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Food beyond the city – Analysing foodsheds and self-sufficiency for different food system scenarios in European metropolitan regions

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ABSTRACT

The debate on urban resilience and metabolism has directed increasing attention to the ecological footprint of food consumption, self-sufficiency as a means of food security, and regionalisation of food systems for shortening supply chains. Recently, metropolitan regions have proposed food policies that aim to foster local food systems connected to their cities. Our research thus focused on the relationship between urban food demand and metropolitan land use.

We have developed the Metropolitan Foodshed and Self-sufficiency Scenario (MFSS) model, which combines regional food consumption and agricultural production parameters in a data-driven approach to assess the spatial extent of foodsheds as well as the theoretical self-sufficiency of the communities they serve. The model differentiates between food groups, food production systems, levels of food loss and waste as well as food origin. With regard to future urban growth, we applied the model to current and future population projections.

Results show substantial variations in the spatial extent of metropolitan foodsheds and self-sufficiency levels between the case study regions London, Berlin, Milan and Rotterdam, depending on population density and distribution, geographical factors and proximity to neighbouring urban agglomerations. The application of the model as a food planning tool offers a new perspective on the potential role of metropolitan regions for strengthening urban self-sufficiency. It also enables the ex-ante assessment of spatial consequences of changes within metropolitan food systems, on both demand and supply sides. In particular, we discuss possible dietary and consumption changes, but also production and supply chain alternatives.

1. Introduction

Responding to challenges of ongoing worldwide urbanisation and metropolitan growth, the debate on urban resilience, metabolism and the ecological footprint is increasingly relevant (Meerow, Newell, & Stults, 2016; Wackernagel, Kitzes, Moran, Goldfinger, & Thomas, 2006). Along with other resource flows, such as energy, water and materials (Davoudi & Stead, 2007), the issue of reliable food supply and regional self-sufficiency as a means of urban food security is of particular interest not only in the Global South, but increasingly in the Global North (Dubbeling, Campbell, Hoekstra, & Veenhuize, 2009; Grewal & Grewal, 2012; Pothukuchi & Kaufman, 1999). In this context, the notion of food self-sufficiency, referring to the ability of cities, regions and countries to obtain required alimentation within their boundaries, has long been discussed (Ligutti & Rawe, 1940; Morris, 1987). More recently, quantitative models of local food production, regionalised food systems and the shortening of supply chains have been popularised in research and policy (Brinkley, 2013; Deakin, Diamantini, & Borrelli, 2015; Kneafsey et al., 2013; Milan Urban Food Policy Pact, 2015).

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Due to food's multifunctional links to a wide range of issues (Morgan, 2014), it is argued, that beyond the reduction of urban food insecurity (Barthel & Isendahl, 2013; Opitz, Berges, Piorr, & Krikser, 2015), the re-shaping of urban food systems by linking urban areas with regional food production brings about manifold benefits (Doernberg, Zasada, Bruszewska, Skoczowski, & Piorr, 2016; Morgan & Sonnino, 2010; Wiskerke, 2009), such as enhanced social participation and inclusion (Dimitri, Oberholtzer, & Pressman, 2016), ecological embeddedness and reduction of food miles (Mundler & Rumpus, 2012; Penker, 2006), and regional agricultural competitiveness (Kneafsey et al., 2013; Zasada, 2011).

With the ongoing process of urbanisation, cities and metropolitan regions are becoming increasingly relevant from a food self-sufficiency perspective (Grewal & Grewal, 2012). In particular, it is increasingly acknowledged that urban consumption centres benefit from being connected to their peri-urban and rural agricultural production areas within a wider metropolitan territory (Piorr, Ravetz, & Tosics, 2011; Sali, Monaco, Mazzocchi, Glavan, & Pintar, 2014; Zasada, 2012). Studying foodsheds is thus a major field of food system research (Brinkley, 2013). They are understood here as the territory around urban areas which is required to feed the (urban) population and which represents the area of interaction between urban consumption and peri-urban production (Brinkley, 2013; Peters, Bills, Lembo, Wilkins, & Fick, 2009). For a long time, agriculture did not seem to be part of most contemporary metropolitan concepts (ESPON, 2006). It is only recently that urban (food) demands, lifestyle and business are considered 'game-changers' with regard to the notion of rurality, agricultural supply and landscape character near cities (Smeets, 2009; Wascher, 2012). Revisiting the theoretical market model developed by economist von Thünen (1826) gave way to a land use based concept for introducing food planning as part of a spatially explicit concept of sustainability at the level of metropolitan regions (Wascher, Kneafsey, Pintar, & Piorr, 2015a).

Many cities, such as London (Reynolds, 2009), Toronto (Blay-Palmer, 2009) or Belo Horizonte (Rocha & Lessa, 2009) have intensified food planning and policy efforts to foster local food systems and connect urban centres with their foodsheds (Jarosz, 2008; Pothukuchi & Kaufman, 1999). However, for effective policy design and governance, an adequate informational and knowledge base is needed to effectively plan food system production, processing, distribution, consumption and infrastructure development (De Smedt, 2010; Giombolini, Chambers, Schlegel, & Dunne, 2011). Along with food supply chain organisation and consumption-related knowledge, spatial information and land demand represent important factors for food planning purposes (Wascher, Zasada, & Sali, 2015b).

In the past, a number of quantitative food production and consumption-based assessments have been conducted at different spatial scales to gain insights into the capacity of regional agro-food systems, the spatial extent of regional foodsheds and regional self-sufficiency (Cassidy, West, Gerber, & Foley, 2013; Peters et al., 2009; Timmons, Wang, & Lass, 2008). Consumption or demand-based models evaluate the theoretical supply in terms of quantities or nutritional value needed or land required on the basis of information about food consumption and dietary patterns (Gerbens-Leenes & Nonhebel, 2002). These models estimate the required food production and subsequently the agricultural area needed to potentially meet food demand (Desjardins, MacRae, & Schumilas, 2010; Peters et al., 2009; de Ruiter, Kastner, & Nonhebel, 2014). Production or supply-based models mainly estimate numbers of people which can be fed depending on available land for production and management practices (Cassidy et al., 2013). Usually, these studies take into account actual dietary intakes or recommendations (Colasanti & Hamm, 2010; Giombolini et al., 2011).

More explicitly integrating food consumption and production, food self-sufficiency studies aim to depict the coverage of food needed by agricultural production for certain cities, regions or countries, expressed through food balance indices or production-consumption ratios. However, these approaches are mostly limited to specific local situations (Atamanova, 2013; Grewal & Grewal, 2012; Sali, Monaco, Mazzocchi, & Corsi, 2016) or focus on specific commodity types (Colasanti & Hamm, 2010).

Despite its relevance within spatial development and planning processes, actual geographical mapping approaches are rather exceptional (Peters et al., 2009). Available models also lack flexible scenario settings, such as changing food supply and demand levels, which are crucial for future-oriented planning. Against this background the paper's objective is to estimate the metropolitan foodshed – the size of the agricultural area needed to supply a city and its metropolitan region with food as well as the area's theoretical food self-sufficiency, taking specific regional conditions into consideration. Therefore, we aim to apply different methods (i) to estimate food consumption differentiated to individual dietary components and food categories; (ii) to apply different scenario alternatives of agricultural production and consumption; and (iii) provide a visual mapping element to enhance understanding of the space involved. To this end, we create scenarios including organic versus conventional agricultural systems, different food loss and waste reduction levels, and population changes based on current diets. We further carry out a comparative assessment of the foodshed area needed to meet regional food demand and the regional self-sufficiency level (SSL). The model is applied to four European Metropolitan regions: London (UK), Berlin (DE), Milan (IT), and Rotterdam (NL).

In the following section, details on model set-up, functional features as well as data and area profiles are introduced. Section 3 presents the results of scenarios covering production, food loss, diet and population size alternatives, which are discussed in Section 4. The final conclusions point to increasing future demand for planning tools that, like MFSS, are easily adaptable to specific local conditions.

2. Data and methodology

Incorporating the two key dimensions of food self-sufficiency analysis, the MFSS model integrates both food demand and supply as functions of regional agricultural production conditions and dietary patterns. We further take into account different production systems, and levels of food waste throughout the different food chains. We also distinguish between domestic products from temperate regions and those which must be imported. Fig. 1 provides an overview of the different modelling steps.

2.1. Regional food production, consumption and food waste

In the first step, food demand is determined by average diet per person and year, which can differ considerably between countries (Gerbens-Leenes & Nonhebel, 2002). To permit comparisons between the studied regions, we use national figures from the FAO's food balance database (2015) for total per capita consumption. To identify the theoretical role of local agricultural production, we distinguish between overall diets and the diet share which can be theoretically produced locally (in temperate regions). To derive the total amount of consumed food, the average per capita consumption is then extrapolated to the regional demand by applying the current and future projected number of the local and regional population for the year 2050 (EUROSTAT, 2016).

The food supply analysis is based on actual regional agricultural conditions depending on climatic and bio-physical conditions, such as soil fertility, resulting in crop yield differences. Systemic capabilities to provide food vary according to how available agricultural land is used, the suitability of the territory itself and the specialization of the primary sector, especially under particular agro-climatic conditions. Therefore average area yield values (in tonnes/ha) for the different commodity types are taken from agricultural statistics, mainly from regional and national databases (CBS Statistics Netherlands, 2016; ISTAT, 2012; Nix,

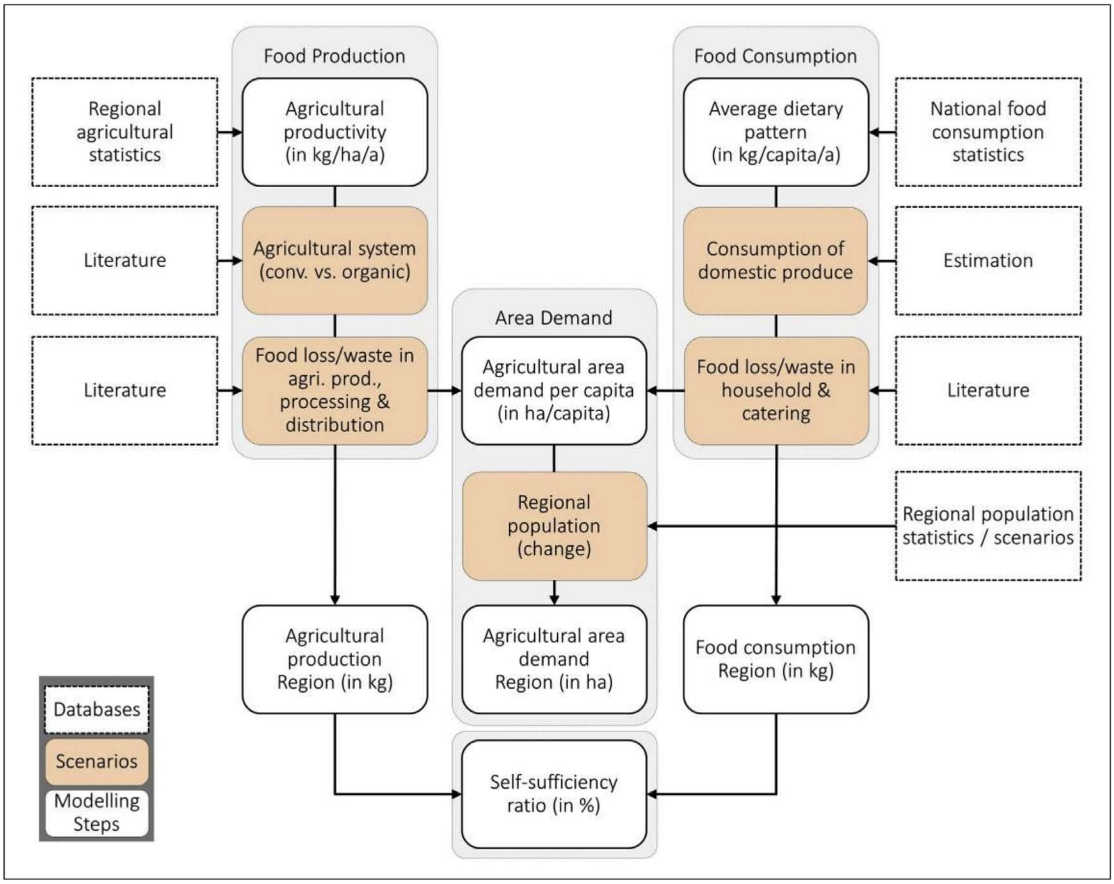

Fig. 1. MFSS modelling approach, databases and scenario elements.

2014; Statistik Berlin-Brandenburg, 2012). For crops that cannot be produced locally, such as exotic fruits, cacao, tea or coffee, global yield values from FAO statistics (2015) are considered.

The modelling of livestock production and fodder demand represents a specific challenge when assessing the area demand for food supply. Especially where various fodder production (on arable land) and grazing regimes are applicable, our modelling approach draws on existing area demand estimations by Woitowitz (2007) for European livestock systems. During food processing, especially in livestock production (e.g., meat, milk, eggs), but also for arable crops and fruits (e.g., sugar, cereals, fruits, alcoholic beverages), there is a significant weight loss during the conversion process from the agricultural production to the final product (etc. edible sugar, milk, butter, cheese, fish), which is also included in the modelling exercise. Table 1 provides an overview of the specific food categories used in the model, their regional yields and the required agricultural areas per kg final product.

As an example of different agricultural production systems, we have differentiated conventional production as a reference system and organic production. Therefore, we have used figures from different studies and meta-analyses (FAO, 2014a; Ponisio et al., 2015; Schneider et al., 2016; de Ponti, Rijk, & van Ittersum, 2012).

Losses and waste along the food supply chain are significant and therefore represent a large potential increase in food systems efficiency that could reduce the required food supply. Therefore, food loss and waste was included in our model. Generally, five steps of food loss and waste are distinguished: (1) reduced production output through animal sickness and death in agricultural production and mechanical damage and spillage during harvest; (2) spillage and degradation during post-harvest handling, storage and transportation and (3) processing and packaging inefficiencies, e.g. through technical malfunction and over or underproduction; (4) losses and waste in the wholesale, retail and distribution system, e.g. write-offs or spoilage; and within households and catering (Buzby & Hyman, 2012; EC, 2010; FAO, 2011); and (5) waste by the end consumer at home or eating out. At each step, a specific share of food gets lost, avoidably and unavoidably, increasing the total demand, which differs between commodity types, e.g. with higher values for perishable vegetables. For European agriculture, we applied FAO estimates (2011).

2.2. Scenario framework

As one of the main objectives of our study, we have developed a scenario framework, using the current situation as baseline scenario, for which current figures for average regional production, dietary levels, five-step food waste and loss, and population in the metropolitan region are applied. In the following scenarios we change four key drivers: (1) organic production, (2) diet, (3) food waste and (4) population. We also combine different key changes to analyse combined effects (see Table 2).

The application of these scenarios should allow for an estimate of possible land demand impacts related to changes through reduction of food loss and waste within the process of production, processing, distribution and household; by the conversion to organic farming; and by confining to domestic production in temperate regions.

To provide relevant information to metropolitan areas on future changes to foodsheds and self-sufficiency, it is essential to look at future population developments. Recent projections at national and European levels for 2050, clearly estimate further rapid growth of populations in urban and metropolitan areas (EUROSTAT, 2016).

2.3. Spatial metropolitan foodshed and self-sufficiency analysis

The commodity-specific area demand per capita is calculated by transforming the hectare yields into area demand per kg final product

Table 1
Food categories, production, conversion, food waste and loss and their application in the model.

Component	Description and Model application
Production of vegetable, potatoes, fruits and berries, cereals, sugar beet, oil seeds	Average regional production areas and yields (t/ha) for individual commodities are taken from regional and national agricultural statistics for the years 2010–2015 or farm management handbooks for the same period (CBS Statistics Netherlands, 2016; ISTAT, 2012; Nix, 2014; Statistik Berlin-Brandenburg, 2012)
Production of rice, coffee, tea, cacao, bananas, citrus and other tropical fruits	These commodities have been included in the area demand model, although they are not produced in the region (with the exception of rice for Milan) and require import from outside. Therefore average global yield values for the years 2003–2013 from FAO food balance sheet statistics are used (FAO, 2015).
Livestock production	For the analysis of agricultural area demand the model of Woitowitz (2007) has been applied for beef cattle, pigs and poultry (chicken, duck, goose, turkey), as well as for egg and dairy production. The value for sheep and goat is estimated based on the value for beef cattle. Within the processing additional weight loss between slaughter weight and final product is included in the model.
Fish production	39.8% (2011) of the total fish production is from aquafarming (FAO, 2014b). According to estimations of the NOAA (2011) app. 1 kg fodder is needed to produce 1 kg fish in aquafarming systems. Agricultural area demand for fish fodder is calculated by on the average value for the individual ingredients based on NOAA (2011).
Conversion in processing sugar	The sugar content of sugar beet can range from 18 to 22% and the crop yields of sugar beet are multiplied by 20% to arrive at sugar yield. Honey production does not require explicit, dedicated agricultural land and is therefore not included in the model.
Conversion in processing milk	The conversion factors for butter (8.792 kg milk) and cheese (9.632 kg milk) from milk are taken from Jacobson (1992).
Conversion in processing in alcoholic beverages	For processing of beer (20 kg malt (barley, wheat) for 100 L) and wine (140 kg grapes for 100 L), we used common conversion figures.
Organic and non-organic yield difference	Based on various meta-studies we use a percentage of relative yields of organic agriculture compared to conventional production: bovine meat (66%), milk and dairy products (76%), poultry (56%), pig meat (70%), laying hens (eggs) (67%) (Woitowitz, 2007); cereals (79%), oil seeds (74%), potato (70%), sugar beet (105%), tomato (81%), other vegetable (77%), roots and tubers (74%), pulses (88%), onion (77%), apple (69%), other fruits and grapes (78%), coffee (92%) (de Ponti et al., 2012); cacao (53%) (Schneider et al., 2016); nuts (93%) (Ponisio et al., 2015); tea (56%) (FAO, 2014a).
Food waste and loss within food supply chain	Based on estimations by the FAO (2011) for Europe: Agricultural production/postharvest handling and storage/processing and packaging/distribution/consumption: cereals (2%/4%/10%/2%/25%), roots and tubers (20%/9%/15%/7%/17%), oilseeds and pulses (10%/1%/5%/1%/4%), fruits and vegetables (20%/5%/2%/10%/19%), meat (3.1%/0.7%/5%/4%/11%), fish and seafood (9.4%/0.5%/6%/9%/11%), milk (3.5%/0.5%/1.2%/0.5%/7.0%)

as a result of the raw production (step 1, A_0) and a conversion factor (step 2, β_{conv}). For organic farming an additional area factor (step 3, β_{org}) is applied. In the next steps the potential area reduction by preventing food loss and waste in agricultural production, post-harvest, processing and distribution (step 4, $\beta_{Loss\,prod}$) as well as in household consumption and catering (step 5, $\beta_{Waste_{cons}}$) is applied. In a last step, a factor determining the share of the commodity, which can possibly be produced locally (step 6, β_{local}, taking climatic requirements into consideration (see equation (1)) is introduced. For example, most cereals are cultivated in temperate regions, whereas the supply of tropical fruits, cocoa, tea and coffee must be imported.

$$\mathrm{A_{cap}} = \mathrm{A_0}{*}\beta_{\mathrm{conv}}{*}\beta_{\mathrm{org}}{*}\beta_{\mathrm{Loss\,prod}}{*}\beta_{\mathrm{Waste\,cons}}{*}\beta_{\mathrm{local}} \tag{1}$$

To obtain the overall regional demand, the per capita demand A_{cap} is projected according to the total municipal and regional population figures (A_{agg}).

$$\mathrm{A_{agg}} = \mathrm{A_{cap}}{*}\mathrm{N_{reg.\ pop}} \tag{2}$$

In our model the aggregated agricultural area demand per municipality or region is represented by a circle with a centre point (centroid) of the administrative boundary polygon. The circle radius of the foodshed r_{FS} is calculated through the following formulas (3–4):

$$A_{FS} = \frac{A_{UAA.reg}}{A_{total.reg}}{*}(A_{agg} + A_{total.mun} - A_{UAA.mun}) \tag{3}$$

$$r_{FS} = \sqrt{\left(\frac{A_{FS}}{\pi}\right)} \tag{4}$$

For the spatial representation of the agricultural area demand, two elements are separately considered: the agricultural area available inside the municipal boundaries ($A_{UAA.mun}$), and the available area outside the boundaries (4). For the spatial modelling of the foodshed area A_{FS}, the aggregated area demand (A_{agg} needs to be increased by the area inside the municipality ($A_{total.mun}$, which cannot be utilized for agricultural production, such as settlement, infrastructure, forest and water areas. When the agricultural area demand exceeds the municipal area capacity, neighbouring areas will be used. The available regional area is represented as the overall agricultural area share of the region

Table 2
Scenario framework.

Scenario	Description
Base15	Conventional, current diet, incl. all current food waste and loss, 2015 (Baseline)
BaseL15	Conventional, current diet, excl. food loss and waste in agri. production, handling, processing, distribution, 2015
BaseLW15	Conventional, current diet, excl. food loss and waste in agri. production, handling, processing, distribution and household, 2015
Org15	Organic, current diet, incl. all food waste and loss, 2015
OrgL15	Organic, current diet, excl. food loss and waste in agri. production, handling, processing, distribution, 2015
OrgLW15	Organic, current diet, excl. food loss and waste in agri. production, handling, processing, distribution and household, 2015
OrgD15	Organic, diet from domestic sources only, incl. all food waste and loss, 2015
OrgDL15	Organic, diet from domestic sources, excl. food loss and waste in agri. production, handling, processing, distribution, 2015
OrgDLW15	Organic, diet from domestic sources, excl. food loss and waste in agri. production, handling, processing, distribution and household, 2015
Base50	Conventional, current diet, incl. all food waste and loss, 2050 population estimate
Org50	Organic, current diet, incl. all food waste and loss, 2050
OrgD50	Organic, diet from domestic sources, incl. all food waste and loss, 2050

($A_{UAA.reg}/A_{total.reg}$), which is effectively increasing the required foodshed area (A_{FS}) and representing the basis for the circle radius calculation (r_{FS}).

Along with the metropolitan foodshed analysis, local and regional food self-sufficiency represents another important indicator for local food planning. Self-sufficiency is understood as the capacity of a territorial unit to meet the local populations' own food requirements (Timmons et al., 2008) within its physical boundaries (Morris, 1987). Within our model, we interpret food self-sufficiency as the relationship between the aggregate area demand (A_{agg} and the available agricultural area ($A_{UAA.mun}$), expressed as self-sufficiency level (SSL), a ratio of available and required agricultural area for regional food demand. In this sense, a SSL of 100% would be realised, when the complete area demand for food production can be covered within the municipal or regional boundaries. Below that value, additional influx of food from outside is required. If it is larger, potential export would be possible. The analysis of the spatial distribution of the SSLs for individual municipalities provides information about the possibility of satisfying local demand through adjacent agriculture. It gives therefore indications of local hotspots of possible future food stresses, where municipalities with low SSL cluster.

2.4. European Metropolitan case study regions

The MFSS model described above has been applied in four European Metropolitan agglomerations and their surrounding regions, i.e. London, Berlin, Milan and Rotterdam. These regions have been selected to cover a range of territorial settings, concerning food demand as a function of the average diets, population size of the core city, the surrounding urban structures; and the regional agricultural production capacity, determined by available farmland and geographical farming conditions with different climatic and soil fertility situations. Table 3 gives an overview of the main regional characteristics.

Regarding the urban structure, Berlin and London represent rather mono-centric agglomerations, but are very different in size (3.5 and 8.2 million inhabitants) and in clear urban-rural gradients, with higher population densities in the region surrounding London (394 inh./km^2) compared to the extensive rural areas in Brandenburg (average population density of 86 inh./km^2). In contrast, Milan, and especially Rotterdam (as part of the Randstad region) are characterised by a much more polycentric settlement structure and by high population densities in the surrounding regions (514 and 1176 inh./km^2). The total populations of the city and regions vary substantially from 3.7 million (Rotterdam, South Holland) to 22.7 million inhabitants (Greater London, and East and South-East England).

Large differences are also found for the future population development. Generally, the regionalised projections (EUROSTAT, 2016) show increasing numbers for all regions and even more for the core cities. However, whereas growth projections for Greater London assume almost 50% until the year 2050, Rotterdam is expected to see a rather moderate increase below 10%. Also the proportion between city and surrounding region is very different. Milan Metropolitan Region and South Holland are expected to grow even faster than the core city. Brandenburg, very much in contrast to the city of Berlin (+31.7%) is expected to lose about 30% of its population, nearly 800,000 people. These future changes in spatial population concentrations will inevitably increase the necessity to respond in metropolitan food planning.

In terms of the bio-physical conditions, which are relevant for agricultural production, most regions (London, Rotterdam and Milan) are located in fertile river floodplains with highly productive agricultural land. Only in Berlin-Brandenburg are the farming conditions limited due to low precipitation and soil quality levels. Otherwise limitations to the regional agricultural production capacity are determined by geographic conditions, such as nearby seas (Rotterdam, London) and mountainous areas (Milan).

Further differences concerning the output of agricultural production are mainly due to the prevalence of certain production systems. South Holland is characterised by intensive dairy and greenhouse production systems with very high yields e.g. for vegetable and tomatoes as well as potatoes. Agriculture in Northern Italy is also specialised in the milk and dairy sector, plus production of rice, wine and vegetables. The London region is specialised in arable and potato production, but also in livestock (especially poultry, pigs, and sheep) as well as traditional vegetable and fruit production. Due to the less favoured area conditions, agriculture in Brandenburg is characterised by extensive grassland production (i.e. beef and dairy), but also cereal, vegetable and fruit production. Organic farming systems, covering 10% of the total agricultural area, are more prevalent than in other study regions.

Table 3
Population, area and natural conditions of the four case study regions.

Core City	London	Berlin	Milan	Rotterdam
Metropolitan Region	Greater London, SE/E England	Berlin, Brandenburg	Lombardy	South Holland
NUTS codes	UKH, UKI, UKJ	DE30, DE40	ITC4, ITC15	NL33
Population				
Population core city, 2015 (in million inh.)	8.17	3.56	1.24	0.62
Population region, 2015 (in million inh.)	22.66	6.10	7.88	3.70
Population density, excl. core city (in inh./km^2)	394	86	514	1176
Population projection core city, 2015–50 (in %)	+47.1%	+31.7%	+18.3%	+8.9%
Population projection total region, 2015–50 (in %)	+30.8%	+5.6%	+20.7%	+9.4%
Area				
Total area (in 1000 km^2)	38.260	30.534	13.111	2.818
Utilised Agricultural Area (UAA, in 1000 km^2)	26.566	14.576	4.892	1.685
% UAA of total area	69.4%	47.7%	37.3%	59.8%
UAA per capita (m^2)	1173	2391	620	456
Natural conditions				
Soils (fertile, average or below average for country)	fertile	marginal	fertile	fertile
Altitude (low = below 50 m)	low	low	high	low
Rainfall (medium = below 650 mm per year, high = above 650 mm per year)	medium	medium	high	high
Yields (low/medium/high = below, average or above average for country)	high	low	high	high
Type of city (one centre or more in the region)	mono-centric	mono-centric	poly-centric	poly-centric

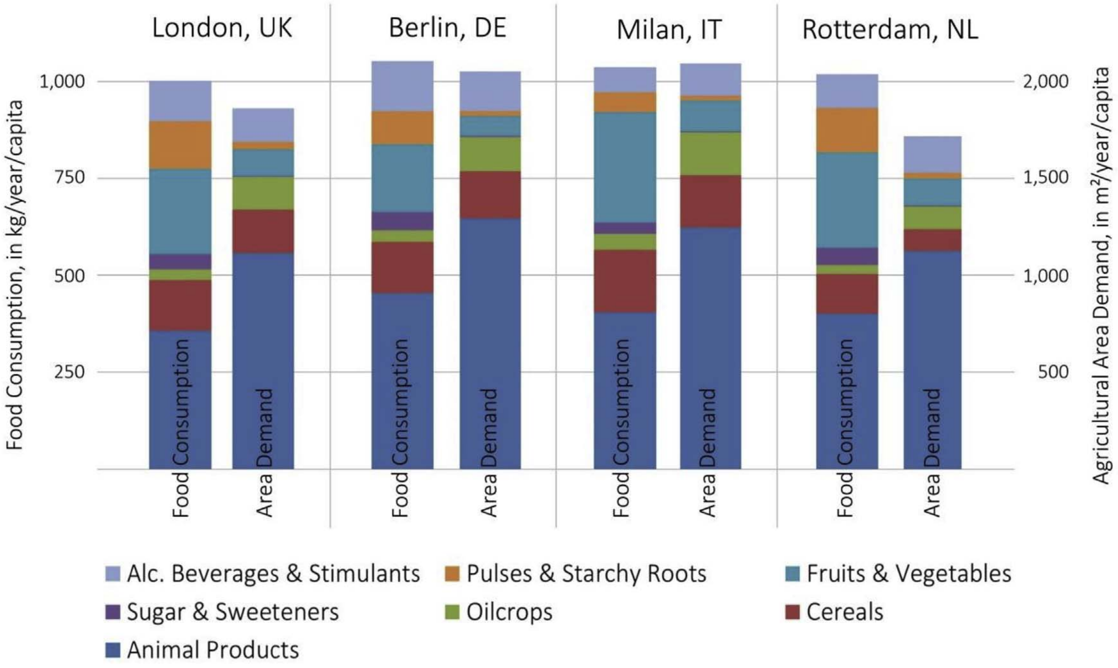

Fig. 2. Annual food consumption and associated agricultural area demand for the baseline scenario Base15, subdivided into food categories.

3. Results

3.1. Agricultural area demand

Based on the foodshed analysis for the four metropolitan regions, we estimate an annual per capita food consumption of around 1000 kg and an associated agricultural area demand of around 2000 m^2 (see Fig. 2). Despite dietary and agricultural production differences, the range of area demand varies only marginally for the baseline scenario (London: 1862 m^2, Berlin: 2052 m^2, Milan: 2093 m^2, Rotterdam: 1735 m^2). In terms of consumption, animal products (357–453 kg), cereals (103–162 kg) and vegetable and fruits (175–285 kg) play important roles across all regions; others such as potatoes (39–101 kg), sugar and sweeteners (29–47 kg) or alcoholic beverages and stimulants (65–130 kg) differ substantially between regions. Due to regionally varying agricultural yields, the consumption patterns translate differently into area demand, which can be e.g. seen for cereals or potatoes. From a food category perspective, the results of the MFSS model show, the impact on the agricultural area demand is quite different across the individual food components. Animal products, which include beef, pig meat, poultry, dairy, eggs and fish account together for an area share of between 59.6 and 65.5%, taking the lion's share of the overall diet.

Throughout all case study regions the food losses along the supply chain account for around 17% of the area demand. Adding waste from household consumption the share increases to around 31% of the production area. When converting to organic farming under current diet conditions (S2*X*), our model findings indicate an increasing area demand between 36% (Rotterdam region) and 41% (London region).

3.2. Metropolitan foodshed analysis

Due to absolute population sizes and territorial constraints, very different spatial extents of regional foodsheds situations are depicted (see Table 4, Fig. 3). With its large population, the London region currently (Base15) requires an agricultural area of around 42,176 km^2 of land for agricultural production. In our circular representation, this area equals a circle with a radius of 91 km^2, stretching out from the city centre of London to Birmingham. A little bit more than 36% of this land is required for food production for London alone (15,217 km^2). The rest is needed to meet the food demand of other cities and towns as well as the regions' rural population. According to the food loss and waste prevention scenarios, the total foodshed area could be reduced to less than 32,000 km^2 (−24%) (BaseLW15). On the other hand, a theoretical total conversion to organic farming would lead to an increase of more than 59,000 km^2 (Org15; +41%), whereas a simultaneous food loss and waste reduction (OrgLW15) could result in a similar area demand compared to the baseline situation. Considering the area demand for food commodities, which can theoretically be produced in the region, the value drops further to 38,000 km^2 (OrgDLW15). Taking into account the strong population growth in London and the surrounding region until 2050, we see an expansion of the foodshed area to more than 55,000 km^2 under production and consumption conditions comparable to today.

In the Berlin metropolitan region about 12,500 km^2 of farmland is currently required to feed the region's population, with 7300 km^2 dedicated to growing food for Berlin. In this mono-centric region, only some minor cities add to the regional area demand. Due to the largely rural, thinly populated peripheral areas, the region with its 14,600 km^2 farmland can accommodate the area demand within its own boundaries under most scenario settings, including the conversion to organic farming. In that scenario only in the case of current food loss and waste levels would the required area exceed that available. The same holds true in the future scenario.

The Milan region is characterised by the highest per capita area demand and by agricultural production being limited by the region's geographical situation, with mountains to the north and agricultural plains mainly in the south. Therefore, with only 4892 km^2 of production area, the region cannot fully accommodate the actual area demand of 16,506 km^2 and needs to rely on imports. It is particularly noticeable that the municipalities surrounding the city of Milan are substantially contributing to the food demand through their high population density and their low share of farmland, especially in the north of the region. As a result, the regional foodshed covers large parts of northern Italy, clearly interfering with other metropolitan areas, such as Turin and Genoa. This situation will be further exacerbated by expected population increases, leading to marked foodshed augmentations.

The competition between a core city (Rotterdam) and a surrounding urban region (South Holland) is even more pronounced in the Dutch

Table 4
Regional Foodshed Analysis: Area demand per capita (in m^2 UAA), per region (in km^2 UAA) and scenario. Source: own calculations.

Scenario	London, UK		Berlin, DE		Milan, IT		Rotterdam, NL	
	per capita (in m^2)	per region (in km^2)	per capita (in m^2)	per region (in km^2)	per capita (in m^2)	per region (in km^2)	per capita (in m^2)	per region (in km^2)
Base15	1862	42,180	2052	12,510	2093	16,510	1718	7580
BaseL15	1586	35,920	1761	10,740	1777	14,010	1471	6510
BaseLW15	1412	31,980	1574	9600	1586	12,510	1316	5820
Org15	2617	59,280	2799	17,060	2851	22,480	2333	10,340
OrgL15	2231	50,540	2408	14,680	2429	19,150	2004	8900
OrgLW15	1989	45,070	2155	13,140	2171	17,120	1794	7960
OrgD15	2151	48,730	2345	14,290	2418	19,070	2031	8670
OrgDL15	1880	42,580	2065	12,590	2107	16,620	1789	7630
OrgDLW15	1676	37,980	1850	11,270	1881	14,840	1606	6840
Base50	1862	55,170	2052	13,210	2093	19,930	1718	8300
Org50	2617	77,540	2799	18,010	2851	27,130	2333	11,320
OrgD50	2151	63,740	2345	15,090	2418	23,020	2031	9480

case. Despite a farmland share of 60% (1684 km^2) and an area demand of 1280 km^2 for Rotterdam, the regional demand of 7583 km^2 overdraws the regional available agricultural area four times. Due to high population densities in the Netherlands, Belgium and Northern France and its coastal location, resulting food stress in Rotterdam-South Holland cannot be alleviated by neighbouring regions.

3.3. *Regional self-sufficiency*

In the last step, we apply our model to gain insights concerning the food self-sufficiency level (SSL) of local communities and regions. Fig. 4 provides an overview of the SSLs in the case study regions. Values of 100% and more (green colour) indicate theoretical self-sufficiency in

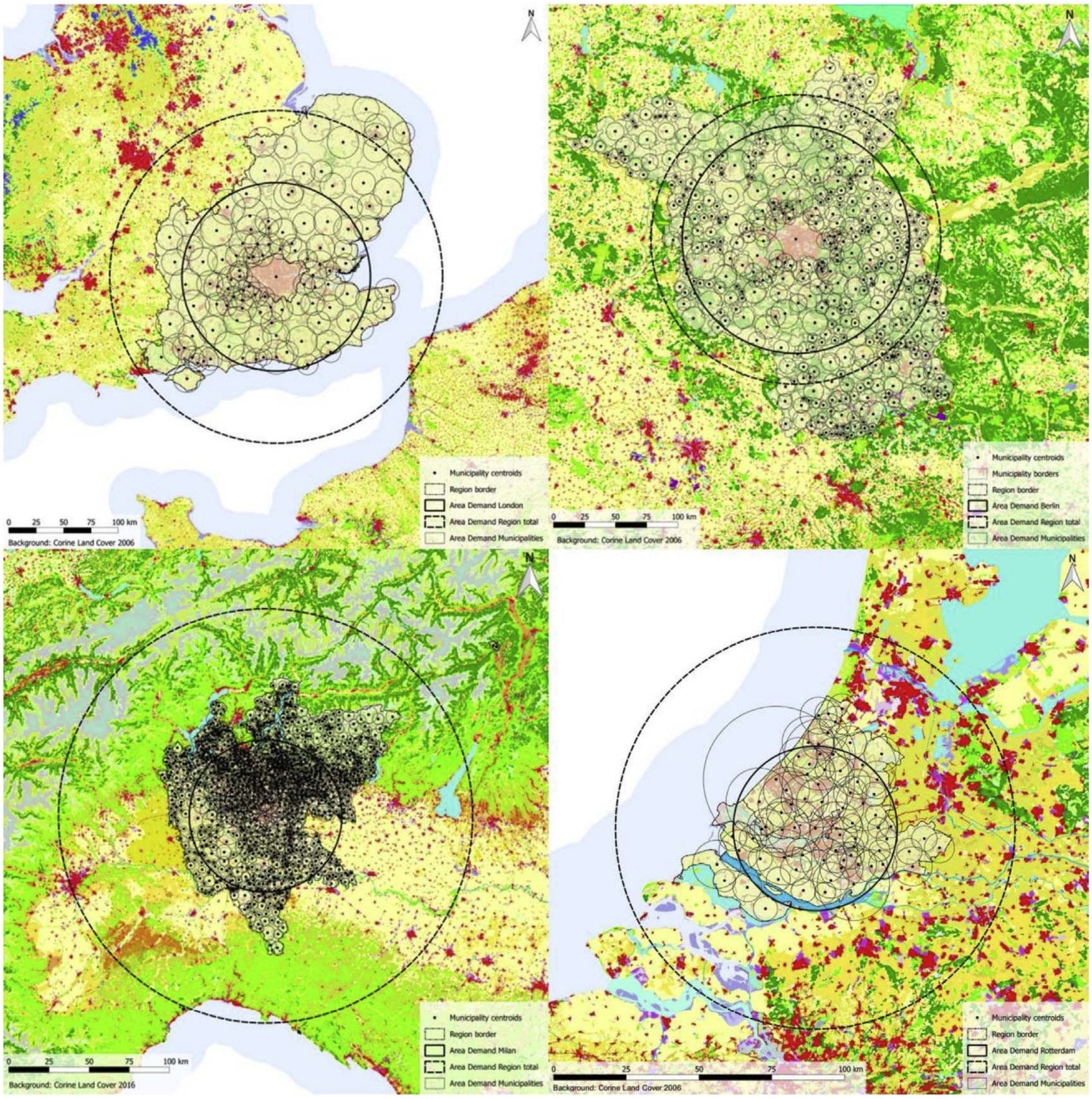

Fig. 3. Metropolitan foodshed extent for London (upper left), Berlin (upper right), Milan (lower left), and Rotterdam (lower right) for scenario Base15. Inner circle: area demand central city; Outer circle: area demand region. Based on population figures 2015. Note: The different maps have different geographical scales.

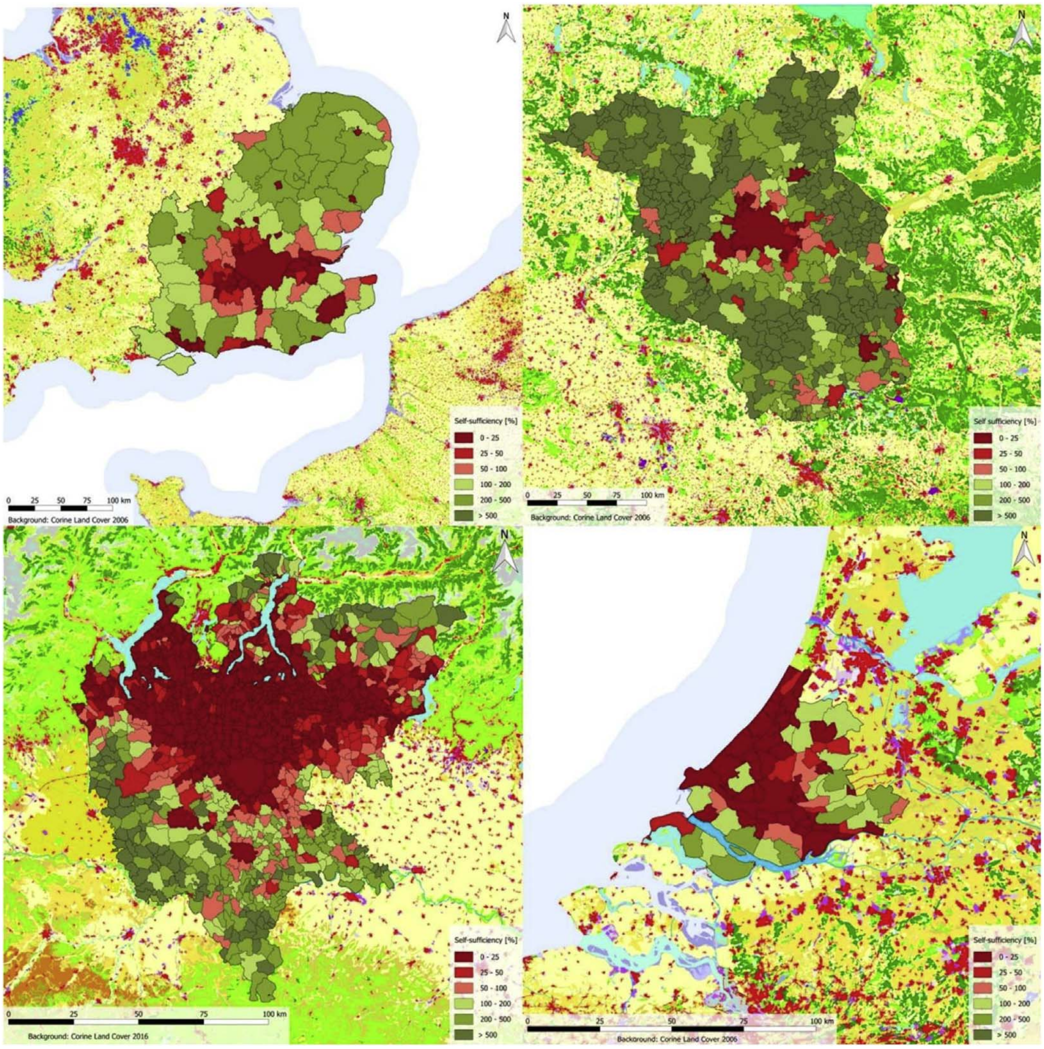

Fig. 4. Self-sufficiency level (SSL) at municipality level for London (upper left), Berlin (upper right), Milan (lower left), and Rotterdam (lower right) for scenario Base15. Red colour indicates under-supply, green colour over-supply. Source: own illustration. Note: The different maps have different geographical scales. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

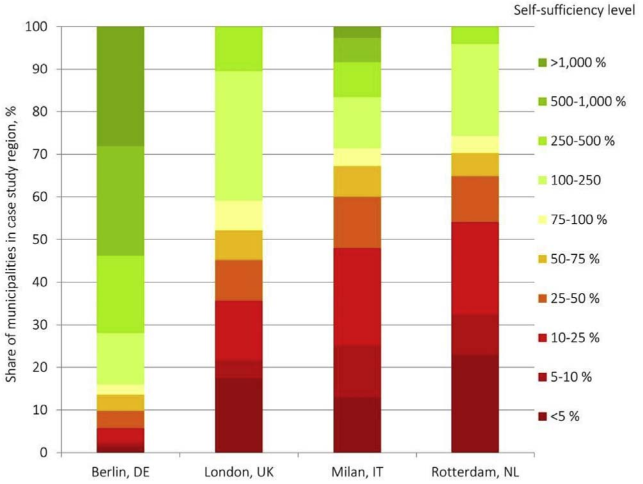

Fig. 5. Value distribution of self-sufficiency levels of municipalities per case study region in scenario Base15.

the respective area, whereas jurisdictions with values lower than 100% (red colour) cannot be supplied from their own territory and require "imports" from outside. Regional differences regarding the spatial distribution of SSL are illustrated by the frequency of SSL class occurrence in Fig. 5.

For the London region, the agricultural area demand of some 42,000 km^2 in the baseline scenario is contrasted by 26,500 km^2 of farmland. Despite an extensive regional agricultural area, the demand is nearly double the potential supply. Particularly due to the high population density around London, its island location, as well as the constraints of the neighbouring population centres' footprint areas, serious food stress can be envisioned. On the other hand, the majority of cities in the regions, such as Cambridge and Norwich in East Anglia, can be easily supplied by the near surroundings, which show an SSL of 100% and more. However, the absolute area demand through the high population number results in an under-supply at the regional level.

The mono-centric Berlin metropolitan region is characterised by a concentration of municipalities which show under-supply of farmland for the city of Berlin and its direct adjacency, whereas large parts of the peripheral rural areas can realise significant food production surpluses, being able to "export" to food stress areas. Despite the poor soil conditions (most of the rural area is designated as less favoured area), both city and regions can theoretically supply themselves within their own boundaries, as the total farmland covers an area of about 13,230 km^2. The relative low population density (and the related low food demand) of the surrounding region mitigates any particular food stress. Roughly only 15% of the regions' municipalities show an actual under-supply of food, whereas in nearly 30% of the municipalities the local supply exceeds demand by a factor of 10 or more.

The majority of municipalities in the South Holland region (Rotterdam) are characterised by an SSL of below 100%, often not even exceeding 25%, so that a rather continuous food stress can be expected in the region. At the same time these municipalities cluster on a strip along the coastline and the Upper Meuse between Rotterdam and Dordrecht. Similarly, but less pronounced is the food stress situation of Milan and its metropolitan region, with a majority of municipalities lacking theoretical self-sufficiency. However, the specific administrative structure of the case study area deserves particular attention, being characterised by many urbanised communities with a small territory on the one side, and large rural communities on the other. Fig. 5 shows the SSL at municipality level in the four case study regions.

4. Discussion

4.1. Metropolitan foodsheds and scenarios

We have developed the MFSS tool to assess the spatial extent of foodsheds of four European metropolitan regions and to analyse food self-sufficiency at local and regional levels. Different scenario settings are applied taking different consumption and production patterns into account. Our findings show that despite regional agricultural yield conditions and dietary variations, the regionalised area demands per capita are within a limited range between a minimum of 1718 m^2 (Rotterdam) and 2093 m^2 (Milan), which is comparable to previous studies (de Ruiter et al., 2014). However, the aggregated area demand values for the overall population, i.e. the spatial extents of metropolitan foodsheds, differ tremendously between the Rotterdam-South Holland region with 7580 km^2 and the region around London, including East and Southeast of England with 42,180 km^2. These results highlight, that in a food policy approach, which takes more integrated, territorially bound food systems into account, consideration of completely different area sizes, depending on the population is required. To this end, the MFSS model provides quantitative indications of these foodshed areas, geographic constraints which affect the agricultural production capacity, and potential interferences with neighbouring ones and is able to inform local and regional policy making related to urban food systems, addressing a major information deficit (Milan Urban Food Policy Pact, 2015). However, the explanatory power of the tool is limited to the required production area, but does consider area linked to natural resource use, leaving room for future development of the model to provide a more comprehensive picture.

With the analysis of local self-sufficiency the MFSS model provides information about the theoretical coverage of the required food produced within the boundaries of local and regional administrative units, depending on the local agricultural area and population. Thus, the model depicts different spatial distribution patterns and clusters of structural food under-supply, as it is the case in regions with a polycentric settlement structure and high population density, such as Rotterdam and Milan. In these cases, urban cores, which usually face strong local food deficits, are surrounded by large areas, where neighbouring communities are also unable to cover their own local food demand through internal production. In contrast to Berlin, which can compensate through neighbouring areas, these regions also have to rely on food supply relationships with more distant locations and which are more vulnerable to global changes or crisis (Dubbeling et al., 2009). Either way, the results of the MFSS model clearly show the large spatial extent of the necessary interaction areas between the urban core and rural periphery and the major incongruence between the administrative structures and the foodshed areas, which deserve close functional integration. They go beyond regional and even national borders and cut across jurisdictions. Policy for and management of metropolitan food systems will be particularly challenging in the face of an administratively fragmented area (OECD, 2013).

Beside the analysis of the current state, we have developed a scenario framework, which considers the effects of relevant food system component changes, including changing food production and consumption and the waste and loss occurring along the food supply chain. With the application of rather extreme “what if”-type of ex-ante scenarios, we tried to sketch out the development scope for regional food systems, without claiming to be realistic. The scenario projections showed similar changes throughout all case study regions, even though with different amplitudes. Particularly the potential impacts of food loss and waste reduction as well as of conversion of production towards organic farming are particularly noteworthy. The prevention of food waste along the entire supply chain can reduce the spatial extent of the foodshed by one third, whereas a conversion of agricultural production to organic farming will entail a marked expansion of the regional foodsheds, increasing land competition with neighbouring regions and reducing self-sufficiency. However, in combination with urban dietary changes and the reduction of food waste and loss, organic production and regional self-sufficiency can be quite compatible. Clearly more holistic urban food strategies are needed to simultaneously address consumption, production and supply chain organisation in a more sustainable way (Morgan & Sonnino, 2010; Wiskerke, 2009).

Accounting for the pronounced global urbanisation trend, we have applied the MFSS model to the regional 2050 population projections (EUROSTAT, 2016), which predict strong urban growth in all regions, finding substantial expansions of the foodsheds to alarming scales. In the London region alone an additional 13,000 km^2 utilized farmland will be needed when agricultural production and food consumption remain under current conditions, augmenting the difficulties of enhancing regional sourcing. Especially to prevent increasing dependency on global sourcing, we see an urgent need to change how we handle food in production, supply chain and consumption. Here, our results provide an insight about potential impacts of different fields of action on urban food strategies and planning, most notably the consumption behaviour. Especially the reduction of food waste in households and catering bears a huge potential for limiting agricultural area demand. But, as animal-based food components account for more than half of the current area demand, dietary changes, such as reducing meat consumption or vegetarian or vegan diets (Li, Zhao, & Cui, 2013; Schmutz and Foresi, forthcoming) would have large effects on territorial food systems.

4.2. Towards a metropolitan food system

We have seen that the theoretical ability of a metropolitan population to feed itself within its own regional borders is not impossible, although it is challenging, particularly in the wake of continuing urban growth. All city regions have a limited potential to expand agricultural production areas. On the contrary, farmland is increasingly under pressure from other land use demands including residential, commercial and industrial uses, as well as for transportation infrastructure, leisure green spaces, reforestation and nature conservation. Further significant reductions of food production areas may result from renewable energy production, mainly in the form of energy crops. In response, more multifunctional, eco-efficient, and location-adapted farming systems could lead the way from theoretical to practical self-sufficiency and to localised metropolitan food systems. Especially, the application of technological innovations, greenhouse production, zero-acreage and urban farming (Opitz et al., 2015; Specht et al., 2014) are proposed to have potential to increase food production output, release pressure on land without further environmental degradation, and resource depletion (Chartres & Noble, 2015).

To balance the different land use interests beyond food production, such as flood protection, fresh air exchange or recreational services, the idea of a multifunctional agriculture gained wide attention for peri-urban areas (Pedrazzini, 2017; Zasada, 2011). Agroecology and circular economy concepts capitalise on an enhanced interaction between urban areas and peri-urban agriculture, e.g. via waste disposal or water management or the establishment of close market relations to support the metabolism of the urban system (Drechsel & Hanjra, 2016; Florin & Renting, 2015) and are therefore well-suited for supporting food production in metropolitan regions. Although all these concepts certainly have the potential to contribute to strong food production in metropolitan areas, eventually it will be necessary to build up a broad societal awareness for the need to restore agriculture to areas near cities and to reconcile conflicts between urban dwellers and nearby farms (Taylor, Butt, & Amati, 2017). Visually illustrative mapping approaches, such as that provided by the MFSS tool can make a valuable contribution to enhancing awareness regarding the land-demand consequences of food-related policy decisions or structural changes to the food system. It further contributes to giving a sense of ownership to citizens about their food and the effects the current and future food consumption have for the city.

Beside fostering regional food production, for its re-connection with urban areas, organisational innovations towards short food supply chains (SFSC) are also important and acknowledged in research and policy (Kneafsey et al., 2013). The diversity of regional actors which comprise SFSCs presents particular challenges and deserves attention in food planning and policy. These actors have different roles, capabilities, needs and interests and new linkages and partnerships need to be established amongst them. In addition numerous concepts must be considered, from traditional direct marketing to innovation-driven community supported agriculture and solidarity purchasing groups to logistical optimised food cluster solutions (Wascher et al., 2015a). Thus any intervention at this scale should involve the collaboration of multiple different stakeholders. With the identification of the key food systems levers, the MFSS tool can deliver relevant information to foster a more local approach to food supply (Sonnino, 2016) to inform effective metropolitan food policy and to support decision-making for policy actions.

5. Conclusion

Integrated metropolitan food systems and corresponding food policy and planning are gaining ground in the wake of growing urban populations, changing diets and consumption patterns, and with sustainable agriculture and food supply chain innovations and solutions to potentially reduce urban footprints and vulnerability to global changes. Thus, quantitative estimates about the relationship between food demand and regional production conditions are required to inform and support the design of food policy. Focussing on the spatial extent of food production, the Metropolitan Foodshed and Self-sufficiency Scenario (MFSS) model represents an approach which considers both regional yield and diet parameters, subdivided into a set of food categories. This provides sensitivity to differences in agricultural production systems (i.e. conventional, organic), levels of food loss and waste, diets and between temperate domestic supplies and required food imports. In the course of this, the MFSS will integrate the analysis of food demand and supply in an easy, transparent and replicable manner.

The model has been applied to four European metropolitan regions: London, Berlin, Milan and Rotterdam. Results from the four case study regions further suggest that despite regional differences in climate, diet, soil quality, and food culture, considerable similarities exist and the tool could be used to highlight these to enable the mutual acquisition of knowledge between the different European regions. An additional strength is the flexible scenario model, where we have focussed only on some extreme ones. In further work more localised scenarios could be run based on improvements in regional agricultural production methods, regional diets and population change including moves from e.g. the city into the metropolitan region and more detailed diet changes due to the ongoing population change.

An important feature of MFSS supporting its use for territorial governance is its capacity to consider region specific yield data and land use situations. At the same time, MFSS allows applicability at different scales, representing a model of analysis which can be applied to all European cities and regions. Hence, MFSS enables policy makers to have a “birds-eye” overview of metropolitan foodshed and self-sufficiency situations. Visualising the actual situation, the tool can then be used to project different ex-ante food policy scenarios.

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