

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

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# Environmental Research Letters



## LETTER

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

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Supplementary material for this article is available [online](#)

## Abstract

This paper develops a generalizable systems framework to analyze the food-energy-water (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 FEW supply-chain risks posed to cities by the environment. Delhi's community-wide food demand includes household consumption by socio-economic-strata, visitors- and industrial food-use. This demand depends 90%, 76%, and 86% on trans-boundary supply of FEW, respectively. Supply chain data reveal unique features of trans-boundary FEW production regions (e.g. irrigation-electricity needs and GHG intensities of power-plants), yielding supply chain-informed coupled energy-water-GHG footprints of FEW provisioning to Delhi. Agri-food supply contributes to both GHG (19%) and water-footprints (72%–82%) of Delhi's FEW provisioning, with milk, rice and wheat dominating these footprints. Analysis of FEW interactions within Delhi found >75% in-boundary water-use for food is for urban agriculture and >76% in-boundary energy-use for food is from cooking fuels. Food waste-to-energy and energy-intensity of commercial and industrial food preparation are key data gaps. Visualizing supply chains shows >75% of water embodied in Delhi's FEW supply is extracted from locations over-drafting ground water. These baseline data enable evaluation of future urban FEW scenarios, comparing impacts of demand shifts, production shifts, and emerging technologies and policies, within and outside of cities.

## 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 *et al* 2012) associated with food supply. Nationally, in the US, approximately 45% of all water withdrawals are for cooling of thermoelectric power plants, followed by agricultural use (33%) and 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 aims to achieve greater self-reliance in the face of supply risks (DVRPC 2011). In reference to water, San Francisco's Climate Action Strategy states the need to protect the city's water supply from climate disruptions (SF DOE 2013).

Many of these plans make reference to the role of the food system in sustainability objectives such as mitigating GHG and water impact (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 authors concluded that '*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. USGS 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 within their own 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 ground water irrigation, the extent of ground water overdraft, and the fuel mix and carbon intensity of regional electricity grids. For example, India's northwestern state of Punjab overdrafts ground water 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, developing spatially detailed supply chains 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 US, Australia and China (Ramaswami *et al* 2008, Hillman and Ramaswami 2010, Baynes *et al* 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. 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 chain relationships (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 operations or thermal power generation occurring within 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 on national or global water and energy flows.

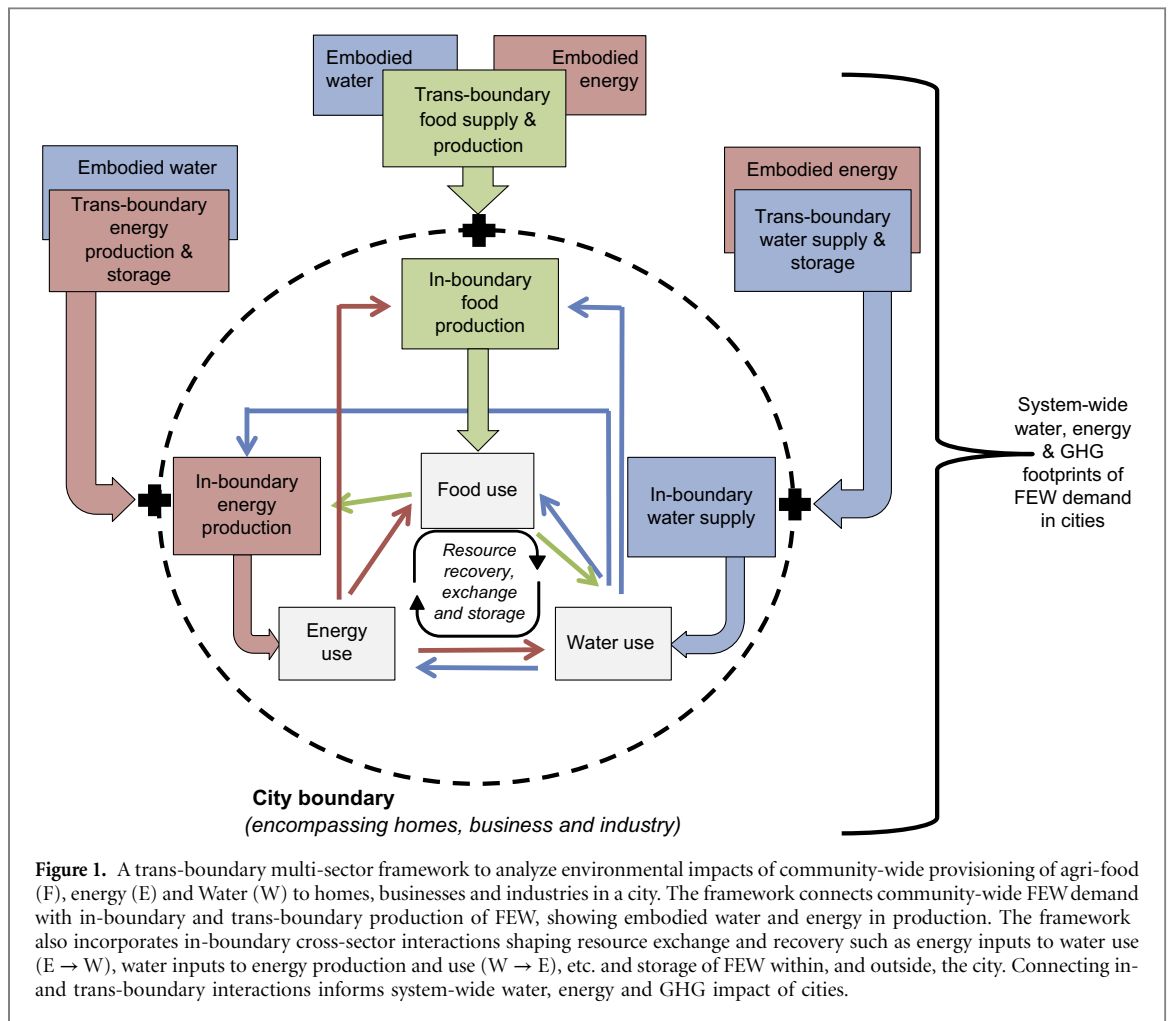
## Framework

The urban systems FEW nexus framework is illustrated in figure 1.<sup>7</sup> The porous circle in figure 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 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 1:

<sup>7</sup> Figure 1 presents an urban systems framework to characterize both environmental impacts and supply chain risk associated with FEW demand in cities. Building upon Wolman’s (1965) early work on tracking urban material-energy flows, urban metabolism studies have expanded to conduct three types of analyses: (1) delineating direct in-boundary resource use to produce goods and services (called territorial or production-based analysis) (Hertwich and Peters 2009); (2) evaluating trans-boundary supply chains that serve households within a city (e.g. Jones and Kammen 2014) called consumption-based footprinting; and, (3) evaluating supply chains to serve community-wide infrastructure provisioning to producers and consumers (i.e. homes, businesses, visitors, industries) called community-wide infrastructure footprinting (CIF) (Ramaswami *et al* 2008, Chavez and Ramaswami 2013, Baynes *et al* 2011, Hu *et al* 2016).



- 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-infrastructure systems (SEIS) framework (Ramaswami *et al* 2012,

2016). Specifically, figure 1 enables evaluation of trade-offs and synergies among four key categories of actions: (a) changes in community-wide urban FEW demand; (b) shifts between 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 1 is applied to the city of Delhi, India occupying an area of 1483 km<sup>2</sup>, home to 16 million people, and generating \$37.2 billion GDP (in 2011) (Delhi DES 2013b, 2013a). Delhi represents a highly populous, water-scarce city grappling with both environmental stresses and supply risk challenges.

The framework in figure 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 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 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 the baseline for any city, against which future interventions, within and beyond the city boundary, can be evaluated for localized or system-wide environmental impact.

## Overview of methods

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 SI-1 and SI-2 respectively (available at [stacks.iop.org/ERL/12/025008/mmedia](http://stacks.iop.org/ERL/12/025008/mmedia)).

### 1. Environmental footprinting of community-wide FEW provisioning

Trans-boundary coupled water-use and 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* 2008, Chavez *et al* 2012, Lin *et al* 2015). Details are in SI-1. 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. (See SI-1 for further details).

#### 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 (GOI MSPI 2011), (ii) *visitors* (GOI Ministry of Tourism 2010), and, (iii) *food processing industries* from the Annual Survey of Industries (Delhi 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 in global cities. 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 (SES) of households (See SI-1, 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 SI-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 (Delhi 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 Delhi DES (2013a), GOI NHB (2011), GOI Ministry of Agriculture (2014), the Delhi Jal Board (CAG 2013) and GOI CGWB (2012), and Delhi DES (2013a), respectively, (see SI-1 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 FEW supply chains 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 (Delhi 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 in a larger grid to demand by a city is a unique contribution of the analysis. For municipal water supply, government sources

(GOI CGWB 2012, CAG 2013) identified that 86% is drawn externally from the Yamuna and Ganges Rivers 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 SI-1 section D, table S-3.

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 for ground water pumping. These characteristics of the agricultural production regions were delineated in our study through data sets of each state's gross agricultural production (GOI 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 (GOI Planning Commission 2014). The water vulnerability of the different states, represented by the degree of ground water overdraft (withdrawal in excess of recharge) is obtained from Suhag (2016). The ground water overdraft in India has been exacerbated by the provision of free electricity for irrigation that has both incentivized cultivation 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 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 agrifood 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 (India 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 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 ground water vulnerability of these states.

#### 2. *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 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  $W \rightarrow F$ ) 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 S-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 US 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. See SI-2.

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.

## Results

- A. **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 (SI-1 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 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.
- B. **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.
- C. **Supply chains and features of regional production systems serving Delhi:** Trans-boundary

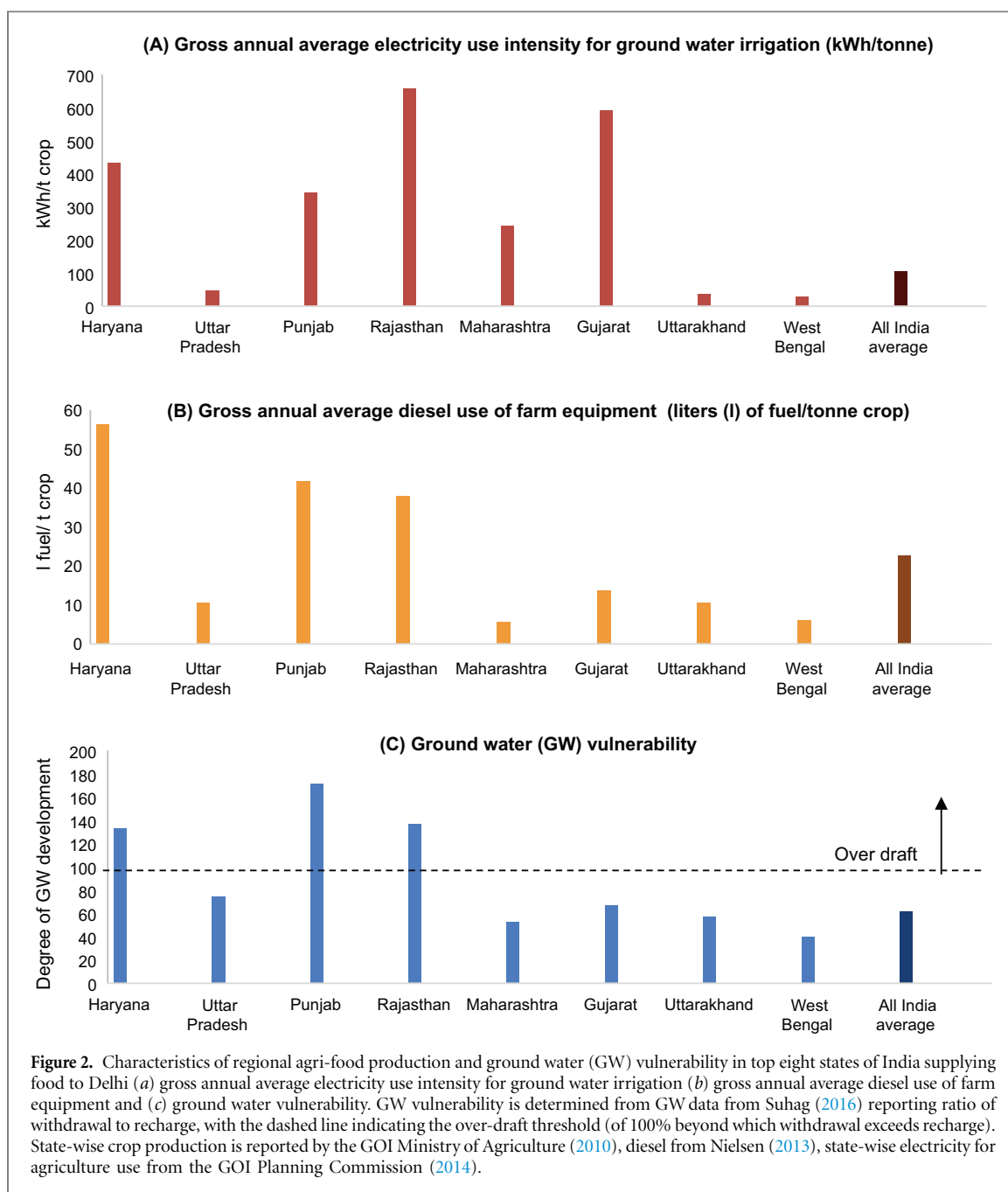
spatial supply chain data (SI-1 table S-3) show that >80% of Delhi's food supply and >45% of electricity come from the neighboring states of Punjab, Haryana and Uttar Pradesh. Delhi and these three surrounding states are highly water vulnerable with ground water overdraft (ratio of annual extractions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

- D. **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 3. 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 to Delhi. Petro-fuels account for 42% of the total GHG emissions footprint, followed by electricity at 36%, and food at 19%, while municipal 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.

Of note is the impact of the second-order GHG and water impacts of agri-food production (shown by the crisscross pattern in figure 3) representing the energy required for ground water pumping (ground water-electricity nexus) and farming equipment (figures 2 and SI table S-4), and the resulting water requirement to produce the needed electricity. The trans-boundary ground water-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 ground water pumping for agri-food production are also clearly seen in figure 4, which illustrates Delhi's food-related consumptive water-loss and GHG footprints disaggregated by food item supplied to Delhi (5b), while also noting the percent of supply sourced within Delhi (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





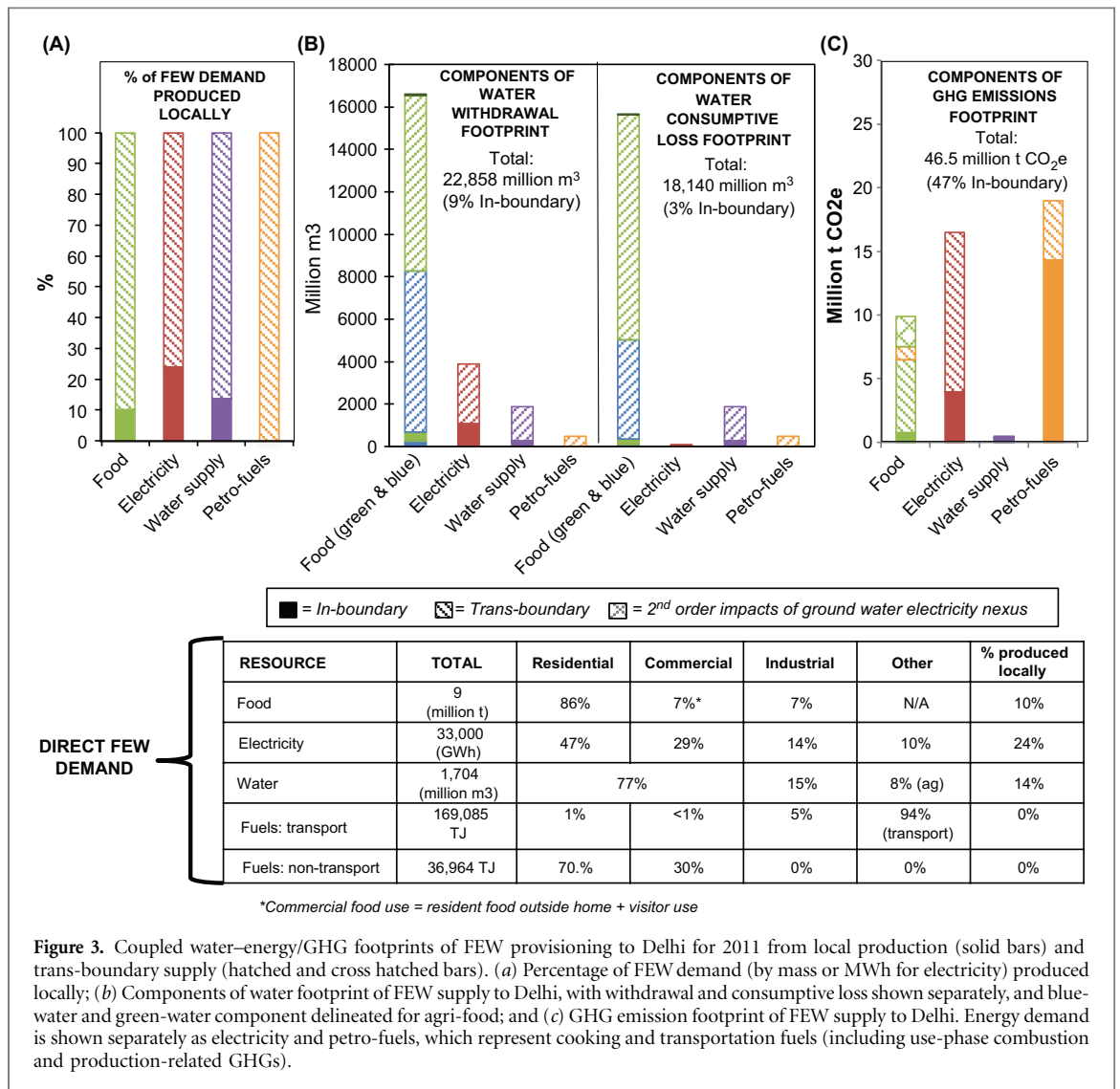
**Figure 2.** Characteristics of regional agri-food production and ground water (GW) vulnerability in top eight states of India supplying food to Delhi (a) gross annual average electricity use intensity for ground water irrigation (b) gross annual average diesel use of farm equipment and (c) ground water 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).

types of agri-foods where changes in demand or production practices can have large impact.

- E. **Visualizing Coupled Water- and GHG Footprints of FEW Supply, and Supply Chain Risks:** Figure 5 illustrates the spatially disaggregated water impact of FEW provisioning to Delhi (see SI table S-3 and S-4). Figure 5 shows that the 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.
- F. **Analysis of in-boundary FEW nexus:** Figure 6 (SI table S-6), illustrates the in-boundary cross-sectoral interactions occurring among FEW

sectors within Delhi. Food-related activities (ranging from cooking to urban agriculture), are prominent within the boundary contributing 25% of Delhi's total direct water withdrawal and 15% of Delhi's direct energy needs. Thus, focusing on food-related efficiencies within Delhi can therefore pay dual dividends in terms of water and energy.

The pie charts in figure 6 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



**Figure 3.** 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).

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 ground water 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 (Delhi DES 2013b) will have minimal impact on city-wide energy use.

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 details in SI-2).

Taken together, as shown in figure 7, the combined results of figures 3–6 provide the baseline against which to evaluate the impact of future actions, including those initiated within the city or beyond its boundaries.

## 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 and outside the city), as well as cross sectoral interactions within the city boundary. Key recommendations on methodology include:

1. Community-wide food demand 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.
2. 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

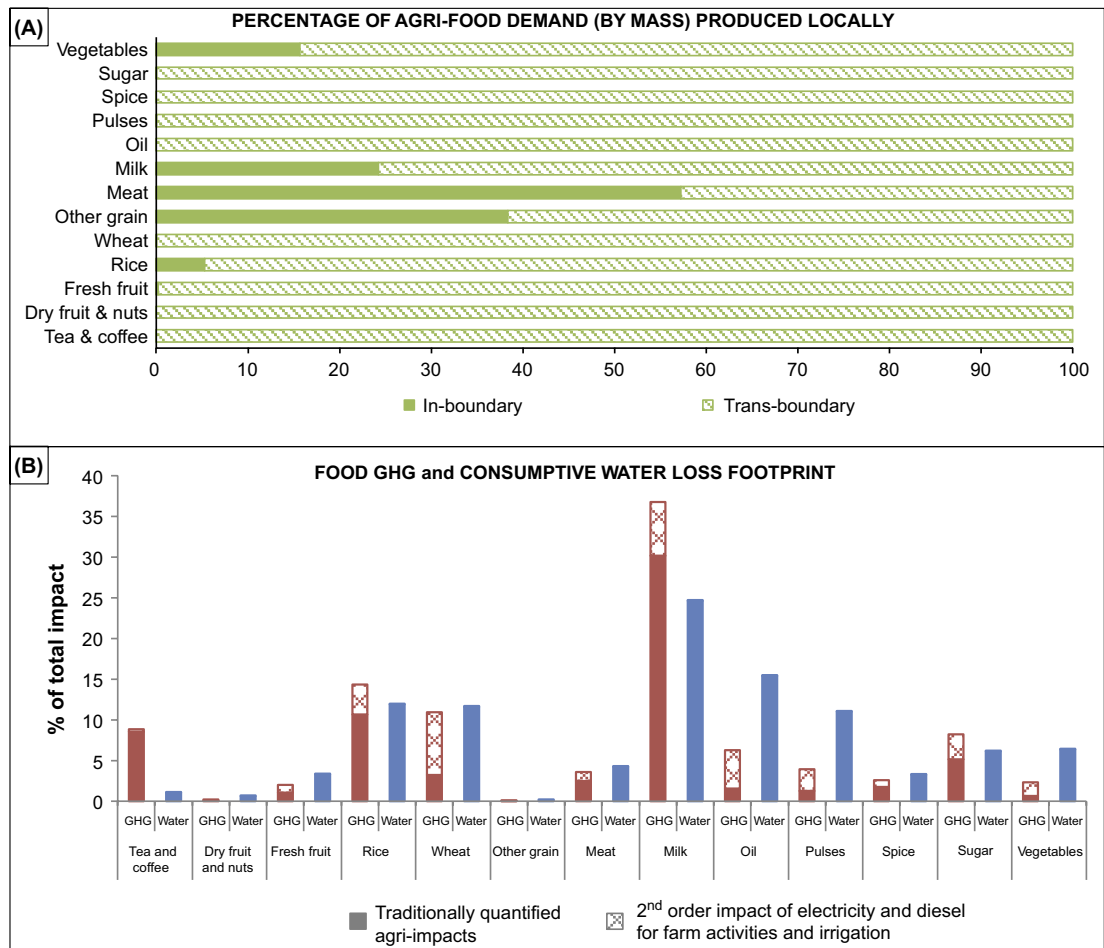


Figure 4. Analysis of Delhi's agri-food (F) demand, disaggregated by food types. (a) Percentage of demand (by mass) produced locally (b) GHG emissions footprint of agri-food supply and water consumptive loss footprint of agri-food supply. (Details in SI-1 section A and table S-1 4-5).

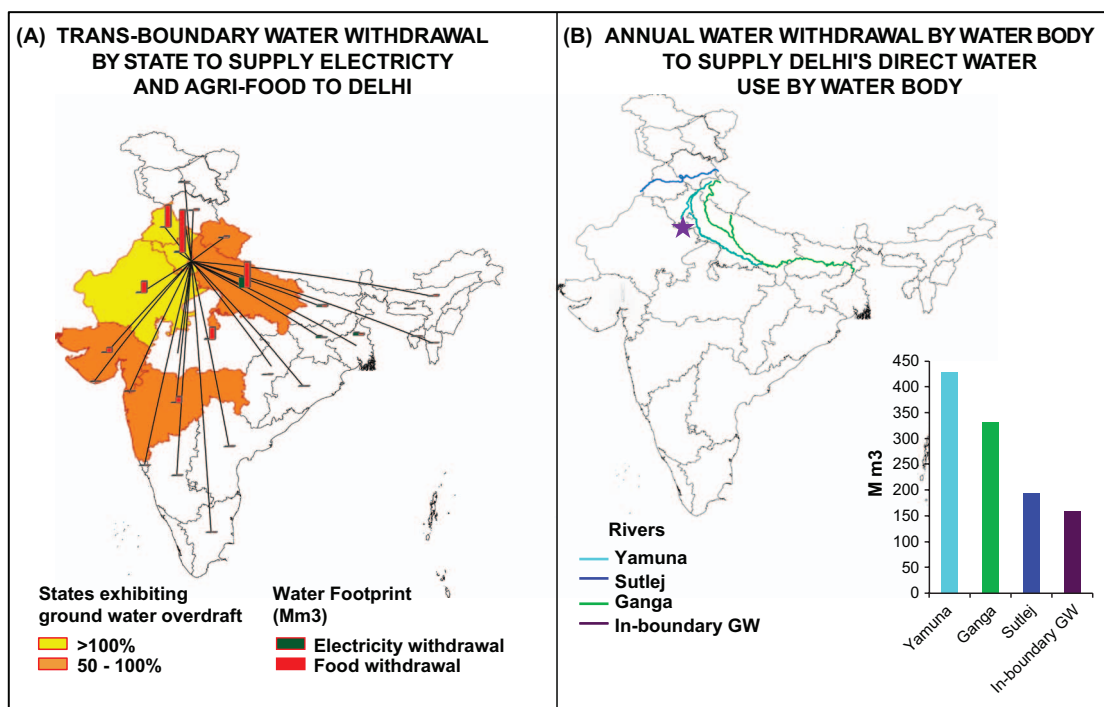
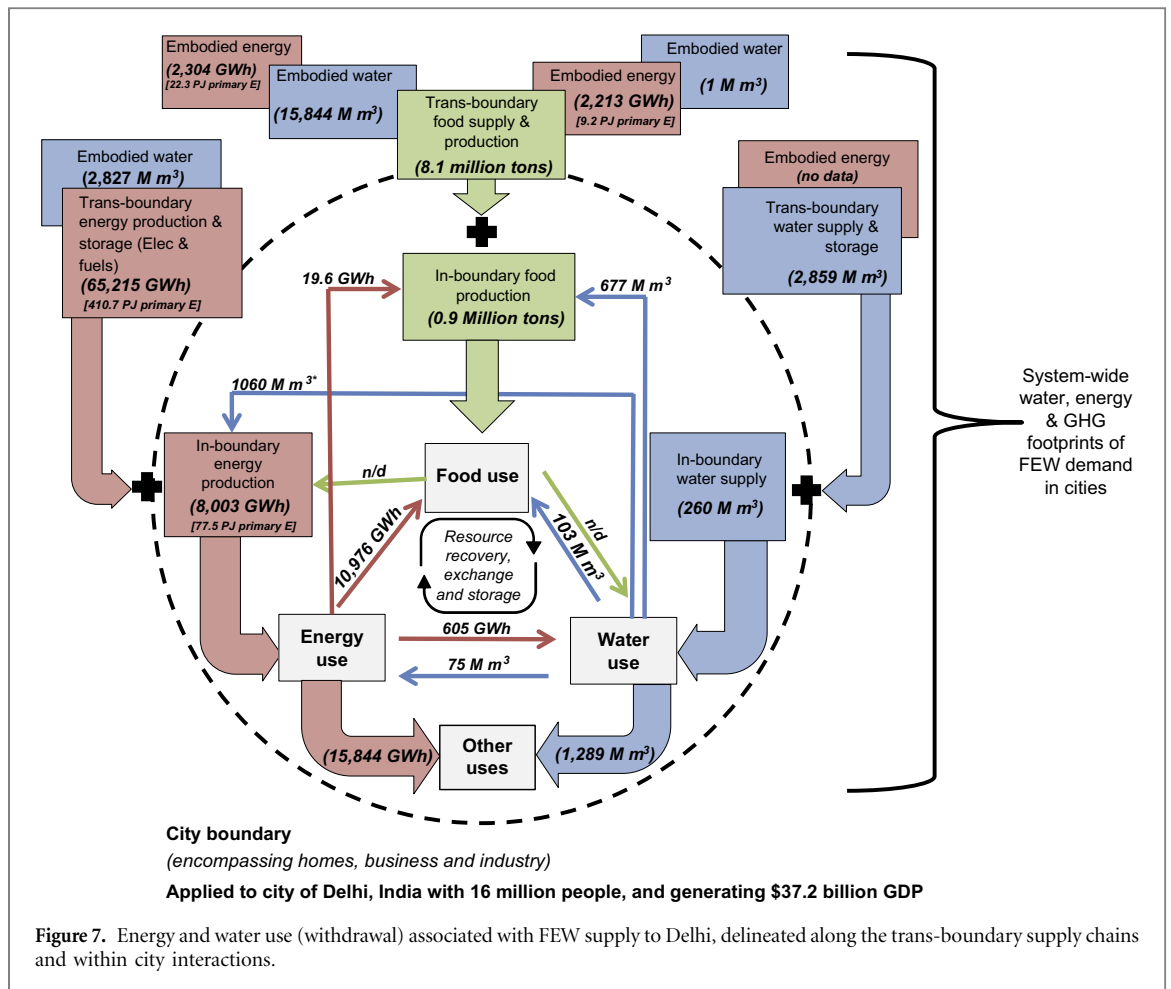
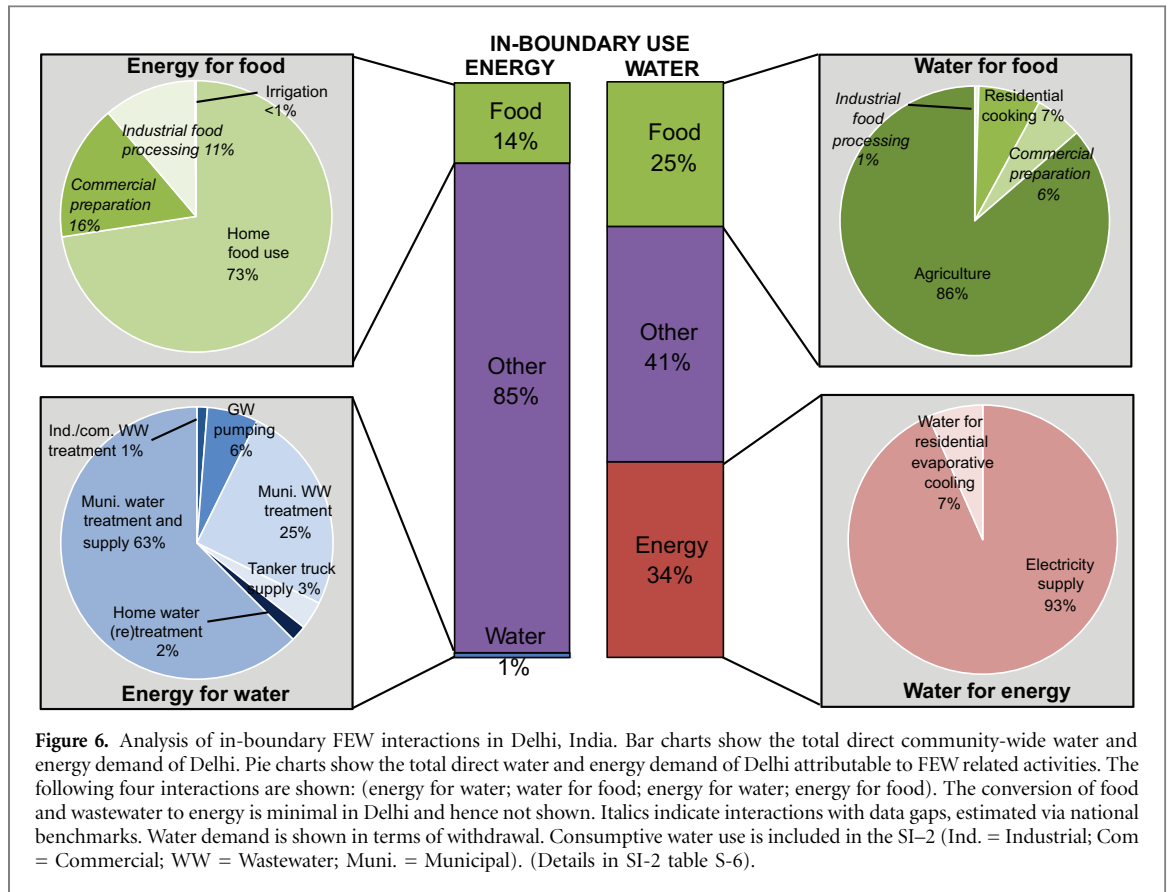


Figure 5. Visualizing supply chain risk to Delhi's FEW supply: (a) Trans-boundary water withdrawal by state to support Delhi's electricity and agri-food supply; and (b) water withdrawal volume by water body (river) supplying Delhi's direct water use for direct water use, versus local ground water withdrawal (shown as a star). (Details in SI-1 table S3). This provides a beginning framework to visualize Delhi's supply chain risk from climate constraints.





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.

3. 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 annual 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 ground water overdraft. 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
4. 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 and commercial establishments in Delhi were identified as data gaps with large potential benefits.
5. Visualizing supply chain data shows a majority of embodied water for FEW supply are from locations already highly water vulnerable due to ground water overdraft, suggesting potential supply chain risk.

Applying the trans-boundary, multi-sector, multi-impact FEW analysis framework in Delhi, India enables future 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 policies, 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.

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