG emissions of the food system are quantified from production through waste management, they are estimated to contribute 19-29% of global anthropogenic GHG emissions (Vermeulen *et al* 2012). The food system refers to much more than just agricultural production, encompassing all activities that support the use of food in society. This includes agricultural production, post-harvest handling, storage, transport, retail, commercial preparation, industrial processing, home use, and waste management (UNEP 2016, Boyer and Ramaswami 2017, Ramaswami *et al* 2017).

Within discussions of greenhouse gas (GHG) mitigation, cities and urban areas have recently come to prominent focus. Home to over half of the global population (UN 2015) and generating over 80% of global GDP, (McKinsey Global Institute 2011) urban areas are large contributors of global GHG, responsible for more than 70% of total global GHG emissions, (Seto *et al* 2014) only quantifying energy and fossil fuel.

Cities have also emerged as proactive players in the movement of global GHG reduction (ICLEI Global 2016). Over 1,500 cities and municipalities globally have committed to mandates to reduce their respective GHG emissions, (ICLEI Global 2016) coordinating through agreements such as the World Mayor's Council on Climate Change's Mexico City Pact and partnering with organizations such as ICLEI and C40 (World Mayors Council on Climate Change 2010). The population of those cities exceeds many nations, with C40 reporting, for example, that member cities account for 1/12th of the world's population and 25% of global GDP (C40 2015).

However, because of the reliance of cities on trans-boundary supply chains, accounting for city carbon emissions can be difficult. Impacts not only include direct emissions (Scope 1), but indirect emissions from the use of imported electricity, heat or steam

(Scope 2) and other indirect emissions embedded in services and materials, including food, fuels and construction materials (Scope 3) (World Resources Insistute 2004, Ramaswami *et al* 2008). Different city GHG accounting methods exhibit variation in what they include. Back in 2005, Denver was among the first cities to include embodied energy associated with construction materials, food and services such as airline travel in their Scope 3 GHG emissions accounting (Mayor's Greenprint Denver Adversory Council 2007). As noted by Chavez and Ramaswami (2013) there have since emerged three main approaches of GHG accounting of: 1) direct, territorial based emissions; 2) purely consumption-based footprint associated with only household goods and services consumed;[1] and 3) community-wide infrastructure footprinting, accounting for all in- and trans-boundary GHG emissions of infrastructure including the food supply supporting community activity of homes, businesses and industries.

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[1] Government and commercial as well

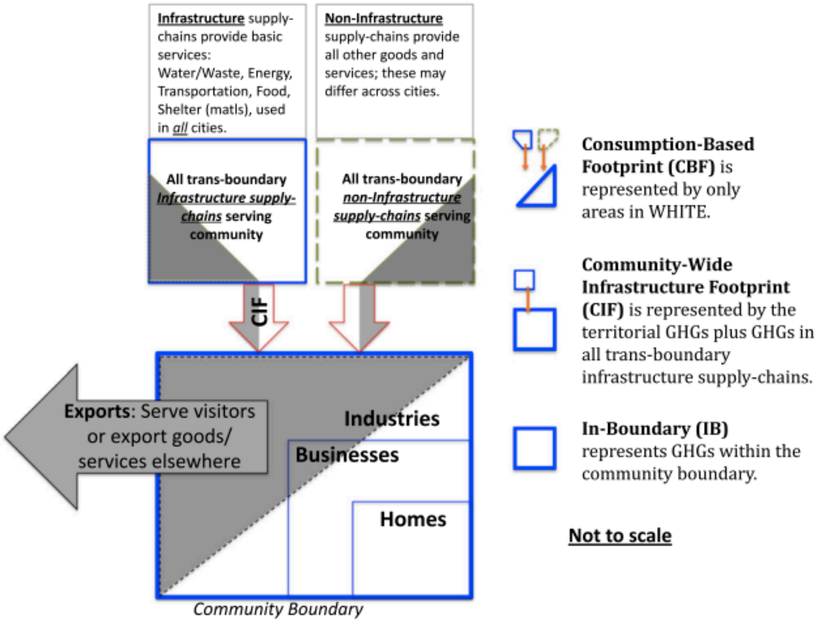
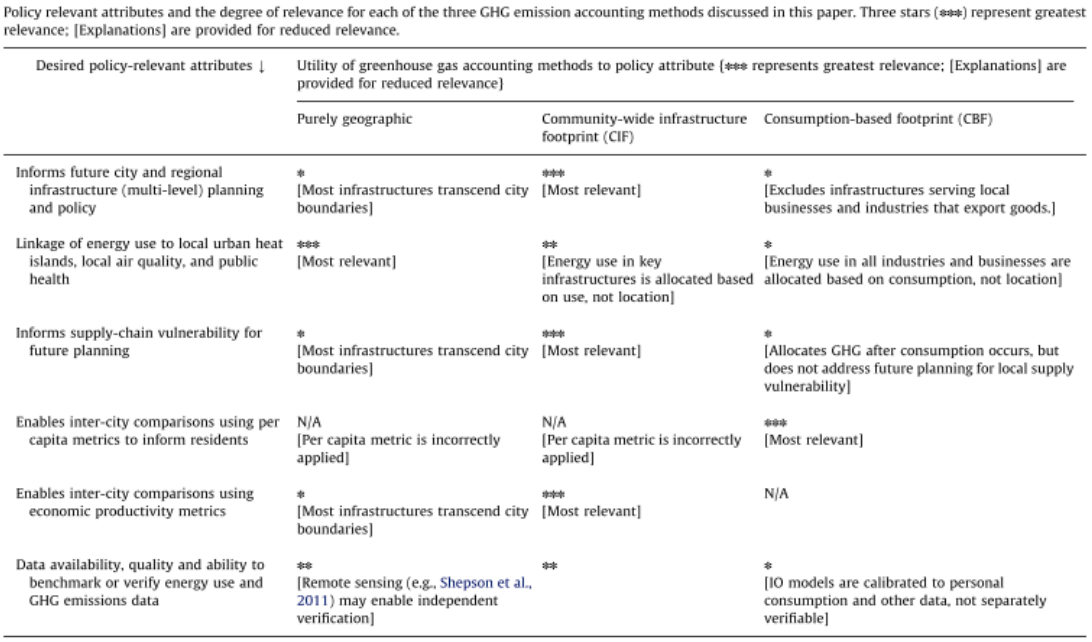


Figure 1-1 | From Chavez and Ramaswami 2013, this figure illustrates the in- and trans-boundary contributions to the community-wide infrastructure footprinting. This includes the provisioning of homes, businesses and industries within the city, some of which then export to other communities. This figure illustrates the difference between community-wide (both grey and white parts of the footprint) and consumption based (grey portion) and territorial, those emissions generated only within the blue community boundary.

The differences of these three approaches are illustrated in Figure 1-1 from Chavez and Ramaswami (2013). More recently, a purely production based footprinting approach has also emerged, but is less integrated in city practice (Lin et al. 2015) Territorial accounting can be attractive for cities because it can align with national level territorial accounts, though has limited utility in inform city infrastructure planning. Community-wide infrastructure footprinting can prove useful in informing city infrastructure planning, though does not neatly line up with national scale accounts, due to quantification of production and consumption within the city, though is sure to emphasis differentiation of in- and trans-boundary emissions. Each of the accounting approaches has varying policy application and differs and what it informs, as described in Box 1-1, taken from Chavez and Ramaswami (2013).

Box 1-1 | Table from Chavez and Ramaswami (2013) describing the policy relevance and value of the three main city footprinting types.



Policy relevant attributes and the degree of relevance for each of the three GHG emission accounting methods discussed in this paper. Three stars (***) represent greatest relevance; [Explanations] are provided for reduced relevance.

Desired policy-relevant attributes ↓	Utility of greenhouse gas accounting methods to policy attribute {*** represents greatest relevance; [Explanations] are provided for reduced relevance}		
	Purely geographic	Community-wide infrastructure footprint (CIF)	Consumption-based footprint (CBF)
Informs future city and regional infrastructure (multi-level) planning and policy	* [Most infrastructures transcend city boundaries]	*** [Most relevant]	* [Excludes infrastructures serving local businesses and industries that export goods.]
Linkage of energy use to local urban heat islands, local air quality, and public health	*** [Most relevant]	** [Energy use in key infrastructures is allocated based on use, not location]	* [Energy use in all industries and businesses are allocated based on consumption, not location]
Informs supply-chain vulnerability for future planning	* [Most infrastructures transcend city boundaries]	*** [Most relevant]	* [Allocates GHG after consumption occurs, but does not address future planning for local supply vulnerability]
Enables inter-city comparisons using per capita metrics to inform residents	N/A [Per capita metric is incorrectly applied]	N/A [Per capita metric is incorrectly applied]	*** [Most relevant]
Enables inter-city comparisons using economic productivity metrics	* [Most infrastructures transcend city boundaries]	*** [Most relevant]	N/A
Data availability, quality and ability to benchmark or verify energy use and GHG emissions data	** [Remote sensing (e.g., Shepson et al., 2011) may enable independent verification]	**	* [IO models are calibrated to personal consumption and other data, not separately verifiable]

Two of the more widely promoted protocols put forth by ICLEI (ICLEI Global 2016) and the British Standards Institute (BSI 2013) include attention to the food system. In terms of city-trans-boundary footprinting, taking either the consumption-based or community-wide infrastructure approaches, the food sector plays a large role. Denver, for example, using the community-wide approach, reports food related emissions as 10% of its total GHG emissions (Ramaswami et al. 2008) while Delhi reports a similarly high 15% (Chavez *et al* 2012). Although these cities use a community-wide approach, they both acknowledge the challenges of accounting for visitor and industrial demand. Using a consumption-based approach, San Francisco reports a similarly high contribution of food, at 19% of total GHG emissions (Jones and Kammen 2015). Goldstein et al.'s (2016) analysis of 100 city GHG reports found that irrespective of quantification method, the food sector, on average, contributed the third largest carbon flow by sector, however, also notes substantial inconsistency in quantification methods across cities. Cities need more systematic tools in order to accurately and consistently assess the impact of their food system and proposed policy changes. A lack of such tools results in the food sector often receiving little attention in GHG accounting and climate action planning, optional in many accounting protocols (Greenhouse Gas Protocol 2014).

Despite the large contribution of the food system to city GHG emissions when it is accounted for, there are limited actions being taken to mitigate this impact. For example, C40's (2015) analysis of 59 megacities cities found that, out of the 12 areas assessed (water; waste; private transport; outdoor lighting; mass transit; information and communication technologies (ICT); food and agriculture; finance and economic development; energy supply; community-scale development; buildings, adaption), the food system was the third least addressed sector in climate action planning.

C40 (2015) also reports that of the limited number of city-scale food system actions for GHG mitigation, the majority were found to either be in the planning or pilot stage. Furthermore, promotion of community gardening comprised 20% of all initiatives, indicating the prevalence of promoting of urban agriculture as a GHG mitigating action. For example, the Climate Action Plan for the City of Minneapolis calls to "promote…local food production" reasoning that "increasing local food production may have indirect carbon emissions and climate adaptation functions," (City of Minneapolis 2013). The use of the wording "*may* have indirect carbon emissions functions" is an important acknowledgement of the uncertainty that surrounds the use of localization as a means to mitigate food-related GHG emissions. Thus in Minneapolis, while urban agriculture might be promoted for other benefits within the city (City of Minneapolis 2016) (i.e. food sovereignty, community), its inclusion in the Climate Action Plan shows the assumption of it having a role in GHG mitigation as well.

Despite widespread promotion of urban agriculture, the academic consensus is that too little research exists to definitively claim a substantial contribution to mitigating environmental impact (see list below). For instance, the following list provides a small example subset of the many studies stating the ambiguity that exists between urban agriculture and environmental impact.

"because of the dearth of studies which examine greenhouse gas emissions across the entire food system, ***it is not possible to answer the question conclusively****."*	(Peters *et al* 2009)
"Only through combining spatially explicit life cycle assessment with analysis of social issues can the benefits of local food be assessed. ***This type of analysis is currently lacking for nearly all food chains****."*	(Edwards-Jones *et al* 2008)
"Future food production ***should not be "local at any price,"*** *but rather committed to increase sustainability."*	(Eigenbrod and Gruda 2015)
"If urban agriculture is to have a legitimate place…it is time to take urban agriculture seriously and ***assess more rigorously both the positive and negative impacts, especially carbon emissions****"*	(Mok *et al* 2014)

So while urban agriculture is being adopted in practice as a tool for GHG reduction, its impact remains largely debated, suggesting a lack of information guiding city action in their endeavors to address the environmental impact of their food system. This makes apparent the need for analysis tools to address this shortcoming, and provide guidance for city food action planning.

The food system is indeed a complicated infrastructure from the perspective of the city. Largely trans-boundary, the system stretches across many geographic locations. In the U.S. for example, food tallies an average delivery distance of 1,640 km with the associated supply chain averaging 6,760 km (Weber and Matthews 2008). Furthermore, the food system is a fairly recent concern of municipal planning departments. As such, there is generally very limited data availability and few analysis tools to date, (Barron *et al* 2010) leaving cities seeking guidance in their endeavor to address food system issues. This has resulted in a disproportionately large emphasis on urban agriculture, rather than providing attention to the whole of the food system. A community-wide systems approach is needed to expand food system analysis, giving due attention to the whole of the system—from production to transport, use, and waste management. This would provide a more comprehensive understanding of the food system and allow greater breadth of strategy opportunities to address environmental impact.

MULTIPLE OBJECTIVES OF CITY FOOD SYSTEMS

Concurrent to discussion of food system GHG reduction, attention to urban food systems has grown substantially in recent years. Historically, food was not a priority concern of cities, especially in comparison to the attention given to other municipal infrastructures such as water and energy. Similarly food systems were not considered a common concern of urban planners (Pothukuchi and Kaufman 2000). This has led to thin understanding of urban food systems and limited data available for analysis. However, amidst growing concerns of food security in an increasingly urbanized world, the topic of "urban food systems" has come to prominence. Cities globally have been joining together through a variety of urban food initiatives including ICLEI's Resilient Urban Food System Forum, (ICLEI 2013) the United Nations Food and Agriculture Organization's Food for Cities, (FAO 2014) the Sustainable Food Cities Network (Sustainable Food Cities Network n.d.) and the Milan Food Pact, (Milan Urban Food Policy Pact 2015) for example. Such initiatives go well beyond concerns of food system GHG emission reduction to address a multitude of additional food related concerns. For instance, the knowledge sharing organization, Sustainable Food Cities Network (Sustainable Food Cities Network n.d.) includes environmental impact as just one of many concerns including:

1. *Promoting healthy and sustainable food to the public;*
2. *Tackling food poverty, diet-related ill health and access to affordable healthy food;*
3. *Building community food knowledge, skills, resources and projects;*
4. *Promoting a vibrant and diverse sustainable food economy;*
5. *Transforming catering and food procurement;*
6. *Reducing waste and the ecological footprint of the food system.*

At the individual city level, food interest has resulted in some analysis and action planning. A few cities have conducted their own food system analyses, (sometimes referred to as a foodshed analysis) to better understand their respective systems. However, the rigor of analysis is generally limited. Reports tend to only quantify residential food use combined with anecdotal description of various aspects of the food system. With little standardization across approaches, cross-city comparison and benchmarking is difficult. Furthermore, while environmental sustainability is often cited as an important concern, and sometimes even a primary motivator for conducting the food system analysis, it is rarely quantified with any sort of metrics. The following Table 1-1 includes the motivation wording from a sample group of analyses. Key motivating factors for city food system analyses include: a desire to improve a system central to human and environmental health; greater self-reliance; environmental sustainability; little existing knowledge (Thompson, Harper, and Kraus 2008; City of Vancouver 2013; DVRPC 2011; Barron et al. 2011).

Table 1-1 | Motivation for city food system analysis from selected reports.

City	Motivation for food system analysis	
Detroit	To figure out "how did this system with so much activity and potential become so dysfunctional"	(Detroit Food and Fitness Collaborative 2014)
New York City	"This study begins to elucidate aspects of the system, revealing major patterns, vulnerabilities, challenges, and areas that require further study."	(Barron *et al* 2011)
Philadelphia	"to envision a more sustainable food system for Philadelphia"--"aim to achieve greater self-reliance in the threat of supply shortage"	(DVRPC 2011)
San Francisco	"A desire to feed San Francisco with food from within 100 miles"	(Thompson *et al* 2008)

Some cities, particularly in North America and Europe, have built upon food system analyses to create action plans aimed at improving the status quo food system. Table 1-2 provides a preliminary overview of city food plans put forth by nine North American cities considered at the forefront of urban food policy and action (Hatfield 2012). Mention of environmental sustainability or localization is highlighted in bold. The table makes apparent the diversity of food related issues receiving attention, ranging from increasing community resilience to decreasing environmental impact, to addressing both hunger and obesity. Also apparent is the vagueness of wording such as that of Vancouver's goal of "supporting food friendly neighborhoods," (City of Vancouver 2013). Greater clarity is needed as to which actions and research would be associated with these broad overarching objectives, in order to ensure positive outcomes and avoid conflict of objectives.

Table 1-2 | Overview of selected city food action plans to illustrate range of urban food concerns with mention to local production and environmental sustainability highlighted in bold to show commonality of reference. Wording is replicated from the actual plans to accurately convey the language of these plans.

City	**Overview of food city action plans**	**Source**
Toronto	• Access to adequate safe, nutritious, culturally-acceptable food • Support secure and dignified access to the food people need • Support events highlighting the city's diverse and multicultural food traditions • Promote food safety programs and services • Sponsor nutrition programs and services that promote healthy growth and help prevent diet-related diseases • Ensure convenient access to an affordable range of healthy foods in city facilities • Adopt food purchasing practices that serve as a model of health, social and environmental responsibility • Partner with community, cooperative, business and government organizations to increase the availability of healthy foods • **Encourage community gardens** that increase food self-reliance, improve fitness, **contribute to a cleaner environment**, and enhance community development • **Protect local agricultural lands and support urban agriculture** • Encourage the recycling of organic materials that nurture soil fertility • Foster a civic culture that inspires all Toronto residents and all city departments to support food programs that provide cultural, social, economic and health benefits • Work with community agencies, residents' groups, businesses and other levels of government to achieve these goals	(City of Toronto 2000)
San Francisco	• Ensure quality of life, **environmental** and economic health • The food system must promote public health, **environmental sustainability** and social responsibility • Eliminate hunger and ensure access to healthy and nutritious food for all residents, regardless of economic means—a concern of all city departments • Develop environments that allow residents opportunity to make healthy food choices and reduce environmental causes of diet related illnesses • **Reduce the environmental impacts** associated with food production, distribution, consumption, and disposal • Whenever possible, city resources will be used to purchase and promote **regionally produced and sustainably certified food**. • Food production and horticulture education will be encouraged within the through **urban agriculture** including community, backyard, rooftop, and school gardens; edible landscaping, and agricultural incubator projects • Promote economic opportunities in the food sector that create green jobs and local food businesses • support policies that conserve the region's agricultural land to **reduce the environmental impacts of the food system**	(Thompson *et al* 2008)

	• Promote regional agriculture through increasing marketing opportunities for regionally grown agricultural products • Recycle all organic residuals, eliminate chemical use in agriculture and landscaping and **use sustainable practices** that enhance natural biological systems • Promote innovative programs that educate food system stakeholders and general public on the value of healthy food, and an equitable and **sustainable food system.** • Advocate for federal and state policies that support the principles of this Food Policy	
Vancouver	• Support food-friendly neighborhoods • Empower residents to take action • Improve access to healthy, affordable, culturally diverse food for all residents • Make food a centerpiece of green economy • Advocate for a just and **sustainable food system** with partners and at all levels of government	(City of Vancouver 2013)
Portland	**Local:** Produced close to where it is consumed and in an environmentally responsible manner • Protect and enhance the agricultural land base • Support small and midscale farms • **Increase urban food production** • Encourage sustainable resource stewardship Healthy: Consumed with as little processing and additives as possible and as part of an active lifestyle • Create environments that support health and quality of life • Increase equitable access to healthy, affordable, safe, and culturally appropriate food in underserved neighborhoods • Promote individual and community health by encouraging healthy food choices • Increase awareness of food and nutrition assistance programs Equitable: Abundant and available to all and produced in a fair manner • Address the causes of hunger, food insecurity, and injustice • Increase community resilience • Facilitate equitable community participation and decision making • Create opportunity and justice for farmers and food system workers Prosperous: Grown, processed, distributed, sold and served by a thriving regional economic cluster that produces local jobs • Develop the regional food economy and infrastructure • **Promote local** and regional food products and producers • Encourage farm to school and institutional purchasing that support the regional food system • Create local food system jobs	(Multnomah County 2010)
New York City	• Preserve and increase regional food production. • **Increase urban food production**. • Generate growth and employment in the food manufacturing sector. • Increase regional products processed in and for the city • **Reduce the environmental impact** associated with food processing • Improve food distribution through infrastructure enhancements, technological advances, alternative transportation, and integrated planning	(The New York City Council 2010)

	• Create a healthier food environment • Strengthen the safety net of hunger and nutrition programs • Improve the nutrition of institutional meals • Increase quantity and quality of opportunities for food, nutrition and cooking knowledge • Decrease waste throughout the food system • Increase resource recapture in the food system	
Philadelphia	Values • Farming and sustainable agriculture • **Ecological stewardship and conservation** • Economic development • Health • Fairness • Collaboration Goals • Stakeholders maintain open communication and personal connections and forge collaborative and cooperative partnerships • **Soil, water, and other natural resources are sustained, replenished**, and regenerated • Farmland is treasured, preserved, and available in a variety of scales from rural to **urban** • Farming is a recognized, respected, and profitable occupation; and both current and new farmers have access to affordable land and diverse markets • Food and farming are cornerstones of a healthy regional economy, with adequate resources and support for business development and entrepreneurship • Diversity and innovation are encouraged and rewarded in the variety of crops grown, different farming practices, successful business models, and increased consumer choices • Food and farmworkers everywhere have decent and fair working conditions and earn a living wage • Access to, affordable healthy, culturally appropriate, nourishing food **produced in ways that respect the environment** and the producers • All of these goals can be met while being adaptable over time to changes in land, population, energy, and climate	(DVRPC 2011)
Los Angeles	Overarching goal to achieve 'good food' that is: • Foods meet the Dietary Guidelines for Americans and provide freedom from chronic ailment. • Food is delicious, safe, and aesthetically pleasing. • Foods that people of all income levels can purchase • All participants in the food supply chain receive fair compensation and fair treatment, free of exploitation • High quality food is equitable and physically and culturally accessible to all. • Produced, processed, distributed, and recycled locally **using the principles of environmental stewardship** (in terms of water, soil, and pesticide management). Priority Action Areas: • Promote a good food economy • Build a market for good food. • Eliminate hunger in Los Angeles	(Los Angeles Food Policy Task Force 2009)

	- Ensure equal access to good food in underserved communities - **Grow good food in our neighborhoods** - Inspire and mobilize good food champions	
Louisville, KY	- Encourage public and private investment in the local food economy - **Support the increase of food production through urban agriculture**	(Louisville Food Policy Advisory Council 2012)
Seattle	- Access to sufficient, affordable, **local**, healthy, **sustainable**, culturally appropriate food. - **Make it easy to grow food in city** and region, for personal use or for business purposes. - Businesses that produce, process, distribute, and sell **local** and healthy food should grow and thrive. - Food-related waste should be prevented, reused, or recycled.	(City of Seattle 2012)

With all nine plans of Table 1-1 promoting urban agriculture, a trend towards localization is once again apparent in the city food space beyond discussions of GHG mitigation. The rationale for urban agriculture varies, as described in Table 1-3. The desire for greater self-reliance and sustainability concerns emerge as two commonly cited motivators. In some cases, though no rationale is given at all. As with climate action planning, there seems to be an assumed level of effectiveness of urban agricultural and localization to benefit urban food woes, especially with respect to environmental sustainability. This again, however, is in spite of a lack of research or analysis tools able to assess which food city strategies are best suited to achieve the desired objectives.

Table 1-3 | City rationale for promotion of urban agriculture, with environmental rationale highlighted in bold.

City	Rationale for urban agriculture/localization	
Seattle	Education; creation of livable, walkable, **sustainable** communities; **help to implement city goals of sustainability**; economic development	(City of Seattle 2012)
Louisville, KY	No justification given	(Louisville Food Policy Advisory Council 2012)
Los Angeles	Community revitalization; education on the benefits of local food; job creation & business opportunity—especially for at risk; exercise for the body, mind, and soul--particularly in underserved; encourages healthy eating; opportunity to grow culturally appropriate foods; help meet food needs; **important environmental benefits** such as capturing, filtering, and reusing rainwater runoff and sequestering carbon.	(Los Angeles Food Policy Task Force 2009)
Philadelphia	Food production and job creation potential, **environmental benefits**, and impact on neighborhood stabilization and revitalization	(DVRPC 2014)
Boston	Increase availability of fresh produce, especially in low income areas; improve aesthetics; bring neighbors together around gardens	(Boston 2016)
New York	Opportunity to green urban landscape, foster nutrition and food education; reconnect New Yorkers to their food.	(The New York City Council 2010)
Portland, OR	Urban access to fresh food – not too much justification	(Multnomah County 2010)
Toronto	**Strong environmental justification** - air quality improvement; trucks burn 10 times more energy in transit than is in the food itself; rainwater storage; decrease building heating/cooling	(City of Toronto 2000)
Vancouver	Improve food system resiliency and promote social inclusion	(City of Vancouver 2013)
San Francisco	No justification given	(Thompson *et al* 2008)
Minneapolis	Not explicitly stated	(City of Minneapolis 2016)

QUANTIFYING FOOD FLOWS TO CITIES

Even quantification of a city's food requirement—a task that one might assume a bit more straight-forward than evaluating the efficacy of any food system intervention—lacks a standardized method. Methods of food quantification for both GHG accounting reports as well as food system analyses tend to vary greatly in terms of data sources, assumptions, and what food is accounted for (Goldstein et al. 2016).

There are multiple approaches that cities employ to estimate city food use. Most common is taking a consumption-based approach, accounting only for the food which is consumed by city residents. But even within this approach, there exists much variation in the type of data used and what it accounts for. For example, a "bottom-up approach" tends to rely on consumer expenditure or food recall data. The resulting food quantity often excludes pre-consumer waste and lacks differentiation of food consumed inside versus outside of the home setting (or excludes outside the home food entirely). A "top-down approach" determines the per capita food consumption based on national level food availability data, often making use of the FAO Food Balance database (FAO 2017). This data accounts for food eaten outside the home (though without differentiation of in- versus out of home use) as well as pre-consumer waste, though does not capture city specific diets. Even though these two approaches, in theory, account for the same thing—that being resident food consumption—their variance of approach often yields multiple fold differences in the estimated total resident food consumption.

Furthermore, both the "bottom-up" and "top-down" approaches are limited in their assessment of total community-wide food use. The consumption-based approach does not quantify the food and associated resources used by tourists, commuters and other visitors, inputs to industrial processing, and in many cases commercial preparation. Freight analysis is one approach that tries to capture community-wide food use, tracking incoming and outgoing food commodities to determine the quantity remaining within the city. However, the aggregate level of detail of this data source can prove a challenge for cities to make meaningful use of (DVRPC 2011).

Table 1-4 provides an overview of the food quantification methods of selected GHG inventories and city food analysis, chosen to demonstrate the diversity of data sources (consumption surveys versus countrywide supply/availability data versus city freight data) and what is accounted for (resident versus community-wide). As noted by

Goldstein’s (2016), food use estimates vary substantially based on the methods of quantification, making consistent assessment of the food system’s baseline environmental impact and potential of self-reliance difficult.

Table 1-4 | Description of different approaches to quantify urban food use.

City	**Method of food estimation** and (**Data sources used)**	**Accounted for**	**Data source**
Food system analyses			
New York City	Freight (Freight Analysis Framework)	Community-wide	(Barron *et al* 2011)
San Francisco	Both Top-down (Loss-Adjusted Food Availability Data, U.S. Department of Agriculture (USDA)) and bottom up (Food Commodity Intake Database, USDA) – does not include visitors	Residents only	(Thompson *et al* 2008)
London	Top-down (FAOSTAT Database)	Residents; acknowledges, but ignores visitor and commuter consumption	(Greater London Authority 2008)
GHG and urban footprinting studies			
Delhi	Top down – (FAOSTAT Food Balance sheet)	Residents only	(Chavez *et al* 2012)
Paris	Freight (Freight database)	Community-wide	(Barles 2009)
Tianjin, China	Bottom up (Daily dietary consumption survey State Statistical Bureau of China)	Residents only	(Qiao *et al* 2011)
Denver CO, Boulder CO, Arvada CO, Ft Collins CO, Portland OR, Seattle WA, Minneapolis, MN, Austin TX	EIO-LCA (Consumer expenditure survey)	Residents only	(Hillman and Ramaswami 2010)

As stated in New York’s food action report: “The more we explored our food system for this report, the more gaps we discovered in basic data about food the city buys and serves and the impacts of various food-related programs. Until we have more comprehensive information about our food system, our attempts to improve it can only be partial solutions,” (The New York City Council 2010).

ENVIRONMENTAL TRADE-OFFS

Of further importance is to acknowledge the food system's enormous environmental impact beyond just GHG emissions to include impacts on water and land resources. The food sector's impact on water resources is particularly substantial, with 70-85% of global freshwater use attributed to agriculture (Gleick 2003). Therefore, when developing interventions to decrease food sector GHG emissions, it is important to take a systems view, analyzing both water and GHG impacts in tandem (often referred to as the food-energy-water (FEW) nexus), rather than in singularity. This allows assessment of tradeoffs and synergies between attempts to decrease the food sector's water and GHG impacts within a systematic framework. Land requirement is a further environmental impact that should be considered when evaluating the food system. With 38% of the world's land area dedicated to crop production and grazing, (Foley *et al* 2011) the food system's land footprint is becoming of greater importance with calls for increasing global production competing with concerns of preservation, deforestation and carbon sequestration (Godfray *et al* 2012).

OBJECTIVES OF THIS THESIS

In light of the challenges of evaluating city food systems and sustainability objectives, this dissertation contributes to the science of sustainable urban systems by:

1) Contributing to the development of an analytical framework to assess community-wide urban food use and the associated system-wide environmental impacts focusing on water, energy/GHG impacts, and land use impacts (Chapter 2, draws upon a framework published in Environmental Research Letters (Ramaswami *et al* 2017a));
2) Expanding the framework of Chapter 2, focusing more specifically on the food system to include land, assessing data needed to model the urban food system and environmental outcomes, and demonstrating how the framework can be mapped to urban actions, illustrating it as a practical tool to begin evaluating tradeoffs

with a focus on environmental impacts (Chapter 3, published in Environmental Science and Technology (Boyer and Ramaswami 2017));

3) Contributing to a deeper understanding of the urban food system by analyzing nine Indian cities for differences of diets, user demand across sectors, food miles, environmental impact and supply risk (Chapter 4);
4) Applying systems analysis tools to Minneapolis, New York, Delhi and Pondicherry to illustrate the policy relevance and suitability across cities of the tools developed in Chapters 2 & 3 and understand differences among city policy levers and action impact in the United States and India to shape environmental outcomes (Chapter 5);

The first two objectives create generally applicable, sustainability system analysis tools that can be applied at the city scale to inform policy on nexus issues in data sparse environments. The third objective applies the method developed by the first two objectives combined with supply chain data to advance understanding of inter-city food system structures in India. The fourth objective applies the analysis framework to the case study cities of Minneapolis, New York, in the United States and Delhi and Pondicherry in India. A case study approach is appropriate given the limited study of urban food systems to date. Not enough research has yet been conducted to carry out any sort of large ‘n’ study of real value. Conducting case studies across countries helps to increase the relevance of the work across different country settings and capture important differences between developed and developing city settings.

The choice of India is motivated by a dearth of food system GHG mitigation studies at any scale in a developing country. Pelletier et al.'s review of the state of research of the energy intensity of agriculture noted only a single partial food system LCA study in a developing country context (Pathak et al. 2010). This is particularly concerning given Vermeulen, Campbell, & Ingram's (2012) assertion that 70% of total global food system GHG mitigation potential exists in low to middle income countries. Comparison of India with the United States provides insight into similarities and differences between developed and developing country settings in regards to data availability, conditions of the food system and city policy priorities.

CHAPTER 2 | An urban systems framework to assess the trans-boundary food-energy-water nexus: implementation in Delhi, India

This paper is part of joint work, published as Ramaswami et al. 2017 in Environmental Research Letters with the following authorship: Anu Ramaswami, Dana Boyer, Ajay Singh Nagpure, Andrew Fang, Shelly Bogra, Bhavik Bakshi, Elliot Cohen, Ashish Rao-Ghorpade. Author contributions are as follows:

- Anu Ramaswami: Conceptual framework, development of methods
- Dana Boyer: Food-related analysis
- Andrew Fang & Elliot Cohen: Energy analysis
- Ajay Nagpure & Ashish Roa-Ghorpade: data collection
- Shelly Bogra & Bhavik Bakshi: India water intensity factors

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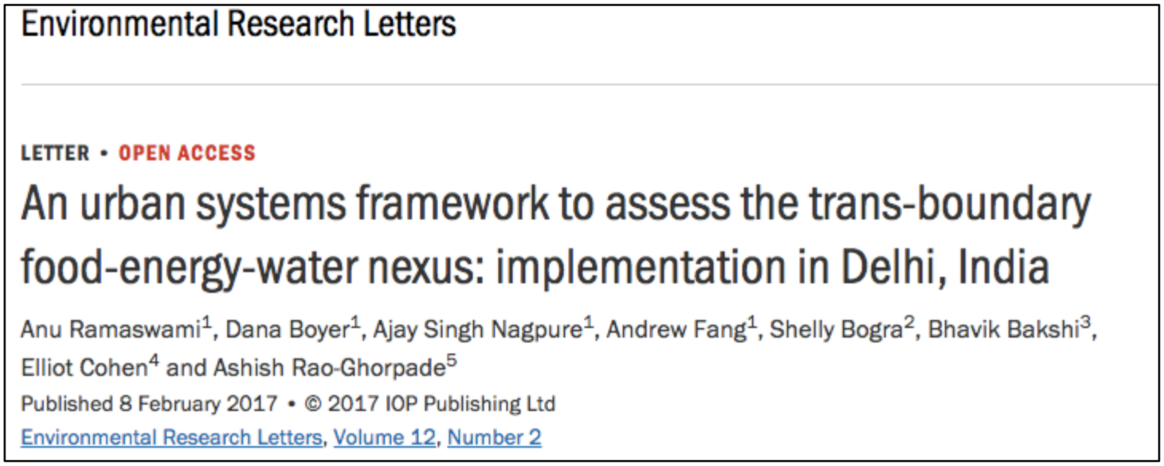

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An urban systems framework to assess the trans-boundary food-energy-water nexus: implementation in Delhi, India

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INTRODUCTION

The food-energy-water (FEW) nexus refers to intersections among food, energy, and water systems that have large impacts on natural resources (water, energy, nutrients), on pollution and greenhouse gas emissions (GHG), and on the security of FEW supplies essential to the well-being of the world's population. The FEW nexus has been analyzed at national and global scales (Bazilian *et al* 2011). Global data show the food sector's dependence on both water and energy, with 70% of global freshwater use (Gleick 2003) and 30% of global GHG emissions (Vermeulen, Campbell, and Ingram 2012) associated with food supply. Nationally, in the U.S., approximately 45% of all water withdrawals are for cooling of thermoelectric power plants, followed by agricultural use (33%) and municipal water for municipal supply (12%) (Maupin *et al* 2014, US DOE 2014).

With more than half the world's population presently living in cities (UN 2015), much of FEW demand occurs in cities. Cities are concerned about energy, food, and municipal water supply risks that affect the entire community—homes, businesses and industries (DVRPC 2011, Denver's Climate Resiliency Committee 2014). For example, large scale power cuts in Delhi during summer 2012, were partially attributed to water constraints on thermoelectric generation (Romero 2012, Xue and Xiao 2013). Cities grappling with drought in California (State of California 2015) are recognizing the competition between municipal water supplies and agricultural irrigation in the hinterland areas serving cities. Several cities have conducted food-system analyses to understand supply risks, vulnerabilities, inequities, and strategies to achieve greater self-reliance (Thompson *et al* 2008, Barron *et al* 2011, DVRPC 2011). Cities have also started to recognize that urban demand for FEW has far-reaching environmental impacts both within and outside city boundaries. In an analysis of over 200 urban metabolism studies, 100 cities were found to have included the trans-boundary embodied energy of food production in their carbon accounts (Goldstein *et al* 2016). The above examples illustrate that cities are increasingly interested in quantifying the impact of their FEW supplies on the larger environment, as well as in reverse, the risk posed by the environment on their supplies. Further, city climate-action and food-action plans seek to identify what actions cities can take to reduce their environmental impact and enhance food security. For example, the Greater Philadelphia Food System plan states the “aim to achieve greater self-reliance in the threat of supply shortage” (DVRPC 2011). In reference to water, San Francisco’s Climate Action Strategy states the need to “protect the city’s water from supply disruptions caused by climate change,” (Department of the Environment 2013).

Many of these plans make reference to the role of the food system in sustainability objectives such as GHG and water impact mitigation (e.g. City of Minneapolis Office of Sustainability 2013, City of Toronto 2000). However, not many analysis frameworks are available to capture the interactions among the FEW sectors within cities as well as between FEW supply chains and the larger environment extending outside of the city boundary, that are important to quantify environmental benefits and trade-offs of city food and sustainability plans.

This paper develops a generalizable systems framework to analyze the FEW nexus from an urban systems perspective, connecting in- and trans-boundary interactions, quantifying multiple environmental impacts of community-wide FEW provisioning to cities, and visualizing supply-chain risks posed to cities by the environment. Frameworks to conduct such analyses must address four gaps in the science and methods, described next.

First, methods must be clarified for quantifying community-wide FEW demand by homes, visitors, businesses and industries. A review by Goldstein *et al* (2016) notes that cities have previously used ad hoc methods, often only capturing residential food demand, but not that of visitors or food processing industries… thus the “*urban foodprint was underestimated in studies where the scope of urban metabolic activities beyond the household boundary were excluded.*” Because city policies have potential to address diverse actors within their jurisdiction (homes, businesses, and industries), developing methods to assess FEW demand by all three user-categories is important. Data on community-wide water and electricity-use are readily available from the respective utilities. While data on food production are available at the county-level in some countries (e.g., U.S. Geological Service (2010)) quantifying *community-wide food* *demand* is more challenging, and requires much more bottom-up data, particularly with attention to local diets, food demands by socio-economic status of households, and food use by visitors and local industry.

Second, *community-wide FEW supply* delineation into in- and trans-boundary components is important, recognizing that few cities can provision all FEW requirements in-boundary (Ramaswami *et al* 2008, Baynes *et al* 2011, Ramaswami et al., 2012). Such spatial supply chains help connect urban demand for FEW with region-specific features of the production systems that shape the trans-boundary FEW nexus, such as the use of rain-fed versus groundwater irrigation, the extent of groundwater overdraft, and the fuel mix and carbon intensity of regional electricity grids. For example, India's northwestern state of Punjab overdrafts groundwater due to subsidized electricity for pumping, resulting in highly water- and energy-intensive cropping of rice and wheat (Devineni *et al* 2013). Large cities may be creating proximal geospatial demands for FEW production that are poorly understood. Further, visualizing FEW production-demand linkages provides understanding of where climate constraints on water can strain FEW supplies to cities. Cities often have data related to their municipal water supply chain. However, the spatial supply of electricity and food to cities is more complex, yet necessary, to assess urban FEW demand interactions with trans-boundary production systems.

Third, given the trans-boundary reliance of community-wide FEW supply, developing coupled water-energy-GHG footprints to represent resources embodied in trans-boundary FEW supply to cities is important to evaluate trade-offs and co-benefits among the different environmental impacts. To-date, a few studies have conducted GHG footprinting of community-wide FEW supply to cities in the U.S., Australia and China, respectively (Ramaswami et al. 2008; Hillman and Ramaswami 2010; Baynes, Lenzen, and Steinberger 2011; Lin et al. 2013) focusing only on energy-use and GHG impacts. Water footprinting studies of cities have largely focused on trans-boundary supply of municipal water demand (e.g. Jenerette *et al* 2006). A few have included water resource draws of water and electricity supply to cities (e.g., (Cohen and Ramaswami 2014) and some on food only (Barron *et al* 2011, Thompson *et al* 2008). To-date the coupling of all three FEW demand-sectors with both embodied water and energy inputs in the production systems, and their nexus relationships, has not been conducted. To accomplish such sub-national scale footprinting, regional features of electricity and food production regions serving cities must be characterized. For example, Blackhurst et al. (2010) cautions, "practitioners against using [national water intensity factors] for regional analyses, given regional variation in hydrologic and industrial or agricultural practices." To the best of our knowledge, no study has coupled spatial supply-chain informed GHG- with water-footprinting of FEW supply to cities, including analysis of water consumptive-loss and withdrawal, delineated into blue and green water. Such an approach would enabling cities to visualize how climate constraints on precipitation (green water) and hence reliance on managed water (blue water) might affect city FEW supply, and, in reverse, inform how cities impact water, energy and GHG emissions.

Lastly, incorporating FEW interactions within city boundaries is a key aspect of the urban FEW nexus. Cities are areas of concentration of diverse human activities which provide opportunities for interactions among FEW sectors within the boundary that are enabled by co-location rather than by supply chains (e.g. waste from food-use in cities can be converted to energy to serve local homes). Each city provides opportunities for FEW interactions within its boundaries —ranging from municipal water reuse in urban agriculture, water and energy inputs for food processing and preparation, energy for water-related services such as water supply and treatment, and, water for energy-related services such as building cooling operation or thermal power generation occurring with cities. Diverse actors—homes, businesses, industries and city waste management-, water- and energy- infrastructure providers—can be involved in these interactions. Determining these linkages is part of evaluating the FEW nexus within the city boundary, which requires systematic methods for evaluating diverse city-wide FEW interactions

The objective of this paper is to develop and implement a multi-sector, trans-boundary urban FEW systems framework that brings together all four aspects described above, linking in-boundary and trans-boundary systems analysis of community-wide FEW supply to cities from the dual perspectives of environmental impact assessment and visualization of FEW supply chain risks. We present a first implementation of the urban FEW framework to a case study city (Delhi, India) to develop methods, identify key data needs and data gaps. Urban FEW nexus studies are in a nascent state; a long-term research agenda is envisioned that would expand the Delhi case study to world cities, identify city typologies and conduct large 'N' studies to capture the aggregate impact of all cities of national or global water and energy flows.

FRAMEWORK

The urban systems FEW nexus framework is illustrated in Figure 2-1. The porous circle in Figure 2-1 represents a city boundary encompassing FEW-use by local homes, businesses, visitors and industries. The community wide FEW-use (demand) is met via supply chains including local in-boundary FEW production plus trans-boundary production. The production regions are characterized by nexus interactions such as energy for crop irrigation or water for electricity generation (as shown in Figure 2-1), yielding spatially detailed resource intensity factors for FEW production along the supply chain serving urban demand. Developing such supply-chain informed coupled water-, energy- and GHG footprints of FEW supply to cities is a key aspect of the framework that focuses on city interaction with processes outside its boundary to address synergies and trade-offs between individual environmental impact categories. The footprinting of water-,energy-, and GHG, shown here, can also be extended to other resources such as land and nutrients.

The development of multiple footprints (e.g. water and energy/GHG) is helpful to evaluate trade-offs and co-benefits among the different environmental impact categories. In terms of water footprinting, both water consumptive-loss and water withdrawal footprints are developed. Water consumptive loss represents absolute removal of water from the watershed, while water withdrawal footprints inform operational risk to thermal power plants due to low stream flow (Cohen and Ramaswami 2014, NETL 2010). Water footprints are also designated as green (rain-fed) or blue (irrigated), to reveal the relative reliance on climate and precipitation, versus managed water systems.

A second key aspect of the urban FEW nexus is highlighted within the city boundary wherein co-location within cities facilitates interactions across FEW sectors. All six FEW nexus interactions within the urban boundary (which encompassing homes, visitors, businesses and industry) are highlighted in Figure 2-1:

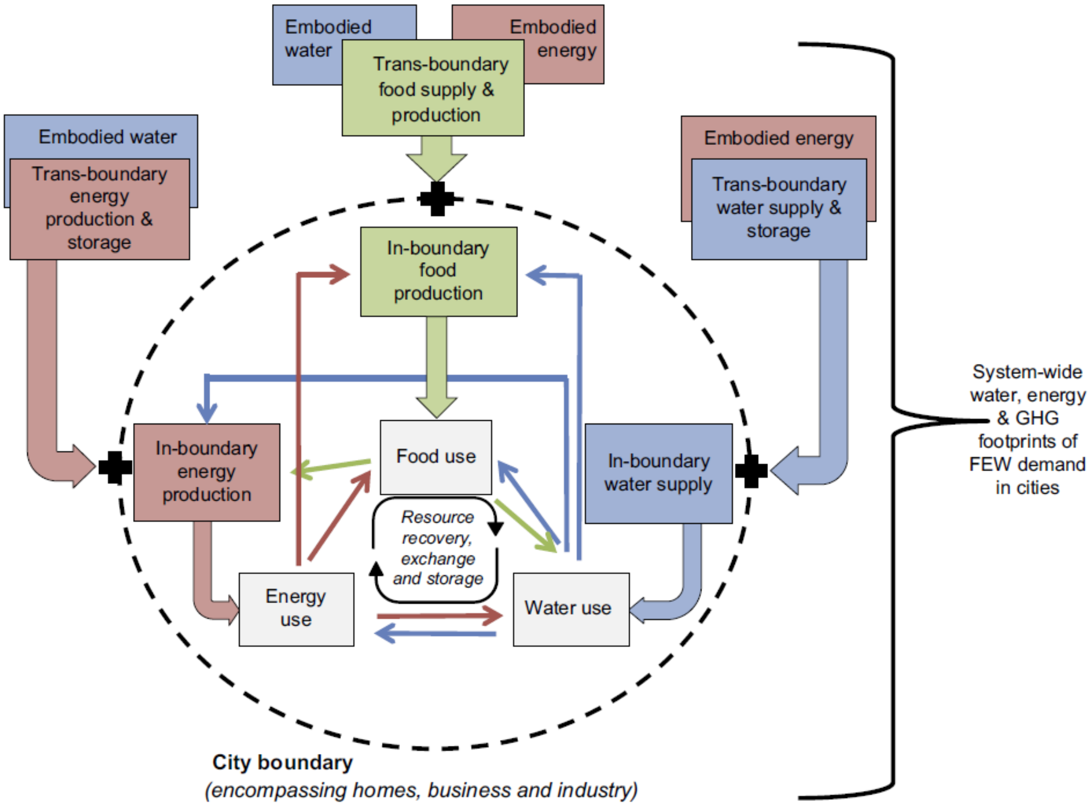
- W➔F: water inputs to community-wide food-related activities (e.g. water for food preparation, processing, and urban agriculture);
- W➔E: water inputs to energy related activities (e.g. water for any local fuel processing, local electricity generation, and cooling of buildings);
- E➔W: energy inputs to water-related activities (energy inputs for community-wide water supply, treatment, and distribution);
- E➔F: energy inputs to food-related activities (energy for food preparation, refrigeration, processing, and urban agriculture);
- F➔E food inputs to energy (e.g., food-waste to energy);
- F➔W: food-related impact on urban water pollution (e.g., from urban agriculture).

These diverse in-boundary and trans-boundary FEW interactions involve diverse actors spanning spatial scales. This enables exploration (in subsequent papers) of what can be done by individuals, businesses and policy-institutions at different scales, consistent with a multi-sector social-ecological-infrastructural systems (SEIS) framework (Ramaswami *et al* 2012a, 2016). Specifically, Figure 2-1 enables evaluation of trade-offs and synergies among four key categories of actions of: (a) changes in community-wide urban FEW demand; (b) shifts of in-boundary versus trans-boundary FEW supply; (c) changes in trans-boundary production systems; versus, (d) changes of in-boundary production and cross-sectoral FEW interactions.

The framework in Figure 2-1 is applied to the city of Delhi, India occupying an area of 1,483km^2, home to 16 million people, and generating $37.2 billion GDP (in 2011) (DES 2013b, 2013a). Delhi represents a highly populous, water-scarce city grappling with both environmental stresses and supply risk challenges.

The framework in Figure 2-1 is generalizable to any city or community. All cities have homes, businesses and industries that together exert demand for F, E, W, which are essential to their functioning. All cities rely to some extent on trans-boundary production to serve their FEW needs. The production of energy/electricity requires water, while the supply of water requires energy, and the production of food requires both water and energy – these processes are known and are universally applicable, as illustrated in Figure 2-1. Coupling FEW demand of cities with regionally-specific city supply-chain informed water- and energy/GHG intensity factors yields community wide water- and GHG- FEW supply footprints of cities. This approach to develop coupled water- and GHG-footprinting of FEW supply to Delhi would be the same approach taken in other cities, although data sources and numeric values would vary. Within city boundaries, the six pairwise in-boundary cross-sectoral FEW interactions (shown in Figure 2-1) are also expected to occur in all cities, although the magnitude of contributions will vary by city type. Integrated assessment of in-boundary plus trans-boundary FEW interactions establishes a baseline for any city, against which future interventions, within and beyond the city boundary, can be evaluated for localized or system-wide environmental impact.

Figure 2-1 | A trans-boundary multi-sector framework to analyze environmental impacts of community-wide provisioning of agri-food (F), energy (E) and Water (W) to homes, businesses and industries in a city. The framework connects community-wide FEW demand with in-boundary and trans-boundary production of FEW, showing embodied water and energy in production. The framework also incorporates in-boundary cross-sector interactions shaping resource exchange and recovery such as energy inputs to water use (E→W), water inputs to energy production and use (W→E), etc. and storage of FEW within, and outside, the city. Connecting in and trans-boundary interactions informs system-wide water, energy and GHG impact of cities.



METHODS OVERVIEW

In this section, we develop and describe methods that are needed to implement the framework in any city, using Delhi as a case example. The case study demonstrates the types of data that are needed (or are missing), the types of analyses and integration that are necessary, and the resulting baseline accounting of the FEW nexus that emerges for Delhi, evaluated within and outside the city boundary.

Framework implementation consists of: (1) Environmental footprinting connecting Delhi’s community wide FEW demand with trans-boundary supply; linked with (2) In-boundary analysis of FEW nexus interactions within Delhi. Methods are summarized here, and described in further detail in subsequent Detailed Methods section

Environmental footprinting of community-wide FEW provisioning

Trans-boundary coupled water-use, energy-use/GHG-emissions footprints of community-wide FEW supply to Delhi are developed using methods previously established for community-wide GHG footprinting (Ramaswami *et al* 2008a, Chavez *et al* 2012, Lin *et al* 2015). Community-wide footprinting approaches have been institutionalized by the British Standards Institute (BSI) (2013) and ICLEI (2012) to represent the broader GHG impacts of cities’ demand for key infrastructure/basic provisioning services (including food). This approach is particularly valuable for urban infrastructure planning and policy, impacting all actors in the city (homes, visitors, businesses, industries). Adopting the community-wide approach, we combine a city's direct material-energy flows associated with community-wide FEW demand with the life cycle impacts of their in- and trans-boundary production, implemented through 5 steps (A-E) described below.

***A. Community-wide FEW demand for Delhi*:** Community-wide food demand was estimated for: (i) *homes* from consumer expenditure surveys, incorporating disparities by income levels (MSPI 2011), (ii) *visitors* (Ministry of Tourism 2010), and, (iii) *food processing industries* from the Annual Survey of Industries (DES 2010). This approach covering all three user-categories is suggested to estimate community-wide food flows not only in India, but more generally for community-wide food supply analysis. Residential food demand is scaled up from household surveys conducted in Delhi which provide insight on food demand by individual food items (e.g., rice, wheat, milk, oil, etc.) by socioeconomic status of households (See Detailed Methods, Section A), to which were added visitor use and industrial agri-food inputs. The uncertainty in these estimates is on the order of 10% (see Detailed Methods 1 Section B). Quantifying residential food consumption data by food items and by SES is valuable in establishing a robust baseline upon which future scenarios such as changes in diets or in household wealth can be modeled. Community-wide demand for water and electricity are obtained directly from at-scale utility data summarized by the Government of Delhi in statistical abstracts and water reports (DES 2013a, 2013b).

B. Local versus trans-boundary production: Local (in-boundary) food production, water supply and electricity generation are estimated from government records of DES (2013a), NHB (2011), Ministry of Agriculture (2014), the Delhi Jal Board (CAG 2013) and CGWB (2012), and DES (2013a), respectively, (see Detailed Methods Section C). The requirement for trans-boundary supply is modeled as the difference between community wide FEW demand and local production. Spatial supply chains (described next) identify the FEW production regions that serve Delhi.

C. Supply chains and features of regional production systems serving Delhi: We identify key data sets available in India to spatially delineate trans-boundary supply chains of FEW supply to Delhi. Food and non-electricity fuel supply chain data are derived from a multi-modal freight study commissioned by India's Planning Commission (2008) as well as discussion with local experts, and updated in this research effort to the year 2011. The freight study notes the mode, quantity, and origin of freight commodities entering Delhi. For electricity supply chains, a new analysis method was developed (Cohen 2014) that uses Delhi's community-wide electricity demand (DES 2013a) combined with dispatch data (Delhi Transco Limited 2014) that details interstate electricity transfers, identifying the generation quantity, fuel type, geographic location and technology of individual power plants in the Northern Grid serving Delhi. Such spatial data linking individual power generators from a larger grid to demand by a city is a unique contribution of the analysis. For municipal water supply, government sources (CGWB 2012, CAG 2013) identified that 86% is drawn externally from the Yamuna and Ganges River, and Bhakra Storage, and the remainder from ground water. It is important to note that spatial detail on all three FEW supply chains for a single city has not previously been accomplished. Delhi's FEW supply chains, with production data aggregated to the state level, are shown in Detailed Methods Section D.

The different states in India differ in their use of mechanization of agriculture, i.e., use of diesel for farm implements, and in their use of electricity for irrigation, i.e., chiefly groundwater pumping. These characteristics of the agricultural production regions were delineated in our study through data sets of each state's gross agricultural production (Ministry of Agriculture 2010), annual average energy use for farm implements (Nielsen 2013), and electricity use data for irrigation reported by the Government of India (Power and Energy Division of the Planning Commission 2014). The water vulnerability of the different states, represented by the degree of groundwater overdraft (withdrawal in excess of recharge) is obtained from Suhag (2016). The groundwater overdraft in India has been exacerbated by the provision of free electricity for irrigation that has both incentivized the growth of water intensive crops such as rice, as well as increased the use of bore-wells to access ever deeper sources of water, and hence increased use of electricity for crop irrigation (Devineni et al 2013, Suhag 2016). These second order impacts represent the water-energy nexus in the trans-boundary food production and are used to enhance the existing water and GHG intensity factors of agri-food production, described next.

D. ***Supply chain informed resource (and pollution) intensity factors***: Coupled water and GHG footprints are developed by multiplying the direct demand for FEW by Delhi (Step A), with the supply chain-informed water intensity and GHG intensity factor of producing FEW. Water footprints include both water withdrawal footprints and water-consumptive loss footprints. India-specific consumptive water loss intensity factors and GHG emission factors for agriculture were sourced from Mekonnen and Hoekstra (2011) and Pathak et al. (2010), respectively. A new data set developed by this team was used for assessing national-average crop water withdrawal and water intensity (blue and green) for food processing industries in India (Bogra *et al* 2016). The above basic agricultural intensity factors were then augmented with production-specific features of each state's agri-food production, incorporating second-order order effects of electricity use for irrigation and mechanization, based on supply chain data, as described in Step C. Likewise, the water intensity of electricity generation was determined by the specific power plant types (generation amounts, technology and fuel) serving Delhi, identified in the dispatch data (Cohen 2014), with corresponding technology-specific water-intensity factors estimated from (NETL 2010). Note that India-specific water intensity of power generation are not available; hence international technology-specific averages were applied. For GHGs, India specific emission factors for power generation (CEA 2011) and international emission factors for petro-fuel refining (IPCC 2006) were applied.

E. Visualizing Coupled Water- and GHG Footprints of FEW Supply, and Supply Chain Risks: The water- and GHG footprints of Delhi's FEW demand are then aggregated by infrastructure sector (e.g., F, E, W and transportation); the food related footprints are further be analyzed by individual crops – all of which show both water and energy/GHG impacts of the city's FEW demand on the larger environment. The supply chain data were also mapped to visualize water-related supply chain risk – i.e., identify which states provided the bulk of water embodied in Delhi's FEW supply, along with the water vulnerability of these states.

Evaluating Delhi's in-boundary FEW nexus

The second aspect of the FEW nexus framework focused on in-boundary FEW interactions occurring within Delhi. Several diverse datasets were integrated to quantify cross-sectoral FEW interactions occurring within the city boundary including sub-sectoral interactions noted below:

- W➔F: water inputs to city food-related activities (water for home cooking, commercial preparation, industrial processing, urban agriculture irrigation);
- W➔E: water inputs to city energy-related activities (water for fuel processing, electricity generation, building cooling);
- E➔W: energy inputs to city water-related activities (energy for water supply, treatment and distribution, (including distribution by tanker trucks), wastewater treatment, home water purification;
- E➔F: energy inputs to food-related activities (energy for home cooking and refrigeration, commercial food preparation, industrial processing and urban agriculture irrigation).

Two additional interactions of food➔water and food➔energy within the city are shown in Figure 2-1 but were not quantified in Delhi as there is no significant existing food waste to energy generation. The diverse activities detailed above within each of the pair-wise interactions were quantified by identifying water or energy intensity factors associated with each sub-activity, along with the scale of that activity occurring in Delhi. For example, water for cooking (a sub-sectoral activity within W➔F) was scaled from a range of water use intensity estimates for cooking, e.g., 10-20 liter water/person per day as noted by (Gleick 1996) and the scale of that activity (i.e., Delhi's population).

We detail all possible interactions within a city in Table 2-6, and detail the data needs, availability and uncertainties in quantifying these interactions for Delhi. City scale data for some of these parameters are unavailable, not only in India but also in U.S. cities. In such cases, we applied international benchmarks for missing information, and conducted a sensitivity analysis to reveal dominant interactions and to identify where further data-gathering is critical for assessing key in-boundary FEW interactions.

Methods outlined in all five steps, together, provide an accounting of the in-boundary and trans-boundary water and energy flows related to urban FEW demand, and the six pairs of urban FEW interactions.

DETAILED METHODS

Environmental footprinting of community-wide FEW provisioning

The general calculations for the total Community-wide Consumptive Water Loss, Water Withdrawal and GHG Footprints of FEW provision (WCLF, WWF, $GHGF_{\text{FEW infrastructure provision}}$, respectively) are explained by Equations 2-1, 2-2, and 2-3, respectively, where $MEFA_{use,,i}$ represents the direct material energy flow demand of electricity, fuels, food or water used in the city, and *IF* the supply chain informed resource intensity factor (or pollution emission intensity factor, e.g. GHG) of producing that sector, *i*. IB and TB indicate in- and trans-boundary contributions, respectively.

$$WCLF_{infrastructure\ provision} = \sum_i MEFA\ use_i * (IF_{i,CL,production}^{IB+TB,consumptive\ loss} + IF_{i,CL,use}^{IB,consumptive\ loss}) \qquad (2\text{-}1)$$

$$WWF_{infrastructure\ provision} = \sum_i MEFA\ use_i * (IF_{i,W,production}^{IB+TB,withdrawal} + IF_{i,\ i,W,use}^{IB,withdrawal}) \qquad (2\text{-}2)$$

$$GHGF_{FEW\ infrastructure\ provision} = \sum_i MEFA\ use_i * (IF_{i,production}^{IB+TB,GHG} + IF_{i,\ i,use}^{IB,GHG}) \qquad (2\text{-}3)$$

The footprinting is accomplished in five steps, where we quantify the following:

A. Community-wide FEW demand (material flows) for Delhi
B. Uncertainty in community-wide FEW estimation
C. Local versus trans-boundary production
D. Supply chains of transboundary FEW supply to Delhi
E. Supply chain informed resource (pollution) intensity factors

The parameters quantified above, enable developing the coupled water, energy, GHG footprint as shown in Figure 2-5 of the main text. ‘Trans-boundary’ refers to activity (impact, production etc.) that occurs beyond the geographical city boundary, while the terms ‘in-boundary’ and ‘local’ refer to being within the geographical city

Community-wide FEW demand (material flows) for Delhi

Total community-wide food, electricity, water and fuel use for Delhi are computed based on the methods summarized below.

Community wide food use includes resident, visitor, and industrial food use.

- Residential use by mass was estimated by adding all agri-food types from the National Sample Survey in Delhi as average per capita food use (by mass) in 12 socio-economic strata (SES), multiplied by the population in each of the 12 SES categories (Ministry of Statistics and Programme Implementation 2011). This yielded a residential food mass of 6.1 million tons.

- Visitor food use was estimated from data of annual Delhi visitors from the Ministry of Tourism, (2010) reporting number of visitors and average trip duration. This was multiplied by an estimated average three meals per day and meal weight. Meal weight was estimated as an average of the range 0.4-0.74 kg per meal as determined by bottom up and town down estimations (determined by author calculation and the FAO (2011) Food Balance Sheet). This yielded, a total of 61,121 tons, making a much smaller (<1%) contribution than residential food use.
- Industrial food was estimated from data on industry output reported in the Annual Survey of Industries (DES, 2010). GDP output to mass of food (tons) was converted using data on consumer expenditure data that provides expenditure and tons of processed food consumed. Industry output that exceeded processed food consumed by residents and visitors was assumed exported, a likely scenario given that Delhi has >100 food related industries. The agri-inputs to industry are assumed the same as homes. Industrial agri-food use was computed to be 518,420 tons and is also relatively small (<8%) compared to residential food use.
- The total community-wide direct food demand was 6.7 million tons, to which was applied a factor of 35% of pre-consumer (as determined by review of India-specific wastage studies; (Basavaraja *et al* 2007, Gauraha, AK Thakur 2008, Kumar *et al* 2005, Sharma and Singh 2011, Gustavsson *et al* 2011)) to assess the quantity of agri-food production needed to serve Delhi's demand. This resulted in a total of 9 million tons of agri-food production needed for Delhi's food inputs.

Community-wide electricity use was obtained from at-scale community-wide electricity use data from two different sources, the Delhi Statistical Handbook (DES 2013a) and electricity dispatch data (Delhi Transco Limited 2014) which report 33,390 GWh and 25,893 GWh, respectively. Electricity dispatch data reports the electricity consumed in Delhi, while the statistical handbook reports electricity generated; the difference likely lies in transmission and distribution losses as well as electricity theft, estimates of which range from 20 to 50% (NBR 2014, TERI 2000, Bloomberg 2014). We used at-scale community-wide electricity use data reported by Delhi's Statistical Handbook (DES 2013a), as has been done in prior energy-use studies at the city-scale (e.g. Toronto, Denver, Delhi (Kennedy *et al* 2009, Hillman and Ramaswami 2010, Chavez *et al* 2012)). The residential electricity use of 10,396 GWh obtained from the statistical handbook (DES 2013a) was consistent (+/- 10%) with the residential electricity computed independently from the household surveys (MSPI 2011) of 9,380 GWh; providing confidence in the data set.

Community-wide fuel use such as LPG, petrol, and diesel is reported by the Delhi Statistical Handbook from which the residential component was estimated from the National Sample Survey, (DES, 2013a; Ministry of Statistics and Programme Implementation, 2011) to provide the split by household use.

Community-wide direct water use is reported by the Economic Survey of Delhi (2013), as 1,891 million m^3 of domestic water supply of which 14% is supplied locally from groundwater as estimated by the Central Groundwater Board (CGWB 2012), with the remaining 86% sourced from the Yamuna River, Ganges River and Bhakra Storage (Comptroller and Auditor General of India 2013). The water use was allocated to residential and commercial combined, and industrial based on reports from the Delhi Government as described in Table 2-1.

Table 2-1 | Total community-wide FEW use in Delhi and its distribution across, residential, commercial, and industrial sectors and the percentage of demand met locally. This table is informed by Detailed Methods Sections A, B, C. This also informs Figure 2-5a of the main text.

FEW resource	Total	Residential	Commercial	Industrial	Other	% supplied locally	Data Sources
Food	9 (mill. t)	86%	*7%**	7%	N/A	10%	(DES, 2010; Ministry of Tourism, 2010; MSPI, 2011)
Electricity	33,000 (GWh)	47%	29%	14%	10%	24%	(DES, 2013a)
Water	1,704 (million m3)	77%		15%	8% (irrigation)	14%	(DES, 2013b)
Fuels – transport	169,085 (TJ)	1%	<1%	5%	94%	0%	(DES, 2013a; MSPI, 2011)
Fuels – non transport	36,964 (TJ)	70%	30%	0%	0%	0%	

**Commercial food use = resident food outside home (6%) + visitor use (1%)*

Uncertainty in community-wide FEW estimation

Community-wide electricity and water use are obtained from at-scale data reported by city utilities. The uncertainty of these data are unknown, however, utility data have been conventionally used in scientific papers reporting on bottom-up urban metabolism (Kennedy *et al* 2009, Baynes *et al* 2011). In this work, we use per capita and per household benchmarks to confirm that the utility data are reasonable, as noted for electricity above.

Compared to electricity and water-use data reported by utilities, greater uncertainty can be expected in estimating community-wide food use since these data are not reported in Delhi's statistical abstract. Community-wide food use includes household consumption, visitor consumption and food use by industries of which residential consumption dominated. Household food consumption was estimate from 937 consumer surveys conducted in Delhi by the National Sample Survey (MSPI 2011). Residential food use is reported in both mass units and expenditure units. Mass and expenditure showed good correlation, with R^2 values of 0.95, 0.88, 0.83 (see Figure 2-2) for the largest food mass items of milk, wheat and rice, respectively, indicating confidence in the survey data.

Combined, the three food items, of milk, wheat and rice add up to more than half of the total mass of food. Therefore, we use these items to quantify uncertainty in scaling up the household consumption data from surveys to the population of Delhi.

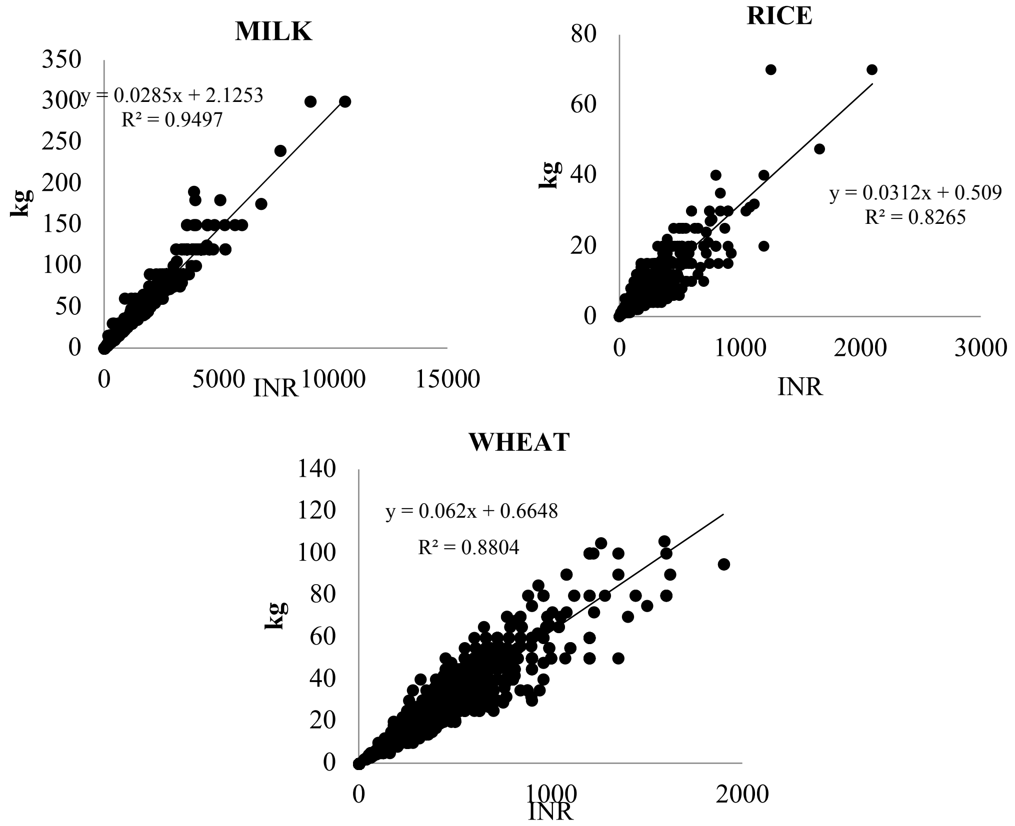


Figure 2-2 | Scatterplots of reported mass (kg) versus expenditure (INR) per household as reported by the NSS for milk, rice and wheat.

Total food use is estimated from the National Sample Survey as average per capita food use (by mass) in 12 socio-economic strata (SES), multiplied by the population in each of the 12 SES as shown in Table 2-2. The Government of Delhi has mapped its population into 12 SES fractiles, and identifies the percentage of Delhi's population (% $\text{population}_{\text{SES},i}$) within each fractile based on monthly per capita expenditure. The 937 surveys were sought from the 12 different percentiles. As an example, Delhi's total residential consumption of purchased rice is derived from the consumer purchase data in each of the 12 fractiles and is shown in Table 2-2 as a product of the estimated population mean of the rice consumption within each SES group and the population of that SES group. The standard error (σ_M) of the population mean is computed from the sample standard deviation (σ) using Equation 2-4 below, where n is the sample size, representing the number of surveys in each fractile.

$$\sigma_M = \frac{\sqrt{\sigma^2}}{\sqrt{n}} \qquad (2\text{-}4)$$

Table 2-2 | Uncertainty analysis for purchased rice consumed by SES.

Fractiles of SES	Delhi population in each fractile	Population average per capita rice consumption (kg)	Sample standard deviation (kg)	# of samples	SE of distribution of the mean (kg)	Relative SE of distribution of the mean	Total Delhi rice consumed (ton)	Error in estimating total rice consumed by SES	
								(ton)	(%)
5	820,989	16.6	17.8	23	3.7	22%	13,632	3,042	22%
10	820,989	17.1	16.2	37	2.7	16%	14,009	2,188	16%
20	1,641,979	22.3	16.8	92	1.7	8%	36,536	2,873	8%
30	1,641,979	22.2	15.7	58	2.1	9%	36,411	3,382	9%
40	1,641,979	20.8	12.5	55	1.7	8%	34,114	2,761	8%
50	1,641,979	21.0	14.6	66	1.8	9%	34,538	2,945	9%
60	1,641,979	22.9	22.4	94	2.3	10%	37,683	3,795	10%
70	1,641,979	23.9	16.5	108	1.6	7%	39,184	2,611	7%
80	1,641,979	24.0	18.2	138	1.6	6%	39,424	2,548	6%
90	1,641,979	24.9	14.1	140	1.2	5%	40,843	1,951	5%
95	820,989	24.1	18.0	63	2.3	9%	19,758	1,862	9%
100	820,989	28.7	20.2	63	2.5	9%	23,547	2,091	9%
Total	**16,419,787**	**22.5**	**5.0**	**937**	**--**	**--**	**369,680**	**32,049**	**9%**

*population mean is estimated as the sample mean

Therefore, the total purchased rice consumed by Delhi by approach 2 is found to be 369,680 tons with the error in estimation of 32,049 tons (+/- 9%). Applying the method of Table 2-2 found Delhi's total food use of 6.1 tons, and error of +/- 10% across all food categories. Since the mass of commercial and industrial agri-food inputs are very low in comparison to residential use, the uncertainty (~10%) of the household food estimate dominates total food demand of Delhi.

Local versus trans-boundary production

Local food production within Delhi is provided by the Delhi Statistical Handbook (DES 2013a) for grain and pulse crops, India Horticulture Database (NHB 2011) for some fruits and vegetables, and Ministry of Agriculture (Ministry of Agriculture 2014) for dairy and meat items.

Local electricity generation is reported by the Delhi Statistical Handbook (DES, 2013a)

Local water supply that is extracted from groundwater is denoted as in-boundary and was provided by Delhi Jal Board (Comptroller and Auditor General of India 2013) and from the CGWB (2012).

Trans-boundary FEW quantities are then determined by the mass balance of total community demand (as described in section B) minus local production. See Table 2-1 for a summary.

Supply chains and Characteristics of Regional Production Systems

Supply chain data for food, electricity, fuels and water supply to Delhi are derived from the following sources.

- Supply chains of community-wide food to Delhi are estimated from the freight data that provides inflows of various agri-products into the Delhi National Capital Region (NCR) from all states of India – provided by the Total Transportation System Study on Traffic Flows and Modal Costs, commissioned by the GOI Planning Commission (2011) and reported in Table 2-3 below. The authors commissioned work to the government agency to extract the data relevant to our study. The authors then further analyzed this data to determine the locations of production that matched Delhi's demand.
- Supply chains of community-wide direct electricity to Delhi was apportioned to different states based on Dispatch data and inter-state transfers reported by State Load Dispatch Centre (Delhi Transco Limited 2014). Dispatch data are available at the individual power plant level, and are aggregated at the State level and reported in Table 2-3 below. The fuel mix for power generation in each state is from CEA (2011). Knowledge of individual power plants by fuel use and

technology enables water intensity factors to be computed based upon specific features of the generators serving Delhi.

- Supply chains of community-wide direct transportation fuel and LPG fuel were determined by researcher Ajay Nagpure through personal communication with experts in Delhi – who indicate Mathura, Paniput, Great Bombay, Mathinda and Sagar refineries to be key supply chains for petro-fuels supply to Delhi. This information was verified with the freight study.
- Supply of community-wide direct water is sourced 14% from ground water within Delhi as reported by Jal (Water) Board (DES, 2013b) and the CGWB (2012) within the city. As reported Jal Board, the remaining is sourced from the Yamuna River, Ganges River and Bhakra Storage (Sutlej River).

Delhi's food and electricity demand are connected with the eight top producing states shown Table 2-3.

Table 2-3 | Connecting demand for food and electricity in Delhi to various production states, including local production are shown in columns 1-4. Features of the production states are shown in Columns 5-8.

Production state serving Delhi	**Food imports to Delhi**[1]			**Total state agri-food production (tons)**[2]	**Gross annual average electricity intensity of irrigation (kWh/ t crop)**[3]	**Total state electricity generation (BU)**[4]	**Elec. imported to Delhi from each states in BU (% of Delhi demand)**[5]
	Total Tons (% of Delhi's demand met)	**Detail on top food items being supplied per state**					
	Imports to Delhi	**Product**	**Tons (% of Delhi's demand met)**				
Delhi (local production)	882,019 (10%)	Milk and products	479,630 (19%)	824,317	104*	8.0	8.0 (24%)
		Fruits and vegetables	236,700 (12%)				
		Meat	42,467 (57%)				
		Rice	30,297 (5%)				
Haryana	2,548,983 (28%)	Milk and products	898,228 (35%)	21,495,890	431	22.7	0.8 (2%)
		Wheat	858,907 (48%)				
		Rice	287,235 (50%)				
		Fruit and vegetables	226,130 (12%)				
Uttar Pradesh	2,053,246 (23%)	Milk and products	778,744 (31%)	182,415,201	48	30.2	14.3 (43%)
		Fruits and vegetables	683,460 (36%)				
		Wheat	193,677 (11%)				
		Sugar	131,116 (21%)				
Punjab	783,309 (9%)	Wheat	241,690 (14%)	29,787,150	344	30.0	0.0 (<1%)
		Milk and products	180,529 (7%)				
		Fruits and vegetables	126,547 (32%)				
		Rice	125,760 (22%)				
Rajasthan	719,870 (8%)	Fruits and vegetables	173,721 (9%)	22,950,459	657	36.7	0.9 (3%)
		Milk and products	150,562 (6%)				
		Wheat	121,511				

			(7%)				
		Grams and pulses	56,940 (21%)				
Madhya Pradesh	405,623 (4%)	Wheat	122,667 (7%)	Unavailable	104*	21.6	0.6 (2%)
		Fruits and vegetables	113,211 (6%)				
		Grams and pulses	82,316 (30%)				
		Sugar	17,735 (3%)				
Maharashtra	294,238 (3%)	Fruits and vegetables	155,030 (8%)	89,846,559	241	80.8	0.0 (<1%)
		Wheat	41,062 (2%)				
		Grams and pulses	28,192 (10%)				
		Sugar	26,008 (4%)				
Gujarat	245,673 (3%)	Fruits and vegetables	86,114 (5%)	23,610,995	591	69.8	0.0 (<1%)
		Wheat	50,455 (3%)				
		Sugar	39,680 (6%)				
		Rice	11,544 (2%)				

**National average used when data unavailable*
1: Data from multi-modal freight survey, adjusted to 2011 (Planning Commission 2008)
2: State-wise production data from (DES, 2010a)
3:Calculated gross annual average as total agricultural electricity (Power and Energy Division of the Planning Commission 2014) *divided by total state-wise production (DES, 2010a)*
4: Total state generation is reported by CEA (2011); BU = Billion kWh
5: Electricity imports to Delhi reported by Delhi Transco Limited (2014)

The second order impacts were calculated from dividing the gross annual state-wise electricity use for irrigation (as reported by the Government of India Power and Energy Division of the Planning Commission (2014)) and diesel use for on-farm implements (as reported by (Nielsen 2013)) each by total state agricultural output in mass (Ministry of Agriculture 2010). This provided a gross annual average electricity for irrigation and diesel requirement for nine states serving Delhi's food supply and an all-India average (see Table 2-4). Table 2-5 also shows percentage of groundwater development (defined as the ratio of annual groundwater withdrawal over groundwater recharge) as reported by Suhag (2016) to illustrate how groundwater overdraft can correspond with increase electricity requirement for irrigation. The values of Table 2-4 inform creation of Figure 2-3.

Table 2-4 | Gross annual averages of state specific diesel and electricity factors for agricultural production as well as percentage of groundwater develop (defined as the quantity of groundwater withdrawal divided by groundwater recharge). These values were used in the development of Figure 2-3.

State	**L diesel fuel / t crop production**	**kWh elec./ton of food produced**	**Diesel CO_2 e/ton crop**	**Elec CO_2e /ton crop**	**% of GW development**
Delhi local supply	12	21	32	16	137
Haryana	47	431	128	340	133
Uttar Pradesh	8	48	21	38	74
Punjab	33	344	89	272	172
Rajasthan	34	657	91	519	137
Maharashtra	4	241	10	190	53
Gujarat	11	591	30	467	67
Uttarakhand	11	37	28	30	57
West Bengal	4	28	11	22	40
All India average	23	104	61	82	62

Supply chain informed resource (GHG) intensity factors

India average basic GHG, consumptive-water loss and water-withdrawal intensities for agri-food production were sourced from Pathak *et al* (2010), Mekonnen and Hoekstra (2011), Bogra *et al* (2016), respectively, shown in Table 2-5. These values were augmented with production specific features of each state relating to the second order impacts of diesel use for farm equipment and electricity use for pumping, as described in Section D.

Table 2-5 | Sources of India-average basic GHG and water intensity factors (IF) for footprinting.

Direct MEF Flow Item	GHG intensity factor & source	Water withdrawal intensity factor	Water consumptive loss intensity factor
Electricity	0.76 - 0.79 kg CO_2e/kWh (CEA, 2012)	250 - 35,000 gal water/MWh (Cohen, 2014; NETL, 2010)	50 - 4,491 gal water/MWh (Cohen, 2014; NETL, 2010)
Fuel	56,100-74,100 kg CO_2e /TJ (IPCC, 2006)	5.25 L water/liter petroleum based fuel (average) (Cohen 2014)	5.25 L water/liter petroleum based fuel (average) (Cohen 2014)
Food	28 - 12,352 kg CO_2e /t crop (Pathak *et al* 2010), supplemented with author calculation for transport, on-farm diesel use, electricity for irrigation– See Table 2-4	Green: 0 – 24,889 m^3/crop Blue: 0 – 4302 m^3/crop (Bogra *et al* 2016)	Green: 0 – 24,889 m^3/crop Blue: 0 – 4302 m^3/crop (Mekonnen and Hoekstra 2011)

Data sources and methods for evaluating the in-boundary FEW interactions

The following Table 2-6 describes the data used in the development of the in-boundary FEW nexus. Each of these categories is comprised of Delhi specific sub-category interactions. For example, water for food includes the activities of urban production, home preparation, commercial preparation, and industrial processing, (see Table 2-6 for all categories). Each of these sub-categories is estimated based on an intensity factor of each of these activities multiplied by an activity parameter for scale up, described by Equation 2-5.

Impact of sub-category activity = (Intensity Factor) x (Activity parameter for scale up) (2-5)

Table 2-6 | Data sources to estimate four categories (labeled 1 – 4) of water-energy flows associated with the FEW nexus within cities. Intensity factors are scaled by appropriate activity level and underlined/bolded value is the activity number used for calculation, ('C' = consumption; 'W' = withdrawal; energy and water in hotels includes only that used for food preparation and refrigeration). Green shaded boxes indicated inclusion in sensitivity analysis.

Interaction	Intensity factor		Activity for scale up		Subtotal and (% of category total)
	Intensity factor	Data source	Activity parameter	Data source	
1. In-boundary Water for Food (W➔F): Category total = 461.5 (Consumptive loss, C) & 787.0 (Withdrawal, W) M m^3					
Water for growing agri-food	**70 – 15,537** green m^3/t crop, C	*(Crop specific C data from* Mekonnen and Hoekstra 2011*))*	**1,303,600 tons** in-boundary agri-food production, by specific crops noted in SI	(DES 2013a, NHB 2011, Ministry of Agriculture 2014)	**351 M m^3** (C - 77%)
	0 - 2,779 blue m^3/t crop, C				
	0 - 24,889 green m^3/t crop, W	*(Crop-specific W data from* (Bogra *et al* 2016)*)*			**677 M m^3** (W - 86%)
	0 – 4,302 blue m^3/t crop, W				
Water for cooking (residential)	2-**10** L/person/day	(Gleick 1996, Howard and Bartram 2003)	**16,000,000 × 365** Population × days	(DES 2013a)	**58 M m^3** (C - 13%) (W - 7%)
Water for food preparation (Hotel and restaurant, commercial)	*Restaurant*				**44 M m^3** (C - 10%) (W - 6%)
	16 m^3/seat/year	(DPCC 2013)	**2,732,603** restaurant seats in Delhi	(FHRAI 2012)	
	Hotel				**1 M m^3** (C - 0%) (W - 0%)
	128 – 160 (**144**) L/guest/night	(DPCC 2013, EarthCheck 2013)	**8,087,003** Delhi visitors × nights stayed	(Ministry of Tourism 2010)	
Water for food processing (industrial)	**0.034** L/INR	(Nestlé 2014, Nestlé India Limited 2014)	**1.11×10^{11} INR** Output of Delhi food processing industry	(DES 2014)	**4 M m^3** (C - 1%) (W - 1%)
2. In-boundary Energy for Food (E➔F): Category total = 7,588,788 MWh					
Energy for food use, (Residential: cooking)	1.25 - **1.97** MWh/household/yr	(de la Rue du Can *et al* 2009; author calculations)	**3,340,538** households in Delhi	(DES 2013a)	7,963,241 **MWh** (68%)
Energy for in-boundary food transport	*Assumed to be relatively small based on field observations of large numbers of non-motorized rickshaws and carts hauling agricultural products within the city from freight centers. To be verified in future work.*				
Energy for food preparation (commercial: restaurants, hotels)	*Restaurant*				**2,421,120 MWh** (18%)
	0.57-3.5 kWh/meal (**2 kWh/meal**)	*(Author calculation from hotel food prep energy use)*	**1,210,560,000** All – Delhi meals taken outside the home (restaurants,	(MSPI (Ministry of Statistics and Programme Implementation) 2011)	

			business, other)		
	Hotel				**37,605 MWh** (<1%)
	2.3-7 kWh/ guest/night (**4.65 kWh**)	(Bhatt *et al* 2005, ICH (Indian Hotels Company) Limited 2012)	**8,087,003** visitors × nights stayed in Delhi	(Ministry of Tourism 2010)	
Energy for food processing (industrial)	**0.0017-0.011** kWh/INR	(Nestlé India Limited 2014, Ministry of Agriculture Deparment of Animal Husbandry 2014)	**1.11 × 10^{11} INR** output of Delhi food processing industry	(DES 2014)	**1,210,475 MWh** (13%)
Energy for agriculture (irrigation GW pumping)	**0.14** kWh/m^3 water	*Author calculation of pumping energy using depth to water table and water extracted*	**140,000,000** m^3 irrigation groundwater	(CGWB 2012)	**19,600 MWh** (<1%)
3. In-boundary Energy for Water (E➔W): Category total = 622,511 MWh					
Energy for water supply	*Municipal water supply and treatment*				**378,214 MWh** (62%)
	0.2 Wh/L	(Miller *et al* 2012)	**1891 M m^3** municipal water supplied	(DES 2013b)	
	Groundwater pumping				**36,516 MWh** (6%)
	0.14 kWh/m^3	*Author calculation of pumping energy using depth to water table and water extracted*	**260 M m^3** groundwater use (excluding irrigation)	(CGWB 2012)	
	Tanker water distribution				**19,431 MWh** (3%)
	5.35 kWh/m^3	(Parikh and Khedkar 2013, Comptroller and Auditor General of India 2013; author mapping of tanker truck travel)	**3.79 M m^3** water supplied by tanker truck	(Comptroller and Auditor General of India 2013)	
Energy for waste water treatment	**0.1** Wh/L	(Miller *et al* 2012)	*Municipal wastewater treatment*		**151,256 MWh** (24%)
			1513 M m^3 Wastewater treated by municipal	(DES 2013b)	

			plants		
			Business & industry wastewater treatment		**26,000 MWh** (4%)
			75.14 M m3 Wastewater treated by business and industry	(Bogra *et al* 2016, DES (Directorate of Economics and Statistics) 2014, Nestlé India Limited 2013)	
Energy for additional home water treatment	**0 – 93** Wh/L (depending on purification method)	(Eureka Forbes 2015, Kent RO Systems Ltd 2012)	**8,869,600** population using home purification, by purification type in SI	(Dutta 2006, Hussain 2014)	**11,094 MWh** (2%)
4. In-boundary Water for Energy (W➔E) – Category total: 4.2 (Consumption, C) & 1060.2 (Withdrawal, W) M m^3					
Water for energy supply *(excluding residential)*	**35000** gal water/MWh (W)	(Cohen and Ramaswami 2014, Macknick *et al* 2011, Meldrum *et al* 2013)	**8003 GWh** total annual Delhi electricity use	(DES 2013a)	**1,060 M m^3** (W – 100%)
	140 gal water/MWh (C)				**4 M m^3** (C - 100%)
Water for household evaporative cooling	**4.8** gal water/unit/year	Author calculation based on household cooling use and equipment water use	**4,123,199** units	(World Bank 2008)	**75 M m^3**

Sensitivity analysis of in-boundary FEW interactions

Because the data of Table 2-6 are derived from diverse sources, we conducted an analysis to understand the sensitivity of the in-boundary nexus to the range of available intensity factors. In estimating the in-boundary FEW interactions, the authors compiled a range of possible intensity factors whenever possible and compared with available international benchmarks to assess the reasonable-ness of the numbers, given the newness of the field. The ranges are listed as numerical ranges in column 2 of Table 2-6, with the underlined value indicating the value used for calculation. The underlined value was chosen based on it being derived from or applicable to the Delhi/India context. The following is a rationale for each choice:

Interaction		Rationale for value selection
Water for cooking food/drinking	-	Upper range chosen due to hot climate of Delhi
Energy for residential cooking	-	At scale data reported for Delhi
Energy for food processing	-	India specific value
Water for food processing	-	India specific value

In some relationships (water and energy for commercial food preparation), where there existed little past study and guidance on selection of a reasonable intensity factors, the average value was chosen from the range of possible values. The main text also notes the lack of data availability and prior study in quantifying the water and energy for commercial food preparation both in India and globally. These intensity factors are illustrated with green shading in Table 2-4. For these intensity factors, where an average was used as the nominal value in the main manuscript, but no guidance was available to inform the choice, we conducted a sensitivity analysis. We assessed if our conclusions changed when we applied the high and low values in comparison to the average. Such a sensitivity analysis (see Figure 2-10 in Supplementary Results) showed the only parameter that significantly altered our conclusion was energy for food, which we indicate in the main text to be a parameter where the data gap is most critical.

RESULTS

Community-wide FEW demand for Delhi: Delhi's 2011 community-wide FEW demand are 9 million tons of food, 33,000 GWh electricity, 206,049 TJ of fuels and 1,704 million m^3 water. Demand is apportioned as residential, commercial, and industrial to illustrate the various in-boundary uses (Detailed Methods, Section A). Demand for food is dominated by direct inputs to homes; thus using consumer surveys to estimate demand for food is valuable in assessing future scenarios such as change in diet, and/or nutrition, including more equitable diets. Electricity is split equally among homes, businesses, and industry, while water-flows are only disaggregated between residential and non-residential end users. The sectoral split by direct end-use of FEW can vary in different world cities.

Local versus trans-boundary production: Delhi, locally produces only 10%, 24%, 0, and 14% of its direct community-wide food, electricity, other fuels, and water needs, respectively, highlighting the importance of understanding both local and trans-boundary production supply chains that serve FEW provisioning to Delhi.

Supply chains and features of regional production systems serving Delhi: Trans-boundary spatial supply chain data (Detailed Methods) show that >80% of Delhi's food supply and >45% of electricity come from the neighboring states of Punjab, Haryana and Uttar Pradesh. Delhi and these three surrounding states are highly water vulnerable with groundwater overdraft (ratio of annual extractions versus recharge) being 137% 170%, 130% and 74%, respectively (Suhag 2016). Figure 2-3 illustrates that both the degree of groundwater overdraft and electricity use intensity for crop production (annual average) for groundwater pumping are high in many states that provide >75% of Delhi's food, reflecting the feedback loop between electricity use and declining groundwater levels. This is a powerful representation of the trans-boundary FEW nexus, shown in Figure 2-1, that represents second-order energy inputs due to electricity needed for irrigation and water to produce this electricity.

Supply chain informed resource (and pollution) intensity factors: The system-wide environmental impact of Delhi's FEW provisioning in terms of water energy, and GHG emissions, is shown in Figure 2-4. In the case of water resource impacts, food clearly dominates, responsible for 72% water-withdrawals and 86% of consumptive-water-loss associated with FEW provisioning in Delhi. Petro-fuels account for 42% of the total GHG emissions footprint, followed by electricity at 36%, and food at 19%, while water supply contributes relatively little (<1%) to the GHG footprint. Thus, food is identified as a key sector that substantially contributes to both water and GHG footprints.

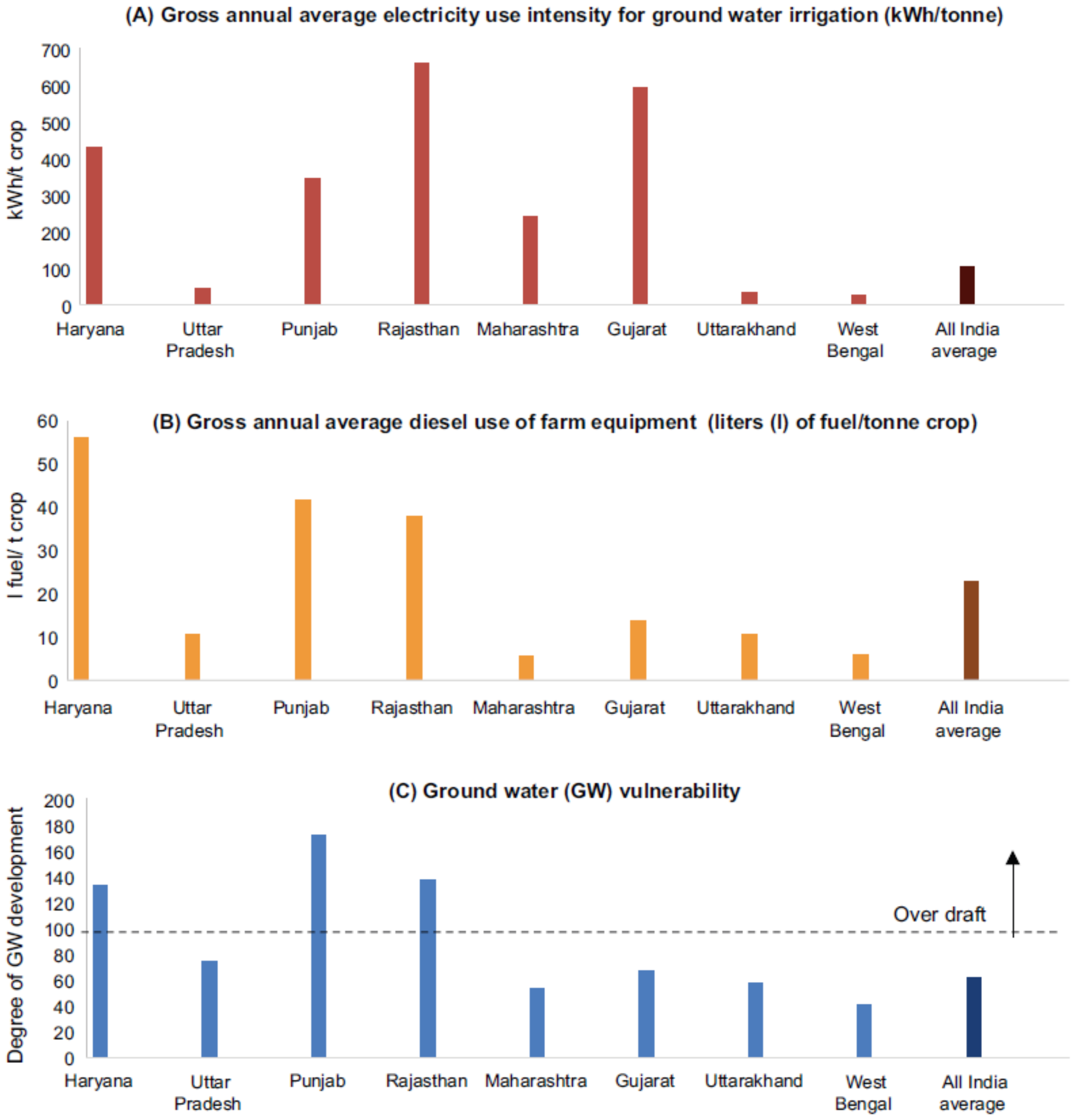
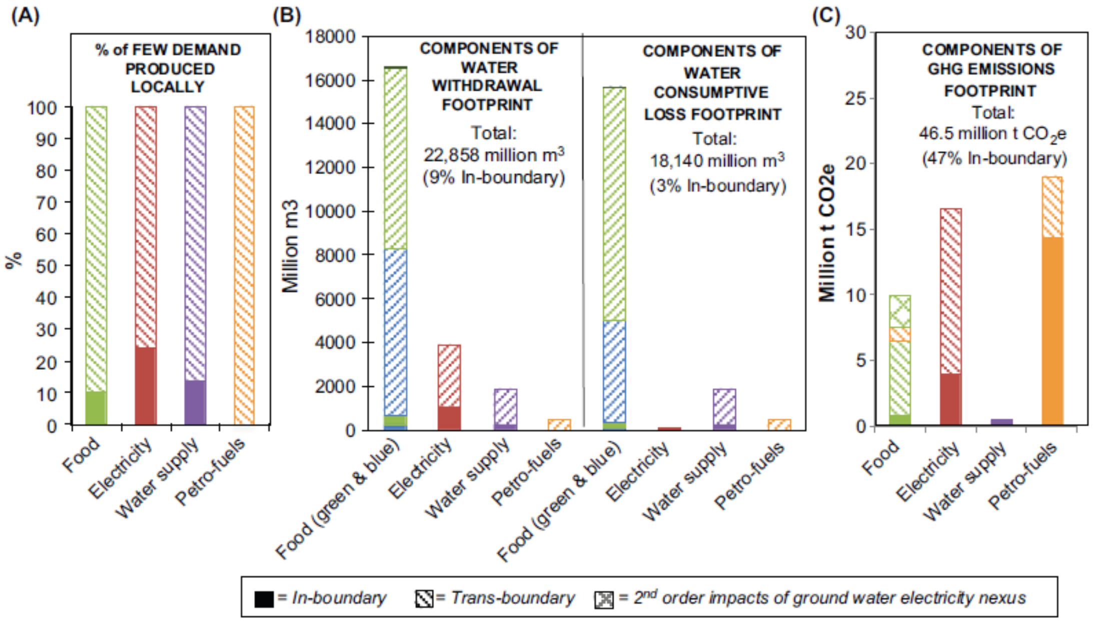


Figure 2-3 | Characteristics of regional agri-food production and ground water (GW) vulnerability in top eight states of India supplying food to Delhi (a) gross annual average electricity use intensity for ground water irrigation (b) gross annual average diesel use of farm equipment and (c) ground water vulnerability. GW vulnerability is determined from GW data from Suhag (2016) reporting ratio of withdrawal to recharge, with the dashed line indicating the over-draft threshold (of 100% beyond which withdrawal exceeds recharge). State-wise crop production is reported by the GOI Ministry of Agriculture (2010), diesel from Nielsen (2013), state-wise electricity for agriculture use from the GOI Planning Commission (2014).

Of note is the impact of the second-order GHG and water impacts of agri-food production (shown by the crisscross pattern in Figure 2-4) representing the energy required for groundwater pumping (groundwater-electricity nexus) and farming equipment (Figures 2-3, Table 2-4), and the resulting water requirement to produce the needed electricity. The trans-boundary groundwater-electricity nexus of agri-food production is seen to have large impact on the total GHG footprint of food, adding an additional 38% to the existing GHG intensity of crop production and transport. The water embodied in this electricity is relatively small (not visible) in comparison to the direct water inputs.

The second order impacts of groundwater pumping for agri-food production are also clearly seen in Figure 2-5, which illustrates Delhi's food-related consumptive water-loss and GHG footprints disaggregated by food item supplied to Delhi (2-5b), while also noting the percent of supply sourced within Delhi (2-5a). Milk noticeably dominates both the water and GHG emission footprints (nearly 25 and 40%, respectively), with rice, wheat, oil, and pulses all contributing substantially to both impacts, highlighting the types of agri-foods where changes in demand or production practices can have large impact.

***Visualizing Coupled Water- and GHG Footprints of FEW Supply, and Supply Chain Risks*:** Figure 2-6 illustrates the spatially disaggregated water impact of FEW provisioning to Delhi (see Tables 2-3 and 2-4). Figure 2-6 shows that majority of water embodied in Delhi's FEW demand is extracted from the highly water-vulnerable producing regions (shown in yellow and orange), helping to visualize supply risk and future climate constraints to Delhi's FEW provisioning.



DIRECT FEW DEMAND

RESOURCE	TOTAL	Residential	Commercial	Industrial	Other	% produced locally
Food	9 (million t)	86%	7%*	7%	N/A	10%
Electricity	33,000 (GWh)	47%	29%	14%	10%	24%
Water	1,704 (million m3)	77%		15%	8% (ag)	14%
Fuels: transport	169,085 TJ	1%	<1%	5%	94% (transport)	0%
Fuels: non-transport	36,964 TJ	70.%	30%	0%	0%	0%

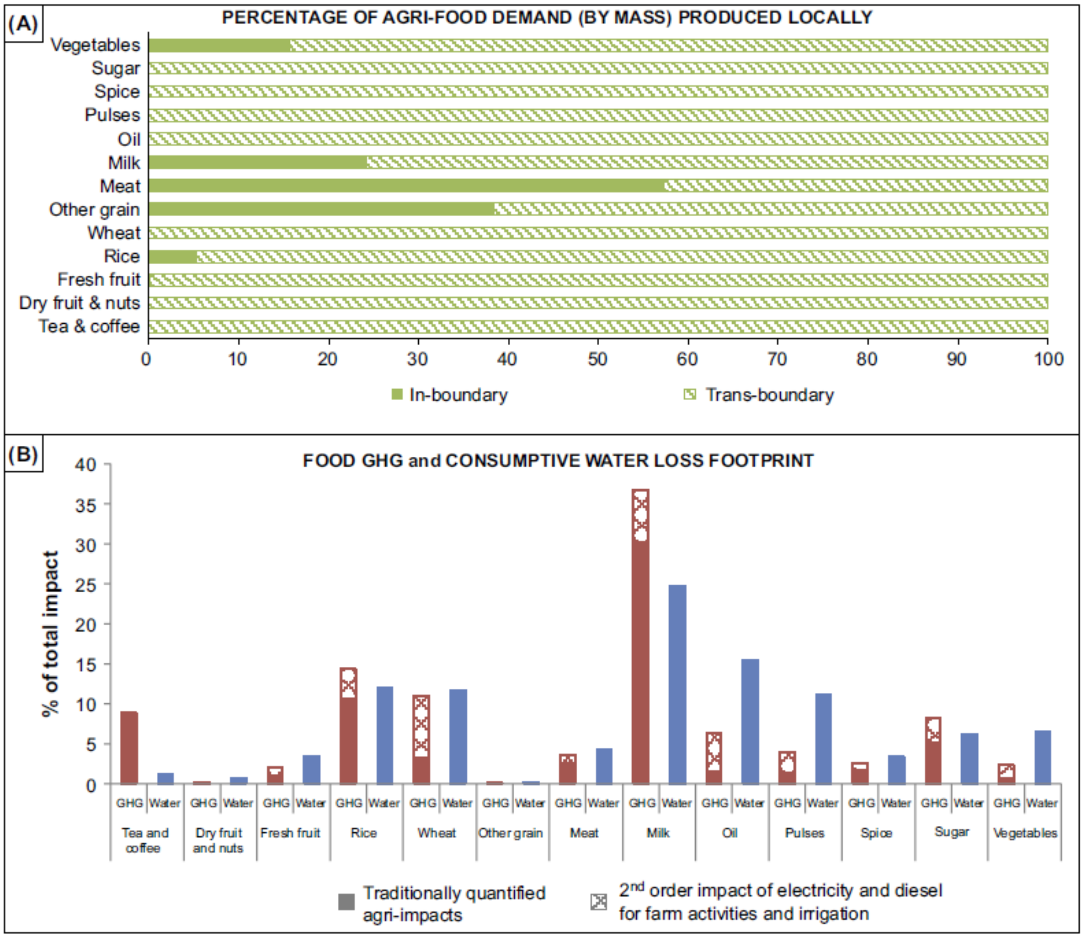
**Commercial food use = resident food outside home + visitor use*

Figure 2-4 | Coupled water–energy/GHG footprints of FEW provisioning to Delhi for 2011 from local production (solid bars) and trans-boundary supply (hatched and cross hatched bars). (a) Percentage of FEW demand (by mass or MWh for electricity) produced locally; (b) Components of water footprint of FEW supply to Delhi, with withdrawal and consumptive loss shown separately, and blue water and green-water component delineated for agri-food; and (c) GHG emission footprint of FEW supply to Delhi. Energy demand is shown separately as electricity and petro-fuels, which represent cooking and transportation fuels (including use-phase combustion and production-related GHGs).

Analysis of in-boundary FEW nexus: Figure 2-7 (Table 2-6), illustrates the in-boundary cross-sectoral interactions occurring among FEW sectors within Delhi. Food-related activities (ranging from cooking to urban agriculture), that contributed 25% of Delhi's total direct water withdrawal and 15% of Delhi's direct energy needs, are prominent within the boundary. Thus, focusing on food-related efficiencies within Delhi can therefore pay dual dividends in terms of water and energy.

The pie charts in Figure 2-7 depict the sub-sector activities and help identify those with the greatest potential for future impact. For example, 90% of energy for food is dominated by household and commercial food preparation, indicating that cooking fuel interventions can be important for GHG mitigation at the FEW nexus within cities. In terms of water, urban agriculture contributes 86% of water withdrawal, suggesting value in exploring the application of water efficient vertical agriculture technologies (Specht *et al* 2014) to mitigate Delhi’s current groundwater overdrafts (Suhag 2016). In contrast, the energy impact of water services is <1%, suggesting that developing a more water-equitable city (providing basic sewerage and wastewater treatment to the 34% of the population not presently served (DES 2013b) will have minimal impact on city-wide energy use.

Figure 2-5 | Analysis of Delhi's agri-food (F) demand, disaggregated by food types. (a) Percentage of demand (by mass) produced locally (b) GHG emissions footprint of agri-food supply and water consumptive loss footprint of agri-food supply.



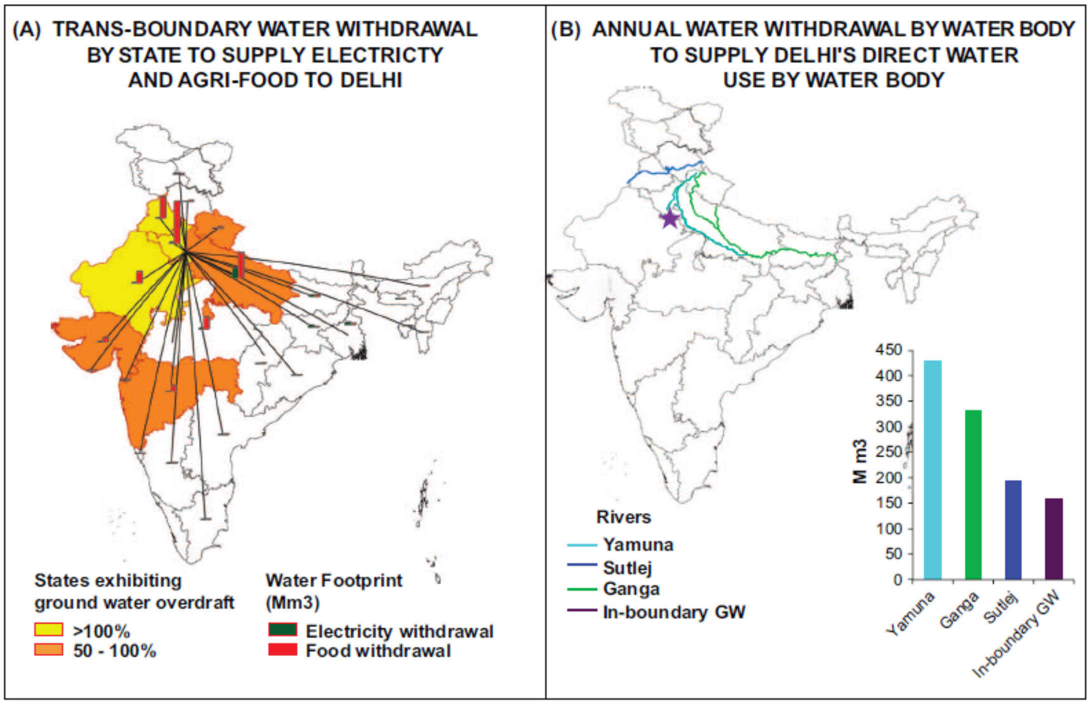


Figure 2-6 | Visualizing supply chain risk to Delhi's FEW supply: (a) Trans-boundary water withdrawal by state to support Delhi's electricity and agri-food supply; and (b) water withdrawal volume by water body (river) supplying Delhi's direct water use for direct water use, versus local ground water withdrawal (shown as a star). This provides a beginning framework to visualize Delhi's supply chain risk from climate constraints.

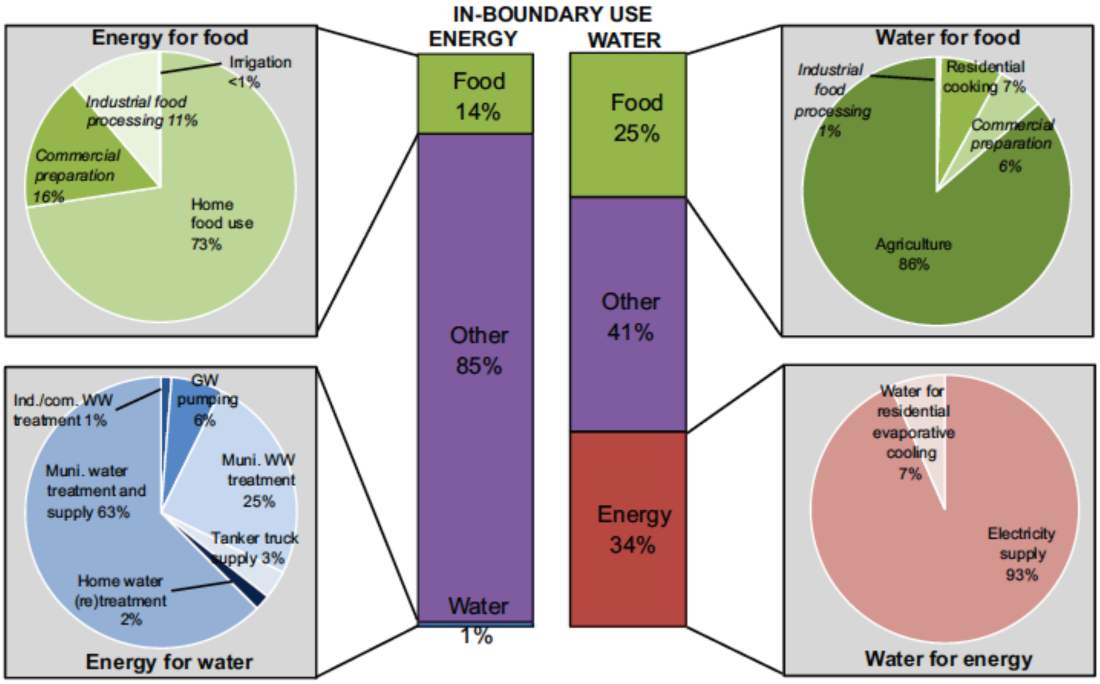


Figure 2-7 | Analysis of in-boundary FEW interactions in Delhi, India. Bar charts show the total direct community-wide water and energy demand of Delhi. Pie charts show the total direct water and energy demand of Delhi attributable to FEW related activities. The following four interactions are shown: (energy for water; water for food; energy for water; energy for food). The conversion of food and wastewater to energy is minimal in Delhi and hence not shown. Italics indicate interactions with data gaps, estimated via national benchmarks. Water demand is shown in terms of withdrawal. Consumptive water use is included in the supplementary results (Ind. = Industrial; Com = Commercial; WW = Wastewater; Muni. = Municipal).

A sensitivity analysis was conducted to identify if the dominant in-boundary interactions change significantly based on uncertainty of the input parameters. The analysis identified energy/water intensities of commercial food preparation, and possible efficiencies realized by food waste to energy conversion, as areas where more data are needed in Delhi (see Detailed Methods).

Taken together, as shown in Figure 2-8, the combined results of Figures 2-4 through 2-7 provide the baseline against which to evaluate the impact of future actions, including those initiated within the city or beyond its boundaries.

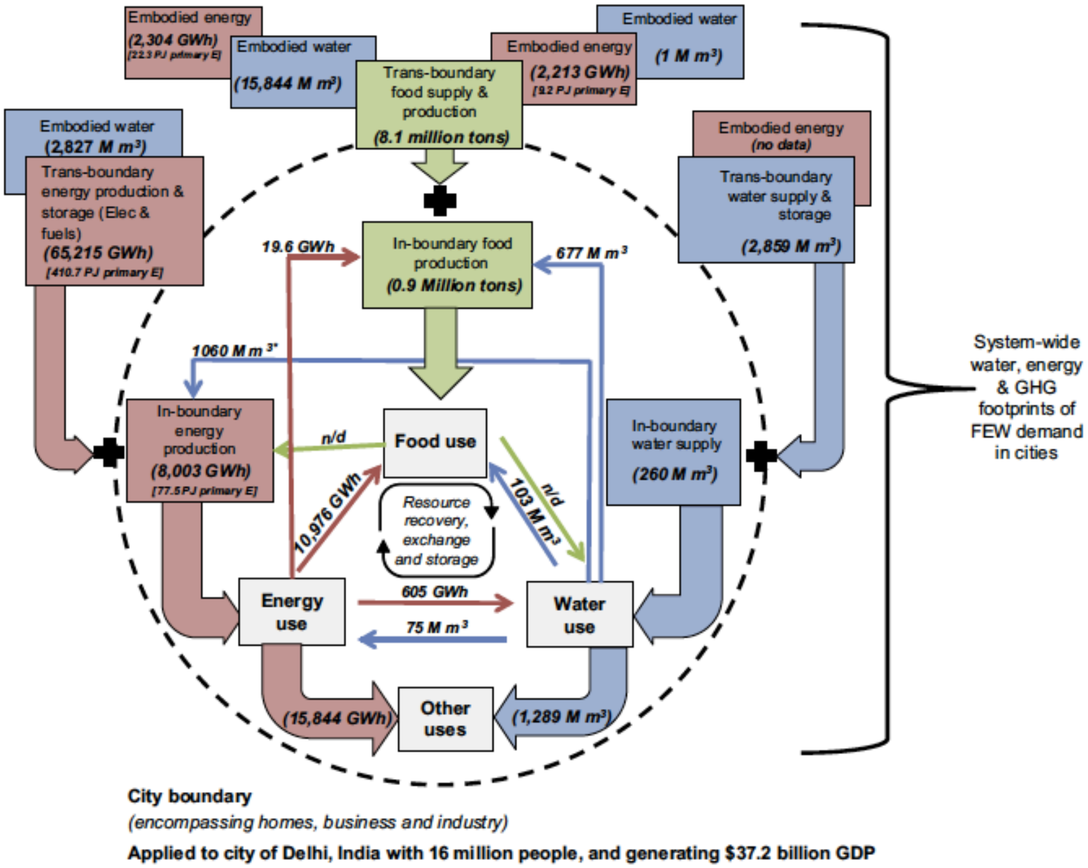
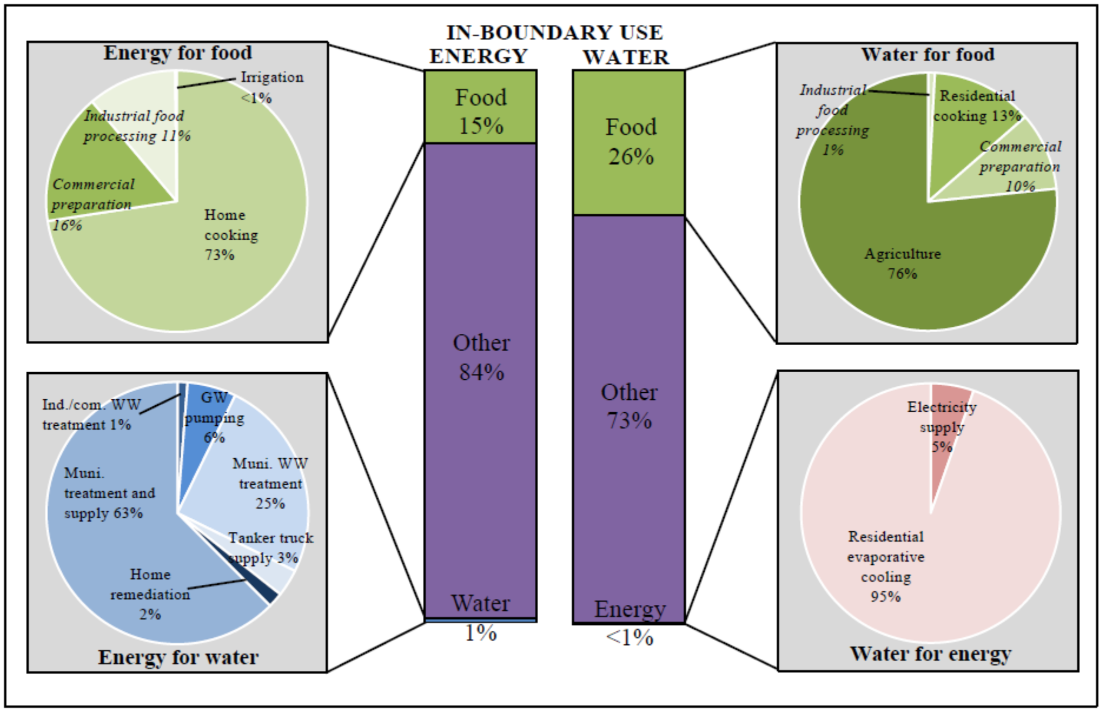


Figure 2-8| Energy and water use (withdrawal) associated with FEW supply to Delhi, delineated along the trans-boundary supply chains and within city interactions.

SUPPLEMENTAL RESULTS

Figure 2-9 | (Modified Figure 2-7 from main results). Analysis of in-boundary FEW interactions in Delhi, India. Bar charts show the total direct community-wide water and energy demand of Delhi. Pie charts show the total water and energy demand of Delhi attributable to FEW related activities. The following four interactions are shown: (energy for water; water for food; energy for water; energy for food). The conversion of food and wastewater to energy is minimal in Delhi and hence not shown. Italics indicate interactions with data gaps, estimated via national benchmarks. Water demand is shown in terms of consumptive use. (Ind. = Industrial; Com = Commercial; WW = Wastewater; Muni. = Municipal);
(See Table 2-6)



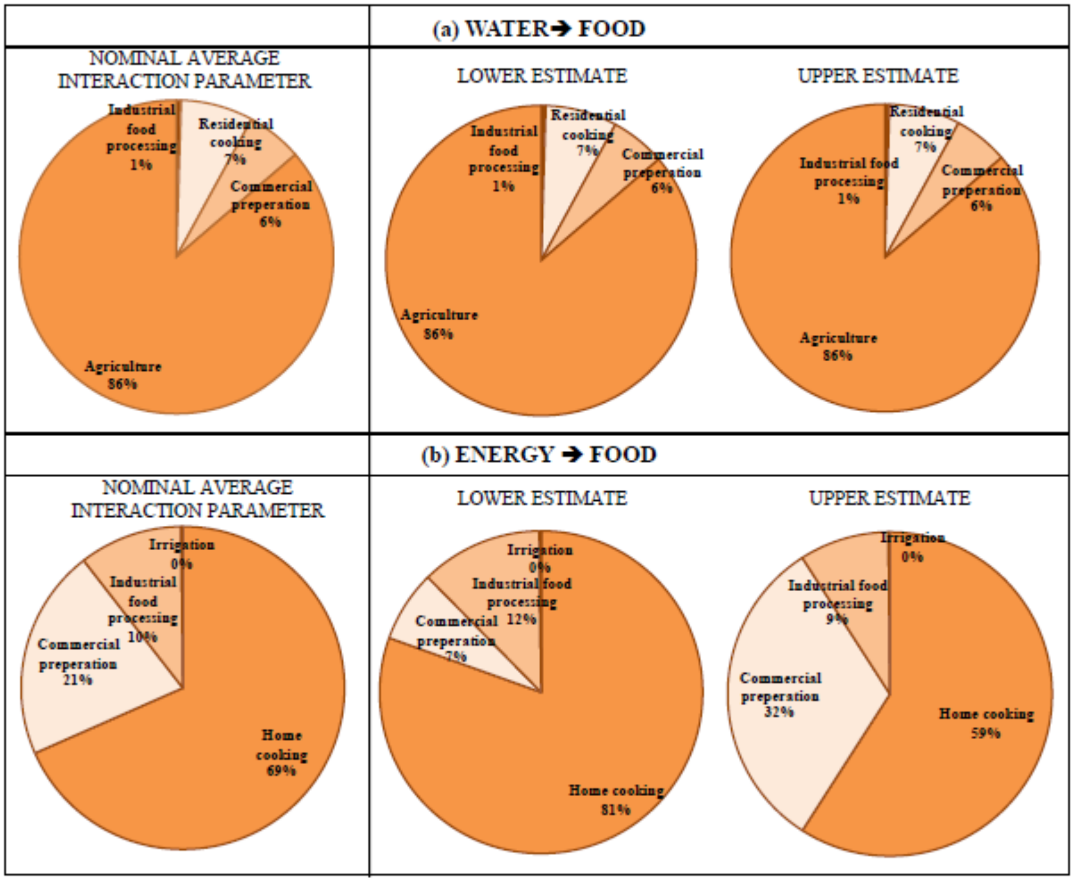


Figure 2-10 | Sensitivity of in-boundary nexus interactions to range of intensity factors: (a) Water inputs to food-related activities within Delhi shows low sensitivity to variation. (b) Energy inputs to food-related activities shows high sensitivity to variation in interaction parameter related to energy intensity of commercial food prep.

DISCUSSION

This paper has advanced methods and datasets to assess the FEW nexus from an urban systems perspective. The method combines community-wide FEW demand of cities with spatially detailed coupled water, energy/GHG footprints of FEW production (within or outside the city), as well as cross sectoral interactions within the city boundary. Key recommendations on methodology include:

<u>Community-wide food demand</u> analysis must consider homes and visitors, as well as, food related businesses and industries within city boundaries. Delineating household consumption by SES and by food items is valuable; data on visitors and food-related

commercial- industrial establishments are sparse, yet essential to address the urban FEW nexus.

Freight data provide rich detail on spatial distribution of food supply chains to cities. This allows specific areas of production outside the city to be linked to food use within the city, enabling consideration of diverse actors and policies across scales which shape the FEW nexus. Spatially delineated supply chains also make visible the climate and water vulnerable locations that serve a city's FEW demand.

Spatially disaggregated supply chains enable spatially-resolved water and energy/GHG intensity factors associated with food and energy production to be included in coupled water-energy-GHG footprints of community-wide FEW supply. This is essential to assess the FEW nexus outside of the city boundary, incorporating the wide variation in energy and water intensities among the different food producing regions. Demonstrated for India, the gross average electricity needed for crops varies from 21 kWh to > 500 kWh per ton, with the higher electricity requirements in states with a high degree of groundwater overdrafts. We also find milk, rice, wheat and pulses to be agri-foods where improved production technologies, practices and policies or diet shifts can have large impacts.

In-boundary analysis of cross-sectoral FEW interactions requires vast and diverse datasets covering energy-food, water-food, energy-water, and water-energy interactions. Among these, urban agriculture and cooking fuels use within the city emerged as dominant interactions within Delhi that shaped water and energy for food, respectively. Other in-boundary interactions such as food-waste-to-energy and energy intensities of food related industries in Delhi were identified as data gaps with large potential benefits.
Visualizing supply chain data shows a majority of embodied water for FEW supply are from locations already highly water vulnerable due to groundwater overdraft, suggesting potential supply chain risk.

Applying the multi-scale, multi-sector, multi-impact FEW analysis framework in Delhi, India enables assessment of system dynamic interactions among all four key action categories noted above. In this paper, the implementation has focused on water (blue, green, consumptive-loss and withdrawal), energy, and GHG impacts. Future work can incorporate land and nutrient impacts as well as impacts on livelihoods and equity along the supply chains. More spatial detail on Indian agriculture and power generation, and seasonal variation in water intensity factors, would add further value. The framework provides a baseline "big picture view" on which scale (in-boundary versus trans-boundary), sectors, crops and technologies shape the present-day environmental impact of FEW supply to cities. Household diets and behaviors, city policy actions as well as national agriculture, energy, and water polices, and emerging transformative technologies such as vertical farming (Specht *et al* 2014) or food waste to energy (Levis and Barlaz 2011), can potentially improve sustainability of the FEW nexus; a quantitative framework for analyses of all these actions together is presented herein. The framework enables the role of different actions at different scales and the tradeoffs among impacts to be quantified, essential for local and global sustainability.

ACKNOWLEDGEMENTS

This work was supported by a grant from the National Science Foundation: Partnership in International Research and Education (grant number PIRE-1243525). AR developed the coupled GHG-water footprint concept for FEW supply, designed the overall framework, methods and graphics; DB, AF implemented the water footprints of FEW supply, DB analyzed FEW supply chain data and connected all datasets together. ASN, AF, DB contributed the GHG footprints, identified key datasets, and conducted energy supply chain analysis. SB and BB contributed water footprinting data for India. EC contributed background methods and information on electricity supply chains and ARG supported data gathering in Delhi. AR & DB wrote the major portions of the paper. We thank Mr. Jatin Sarkar for providing the freight database to assess food flows in this paper.

CHAPTER 3 | What is the contribution of city-scale actions to the overall food system's environmental impacts? Assessing water, GHG, and land impacts of future urban food scenarios

This work has been published in the journal Environmental Science and Technology as:

Boyer D and Ramaswami A 2017 What Is the Contribution of City-Scale Actions to the Overall Food System's Environmental Impacts?: Assessing Water, Greenhouse Gas, and Land Impacts of Future Urban Food Scenarios *Environ. Sci. Technol.*

Author contributions: Boyer wrote manuscript and completed all analysis, Ramaswami provided overall guidance and high level comments

INTRODUCTION

The global food supply is heavily dependent on energy, water, and land resources. Seventy to 85% of global consumptive water loss is attributed to food production, with 19-29% of global greenhouse gas (GHG) emissions emitted from food system activities spanning production through consumption (Gleick 2003, Vermeulen *et al* 2012) Similarly, 12% of global ice-free land area is for agricultural cultivation, with a further 28% for pasture (Ramankutty *et al* 2008). With such high resource use, the environmental impact of the food system has received substantial attention at national and global scales (Bazilian *et al* 2011). Attention to these interactions from a city perspective, however, has received little attention, (Ramaswami *et al* 2017) with the important question being: the extent to which city-scale actions shape the larger food system's environmental impact, particularly in terms of GHG, water, and land.

Despite historic city involvement in food system planning, (Hamilton *et al* 2014, Mok *et al* 2014, McClintock 2010) with the rise of industrialization and refrigerated freight cities became seen as lesser players in shaping the food system (Pothukuchi and Kaufman 2000)—with the food system being associated predominately with agriculture, rather than expanded to include not only production, but consumption, transport, retail and food waste management activities, acknowledging the linkages between production and demand. Recent conceptualizations of the food system that include cities as demand centers, (UNEP 2016) embed the city within the larger food system that extends well beyond the urban boundary (Ramaswami *et al* 2017).

Facilitated through programs such as the Milan Food Pact, (Milan Urban Food Policy Pact 2015) the UN FAO's Food for the Cities (FAO 2014) and C40's Food System Network, (C40 2015) the concerns of urban food systems are many and diverse. At the individual city level, municipalities have begun developing objectives and initiatives aimed at addressing a multiplicity of urban food concerns, ranging from improving nutrition, health of diet, food access/equity, environmental sustainability, management of food waste, and increasing local production (City of Vancouver 2013, The New York City Council 2010, Los Angele Food Policy Task Force 2009) With the city embedded in the larger trans-boundary food system (see Figure 3-1), city-scale food system actions are likely to create changes in the environmental impact both locally, and beyond the city boundary. City-scale food system actions are those initiatives taken by actors within the city, and could include, changes in consumer behaviors, diets and purchasing, urban production, and infrastructure changes of water, energy, and waste management that interact with the food system. Cities, however, do not yet have analytical tools to assess the extent to which city-scale food system actions affect GHG, water and land impacts through the whole of the food system. Such analysis is essential to understand how the multitude of urban food system objectives may coincide, or conflict, with concerns of environmental sustainability and resource constraints facing the food system both within, and beyond, city boundaries.

Conceptually, city-scale food system actions can be expected to have large impact on the global food system. Urban areas are expected to hold two thirds of the 2050 projected population (UN 2015) and currently responsible for substantial environmental impact, with urban energy use accounting for 75% of the global GHG emissions (Seto *et al* 2014) and large water demand (Jenerette *et al* 2006). Individual cities have also reported the embodied energy of the food supply. Denver, for example, reports food related emissions as 10% of its total community-wide infrastructure GHG emissions (Ramaswami *et al* 2008) while Delhi reports a comparably high 15% (Chavez *et al* 2012). Similarly, San Francisco reports that food accounts for 19% of total GHG emission footprint of households (Jones and Kammen 2015). A recent analysis (Goldstein *et al* 2016) of 100 cities' urban metabolism reports found that, across accounting methods, the food sector, on average, had the third largest mass and carbon flow by sector, suggesting consistently high impact of urban food use. Environmental resource-use footprinting in terms of water has also found the food sector to make large contribution (Luck *et al* 2001, Vanham and Bidoglio 2014, Zhao *et al* 2011). The embodied land of city food supply specifically has not been reported in the scientific literature in a manner disaggregated from ecological footprints, with the exception of some grey literature analyses of smaller UK cities (ESTA 2012).

Thus city-scale action could be highly impactful in shaping the overall environmental impacts of the food system on water, GHG and land. Recent advances in urban footprinting methodology by Ramaswami et al. (2017) has provided a first framework to capture both in- (i.e. transport within the city, in-boundary waste management, urban agriculture) and trans-boundary (i.e. agricultural production beyond city boundary) impacts of community-wide urban food demand on water and GHG (Ramaswami *et al* 2017). This paper builds upon that framework to incorporate land impacts to assess the nexus between water, energy and land, and focuses on conducting a scenario analysis to assess the impact of a range of city-scale actions on the overall environmental footprints of the food system.

The key question that this study asks is: ***what is the contribution of city-scale actions (i.e. actions taken within individual cities) to the overall food system's environmental impacts within, and outside, the city boundary?*** The environmental impacts of focus are water use, energy use/GHG and land. The actions include those of multiple actors within the community of consumers (households), producers, and community-wide infrastructure providers (i.e. waste managers).

Applied to Delhi, India, this study examines the actions of various diet changes, greater equity of household food consumption, increased urban agriculture, improved cooking fuel and food waste management, each of which is compared with the reference trans-boundary intervention of reducing food waste along the pre-consumer supply chain. Thus, actions occurring within the city boundary are compared with pre-consumer actions typically occurring outside of the city boundary at a first order level. It should be noted that the motivation for these city-scale actions is not solely mitigation of environmental impact, and may include other societal priorities such as improved food access, nutritional equity, and support of local food production.

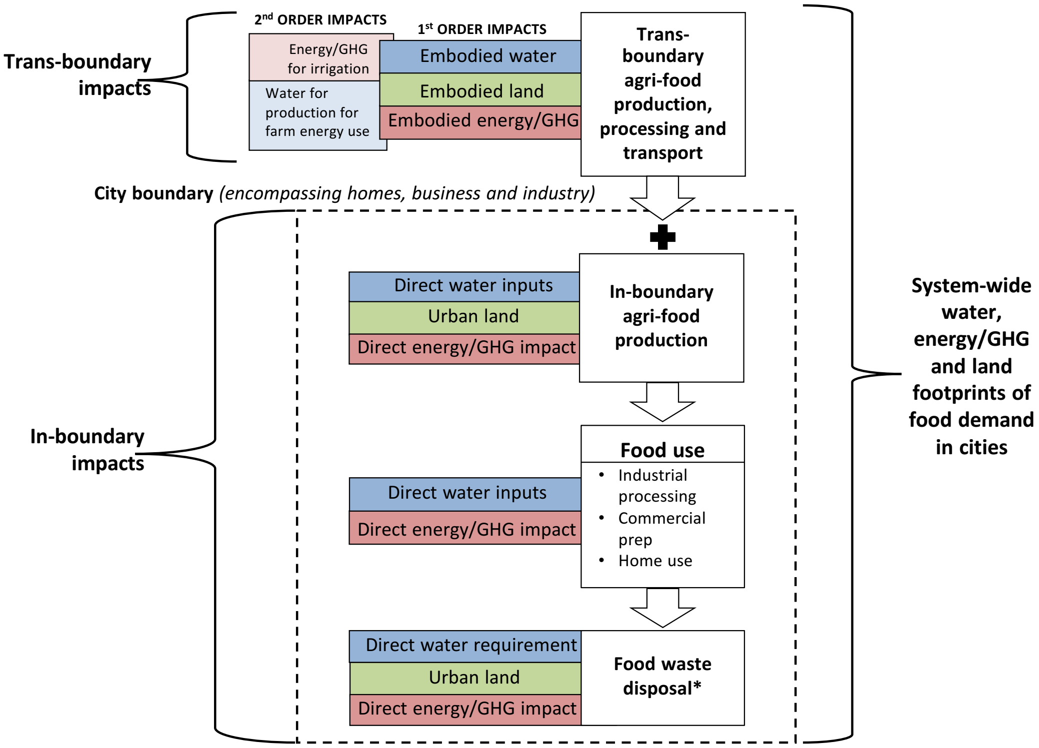
The development of the linked water-energy/GHG-land footprinting along with scenario analysis of city-scale actions is applied to Delhi, India to develop the methodology, though is generalizable to any city where the requisite data are available. Benefits of the methodology include: ability to compare the environmental impact both within, and beyond the city boundary of city-scale action against supply chain and/or production level interventions; informing of policy and action in data poor environments; determining largest city policy levers that can provide water, GHG and land benefits; and identifying instances of complementary or conflicting sustainability outcomes (i.e. equity versus multiple environmental impacts).

METHODS

Delhi (in the year 2011; population of 16.4 million) serves as a case study to develop and implement the methodology due to a uniquely large amount of food-related data in the public domain (See SI). Furthermore, the authors were successful in obtaining city food supply chain data, not readily available in many cities, allowing for use of spatially explicit resource intensity factors (Ramaswami *et al* 2017). This allows scenario assessment to determine the extent of impact that city-scale actions have on the larger food system, without the impediment of limited data.

The trans-boundary framework of community-wide food supply to a city assessing linked water-GHG/energy-land impacts is shown in Figure 3-1. This figure illustrates the different components of the food system, as they intersect with the city (illustrated by the dotted square that includes home, businesses and industries) allowing differentiation between in- versus trans-boundary impacts.

Figure 3-1 | A multi-scale, multi-sector framework to analyze environmental impact of community-wide provisioning of agri-food to homes, businesses, and industries in a city. The framework connects community-wide food demand with in-boundary and trans-boundary production showing embodied and direct water (blue), GHG/energy (red) and land (green). *Activity can occur either within or outside the city, based on individual cities.



Baseline

Total annual community-wide food use for homes, business, and industry is calculated with data first reported by Ramaswami et al. 2017) This work further expands the food use analysis, delineating use by households of different socio-economic-class (SEC), as determined by the Indian Government by monthly per capita expenditure. The authors obtained important data on all components of the food system of agricultural production (in- and outside of the city), freight transport, use (household, commercial, industrial) and food waste management. Taking such a community-wide footprinting approach (Ramaswami *et al* 2008, Lin *et al* 2015, Chavez and Ramaswami 2013) allows visualization of potentially beneficial synergies between sectors—greater potential than can be realized by looking at each sector in isolation.

India-specific water consumptive loss (blue and green) (Mekonnen and Hoekstra 2011) and GHG (Pathak et al. 2010) resource intensity factors of production literature studies were supplemented with second order impacts from spatially explicit electricity-use and diesel-use for irrigation and on farm machinery (Ramaswami *et al* 2017). Thus, the water embodied in electricity production (power plant cooling) and fuel is included in addition to water use in crop irrigation. The GHG of production does not include emissions as a result of land use change.

The land footprint of production was calculated in line with methods described by various past studies (Gerbens-Leenes *et al* 2002, Bruckner *et al* 2015) as a function of community-wide agri-food demand and crop specific yields. India-specific crop yields were obtained from FAOSTAT (FAO 2017) and Government of India reports.(Government of India Ministry of Agriculture 2011, Government of India Directorate of Economics and Statistics Department of Agriculture and Cooperation 2012) International agri-food imports are relatively small for India, and verified with Delhi's food supply chain data (Hoff *et al* 2014). Potential uncertainties include knowledge of multi-cropping and lack of country specific animal land area requirements, further discussed in the SI. However, most land-footprinting estimates in the literature face similar constraints (Bruckner *et al* 2015).

Methods for determining resource impact of freight transport, use (home use, commercial preparation, industrial processing), and food waste management (solid and waste water) are detailed in the SI.

Scenario analysis

The scenario analysis quantifies changes in the annual GHG, water and land footprints of Delhi's community-wide food demand from the baseline case, with several city-scale food system actions, motivated by a variety of goals described below and summarized in Table 1. Detailed methods for each scenario are included in the SI.

(a) City equity & health scenario action: Addressing hunger and food security is an explicit objective of the Sustainable Development Goals (United Nations 2015). This is particularly relevant in India, a country home to nearly 25% of the world's undernourished population (WFP 2016) In Delhi's baseline case specifically, the top 5% of the population consumes 2.5 times by mass the quantity of food consumed by the lowest 5%. Similarly, the highest 5% consumes much greater quantities of fruits and vegetables than the lowest 5%, resulting in greater dietary diversity (92 kg versus 46 kg per capita per year) (Ramaswami *et al* 2017). This scenario therefore assesses the resulting impact of the lower 50% of the population by SEC consuming the same diet as the median SEC population—a diet deemed sufficient in terms of calories and protein (National Institute of Nutrition 2009).

(b, c, d, e) City diet change scenario action: Much research exists to recommend "sustainable diets"—i.e. a diet that meets the nutritional needs of the population while minimizing environmental impact (Nelson *et al* 2016, Duchin 2005). This research, however, generally speaks only to the Western context, assuming a high baseline meat and dairy consumption and availability of alternatives (Audsley *et al* 2009, Garnett 2014). Applicability of these recommendations is questionable in developing country

settings, with a research need to examine “sustainable diet” shifts in developing countries, conscious of local food system conditions and limitations (Garnett 2014). A decrease in rice consumption is of potential interest in the Indian context due to: a) in-country concern over high white rice consumption linked to diabetes (Hu *et al* 2012); b) rice’s large environmental impact (Pathak et al. 2010); and c) available alternatives within the Delhi context (wheat, sorghum, millet). Actions in the diet change scenarios therefore explore the impact of a 100% shift from rice to wheat, sorghum, and millet, on a calorie-to-calories basis. A shift from meat to pulses is also assessed to provide quantitative comparison with North American and European analyses.

(f, g, h) Urban agriculture scenario action: Urban agriculture is promoted globally for a variety of reasons ranging from various environmental benefits to mitigation of urban malnutrition and livelihood generation (Hamilton *et al* 2014, Mok *et al* 2014). Benefits are claimed for both conventional (soil-based) farming methods and vertical technology (VFT) (i.e. hydroponics, aero-ponics). VFT, in particular, is promoted for high water savings and its independence from land/soil quality (Kozai 2013, Despommier 2013). VFT has received some attention in India, (Sanye-Mengual *et al* 2015, Assocation for Vertical Farming 2016) where water scarcity and land degradation can present a challenge for conventional production methods. While types of urban agriculture vary greatly (i.e. community gardens v. residential plots v. rooftop etc.), In Delhi, urban agriculture currently takes the form of large agricultural lands along the Yamuna River cutting through the middles of the city. Three urban agriculture scenario actions therefore assess: 1) a doubling of current soil-based urban practices (some fruits, vegetables, milk, grains); 2) conversion of current in-boundary agriculture production to VFT (without any increase in production quantity); and 3) conversion of all viable crops within the whole of Delhi’s food supply (in- and trans-boundary) to VFT, to be grown within Delhi.

(i) City food preparation scenario action: Fumes of dirty cooking fuels, (i.e. firewood and cow dung) have large impact on human health, causing respiratory issues, particularly for women and children (Parikh 2011, Foell *et al* 2011). In Delhi, 22% of household cooking energy is provided by dirty fuels, with use concentrated in the lower

SECs (Ministry of Statistics and Programme Implementation 2011). Thus the Government of India provides household subsidies to allow greater access of liquefied petroleum gas (LPG) as a cleaner alternative (Ministry of Petroleum and Natural Gas 2016). This scenario therefore determines the impact of a shift of all current dirty household cooking fuels to LPG.

(j, k) City food waste management scenario action: While India is estimated to have lesser consumer level food waste than developed countries, organic kitchen scraps contribute over 50% of total municipal solid waste generated and 80% of household waste (Annepu 2012, Nagpure *et al* 2015). This results in accumulation of food waste on the streets, in landfills and associated methane emissions. This scenario action explores the impact change with alternative food waste management options of: j) composting and k) anaerobic digestion (AD), (Adhikari *et al* 2006) producing organic fertilizer and in the case of AD, electricity generation. Land change of this scenario was not assessed due to data limitation.

l) Trans-boundary reference scenario action: Pre-consumer food waste is a particular problem in India due to poor food transport and storage infrastructure, such as lack of refrigeration (Halder and Pati 2011, Joshi *et al* 2009, Bräutigam *et al* 2014). This provides much scope for waste reduction along the supply prior to the city boundary, estimated as high as 40-50% in developing countries (Gustavsson *et al* 2011). This scenario analyzes the impact if the percentage of pre-consumer food waste is decreased to levels of international best practice. This scenario provides a point of comparison of how a lever outside of the city boundary compares with that of city-scale actions.

If the impact of city-scale actions ((a) through (k)) rival those of trans-boundary reduction of agri-food waste (action l), it is of high significance, indicating the role a city can play in shaping the larger food system.

Table 3-1 | Summary of city-scale scenario actions to be analyzed for change of water, GHG and land impacts.

Category	Scenario
City equity & health **(a)**	**a.** Lower 50% of the population by socio-economic-class (SEC) consuming same diet as median SEC population (deemed sufficient in terms of calories and protein)
City diet change **(b, c, d, e)**	**b.** 100% rice calories to wheat
	c. 100% rice calories to sorghum
	d. 100% rice calories to millet
	e. 100% meat calories to pulses
Urban agriculture **(f, g, h)**	**f.** Doubling of current urban agriculture production
	g. Shift of all viable in-boundary production to VFT (holding production levels constant)
	h. Shift of all viable crops to VFT (to be grown in Delhi)
City food preparation **(i)**	**i.** Conversion of all cooking fuels in Delhi to LPG
City food waste management **(j, k)**	**j.** All household organics to composting
	k. All household organics to anaerobic digestion
Trans-boundary reference scenario: Pre-consumer food waste **(l)**	**l.** Decrease of pre-consumer food waste to international best practice

DETAILED METHODS

Baseline analysis: water, greenhouse gas emissions, land

Production

The baseline water, GHG and land footprints of production were determined by multiplying the quantities of community-wide food use by crop-specific resources intensity factors. This work makes use of India specific GHG intensity factors, (Pathak *et al* 2010) supplementing with Southeast Asia values when necessary (Doublet and Jungbluth 2010, Yuttitham *et al* 2011). The production GHG intensity values provided for India, (Pathak *et al* 2010) however, did not include GHG emissions from farm equipment nor emissions from electricity and diesel use for the pumping of groundwater irrigation. This study expands on these values(Pathak *et al* 2010) by supplementing with state specific on-farm emissions from farming equipment and groundwater irrigation, referred to in this paper as "2nd order emissions," as first described in Ramaswami et al. 2017. GHG from land use change is not included.

India specific consumptive water loss intensity factors for blue and green water were sourced from Mekonnen and Hoekstra (2011), reported per ton of crop (Mekonnen and Hoekstra 2011).

The land requirements are reported by both the India Ministry of Agriculture (Government of India Ministry of Agriculture 2011) and FAOSTAT's (FAO 2017) reporting of per crop yields for 2011, the year of study. Land footprinting was carried out in accordance with the methods of prior food land footprinting studies (Gerbens-Leenes *et al* 2002, Bruckner *et al* 2015). The authors acknowledge uncertainties regarding potential multi-cropping (multiple crops occupying the same land) and limited data on India-specific animal land requirements. Yet as noted by others (Bruckner *et al* 2015) this is a common uncertainty involved in land footprinting studies. A recent review of land footprinting studies, for example, noted that only three of 41 studies attempted to factor in the impact of multi-cropping and fallow (Bruckner *et al* 2015).

Transport

Supply chain data is reported by the Total Transportation System Study on Traffic Flows and Modal Costs, commissioned by the GOI Planning Commission (2011). The authors traveled to Delhi to obtain data informing the report of specific Delhi supply chain data. This includes all agri-food products entering Delhi and their points of origin.(Planning Commission 2008) This allowed calculation of GHG emissions associated with food transport, multiplying distance by average truck size from in-person observation in Delhi, and India-specific fuel economy (Nesamani 2009) with diesel GHG emissions factors (IPCC 2006) 749,959 t CO2 e is attributed to freight transport. Within Delhi, transport was unable to be calculated due to lack of available data.

Use

Food use within Delhi includes residential use, commercial preparation, and industrial processing. Each activity is described below, with the calculation of energy/GHG and water requirements. Chapter 2 Table 2-6 summarizes the intensity factors and activity parameter for scale up.

Food waste management

Solid food waste

The average annual per capita wastage generation across SECs is reported as 120 kg (Nagpure *et al* 2015). Multiplied by Delhi's population and the reported proportion of total waste as food organics, provides the total quantity of household food waste generated in Delhi annually as 1.5 million tons of food waste. Adjusted for 9% of waste currently composted (Talyan *et al* 2008) and verified against landfill composition reports (Annepu 2012) this quantity is multiplied by the methane emissions factor for landfilled food waste of 0.699 kg CH_4/kg (Aye and Widjaya 2006) to provide an annual baseline emissions of 1,050,381 t CO_2e.

Waste water

The quantity of untreated waste water for Delhi is reported by the Ministry of Urban Development as 339,633 million L per year (Chavez *et al* 2012). Reported emissions factors for nitrous oxide and methane release from untreated wastewater are 298 kg CO_2 e/mil L and 244 kg CO_2 e/mil L, respectively (Chavez *et al* 2012). This results in 184,081 t CO_2 e emitted from the quantity of untreated waste water in the baseline scenario.

Scenario analysis

The follow section details the methods used to analyze each of the scenarios described in the main text, (see Table 3-1).

(a) City equity & health

The equity scenario (a) forecasts how diets might change in response to rising incomes and improved nutritional access. The scenario assesses the resulting resource impact if the bottom 50% of Delhi's population by SEC consumes the same diet as that of the median SEC. The diets of those consuming at, or above the median SEC, are held constant. Diet by SEC was determined by the GOI National Sample Survey including 937 observations within Delhi (MSPI 2011) The diet of the median class was compared with dietary recommendations as set by the Indian National Institute of Nutrition, to determine that this median diet falls within the recommended range of daily intake of both calories and protein (National Institute of Nutrition 2009).

(b, c, d, e) City diet change

Wheat, sorghum, and millet serve as the rice alternatives due to their relatively lesser GHG emissions, availability within Delhi, and ability to serve as a culinary replacement to rice. While milk also stands out as a large contributor to GHG, water, and land, it poses a challenge to address. Approximately 15% of total calorie intake and over 20% of protein calories on average come from dairy products, with no real substitutes available for the function of milk in Indian cuisine. Diet change scenarios are only realistic with the availability of a suitable replacement food item. Therefore, promoting reduction of milk is not a reasonable scenario to pursue in a location whose population exhibits such high under nutrition. The small contribution of meat to the total water and GHG footprints suggests that a meat reduction scenario would have limited aggregate impact. However, a meat reduction scenario is conducted nonetheless, to provide a concrete comparison to existing Western studies. Furthermore, unlike milk, protein alternatives to meat do exist, with pulses chosen as the replacement food grouping in this case.

(b) *Rice to wheat* - Entirety of annual rice consumption converted to wheat on a calorie-for-calorie basis.
(c) *Rice to millet* - Entirety of annual rice consumption converted to millet on a calorie-for-calorie basis.

(d) *Rice to sorghum* - Entirety of annual rice consumption converted to sorghum on a calorie-for-calorie basis.

(e) *Meat to pulses* - All meat calories converted on a calorie-for-calorie basis to pulses, consistent with the pulse type (arhar, besan, gram, masur, moong, urd) distribution of the current diet.

(f, g, h) Urban agriculture

(f) *Increase of conventional urban agriculture*: This scenario examines the impact change that would be associated with a 100% increase of urban agriculture in Delhi, holding crop types constant from current production levels. The scenario assumes that the crops produced would be replacing that of incoming quantities, shifting water, GHG and land impacts from trans- to in-boundary and eliminating GHG emissions associated with trans-boundary freight transport. Lacking any additional data, it is further assumed that the urban agriculture production practices would have the same water, GHG and land intensity factors as conventional soil-based farming practices.

(g, h) *Vertical farming technology*: From a technical stand point, all crops can be grown with soilless techniques. In reality, however, only a small subset tends to be grown, that of smaller, more compact plants, with quicker harvest periods—shown to be the most economically viable in the current agricultural system (Kozai 2013). This includes small fruiting plants (tomatoes, strawberries, etc.), leafy greens (microgreens, lettuce etc.) and some tubers (carrots, potatoes) (Specht *et al* 2014). Typically excluded are larger, slower growing plants such as and tree crops (oranges, apples etc.) and crops able to store for longer periods, namely grains (rice and wheat) (Yamori *et al* 2014). Therefore, in the case of the VFT scenarios, non-tree fruits and vegetables were considered "viable." All the remaining food items were assumed to be produced with current soil-based methods. The quantity, crop type, and location of production (in- versus trans-boundary) were also held constant.

Estimating the water and energy/GHG intensity factors of vertical farming growing techniques posed a significant challenge. As an emerging technology, there have been very few LCA studies assessing the water and energy/GHG intensity of crop production with VFT (Specht *et al* 2014). A recent review of agriculture-building integration discovered only 19 peer-reviewed articles at all addressing the topic of vertical farming (this also included rooftop soil-based farming), with even fewer addressing resource use intensity (Specht *et al* 2014b). The few that have been conducted make evident the context specificity of resource intensity use (Sanye-Mengual *et al* 2015, Mok *et al* 2014, Marris 2010). Particularly for energy/GHG, the variables of determination are many, including ambient temperature, natural lighting, degree of technological control, indoor versus outdoor setting, building materials, and technology employed. Generally, VFT on a crop weight comparison is considered more energy intensive than that of conventional methods. Assessing trade-offs between conventional field versus VFT methods presents a substantial challenge and thus GHG/energy was excluded from this scenario analysis.

VFT water intensity is more generalized in the literature than that of energy/GHGs. While water requirement is also context variable, the figure of a 70% reduction from conventional field methods across all crop types tends is commonly referenced as a conservative estimate (Despommier 2010, International Water Management Institute 2007, Despommier 2013). Others list a reduction of even greater savings such as a 2015 study (Barbosa *et al* 2015) reporting of 92% water use reduction of hydroponic lettuce versus conventional methods, while others report as high as 80% reduction (Linsley and Caplow 2008). Thus, lacking water intensity figures at any greater detail, a 70% reduction in water requirement from the baseline India-specific field water requirement (Mekonnen and Hoekstra 2011) was assumed, with the potential range reflected in the error bars of the calculation (Figure 5 of main text).

Scenario (g) applies vertical farming technologies to viable crops already being grown within Delhi, with scenario (h) applying the technologies to all viable crops, irrespective of in- versus trans-boundary production location.

(i) City food preparation

Current fuel use by SEC is provided by the GOI National Sample Survey, (Ministry of Statistics and Programme Implementation 2011) distributed by fuel types of coal, firewood, LPG, dung cake and kerosene, scaled by Delhi's population. The CO_2 emissions factors per kg of fuel were sourced from literature (Murthy and D'Sa 2004). All non-LPG fuels were traded in favor of LPG on a kWh per kWh basis with the energy intensity per mass of fuel.

(i) City food preparation

GHG reduction is calculated as the difference between baseline food waste management practices (street dumping and landfilling) and management with composting and AD methods. Lacking Delhi, or even India, specific AD and composting LCAs, a literature review was conducted to determine suitable composting and AD GHG emissions factors. Studies were sourced from Bernstad Saraiva Schott et al.'s (2016) study of 19 AD and composting studies (Bernstad Saraiva Schott *et al* 2016). Emission factors were sourced from Aye and Widjaya (2006) study of waste management alternatives in Jakarta, Indonesia, as the most similar of country context to India (most other studies were conducted with North American and European assumptions). This study reported a composting range of 39 to 40.5 kg CO2e/t waste depending on the system and an AD value of -54.4 kg CO2e/t waste. The LCA study includes transport emissions, process emissions, fertilizer offset credits, and energy offset credits (in the case of AD). The AD EF was calculated based on an electricity replacement credit in Indonesia. However, this value was not disaggregated from the total EF so was not able to be adjusted to Delhi's electricity and fuel mix, posing a point of uncertainty. The uncertainty value was determined based on the range of EF values reported from the studies included in Bernstad Saraiva Schott et al.'s (2016) review.

The calculation of the GHG reduction is described by Equation (1).

$$Food\ waste\ GHG\ reduction_{composted\ foodwaste,AD\ foodwaste} = (HH\ foodwaste\ diverted\ from\ landfill) \times (EF\ landfill\ foodwaste) - (HH\ foodwaste\ diverted\ from\ landfill) \times \left(EF_{composted\ foodwaste,AD foodwaste}\right) \quad \text{(S-2)}$$

Both composting and anaerobic digestion processes require a specific water content. Wet anaerobic digestion requires a solids content of 10-20%, with an average 15% assumed for this calculation (Angelonidi and Smith 2015). Food waste, on average, is estimated on average to have about 25% solids content (Lee *et al* 2007). Therefore, every ton of food waste requires an additional 667 kg of water (approximately 0.667 m^3 water). Multiplying this figure by the total composted waste provides the additional water burden of these processes. This is in comparison to a dry system, (particularly popular in Europe) would require little to no additional water inputs (Cho *et al* 2013). Wet digestion was assumed in order to provide a conservative estimate of additional water requirement.

Composting requires no additional water inputs as the natural water composition of food waste of 75% (Lee *et al* 2007) falls within the range of acceptable water content (Makan *et al* 2014).

(l) Trans-boundary scenario: pre-consumer wastage reduction

A literature review determined India-specific farm to consumer food wastage factors to understand the current state of food waste in India. This included study of specific food items, tracking loss along the supply chain, as well as aggregate food wastage factors. The findings of individual food items are displayed in Table 3-2.

Table 3-2 | Review of India specific bottom up food waste studies.

Food type	**Item**	**Pre-consumer waste by stage** (% loss of total harvest)					**Data source**
		Farm	**Wholesale**	**Processing**	**Retail**	**TOTAL**	
Grain	Rice	3.8	0.3	0.03	1.1	5.2	(Basavaraja *et al* 2007)
	Wheat	3.3	0.2	0.03	0.8	4.3	
Vegetable	Tomato					32.6	(Gauraha, AK Thakur 2008)
		8.6	6.4		0.1	15.2	(Sharma and Singh 2011)
	Pea	5.9	3.7		0.4	10.1	
	Potato	4.9	0		2	6.9	
	French bean	4.7	5.9		0.5	11.1	
	Cauliflower	4.2	2.5		1.6	8.3	
	Cabbage	3.1	1.0		1.2	5.3	
	Chilly	4.8	4.6		0.5	9.9	
	Radish	3.9	0			3.9	
	Capsicum	2.8	1.8			4.6	
	Okra	7.6	0.9			8.5	
	Eggplant	10.5	0.5			11	
	Onion	4.8	0		1.2	6.0 - 13.8	
						13.8	(Basavaraja *et al* 2007)
	Potato	6.2	1.85		2.36	10.4	(Kumar *et al* 2006)
	Mango	15.6	8.89		5.25	29.7	(Murthy *et al* 2009)
Fruit	Grapes	7.31	4.21-10.8		2.9 - 3.2	14.4 - 21.3	
	Banana	5.5 - 7.8	1.77-6.65		8.7 - 16.7	18.3 - 28.8	
	Pomegranate	9.86	10.1		15.5	35.4	
	Mandarin	2.51	2.3			14.87	(Gangwar *et al* 2007)
Dairy	Dairy products (SEA average)					21.5	(Gustavsson *et al* 2011)
Meat	Meat, (SEA)					17	
Sugar	Sugar (Average for all of SEA)					18	(Kummu *et al* 2012)
Pulses	Chickpea					7	(Nag *et al* 2000)

Studies tracking individual crops from farm to consumer tend to provide lower estimates than the aggregate values. For instance, as an aggregated figure, waste is estimated as high as 50% for developing countries in general, (Gustavsson *et al* 2011) with India's fruit and vegetable loss reported as high as 50% (Rolle 2006). Therefore, given the acknowledged uncertainty of food waste measurement (Kummu *et al* 2012) a conservative value of 35% was chosen as the baseline wastage factor in order serve as a middle value between the crop specific and aggregate waste estimates.

Large amount of food waste in India occurs from poor supply chain infrastructure. This is in comparison with developed countries, with more sophisticated food system infrastructure (i.e. transport, post-harvest storage, refrigeration). Thus comparison of India's pre-consumer waste factors with developed countries' determined the scope of realistic improvement for the scenario. For the scenario, a value of 13% pre-consumer wastage was chosen as the international best practice (See Table 3-3).

Table 3-3 | Reported pre-consumer food waste percentages from select developed countries.

Country	**Production**	**Post-harvest handling, storage, trade**	**Processing**	**Retail**	**TOTAL**	**Source**
United States	16			8	24	(Heller and Keoleian 2014)
Switzerland	14	1	7	2	24	(Beretta *et al* 2013)
Netherlands	4-8	1-4		3-6	8-18 (13)	(Ministry of Agriculture Nature and Food Quality 2010)

Despite large uncertainty of food waste estimation, (Bräutigam *et al* 2014) this analysis still provides an approximate scope for reduction that can be compared with other in-boundary interventions.

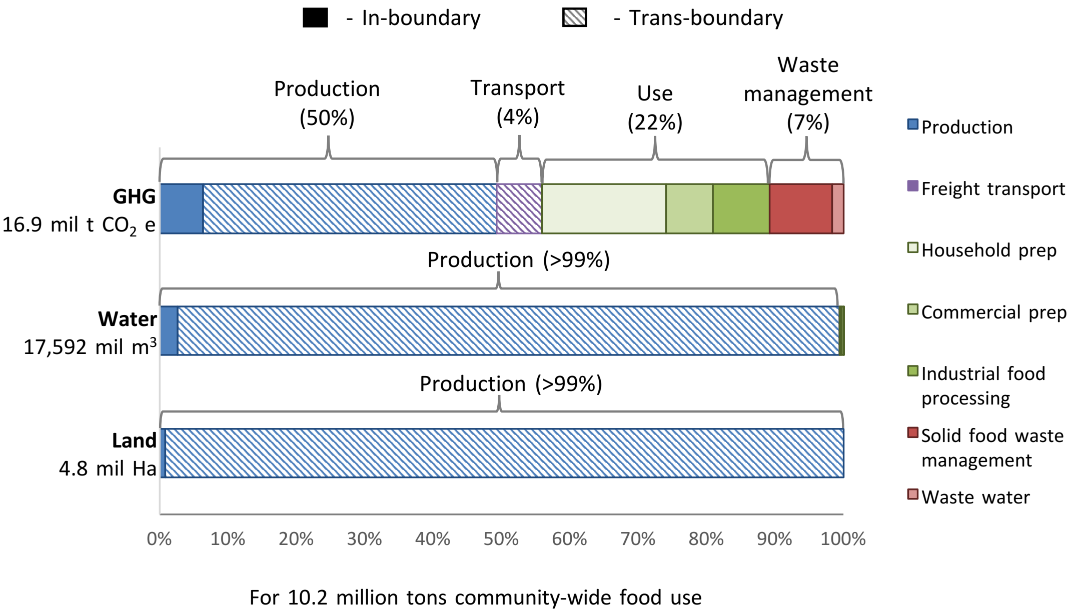
RESULTS

Baseline

1. <u>Baseline system-wide impacts</u>

Figure 3-2 illustrates the whole system-wide GHG (16.9 mil t CO_2e), water (17,592 mil m^3), and land (4.8 mil ha) impacts of Delhi's baseline food system.

Figure 3-2 | System wide impacts of Delhi's annual communit-wide food use in terms of GHGs (top), consumpitve water sloss (middle) and land (bottom). Production quanity includes trans-boundary pre-consumer waste.

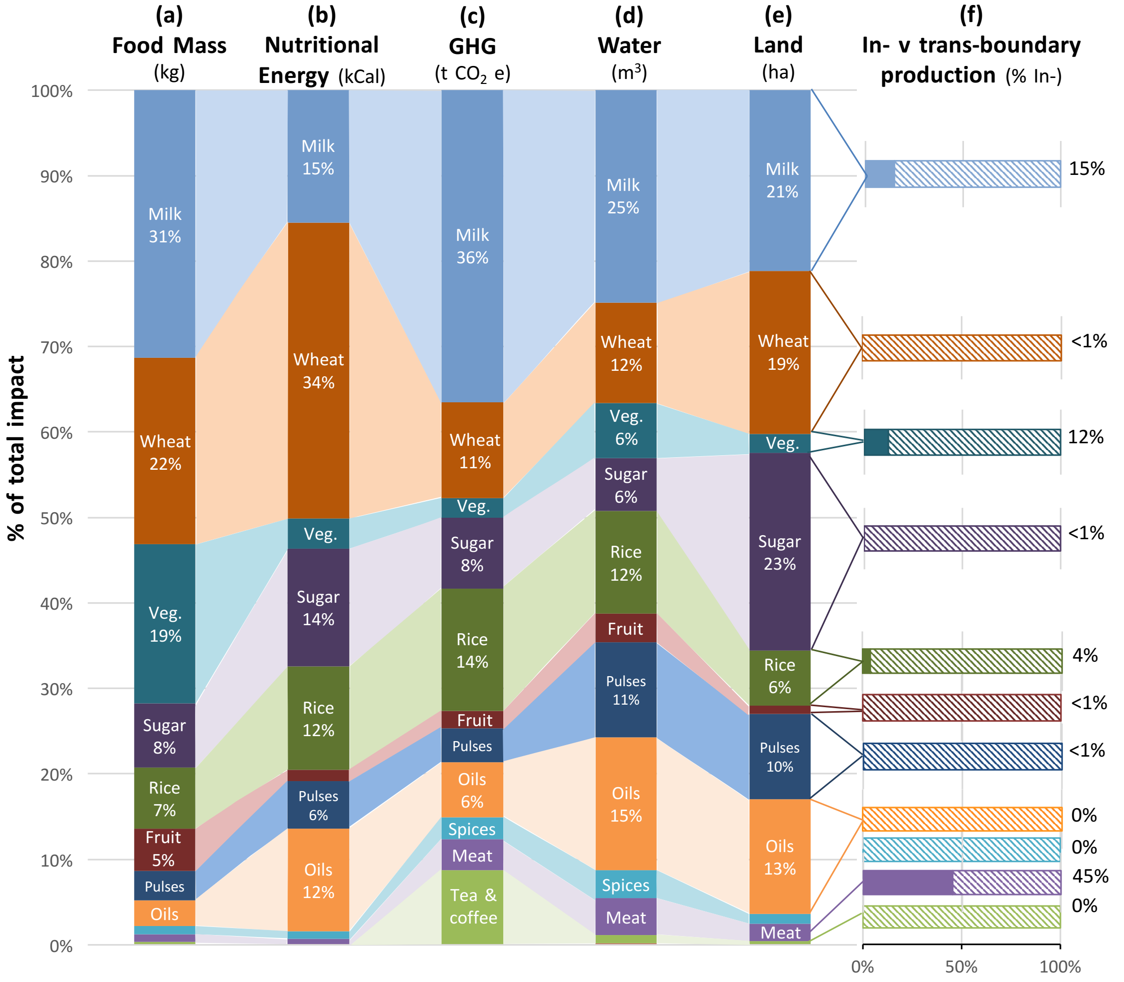


Different portions of the system are illustrated by the various colors, with the hatched bar portion signifying trans-boundary impact and the solid bar portions indicating in-boundary impact. The figure illustrates that for both water and land, total impact is dominated by the production stage (>99% for both). GHG impact exhibits a more even distribution throughout the whole of the supply chain, with only 50% attributed to the production stage, and substantial in-boundary emissions from households mainly from cooking-related emissions (12%), commercial (5%) food preparation (cooking fuel emissions), industrial processing (5%) and food waste emissions from both solid waste landfill methane emissions (6%) and liquid waste (1%).

2. *Distribution of agricultural production impacts by food types*

Figure 3 delineates the production impacts into specific food categories. The vertical bars of the figure (Figure 3-3a-e) show the percentage contribution of each food category to the total impact in terms of mass, nutritional intake, GHG, water and land by each of the respective food categories. The horizontal bars (Figure 3-3f) on the far right illustrate the percentage of each food group (and associated impact) occurring in- versus trans-boundary. This helps to demonstrate which food categories are exhibiting high impact as a result of high quantity of consumption in Delhi versus high resource requirement of production. For instance, wheat (burnt orange) contributes 34% of total calories, versus a proportionally lesser 11% of GHG impact. Milk (light blue) clearly dominates in terms of GHG, with 36% of the total environmental impact of production, with substantial contributions to the water (25%) and land (21%) production footprints as well. Meat (light purple) makes very little contribute across all footprints due to low consumption.

Figure 3-3 | Mapping the water, land and GHG impacts of production of Delhi's annual food demand. (The production phase dominates land, water, and GHG footprints). The figure illustrates the distribution of food type by a) food mass b) nutritional energy (calories) c) GHG footprint d) consumptive water loss footprint and f) distribution of these impacts as in- or trans- boundary (in = solid, trans = hatched; veg = vegetable.)



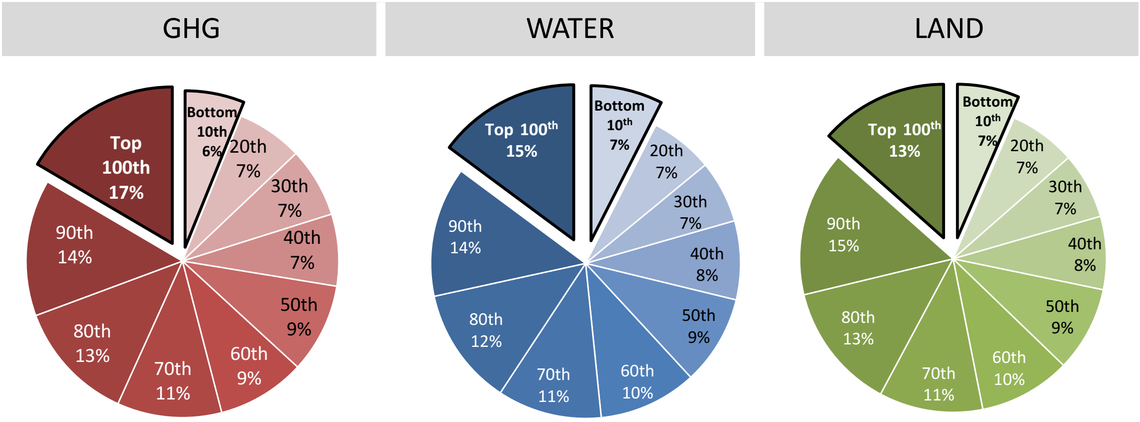
3. *Delineation of in-versus trans-boundary impact*

Figure 3-3f illustrates the in- versus trans-boundary distribution of food production by mass to meet Delhi's food demand with the horizontal bars on the right of the figure. This provides understanding into the distribution of localized versus trans-boundary impact. Currently 8% of food by mass is produced within the city, with substantial in-boundary reliance on meat and milk products, provisioning 45% and 15% of total Delhi demand and lesser contributions to rice, vegetable and fruit. Thus, while there are some levels of urban production, the majority of resource impact occurs beyond the city boundary. This baseline analysis is also important to inform reasonable localization strategies—currently one of the most commonly promoted food system interventions (Mok *et al* 2014, Hamilton *et al* 2014).

4. *Impact distribution by socio-economic class*

Figure 3-4 illustrates the large differences that exist between SECs in terms of water, GHG and land impact of food demand. Each of the pie slices represents 10% of the population, with the wedge size proportionate to the contribution of that class to the whole of Delhi's food resource impact. Thus an "equitable" society in terms of resource use would have uniformly sized slices. The lowest (5th) and highest classes (100th) are outlined to illustrate the large difference between the lowest and highest classes. For instance, in the case of GHG, the wealthiest class is responsible for 17% of the impact, while the lowest class only 6%.

Figure 3-4 | Distribution of GHG, water and land impacts of Delhi's annual food demand by socio-economic class (SEC). Each pie piece represents 10% of the population, with the pie wedge size proportional to the contribution of that class's impact. The highest (100th) and the lowest (10th) are outlined in red to illustrate difference in impact.

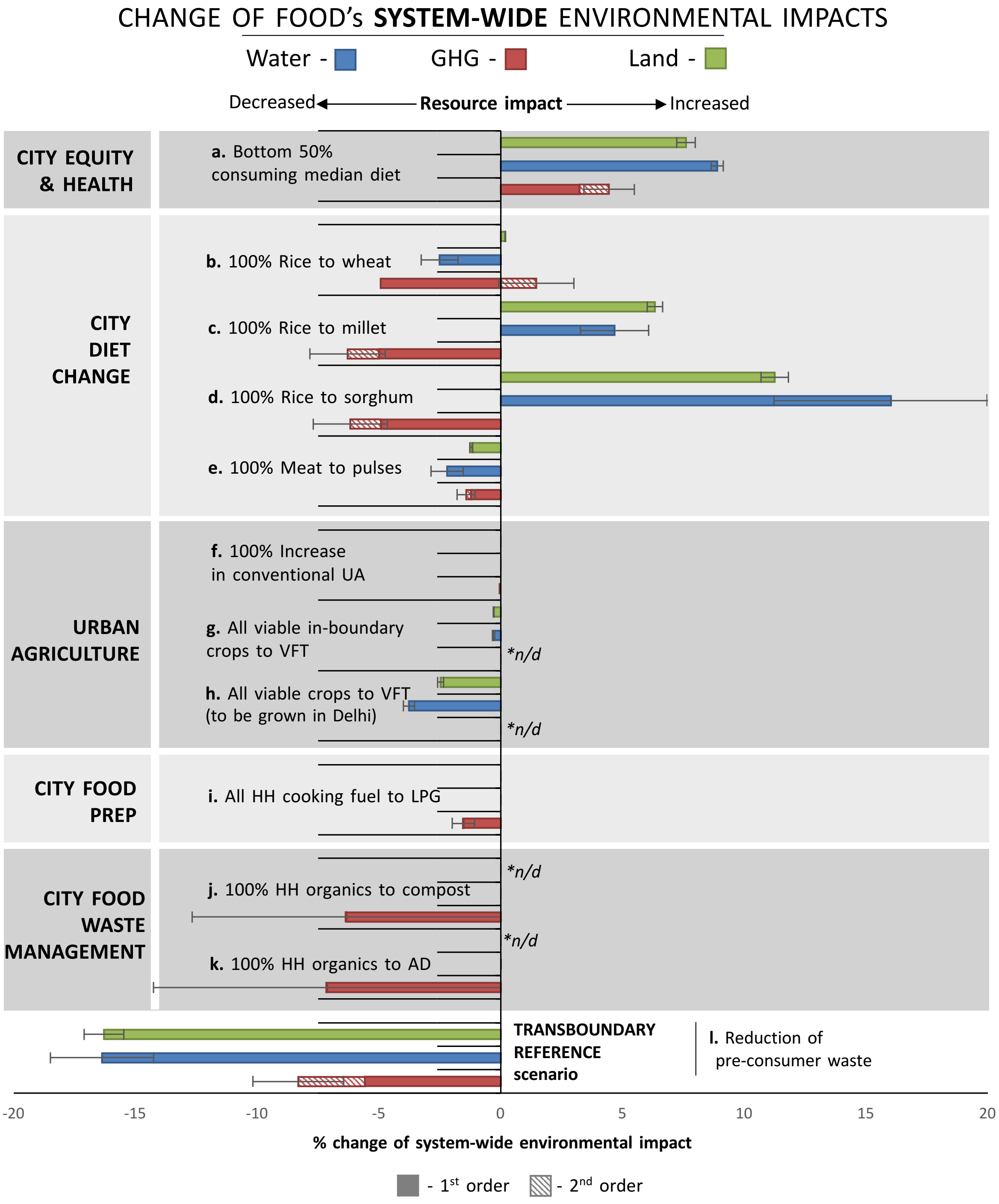


Scenario analysis

1. System-wide impact

Figure 3-5 summarizes the change in full system-wide GHG, water, and land impacts with each of the city-scale food system actions described in Table 1. The bottom axis indicates the percentage change of the total food system's (in- plus trans-boundary) land (green), water (blue) and GHG (red) footprint with each of the food system interventions ((a) through (l) as described in Table 1). Second order impacts are indicated with hatching.

Figure 3-5 | Percent reduction of annual system-wide food GHG, water and land impacts as a result of 100% adoption of food system scenarios. Results are shown as a percentage change to the system-wide water (blue), GHG (red) and land (green) food footprint and expressed in terms of 1st order (solid bars) and 2nd order (hatched bar) impact. (*n/d – insufficient data to determine). Error bars represent the range of intensity factors and technologies for each scenario.



City equity & health: When the bottom 50% of the population consumes the diet of the median class (Figure 3-5a), system-wide GHG, water and land impacts increase by 4%, 9%, and 8%, respectively.

City diet change**:** A 100% shift of rice to wheat reduces total system-wide water and GHG impacts of 3% each with a slight increase in land footprint (<1%) (Figure 3-5b). Rice to sorghum and rice to millet (Figure 3-5c & d) both exhibit greater GHG reduction (6%, 6%) though with substantial increases of water (16%, 5%) and land (11%, 6%). A 100% shift from meat to pulses (Figure 5e) is associated with only modest impact reductions of 1%, 2%, and 1% for GHG, water and land, respectively, due to a predominantly vegetarian baseline diet in Delhi (see Figure 3-3a&b).

Urban agriculture: A doubling of current soiled-based urban agriculture (Figure 3-5f) production levels, has very little system-wide impact (only a <1% decrease in GHG from decreased freight transport), as the impacts are shifted from trans- to in-boundary, rather than decreased. A similar finding is also reported in a recent US city analysis.(Goldstein *et al* 2017)

Changing Delhi's current conventional urban agriculture production to VFT methods would have negligible system-wide impacts (Figure 3-5g), due to a relatively low quantity of current fruit and vegetable production in-boundary (<10% of total demand, see Figure 3-3f). Converting all VFT viable crops (in- and trans-boundary) serving Delhi's food supply to VFT methods would decrease the system-wide water and land needs by 4 and 2%. This impact is relatively low due to currently viable VFT crops (a subsection of fruits and vegetables) tending to have lesser water impact than other food groupings (i.e. grains, animal products, etc., see Figure 3-3d). Due to the ability of VFT to be employed in such a variety of spaces (small scale in-residence, roof top, multi-layer stacked), we considered it not to require its own land footprint, but rather could coincide with other land uses. Change in GHG was unable to be calculated due to lack of data for VFT.

Food preparation: Conversion of all dirty (dung cake, biomass, charcoal) household cooking fuels to LPG (Figure 3-5i) exhibits a 2% reduction of the system-wide GHG footprint, illustrating an instance of complementing government priorities of health and environment.

Food waste management: Management of household organics in the form of anaerobic digestion and composting exhibit high GHG reduction potentials of 7 and 6%, respectively, with negligible additional water requirement to facilitate the process (Figure 5j-k).

Trans-boundary intervention: The trans-boundary scenario action reducing pre-consumer waste from 35% to 13% of the total supply exhibits the greatest impact reduction in terms of water, GHG and land, of 16%, 8%, and 16%, respectively (Figure 3-5l). A lesser reduction is exhibited for GHG, in comparison to land and water impacts, as the GHG impact is distributed more evenly further down the supply chain, (i.e. cooking, disposal), whereas water and land impacts are concentrated almost entirely in the production stage.

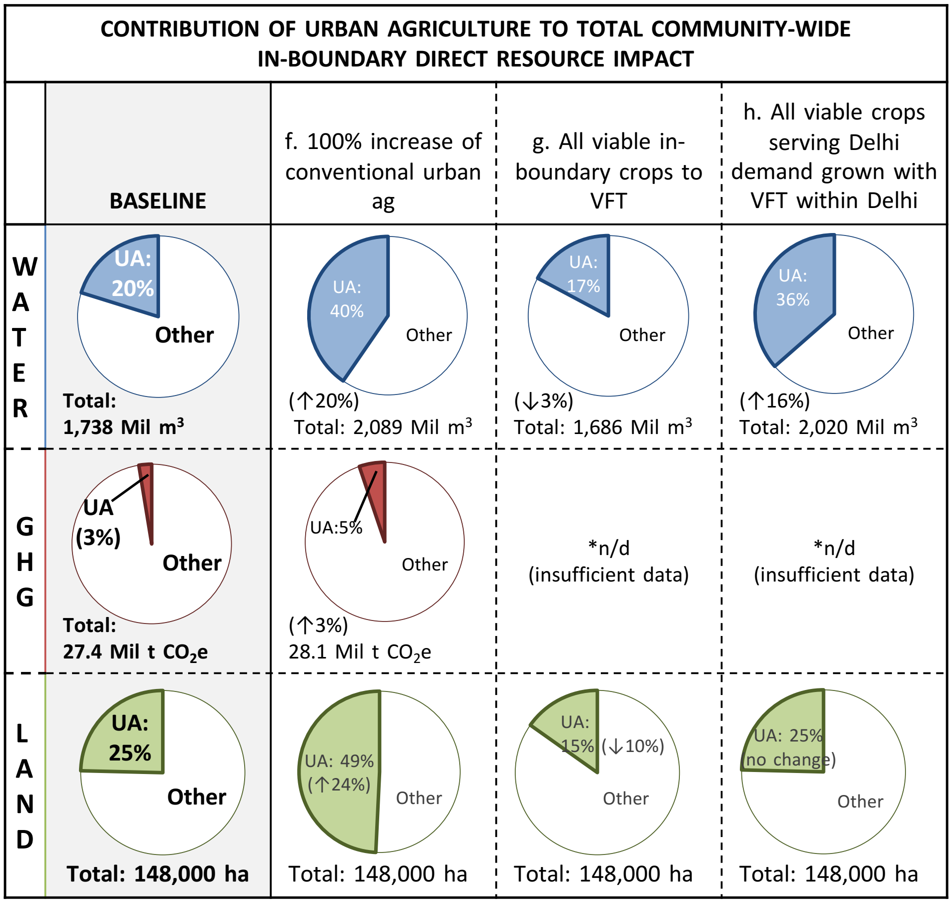
The uncertainty of the above estimates is discussed in the Detailed Methods and shown in Figures 3-5 including estimates of a high and low level of benefit reported for each action resulting from a range of intensity factors and technology options.

2. In-boundary impact

Figure 6 demonstrates the direct in-boundary resource impact resulting from select city-scale actions. The pie charts illustrate the proportion of resource use attributed to urban agriculture as a percentage of the total in-boundary land, water and GHG impacts across the total of all infrastructure sectors (i.e. energy supply, water supply/sanitation, building materials (concrete/steel), and food supply). Such community-wide accounts have been used for many cities (Lin *et al* 2013, Hillman and Ramaswami 2010, Chavez *et al* 2012). This in-boundary footprint was informed by data from existing studies (Chavez *et al*

2012, Ramaswami *et al* 2017) for water and GHGs, and the Delhi Statistical Handbook (Directorate of Economics and Statistics 2013) for Delhi's land area.

Figure 3-6 | Contribution of urban agriculture to total community-wide annual direct resource impact of water (blue), GHG (red), and land (green). The left most column illustrates the baseline conditions, while the following 3 right columns illustrate the changes from three of the urban agriculture scenarios (f-h). UA = urban agriculture, other = all other infrastructure use.



While a doubling of conventional urban agriculture has little system-wide effect, this action would have substantial in-boundary impact, increasing Delhi's total in-boundary water use by 20% and requiring 49% of Delhi's land area—(an increase from the 25% of Delhi's land area currently occupied by urban agriculture) (Figure 3-6f & g), with only a 2% increase in the direct GHG impact. With Delhi already experiencing water scarcity, with a rate of annual groundwater withdrawal at 137% that of recharge, (Suhag 2016) and land constraints of rapid urbanization, an increase in urban agriculture would likely present a challenge in the face of local water and/or land constraints.

Converting all viable crops serving Delhi's demand to VFT does provide small reduction of system-wide water and land impact (Figure 3-5), though if the whole of this VFT production were to be located within Delhi's boundary, the city's total direct water use would increase by 16%—again presenting a challenging scenario in the face of local water constraints (Figure 3-6).

Converting viable crops currently being grown within Delhi to VFT would result in some local resource benefit, decreasing the total amount of land use for agriculture from 25% to 10% of Delhi's total land area, holding production levels constant. Delhi's annual water requirement would also be decreased by 3%. While these impacts would be considered substantial in terms of local impact, they register little benefit when considered from the system-wide perspective (Figure 3-5g), due to low contribution of urban production to the whole of Delhi's demand. This illustrates the importance of determining direct local, as well as system-wide, impact.

DISCUSSION

This study develops a method customizable to individual cities, that provides insight into system-wide GHG, land and water impacts of city-scale food system actions. These insights enable assessment of tradeoff and co-benefits arising from city-scale actions, determining positive and negative impacts within, and outside, the city, for multiple environmental parameters.

The analysis for Delhi illustrates that the water, GHG and land impacts of city-scale food system actions can rival those taken beyond the city boundary (e.g, reduction of pre-consumer food waste). In particular, city-scale food waste management (food waste to fertilizer and/or energy) has a food system-wide GHG reduction potential (7%) that matches, and even potentially exceeds, the impact of trans-boundary food waste reduction, depending on the technology employed. Emerging technologies that combine food waste with sewage to generate energy could provide even greater benefit, (McCarty *et al* 2011, Smith *et al* 2012) and should be evaluated as these technologies evolve.

However, no single city-scale action can rival the trans-boundary intervention impact across all three environmental parameters, GHG, water and land. At the same time, Figure 3-5 illustrates that when the city-scale actions are implemented in tandem, they can create large cumulative impact across the resource categories of water, GHG and land. These combined impacts of multiple city-scale actions are significant compared to actions relating to agricultural production that are the typical focus of analyses of sustainable food system policy levers (Foley *et al* 2011, Godfray *et al* 2012). In addition, the urban actions can provide local co-benefits, such as improved respiratory health from LPG fuel conversion, and potential urban livelihoods from localization, for example.

Various diet changes as well exhibit reduction in GHG impact, though often accompanied with an increase in water and/or land impact. This illustrates the importance of analyzing multiple linked environmental impacts simultaneously to understand potential tradeoffs. Rice to sorghum and rice to millet both exhibit a GHG reduction (6%, 6%), but a substantial increase in both water (16%, 5%) and land (11%, 6%) impacts. This increase of land and water associated with a shift towards millet and sorghum is an important finding to highlight, as these crops, with nutritional values above that of white rice, are promoted for drought tolerance, suggesting the potential for water use reduction.(Sasaki and Antonio 2009, CGIAR 2012) Our analysis finds, however, that while sorghum and millet may be able to survive instances of low water availability, the crops' low yields (less than half the yield of rice and wheat (FAO 2017)) result in a large increases in water and land needed to produce the quantities required to nourish Delhi's population. Further important to note, is how the type of water changes between these diet scenarios. For example, shifting rice to wheat requires 3% less total (green plus blue) water, but increases the irrigation demand (blue water). This is illustrated in Figure 3-5b by the increase of second order GHG impact from energy for irrigation (hatched bar). These nuances are important and illustrate the capacity of the methodology. In the case of diet shifts, further work is also required to incorporate nutritional impacts (i.e. micronutrients), beyond a calorie-for-calorie conversion and the cultural acceptability of such recommendations (Burlingame and Dernini 2013, Garnett 2014).

In the case of greater equity of diet, improving nutrition status for the bottom 50% of the population to achieve the median and sufficient diet, is accompanied by a much smaller proportional increase of water, GHG and land impacts (4%, 9%, and 8%). This is a positive result that improving diets for over 8 million people in Delhi (UN Sustainable Development Goal #2 – ending hunger) (United Nations 2017) can be achieved with today's technologies with a relatively small added environmental impact. Further, this study suggests that the added impact may also be mitigated by implementing multiple tandem city-scale actions through, for example, a combination of in-boundary food waste management and vertical farming technologies.

The analysis also demonstrates the importance of delineating the role of in- versus trans-boundary actions. It is generally presumed that greater localization of food production in cities is more desirable, while this analysis draws attention to the in-boundary resource constraints that may arise with increased urban production. Our methodology provides each individual city the ability to analyze the tradeoffs of multiple social and environmental outcomes, evaluating the role of actors and policies within, and outside the city. Such systems analytics provides cities with customized locally specific information, while informing trans-boundary impacts on larger system—essential to advance the science of sustainable urban systems.

ACKNOWLEDGEMENTS

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CHAPTER 4 | Diversity of food flows, diets, supply chains and environmental impacts of nine Indian cities

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Author contributions: Boyer wrote manuscript and completed all analysis, Sarkar is the official in India responsible for Ramaswami provided overall guidance and high-level comments

INTRODUCTION

With an ever-growing urban population, expected at two-thirds of the world's population by 2050, (UN 2015) cities are beginning to understand the importance of ensuring a well-functioning food system. The urban food system, referring to the demand of food in cities, linked with upstream agricultural production, transportation, supply chains, and use phase, as well as downstream food waste management (UNEP 2016). Various sustainability outcomes can be assessed across the system including environmental sustainability, health and nutrition, and supply risk, provided that basic urban food demand and supply data are available. Environmental sustainability includes impacts on climate, water and land as called for by the Sustainable Development Goals (SDGs) (United Nations 2017).

Yet, despite the emerging interest of cities of their food systems, the state of knowledge remains rather limited about differences between individual cities, based on their unique socio-cultural characteristics and supply chains. General data limitations that have impeded city analysis in many instances. For one, quantification of city-wide agri-food demand is usually limited to residential use with this quantity often estimated by national scale data (i.e Barron *et al* 2011, Los Angele Food Policy Task Force 2009, DVRPC 2011, Goldstein *et al* 2017))—without accounting for the potentially large variation in diet across cities within a single country. Beyond residents, other sectors demanding agri-food flows in cities such as commercial establishments (restaurants, hotels) and food processing industries often go ignored and unquantified entirely, an important oversight in cities where residents might not be the predominant users.

Further, supply chain data is often lacking. Conceptually, cities likely draw on food supply chains that extend great distances, but knowledge of the nature of these supply networks is largely unknown. There have been few studies of urban food systems that have included estimated city-specific supply chain data across all food commodity types serving urban demand. Studies that do exist, tend to focus on national level averages of food traveled (Weber and Matthews 2008). Yet, linking urban demand centers with location of production is important in order to quantify environmental impacts of production that vary by region, as well as beginning to understand risk due to various supply constraints at locations of production, such as water scarcity, for example.

The analysis of this data across multiple cities allows understanding of diversity of community-wide food flows, diet, and production in context of socio-economic classifications and food security, and how this translates to differences in food miles and environmental impact. This combination of data allows quantification of disaggregated, spatially explicit resource impact of urban food demand, as well as visualization of the overlap of production locations with areas of water scarcity, to illustrate potential risk.

Water, land and greenhouse gas emissions (GHG) are the environmental impacts of focus due to their substantial association with the food system. In the case of water, 70-85% of global freshwater use (Gleick 2003) is attributed to the food supply, while 12 and 25% of ice-free land is for crop production and pasture grazing, respectively (Ramankutty *et al* 2008). Further, in terms of environmental impact, 19-29% of global anthropogenic GHG emissions (Vermeulen *et al* 2012) are attributed to the food system—of importance to quantify as cities globally agree to carbon mitigation mandates. While the potential risks to food supply may be many (i.e. transportation disruption , energy failure, climate variation), (Gregory *et al* 2005, Rasul 2014) this study begins to visual potential risk from water scarcity, as limitation of water availability can present as a risk to the food supply, due to the high water requirement necessary for agricultural production (Gleick 2003, Gassert et al. 2018) This is often cited as a key risk to food provisioning, particularly, in India (Hanjra and Qureshi 2010, Rasul 2014). Thus linking locations of productions with measures of water scarcity, allows insight into the availability of water resources at locations of production serving urban demand.

Such an analysis is particularly important in the rapidly growing and urbanizing country of India, where the urban food system has been relatively understudied. Thus studying nine separate cities, totaling a population of 45 million people, is valuable in gaining insight into the similarities and differences that exist between urban food systems. A multi-city study within a single country has not been done before.

This paper therefore has the objectives to explore:

- How does the diversity of city diets and economic structure shape urban flows?
- What are the different foodmiles for each city?
- How does the environmental impact (water, land, GHG) vary by city, when taking into account city-specific diets and production origins?
- How does potential supply risk from water scarcity in food producing areas, within and outside city boundaries vary across cities?

METHODS

Choice of cities

The wide geographic distribution of the nine cities of Delhi, Chandigarh, Rajkot, Ahmadabad, Surat, Chennai, Goa, Bangalore, and Pondicherry is meant to capture regional differences of diets, resource use and potential supply risk. The range of city size intends to show differences that might occur between cities as a result of size and economic structure in terms of overall community-wide food flows as well as distribution of supply networks.

Community-wide food flows

Analysis of community-wide food flows includes quantification of residential (both food taken in and outside the home), visitors and industrial use (Ramaswami *et al* 2017, Boyer and Ramaswami 2017). Details and data of each flow are included in the SI. Industrial use is only available at this time for the four city-states of Pondicherry, Goa, Delhi, and Chandigarh (due to their status as city states) by the Government of India (GOI) Annual Survey of Industry, (Ministry of Statistics and Programme Implementation 2013) reporting physical food mass inputs by food type. All other cities demand only includes residential and commercial use. Visitor food use is estimated by tourism data for each city across multiple data sources. Community-wide food use values include food waste incurred upstream of the city, to account for total production quantity serving city demand.

Residential diet

Residential use is reported by the GOI National Sample Survey (NSS) (Ministry of Statistics and Programme Implementation 2011) for all nine cities of this study, across socio-economic-classes within each city. This survey accounts for both food taken inside the home as well as meals and prepared food items consumed outside of the home.

Supply chains

Supply chains are informed by a Government of India commissioned multi-modal freight survey, detailing the origins and destination of thirteen food commodity types (Planning Commission 2008). This allows linking of urban demand centers with locations of production throughout India. International imports and processed food play only a minor role in the Indian food supply (Hoff *et al* 2014, FAO 2017, Ministry of Statistics and Programme Implementation 2011). Supply chain distance is considered the Euclidean distance between the state capital of the food’s origin state and the destination city. Supply chain data were available for all cities except Chandigarh. This analysis uses the supply chain data to allocate demand by origin only, not the quantity of food entering the city.

Environmental impact

Environmental impact of production in terms of water, energy and GHG are informed by country specific resource intensity factors (Hoekstra *et al* 2011, Pathak *et al* 2010, FAO 2017) Location specific second order GHG intensity factors are informed by the supply chain data to account for energy use of on-farm equipment and irrigation, (Nielsen 2013, CEA 2011) as described by Ramaswami et al. 2017. This is in addition to the traditionally quantified first order impacts of agri-food production, such as soil emissions of nitrous oxide and methane (Pathak *et al* 2010).

Water scarcity

Calculation of water scarcity in areas of production uses a measure of "baseline water scarcity" data calculated as total annual withdrawals (across municipal, industrial, and agricultural uses) as a percentage of average total annual available flows, as determined by the World Resources Aqueduct project making use of various global data sets (Gassert et al. 2018). This data assigns a numerical value to each river basin from low (1) to extreme (5), with low classified as (<10%) and extreme as (>80%). We calculate the city-specific water scarcity per food item as the sum of state-wise area-weighted baseline water stress value times the state-wise percentage contribution to the city's specific food supply by item grouping, described by Equation 3-1. Freight data informs the state contribute to each city's supply.

$$Water\ scarcity\ risk_{food\ i,city\ i} = \sum(State_i\, baseline\ water\ scaricity) \times$$
$$(\%\ of\ city_i\ supply\ of\ food_i\ originating\ from\ state_i) \qquad (4\text{-}1)$$

While there are many metrics of water scarcity, (Damkjaer and Taylor 2017) comparing this baseline water scarcity data set against other studies and measures of water scarcity, such as groundwater scarcity and inter-annual variability, shows a similar pattern of water scarcity across India, (see for comparison Devineni *et al* 2013, Brauman *et al* 2016, Gassert et al. 2018). We chose this data set due to its comprehensive by-basin values for the whole of India.

DETAILED METHODS

Community-wide food flows

Table 4-1 | Annual community-wide food flows (including upstream waste) and data sources.

City	**Population**(Ministry of Home Affairs 2011)	**Residential use (including food inside and outside of home)**(Ministry of Statistics and Programme Implementation 2011)	**Visitors food use (tons)**	**Industrial food use (tons)**(Ministry of Statistics and Programme Implementation 2013)
Ahmadabad	5,577,940	2,328,967	3,067	n/a
Bangalore	8,443,675	3,879,669	11,458	n/a
Chandigarh	961,587	473,812	634	67,228
Chennai	4,646,732	2,174,392	10,785	n/a
Delhi	16,419,787	12,451,303	13,766	4,257,040
Goa	1,458,545	621,950	1,877	1,151,476
Pondicherry	1,244,464	865,069	676	1,177,544
Rajkot	1,286,678	573,543	707	n/a
Surat	4,467,797	2,010,313	2,457(	n/a

Sources: (National Council of Applied Economic Research 2010;) (ACNielsen ORG-MARG Pvt. Ltd 2008) (Nielsen India Pvt. Ltd 2014) (Ministry of Tourism 2010) (Department of Tourism Government of Puducherry India n.d.) (National Council of Applied Economic Research 2010) National Council of Applied Economic Research 2010)

Uncertainty

With the exception of Goa and Pondicherry, residential food use is the dominate community-wide flow, and thus the focus of the uncertainty analysis.

An ANOVA analysis of the food items of wheat, rice and milk (three items comprising over 50% of the food intake by mass and calories) established statistical differences in the food intake averages across the cities. A statistical analysis to determine uncertainty of food quantities within the NSS is included in both Ramaswami et al. 2017 and Boyer & Ramaswami 2017.

Local production

Table 4-2 | Quantity of local production across city districts.

City	Total tons local production
Delhi	824,317
Ahmadabad	1,276,252
Bangalore	249,055
Chandigarh	49,686
Rajkot	1,475,614
Surat	1,709,194
Pondicherry	7,103,223
Chennai	57,357
Goa	205,452

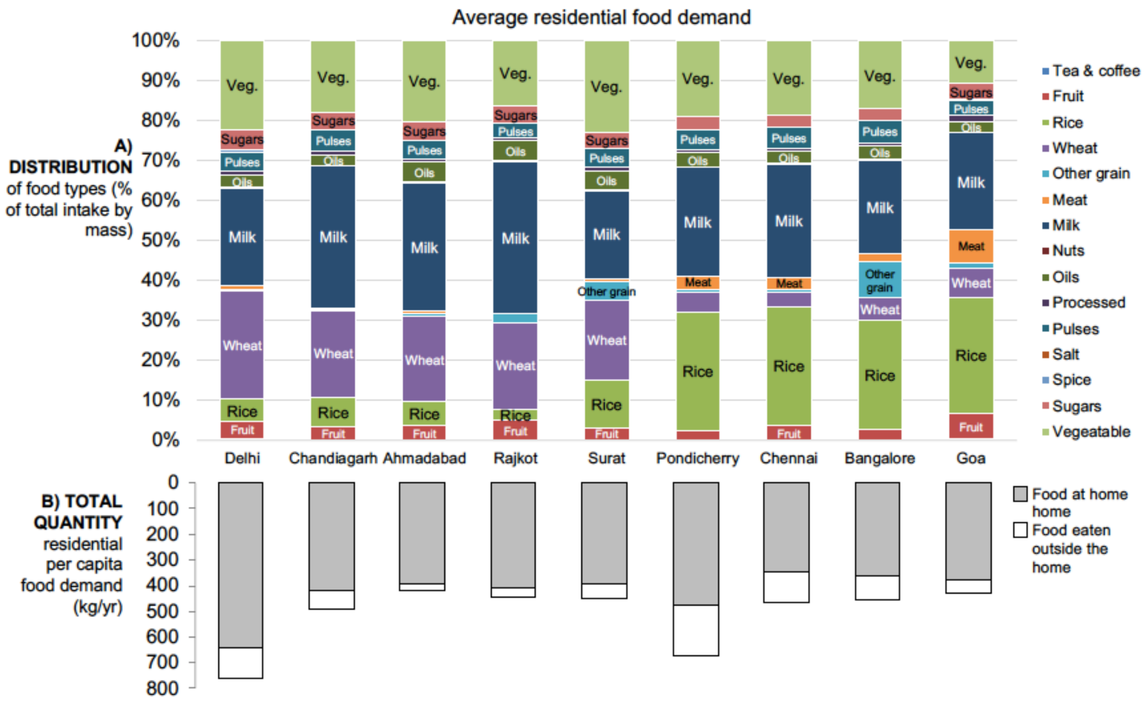
Sources: (Ministry of Agriculture Deparment of Animal Husbandry 2014, Ministry of Agriculture 2014, National Dairy Development Board 2014, 2013, 2015, Directorate of Animal Husbandry 2013, n.d., 2016, Department of Animal Husbandry and Veterinary Services 2012, Chandigarh Agriculture Department 2012)

RESULTS

Community-wide flows vary across the four cities of Delhi, Pondicherry, Goa and Chandigarh (See Supplemental Results, Figure 4-7). In the case of Pondicherry, Chandigarh and Goa, the industrial flow dominates (at 58, 61, 59% of total flow by mass, respectively). In the case of Delhi, residential flow dominates, at 69% of total annual food demand by mass. Commercial food demand constitutes less than <10% of total food demand across all four cities. The food types demanded by these cities greatly vary by city (see Supplemental Figure 4-8), with the flow largely dominated by the industrial demand.

Residential diets vary across cities with statistical significance (Figure 4-1a), with a

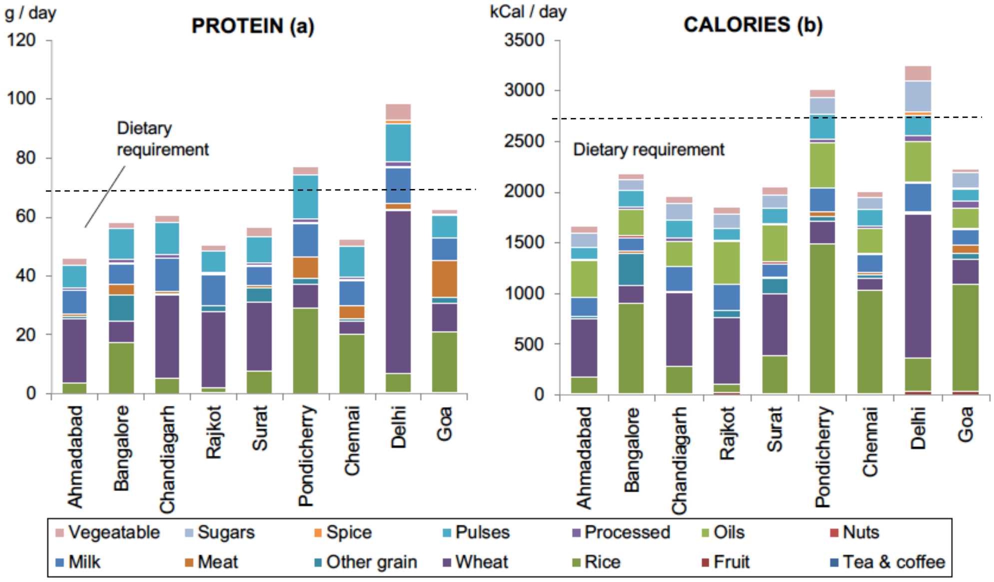
Figure 4-1 | Per capita residential food type demand across 9 cities, illustrating distribution of food type as a percentage of total intake by mass and quantity of total food intake including both food inside and outside of the home.



particularly notable difference between rice and wheat consumption of northern and western (Delhi, Chandigarh, Rajkot, Surat, Ahmadabad) versus southern (Chennai, Pondicherry, Bangalore, Goa) cities. Figure 4-1b illustrates the variation of the quantity of annual per capita consumption, with Pondicherry and Delhi reporting highest quantities of consumption by mass. Conversion of food mass to calories and protein provides insight into the nutritional status of the average residential diet of the nine Indian cities (Figure 4-2a&b). Only the average residential diets of Delhi and Pondicherry exceed the Indian dietary recommendation for daily caloric intake (Figure 4-4-2b). The average residential diet of five of the nine cities Bangalore, Chandigarh, Pondicherry, Delhi and Goa, meet the protein requirements. These findings are in line with national level statistics reporting 70% of households inadequate in terms of calories, and 27% lacking in protein (National Institute of Nutrition 2011). Such deficiencies of nutrition at the urban scale illustrate the role cities must play in alleviating under nutrition in India.

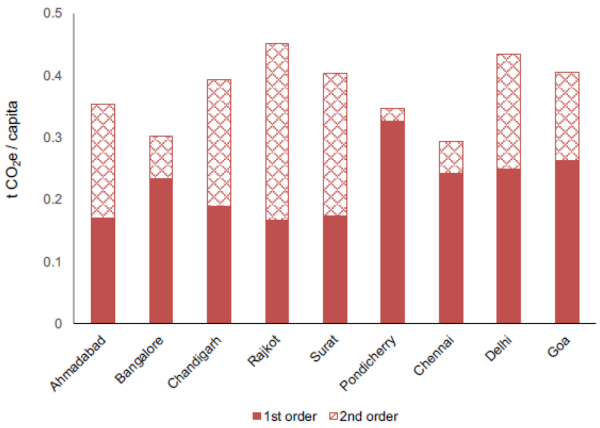
Associated with variation in residential diet, is a difference of environmental impact of production across the nine cities (Supplementary Figure 4-8). Pondicherry reports the highest per capita 1st order GHG emissions for food at 327 kg CO_2e while Delhi exhibits the highest per capita land and water for food production of 0.283 ha and 1,148 m^3 per capita, respectively. The picture of per capita GHG, however, varies when we incorporate spatially explicit variation of energy use for ground water pumping and on-farm use (2nd order GHG impact), as illustrated in Figure 4-3. Pondicherry, for example, reports the highest 1st order GHG emissions (solid bar), but is passed by six cities when including 2nd order impacts (hatched bar). This is a result of Pondicherry consuming foods with lesser irrigation requirement and sourcing from wetter regions of the country.

Figure 4-2a-b | Daily per capita protein and calorie intake (average residential diet) across 9 Indian cities showing contribution of each food type. The dotted line illustrates the recommended dietary requirement as determined by the Government of India.



This trend is also noted for the other cities of Goa, Chennai and Bangalore located in southern regions of lesser water scarcity. Notably, the cities sourcing the majority of their food supply from dryer regions (i.e. the northern and western parts of the country), of Surat, Rajkot, Chandigarh and Ahmadabad, the GHGs associated with irrigation actually exceed that of 1st order GHG impacts. These city diets also have greater demand of wheat, a crop with particularly high irrigation requirements, in comparison to the rice-based diets of the south.

Figure 4-3 | 1st and 2nd order GHG impact per capita based on city-specific diets and production locations.



Moving from demand to production serving cities, all cities have some level of local agriculture, though no city can source locally across all food types, illustrating the importance of city supply chains in supporting urban populations (Supplementary Figure 4-11). Figure 4-4 shows the disaggregated food supply in terms by mass, informed by freight data, with city location marked with a red star. The results show cities generally sourcing from nearby areas (Figure 4-4), with some exceptions, such as Chennai’s reliance on the far region of Assam for the majority of its rice supply. Water and land impacts seem to track relatively closely with the disaggregation by mass, though the GHG impact is heavily concentrated based on the production location of the rice supply, (see Supplemental Figure 4-10).

Figure 4-4 | Supply chain distributed food by mass supporting city demand, by mass. Grey circles are sized based proportionally to the contribution of each production location to the specific city's demand. Dot sizes are not comparable across cities. Red stars mark city location.

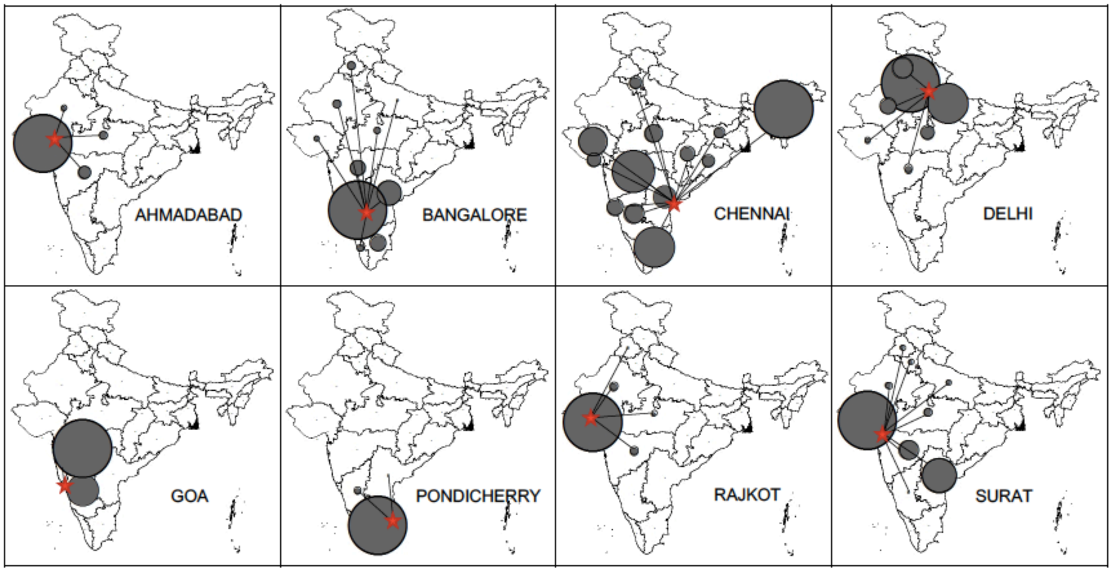
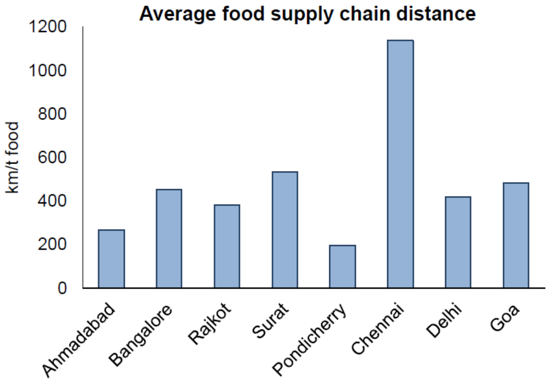


Figure 4-5 illustrates the difference of supply distance, or "foodmiles" by city. Chennai's average supply distance is greatest at 1,137 kilometers per ton of food, with the next highest a much lesser 533 km/ton of food for Surat, while Pondicherry reports the shortest distance of only 196 km/ton.

Figure 4-5 | Average food supply chain distance per city.



Average water scarcity measures of production areas serving urban demand varies both by city, and by agri-food type. Figure 4-6 presents a map of India with water scarcity measures indicated by color, from extremely high scarcity (deep red) to low (light yellow). Table 4-3 describes the water scarcity related risk for each city by agri-food type based on supply chains serving urban demand, ranking from extreme (deep red) to high (bright red) to medium-high (orange) to medium-low (yellow). Ahmadabad, Surat, and Delhi all have multiple agri-foods that predominantly originate from areas with "extreme" baseline water scarcity. The specific agri-food types falling in the designation of "extreme" varies by city. For example, rice predominately originates from areas of extreme water scarcity for Ahmadabad, Chennai and Delhi though in the case of Pondicherry, rice mainly originates from areas of low water scarcity. This provides a first visualization of how the supply chain can begin to inform city food supply risk as it relates to water scarcity.

Figure 4-6 | India water scarcity map with location of study cities. Baseline water scarcity is defined as annual water withdrawals (municipal, industrial, agricultural) over annual available blue water, as determined by (Gassert, F., M. Landis, M. Luck, P. Reig 2018).

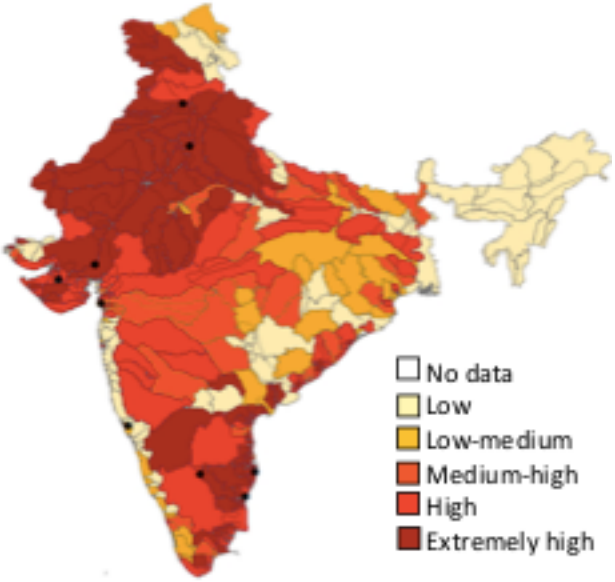
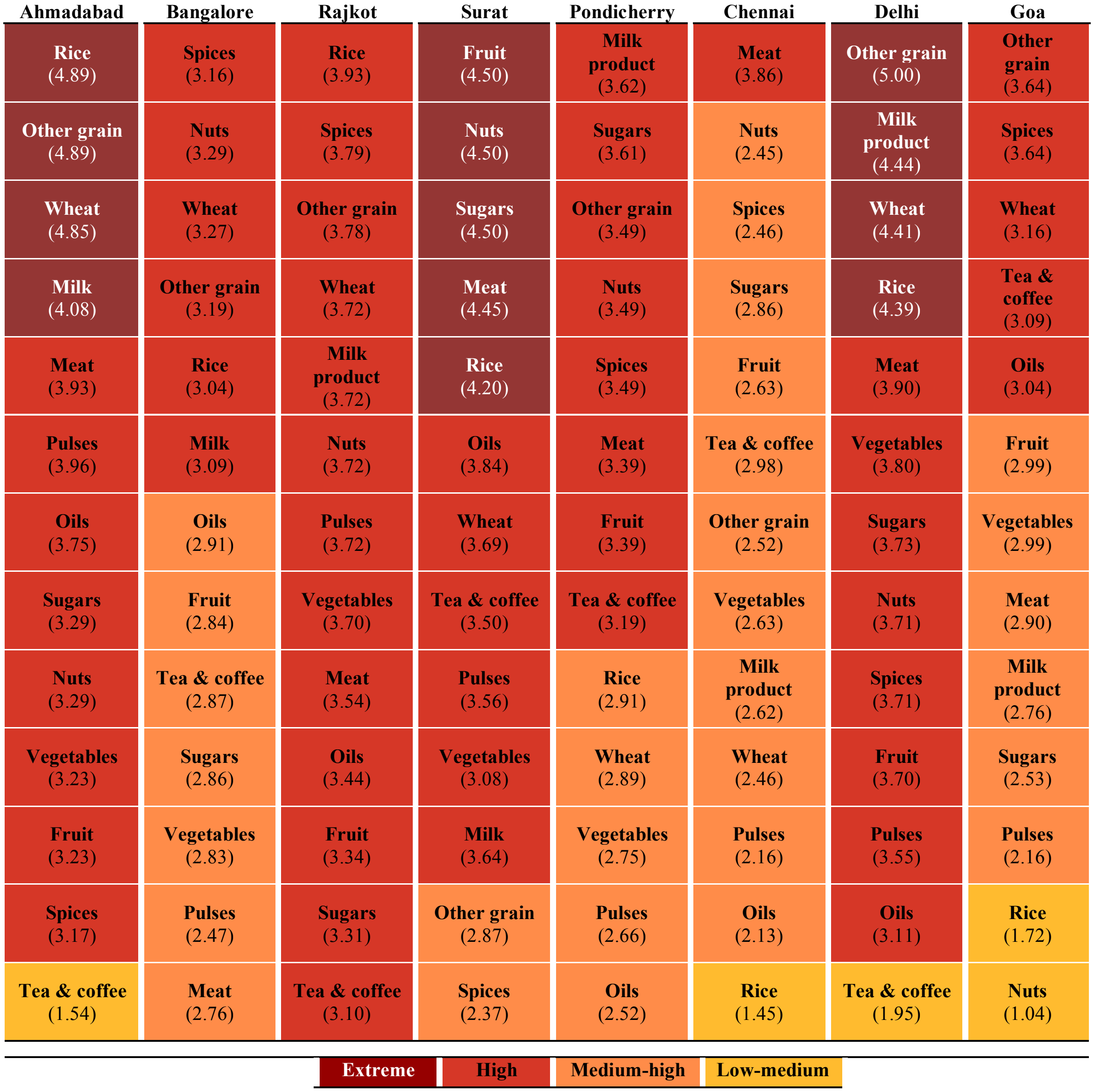


Table 4-3 | Water scarcity related risk per city, as determined by area-weighted baseline water scarcity per state, as a function of total water withdrawals over annual average availability.



Ahmadabad	Bangalore	Rajkot	Surat	Pondicherry	Chennai	Delhi	Goa
Rice (4.89)	**Spices** (3.16)	**Rice** (3.93)	**Fruit** (4.50)	**Milk product** (3.62)	**Meat** (3.86)	**Other grain** (5.00)	**Other grain** (3.64)
Other grain (4.89)	**Nuts** (3.29)	**Spices** (3.79)	**Nuts** (4.50)	**Sugars** (3.61)	**Nuts** (2.45)	**Milk product** (4.44)	**Spices** (3.64)
Wheat (4.85)	**Wheat** (3.27)	**Other grain** (3.78)	**Sugars** (4.50)	**Other grain** (3.49)	**Spices** (2.46)	**Wheat** (4.41)	**Wheat** (3.16)
Milk (4.08)	**Other grain** (3.19)	**Wheat** (3.72)	**Meat** (4.45)	**Nuts** (3.49)	**Sugars** (2.86)	**Rice** (4.39)	**Tea & coffee** (3.09)
Meat (3.93)	**Rice** (3.04)	**Milk product** (3.72)	**Rice** (4.20)	**Spices** (3.49)	**Fruit** (2.63)	**Meat** (3.90)	**Oils** (3.04)
Pulses (3.96)	**Milk** (3.09)	**Nuts** (3.72)	**Oils** (3.84)	**Meat** (3.39)	**Tea & coffee** (2.98)	**Vegetables** (3.80)	**Fruit** (2.99)
Oils (3.75)	**Oils** (2.91)	**Pulses** (3.72)	**Wheat** (3.69)	**Fruit** (3.39)	**Other grain** (2.52)	**Sugars** (3.73)	**Vegetables** (2.99)
Sugars (3.29)	**Fruit** (2.84)	**Vegetables** (3.70)	**Tea & coffee** (3.50)	**Tea & coffee** (3.19)	**Vegetables** (2.63)	**Nuts** (3.71)	**Meat** (2.90)
Nuts (3.29)	**Tea & coffee** (2.87)	**Meat** (3.54)	**Pulses** (3.56)	**Rice** (2.91)	**Milk product** (2.62)	**Spices** (3.71)	**Milk product** (2.76)
Vegetables (3.23)	**Sugars** (2.86)	**Oils** (3.44)	**Vegetables** (3.08)	**Wheat** (2.89)	**Wheat** (2.46)	**Fruit** (3.70)	**Sugars** (2.53)
Fruit (3.23)	**Vegetables** (2.83)	**Fruit** (3.34)	**Milk** (3.64)	**Vegetables** (2.75)	**Pulses** (2.16)	**Pulses** (3.55)	**Pulses** (2.16)
Spices (3.17)	**Pulses** (2.47)	**Sugars** (3.31)	**Other grain** (2.87)	**Pulses** (2.66)	**Oils** (2.13)	**Oils** (3.11)	**Rice** (1.72)
Tea & coffee (1.54)	**Meat** (2.76)	**Tea & coffee** (3.10)	**Spices** (2.37)	**Oils** (2.52)	**Rice** (1.45)	**Tea & coffee** (1.95)	**Nuts** (1.04)

Extreme **High** **Medium-high** **Low-medium**

SUPPLEMENTARY RESULTS

Figure 4-7 | Distribution of food demand by residential at home use (res), commercial use by residents and visitors (com) and industrial food processors (ind).

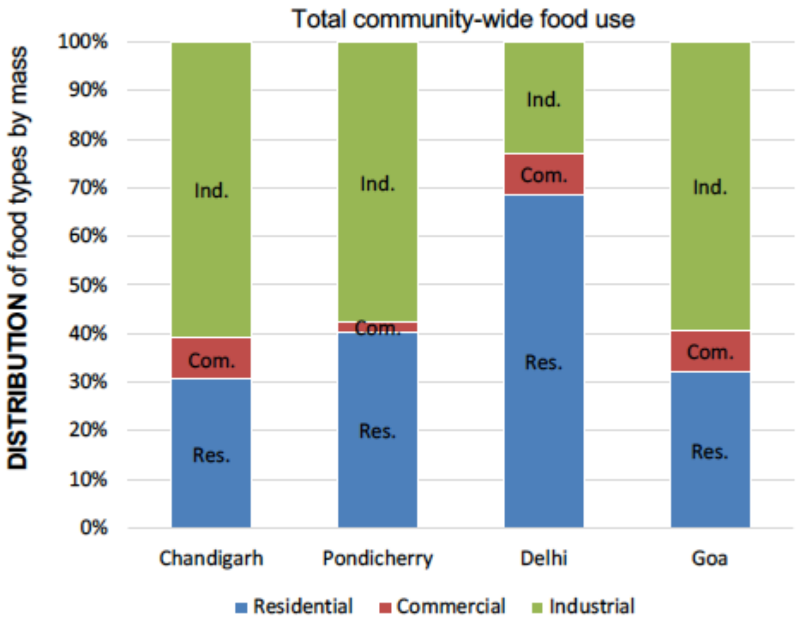


Figure 4-8 | Community-wide food demand (inclusive of homes, businesses and industries) across four cities by food types.

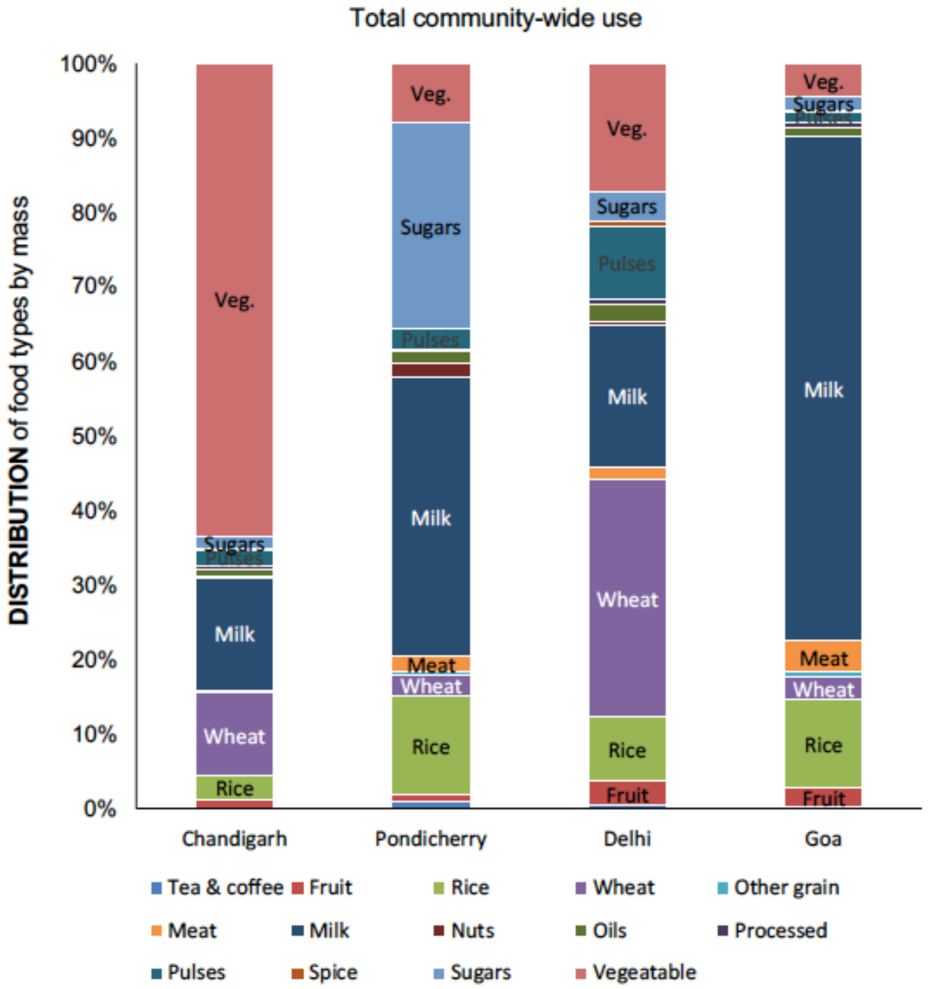


Figure 4-9 | Distribution of community-wide food demand across agri-food types by end use sector of residential, commercial and industrial food processing.

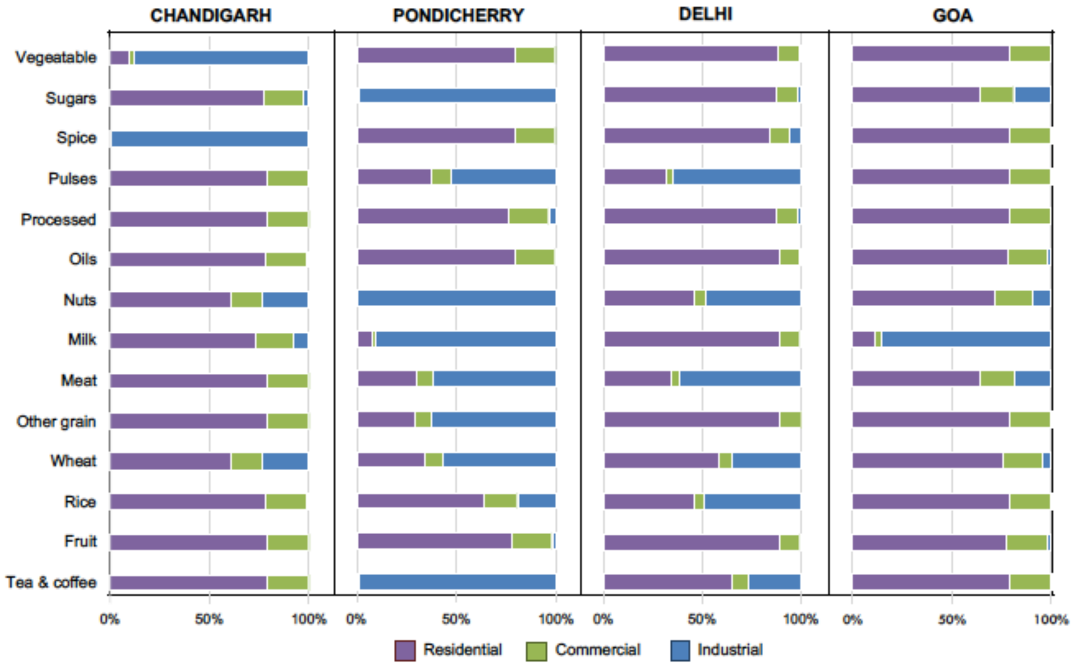


Figure 4-10 a,b,c | Environmental impact of annual per capital residential food demand in terms of a) 1st order GHG emissions; b) consumptive water loss; c) land use.

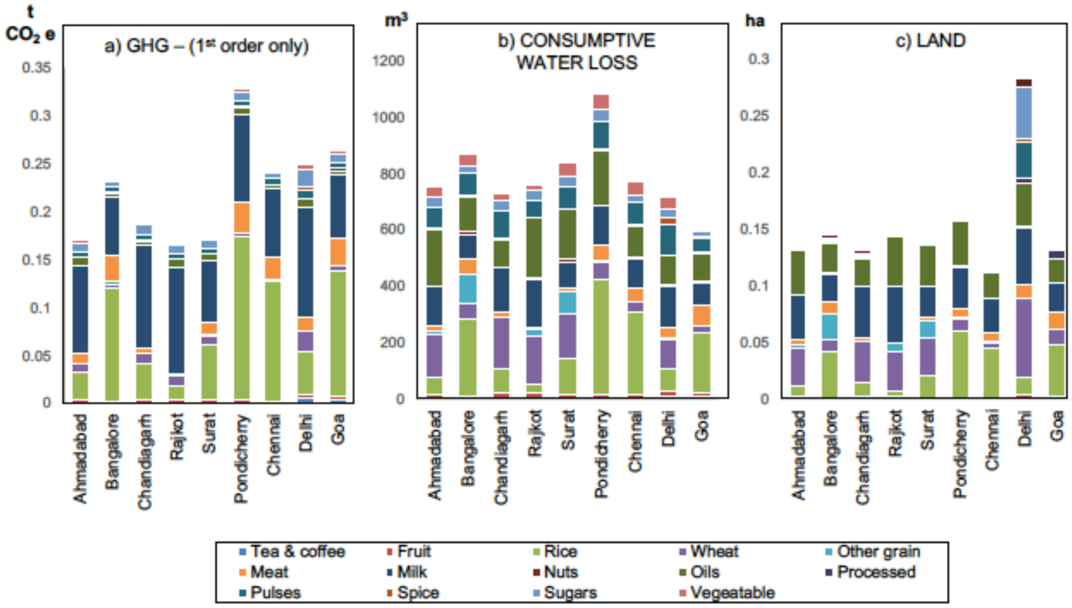


Figure 4-11 | Comparison of local availability as a percentage of total city-wide food demand. Percentage of food not matched with local availability is marked with hatching, labeled as trans-boundary supply.

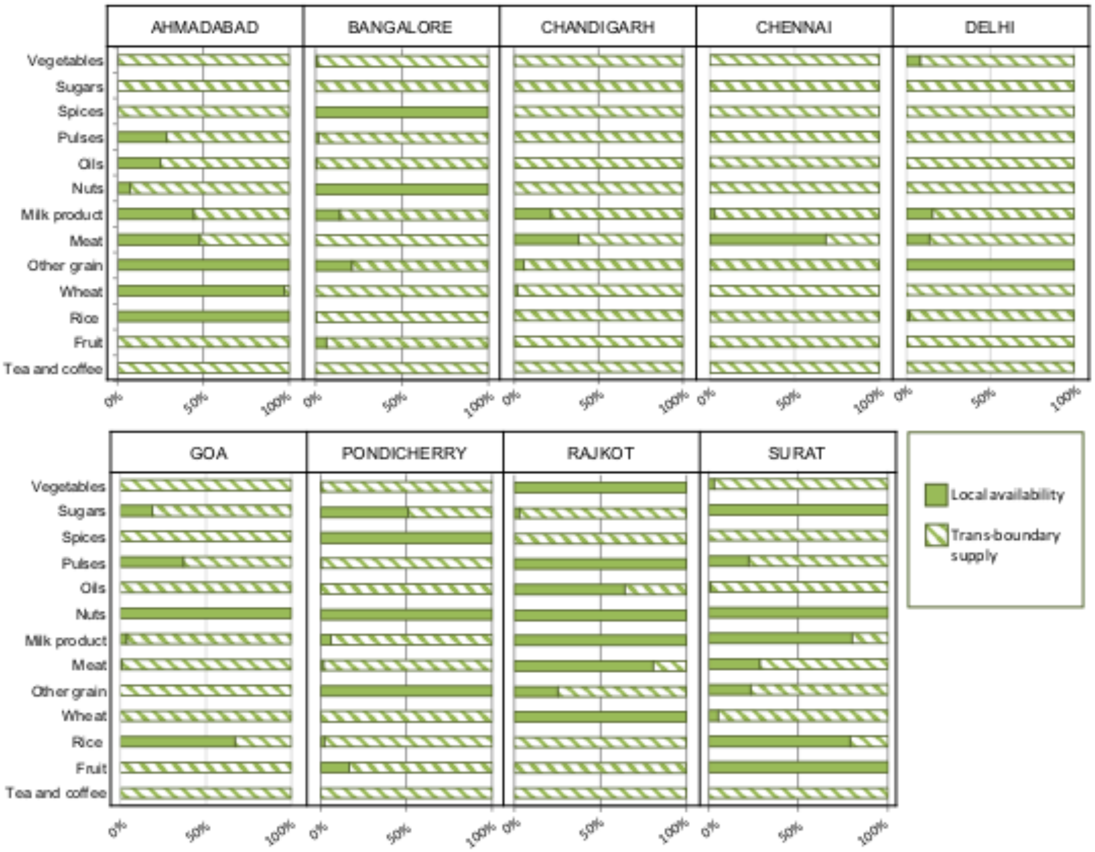
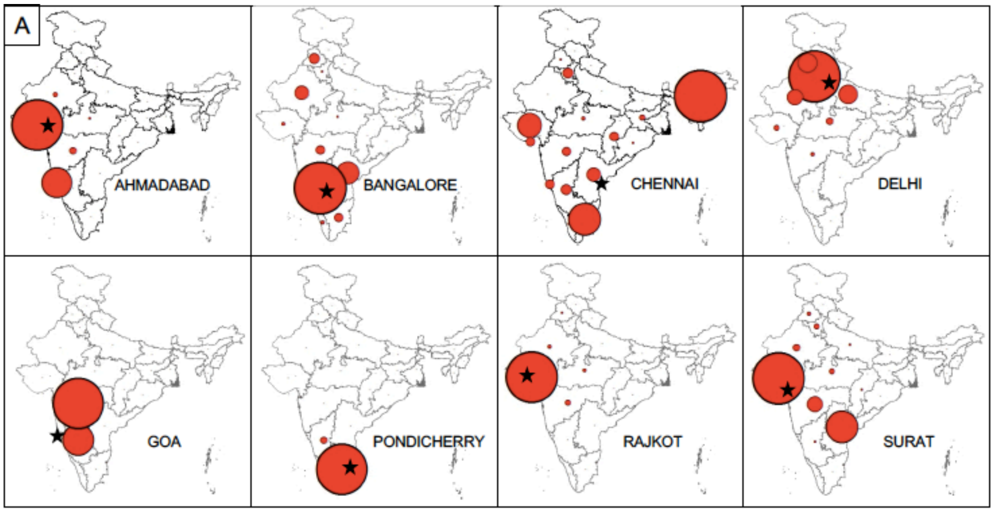
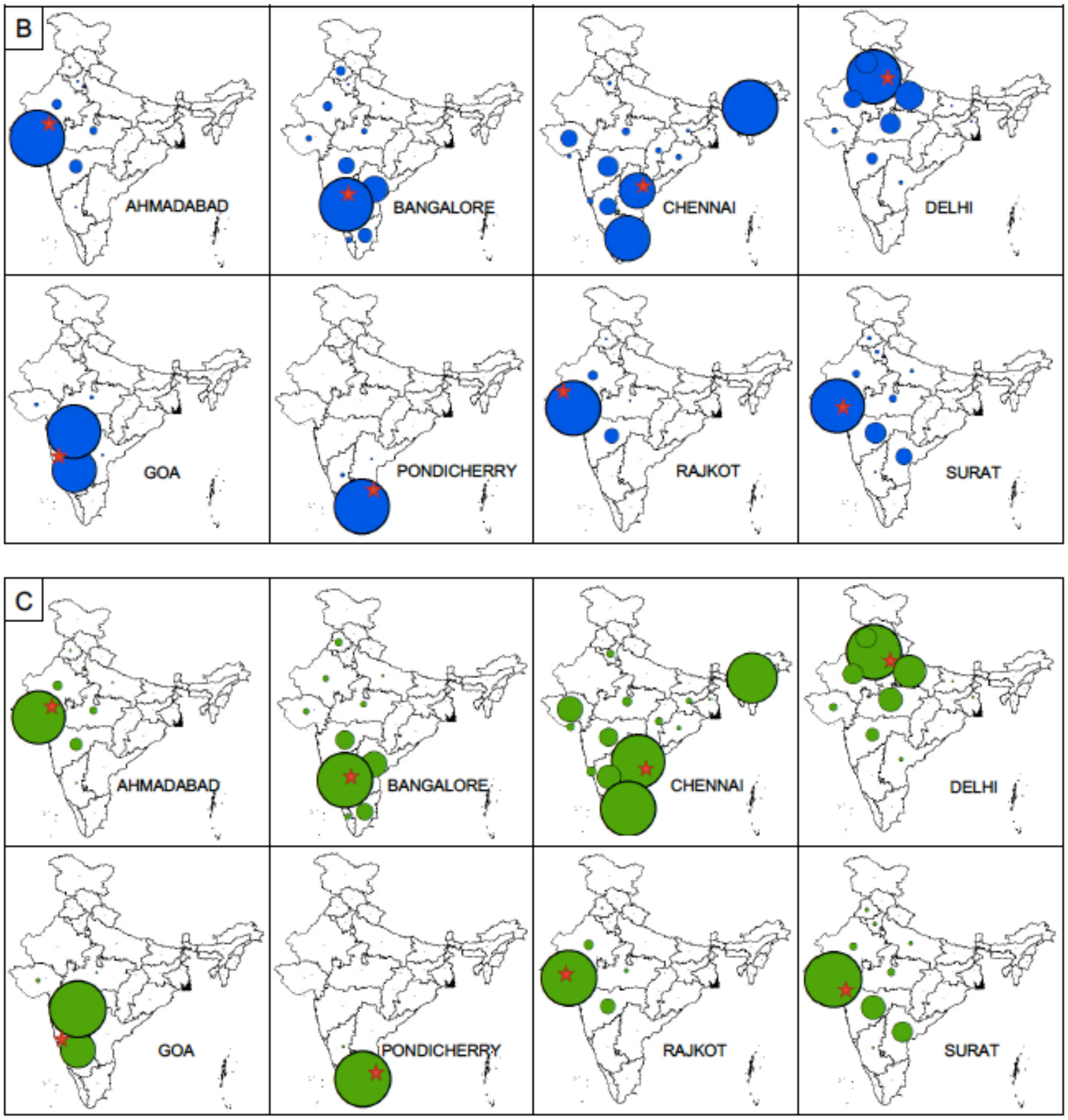


Figure 4-12 | Supply chain distribution food supporting city demand by a) GHG (red); b) water (blue); c) land (green). Circles are sized proportionally to the contribution of each production location to the particular city's demand. Dot sizes are not comparable across cities.





DISCUSSION

Overall, large variation exists across all cities in terms of community-wide food flows, residential diet, supply chains, and environmental impact. Examination of city-specific diets found great variation across diet composition, particularly for grain consumption. Such variation even in a single country suggests that the common approach of down-scaling national level dietary data for city food studies is ill-suited to capture the variation of food demand between individual cities. This provides a call for greater data collection and study of spatially explicit diets, in order to more accurately understand environmental impact and resource demands and the health and nutrition status of city residents.

With respect to health and nutrition, this analysis illustrates the high levels of under nutrition existing in Indian cities, inline with national level nutrition statistics. The combination of the high populations residing in urban areas and the apparently low level of food security, establishes the mandate and opportunity for cities to have a central role in national-level food security agendas. This is particularly important when food security studies and measurements in developing countries have traditionally based on the conditions of rural areas (FAO 2014).

With respect to provisioning, this analysis shows high local availability able to contribute to city demand. However, as cities continue to expand, particularly in a rapidly urbanizing country as India, municipalities must be aware as to how urban expansion may overtake areas traditionally used for agriculture, and the affect that this may have the city's food supply. This awareness would allow cities to be proactive in either preserving local agricultural lands or securing supply substitutions from elsewhere. Further, local water scarcity measures for every city except Goa were higher than the supply chain connection production areas serving urban demand. This study questions the strategy of increasing urban food production, suggesting that perhaps at times a wiser approach is to locate agriculture in areas that do not face the multiple competing demands of urban water use.

Supply chain distance vary substantially across cities. Though even Chennai, which has an average supply distance of more than double any other city, is substantially less at 1,137 km/ton than Weber and Matthew's reported value of 1,640 km average delivery distance of American food items (Weber and Matthews 2008). This is likely due to lesser developed supply chain infrastructure, often lacking storage technologies and refrigeration and the informal nature of the system.

Visualization of supply chains in general provides great value to cities, both in terms of quantifying environmental impact and potentially informing risk. For example, the supply chain distribution of Pondicherry results in only a small contribution of 2nd order GHG impact from irrigation, by sourcing from wetter areas and consuming crops with lesser irrigation requirement. Cities, such as Rajkot, however, sourcing from both drying regions and eating crops such as wheat with high irrigation requirement, exhibit second order impacts that exceed that of first order. This illustrates the nuance of understanding that can be achieved through incorporation on supply chain data, in comparison with national averages.

While just a preliminary visualization, overlaying city food supply chains with water scarcity data suggests that potential risk related to water availability varies across food items and cities. This illustrates the value of cities tracking their own food supply chain to understand conditions of production locations. This initial inquiry provides incentive for further research into the supply risks of urban food demand. An important next step would be to study the likelihood of supply disruption occurring based on the water scarcity measure of production location. This work only matches urban demand with water scarcity of production locations, it does not go so far as to understand if this will indeed impede supply. A further line would also be to understand the flexibility of these supply chains, and their ability (or lack thereof) to adapt in the face of production disruptions, should they occur. With such high population concentrations in cities, these questions are important to explore, if cities are to be successful in tackling both challenges of food security and environmental sustainability.

ACKNOWLEDGEMENTS

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CHAPTER 5 | Comparing urban food system characteristics and actions in across U.S and Indian cities

Dana Boyer, Anu Ramaswami

INTRODUCTION

A well-functioning food system, from agricultural production, to transport, processing, use and food waste management is necessary to nourish the development, health, and well-being of any human population. Yet the food system, functioning in its current state, exhibits many shortcomings globally, ranging from environmental degradation to diet related diseases ranging from inadequate provisioning to over-consumption (Lim *et al* 2012, Sabiha *et al* 2016, Vermeulen *et al* 2012).

Cities in particular are taking up the mandate to address shortcomings of the food system. Populations globally are increasingly residing in cities, with two thirds of the projected 2050 global population expected to be urban and hence cities function as demand centers for the food supply (UN 2015). With such large populations, cities have a high interest in food to support the well-being of their residents. Urban areas are also focal points where multiple infrastructures converge as well as production and consumption activities are co-located, providing unique opportunities for food system interventions such as food waste to energy (Ramaswami *et al* 2017, Boyer and Ramaswami 2017). Many cities are also looking at developing new infrastructure such as soil-based urban agriculture or soilless vertical farms, (Despommier 2013) with the common of assumption that increasing localization has beneficial outcomes. Leading proactive cities have even begun forming food action plans, outlining a wide variety of initiatives aimed at addressing a whole suite of system objectives including equity of access, nutrition, resilience and environmental sustainability, with city policies championed by organizations such as the Milan Food Pact, the United Nations Food for the Cities and C40 Food Network (FAO 2014, C40 2015, Milan Urban Food Policy Pact 2015).

Addressing food system environmental sustainability is a common objective of city food policy councils (City of Minneapolis 2016, City of Vancouver 2013, Thompson *et al* 2008). This attention is important considering the high resource impact of the food system. For example, 70-85% of global fresh water use is attributed to agricultural practices, while 12% of global land is attributed to crop production, with a further 28% required for grazing (Gleick 2003, Ramankutty *et al* 2008). Further, the food system is estimated to contribute as high as 30% of global anthropogenic GHG emissions (Vermeulen *et al* 2012). Yet while these impacts have been quantified on global and national scales, the ability of cities to shape these interactions remains largely unknown.

The multi-objective aspirations of city actions do not yet have the necessary analytical tools able to assess food systems outcomes quantitatively and track progress towards objectives. Cities endeavoring to develop and improve their food system are faced with a multitude of challenges. Even methods of quantifying food use—a necessary first step in understanding city food systems and environmental impact—vary greatly across cities, as noted in a recent study of a 100 cities (Goldstein *et al* 2016). Moreover, the study found that food use estimates vary substantially based on the methods of quantification, illustrating a challenge of standardized city comparison.

Further the food system is multi-scaled, with cities reliant on many activities that occur at various locations beyond the city boundary, such as agriculture, for example. The food system is multi-sector, involving diverse actors such as food processors, households, and food waste managers. Thus cities must understand and attempt to create action in a system that spans across sectors (residents, business, industry) and extends well beyond the city's geographic boundary (Ramaswami *et al* 2017, Boyer and Ramaswami 2017). In addition, a city must grapple with the many (and sometimes competing) considerations of a well-functioning food system, i.e. health and nutrition of diet, equity of access, resiliency of supply, and environmental sustainability.

Thus, to-date, there is limited understanding of the urban food system and variation between cities. This variation of food system structure, can take form both within, and outside the city boundary, to include, for example: differences of community-wide demand, diet, production, supply chains. Of further importance is to understand how inter-city differences of food system structures can be reconciled to analyze food systems and develop strategies able to be inform policy, irrespective of system structures and data availability.

Recent work by Ramaswami *et al* 2017 developed a framework to assess the system-wide environmental impacts of the food system, with an initial application to Delhi, India to illustrate the analysis in the context of competing food system priorities (i.e. improved diets) (Boyer and Ramaswami 2017). The purpose of this paper is to understand how methods, data, food system characteristics and strategies for sustainability vary between diverse cities. This work specifically focuses on four cities, Delhi and Pondicherry within India, and New York City and Minneapolis within the United States.

This paper builds upon this prior work, applying the systems framework to the four diverse cities of Delhi and Pondicherry in India and New York and Minneapolis in the United States. This analysis includes quantification of the baseline system, and various scenarios based on proposed policy actions in these cities. This work tests the applicability of these methods as a standardized policy tool, irrespective of city location to assess the tradeoffs and co-benefits of various city-scale food system actions with environmental sustainability in terms of water, energy/GHG and land impacts.

New York and Delhi, as large, highly populous cities are largely food consumers, while Minneapolis and Pondicherry have substantial land designated to food production and larger food processing industries. The city selection captures this variation of urban food demand by producers and consumers in two countries with large differences in diets, degree of food processing, types of urban agriculture, and level of formality/informality of the food system. Capturing this diversity of city and food system structure to increase understanding of food system analyses across despite varying data sources and potential data scarcity, to develop metrics to quantify changes within the food system. A further benefit of a side-by-side analysis of four cities is describing the types of data that can be leveraged to conduct a first order analysis of an urban food system—a system that is notoriously data scarce and opaque (Barron *et al* 2010).

For each city, the analysis first leverages city specific data to develop baseline water, energy/GHG and land impact and then explores the questions of: what are instances where multiple food system objectives (i.e. health and environment) complement or conflict? what are the most strategic leavers to create change, whether within or outside the city boundary? and how can potential conflicts be mitigated through simultaneous food system actions? Quantifying the water, land and energy/GHG impacts of city-scale food system actions is necessary in a time of increasing resource scarcity and concerns of environmental sustainability.

METHODS

Case study city selection captures a wide spectrum of city food systems, with Table 5-1 describing city size, location, and food system features, capturing differences between industrialized and developing food systems, Western versus non-western diets and cities with high versus low levels of local agriculture. Minneapolis is here forward referred to as Hennepin County, which encompasses the city and surrounding area.

Table 5-1 | Description of case study cities and their food systems.

CITY	POPULATION	CITY & FOOD SYSTEM DESCRIPTION
Hennepin County (Minneapolis), U.S.	1.2 million (0.4 million city population)	-**Food system:** Industrialized -**Size:** Smaller city -**Diet:** Western with heavy meat consumption -**Local food system:** high amounts of local agriculture and food processing industry
New York City, U.S.	8.5 million	- **Food system:** Industrialized - **Size:** Larger city - **Diet:** Western with heavy meat consumption **- Local food system:** little local agriculture, some food processing, highly urban area
Delhi, India	16.4 million	**- Food system:** Developing, large informal sector - **Size:** Large city - **Diet:** Largely vegetarian, substantial under nutrition - **Local food system:** Some local agriculture and food processing
Pondicherry, India	1.2 million	- **Food system:** Developing, large informal sector - **Size** Medium-sized city - **Diet**: Largely vegetarian, substantial under nutrition - **Local food system**: High levels of local production and food processing

(Ministry of Home Affairs 2011, GNCTD 2013, U.S. Census Bureau 2010, United States Census Bureau 2010)

The general method for this analysis is outlined in Table 5-2, as a guide for city food system scenario analysis. Each stage of the method diagram of Table 5-2 corresponds with a different section of the methods and SI, providing a guide for urban food system analysis, no matter the city.

Table 5-2 | Steps of tool to develop the baseline environmental impact of food systems and change of environmental impact with future city-scale food system actions.

Step	Steps of scenario urban food system scenario analysis	
1	Quantify community-wide food demand	Include residents, visitors, industry
2	Current local production	Estimate current local production, by agri-food type
3	Supply chains	Estimate origins of production by agri-food type
4	Current in-boundary & trans-boundary environmental impact	Assess environmental impact of baseline system-wide in terms of water, land and GHG, including production, transport, processing, use, and waste management, making use of supply chain data, and designating impact as in- or trans-boundary
5	Future scenario development	Develop future food system action scenarios
6	Future scenario analysis	Model resulting change in environmental impact

1. **Quantify community-wide food use:** Community-wide food use includes food used by households, visitors, and industries within the city. The methods for determining community-wide food use make use of multiple data sources for each city. For India, the National Sample Survey reports city specific residential food use, (Ministry of Statistics and Programme Implementation 2011), industrial use is informed by a government survey detailing material inputs into food processing sectors (Ministry of Statistics and Programme Implementation 2013). Visitor use is informed by the by tourism data for each respective city, multiplied by an average meal weight. The total community-wide food use accounts for location-specific waste along the supply chain prior to end use.

In the U.S. the National Health and Nutrition Examination Survey reports the food intake of the average American, detailing differences by race, class, age, and gender (Centers for Disease Control and Prevention 2012). Visitor use is informed by tourism data and average meal weight. Industrial use within the city includes both food that is processed for local consumption as well as export. The quantity of industrial processing for local consumption is captured in the NHANES value of per capita residential use.

Thus to avoid double counting, for the quantity of agri-food inputs to industrial processing, we quantify only processing for export from the county, as reported by county-level IO table. The monetary export value multiplied by the Leontif matrix, provides the agri-food \$ inputs associated with the output of the food processing industries. This monetary value is converted to physical agri-food mass with a new B vector. This B-vector is a function of (mass of agri-food input, kg) / (total output of each of 9 primary and 4 meat producing sectors)

Local food processing serving local demand is accounted for the NHANES survey. The mass of food embedded in the local food processing for export is accounted by multiplying the export value from the county-level IO table by the Leontif matrix by a B vector of agri-food mass we developed.

This B-vector is calculated as: (mass of agrifood input, kg) / (total output of each of 9 primary and 4 meat producing sectors)

For the B-vector, Sherwood *et al* (2017) report primary producing sectors of:

kg/USD	**Sector**
5.6	Oilseed farming
10.32	Grain farming
2.22	Vegetable and melon farming
2.77	Fruit farming
1.27	Tree nut farming
0.071	Greenhouse, nursery, and floriculture production
29.57	Sugarcane and sugar beet farming
1.01	All other crop farming
0.00019	Forest nurseries, forest products, and timber tracts

We expand to meat and dairy categories of using national level production data and economic output:

kg/USD	**Sector**
0.01 (Meat) 4.8 (Milk)	Dairy cattle and milk production
0.17	Beef & cattle ranching and farming
0.97	Poultry and egg production
0.37	Animal production, except cattle, poultry, eggs

2. **<u>Estimate local production</u>:** Local availability is reported across agri-food types (crops and livestock productions) via multiple data sources (GOI Ministry of Agriculture 2011, U.S. Department of Agriculture 2017, GNCTD 2013, Ministry of Agriculture Deparment of Animal Husbandry 2014) For U.S. cities, the U.S. Department of Agriculture reports agri-food production statistics for each U.S. county, while National and State agricultural ministries report production and animal products for each district in India.

3. **<u>Supply chains</u>:** Linking urban demand with location of production is important for use of location specific resource intensity factors. Food supply chain data is particularly limited for cities. Data for Indian cities is available via a Government of India freight study linking urban demand with location of production of 13 food commodity groups (Planning Commission 2008).

   For U.S cities, there is no city-specific food supply chain data. Thus, to calculate spatially explicit GHG intensity factors for irrigation, this paper develops a to assess the sensitivity of 2nd order GHG emissions to various assumptions of the structure of city food supply chains. This work makes use for three approaches:

   1) Assume all food is produced in the state with maximum GHG intensity of irrigation
   2) Assume all food is produced in the state with lowest GHG intensity of irrigation
   3) Assume that production areas supplying urban demand our proportionate to each states' proportional contribution to the national supply. For instance, in state Y produces 10% of the national supply of oranges, then it is assumed that 10% of a city's supply of oranges will be from state Y. The resulting distribution of contributions by both domestic states and international locations results in a weighted average GHG intensity of irrigation.

Analysis at the state level

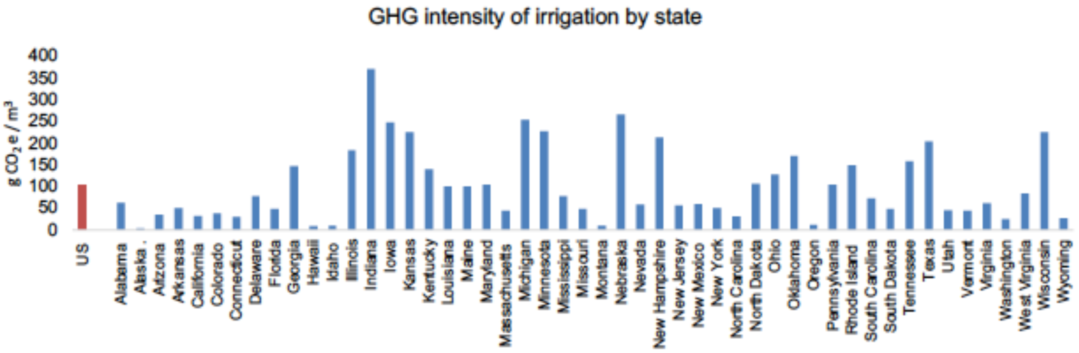
Total state-wise expenses of energy for irrigation are reported by the USDA National Agricultural Statistics Service (2013) across energy types. Multiplying by state specific energy prices provides total state-wise energy use for irrigation on an annual basis. The U.S Geological Service (Maupin *et al* 2014) reports by state total water use for irrigation on an annual basis. Dividing state total energy for irrigation by state total water use for irrigation multiplying by GHG intensity factors for each energy type (accounting for inter-state variation of GHG intensity of electricity as reported by the EPA eGRID (EPA 2018) yields state specific GHG intensity of irrigation, as described in Equation 5-1.

$$GHG\ intensity\ of\ irrigation\ in\ state_i =$$
$$\frac{Total\ energy\ for\ irrigation\ in\ state_i}{Total\ water\ use\ for\ irrigation\ in\ state_i} \times (GHG\ intensity\ of\ energy\ by\ type)$$

(5-1)

Applying Equation 5-1 to all 50 U.S states results in the distribution of GHG intensity of irrigation displayed in Figure 5-1.

Figure 5-1 | By-state variation of GHG intensity of irrigation.



Alaska reports the minimum intensity at 4.45 g CO_2 e / m^3, while Indian reports the maximum of 370 g CO_2 e / m^3, in comparison to the U.S average of 104 g CO_2 e / m^3.

4. **Environmental impact:** GHG, water and land impacts of production are calculated by specific resource intensity factors developed previously (Pathak *et al* 2010, Clark and

Tilman 2017, FAO 2017, Mekonnen and Hoekstra 2011). Second order GHG impact (on farm energy use for irrigation) is informed by supply chain data linking location specific energy intensity for irrigation with city demand.

Calculation of resource requirement of transport, use (household, commercial, industrial) and food waste management practices within the city are detailed in the SI.

This approach is compared with environmental extended input-output life-cycle assessment (EEIO-LCA) approach to compare this bottom up method with a top down approach. The U.S. Consumer Expenditure Survey (CEX) (U.S. Bureau of Labor Statistics 2011) provides household expenditure by food grouping, quantifying food both food taken within, and outside the home. Using the Carnegie Mellon (2008) EIO-LCA database, allows calculation of water, GHG and land impacts of the whole economy related attributed to per capita food use food use. CEX was chosen over the and Personal Consumption Expenditure data (PCE) (Proximity One 2015) due to its greater detailing of food items. PCE data reports the dollar amount of food purchased at home as 36% higher than the CEX data.

5-6. Scenario development and analysis: Scenarios fit within the categories of: city equity and health, city diet change, urban agriculture, city food preparation, city food-waste management, and trans-boundary reference scenarios. The categories are informed by actual food policy agendas and city action plans. Each city action, however, is customized to each city, in order to develop strategies accounting for specific city conditions and reasonable diets for local culture. The scenario analysis quantifies the water, energy/GHG and land impact of city-scale food system actions across various objectives. The following outlines the associated rationale of each policy grouping, with methods detailed in the SI.

City equity and health: Improving health and equity of diet is a concern no matter global location, though the nature of diet-related disease varies by location. In India, hunger and undernutrition remain substantial challenges, (WFP 2016). In the U.S. and other developed nations, overconsumption of salt, fat and sugars, often in the form of processed food results in many diet-related concerns (Garnett 2014). This can present a greater challenge to evaluate than a simple adjustment of the types of food eaten, as the health effects are often a result of how the food is prepared and processed. In light of these challenges, in the case of Indian cities, this scenario examines an increase of protein and calories to a level of sufficiency, while the U.S. cities examines the whole of the city populations consuming in accordance with the national level dietary recommendations, with the assumption that such a diet will lead to improved health.

City diet change: Diet change is often promoted as a means to minimize environmental impact (Bajželj *et al* 2014, Garnett 2011). Some cities are even beginning to discuss policies aimed at curbing currently consumption levels of animal products (i.e. Turin (Marsh and Owens 2016)). Yet diet change recommendations are usually made with an assumed universal diet, without considering regional variation (Garnett 2011). For instance, the common recommendation of decreasing meat consumption is not so applicable in the predominantly vegetarian cities of India. This scenario explores which diet changes are most effective in the various city contexts, conscious of city diet variation, while still meeting the nutritional meets of the residents.

Urban agriculture: Ranging from increased livelihoods, to supposed environmental benefits, urban agriculture is being promoted in cities all over the world (Hamilton *et al* 2014, Mok *et al* 2014). The nature of urban agriculture, however, varies across cities in terms of quantity, and crops produced. This scenario looks in- and trans-boundary resource implications of increasing urban agriculture and its contribution to local food supplies with both conventional soil-based methods as well as hydroponic vertical farming technologies (VFT).

City food preparation: Practices of city food preparation vary across country contexts. In some cases, city food preparation is known to cause substantial GHG and air pollution emissions (Boyer and Ramaswami 2017, Parikh 2011). This scenario set explores the resource impact of movement away from existing cooking energy fuel towards preferable alternatives, based on city-specific policy and location.

City food waste management: Food waste often receives substantial attention for both issues related to methane emissions of landfilling, waste resources, and public health hazards (Eriksson *et al* 2015, U.S. Environmental Protection Agency 2017). Policies at both local and national levels exist around the world aimed at mitigating food waste impacts (European Commision 2016, U.S. Environmental Protection Agency 2017). Yet the nature of waste is known to vary between country context. In India, for example, waste occurs predominant upstream of the end user as a result of poor transport and storage infrastructure, (Gustavsson *et al* 2011) while in the U.S. waste is more concentrated at the consumer level (Heller and Keoleian 2014).

Table 5-3 summarizes each city's food system action for each respective category, and the rationale for each scenario.

Table 5-3 | Urban food system scenario development for four cities to analyze change in system-wide GHG emissions, consumptive water loss and land use associated with each future food scenario.

	DELHI & PONDICHERRY	HENNEPIN & NEW YORK
City equity & health	-The lowest 50% of the population by socio-economic-class (SEC) consuming same diet as median SEC population *To achieve sufficiency in calories and protein, to address high levels of undernutrition (National Institute of Nutrition 2011).*	-100% of population consuming the recommended U.S. dietary guidelines *To address levels of over consumption in the U.S. (U.S. Department of Health and Human Services & U.S. Department of Agriculture 2015)*
City diet change	-100% of rice consumption to wheat; -100% of rice consumption to sorghum; -100% of rice consumption to millet; -100% of meat consumption to pulses; *To explore reduction potentials targeting rice consumption and associated methane emissions of production in a largely vegetarian country (Pathak et al 2010).*	-100% of population consuming a vegetarian diet (as determined by the U.S. government guidelines) -100% of meat consumption to pulses -100% of dark meat (i.e. beef, mutton) consumption to light meat *To address levels of high meat consumption environmental impact (Weber and Matthews 2008).*
Urban agriculture	-Doubling of current ag production levels -Shift of all viable in-boundary production to VFT -Shift of all viable crops to VFT *To assess current proposed action towards localization (Association for Vertical Farming 2016, Hamilton et al 2014).*	-Doubling of current ag production levels (at county level) -Shift of all viable in-boundary production to VFT -Shift of all viable crops to VFT *To assess current proposed action towards localization (NYC Council 2010, City of Minneapolis 2016).*
City food preparation	-All cooking fuels to liquefied petroleum gas (LPG) *To assess action called for by government initiative (Ministry of Petroleum and Natural Gas 2016).*	-Switch from household electric cooking to renewables *To assess action called for by state renewable targets (Minnesota State Gov't n.d., NY State Gov't 2015).*
Food waste management	-All household organics to composting -All household organics to anaerobic digestion *To better manage household organic waste of kitchen scraps (Nagpure et al 2015).*	-All food waste to composting -All food waste to anaerobic digestion -Elimination of avoidable (excluding peels, etc.) household and commercial food waste *To assess management options of the high quantities of edible and non-edible consumer-level food waste (Heller and Keoleian 2014).*
Trans-boundary reference: Pre-consumer food waste	-Decrease of food waste to international best practice *To address high levels of pre-consumer food waste from poor storage and transport infrastructure (Gustavsson et al 2011).*	-Decrease of food waste to international best practice *To address reduction of pre-consumer food waste (Heller and Keoleian 2014).*

DETAILED METHODS

This section includes detailed methods and data for the Hennepin County (containing the city of Minneapolis and adjoining areas) New York City, and Pondicherry analyses. The full Delhi analysis is included in Chapters 2 & 3.

Community-wide food use

Community-wide food use includes food used by residents, visitors and industry.

Residential

Residential food use for U.S cities is determined by national scale data of the National Health and Nutrition Examination Survey Data (Centers for Disease Control and Prevention 2012). This survey, conducted by the Centers for Disease Control reports individual food intake as determined from a sampling of 5,000 individuals in the U.S. across demographic characteristics. Pondicherry's residential food use is determined the Government of India (GOI) National Sample Survey data (Ministry of Statistics and Programme Implementation 2011).

Commercial

Commercial food includes food that was eaten by city residents outside the home as well as that eaten by visitors and commuters.

Resident food eaten outside is reported at the national scale by a recent study as an average of 114 meals/year. A per meal weight was assigned as 1 kg food per meal (determined by dividing total annual food use by estimated number of meals).

Visitor food use is determined by the total annual visitors multiplied by average stay duration times an average of three meals per day with data from local tourism statistics

(Meet Minneapolis 2017, NYC & Company 2017, Department of Tourism Government of Puducherry India n.d.)

For commuter use, the U.S. Census Bureau reports daily commuters between counties in the U.S. Thus the total daily influx of commuters is the difference between incoming workers and outgoing residents. This number is scaled with an assumed 1 meal per day, 5 days per week during the year. No data was available for Pondicherry commuters.

Industrial

Input-output data for each city reports the economic activity of each city's food processing industries. Using a method outlined by Sherwood et al, each dollar of output is associated with a kg of raw food input, yielding a total raw food input into the city's food processing industry. Pondicherry's industrial food use is available with the GOI Annual Survey of Industry Data (Ministry of Statistics and Programme Implementation 2013) reporting agri-food by food processing industries.

The following Table 5-4 provides the numbers and data sources for Pondicherry, Minneapolis, New York.

Table 5-4 | Community-wide food use across residential, commercial and industrial demand.

	PONDICHERRY		**HENNEPIN**		**NEW YORK**	
Residential food (tons)	**823,161**	(Ministry of Statistics and Programme Implementation 2011)	**703,914**	(Centers for Disease Control and Prevention 2012)	**4,610,155**	(Centers for Disease Control and Prevention 2012)
Commercial food (tons)	**42,578**	(Department of Tourism Government of Puducherry India n.d., Ministry of Statistics and Programme Implementation 2011)	**482,651 total** *(201,497 – residential)* *(198,871 – visitor)* *(82,284 – commuter)*	(Liu *et al* 2015, Meet Minneapolis 2017, U.S. Census Bureau 2013)	**2,582,056 total** *(1,346,711 - residential)* *(790,603 – visitor)* *(444,742 – Industrial)*	(U.S. Census Bureau 2013, Liu *et al* 2015, NYC & Company 2017)
Industrial food (tons)	**1,177,519**	(DES 2010b)	**15,026**	(IMPLAN 2014a)	**651,143**	(IMPLAN 2014b, Sherwood *et al* 2017)

Uncertainty

Compared to electricity and water-use data reported by utilities, greater uncertainty can be expected in estimating community-wide food use. Community-wide food use includes household consumption, visitor consumption and food use by industries. Of these contributions, residential consumption dominated across all three cities, and thus the focus of the uncertainty analysis.

National scale NHANES data estimates residential food use in both Hennepin and New York. Each city's total community-wide use was based on a reported average national-scale per capita use. This per food type average was compared with its sensitivity to demographic variations of gender, race and income, which yielded a percent error of <3% across all major food groups (Centers for Disease Control and Prevention 2012). Uncertainty analysis of NSS data used to calculate Pondicherry's residential data is included in the SIs of Ramaswami et al 2017 and Boyer and Ramaswami 2017.

Local production

Local food production is reported per county by the U.S Department of Agriculture per crop and livestock product (U.S. Department of Agriculture 2017). Pondicherry's local production is reported by the Ministry of Agriculture (Government of India Ministry of Agriculture 2011, Ministry of Agriculture Deparment of Animal Husbandry 2014). Figure 4-3 of the main text illustrates the quantity of local demand (solid bar) as a percentage of total community-wide demand.

Supply chains

India food supply chain data is available through a Government of India study of multi-modal freight transport, reporting food commodity origin-destinations (Planning Commission 2008). We used two approaches to estimate origin of production serving New York and Minneapolis demand. The first assumes that a state's contribution to any city's food supply is proportional to that states contribution to the national supply as reported by U.S. Department of Agriculture data (U.S. Department of Agriculture 2017). For example, if a state produces 50% of the country's orange supply, it provides 50% of the city's orange supply. We incorporate international contribution to urban supply with the U.S. of county-level input-output tables (IMPLAN 2014a, 2014b). The second method is a physical model of the agri-food supply chains, emulating methods used to estimate trade between countries in the field of economics, also known as gravity modelling as developed in (Nixon and Ramswami 2018 – under review). Both methods for the U.S. link location of production with consumption, but do not calculate total supply chain distance.

Baseline environmental impacts: water, energy/GHG, land

Baseline environmental impacts of water, energy/GHG and land include impacts from production (1st and 2nd order), transport, processing, use, and waste management.

Production – 1st & 2nd order impacts GHG: The baseline water, GHG and land footprints of production multiply the quantities of community-wide food use by crop-specific resource intensity factors. GHG emissions for New York and Hennepin use average GHG intensity factors (Clark and Tilman 2017) based primarily on developed country studies. India-specific GHG intensity factors for agriculture inform the GHG footprints of production for Pondicherry (Pathak *et al* 2010). This work expands upon 1st order GHG impacts to include GHG emissions from electricity and diesel use for irrigation referred to in this paper as "2nd order emissions," as first described in Ramaswami et al. 2017. The GHG intensities are location specific, with a state-specific calculated GHG emissions per m^3 irrigation water applied. We calculated GHG per unit water irrigation by dividing state totals of energy used for agriculture by total state-wise irrigation quantities, (Maupin *et al* 2014, Carolina *et al* 2013) then allocated emissions based on agri-food specific irrigation requirements.

Production - Consumptive water loss: U.S. specific consumptive water loss intensity factors for blue and green water are provided by Mekonnen and Hoekstra (2011), reported per ton of crop (Mekonnen and Hoekstra 2011). The total community-wide footprint of production is described by Equation 5-2, where *i* denotes the food type *i*=153 for India, and *i*=214 for the U.S.), IF is consumptive water loss intensity factor associated with agricultural production and the water for energy for irrigation.

Production – Land: The land requirements are based off of FAOSTAT's (FAO 2017) reporting of per crop yields for 2011, the year of study. Land footprinting was carried out in accordance with the methods of prior food land footprinting studies (Gerbens-Leenes *et al* 2002, Bruckner *et al* 2015) .The authors acknowledge uncertainties regarding potential multi-cropping (multiple crops occupying the same land) and limited data on India-specific animal land requirements. Yet as noted by others (Bruckner *et al* 2015) this is a common uncertainty involved in land footprinting studies. A recent review of land footprinting studies, for example, noted that only three of 41 studies attempted to factor in the impact of multi-cropping and fallow (Bruckner *et al* 2015).

The GHG, consumptive water loss and land footprints of production are described by equations, 5-1, 5-2, and 5-3 respectively. The land footprint of production is described by Equation 5-3. Each intensity factor (IF) is crop specific, denoted by i.

$$GHG\ footprint\ of\ production = \sum_{i=0}^{n}(Community - wide\ food\ use_i) \times \left(IF_{agriculture,i}^{GHG} + IF_{irrigation,i}^{GHG}\right) \quad (5\text{-}1)$$

$$Water\ footprint\ of\ production = \sum_{i=0}^{n}(Community - wide\ food\ use_i) \times \left(IF_{agriculture,i}^{water} + IF_{irrigation,i}^{water}\right) \quad (5\text{-}2)$$

$$Land\ footprint\ of\ production = \sum_{i=0}^{n}(Community - wide\ food\ use_i) \times \left(IF_{agriculture,i}^{land}\right) \quad (5\text{-}3)$$

Processing: National total GHG emissions and water associated with processing of per capita food consumption are reported for India (DES 2014) and the US (U.S. Energy Information Administration 2014). Accounting for the proportion of total output serving domestic demand, divided by total country population and multiplying by the respective resource intensity factor results in a water and GHG intensity per capita for processed food consumption of 8 m^3 water and 0.58 t CO_2e per year for the US, and 0.014 m3 water and 0.0036 t CO_2e per year for India. Scaling by each respective city population provides the city-wide total.

Transport: For New York & Minneapolis, lacking city specific supply chain data, Weber and Matthews (2008) provide an average GHG emissions of 0.91 tons t CO_2e per household for food transport, or 0.48 t CO_2e/ton food item. This value multiplied by each city's community-wide food demand determines the estimated GHG emissions attributed to freight transport. Average foodmiles and associated GHG emissions for transport for Pondicherry are informed by a government of India report on multi-modal freight transport, connecting location of production with urban food demand (Planning Commission 2008).

Use: Table 5-5 described in-boundary food activities, resource intensity factors and parameter for scale up.

Table 5-5a | Hennepin County water, energy and GHG resource impact of the in-boundary food system activity.

HENNEPIN COUNTY					
Interaction	**Intensity factor**		**Parameter for scale up**		**Subtotal**
	Intensity factor	**Data source**	**Activity parameter**	**Data source**	
1. Water for in-boundary food use (Category total: 132 M m^3)					
Water for growing agri-food	**0 - 19,745** green m^3/t crop, C **0-5,084** blue m^3/t crop, C	Crop specific – (Mekonnen and Hoekstra 2011)	**18,406** tons in-boundary agri-food production, by specific crops	(U.S. Dept of Agriculture 2017)	**110 M m^3**
Water for cooking (residential)	**15-45 (28.25)** L/person/day	(Gleick 1996, Howard and Bartram 2003)	**1,223,149 × 365** Population × days	(United States Census Bureau 2010)	**58 M m^3**
Water for food preparation (Hotel and restaurant, commercial)	Restaurant				**6 M m^3**
	10-61(36) l/meal	(American Water Works Association 2000)	**170,405,246** commercial meals served	(Meet Minneapolis 2017, Liu *et al* 2015)	
	Hotel				**<1 M m^3**
	63-69 (66) L/guest/night	(International 2016, EarthCheck Research Institute 2013, U.S. EPA 2012)	**10,159,000** visitors × nights stayed	(Meet Minneapolis 2017)	
Water for food processing (industrial)	**8** l/USD	(Carnegie Mellon 2008)	**516,933,753** USD output of Hennepin County food processing industry	(IMPLAN 2014a)	**4 M m^3**
2. Energy for in-boundary food use (Category total: 7,569,188 MWh / 3,723,725 t CO_2 e)					
	Cooking				
Energy for residential food use, (Cooking, refrigeration)	**1.97** MWh/household/yr	(U.S. Dept. of Energy 2011)	**522,864** households in Hennepin County	(United States Census Bureau 2010)	**462,647 MWh/ 288,674 t CO_2 e**
	Refrigeration				
	660	(U.S. Dept. of Energy 2011)	**1.3 × 522,864** (Fridge/household) × (households)	(EIA 2017)	**460,120 MWh/ 287,097 t CO_2 e**
Energy for food preparation (commercial :	*Restaurant*				**241,782 MWh / 91,975 t CO_2 e**
	.11-2.54 (1.4) kWh/meal	(U.S. Dept of Energy 2011, American Water Works	**170,405,246** commercial meals served	(Meet Minneapolis 2017, Liu *et al* 2015)	

restaurants, hotels)		Association 2000)			
	Hotel				**61,970 MWh / 11,224 t CO_2 e**
	6 kWh/guest/night	(U.S National Grid & Energy Information Administration 2004, Gautam *et al* 2010)	**10,159,000** visitors × nights stayed	(Meet Minneapolis 2017)	
Energy for food processing (industrial)	**1.43** kWh/USD	(Carnegie Mellon e 2008)	**516,933,753 USD** output of food processing industry	(IMPLAN 2014a)	**739,939 MWh / 458,762 t CO_2 e**
Energy for urban ag	**96** kWh/m3	Author calculated	**1.465** m3 groundwater for irrigation	(Maupin *et al* 2014)	**141,149 MWh / 88,072 t CO_2 e**

Table 5-5b | New York water, energy and GHG resource impact of the in-boundary food system activity

NEW YORK					
Interaction	**Intensity factor**		**Parameter for scale up**		**Subtotal**
	Intensity factor	**Data source**	**Activity parameter**	**Data source**	
1. Water for in-boundary food use (Category total: 194 M m^3)					
Water for growing agri-food	**0 - 19,745** green m^3/t crop, C **0 - 5,084** blue m^3/t crop, C	Crop specific – (Mekonnen and Hoekstra 2011)	**64 tons** in-boundary agri-food production, by specific crops	(U.S. Dept of Agriculture 2017)	**< 1 M m^3**
Water for cooking (residential)	**15 - 45 (28.25)** L/person/day	(Gleick 1996)	**8,174,962 × 365** Population × days	(U.S. Census Bureau 2010)	**84 M m^3**
Water for food preparation (Hotel and restaurant, commercial)	Restaurant				
	10 - 61(36) l/meal	(American Water Works Association 2000)	**1,793,094,193** meals served	(Liu *et al* 2015, U.S. Census Bureau 2013, NYC & Company 2017)	**11 M m^3**
	Hotel				
	63 - 69 (66) L/guest/night	(International 2016, EarthCheck Research Institute 2013, U.S. 2012)	**183,010,000** visitors × nights stayed	(NYC & Company 2017)	**53 M m^3**
Water for food processing (industrial)	**6.8** l/USD	(Carnegie Mellon 2008)	**6,611 million USD** Output of New York City's food processing industry	(IMPLAN 2014b)	**45 M m^3**
2. Energy for in-boundary food use (Category total: 14,582 GWh / 4,767,383 t CO$_2$ e)					
Energy for residential food use, (Cooking, refrigeration)	*Cooking*				
	1.98 MWh/household/yr	(U.S. Department of Energy 2011)	**3,129,147** households in NYC	(U.S. Census Bureau 2010)	**6,199 GWh / 1,404,276 t CO$_2$ e**
	Refrigeration				
	660 kWh/fridge/yr	(U.S. Department of Energy 2011)	**1.15 × 3,129,147** (Fridge/household) × (households)	(U.S. Census Bureau 2010, EIA 2017)	**2,375 GWh / 1,282,512 t CO$_2$e**
Energy for food preparation (commercial: restaurants, hotels)	*Restaurant*				
	1.4 kWh/meal	*(Author calculation from hotel food prep energy use)*	**1,793,094,193** meals served	(Liu *et al* 2015, U.S. Census Bureau 2013, NYC & Company 2017)	**2,544 GWh / 460,817 t CO$_2$ e**
	Hotel				**1,116 GWh / 202,204 t CO$_2$ e**
	6.1 kWh/guest/nig	(U.S National Grid & Energy	**183,010,000** visitors × nights	(NYC & Company 2017)	

	ht	Information Administration 2004, Gautam *et al* 2010)	stayed		
Energy for food processing (industrial)	**0.36** kWh/USD	(Carnegie Mellon 2008)	**6,611 million USD** output of NYC’s food processing industry	(IMPLAN 2014a)	**2,380 GWh / 1,285,250 t CO_2 e**
Energy for urban ag	**0**	(n/a)	**0**	(n/a)	**0**

Table 5-5c | Pondicherry water, energy and GHG resource impact of the in-boundary food system activity

PONDICHERRY

Interaction	Intensity factor		Parameter for scale up		Subtotal
	Intensity factor	**Data source**	**Activity parameter**	**Data source**	
1. Water for in-boundary food use (Category total: 461.5 M m^3)					
Water for growing agri-food	**138 – 14,270** green m^3/t crop, C **0 - 600** blue m^3/t crop, C	Crop specific – (Mekonnen and Hoekstra 2011)	**7,122,667 tons** in-boundary agri-food production, by specific crops	(DES 2013, NHB 2011, Ministry of Agriculture Deparment of Animal Husbandry 2014)	**17,640 M m^3**
Water for cooking (residential)	2-**10** L/person/day	(Gleick 1996, Howard and Bartram 2003)	**1,247,953 × 365** Population × days	(DES 2013)	**5 M m^3**
Water for food preparation (Hotel and restaurant, commercial)	Restaurant				**12 M m^3**
	36 L/meal	(DPCC 2013)	**323,428,111** Meals served	(FHRAI 2012)	
	Hotel				**2 M m^3**
	128 – 160 (**144**) L/guest/night	(DPCC 2013)	**1,352,095** Pondicherry visitors × nights stayed	(Ministry of Tourism 2010)	
Water for food processing (industrial)	**0.034** L/INR	(Nestlé 2014, Nestlé India Limited 2014)	**2.94×10^{10} INR** Output of Pondicherry food processing industry	(DES 2014)	**1 M m^3**
2. Energy for in-boundary food use (Category total: 7,569,188 MWh / 3,723,725 t CO_2 e)					
Energy for food use, (Residential: cooking)	1.25 – **2.43** MWh/household/yr	(de la Rue du Can *et al* 2009)	**301,565** households in Pondicherry	(DES 2013)	**732,801 MWh / 188,022 t CO_2 e**
Energy for in-boundary food transport	*Assumed to be relatively small based on field observations of large numbers of non-motorized rickshaws and carts hauling agricultural products within the city from freight centers. To be verified in future work.*				
Energy for food preparation (commercial: restaurants, hotels)	*Restaurant*				**646,856 MWh / 164,807 t CO_2 e**
	0.57-3.5 kWh/meal (**2 kWh/meal**)	*(Author calculation from hotel food prep energy use)*	**323,428,111** All-Pondicherry meals taken outside the home (restaurants, business, other)	(MSPI 2011)	
	Hotel				**6,287 MWh / 1,601t CO_2 e**
	2.3-7 kWh/ guest/night (**4.65 kWh**)	(Bhatt *et al* 2005, ICH 2012)	**1,352,095** visitors × nights stayed in Delhi	(Ministry of Tourism 2010)	
Energy for food processing (industrial)	**0.0017-0.011** kWh/INR	(Nestlé India 2014, Ministry of Agriculture	**2.94×10^{10} INR** output of Delhi food processing industry	(DES 2014)	**319,627 MWh / 44,714 t CO_2 e**

		Deparment of Animal Husbandry 2014)			
Energy for urban ag	**Reported at scale** (CEA 2011)				**56,600 MWh/ 44,714 t CO$_2$e**

Food waste generation and management

Pondicherry Food Waste Generation

Households = (120 kg/capita) x (1,244,464) = 149,754 (Nagpure *et al* 2015)

Commercial & Industrial = unknown

Hennepin Food Waste Generation

Consumer level (homes, eating establishments) = (163 kg per capita) x (1,152,425 population) = 187,673 tons (Heller and Keoleian 2014, United States Census Bureau 2010)

Retail level = (59 kg/capita) x (1,152,425 population) = 68,245 tons (United States Census Bureau 2010, Heller and Keoleian 2014)

Industrial = (15,026 tons industrial food use) x (7% loss) = 1,052 tons (Sherwood *et al* 2017, Heller and Keoleian 2014)

TOTAL = 256,970 tons

New York Food Waste Generation

Residential: (163 kg per household) x (3,129,147 households) = 510,051 tons from curbside pickup (Study 2013, U.S. Census Bureau 2010)

Commercial: Reported as a total of 600,000 from restaurants, grocery stores, hospitals, cultural, educational institutions (PlanNYC 2011)

Retail: 484,108 tons (PlanNYC 2011, Heller and Keoleian 2014)

Industrial: (651,143 tons of industrial food use in NYC) x (7% loss) = (45,580 tons) (Sherwood *et al* 2017, Heller and Keoleian 2014)

TOTAL: 1,183,031 tons

Table 5-6 | Food waste generation quantities, management, and emissions of food waste in Pondicherry, Hennepin & New York

	Total food waste (t)	Composting		Landfill		Total food waste emissions (t CO_2e /yr)
		Quantity managed (t)	Emissions factor (kg CO_2 e/t waste)	Quantity managed (t CO2 e/t waste)	Emissions factor (t CO2 e/t waste)	
Pondicherry	149754	n/a	--		0.7 (Aye and Widjaya 2006)	104,678
Hennepin	256,970	346	-160 (Levis and Barlaz 2011)	256,624	0.69 (Levis and Barlaz 2011)	121,710
New York	1,627,739	12,000		1,171,031		1,121,220

Liquid waste generation & management

Table 5-7 | Liquid waste generation quantities, management and emissions in Pondicherry, Hennepin, and New York

	Annual wastewater generation (mil gal)	GHG emissions (t CO_2e/mil gal)	Emissions generated (t CO_2e)	Data sources
Pondicherry	13,113 (6,605 treated)	0.63 – treated 2.05 - untreated	17,501	(Chavez *et al* 2012, Center on Hygeine Sanitation Sewage Treatment Systems and Technology 2016)
Hennepin	39,898	1.76	70,220	(Hillman and Ramaswami 2010, Metropolitan Council 2013)
New York	474,500	1.00	476,279	(City of New York Mayor's Office of Sustainability 2016)

Scenario development and analysis

Table 5-8 provides an overview of the scenarios applied to the U.S. and India cities. Methods for the U.S. cities follow, while methods for Delhi and Pondicherry can be found in the Supplementary information for Boyer and Ramaswami 2017. All methods reported for Delhi in Boyer and Ramaswami 2017 are directly applied to Pondicherry, modifying the baseline footprint described above (Boyer and Ramaswami 2017).

Table 5-8 | Overview of city-scale food system actions in Delhi, Pondicherry, New York and Hennepin.

SCENARIO	DELHI & PONDICHERRY	HENNEPIN & NEW YORK CITY
City equity & health	• Lowest 50% of the population by SEC consuming same diet as median SEC population	• Whole of population consuming at USDA recommended values
City diet change–objective of sustainability	• Rice to wheat • Rice to sorghum • Rice to millet • Meat to pulses	• Meat to pulses • Light meat to dark meat • USDA recommended vegetarian diet
Urban agriculture	• Doubling of current ag production levels • Shift of all viable in-boundary production to vertical farming technology (VFT) • Shift of all viable crops to VFT	• Doubling of current ag production levels • Shift of all viable in-boundary production to VFT • Shift of all viable crops to VFT
City food preparation	• All cooking fuels to liquefied petroleum gas (LPG)	• Switch from gas and electric to renewable fueled electricity
City food waste management	• All household organics to composting • All household organics to anaerobic digestion (AD)	• If total quantity of HH food waste was composted • If total quantity of HH was AD'd • If total quantity of avoidable HH was eliminated
Trans-boundary reference scenario	• Decrease of food waste to international best practice	• Decrease of pre-consumer food waste to international best practice

Equity & health

All food items currently consumed as determined by the NHANES data, (Centers for Disease Control and Prevention 2012) were adjusted to fit within the U.S. government dietary guidelines of a "healthy" diet (U.S. Department of Health and Human Services & U.S. Department of Agriculture 2015). Food conversions are on a calorie to calorie basis.

Diet change

<u>*USDA recommended vegetarian diet*</u>: This scenario adjusts all food items currently consumed as determined by the NHANES data, (Centers for Disease Control and Prevention 2012) to fit within the U.S. government dietary guidelines for a vegetarian diet (U.S. Department of Health and Human Services & U.S. Department of Agriculture 2015).

Meat to pulses: This scenario converts entirety of annual meat consumption to pulses/legumes on a calorie-for-calorie basis.

Dark meat to light meat: This scenario converts entirety of annual dark meat (beef, mutton) consumption to light meat (poultry) on a calorie-for-calorie basis.

Urban agriculture

Increase of conventional urban agriculture: This scenario doubles production levels of current soil-based agriculture. Crop types are held constant.

Shift of all viable in-boundary production to VFT: From a technical stand point, all crops can be grown with soilless techniques. In reality, however, only a small subset tends to be grown, that of smaller, more compact plants, with quicker harvest periods—shown to be the most economically viable in the current agricultural system (Kozai 2013). This includes small fruiting plants (tomatoes, strawberries, etc.), leafy greens (microgreens, lettuce etc.) and some tubers (carrots, potatoes) (Specht *et al* 2014). Typically excluded are larger, slower growing plants such as and tree crops (oranges, apples etc.) and crops able to store for longer periods, namely grains (rice and wheat) (Yamori *et al* 2014). Therefore, in the case of the VFT scenarios, non-tree fruits and vegetables were considered "viable." All the remaining food items were assumed to be produced with current soil-based methods. This scenario converts only crops currently grown with in the city/county boundary

Estimating the water and energy/GHG intensity factors of vertical farming growing techniques posed a significant challenge. As an emerging technology, there have been very few LCA studies assessing the water and energy/GHG intensity of crop production with VFT (Specht *et al* 2014). A recent review of agriculture-building integration discovered only 19 peer-reviewed articles at all addressing the topic of vertical farming (this also included rooftop soil-based farming), with even fewer addressing resource use intensity (Specht *et al* 2014). The few that have been conducted make evident the context specificity of resource intensity use (Sanye-Mengual *et al* 2015, Mok *et al* 2014, Marris 2010). Particularly for energy/GHG, the variables of determination are many, including ambient temperature, natural lighting, degree of technological control, indoor versus outdoor setting, building materials, and technology employed. Generally, VFT on a crop weight comparison is considered more energy intensive than that of conventional methods. Assessing trade-offs between conventional field versus VFT methods presents a substantial challenge and thus GHG/energy was excluded from this scenario analysis.

VFT water intensity is more generalized in the literature than that of energy/GHGs. While water requirement is also context variable, the figure of a 70% reduction from conventional field methods across all crop types tends is commonly referenced as a conservative estimate (Despommier 2010, International Water Management Institute 2007, Despommier 2013). Others list a reduction of even greater savings such as a 2015 study (Barbosa *et al* 2015) reporting of 92% water use reduction of hydroponic lettuce versus conventional methods, while others report as high as 80% reduction (Linsley and Caplow 2008). Thus, lacking water intensity figures at any greater detail, a 70% reduction in water requirement from the baseline field water requirement (Mekonnen and Hoekstra 2011) was assumed, with the potential range reflected in the error bars of the calculation displayed in the main manuscript.

<u>Shift of all viable crops to VFT</u>: Using the same selection criteria for viable as the above description, this scenario applies VFT to all viable crops serving city demand, both within, and beyond the city boundary. The crops converted to VFT are located within the city boundary.

Food preparation

<u>Change of cooking fuel</u>: Switch from electric to renewable fueled electricity: Current energy provided by electricity is converted to carbon neutral renewable sources from current energy mix from baseline quantification.

Food waste management

<u>Food waste to compost</u>: This scenario examines the GHG reduction of addressing city food waste through composting. The calculation of the GHG reduction is described by Equation (A4-4).

$$Food\ waste\ GHG\ reduction_{composted\ foodwaste, AD\ foodwaste} = (Foodwaste\ diverted\ from\ landfill) \times (EF\ landfill\ foodwaste) - (\ Foodwaste\ diverted\ from\ landfill) \times (EF_{composted\ foodwaste, AD foodwaste}) \quad \text{(A4-4)}$$

> Landfilled emissions factor (EF): 0.69 t CO2e/t food waste (U.S. average)
> (Levis and Barlaz 2011)
> Composted EF: -0.16 t CO2e/t food waste (average of multiple composting technologies in the U.S.)
> (Levis and Barlaz 2011)
> Scenario assumes all community-wide food waste currently landfilled is composted.

Composting requires no additional water inputs as the natural water composition of food waste of 75% (Lee *et al* 2007) falls within the range of acceptable water content (Makan *et al* 2014).

Food waste to anaerobic digestion*:* This scenario examines the GHG reduction of addressing city food waste through anaerobic digestion. The calculation of GHG reduction is described by Equation (4-4).

> Landfilled EF: 0.69 t CO2e/t food waste (U.S. average) (Levis and Barlaz 2011)
> AD EF: -0.458 t CO2e/t food waste (U.S. average) (Levis and Barlaz 2011)
> Emissions factors of food waste management:
> Landfilled: 0.69 t CO2e/t food waste (U.S. average) (Levis and Barlaz 2011)
> Composted: -0.16 t CO2e/t food waste (average of multiple composting technologies in the U.S.) (Levis and Barlaz 2011)
> Scenario assumes all community-wide food waste quantified is composted.

Wet anaerobic digestion requires a solids content of 10-20%, with an average 15% assumed for this calculation (Angelonidi and Smith 2015). Food waste, on average, is estimated on average to have about 25% solids content (Lee *et al* 2007). Therefore, every ton of food waste requires an additional 667 kg of water (approximately 0.667 m^3 water). Multiplying this figure by the total composted waste provides the additional water burden of these processes.

Elimination of avoidable food waste: According to USDA food loss surveys, 18 of the 22% of food loss at the consumer level is edible (Heller and Keoleian 2014). This scenario examines the change in environmental impact when edible food waste (excludes peals, etc) is avoided. The GHG, water, and land savings are calculated as a function of both avoided production impacts and avoided landfilled food waste.

Trans-boundary reference scenario

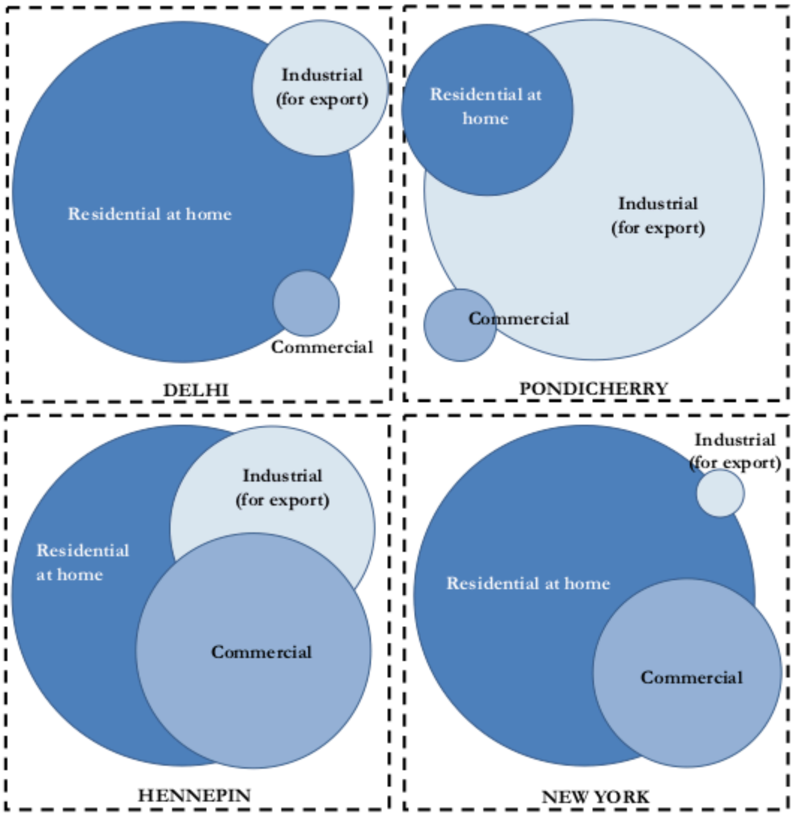
Pre-consumer food waste: This scenario decreases the quantity of farm to retail losses from 24% (16% farm to retail, 8% retail) to international best practice of 13% in the Netherlands, as determined by a literature review reported in Boyer & Ramaswami 2017.

RESULTS

Baseline food flows

Figure 5-1 illustrates the distribution of food flow by sector across cities, of residential, commercial and industrial end-users, with circle size for each city proportional to total sector demand by mass. Pondicherry demonstrates an instance of industrial processing dominating the community-wide food flow at 58% of the total, while Hennepin and New York demonstrate food systems where residential-at-home demand greatly dominates at 59% of the total flow by mass for both cities. Delhi’s food system is also dominated by residential-at-home demand at 69% of the total, followed by industrial use at 23% of the total.

Figure 5-2 | Distribution of community-wide food flows by end user of residential at home, commercial residential use, commercial visitor use, and industrial use across the four cities. Each color indicates a different end user.



Baseline footprints

Figure 5-3 illustrates the system-wide baseline footprints of the four cities in terms of GHG (Delhi: 18.5 Mil t CO_2e; Pondicherry: 3.8 Mil t CO_2e; New York: 41.3 Mil t CO_2e; Hennepin: 5.9 Mil t CO_2e), water (Delhi: 17,494 Mil m^3; Pondicherry: 21,041 Mil m^3; New York: 22,309 Mil m^3); Hennepin) and land (Delhi: 4.8 Mil ha; Pondicherry: 1.1 Mil ha; New York: 4.3 Mil ha; Hennepin: 0.6 Mil ha). Each stage of the food system is marked by a distinct color, with hatching denoting trans-boundary resource impact occurring outside of the city boundary, and solid coloring indicating in-boundary resource impact.

Across all four cities, nearly 100% of the system-wide water and land impact is concentrated in the stage of agricultural production. In the case of GHG, agricultural production also dominates, though is more distributed throughout the system, with substantial in-boundary emissions at 28, 64, 27, 31% of the total GHG emissions for Delhi, Pondicherry, New York, and Hennepin, respectively. With the exception of Pondicherry, the production-level resource impacts occur beyond the city boundary (indicated by the hatched pattern). Pondicherry has substantial local food production with high water requirement and GHG impact, though relatively little reported land use for agriculture. Figure 5-4 provides details of local provisioning across the four cities.

A noticeable difference of resource use between the cities is the required energy and GHG for food processing for industrialized cities. For the industrialized food systems of New York and Hennepin, 21% and 19% of the total GHG footprint is attributed to processing of food serving residential demand, for New York and Hennepin respectively. This is in comparison to a negligible contribution to system-wide GHG totals in the developing food systems of Delhi and Pondicherry.

Figure 5-5 describes the in-boundary resource use supporting urban food system activity, able to inform issues of local resources scarcity. Urban agriculture is dominant in terms of in-boundary food-system use in all cities except for New York (coinciding with Figure 5-4). Household energy use for cooking dominates across all cities in terms of GHG and energy.

Figure 5-3 | Environmental footprints assessed across the urban food system serving community-wide demand in four cities in terms of GHG emissions (top), consumptive water (middle) and land use (bottom) footprints of four cities. Each color is associated with a different stage of the food system of production (blue), processing (orange), transport (purple), multiple uses (greens), and food waste management (reds). In-boundary impact is indicated with hatching while solid shading indicates in-boundary impacts. City footprint totals are displayed by the grey bars to the right of the figure.

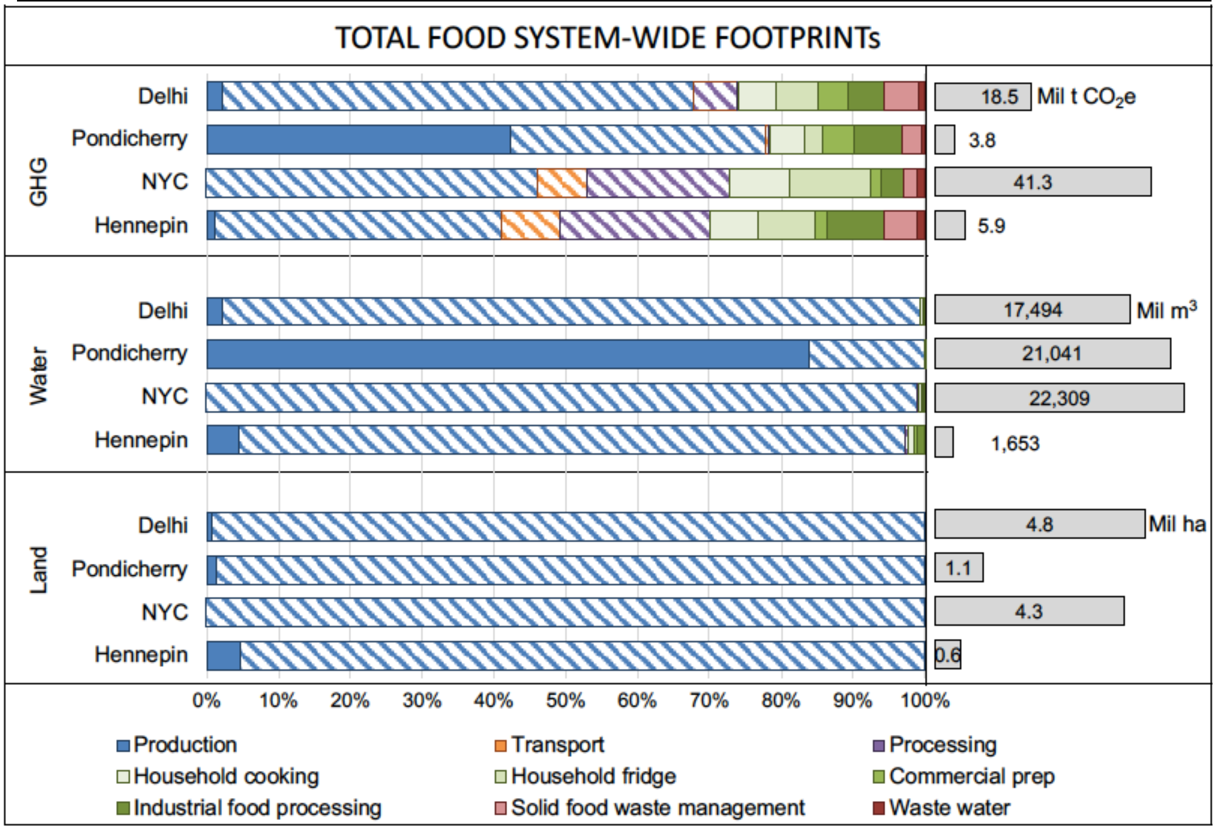


Figure 5-4 | Local availability versus trans-boundary supply serving city community-wide demand for four cities by agri-food type. Local production is illustrated with the solid bar, with the remaining trans-boundary requirement illustrated with hatching.

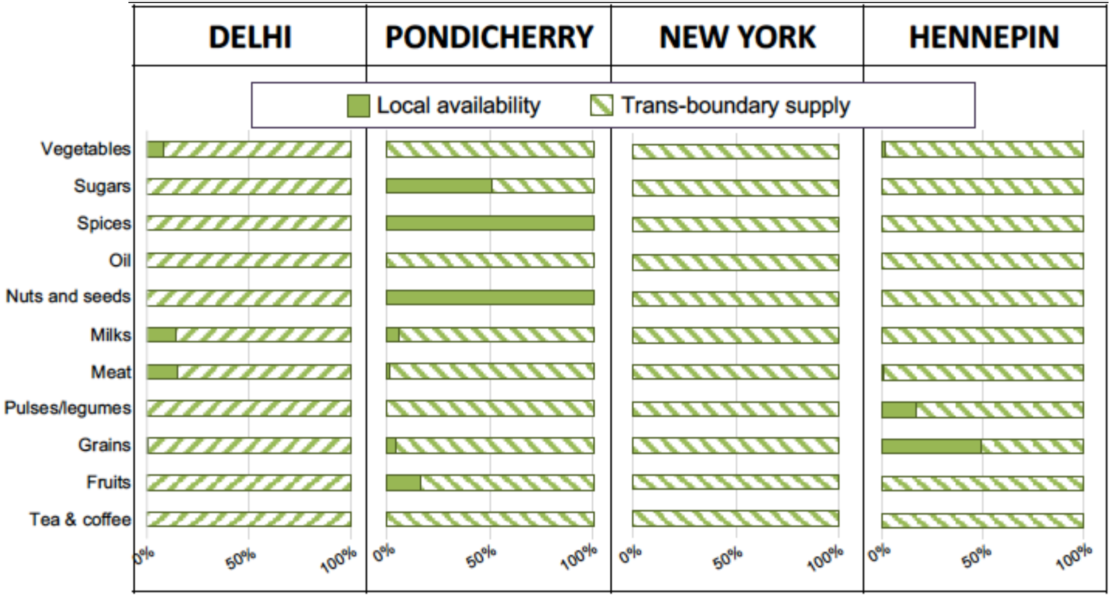


Figure 5-5 | Resource use supporting the in-boundary urban food system quantified in terms GHG emissions, energy and consumptive water loss (blue & green). Uses are shown as a percentage of total in-boundary impact related to food-related activities. Each color represents a different activity as a percentage of the total in-boundary resource use supporting the urban food system to illustrate dominance of impact of particular food related activities.

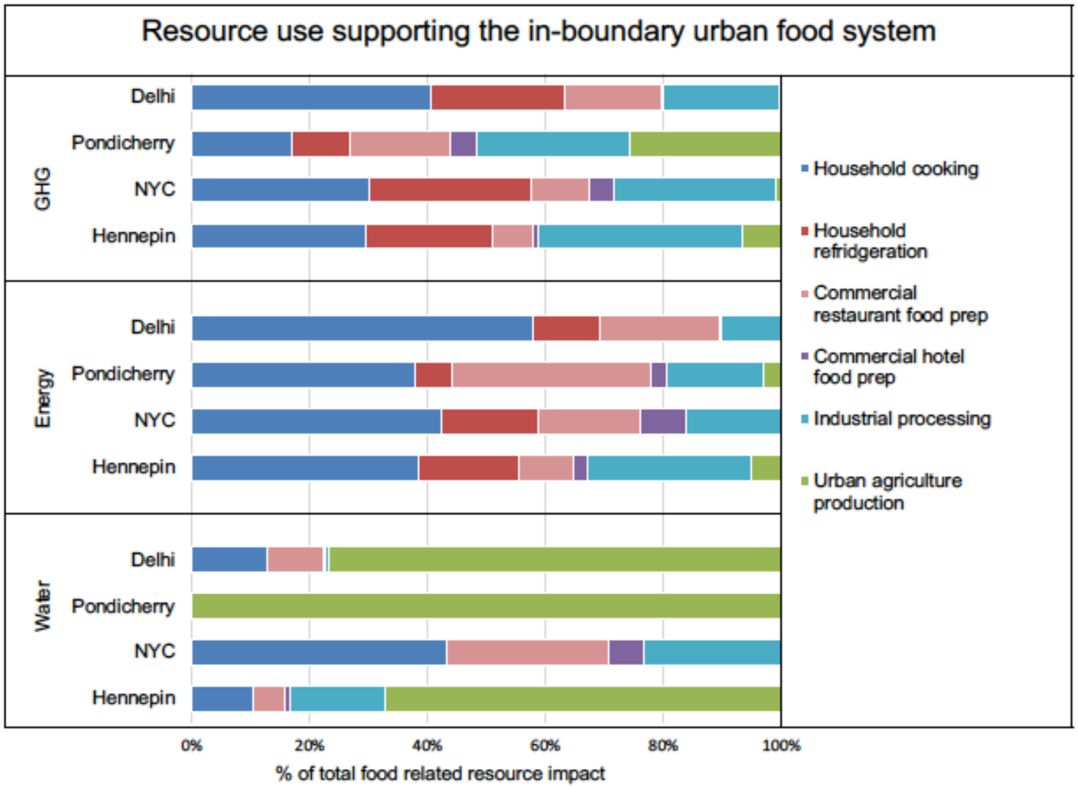


Figure 5-6 | Percentage contribution of 1st versus 2nd order GHG emissions of agri-food production serving the per capita food demand of a complete diet of Pondicherry, Delhi, and U.S. average. 1st order impact is split between emissions directly from animals, animal feed, and all other crop production.

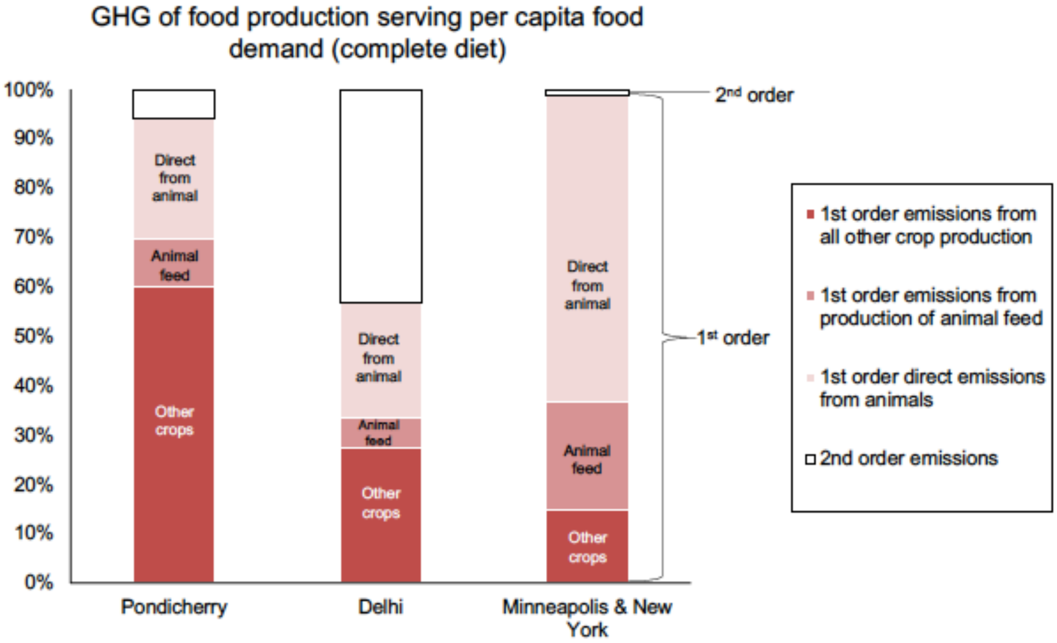


Figure 5-6 illustrates the percentage contribution of 1st versus 2nd order GHG emissions of food production serving the entire per capita dietary demand of Pondicherry, Delhi with the average U.S. diet. Second order emissions contribute 6%, 43%, and 1% of the combined first and second order emissions for Pondicherry, Delhi and U.S. cities respectively. Within 1st order emissions, those attributed to crop production (excluding animal feed) dominate in the case of Pondicherry and Delhi, at 64, and 48% of first order emissions. In the case of the U.S. direct animal emissions dominate, contributing 63% of 1st order emissions.

Figure 5-7 | Sensitivity of 2nd order emissions to inter-state variability (Figure 5-1) and the three supply chain assumptions outlined in the methods as a percentage of GHG of food production serving the complete diet of U.S. per capita food demand

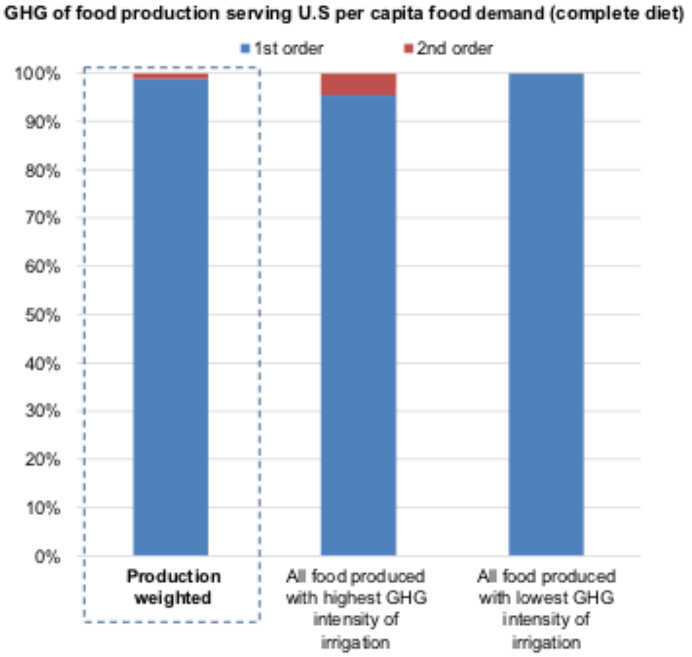


Figure 5-7 illustrates the sensitivity of 2nd emissions from irrigation to production location as a percentage of the GHG of production serving the complete diet of U.S. per capita demand. When production locations serving urban demand are proportional to the contribution to nation-wide supply, 2nd order impacts account for 1% of combined 1st and 2nd order emissions. When all food is assumed produced with the high GHG intensity of irrigation, 2nd order impacts contribute 5% of the total, and <1% when all food is produced with the lowest GHG intensity of irrigation.

Comparison with EEIO-LCA approach

Table 5-9 presents a comparison of water, land and GHG impacts serving U.S per capita food demand with the bottom-up process-based approach of this paper, with the top-down EIO-LCA analysis. For land, GHG, and water (EIO-LCA only quantifies blue water), the EIO-LCA approach reports a higher value. This is expected considering its boundary being the whole economy, though illustrates the bottom up method as providing comparable results given the smaller boundary of analysis.

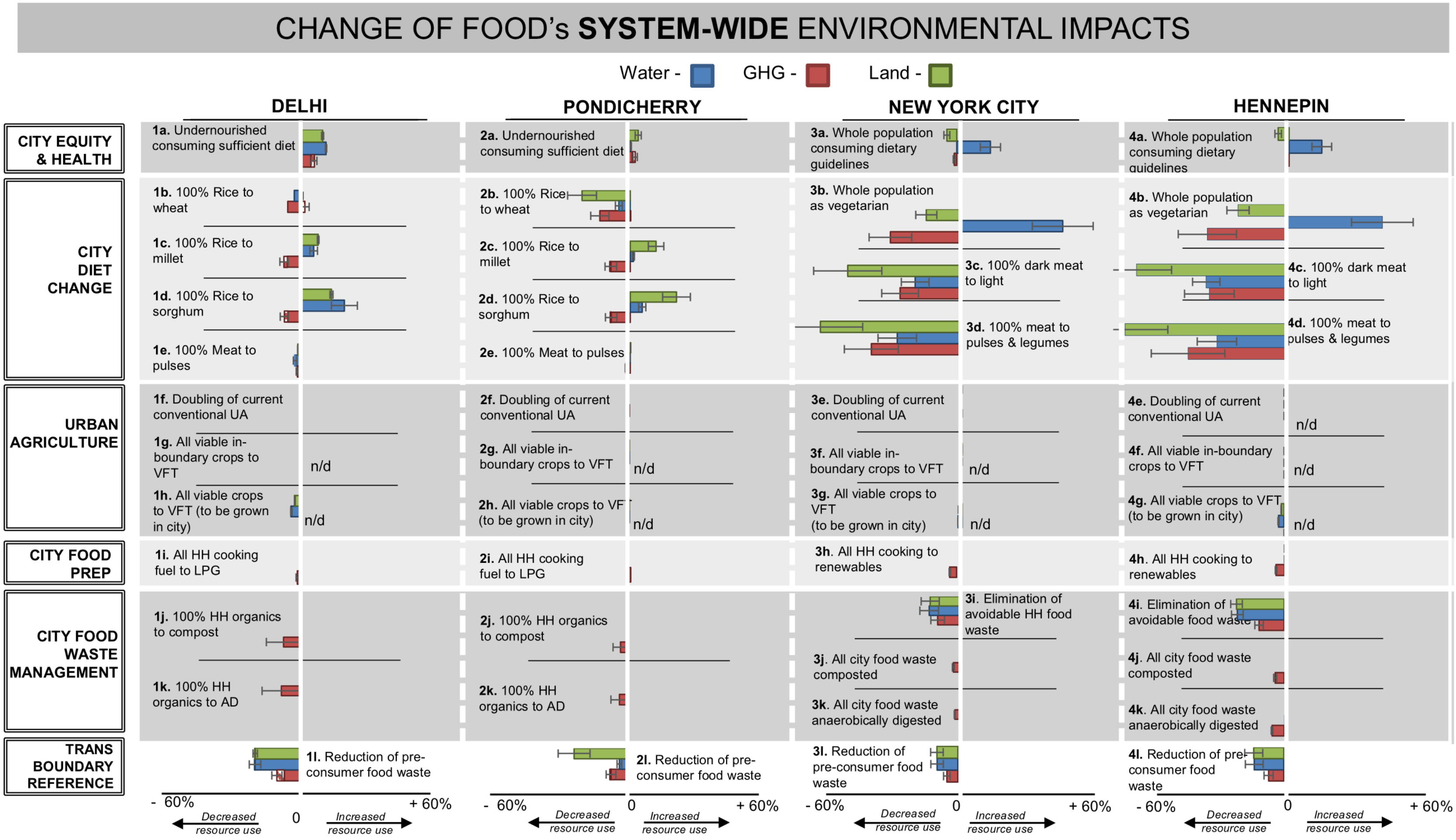
Table 5-9 | Comparison of water, land and GHG impacts of bottom up approach of this paper, in comparison with the top-down EIO-LCA approach of combining consumer expenditure data (CEX) with Carnegie Mellon's (2008) EIO-LCA database).

	Bottom up process-based (this paper)	**Top-down EIO-LCA** (Carnegie Mellon 2008)
Notes:	*Smaller boundary, crop by crop*	*Contributions from the whole U.S. economy*
Water (m^3)	1,143 (blue + green)	849 (blue only)
Land (ha)	0.42 (farm only)	1.43
GHG	2.94	3.59

Scenario analysis

Figure 5-8 displays the resulting change of system-wide GHG (red), water (blue) and land (green) impacts of each city-scale action described in Table 5-3 across the four cities (Delhi – a, Pondicherry – b, New York – c).

Figure 5-8 | Percent reduction of annual system-wide food GHG, water, and land impacts as a result of 100% adoption of food system scenarios. Results are shown as a percentage change to the system-wide water (blue), GHG (red), and land (green) food footprint and expressed in terms of 1st order (solid bars) and 2nd order (hatched bar) impact. (*n/d indicates insufficient data to determine a result). Error bars represent the range of intensity factors and technology each scenario



Equity

For both Indian cities, increasing the nutrition status of the socio-economic classes currently reported as undernourished was associated with only moderate increase of resource use in terms of land, water and GHG for Delhi (8%, 9%, 4%) and Pondicherry (3%, 1%, 2%). Improving the nutrition of New York and Hennepin to be in line with the current U.S Dietary Guidelines is associated with modest decreases of system-wide land (New York: -4%; Hennepin: -6%) and GHG (NYC: -1%; Hennepin: -2%) though a comparatively larger increase in water (New York: 12%, Hennepin: 11%). This increase is largely attributed to the high dairy recommendation of U.S. Dietary Guidelines.

City diet change

In the case of all four cities, diet change presents a large lever for cities to mitigate environmental impacts. This potential impact is much greater for Western cities due to their baseline diet high in meat consumption, in comparison with the largely vegetarian Indian cities. For instance, the largest reduction of GHG reduction potential via diet change for Delhi was -6% (rice to sorghum) and -11% for Pondicherry (rice to wheat), though nearly all (except wheat replacement) diet changes had an associated increase in water and land impacts. In the case of US cities, however, the GHG reduction potential for NYC and Hennepin were 50% and 56%, respectively, when 100% is changed in favor of pulse and legume products, with associated reduction in water and land as well.

Urban agriculture

A doubling of urban agriculture has little system-wide GHG, water and land impact across all four cities, with < 1% system-wide change across all three measures. Application of VFT as well had little system-wide water and land reductions for all cities (Delhi: -4%, -3%; Pondicherry: <-1%; <-1%; New York: -2, -1; Pondicherry: <-1%; <-1%). GHG reduction was unable to be quantified due to data limitations.

City food preparation

Changes from current cooking fuel to LPG for Pondicherry and Delhi result in a GHG reduction of 1 and 2%, respectively. Switching current electricity use for home cooking to renewable sources in New York and Hennepin results in a 3 and 4% reduction in GHG, respectively.

City food waste management

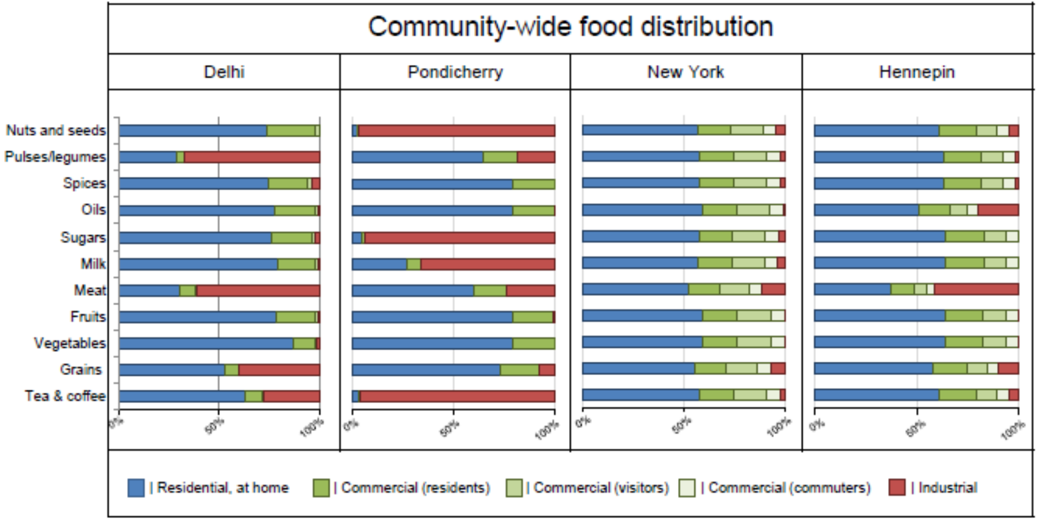
In the case of both Pondicherry and Delhi, food waste management provides GHG reduction benefit by both composting (3%, 6%) and AD (3%, 7%). While Hennepin and New York do also receive benefit from management of food waste through composting (Hennepin: 3%, New York: 2%) and AD (Hennepin: 5%, New York: 3%), a far greater resource benefit is achieved through elimination of avoidable (excluding non-edible organics, i.e. vegetable peels) household food waste, exhibiting a system-wide land, water, and GHG benefit of 18%, 17%, 11% for New York and 18%, 18%, 9% for Hennepin.

Trans-boundary reference scenario

In the case of Delhi, the trans-boundary intervention of decreasing pre-consumer food waste shows the greatest reduction across land, water and GHG impacts (-16%, -16%, -8%). A similarly high reduction potential exists for Pondicherry of -19%, -3%, and -6%, for land, water and GHG. The land, water and GHG reduction associated with the trans-boundary reference scenario the US cities is -8%, -8%, -4% for New York and -11%, -11%, -6% for Hennepin.

SUPPLEMENTARY RESULTS

Figure 5-9 | Community-wide distribution of food use by type and user, for Delhi, Pondicherry, New York and Hennepin.



DISCUSSION

This paper illustrations the insight able to be gained through application of the community-wide food system framework. Despite the diversity of food system and data sources, the framework proves able to provide policy relevant analysis of the GHG, land and water impacts. This tool can fill the current gap of analysis tools able to guide city actions in developing informed policies to both mitigate the environmental impact of their food system, as well as understand the trade-offs and co-benefits with tandem food system objectives (i.e. improved nutrition).

Application of the community-wide systems framework to four diverse cities, illustrates the many inter-city differences in food system between the cities in terms of both community-wide food demand and associated environmental impact. In terms of the baseline impacts, a key different is the additional emissions associated with energy for food processing in U.S. cities. On a per capita basis, the GHG requirement of food processing in the U.S. versus Indian diet is 579 kg CO_2e/capita/year versus 4 kg CO_2e/capita/year, and 8.65 m^3 versus 0.014 m^3 water withdrawal, respectively.

This illustrates the increased environmental burden of processing that might occur as countries pursue greater industrialization of their food system. This is important to highlight as many countries pursue processing as a means to decrease food waste, an explicit plan of the Indian government, (PTI 2017) where increased emissions from processing may negate some benefit from decreased food waste.

A further structural difference in food system characteristics is that between the contribution of emissions attributed to irrigation to total GHG emissions of production serving urban demand between Indian and U.S. cities. The relatively low contribution of 2nd order impacts for U.S. cities (~1%) in comparison to Indian cities, can be explained by a combination of reasons. First, as illustrated by Figure 5-6, the high meat diet of the U.S results in much higher direct animal emissions. Further, there is greater mechanization of the U.S. farm system, increasing the contribution of 1st order on-farm emissions. In addition, low efficiency of irrigation is known problem in India, thus requiring higher energy and emissions per unit of irrigation water. Lastly, according to theoretical crop water demands as modeled by Mekonnen and Hoekstra (2011) U.S. crops rely to a greater degree on rain-fed irrigation than India, further decreasing the energy that is needed to irrigation. These four conditions, combine to explain the far lesser contribution of 2nd order emission to the whole of the emissions serving the complete diet of urban demand in U.S.

As illustrated by Figure 5-7, this results in narrow variation in the contribution of 2nd order impacts based on production location. This highlights a key difference in quantification of second order impacts between India and the US, with the Indian supply chains key in incorporating inter-state variation of 2nd order impacts, with supply chains in the U.S. of far lesser importance in capturing differences of irrigation efficiency. However, we must note that this lesser importance of supply chains is limited to 2nd order impacts of irrigation only, and does not incorporate variation of fertilizer application, which could provide much greater inter-state variation of emissions (i.e. Smith *et al* 2017) and acknowledging the benefit of supply chain analysis for risk analyses.

Despite differences of food system characteristics, this analysis showed that all cities could take action within their food systems to rival actions taken outside of the city. This indicates that cities do indeed have a role to play in shaping the water, energy/GHG and land impact of the overall food system—a notion cities need to be cognizant of as they pursue diverse food system agendas in concert with sustainability objectives and increasing resource scarcity.

The trans-boundary reference scenario provides the greatest reduction potential for Delhi in terms of all three impacts and for Pondicherry in terms of land, though single trans-boundary impacts (i.e. water, land or GHG in singularity) are rivaled by specific in-boundary actions such as in-boundary food waste management and diet change. For New York and Hennepin, however, the trans-boundary reduction potential is dwarfed by in-boundary diet change actions and in-boundary food waste reduction. This is largely a result of the dominance of meat consumption on total impact and greater food waste occurring at the consumer level than further up the supply chain. This indicates the magnitude of the role that cities can have, particularly in industrialized food system.

Applied to two cities with high under nutrition (Delhi and Pondicherry) this analysis illustrates the gains that can be made in achieving greater nutrition without necessarily substantial increase in resource use. It is important to note, however, that this improved nutrition is modeled within the structure of a largely vegetarian diet of lesser resource intensity. Further, these increases in resource requirements can be offset by simultaneous city-scale food system actions such as food waste management and tandem diet changes of higher classes.

This analysis also demonstrates the dominance of city diet change as a tool to mitigate environmental impact, particularly in U.S. cities, when viewed in tandem with other potential food system actions. However, interference with diet tends to be met with substantial resistance, no matter if the motivation is health or environment, with claimed encroachment of individual freedom (Marsh and Owens 2016). This presents urgency in developing behavioral and policy tools able to better achieve diet change. Further, the analysis shows the importance of coordinating diet changes aimed at improved health with those of environmental objectives. For instance, the U.S. dietary guidelines, as they currently stand, calls for very high diary consumption, requiring a large increase in water use, which can be at odds with environmental objectives.

The tool applied in this paper is not meant to be instructive in advising what actions a city should take. Rather, it is meant to provide a quantitative analysis to assess environmental impact of food system actions, fully coconscious of the many competing priorities of urban food systems. For example, the sustainability impact of increasing urban agriculture was negligible across all cities, despite wide-variation in urban agricultural practices. This once again suggests that counter to the current trend of city policy, localization initiatives do not have the advertised environmental benefits. However, this is not to negate urban agriculture as a tool to achieve other food system objectives.

The method presented can be paired with more in-depth analyses of, for example, health and employment. For example, for the case of Hennepin County, local agriculture provides 259 jobs. Thus, a double of existing output could result in an additional 259 local jobs (assuming linear scaling of jobs with output). Such an analysis can be conducted for each of the scenarios presented in this paper and weighed with environmental outcomes. The environmental analysis of this paper can also be paired with more rigorous health analysis, again increasing the number of food system objectives able to be assessed. In this paper, we assess the change of environmental impact associated with a universal city compliance with national dietary recommendations as a means to address health. However, this analysis could be expanded to determine the exact health benefit of this move, expressed in terms of annual deaths, in accordance, for example, with approaches such as the global burden of disease. This analysis would allow better examination of diet change scenarios in particular, to determine quantitatively for both health and environment, which initiative provides greatest advantage.

ACKNOWLEDGEMENTS

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CHAPTER 6 | Conclusions & the current state of urban food policy

City food policy programs & objectives

In the North America and Europe in particular, some leading cities have begun developing food policy programs, formally located within the city government. The nature of these programs, however, varies by city, particularly with respect to level of city support and its position within the city government (Hatfield 2012). For example, Minneapolis and Seattle house their food policy programs in the city sustainability departments, while Philadelphia, San Francisco, and Toronto operate their food programs out of the city health departments, while others still operate directly out of the mayor's office, the departments of social development, plan, economic development, or split between a combination thereof. This illustrates the challenge of where to situate a food policy program that affects so many city priorities and the limitation of addressing the inherent nature of food policy from within strict disciplines. For instance, Minneapolis's food policy program, "Homegrown Minneapolis," transitioned from the health department to the sustainability office, the a sustainability officer stating that, " 'Health had done a lot…but because of the grants, it didn't allow for some movement into environment and economic development and things like that,' " (as reported in (Hatfield 2012)). This illustrates the "very real impact that bureaucratic location can have on program priorities [i.e. health, environmental, economy]," (Hatfield 2012).

City food policy councils & food action plan objective

While the focus of food system actions (i.e. environment, economic development, health etc.), are largely guided by where the program is located within the city government, it also substantially influenced by the make-up of the food policy council. One common component of city food policy programs is the establishment of a food policy council (i.e. Los Angeles, Minneapolis, Toronto, etc. (TFPC 2012, LAFPC 2016, City of Minneapolis 2016)). These councils tend to be a combination of city appointees and community representatives, with meetings often open to the public. Minneapolis, for example, has a council of 25 members, comprised of 15 community members, 6 city representatives, one representative community member appointee of the Parks and Recreation Board, one representative and one community appointee from the Minneapolis Public Schools. In coordination with respective food policy coordinators, these councils are largely responsible for the direction of a city's food policy action. The council holds monthly meetings open to the public, with the majority of policy work is accomplished through various task groups. The author of this dissertation was one such community member invited to serve on the Food Policy Council.

A main strength of this approach is its incorporation of the larger city community into discussions of food policy. However, the current approach to urban food policy is not without limitation. For instance, the councils are largely comprised of volunteers. While one should not discount the effort and ability of a committed group, the lack of compensation calls into question the importance that cities are placing in addressing food issues. Should the improvement of a system that supports so many city interests (health, equity, environment) be predominantly an endeavor of volunteers and non-governmental organizations?

The mandates of food policy councils tend to be so expansive, that the outputs of specific actions and objectives tend to be confused. For example, in the case of Minneapolis, the city tracks progress by metrics of outputs of a particular program, such as the number of urban gardens, or chickens within the city. They do not, however, track how these outputs link to the objectives of improving environmental sustainability. Further, the connection between actions, outputs, and outcomes is tenuous. In the case of Minneapolis, for example, the objectives include addressing the food system as it relates to the economy, health, food security, environment, social connectedness, and food safety (City of Minneapolis 2016). As taken directly from the Homegrown Minneapolis Website, the objectives of the food council include:

- ***Health:*** *Increasing consumption of healthy foods contributes to improved nutrition and reduced levels of obesity and other chronic diseases.*

- ***Food Security:*** *The ability for residents to grow, process sell and easily obtain a consistent, adequate supply of fresh, sustainably grown, local foods can empower families and communities to be more self-sufficient.*
- ***Environment:*** *Producing and buying sustainably grown, local food can improve:*
  Water and soil quality by reducing chemical and water usage; and
  Air quality by reducing the amount of transportation and packaging required to bring our food from farm to table, thereby by decreasing pollution.
- ***Social Connectedness:*** *A local food system enhances community cohesion and encourages individuals to share resources in order to provide for the collective needs of their neighbors and the community as a whole.*
- ***Food Safety:*** *Food grown locally can be processed and distributed by small and mid-size operations where careful attention can be paid to food quality and safety measures.*

However, despite such expansive objectives, in practice, attention of the food policy council tends to be far narrower, predominantly determined by the combination of council interest and expertise. Much attention of urban food policy councils, for example, falls on the promotion of urban agriculture. To-date, a major focus on the council has been the breaking of barriers to urban agriculture, such as allowing the growing of produce on park land. Yet recalling multiple council objectives (economy, health, food security, environment, social connectedness, and food safety), there exists limited research able to link the action of urban agriculture with largely influencing these objectives. So much so that increasing urban agriculture is frequently being misinterpreted as an outcome or objective until itself, rather than an intermediate output, that leads to one of the broader objectives listed above.

Previously, these linkages were limited due to both data and method limitation. This dissertation, however, develops methods to link specific food system actions specifically to create stronger linkages with the broader objectives, evaluating measures of environmental sustainability as a city pursues objectives of food security, economy, and health, for example. Chapter 2 develops methods to overcome data challenges related to estimating community-wide food use, supply chains, and environmental impact. Subsequent Chapters 3-5 develop, and implement, methods in multiple countries to address data challenges and inform food system actions. These methods allow for the needed linkages between actions (i.e. urban agriculture) and multiple objectives (i.e. health, environment, etc.).

For example, in all four cities of Pondicherry, Delhi, Minneapolis, and New York City, the action of doubling current levels of urban agriculture have negligible environmental system-wide benefit across GHG, water, and land. Rather alternative actions, namely food waste management, and diet change actions provided greater reduction potential. The methods can also begin to quantify the linkages of actions with additional objectives, such as food security, and economy. For example, Chapter 5 finds that for the city of Minneapolis, doubling current urban agriculture could meet 20% of Minneapolis's food demand by mass (though this proportion is not distributed evenly across food items, but largely skewed towards grain items) (addressing the objective of 'food security'), and quantifies jobs related to current and doubled urban agriculture as 259 additional jobs (addressing 'economy'). However, these analyses of economy and food security could be further expanded to gather finer scale, city-specific detail on widespread urban food actions.

While this dissertation creates clear methods to establish a linkage of city-scale food system actions with environmental objectives, disaggregating, land, water, and GHG impacts as trans- or in-boundary, for other objectives, the linkages remain tenuous. For example, in the case of health, while the linkages between health and the food system are clear, we do not know which city-scale food system actions will actually result in an improvement of health—whether backyard gardens, community-gardens or food vouchers or other alternatives are most effective. Similarly, we do not have much understanding of which actions lead to improved objectives of social connectedness, economy, and food safety. Without these methods, cities will continue to pursue actions that do not necessarily align with the stated overarching objectives.

Weighting of multiple objectives

A further challenge in creating food action plans is the weighting of multiple objectives within the bounds of limited funding. Even if tools are available to quantify actions with relation to the multiple of objectives of, for example, health and environment, the city will need to prioritize which objective to pursue, particularly in regards of potentially conflicting objectives. For example, should a city pursue dietary recommendations that substantially exacerbate environmental impacts? Or even within the objective of "environment," there are questions of the weighting of multiple environmental indicators. For example, multiple diet changes aimed at decreasing GHG emissions, are associated with an increase in water and, or, land. This question becomes further complicated when incorporating issues of equity, health, and resilience. These decisions should not be made arbitrarily, or by a single entity, but should be reconciled in advanced, through substantial community outreach. Cities should engage in substantial consultation with diverse community representatives. Group design charrettes can help cities to develop visions of an ideal food system, incorporating stakeholders both within, and outside the city, with varying objectives. Incorporating food user feedback early, through methods such as human center design and contingent valuation will further aid in the success of food programs.

Multi-level urban food policy

Further, as discussed throughout this dissertation, the food system supporting urban demand is trans-boundary and thus crosses multiple scales of government including county, state, national and international jurisdictions. Thus, cities need to incorporate attention to this multi-level governance structure, to both understand potential limitations of their own actions and coordinate efforts. For example, cities may encourage a particular diet change. However, this shift in demand needs to be met with a coordinated shift production, where production is largely regulated and influenced, via subsidies, at the national level, through, for example, the U.S. Farm Bill. Thus establishing these linkages is important to help create the trans-boundary change need to improve the urban food system. Linkages with various levels of government also present the opportunity to leverage greater resources than may be available at the city level by coordination of overlapping objectives. For example, a county health department, may be able to provide resources to a city food program for projects related to health.

Developing comprehensive food action plans

Developing comprehensive food action plans, provides a way for cities to pursue coordinated food action planning that gives attention to the various food system objects, as prioritized by diverse community stakeholders. While some cities have established so-called "food action plans," without the methods to link actions to outcomes that lead to improvement of the objectives, the documents remain mainly aspirational in nature, often falling trap to confusing outputs (i.e. increasing number of community gardens) with outcomes (i.e. demonstrating decreased environmental impact) with established links to overarching objectives (i.e. environment, health, equity). This is particularly important when proposing change within the food system—a system which can be notoriously limited in its allowance for government interference. Thus plans must be innovative to incorporate multiple stakeholders and means to achieve the much-needed change in urban food systems of today.

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