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TOPICAL REVIEW

Quantifying the foodshed: a systematic review of urban food flow and local food self-sufficiency research

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Abstract

Cities are net consumers of food from local and global hinterlands. Urban foodshed analysis is a quantitative approach for examining links between urban consumers and rural agricultural production by mapping food flow networks or estimating the potential for local food self-sufficiency (LFS). However, at present, the lack of a coherent methodological framework and research agenda limits the potential to compare different cities and regions as well as to cumulate knowledge. We conduct a review of 42 peer-reviewed publications on foodsheds (identified from a subset of 829 publications) from 1979 to 2019 that quantify LFS, food supply, or food flows on the urban or regional scale. We define and characterize these studies into three main foodshed types: (1) agricultural capacity, which estimate LFS potential or local foodshed size required to meet food demands; (2) food flow, which trace food movements and embodied resources or emissions; and (3) hybrid, which combine both approaches and study dynamics between imports, exports, and LFS. LFS capacity studies are the most common type but the majority of cases we found in the literature were from cities or regions in the Global North with underrepresentation of rapidly urbanizing regions of the Global South. We use a synthetic framework with ten criteria to further classify foodshed studies, which illustrates the challenges of quantitatively comparing results across studies with different methodologies. Core research priorities from our review include the need to explore the interplay between LFS capacity and interregional food trade (both imports and exports) for foodsheds. Hybrid methodologies are particularly relevant to examining such dependency relationships in food systems by incorporating food flows into LFS capacity assessment. Foodshed analysis can inform policy related to multiple components of sustainable food systems, including navigating the social and environmental benefits and tradeoffs of sourcing food locally, regionally, and globally.

1. Introduction

Cities are economic and cultural centers yet rely on flows of resources and other materials from local and global sources (Haberman and Bennett 2019). This applies especially to food given both biophysical and practical constraints on food self-sufficiency in and around urban areas (e.g. Zumkehr and Campbell 2015, Clinton *et al* 2018). Urban food systems are thus 'telecoupled,' with cities and their hinterlands connected over vast distances through flows

of food, money, knowledge, and information (Seto *et al* 2012, Liu *et al* 2013). Because of their linkages with peripheral areas, city-scale actions can lead to complex tradeoffs for land and water resources, as well as greenhouse gas emissions (Boyer and Ramaswami 2017). For example, transitions towards more animal-protein based diets, which may be related to urbanization, can result in agricultural land-use change in exporting countries (Defries *et al* 2010, Seto *et al* 2012, Seto and Ramankutty 2016, Silva *et al* 2017). Accordingly, cities are fundamental

to understanding food systems sustainability (Seto and Ramankutty 2016) and city-regions are recognized as a key governance scale for food systems transformation (Blay-Palmer *et al* 2018). As urban areas now comprise the majority of population growth globally (UNDESA 2014), the reciprocal relationships between cities and their food supplying hinterlands is increasingly important but arguably understudied.

Globalized food systems with long and complex supply chains provide consumers in many countries year-round access to diverse foods, but also increases the physical and social distance between producers and consumers (Clapp 2014). Cities sourcing from international markets might, for example, lack the governance power to configure food supply chains towards greater sustainability (Porter *et al* 2014). At the same time, with current patterns of food production and consumption, just one-third or less of the world population's food demand can be supplied by local sources (Kriewald *et al* 2019, Kinnunen *et al* 2020). Food system mapping can therefore increase our understanding of a city's or country's import dependence and vulnerabilities related to food, including whether or not local or global sourcing is likely to improve or compound this (Dalin *et al* 2012, Cumming *et al* 2014, Dubbeling *et al* 2017).

The 'foodshed' concept is increasingly used to discuss the geography of urban food supply and particularly to describe the linkages between food-producing and food-consuming regions at different scales. The concept initially emerged in the early 20th century, drawing on the analogy of a watershed. To our knowledge, the planner and conservationist Benton MacKaye provided the first empirical study of the linkages between cities and agricultural hinterlands through supply chains. In 1920, he studied Washington D.C.'s food supply to identify logistics efficiencies and proposed a local and national food production and distribution network (Mackaye 1920). In the same decade, a potential strike of the train transit union that could have impacted food shipments to New York City initiated Walter Hedden's book 'How Great Cities are Fed' (Hedden 1929). Hedden mapped food flows from various agricultural sources in the United States, studied the impact of seasonality on food origins, and examined the logistical infrastructure involved (train lines, cooling and storage facilities, distribution centers, and food stores).

Foodshed discussions reemerged in the early 1990s with permaculturist Arthur Getz, incorporating a more normative stance toward the perceived benefits of local food systems and local food self-sufficiency (LFS) (Getz 1991). Shortly after, some rural sociologists embraced foodsheds as a normative concept, proposing local food systems as more sustainable, and hence more desirable (Kloppenburg *et al* 1996, Kloppenburg and Lezberg 1996). In

Kloppenburg *et al*'s (1996) predominantly aspirational notion, a foodshed encompasses a food system that is driven by a 'moral economy,' 'commensal community,' 'self-protection, secession and succession,' local and regional proximity, and the availability of natural resources. They suggest that foodsheds are inherently local and without 'fixed or determinate boundaries.' Lastly, their foodshed concept acknowledges the desired or required embeddedness of a region in global trade relationships, suggesting a self-reliant rather than self-sufficient food system (Kloppenburg *et al* 1996). A further review of Kloppenburg *et al*'s discussion of an aspirational local foodshed in contrast to characteristics of globalized food systems is provided in the Supplementary Material (text S1, available online at stacks.iop.org/ERL/16/023003/mmedia, and table S2).

Going beyond the aspirational narrative of a foodshed, a growing number of empirical studies at various scales highlight the concept's utility as a quantitative framework to analyze urban food supply and rural-urban linkages. This includes innovative methodologies to assess foodsheds for individual cities (e.g. Joseph *et al* 2019) and collectively at the global scale (Kriewald *et al* 2019, Kinnunen *et al* 2020). A review by Horst and Gaolach (2015) examined the feasibility of LFS in North America based on peer-reviewed and community-led foodshed studies published between 2000 and 2013. However, they focused on local agricultural capacity (i.e. the quantity of different food groups that can be produced or the available land to grow food on) and omitted analyses of food flows. To our knowledge, there is no other comprehensive review of urban foodshed research to date.

Current foodshed analyses use disparate methodologies and definitions and are often multi-scalar and geographically context dependent in nature. While these characteristics have fostered the emergence of innovative and complementary approaches, they also limit the ability to compare findings across studies and to inform policy at different scales. To address this gap and to assess 'the state of the art' in urban foodshed research, we conducted a systematic review of empirical studies broadly considering urban food flows or LFS across the peer-reviewed literature. Our main objective was to examine the definition, aims, and potential applications of foodshed analysis in different geographical contexts, and to characterize the methodological approaches and data used. Given the aspirational framing of key writings on the foodshed concept (Getz 1991, Kloppenburg *et al* 1996, Kloppenburg and Lezberg 1996), we also assessed the degree to which Kloppenburg *et al*'s normative interpretation of foodsheds is reflected in quantitative foodshed studies. To do so, we drew on a broad search strategy that returned 829 candidate articles,

which we screened to 42 final articles for our in-depth review. Based on this review, we developed a synthetic framework to classify foodshed studies and help move towards a more discrete research agenda. To this end, we identified several policy areas relevant to foodshed analysis across the 42 reviewed studies and draw on examples from different studies to outline a series of key research priorities and data challenges for an interdisciplinary research agenda on urban foodsheds.
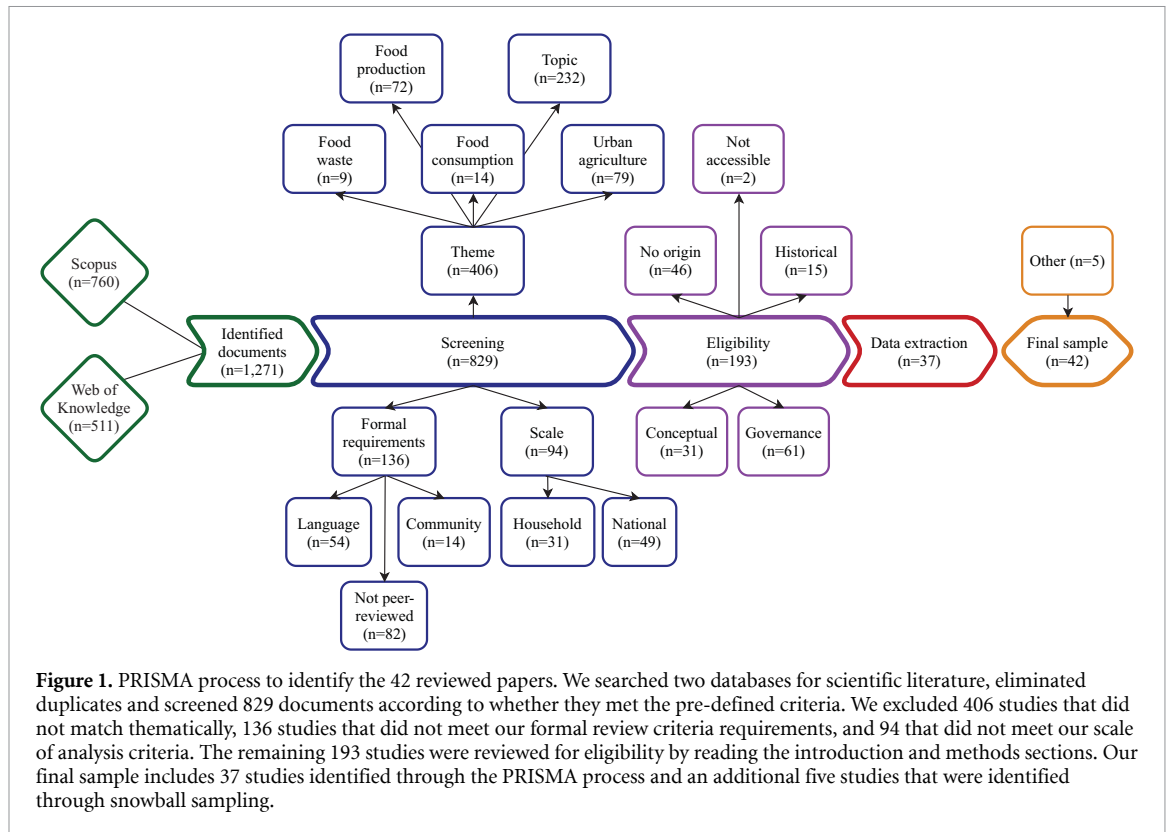
2. Methodology

In our initial literature scoping, we noticed a lack of a concise definition, unifying framework or protocol for analysis across studies using the term 'foodshed'. However, two broad definitions of foodsheds were common: the actual geographic areas from which a population sources its food [*sensu* Hedden] and the region surrounding a city with a certain potential to satisfy the population's food demands [*sensu* Getz and Kloppenburg]. Accordingly, we developed search strings with Boolean operators using term combinations related to these definitions and further informed by a review of key studies (Horst and Gaolach 2015, Tedesco *et al* 2017). We used the preferred reporting items for systematic reviews and meta-analyses (PRISMA), a standard protocol for systematic reviews (Moher *et al* 2009), and applied various search strings (Supplementary Material table S3) in the ISI Web of Knowledge and Scopus databases. To avoid the exclusion of potentially relevant studies that may not use the 'foodshed' term explicitly but that apply similar approaches, we also searched for the closely related terms 'carrying capacity,' 'flow,' and 'local food supply.' As our review focuses on the urban and finer sub-national scales, we accompanied our search with 'city,' 'urban,' and 'metropolitan.' We also included the terms 'urban material flow' and 'urban metabolism'. Urban metabolism is a well-defined area of research (Kennedy *et al* 2007) that we deemed to be synergistic with urban foodsheds despite often using different terminology. 'Food' was added to all strings to omit unrelated material or non-material flows (e.g. energy, water). Wildcards were used to account for divergent spellings or plural forms.

We identified 1271 documents through our initial search in ISI Web of Knowledge and Scopus databases (September 17, 2019). We then removed 442 duplicates and screened titles, abstracts, and keywords of the remaining 829 articles in order to retain those that met the pre-defined criteria of being published in peer-reviewed journals and related to urban foodsheds. Studies lacking consideration of rural or peri-urban food production (e.g. urban agriculture) or food flows were omitted. We retained large-scale studies that included finer subnational analysis, such as those approximating cities or towns and their

surrounding region[4] and omitted studies that were conducted exclusively at the national scale with the exception of a study in Iceland (Halldórsdóttir and Nicholas 2016) that otherwise closely adhered to our inclusion criteria. The remaining papers were then further reviewed for eligibility by reading the articles' introduction and methods sections, and articles that met additional criteria were retained (e.g. empirical analysis, not just conceptual frameworks). We identified two foodshed studies through other means (Zumkehr and Campbell 2015, Kriewald *et al* 2019) and three through snowball sampling (Peters *et al* 2007, Desjardins *et al* 2010, Conrad *et al* 2017), for a total of 42 studies included in our review (figure 1). Each paper was read in full by the first author and then summarized into a database by two authors by identifying study type, location, spatial systems boundaries, calculation method, data sources, foods studied, and the use of scenarios or analysis of temporal changes. The results of the classification and associated meta-data are provided in the Supplementary Material (spreadsheet 'S4_Schreiber *et al*._Quantifying the foodshed'). More information on data sources and the types of foods analyzed across reviewed studies can be found in the Supplementary Material text sections S5 and S7.

Our search strategy is not exhaustive and may therefore not have identified all relevant empirical studies. Since our aim was to capture the emergence of the scientific research field pertaining to foodsheds, we focused on peer-reviewed and English-language studies only, which excluded reports published by community organizations, municipalities, or non-academic stakeholder groups (e.g. Fradkin 2015, Thompson *et al* 2008). Our search strings focused primarily on technical aspects of foodshed analysis (e.g. data and methods to assess food flows and LFS capacity), which we coded and used to compare studies. Our search only encompasses the topic (title, abstract, keywords) and therefore may have missed papers where terms appeared only in the main text. Lastly, even though various papers use urban foodsheds as a conceptual, normative, or aspirational framework in the context of food systems sustainability (Kloppenburg *et al* 1996, Kloppenburg and Lezberg 1996, Lengnick *et al* 2015), we only reviewed empirical studies that mapped and quantified foodsheds. Nevertheless, our search strategy identified a number of non-self-described foodshed studies, providing useful approaches that would have otherwise been omitted (e.g. urban metabolism approaches).

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[4] We identified 19 studies that focus on individual cities and 23 studies that account for multiple cities in a region or state. Larger-scale studies often emphasized the role of key population centers inside of geographic or administrative boundaries, and their inclusion helped to account for additional methodological approaches.

Figure 1. PRISMA process to identify the 42 reviewed papers. We searched two databases for scientific literature, eliminated duplicates and screened 829 documents according to whether they met the pre-defined criteria. We excluded 406 studies that did not match thematically, 136 studies that did not meet our formal review criteria requirements, and 94 that did not meet our scale of analysis criteria. The remaining 193 studies were reviewed for eligibility by reading the introduction and methods sections. Our final sample includes 37 studies identified through the PRISMA process and an additional five studies that were identified through snowball sampling.

3. Results

3.1. Foodshed study types

Drawing from across the 42 retained studies, we defined three main types of foodshed analysis: LFS capacity studies (*Capacity*), food flow studies (*Flow*), and those that combine both (*Hybrid)* (figure 2). We systematically compared each of the three types of studies according to a set of ten criteria describing their aims and methodological approaches (table 1) and provide a representative example of each study type highlighting key inferences and results (tables 2–4). Our definition of *Capacity* studies included those that estimate LFS by comparing the food consumption of one city or multiple cities within a defined spatial boundary (e.g. a state or bioregion/watershed) with the theoretically or actually available quantity of food produced on peri-urban or surrounding rural agricultural landscapes. *Capacity* studies therefore estimate and test LFS potential, which could have implications if city-regions seek to increase reliance on local resources to meet local demands. *Flow* studies trace food shipments on multiple scales to map the various regions and supply networks that sustain cities. They often estimate resources or emissions embodied in food flows and analyze supply vulnerabilities and efficiencies as well as relationships between consumers and producers. *Hybrid* studies are all those that account for the impacts of food flows (e.g. imports and exports) on LFS, or that assess potential resource savings

under food systems localization by combining methods from *Capacity* and *Flow* studies.

A brief overview of how the reviewed empirical studies reflected Kloppenburg *et al*'s (1996) aspirational notion of foodsheds can be found in the Supplementary Material (text S1). Most reviewed studies embrace the 'Nature as measure' principle but do not or only partially adopt the other four principles. *Hybrid* studies align primarily with the idea of 'Proximity,' while several *Flow* studies incorporate 'Moral economy' and 'Commensal community' dimensions. This illustrates the broad theoretical basis and evolving aims of foodshed research.

3.1.1. Capacity studies

Capacity studies used different calculation approaches, which we grouped into three categories: self-sufficiency threshold (ST), inverse self-sufficiency threshold (IST), and foodshed size (figure 3 and table 1). ST and IST compared production and consumption to calculate a ratio representing the share of food demand that could be satisfied through local production—an indicator of LFS potential (Kurita *et al* 2009, Hu *et al* 2011b, Morrison *et al* 2012, Hara *et al* 2013). ST calculations estimated to what degree agricultural production in a given area can meet the food demands of a given population. Values ⩾100% indicated that an area has a high LFS potential or produces surplus food. IST calculations examined what share of available agricultural capacity would

Column headers (reviewed studies, left to right):

Cardoso et al. 2017 · Conrad et al. 2016 · Desjardins et al. 2010 · Filippini et al. 2014 · Galzki et al. 2015 · Galzki et al. 2017 · Giombolini et al. 2011 · Griffin et al. 2015 · Halldórsdóttir and Nicholas 2016 · Hu et al. 2011a · Hu et al. 2011b · Huang et al. 2019 · Joseph et al. 2019 · Kremer and Schreuder 2011 · Kurita et al. 2009 · Li et al. 2019 · Liao et al. 2019 · Morrison et al. 2012 · Newcombe and Nichols 1979 · Nixon and Ramaswami 2018 · Orlando et al. 2019 · Peters et al. 2007 · Peters et al. 2009 · Peters et al. 2012 · Tedesco et al. 2017 · Zasada et al. 2019 · Zumkehr and Campbell 2015 · Akoto-Danso et al. 2019 · Aucoin and Fry 2015 · Brinkley 2017 · Grigsby and Hellwinckel 2016 · Karg et al. 2016 · Swider et al. 2018 · Wegerif and Wiskerke 2017 · Zazo-Moratalla et al. 2019 · Billen et al. 2012 · Hara et al. 2013 · Iizuka and Kikuchi 2014 · Kriewald et al. 2019 · Lu and Campbell 2009 · Porter et al. 2014 · Zhou et al. 2012

Row categories and sub-criteria:

Category	Criterion
	Self-described foodshed study
Aim	Degree of LFS
	Foodshed size
	Embodied resources
	Supply network
Calculation method	Self-sufficiency threshold
	Inverse self-sufficiency threshold
	Foodshed size
Unit	Weight
	Land
	Nutrition
	RE and other*
Data source	Primary data
	Secondary data
Diet model	Actual diet
	Theoretical diet
	HNE**
Spatial boundaries	Administrative unit
	Radius
	Bioregion or island
	Multi-scale
	Metropolitan area
	National
Optimization model	Distance
	Crop yield
Food surpluses	Regional reallocation
	Exports
Food flows	Inter-regional
	International
Scenarios and temporal changes	Age, gender, activity
	Production
	Consumption
	Intra- and Inter-annual variability

* embodied resources or emissions (e.g., water, energy, nitrogen, greenhouse gas) and others (e.g., distance) **Human Nutritional Equivalent

Table 1. Detailed overview and comparison of the 42 reviewed studies. We assessed all studies according to ten specific criteria that emerged in our review: (1) the aim, (2) calculation method, (3) functional unit of analysis, (4) predominant data source, (5) diet model used to estimate food consumption, (6) spatial boundary of the analysis, (7) optimization method used in the model (if applicable) to allocate food, (8) how surplus food in the region was allocated, (9) whether or not the study traces flows from regional or international sources, and (10) whether or not studies included scenarios or temporal changes. Color-coding refers to that of the foodshed study type in figure 1 (yellow is *Capacity*, blue is *Flow*, and green is *Hybrid*).

need to be utilized if the population were to rely fully on local agriculture. Values <100% indicated that an area has a high LFS potential and produces surpluses. Food surpluses could be allocated to deficient population centers within the studied region or exported (table 1). Foodshed size calculations determined how much local land is needed to meet the food demands of the given area as well as the radius that defines the maximum distance a population has to travel to meet those food needs. These approaches are not mutually exclusive and have been combined in some studies (table 1, figure 3).

Foodshed studies used three main functional units for food consumption and production values: weight, nutrition, and land (figure 4 and table 1). Food consumption was generally a function of the population of a given city and one functional unit (e.g. servings) on a per capita basis, whereas multiplying crop yield by the functional unit (e.g. hectares) was typically used to determine food production (figure 4). *Capacity* studies often used secondary data to calculate production and consumption (table 1, figure S6). Due to a lack of spatially-explicit household consumption data,

Capacity studies used 'actual diet' or 'theoretical diet' models, which follow dietary guidelines or scenarios, respectively (table 1) (see Supplementary Material text S7 for details on data sources, and their advantages and limitations). Gridded spatial representations of a region with resolutions of 1 × 1 km (Kurita *et al* 2009, Hara *et al* 2013), 2 × 2 km (Galzki *et al* 2017) to 5 × 5 km (Galzki *et al* 2014) often helped to calculate food production and consumption in each cell. This is particularly useful for *Capacity* studies that estimate local foodshed size, and those applying distance and crop yield optimization.

Multiple studies used optimization models and scenarios to estimate the impact of local food system changes on LFS (e.g. reducing distance between farms and population centers, effects of dietary changes, or crop allocation to increase yields and other ecosystem services). Many *Capacity* studies analyzed the variability of LFS in terms of production, consumption, or spatial extent of a foodshed (figure 2 and table 1). Factors included food losses and waste, inedible parts of food, land management (e.g. irrigation), and locally relevant biogeophysical conditions such

Table 2. Representative example of a *Capacity* study. Joseph *et al* (2019) estimated potential LFS under different dietary and production system scenarios, particularly for low-input agriculture (organic), changes in livestock systems, and reduced meat consumption, using primary and secondary data.

Study	Joseph *et al* 2019 Can Regional Organic Agriculture Feed the Regional Community? A Case Study for Hamburg and North Germany
Context	Hamburg, Germany (and counties in 50 and 100 km radius)
Aims	• Estimation of LFS potential for Hamburg • Impact of diets on LFS potential (foods with high/low land requirements) • Production system impacts on LFS potential (conventional, organic)
Data sources	• Previous studies, governmental and FAO statistics • Primary crop yield data collection from farms in study area
Calculation methods	• Self-sufficiency threshold • Foodshed size
Scenarios used	• Impact of different diets and production system combinations on LFS (status quo, conventional, organic, 30% meat/legumes substitute) • Sensitivity analysis, measuring impact of change from three-tier cow system (dairy cows, meat cows, dual-use cows) to dual-use cows
Key findings	• High potential for LFS within 50 km (34–57%) and 100 km (74–100%) radius • Available agricultural land and per capita meat consumption have large impacts on LFS

as fertilizer requirements, precipitation, soil erosion, or heavy metal concentrations (table 1). For instance, Joseph *et al* (2019) estimated LFS under different diet and production system scenarios (table 2). Several studies used spatial optimization models in order to determine LFS based on the minimum distance between consumer and producer (distance optimization) or to maximize production output (crop yield optimization). Optimization approaches complemented the basic calculation schemes through linear programming models, land and climate suitability, and crop yield models (Cardoso *et al* 2017). Others accounted for differences in age, gender, and activity levels of urban residents in their respective context and the impact of commuters and vacationers on urban food consumption (Tedesco *et al* 2017).

3.1.2. Flow studies

Flow studies mapped food flow networks between cities and peri-urban, regional, national or international sources (figure 2). Generally, these encompassed directional flows (countryside to city), but two studies also mapped bi-directional flows between urban, suburban, and rural areas (Zhou *et al* 2012, Karg *et al* 2016). *Flow* studies analyzed food distribution networks between cities and local food producers, and also estimated resource use or emissions (RE) embodied in producing foods as a product of food flow quantities and the ratio of a RE indicator and crop yields (figure 4). Tracing of food flows and mapping networks often used primary data or a mixture of primary and secondary data (figure S6, see S7 text for more details on the data sources and their advantages and limitations). *Flow* studies were often limited to

the tracing of the origin of processed and unprocessed foods but did not typically identify actual processing and distribution stages along the way (but see Wegerif and Wiskerke 2017).

Flow analysis can provide knowledge on embodied emissions or resource use (table 1), such as virtual water embodied in a city's food supply (table 3). This can inform sustainable food systems strategies as resource efficiency is geographically context dependent. For instance, while low-input food production systems or resource recycling in combination with short supply chains can result in resource savings and emission reductions (Yang and Campbell 2017, Pérez-Neira and Grollmus-Venegas 2018), other studies have shown that local food is not always more resource efficient (Weber and Matthews 2008) or can even increase negative environmental impacts (Edwards-Jones 2010, Avetisyan *et al* 2014, Huang *et al* 2014). Specialization arising from agricultural globalization may therefore enhance resource-use efficiency but carry other social and environmental costs (Clapp 2014, Schipanski *et al* 2016).

Flow analysis can also help outline the limitations of 'localized' food systems. For instance, Akoto-Danso *et al*'s study (2019) concluded that the decentralization of food supply can spread the risk of food insecurity due to environmental shocks and resource shortages in the city's surrounding hinterland. Vulnerabilities (e.g. susceptibility to water shortages) can arise due to extreme weather or geopolitical crises (Bren d'Amour *et al* 2016). Diversifying the sourcing regions of a city for risk distribution can be a way to avoid this vulnerability and ensure food supply (Karg *et al* 2016, Akoto-Danso
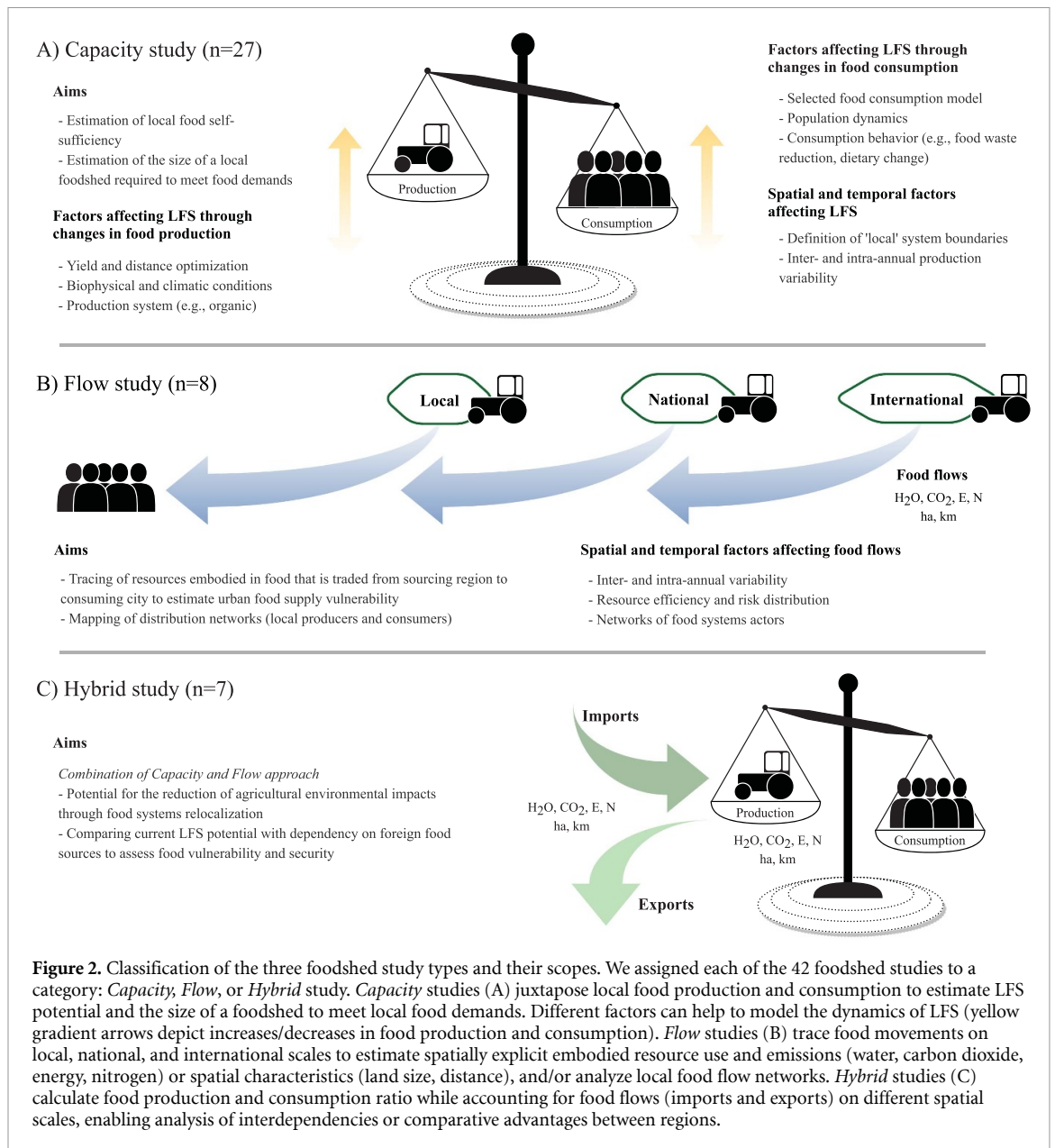
Figure 2. Classification of the three foodshed study types and their scopes. We assigned each of the 42 foodshed studies to a category: *Capacity, Flow,* or *Hybrid* study. *Capacity* studies (A) juxtapose local food production and consumption to estimate LFS potential and the size of a foodshed to meet local food demands. Different factors can help to model the dynamics of LFS (yellow gradient arrows depict increases/decreases in food production and consumption). *Flow* studies (B) trace food movements on local, national, and international scales to estimate spatially explicit embodied resource use and emissions (water, carbon dioxide, energy, nitrogen) or spatial characteristics (land size, distance), and/or analyze local food flow networks. *Hybrid* studies (C) calculate food production and consumption ratio while accounting for food flows (imports and exports) on different spatial scales, enabling analysis of interdependencies or comparative advantages between regions.

et al 2019). Cities can also function as hubs for processing and re-export (Karg *et al* 2016, Akoto-Danso *et al* 2019). Specifically in locations with networks of strong reciprocal rural-urban and urban-urban interdependencies, tracing food flows is crucial for identifying potential supply bottlenecks and vulnerabilities.

Spatial mapping of food production networks can also reveal social connectivity between diverse local actors. Wegerif and Wiskerke (2017) showed that the nature of relations among supply chain actors and regional differences in crop yields were more relevant for food systems sustainability than physical distance between producers and consumers. Some *Flow* studies drew from alternative food networks (AFNs) and identified flows between farmers, markets, and consumers (Aucoin and Fry 2015, Grigsby and Hellwinckel 20162016, Brinkley 2017, Zazo-Moratalla *et al* 2019). For example, Brinkley

(2017) traced the linkages between farms and various local food distribution entities (e.g. food hubs, farmers' markets, restaurants, food banks). Aucoin and Fry (2015) mapped flows of specific foods from farm to market (foodshed) as well as flows of people buying at those markets, illustrating the 'consumer draw' around a market called 'marketshed.'

3.1.3. Hybrid studies

Hybrid studies combined *Capacity* and *Flow* approaches to study a city-region's LFS with regard to their embeddedness in national and global food supply chains (table 1). The calculation approaches (figure 3) and data sources for *Hybrid* studies are similar to *Capacity* and *Flow* studies (figure S6 and text section S7 for details on the data sources, and their advantages and limitations). *Hybrid* studies combine the benefits of both *Capacity* and *Flow* analyses and can therefore help investigate how exports

Figure 3. Synthetic framework for foodshed analysis. We devised the decision tree based on a synthesis of LFS calculation methodologies across the *Capacity, Flow,* and *Hybrid* studies. Our framework differentiates between local food self-sufficiency (LFS) capacity analysis (as utilized in *Capacity* and *Hybrid* type studies) and food flow analysis (*Flow* and *Hybrid* type studies). This hierarchy of steps (defining broad study type and aim; choosing the target analysis and calculation method) provides a heuristic that can help guide more systematic foodshed research with consistent calculation approaches.
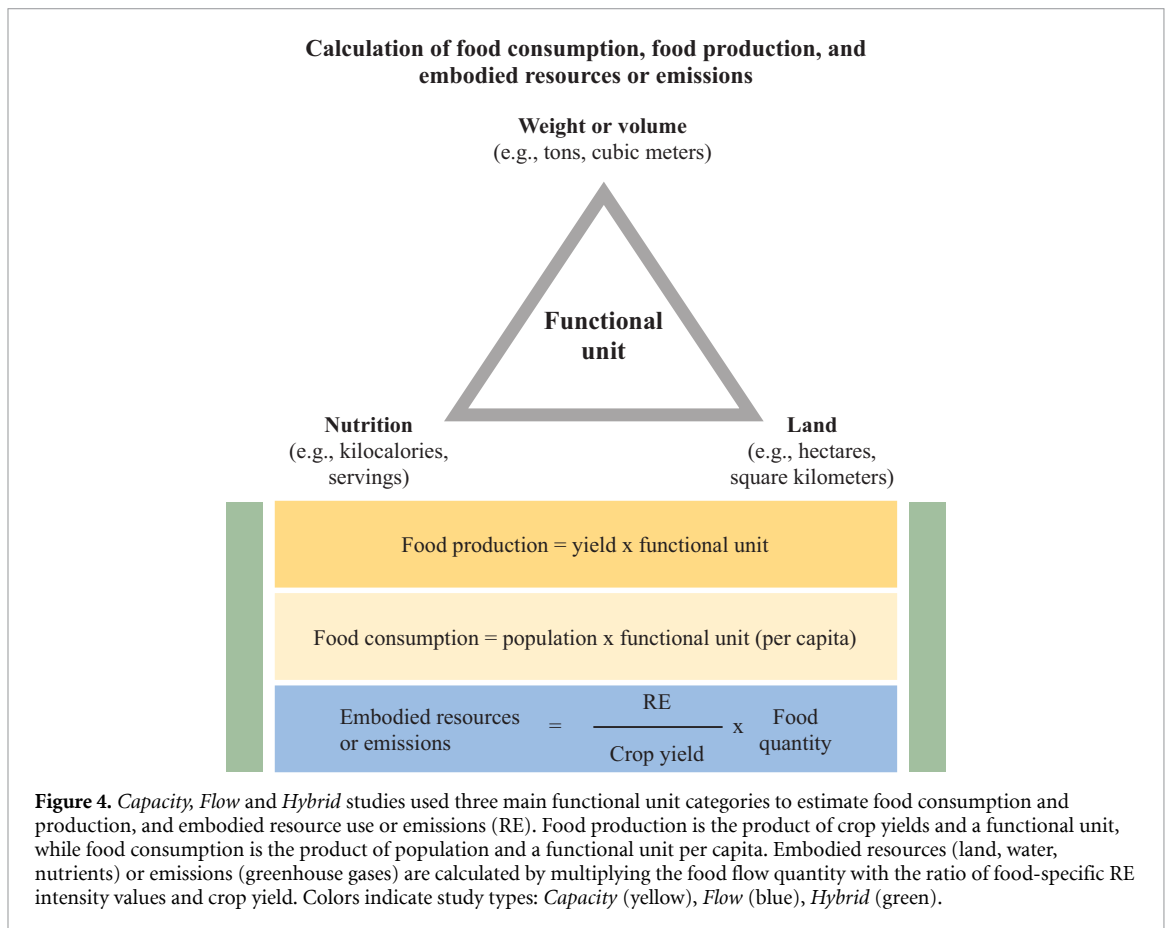
Figure 4. *Capacity, Flow* and *Hybrid* studies used three main functional unit categories to estimate food consumption and production, and embodied resource use or emissions (RE). Food production is the product of crop yields and a functional unit, while food consumption is the product of population and a functional unit per capita. Embodied resources (land, water, nutrients) or emissions (greenhouse gases) are calculated by multiplying the food flow quantity with the ratio of food-specific RE intensity values and crop yield. Colors indicate study types: *Capacity* (yellow), *Flow* (blue), *Hybrid* (green).

and imports affect LFS potential in globalized food systems. Understanding the implications of trade on LFS is important since, as Zhou *et al* (2012) claimed, a region can have a high theoretical LFS potential but low actual LFS. This can occur in export-oriented regions with a comparative advantage in the production of a specific food commodity (e.g. corn). Moreover, a holistic analysis of ecological, economic, and infrastructural circumstances provides more realistic insights into LFS potentials beyond physical land capacity. Emergy synthesis, a concept merging the analysis of biophysical material, energy, and financial flows has been used to assess opportunities and constraints to growing food for local and

Table 3. Representative example of a *Flow* study. Akoto-Danso *et al* (2019) calculated virtual water content of food flows to two West African cities and analyzes source diversity to estimate resilience to water-related shocks in producing regions.

	Akoto-Danso *et al* 2019
Study	Virtual water flow in food trade systems of two West African cities
Context	Tamale, Ghana, and Ouagadougou, Burkina Faso
Aims	• Mapping food flows to examine resilience of urban food supply to water-related shocks
Data sources	• Road and market surveys over six days at the end of two production seasons (peak and lean), one year in Ouagadougou and two years in Tamale (Karg *et al* 2016)
	• Monthly market foodshed survey (interviews with 33% of market food traders)
	• Extrapolation of six day road survey with market survey, secondary data from literature and interviews with officers from government ministries and market leaders
	• Crop yields (FAOSTAT, West Africa averages), location-specific water use (previous research)
	• Inflows and outflows (re-distribution)
Calculation method	• Embodied resources or emissions
Temporal changes	• Intra- and inter-annual sourcing changes
Key findings	• Highest contribution by cereals (most common food in diet)
	• 68% (peak season) and 40% (lean season) of imported foods were re-exported out of the cities
	• Tamale: Southern Ghana is major net virtual water importer (cereals, legumes, vegetables, livestock), Northern Region of Ghana is net exporter (all food groups except fruits)
	• Ouagodougou: rice imports from Asia via Ivory Coast
	• Seasonal variation in flows: 514 (peak season) and 2105 (lean season) million m^3 yr^{-1}
	• Ouagodougou is more resilient to shocks (food supply and water) than Tamale

global markets (see Lu and Campell's (2009) work for Shunde, China).

As with *Flow* studies, the *Hybrid* approach can be used to compare embodied RE in food production between current distant and potential local producing regions (Hara *et al* 2013, Porter *et al* 2014, Kriewald *et al* 2019). An analysis considering such factors can aid decisions about the environmental sustainability and food security of a city's food supply. Hara *et al* (2013) provide an illustrative case for this kind of analysis (table 4).

3.2. Descriptive statistics
Out of the 42 reviewed papers, we identified 24 self-described foodshed studies (those using the term 'foodshed' in the title, abstract, or keywords). Another 18 foodshed studies did not prominently use the term 'foodshed' but were otherwise deemed relevant (see Supplementary Material spreadsheet S4 for studies falling into each category). Seven studies, primarily in the *Capacity* category, provided an original foodshed definition (listed in Supplementary Material table S8).

Capacity studies were the most frequent type of foodshed study (Supplementary Material figure S6 and S9). We find a gap in any scholarship between 1979 and 2007 (Newcombe and Nichols 1979, Peters *et al* 2007), which could indicate a lack of empirical advancements in the field despite important conceptual and theoretical contributions (Kloppenburg *et al* 1996, Kloppenburg and Lezberg 1996). The higher

number of foodshed publications in 2019 (only partially covered due to our search date cutoff) seems to indicate increased interest in the foodshed framework coinciding with current research trends on food systems.

Foodshed research has been concentrated in a few regions (figure 5), mainly North America ($n = 19$), Europe ($n = 13$), and Asia ($n = 6$) (Supplementary Material S4 spreadsheet). *Capacity* studies have primarily covered North American ($n = 14$) and European ($n = 10$) regions. Most *Flow* studies were conducted in the USA ($n = 3$) and Africa ($n = 3$). We found most *Hybrid* studies in Asia ($n = 5$), when compared to Europe ($n = 2$) and Australia ($n = 1$). One *Hybrid* analysis was conducted at a global scale (Kriewald *et al* 2019).

Spatial system boundaries varied greatly among the studies, with contrasts among *Capacity, Flow*, and *Hybrid* studies. We identified three main spatial system boundaries for *Capacity* studies: radius (e.g. '100-mile diet'); subnational administrative unit (SAU), such as state, district, county, or province, encompassing multiple cities; and bioregions (table 1). Kriewald *et al*'s global study (2019) is an exception that focused on peri-urban areas as food supplying territories (defined from remote sensing, agricultural model estimates, and population density statistics). *Flow* studies generally traced food flows within one metropolitan area, between a city and the surrounding hinterland, from national or international sources or a combination for multi-scalar

Table 4. Representative example of a *Hybrid* study. Hara *et al* (2013) estimated potential for energy savings and transformation of abandoned land through food systems localization, in a context with fragmented rural land use due to urbanization, using intra-national food flow data. Governmental and non-governmental organizations supported local food as more sustainable despite little evidence and expected increase in food imports due to trade agreements.
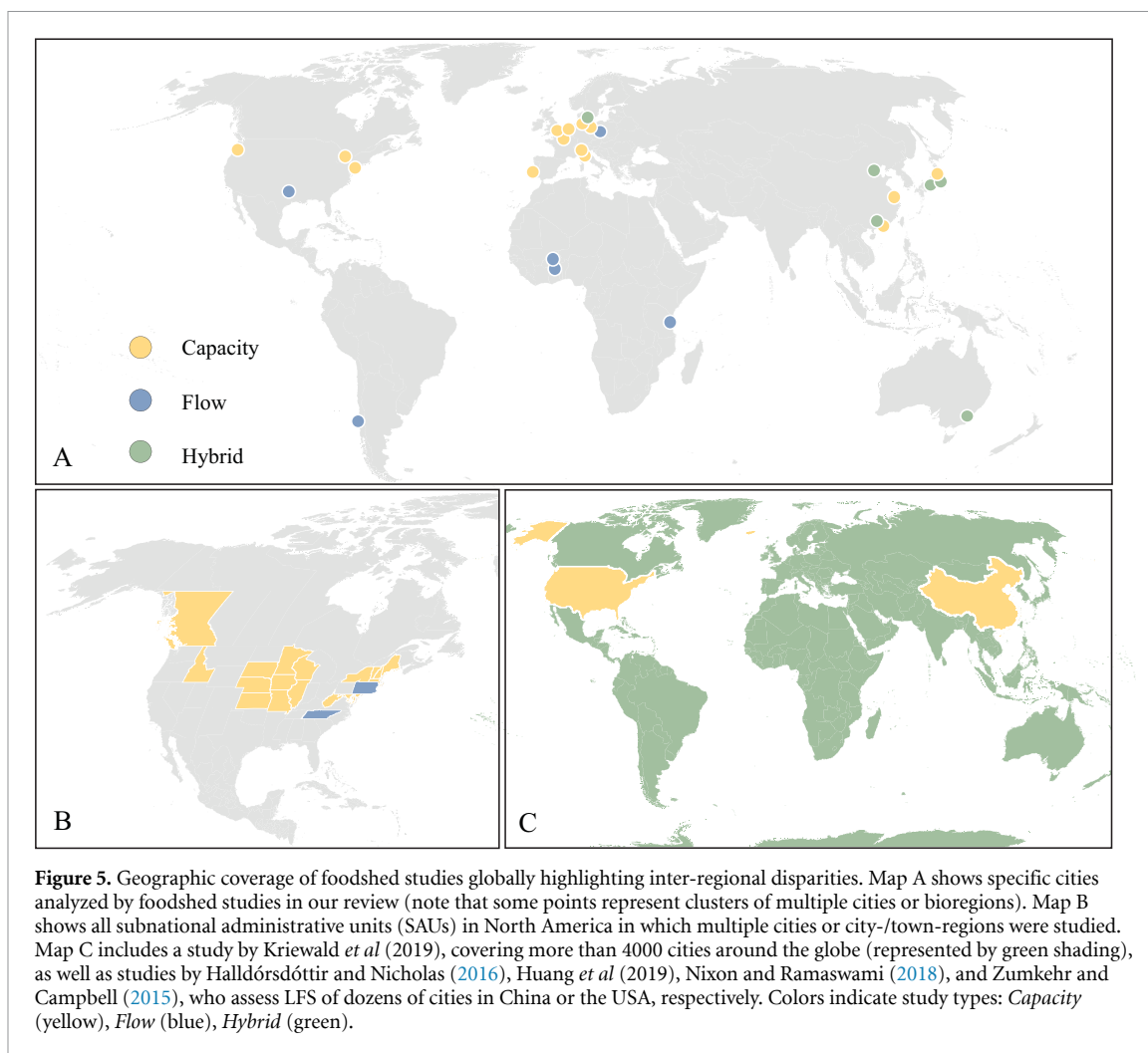
Study	Hara *et al* 2013 Quantitative assessment of the Japanese 'local production for local consumption' movement: a case study of growth of vegetables in the Osaka city region
Context	Osaka city region, Japan
Aims	• *Flows*: Tracing quantity and origin of vegetables, and calculation of energy consumption due to production (inorganic fertilizer and pesticide production, onsite electricity consumption and heating) and transportation • *Capacity*: Calculation of consumption/production quotient for 1 km^2 cells in grid and for 20, 40, 60, and 80 km buffer zones around Osaka Castle • Mapping of land use, transportation networks, farmers' markets, and supermarkets • 500 m buffer zones to determine consumer access (distance of 500 m is used in other Japanese food access studies, accounting for aging population) • Outline of opportunities, motivations, incentives and limitations with regard to farmers' markets and governmental support
Data source	• Governmental statistics • Interviews with producers at farmers' markets about motivations and with representatives from municipality about governmental support of local food
Calculation methods	• Self-sufficiency threshold • Foodshed size
Scenarios used	• Energy savings: elimination of exports and imports, transformation of abandoned farmland into vegetable production, organic agriculture and food distribution through farmers' markets
Key findings	• High embodied energy in vegetables from remote prefectures due to transportation and heating, 80% of embodied energy in nearby prefectures is due to the application of inorganic fertilizers and pesticides • Self-sufficiency: 20 km—5.7% of population fed, 40 km—21.7%, 60 km—50.0%, 80 km—68.5% • Energy savings scenario: 20 km—6.2% of population fed, 40 km—24.5%, 60 km—55.0%, 80 km—75.5% • High local food systems potential with reuse of farmland abandoned due to urbanization and land speculation • Scenario with embodied energy reduction (transportation): Fewer exports—25% energy reduction; reuse of abandoned farmland—19%; Organic farming—33%

analysis (table 1). *Capacity* studies primarily used SAU and radius. The choice of systems boundary is often linked to the study objective and data availability in the given region (Supplementary Material text S10).

3.3. Quantitative comparison across foodshed studies

Our classification and framework for foodshed analysis (figure 3, table 1) illustrates difficulties in comparing results across the 42 reviewed studies given differences in methodologies, aims, and assumptions. Following patterns in table 1, we selected a subset of more comparable *Capacity* studies that used the 'foodshed size' calculation method in the United States to examine average distance to meet all or a share of food demands. We then compared mean values from the main analysis presented in each, excluding ranges or scenarios (figure 6). For example, Hu *et al* (2011b) showed that more than half of the

population in eight states in the Mid-Western US could be supported within an 8 km range due to the high quantities of arable land and small towns (population <1000 people). For cities, foodshed sizes ranged from 16 km (De Moines) to 122 km (Chicago area). This illustrates the utility of quantitative comparison, for example, in assessing the influence of city characteristics (e.g. population density) and geographic context (e.g. relative availability of arable land and crop yields) on foodshed outcomes. However, it is generally difficult to quantitatively compare past *Capacity* and *Hybrid* studies because of their divergent approaches (compare across rows in table 1). For example, Peters *et al* (2009) found that 34% of New York State's total food demands can be met within 49 km while Peters *et al* (2012) found that 69% of the State's food needs can be met within 238 km. Discrepancies between the two estimates reflect methodological variations pertaining to optimization and allocation models used (i.e. to minimize food distance

Figure 5. Geographic coverage of foodshed studies globally highlighting inter-regional disparities. Map A shows specific cities analyzed by foodshed studies in our review (note that some points represent clusters of multiple cities or bioregions). Map B shows all subnational administrative units (SAUs) in North America in which multiple cities or city-/town-regions were studied. Map C includes a study by Kriewald *et al* (2019), covering more than 4000 cities around the globe (represented by green shading), as well as studies by Halldórsdóttir and Nicholas (2016), Huang *et al* (2019), Nixon and Ramaswami (2018), and Zumkehr and Campbell (2015), who assess LFS of dozens of cities in China or the USA, respectively. Colors indicate study types: *Capacity* (yellow), *Flow* (blue), *Hybrid* (green).

travelled and to maximize economic land use values, respectively).

4. Reflections on the value of foodshed analysis for holistic food systems research

4.1. Sustainability and dependency issues in food systems from a city perspective

The foodshed concept provides an interdisciplinary approach to investigate food systems by linking culture (*food*) with nature (*shed*) and therefore aspects of both people and place (Kloppenburg *et al* 1996). Foodshed analyses can highlight links between multiple production and consumption factors and the feasibility of LFS (figure 7(A)). For example, understanding the impacts of changes in local diets towards less (Joseph *et al* 2019) or more animal-based proteins (Zumkehr and Campbell 2015) is crucial to estimating LFS potential. This applies particularly to regions facing pressures on local resources or high emissions, where agricultural intensification or extensification may be unfeasible. Foodshed studies have also investigated city-specific scenarios linking multiple social and ecological sustainability issues, such as the contribution of dietary changes and organic agriculture to human health and environmental quality

(Joseph *et al* 2019), enhancing local nutritional sufficiency and the support of local farms and food enterprises (Desjardins *et al* 2010, Kremer and Schreuder 2012), as well as maximizing energy savings and reutilization of abandoned land (Hara *et al* 2013). Tools from business development, such as *strengths, weaknesses, opportunities, and threats* (SWOT) analysis, have also been used to systematically record the findings and juxtapose competing goals and outcomes (Orlando *et al* 2019).

Foodshed analysis can also help in weighing the benefits and limitations of local versus global food sourcing through comparative studies of agricultural capacity and food flows (figure 7(B)). Localization strategies aim towards LFS by decreasing exports and imports. However, in contexts with high food trade, foodshed assessments must not only consider LFS potentials in the region of interest but all other regions that are connected through trade relationships. Foodshed studies can identify and map existing interdependencies with regard to resources and food security (figure 7(B)). *Hybrid* approaches are particularly useful for assessing a region's embeddedness in those physical, economic, and cultural systems on multiple scales. Our review shows that *Capacity* studies, the most common foodshed study
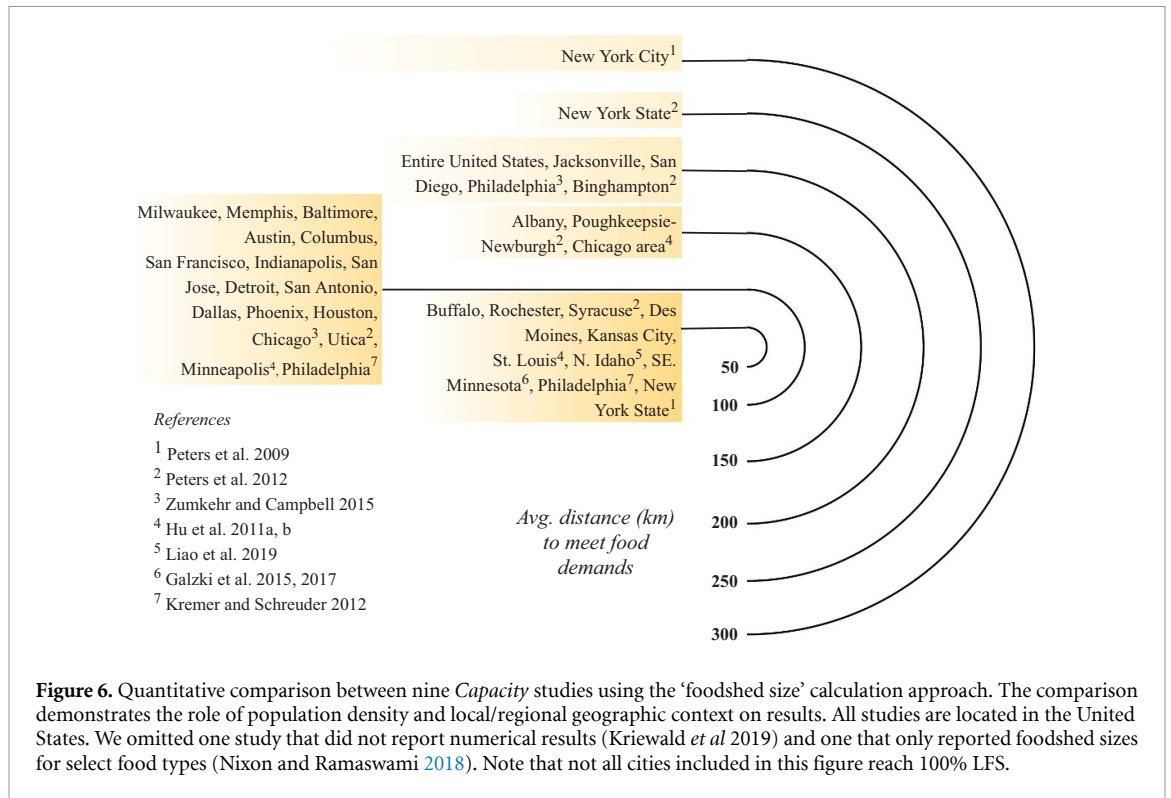
Figure 6. Quantitative comparison between nine *Capacity* studies using the 'foodshed size' calculation approach. The comparison demonstrates the role of population density and local/regional geographic context on results. All studies are located in the United States. We omitted one study that did not report numerical results (Kriewald *et al* 2019) and one that only reported foodshed sizes for select food types (Nixon and Ramaswami 2018). Note that not all cities included in this figure reach 100% LFS.
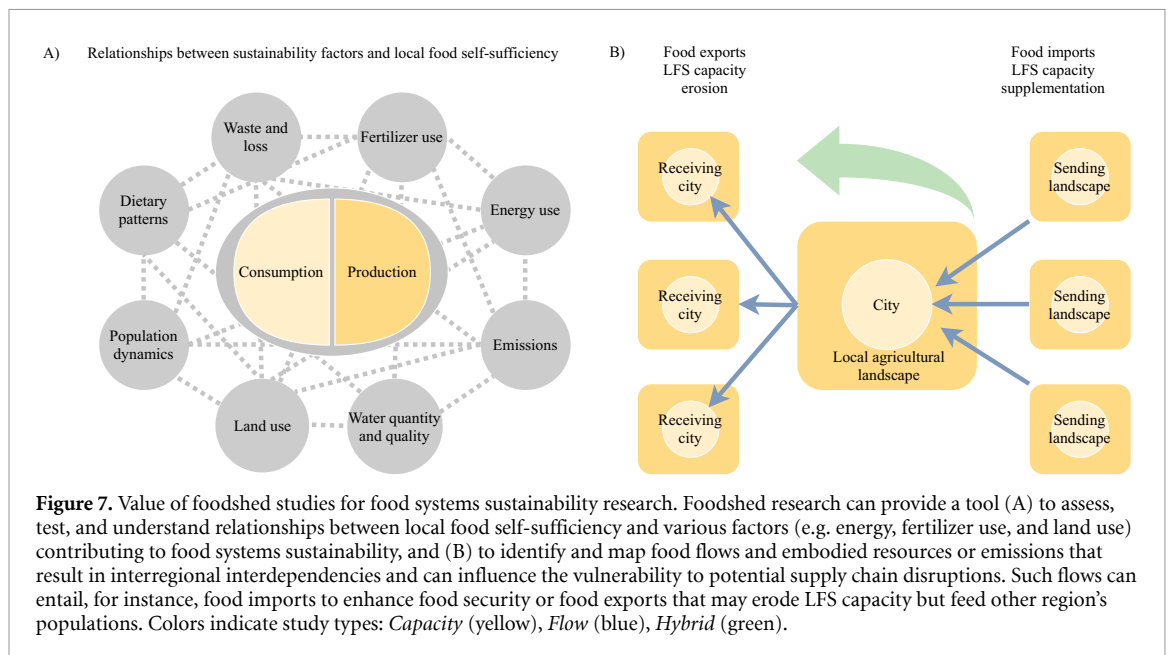

Figure 7. Value of foodshed studies for food systems sustainability research. Foodshed research can provide a tool (A) to assess, test, and understand relationships between local food self-sufficiency and various factors (e.g. energy, fertilizer use, and land use) contributing to food systems sustainability, and (B) to identify and map food flows and embodied resources or emissions that result in interregional interdependencies and can influence the vulnerability to potential supply chain disruptions. Such flows can entail, for instance, food imports to enhance food security or food exports that may erode LFS capacity but feed other region's populations. Colors indicate study types: *Capacity* (yellow), *Flow* (blue), *Hybrid* (green).

type, are limited in this regard. Without food flow analysis, high LFS potentials could result in misleading conclusions and policy recommendations. Several *Capacity* studies have emphasized potential impacts of food exports on LFS, such as the erosion of LFS or the dependency on food imports to fill local food supply gaps (i.e. Galzki *et al* 2014, Hu *et al* 2011a Giombolini *et al* 2011, Billen *et al* 2012, Porter *et al* 2014, Nixon and Ramaswami 2018). To date, two studies have included exports in their calculations (Lu and Campbell 2009, Zhou *et al* 2012). Nevertheless, the relationship is not well understood. *Hybrid* studies are

therefore a promising tool with potential for further exploration.

4.2. Research priorities and data challenges in the quantitative assessment of urban foodsheds

Our review highlights the diverse ways that urban foodshed analysis can be used to create new, and synthesize existing, knowledge on food systems sustainability (Peters *et al* 2009). To provide useful information for planners and decision-makers, foodshed researchers need to overcome several

methodological and analytical challenges, particularly regarding subnational food flow data. Governments and private sector actors can aid this development by compiling and making necessary data accessible.

4.2.1. Research priorities and policy areas
Based on our review of the 42 publications, we have identified several broad policy areas, and associated examples, that require further attention in the context of foodshed analysis. These policy areas span the food system, from production to consumption (see table 5), and, taken together, suggest two priority research areas for applied foodshed scholarship.

Priority #1: *How do physical and social barriers interact in local food systems?*

Almost all studies critically discuss, to some degree, the infrastructural, behavioral, and logistical barriers and limitations in the pursuit of LFS. A major point of critique of *Capacity* studies is that a high LFS potential cannot be exploited if neither adequate processing, storage, and transportation infrastructure nor the economic incentive to source locally prevail in a region (Kurita *et al* 2009, Peters *et al* 2009, Hu *et al* 2011a, Galzki *et al* 2014). Only a few studies suggest measures such as the establishment of food processing facilities to decrease the loss of local physical resources and increase the local job market (Lu and Campbell 2009) or transforming nearby vacant land to revive the areas' economic productivity (Hara *et al* 2013).

Most *Capacity* studies neglected social preferences, assuming that farmers will supply to the closest population center (Galzki *et al* 2017) and that citizens will refrain from buying imported foods and replace them through local options (Galzki *et al* 2014, Joseph *et al* 2019, Zasada *et al* 2019) or will eat seasonally (Conrad *et al* 2017). Only two studies in our sample conducted consumer surveys on preferences concerning local food sourcing (Halldórsdóttir and Nicholas 2016, Liao *et al* 2019). Further, few *Capacity* studies differentiated between production and distribution systems (e.g. community supported agriculture, greenhouse horticulture) (Aucoin and Fry 2015, Grigsby and Hellwinckel 2016, Brinkley 2017) or seasonal variability (Peters *et al* 2007, Karg *et al* 2016, Akoto-Danso *et al* 2019) despite the potential impact on food systems sustainability, resilience, and LFS.

Some foodshed study authors claimed that small and medium-sized cities might be better equipped for food systems localization due to the smaller physical distance to peri-urban agriculture and greater governance capacity (Kurita *et al* 2009, Filippini *et al* 2014, Liao *et al* 2019). Yet, empirical evidence on the relationship between city size and the physical and social capacity for local food systems remains scarce. Examples of studies on subnational (Galzki *et al* 2014, 2017), national (Zumkehr and Campbell 2015, Nixon and Ramaswami 2018) and global scale (Kriewald

et al 2019) have already assessed potential LFS of cities of multiple sizes and their respective local hinterland. Accordingly, more studies should incorporate various city sizes and assess physical and social capacity in parallel.

Priority #2: *How are food flows linked with other urban material flows and embodied resources?*

Most *Capacity* and *Hybrid* studies assess the feasibility of LFS if regions were to move towards circular and integrated production systems or if consumers were to consume less animal-based proteins (table 1). Accordingly, regions could reduce the dependency on external inputs, such as fertilizers, pesticides, or livestock feed. Future foodshed research could extend its analysis beyond the farm by identifying the origins of food production input materials. For example, Hedberg (2019) studied phosphorus flows to farms to identify dependency, vulnerability, and sustainability of fertilizer supply chains that are necessary for local food production in the Northeastern US.

Combining foodshed analysis with urban metabolism and circular economy scholarship can also reveal the (potential) environmental sustainability of a city's food supply as a territorial ecology and territorial metabolism framework (Tedesco *et al* 2017). This can encompass streams of urban liquid and solid wastes to be reused in local agriculture ('wastesheds'), such as nutrients (Metson *et al* 2018) as well as potentials to reduce environmental degradation through integrated production systems (Liang *et al* 2019, Zeller *et al* 2019). Billen *et al*'s (2012) analysis provides an interesting example for a metabolism-based foodshed analysis, linking LFS, fertilizer use, and water quality.

4.2.2. Data challenges and uncertainties
Models are generalizations of the real world that can inhibit a number of uncertainties that need to be considered when interpreting results, including related to data limitations and quality. Authors of *Capacity* studies, for instance, mentioned scarce, unreliable, and fragmented data on crop yields and soil properties (Desjardins *et al* 2010, Giombolini *et al* 2011, Kremer and Schreuder 2012, Filippini *et al* 2014, Galzki *et al* 2014, Cardoso *et al* 2017). Further, aggregation of various types of data across administrative units can introduce uncertainty in *Capacity* models. Sensitivity analysis is a mathematical approach to estimate the uncertainty of models and their results (Saltelli *et al* 2004) yet few reviewed foodshed studies used this tool. Nixon and Ramaswami (2018) estimate the impact of foodshed radius and Peters *et al* (2012) the impact of crop yields on LFS. Joseph *et al* (2019) assess how land use and livestock production systems affect LFS. The most comprehensive sensitivity analysis we found, by Zumkehr and Campbell (2015), encompassed six factors, including diets, crop yields, and cropland allocation.

Table 5. Areas of potential policy relevance for foodshed identified from the 42 reviewed studies. The table lists the topics that have already been addressed or that were identified as critical but not further considered in the study.

Food system component	Policy area	Examples from the reviewed literature
Production	Farmer livelihoods and rural development	• Consider livelihood implications of changes in crop mix (Desjardins *et al* 2010; Giombolini *et al* 2011) • Understand effects of LFS for counteracting rural population decline (Desjardins *et al* 2010) • Benefits of establishing long-term agreements between rural producers and the city (Orlando *et al* 2019) • Account for economic relevance of agricultural sector in the region (Nixon and Ramaswami 2018)
	Infrastructure	• Plan for slaughterhouses and other processing facilities (Conrad *et al* 2017; Filippini *et al* 2014; Peters *et al* 2009) • Assess storage requirements for staple crops (Akoto-Danso *et al* 2019; Desjardins *et al* 2010; Peters *et al* 2007, Peters *et al* 2009, Peters *et al* 2012)
	Land competition and management	• Consider overlapping foodsheds and shared agricultural landscapes in metro-clusters (Joseph *et al* 2019; Kremer and Schreuder 2012; Nixon and Ramaswami 2018) • Understand effects of urban expansion on food production (Cardoso *et al* 2017; Huang *et al* 2019; Kriewald *et al* 2019) • Highlight potential conflicts related to meat industry in close proximity to the city (Giombolini *et al* 2011) • Account for conflicts between food vs. non-food use of croplands and competition between adjacent croplands in terms of crop mix or plant diversity (e.g. brassica family) (Giombolini *et al* 2011) • Plan for the restoration or protection of ecosystem services on landscape scale (e.g. abandonment of marginal land) (Conrad *et al* 2017; Griffin *et al* 2014; Liao *et al* 2019)
	On-farm management and decision making	• Contextualizes advantages and limitations of organic agriculture (Joseph *et al* 2019) • Understand impacts of conversion from commodity crops to specialty crops (Griffin *et al* 2014) • Explore 'circular economy' scenarios (Tedesco *et al* 2017; Zhou *et al* 2012) • Quantify impacts of climate change on crop yields (Kriewald *et al* 2019) • Consider the conversion of livestock systems (Joseph *et al* 2019; Zhou *et al* 2012)
Distribution	Supply chains and marketing	• Account for export-orientation for crops like wheat and blueberries (Giombolini *et al* 2011; Nixon and Ramaswami 2018; Zhou *et al* 2012) or dependence on imports (Akoto-Danso *et al* 2019; Halldórsdóttir and Nicholas 2016; Karg *et al* 2016) • Account for seasonal variability (Akoto-Danso *et al* 2019; Karg *et al* 2016; Zhou *et al* 2012) • Plan for alternative market schemes (e.g. community supported agriculture, farmers markets) (Brinkley 2017; Grigsby and Hellwinckel 2016; Świąder *et al* 2018) • Examine the impacts of locally-produced versus imported feed (Porter *et al* 2014)
Consumption	Diets, food preferences, and access	• Highlight the effects of a potential decrease in food supply diversity (Halldórsdóttir and Nicholas 2016) • Consider willingness to pay for local foods (Orlando *et al* 2019) • Illustrate potential effects of local dietary change scenarios (Joseph *et al* 2019; Kriewald *et al* 2019)

Challenge #1: *Accounting for local socio-economic and cultural differences in food consumption*

The availability of high-quality data has a major impact on the spatial and temporal resolution of foodshed analysis. Our review shows that socioeconomic and biophysical context, as well as urbanization and development histories, can impact LFS potential and the nature of food flows (Porter *et al* 2014, Wegerif and Wiskerke 2017, Akoto-Danso *et al* 2019, Li *et al* 2019). Low resolution data can make it harder to distinguish whether results are city-specific or reflect national averages rescaled to population and land area. For instance, dietary preferences in large cities may vary from average national figures as well as between cities in the same country (Vanham *et al* 2016, 2017, González-García and Dias 2019). Further, household food expenditure data is often aggregated geographically or by food group (Nixon and Ramaswami 2018). Several studies raised concerns that production, consumption, and food flow data on subnational scales is often fragmented and/or unreliable (Desjardins *et al* 2010, Giombolini *et al* 2011, Kremer and Schreuder 2012, Filippini *et al* 2014, Galzki *et al* 2014, Cardoso *et al* 2017). Such data gaps can lead to an over- or underestimation of regional cultural or socio-economic food demands (see text S7 'Capacity studies' for examples) or the relevance of certain supplying regions.

Challenge #2: *Need for temporal data on inter- and intra-annual food supply dynamics*

Many foodshed studies (particularly *Capacity* studies) treat food supply and agricultural capacity as being static. In most regions, agricultural seasons are crucial determinants of type, quantity, and availability of foods, but seasonality is rarely addressed in foodshed studies. Peters *et al* (2007) account in their *Capacity* study for this limitation by defining summer and winter diets (e.g. processed or storable fruits and vegetables). However, the willingness of consumers to shift to seasonal diets is most likely low. Seasonality analysis is more prevalent among *Flow* studies than other study types, for example, through the use of local vegetable harvest and flow calendar (table 1). Unless diets are adjusted to seasonal availability of foods, consumer demands for perishable food off-season can only be satisfied through food imports or greenhouse horticulture. Foodshed studies should therefore take this seasonal variability as well as the intra-annual flows (e.g. imports) that compensate for the lack of local agricultural capacity into account.

Increasing the temporal scope and resolution of foodshed studies could also make significant contributions to increasing their usefulness for planning, but sub-annual data are rarely readily available. We found that multiple studies model intra- or inter-annually variability of food flows or model the LFS capacity under different scenarios; what Porter *et al* (2014) call a 'bio-historical' approach (table 2). For example, Kriewald *et al*'s (2019) global study used various scenarios (e.g. urban growth, climate change, diet change) and time-series modeling to estimate each scenario's influence on LFS from 2010 to 2050 across different world regions. Some studies also use time-series data to model intra-annual changes (table 1).

Challenge #3: *The need for primary data collection to compensate gaps in data-poor regions*

A lack of standardized data on household food consumption and food availability, the various food types consumed, and their origin on a monthly basis poses a challenge to foodshed quantification. Studies have addressed this issue by either using national average data or via extensive primary data collection via market and street surveys. Karg *et al* (2016) and Akoto-Danso *et al* (2019) combined street and market surveys, literature, and interviews to build a more comprehensive data base for their analysis. Quantitative surveys among smaller samples of selected food systems actors, such as farmers participating in local or short food supply chains, can help to assess the agricultural capacity of a particular producer group to feed local consumers (Kurita *et al* 2009, Filippini *et al* 2014, Liao *et al* 2019). Similarly, interviews and surveys can help to trace supply and value chains (production, processing, and distribution) or bi-directional flows of food between different scales (Zhou *et al* 2012, Karg *et al* 2016). Wegerif and Wiskerke (2017) used ethnographic methods in their study of Dar es Salaam (Tanzania) to illustrate the value of understanding the relationships between material flows (food) and social relationships. The mapping of social networks underpinning urban food supply and consumption in order to measure structural and relational factors (e.g. trust, reciprocity, proximity, density, formality) is a helpful tool. However, in both examples, primary data collection requires considerable resources, with a resulting focus on smaller spatial extents and/or sample sizes.[5]

Especially in Global South countries, where urban growth is expected to have considerable impacts on agricultural land (Avellan *et al* 2012, Bren d'Amour *et al* 2016), planning for sustainable food systems means finding ways to decouple food supply from resource shortages, extreme weather, as well as geopolitical conflict. However, such regions are understudied in terms of LFS capacity in particular. Data on food availability, the roles of intermediaries, food types, safety, and quality, as well as nutritional content, spoilage, and food origin on a monthly basis are important to identify gaps and vulnerabilities in

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[5] Case studies such as Penker's work on the ecological embeddedness of the bread supply chain in Austria (2006) or Saguin's study (2014) on the bighead carp in the Philippines (not reviewed) offer more detailed insights into such pathways. However, their approach is very resource intensive and requires the focus on a type of food and its supply chain. Hence, it only allows conclusions about the ecological and social implications of a small fraction of the urban food supply.

food supply chains. These data can further be linked to questions of equity (e.g. youth and female participation), production (e.g. water usage, pest management), and infrastructure. Foodshed researchers working in this context must consider both formal and informal markets but note that food supply chain consolidation could limit transparency and access to proprietary data.

To summarize, we encourage researchers, policymakers, and food supply chain actors to collaboratively develop strategies to harness technological advancements to provide missing data. Promising examples relevant to foodshed analysis include machine learning approaches to predict subnational food flows (Lin *et al* 2019), spatially-explicit predictive modeling of food consumption and production (Morrison *et al* 2011, 2012), and blockchain or other 'big data' approaches that draw on different data streams (Holden *et al* 2018, Saberi *et al* 2019). Such advancements could help to fill gaps in understudied regions and to take greater advantage of *Hybrid* approaches that combine multiple food systems issues. To achieve this, co-development of foodshed research with key stakeholders (e.g. food corporations and governments) may help to address multiple research priorities and data challenges (Smith *et al* 2017). Large-scale projects focused on a specific region could provide the necessary data and knowledge to produce scientific evidence for the social, economic, and ecological opportunities and limitations with regard to food systems localization (see Griffin *et al* (2014) and Conrad *et al* (2017) for studies embedded in the 'Enhancing Food Security in the Northeast through Regional Food Systems (EFSNE)' project, targeting local food security and rural development). Furthermore, large-scale projects can combine multiple complementing analyses, using the same data, which can justify an extensive primary data collection (see Karg *et al* (2016) and Akoto-Danso *et al* (2019)).

5. Conclusions

Foodshed research is an increasingly popular interdisciplinary approach to urban food systems research. However, our review shows a wide range of methods that have been used to assess urban foodsheds worldwide that presently limit comparison across studies. Due to the high complexity of food systems, integrated studies along more than just a few dimensions are also rare. Data limitations, specifically on local food consumption patterns and intra-annual food flows, are major hurdles that constrain foodsheds analyses from moving away from the hypothetical toward explicit quantification of urban food supply chains. Particularly for *Flow* studies, reliable and up-to-date data on a sub-national level are often unavailable or are inaccessible, requiring extensive primary data collection. Finally, drawing from examples across the foodshed literature, we discussed the value of foodshed analysis and how it could progress towards a more consolidated and interdisciplinary research agenda. By drawing on a common framework and coherent set of methodological criteria, future urban foodshed research can more readily contribute to informing policies to address food systems sustainability and resilience.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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References

Akoto-Danso E K, Karg H, Drechsel P, Nyarko G and Buerkert A 2019 Virtual water flow in food trade systems of two West African cities *Agric. Water Manage.* **213** 760–72

Aucoin M and Fry M 2015 Growing local food movements: farmers' markets as nodes for products and community *Geogr. Bull.* **56** 61–78

Avellan T, Meier J and Mauser W 2012 Are urban areas endangering the availability of rainfed crop suitable land? *Remote Sens. Lett.* **3** 631–8

Avetisyan M, Hertel T and Sampson G 2014 Is local food more environmentally friendly? The GHG emissions impacts of consuming imported versus domestically produced food *Environ. Resour. Econ.* **58** 415–62

Billen G, Garnier J, Thieu V, Silvestre M, Barles S and Chatzimpiros P 2012 Localising the nitrogen imprint of the Paris food supply: the potential of organic farming and changes in human diet *Biogeosciences* **9** 607–16

Blay-Palmer A, Santini G, Dubbeling M, Renting H, Taguchi M and Giordano T 2018 Validating the city region food system approach: enacting inclusive, transformational city region food systems *Sustainability* **10** 1680

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.* **51** 12035–45

Bren d'Amour C, Wenz L, Kalkuhl M, Christoph Steckel J and Creutzig F 2016 Teleconnected food supply shocks *Environ. Res. Lett.* **11** 035007

Brinkley C 2017 Visualizing the social and geographical embeddedness of local food systems *J. Rural Stud.* **54** 314–25

Cardoso A S, Domingos T, de Magalhães M R, de Melo-abreu J and Palma J 2017 Mapping the Lisbon potential foodshed in Ribatejo e Oeste: a suitability and yield model for assessing the potential for localized food production *Sustainability* **9** 2003

Clapp J 2014 Food security and food sovereignty: getting past the binary *Dialogues Hum. Geogr.* **4** 206–11

Clinton N, Stuhlmacher M, Miles A, Uludere Aragon N, Wagner M, Georgescu M, Herwig C and Gong P 2018 A global geospatial ecosystem services estimate of urban agriculture *Earth's Future* **6** 40–60

Conrad Z, Tichenor N E, Peters C J and Griffin T S 2017 Regional self-reliance for livestock feed, meat, dairy and eggs in the Northeast USA *Renew. Agric. Food Syst.* **32** 145–56

Cumming G S, Buerkert A, Hoffmann E M, Schlecht E, von Cramon-taubadel S and Tscharntke T 2014 Implications of agricultural transitions and urbanization for ecosystem services *Nature* **515** 50–57

Dalin C, Konar M, Hanasaki N, Rinaldo A and Rodriguez-Iturbe I 2012 Evolution of the global virtual water trade network *Proc. Natl Acad. Sci.* **109** 5989–94

Defries R S, Rudel T, Uriarte M and Hansen M 2010 Deforestation driven by urban population growth and agricultural trade in the twenty-first century *Nat Geosci* **3** 178–81

Desjardins E, Macrae R and Schumilas T 2010 Linking future population food requirements for health with local production in Waterloo region, Canada *Agric. Human Values* **27** 129–40

Dubbeling M, Santini G, Renting H, Taguchi M, Lançon L, Zuluaga J, de Paoli L, Rodriguez A and Andino V 2017 Assessing and planning sustainable city region food systems: insights from two Latin American cities *Sustainability* **9** 1455

Edwards-Jones G 2010 Does eating local food reduce the environmental impact of food production and enhance consumer health? *Proc. Nutr. Soc.* **69** 582–91

Filippini R, Marraccini E, Lardon S and Bonari E 2014 Assessing food production capacity of farms in periurban areas *Ital. J. Agronomy* **9** 63

Fradkin E 2015 *Can Lopez Island Feed Itself? A Foodshed Assessment of Lopez Island, Washington* (Lopez Island, WA: Lopez Community Land Trust) (www.lopezclt.org/wp-content/uploads/Lopez-Island-Foodshed-Assessment.pdf)

Galzki J, Mulla D J and Peters C J 2014 Mapping the potential of local food capacity in Southeastern Minnesota *Renew. Agric. Food Syst.* **30** 364–72

Galzki J, Mulla D and Meier E 2017 Mapping potential foodsheds using regionalized consumer expenditure data for Southeastern Minnesota *J. Agric. Food Syst. Community Dev.* **7** 1–16

Getz A 1991 Urban foodsheds *The Permaculture Activist*, 26–27

Giombolini K J, Chambers K J, Schlegel S A and Dunne J B 2011 Testing the local reality: does the Willamette Valley growing region produce enough to meet the needs of the local population? A comparison of agriculture production and recommended dietary requirements *Agric. Human Values* **28** 247–62

González-García S and Dias A C 2019 Integrating lifecycle assessment and urban metabolism at city level: comparison between Spanish cities *J. Ind. Ecology* **23** 1062–76

Griffin T, Conrad Z, Peters C, Ridberg R and Tyler E P 2014 Regional self-reliance of the Northeast food system *Renew. Agric. Food Syst.* **30** 349–63

Grigsby C and Hellwinckel C 2016 Locational advantage and the impact of scale: comparing local and conventional fruit and vegetable transportation efficiencies *J. Agric. Food Syst. Community Dev.* **6** 121–40

Halldórsdóttir Þ Ó and Nicholas K A 2016 Local food in Iceland: identifying behavioral barriers to increased production and consumption *Environ. Res. Lett.* **11** 115004

Hara Y, Tsuchiya K, Matsuda H, Yamamoto Y and Sampei Y 2013 Quantitative assessment of the Japanese 'local production for local consumption' movement: a case study of growth of vegetables in the Osaka city region *Sustain. Sci.* **8** 515–27

Hedberg R C 2019 Coming out of the foodshed: phosphorus cycles and the many scales of local food *Ann. Am. Assoc. Geogr.* **110** 1–21

Hedden W 1929 *How Great Cities are Fed* (Boston, NY: D.C. Heath and Company) *How Great Cities are Fed* 1929 (Boston, NY: D.C. Heath and Company)

Holden N M, White E P, Lange M C and Oldfield T L 2018 Review of the sustainability of food systems and transition using the Internet of Food *Npj Sci. Food* **2** 18

Horst M and Gaolach B 2015 The potential of local food systems in North America: a review of foodshed analyses *Renew. Agric. Food Syst.* **30** 399–407

Hu G, Wang L, Arendt S and Boeckenstedt R 2011a Analyzing sustainable, localized food production systems with a systematic optimization model *J. Hunger Environ. Nutr.* **6** 220–32

Hu G, Wang L, Arendt S and Boeckenstedt R 2011b An optimization approach to assessing the self-sustainability potential of food demand in the Midwestern United States *J. Agric. Food Syst. Community Dev.* **2** 195–207

Huang J, Ridoutt B G, Zhang H, Xu C and Chen F 2014 Water footprint of cereals and vegetables for the beijing market: comparison between local and imported supplies *J. Ind. Ecology* **18** 40–48

Joseph S, Peters I and Friedrich H 2019 Can regional organic agriculture feed the regional community? A case study for Hamburg and North Germany *Ecological Econ.* **164** 106342

Karg H, Drechsel P, Akoto-Danso E, Glaser R, Nyarko G and Buerkert A 2016 Foodsheds and city region food systems in two West African cities *Sustainability* **8** 1175

Kennedy C, Cuddihy J and Engel-Yan J 2007 The changing metabolism of cities *J. Ind. Ecology* **11** 43–59

Kinnunen P, Guillaume J H A, Taka M, D'Odorico P, Siebert S, Puma M J, Jalava M and Kummu M 2020 Local food crop production can fulfil demand for less than one-third of the population *Nat. Food* **1** 229–37

Kloppenburg J, Hendrickson J and Stevenson G W 1996 Coming in to the foodshed *Agric. Human Values* **13** 33–42

Kloppenburg J and Lezberg S 1996 Getting it straight before we eat ourselves to death: from food system to foodshed in the 21st century *Soc. Nat. Resour.* **9** 93–96

Kremer P and Deliberty T L 2011 Local food practices and growing potential: mapping the case of Philadelphia *Appl. Geogr.* **31** 1252–61

Kremer P and Schreuder Y 2012 The feasibility of regional food systems in metropolitan areas: an investigation of Philadelphia's foodshed *JAFSCD* 171–91

Kriewald S, Pradhan P, Costa L, Ros AGarcía, Kropp JP 2019 Hungry cities: how local food self-sufficiency relates to climate change, diets, and urbanisation *Environ. Res. Lett.* **14** 094007

Kurita H, Yokohari M and Bolthouse J 2009 The potential of intra-regional supply and demand of agricultural products in an urban fringe area: a case study of the Kanto Plain, Japan *Geogr. Tidsskrift-Danish J. Geogr.* **109** 147–59

Lengnick L, Miller M and Marten G G 2015 Metropolitan foodsheds: a resilient response to the climate change challenge? *J. Environ. Stud. Sci.* **5** 573–92

Li K, Jin X, Ma D and Jiang P 2019 Evaluation of resource and environmental carrying capacity of China's rapid-urbanization areas—a case study of Xinbei district, Changzhou *Land* **8** 69

Liang S *et al* 2019 Quantifying the urban food–energy–water nexus: the case of the detroit metropolitan area *Environ. Sci. Technol.* **53** 779–88

Liao F H, Gordon B, Dephelps C, Saul D, Fan C and Feng W 2019 A land-based and spatial assessment of local food capacity in Northern Idaho, USA *Land* **8** 121

Lin X, Ruess P J, Marston L and Konar M 2019 Food flows between counties in the United States *Environ. Res. Lett.* **14** 084011

Liu J *et al* 2013 Framing sustainability in a telecoupled world *Ecology Soc.* **18** art26

Lu H and Campbell D E 2009 Ecological and economic dynamics of the Shunde agricultural system under China's small city development strategy *J. Environ. Manage.* **90** 2589–600

Mackaye B 1920 A plan for cooperation between farmer and consumer *Mon. Lab. Rev.* **11** 1–21

Metson G S, Cordell D, Ridoutt B and Mohr S 2018 Mapping phosphorus hotspots in Sydney's organic wastes: a spatially explicit inventory to facilitate urban phosphorus recycling *J. Urban Ecology* **4** juy009

Moher D, Liberati A, Tetzlaff J and Altman D G 2009 Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement *PLoS Med.* **6** e1000097

Morrison K T, Nelson T A, Nathoo F S and Ostry A S 2012 Application of Bayesian spatial smoothing models to assess agricultural self-sufficiency *Int. J. Geogr. Inf. Sci.* **26** 1213–29

Morrison K T, Nelson T A and Ostry A S 2011 Methods for mapping local food production capacity from agricultural statistics *Agric. Syst.* **104** 491–9

Newcombe K and Nichols E H 1979 An integrated ecological approach to agricultural policy-making with reference to the urban fringe: the case of Hong Kong *Agric. Syst.* **4** 1–27

Nixon P A and Ramaswami A 2018 Assessing current local capacity for agrifood production to meet household demand: analyzing select food commodities across 377 U.S. Metropolitan areas *Environ. Sci. Technol.* **52** 10511–21

Orlando F, Spigarolo R, Alali S and Bocchi S 2019 The role of public mass catering in local foodshed governance toward self-reliance of Metropolitan regions *Sustain. Cities Soc.* **44** 152–62

Penker M 2006 Mapping and measuring the ecological embeddedness of food supply chains *Geoforum* **37** 368–79

Pérez-Neira D and Grollmus-Venegas A 2018 Life-cycle energy assessment and carbon footprint of peri-urban horticulture. A comparative case study of local food systems in Spain *Landsc. Urban Plan.* **172** 60–68

Peters C J, Bills N L, Lembo A J, Wilkins J L and Fick G W 2009 Mapping potential foodsheds in New York State: a spatial model for evaluating the capacity to localize food production *Renew. Agric. Food Syst.* **24** 72–84

Peters C J, Bills N L, Lembo A J, Wilkins J L and Fick G W 2012 Mapping potential foodsheds in New York State by food group: an approach for prioritizing which foods to grow locally *Renew. Agric. Food Syst.* **27** 125–37

Peters C J, Wilkins J L and Fick G W 2007 Testing a complete-diet model for estimating the land resource requirements of food consumption and agricultural carrying capacity: the New York State example *Renew. Agric. Food Syst.* **22** 145–53

Porter J R, Dyball R, Dumaresq D, Deutsch L and Matsuda H 2014 Feeding capitals: urban food security and self-provisioning in Canberra, Copenhagen and Tokyo *Glob. Food Secur.* **3** 1–7

Saberi S, Kouhizadeh M, Sarkis J and Shen L 2019 Blockchain technology and its relationships to sustainable supply chain management *Int. J. Prod. Res.* **57** 2117–35

Saguin K 2014 Biographies of fish for the city: urban metabolism of Laguna Lake aquaculture *Geoforum* **54** 28–38

Saltelli A, Tarantola S, Campolongo F, Ratto M *et al* 2004 Global sensitivity analysis for importance assessment *Sensitivity Analysis in Practice*, ed A Saltelli, S Tarantola, F Campolongo and M Ratto (New York: Wiley) pp 31–61

Schipanski M E *et al* 2016 Realizing resilient food systems *BioScience* **66** 600–10

Seto K C and Ramankutty N 2016 Hidden linkages between urbanization and food systems *Science* **352** 943–5

Seto K C, Reenberg A, Boone C G, Fragkias M, Haase D, Langanke T, Marcotullio P, Munroe D K, Olah B and Simon D 2012 Urban land teleconnections and sustainability *Proc. Natl Acad. Sci.* **109** 7687–92

Silva R, Batistella M, Dou Y, Moran E, Torres S and Liu J 2017 The Sino-Brazilian telecoupled soybean system and cascading effects for the exporting country *Land* **6** 53

Smith T M, Goodkind A L, Kim T, Pelton R E O, Suh K and Schmitt J 2017 Subnational mobility and consumption-based environmental accounting of US corn in animal protein and ethanol supply chains *Proc. Natl Acad. Sci.* **114** 201703793

Świąder M, Szewrański S and Kazak J 2018 Foodshed as an example of preliminary research for conducting environmental carrying capacity analysis *Sustainability* **10** 882

Tedesco C, Petit C, Billen G, Garnier J and Personne E 2017 Potential for recoupling production and consumption in peri-urban territories: the case-study of the Saclay plateau near Paris, France *Food Policy* **69** 35–45

Thompson Jr E, Harper A and Kraus S 2008 *Think Globally ∼ Eat Locally San Francisco Foodshed Assessment* Farmland Trust p 48 (www.sagecenter.org/publications/san-francisco-foodshed-assesement/)

Vanham D, Gawlik B M and Bidoglio G 2017 Food consumption and related water resources in Nordic cities *Ecol. Indic.* **74** 119–29

Vanham D, Mak T N and Gawlik B M 2016 Urban food consumption and associated water resources: the example of Dutch cities *Sci. Total Environ.* **565** 232–9

Weber C L and Matthews H S 2008 Food-miles and the relative climate impacts of food choices in the United States *Environ. Sci. Technol.* **42** 3508–13

Wegerif M C A and Wiskerke J S C 2017 Exploring the staple foodscape of Dar es Salaam *Sustainability* **9** 1081

Yang Y and Campbell J E 2017 Improving attributional life cycle assessment for decision support: the case of local food in sustainable design *J. Clean. Prod.* **145** 361–6

Zasada I *et al* 2019 Food beyond the city – analysing foodsheds and self-sufficiency for different food system scenarios in European metropolitan regions *City Cult. Soc.* **16** 25–35

Zazo-Moratalla A, Troncoso-González I and Moreira-Muñoz A 2019 Regenerative food systems to restore urban-rural relationships: insights from the concepción metropolitan area foodshed (Chile) *Sustainability* **11** 2892

Zeller V, Towa E, Degrez M and Achten W M J 2019 Urban waste flows and their potential for a circular economy model at city-region level *Waste Manage.* **83** 83–94

Zhou D, Matsuda H, Hara Y and Takeuchi K 2012 Potential and observed food flows in a Chinese city: a case study of Tianjin *Agric. Human Values* **29** 481–92

Zumkehr A and Campbell J E 2015 The potential for local croplands to meet US food demand *Front. Ecol. Environ.* **13** 244–8