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

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Keywords: PRISMA, food systems, cities, food supply chains, agricultural capacity

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 titled, 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’ 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).

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.
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 \( \geq 100\% \) indicated that an area has a high LFS potential or produces surplus food. IST calculations examined what share of available agricultural capacity would
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
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

| 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 |
| Data sources | Previous studies, governmental and FAO statistics |
| 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) |
| 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 |
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
Capacity: Can a given region be self-sufficient, to what degree and under which circumstances? What is the maximum distance between producer and consumer in a local foodshed? How much of total food demand can be met with total capacity? (n=27) (e.g. Griffin et al. 2015)

Flow: What are the resources and emissions embodied in food flows to a city? What is the size of a foodshed to reach X% self-sufficiency? (n=12) (e.g. Zasada et al. 2019)

Hybrid: What are the resources and emissions embodied in food flows to a city? How much of the total capacity is needed to meet total food demand? (n=4) (e.g. Li et al. 2019)

Self-sufficiency threshold (ST)

| Calculation method | Food production | Food consumption |
|--------------------|-----------------|------------------|
| Value ≥ 100 % implies LFS | x 100 | x 100 |

Inversely self-sufficiency threshold (IST)

| Calculation method | Food production | Food consumption |
|--------------------|-----------------|------------------|
| Value < 100 % implies LFS | x 100 | x 100 |

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.

Calculation of food consumption, food production, and embodied resources or emissions

1. Food production = yield x functional unit
2. Food consumption = population x functional unit (per capita)
3. Embodied resources or emissions = RE x Food quantity

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. Emerge 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
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
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.

**Table 4.**

| Study | Context | Aims | Data source | Calculation methods | Scenarios used | Key findings |
|-------|---------|------|-------------|--------------------|---------------|-------------|
| Hara et al 2013 | Osaka city region, Japan | • 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 km² 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  
• 300 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 | • Governmental statistics  
• Interviews with producers at farmers’ markets about motivations and with representatives from municipality about governmental support of local food | • Self-sufficiency threshold  
• Foodshed size | • Energy savings: elimination of exports and imports, transformation of abandoned farmland into vegetable production, organic agriculture and food distribution through farmers’ markets | • 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...
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
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 (Hará 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 2016, 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 Hellwinkel 2016; Świądor 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 socio-economic 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-Garcia and Días 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).

Acknowledgments

This work was supported by the McGill Sustainability Systems Initiative (MSSI) and the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grants Program (Grant Number RGPIN-2016-04920 to GKM).

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