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Urban food crop production capacity and competition with the urban forest

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ABSTRACT

The sourcing of food plays a significant role in assessing the sustainability of a city, but it is unclear how much food a city can produce within its city limits. In this study, we propose a method for estimating the maximum food crop production capacity of a city and demonstrate the method in Seattle, WA USA by taking into account land use, the light environment, and a mix of food crops necessary to supply a year-round vegetarian diet. By artificially removing trees from the city, we estimate the effect of tree shading on food crop production capacity. We find that at maximum food production, urban food crops can produce between 1% and 4% of the city's food needs under the most realistic land use scenarios, and that tree shading reduces food crop production capacity between 19% and 35%. We expand beyond the city Seattle limits to find that a buffer of 58 km around the city is required to meet 100% of the city's food needs.

With more than more than fifty percent of the global population living in urban areas (United Nations Food and Agriculture Organization, 2011), there is a growing interest in the long - term sustainability of urban and peri-urban ways of living (Grimm et al., 2008). A core question regarding urban sustainability is the sourcing and long-term supply of food to support a large, dense population. Considerable research and public interest has been focused on the locality of the food in a city dweller's diet (Born and Purcell, 2006; SFUSA, n.d.; Feenstra, 1997) and the security of the food supply (Godfray et al., 2010; Kremer and DeLiberty, 2011); consequently, there is interest in the ability of individuals and collectives to produce food within an urban environment. This type of food production, referred to here as urban agriculture, may be able to increase the sustainability of cities. While urban agriculture can encompass a wide range of food production techniques, such as aquaculture, livestock, and insect production (United Nations Development Programme, 1996), in this paper we focus solely on plants that can be grown in soil for food.

Many factors affect the quantity and quality of the food produced within a city, ranging from the geography of a city to the socioeconomic status of its residents (Orsini et al., 2013; Martellozzo et al., 2014). The maximum food crop production capacity (MFCPC) of a city, though, is based on available growing space, abiotic factors such as light, nutrients, water, and suitable temperatures, and biotic factors such as the suite of crops grown. Thus, each city has a unique MFCPC that can help to determine to what degree urban agriculture can support the sustainability of that city. Several studies have focused on aspects of estimating MFCPC. Land that is currently used for urban agriculture has been mapped in Chicago (Taylor and Lovell, 2012), areas of grass and bare soil within residential parcels that may be suitable have been mapped in Philadelphia (Kremer and DeLiberty, 2011), the land area available for vegetable production has been assessed in New York City (Ackerman et al., 2014) and globally at the country level (Martellozzo et al., 2014), while regional food sheds have been modeled using different combinations of remote sensing and GIS both in terms of current food production capacity and MFCPC (Peters et al., 2009; Morrison et al., 2011; Giombolini et al., 2011). A case study of Cleveland, OH, USA estimated the proportion of the city's needs for vegetables, fruits, poultry, meat, and eggs that could be met through urban agricultural on vacant lots, residential lots, commercial lots, and rooftops, although it did not examine the total nutritional needs of the city (Grewal and Grewal, 2012). These studies suggest that a geospatial framework is needed to assess the available land base for food production within a city, but we suggest that increased complexity is needed to arrive at a more comprehensive assessment of MFCPC that incorporates a key abiotic factor, light, and locally suitable crops.

In this study, we describe a geospatial methodology for estimating MFCPC, with an application of the method in Seattle, WA USA. We use remotely sensed data and geospatial analysis to derive land use, assess the light environment by taking into account

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three-dimensional structure within the city, and develop a mix of crops adapted to local conditions that are needed to supply a complete vegetarian diet. By modeling the virtual removal of trees from the city using three-dimensional information derived from remote sensing, we estimate the effect of tree shading on food production capacity. In addition, we expand the extent of the analysis to areas surrounding Seattle to estimate the foodshed required to meet 100% of the nutritional needs of the population.

1. Methods

1.1. Study area

Seattle, WA has a 2010 population of 608,660, a land area of 217.2 km^2 (U.S. Census Bureau, 2010), and is bordered by Puget Sound to the west and Lake Washington to the east. Mixed conifer forest dominated land cover before European Settlement in the

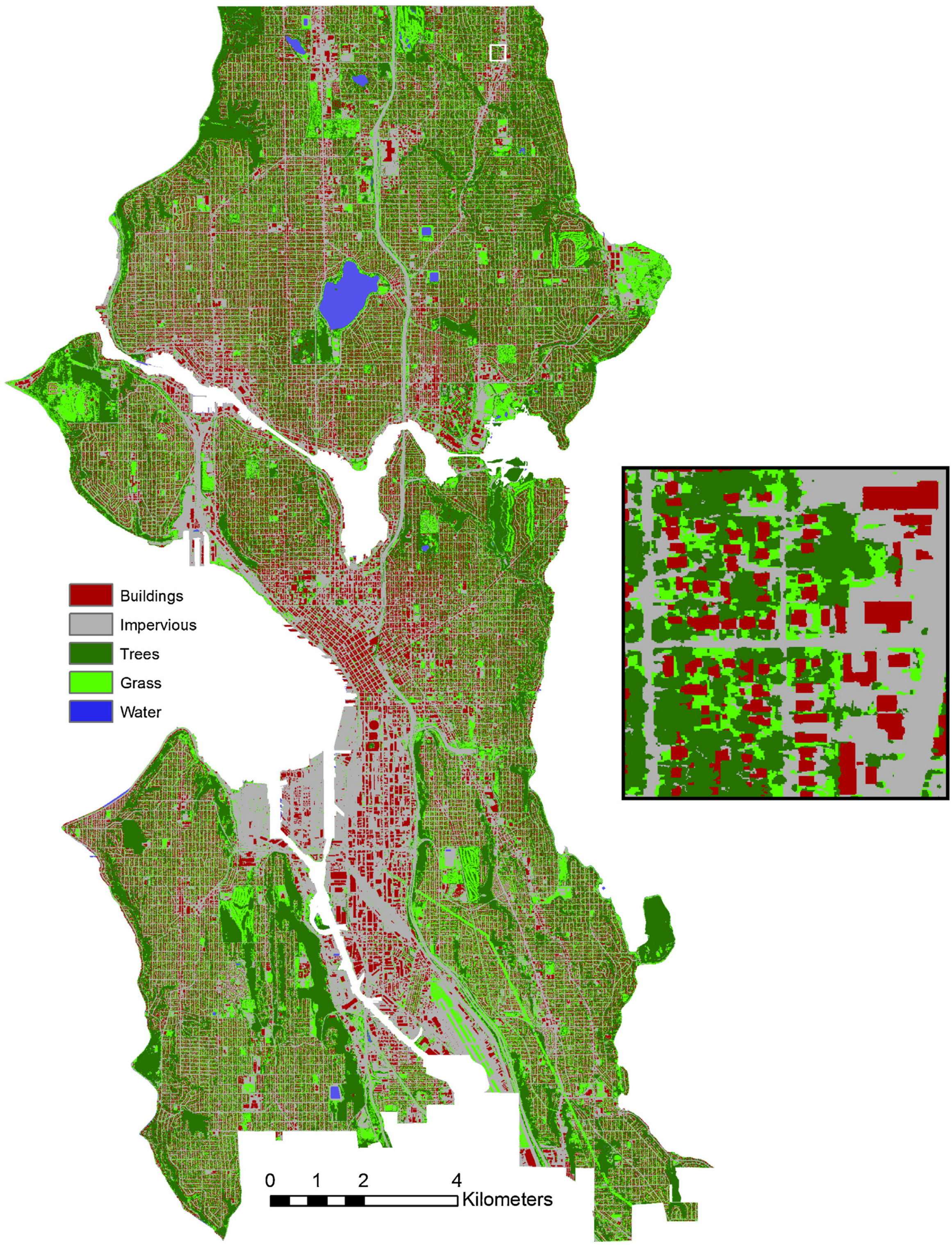

Fig. 1. Categorical raster of land use for Seattle, WA. The white box in the Northeast corresponds to the enlarged inset.

19th century. The greater Puget Sound Region has experienced rapid urbanization in the last several decades (Alberti et al., 2004). Today, municipal land use is dominated by a highly developed urban core with the majority of surrounding lands consisting of large parkland parcels and single-family residential dwellings.

1.2. Determining Seattle's land use

We utilized Object Based Image Analysis (OBIA) to classify every location in Seattle to five classes: water, trees, grass, buildings, and impervious surfaces (Fig. 1). Details of this classification can be found in a recent study (Richardson and Moskal, 2014), but in summary: aerial lidar, aerial imagery, and City of Seattle supplied GIS data were used to produce a raster classification with a 1 m pixel resolution. For this study, we edited the classification appearing in (Richardson and Moskal, 2014) to reduce the overestimation of the grass class.

Publicly available City of Seattle parcel data shows that there are 175,032 single family residential (SFR) parcels within city limits, with an average household size of 2.06 taken from the 2010 U.S. census. Thus, the population of Seattle residing in SFR homes is estimated to be 360,566. The spatial extent of the SFR population was taken from the City of Seattle parcel data and overlaid with the OBIA classification. We chose to focus on SFR parcels as a subset of the total available land because of the assumption that a resident of an SFR parcel is more likely and able to convert their land to agricultural production as compared to publicly owned parcels or parcels housing multiple families with shared use of open space.

1.3. Modeling the light environment and effect of the urban forest

Aerial lidar data were acquired for Seattle WA in 2003. This lidar dataset was used to create two raster surfaces: a highest hit model (HHM) and a digital elevation model (DEM). The HHM is a raster surface where the value of every cell is equal to the highest elevation lidar point. The DEM is the bare earth elevation with trees, buildings, and other human-made objects removed. By selecting the raster cells where trees are located in the OBIA classification and replacing those cells with the DEM elevation, we were also able to create an HMM under the alternative land use scenario where the urban forest was removed.

Single-day solar insolation was calculated in ArcGIS 10.1 (ESRI) using the Solar Radiation tool for August 1st assuming no cloud cover for both HHM scenarios. This day was chosen because it was in the middle of the growing season for Seattle, WA. In this part of the season, skies are normally clear, so we chose to focus only on direct rather than diffuse radiation. We discovered a limitation of the Solar Radiation tool during this processing. In areas with relatively large elevation differences in a small area, such as cities with buildings and trees, the Solar Radiation tool underestimates the total solar insolation because it models each raster cell as a flat surface and does not account for radiation that would strike the vertical surfaces between the raster cells if modeled in three-dimensions. For instance, tall open-grown trees intercept a large amount of radiation because of the radiation that strikes the sides of the trees. For the purposes of this study, the underestimation of solar radiation was not a major issue because the focus is on relatively flat surfaces where short plants can be grown. We transformed the solar insolation rasters into three categories to facilitate modeling and to account for the imprecision in the raw insolation values: shade (<1 kW h/m^2/day), part sun (1–2.5 kW h/m^2/day), and full sun (>2.5 kW h/m^2/day) (Fig. 2). We assume that full sun is necessary to provide reasonable yields of the crops modeled in this study.

1.4. Crop mix, yield, and nutrition

Our objective was to produce a mix of crops that provided variety in diet, provided complete nutrition for citizens following a vegetarian diet, and could be reliably grown in the Mediterranean climate of Seattle. Thus, we include some crops that are not typically grown in urban environments, such as barley. Table 1 details the nine crops we selected in this study, all of which are currently grown commercially in the Puget Sound Region and within 200 km of Seattle (Washington State University Skagit County Extension, 2013). Yield information for each crop was provided by the National Agricultural Statistics Service (National Agricultural Statistics Service, 2013). We used yields for regions as close to Seattle as possible, using data for Skagit County for potatoes, the State of Oregon for hazelnuts and squash, the State of California for kale, and the State of Washington for all other crops. We could not find peer-reviewed information on yields for urban crop production systems. Note that we do not model variability in soil nutrients, texture, or moisture levels in this study and thus each pixel in the classification is assumed to produce the same yield, except for variability in the light environment which is discussed above. We also did not account for the possibility of contaminated urban soils which could render some locations unfit for crop production.

Nutritional information was taken from the National Nutrient Database (U.S. Department of Agriculture, 2013), and the energy content, macronutrients and micronutrients assessed for each portion of the diet, weighted to the proportion of the diet for each crop. Energy content of each crop is given in Fig. 3. Reference diets were computed using the Interactive DRI for Health Care Professionals (U.S. Department of Agriculture, 2014) for men and women corresponding to the median age (35) and median height for the U.S.A. (1.8 m for men, 1.6 m for women) and assumed to be living an active lifestyle. The mix of each of the nine food sources was balanced to meet the needs of carbohydrates, fat, and protein given by the reference diet. In addition, all essential micronutrients and each of the essential amino acids were checked, and all met at least 100% of the daily recommended values except sodium and vitamin D. Table 1 shows the proportion that each crop plays in the diet, as well as the contribution of that crop to providing carbohydrates, fat, and protein.

1.5. Computing the maximum food production capacity

We used ArcGIS to determine the areal extent of each of the five land uses in Seattle (Fig. 2) that coincided with the "full sun" class from Fig. 2 for all areal extents in Seattle as well as for land uses only in SFR zones. It was determined that that 16.78 women and 10.39 men could be supported from 1 ha of land based on the reference diet and yield assumptions. We used the arithmetic mean to assume that the diet of 13.59 people could be supported for one year from 1 ha of land. The food production capacity for each land use was determined by multiplying the areal extent of each land use class by the number of people supported per hectare.

1.6. Modeling the foodshed

Since our OBIA classification does not extend beyond the city limits of Seattle, an alternative land use classification was necessary to model food production beyond Seattle. We used the 2006 National Land Cover Database, which is a raster derived from satellite imagery with a 30 m pixel resolution. Existing agricultural land uses of pasture/hay and cropland were used to determine viable food production areas.

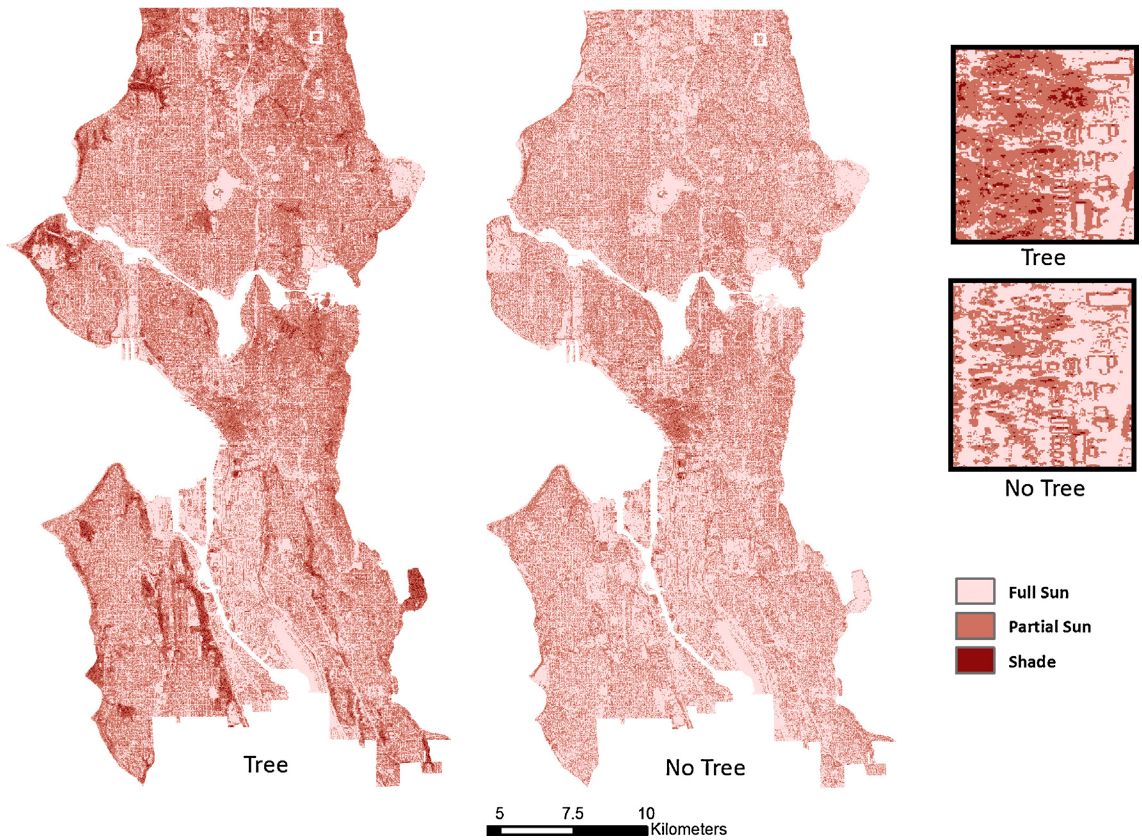

Fig. 2. Solar insolation modeled as three categories of sun intensity. Insolation is shown for the current landscape (tree) and with all trees removed (no tree). Insets show the area of the white box (same as Fig. 1).

Table 1
Statistics related to nine crops used in modeling a complete vegetarian diet in this study. The second, third, and fourth columns show the percentage of carbohydrate, fat, and protein provided by each crop in the diet (columns sum to 100%). The fifth and sixth column show the modeled yield and the relative energy density of the crops, while the last column shows the proportional amount of land required to achieve this complete vegetarian diet.

Crop	Carbohydrate (%)	Fat (%)	Protein (%)	Yield (Mg/ha)	Energy (kCal/ha)	Percent of available land devoted to production (%)
Beets	5.6	0.6	5.3	39.0	16.8	3.6
Squash	6.6	0.3	3.2	22.6	10.2	6.1
Potatoes	27.9	1.0	16.8	44.2	30.5	9.7
Carrots	8.2	1.2	4.5	68.1	27.9	3.0
Dry beans	6.3	0.7	12.2	2.0	7.0	12.1
Barley	24.4	4.5	23.3	5.8	20.4	13.9
Kale	4.6	2.9	12.7	17.6	8.6	7.3
Hazelnuts	4.1	87.9	20.7	1.5	9.5	39.4
Apples	12.2	0.9	1.3	44.0	22.9	4.8

2. Results and discussion

2.1. Seattle maximum food production capacity and competition with the urban forest

Table 2 shows the model results for the amount of land available in the four different land use classes and in the three different solar radiation regimes for both SFR zoning and for the full land extent of the City of Seattle. We show SFR land separately because we assume that that most landowners in SFR zoning have single, detached homes and a dedicated yard space, and thus much of the grass cover use in these zones is lawn that could be easily converted to agricultural production. The results show that much of the land use is building, tree, or impervious, and while we modeled the conversion of these land use classes to intensive food production, we must acknowledge that conversion of impervious surfaces to cropland, installation of rooftop gardens, or destruction of the urban forest for crop production is extremely unlikely. While converting all available land use classes in full sun to crop production could potentially allow for 5.1% of Seattle's food needs if restricted to SFR zones or 21.3% for the entire city, this scenario would radically reshape the city.

A seemingly more realistic scenario is the conversion of existing grass cover into agricultural production. In this scenario, less than 1% of the city's food needs could be met, or about 6000 people if conversion occurred on SFR lands alone (Fig. 3). If the extent were expanded to include the entire city, approximately 4% of the food need could be met, or about 24,000 people. The results of the scenario where trees are virtually removed from the city are shown in Table 3 and the effect of tree shading is shown in the darker areas of Fig. 3. If tree canopy shading was not present, food production could be increased by 35% in SFR zones and 19% for the non-SFR

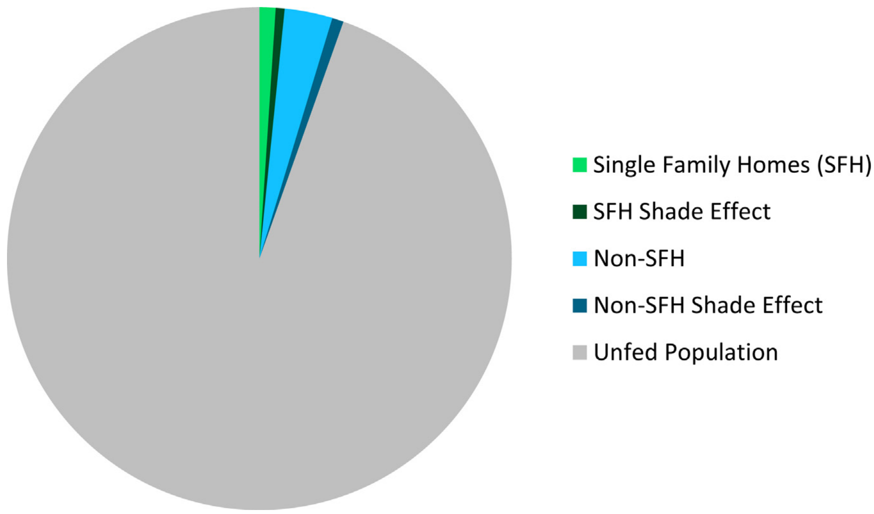

Fig. 3. The proportion of the population of Seattle fed by converting grass land cover in full sun in Seattle to intensive agriculture under different scenarios (the area of the chart is proportional to the population of Seattle). The green section represents the proportion of the population fed if Single Family Home zoned land is converted to intensive agriculture and the blue section represents all other lands. The dark green and dark blue sections represent the additional population that could be fed if the shading from trees was eliminated.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
The areal extent of land in Seattle within four different land use classes and three solar radiation classes. Extents are given for parcels zoned single family residential and for all lands in Seattle.

Land use	Single family residential land area (ha)			All land area (ha)		
	Shade	Part Sun	Full Sun	Shade	Part Sun	Full Sun
Grass	32.4	835.1	470.3	75.4	1696.0	1864.2
Building	31.6	1251.4	870.7	58.6	1971.5	1936.3
Tree	169.3	2276.1	591.1	652.7	4520.0	1173.2
Impervious	21.3	662.0	344.8	116.8	2869.4	4549.2

Table 3
The areal extent of land in Seattle within four different land use classes and three solar radiation classes in a scenario when the shading from trees is removed. Extents are given for parcels zoned single family residential and for all lands in Seattle.

Land use	Single family residential land area (ha)			All land area (ha)		
	Shade	Part Sun	Full Sun	Shade	Part Sun	Full Sun
Grass	7.2	603.6	727.3	20.5	1159.6	2456.1
Building	13.8	1249.5	890.4	41.6	1987.3	1937.7
Tree	60.9	1426.8	1549.1	106.8	2599.1	3641.0
Impervious	9.6	564.8	453.8	74.7	2352.6	5108.9

zones. The greater impact of trees in the SFR zones is likely due to the pattern seen in most Seattle yards where a small patch of lawn is interspersed with a few large trees. In non-SFR lands, many grassed areas include sports fields and public parks that have few trees to create shade. The removal of trees would also create additional full-sun areas in the other land cover classes, which would increase the amount of food that could be produced in the total conversion scenario to 29% of the city's food needs.

While we have described different land use conversion scenarios with different MFPCs, we suggest that a reasonable MPFC for Seattle is 4% of the city's food needs through conversion of all the available grass cover in the city. Achieving this intensity of crop production would be a difficult undertaking, thus it's reasonable to conclude that urban crop production as modeled in this paper can't significantly contribute to Seattle's food security, here defined narrowly as the ability of a city to meet the nutritional needs of its residents. As such, the 19–35% reduction in MPFC by shading from urban trees is likely a minor effect when compared to the major benefits the urban forest provides (Ciecko et al., 2012; Wolf, 2009). On the other hand, urban crop production can provide other benefits to the city. For instance, urban food projects can promote community development. One example is the Beacon Food Forest (BFF) in Seattle, which is in the process of transforming 2.8 ha of publicly owned grass-covered land into a large community garden and orchard (Beacon Food Forest, 2014). While the BFF can only support a complete vegetarian diet for 38 people according to our results, it has the ability to benefits thousands of nearby community members through education, community building, and providing partial nutrition.

By focusing on certain crops, instead of the complete vegetarian diet modeled in this paper, urban food crops may also be able to provide significant quantities of nutritious, but not necessarily energy dense vegetables such as kale, spinach, chard, and lettuce. Foods such as these may be able to combat the lack of access to fresh produce found in so called "food deserts" (Walker et al., 2010; Kato and McKinney, 2015; Weatherspoon et al., 2015). These vegetables don't need any specialized equipment, can be grown in small spaces, and can produce in partial shade, which enlarges the potential cultivatable area from the full sun areas examined in this study. For instance, 17.5 Mg of kale can be produced from 1 ha (National

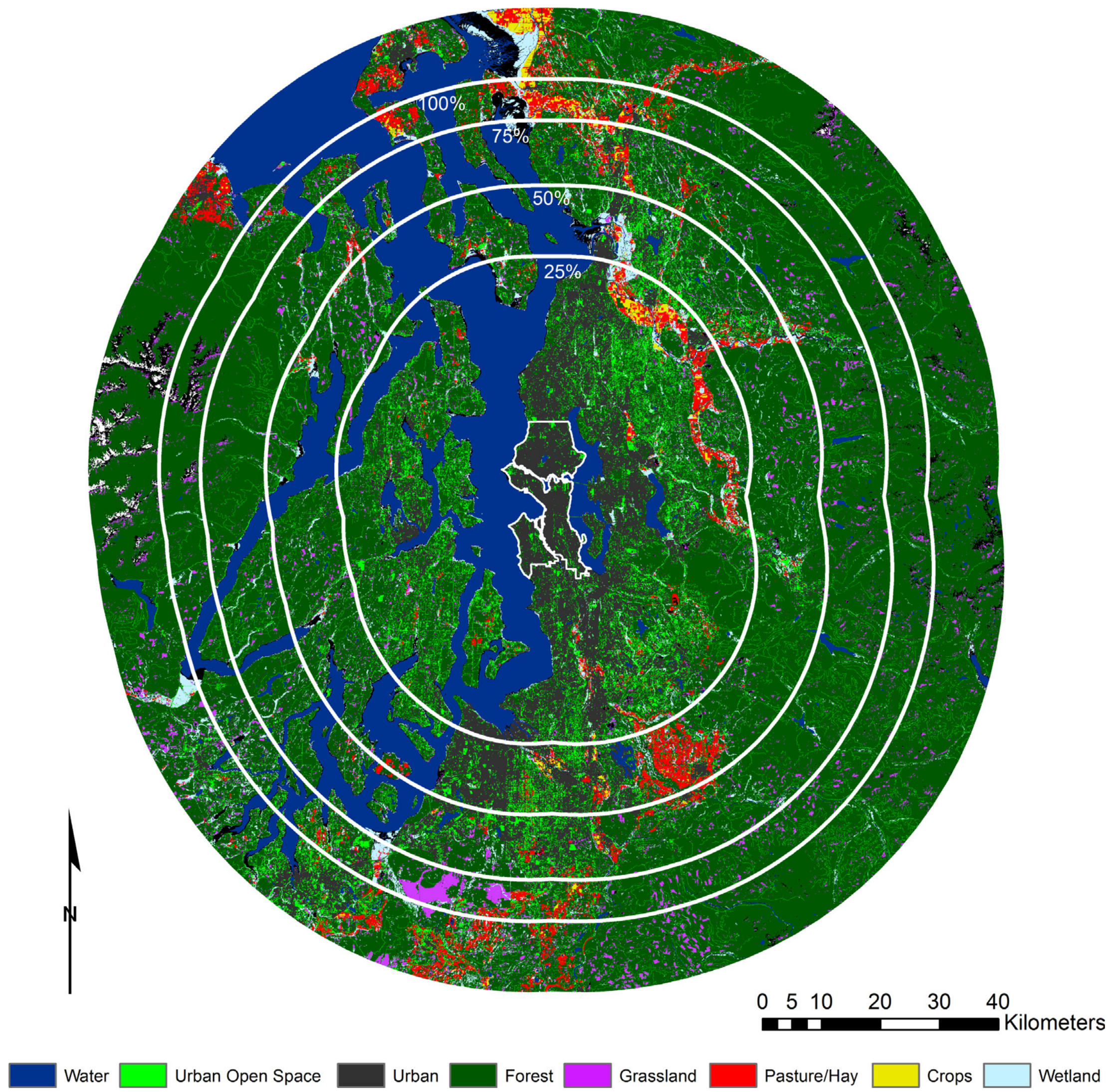

Fig. 4. Land uses derived from the National Land Cover Database for areas surrounding Seattle. The boundary of the City of Seattle is shown in the middle, and the four white isolines show percentage of Seattle fed if the Pasture/Hay and Crops land uses are converted to intensive agriculture.

Agricultural Statistics Service, 2013), thus about 6.2 kg of kale could be grown for every person in Seattle on just SFR lawns in full sun each year. It may also be possible to boost yields of urban food crops through intensive cultivation methods that are more often found in urban food production (Ackerman et al., 2014), but future research is necessary to assess the range of yields possible in urban environments.

2.2. Seattle foodshed

Fig. 4 shows the area of land required to produce 25%, 50%, 75% and 100% of Seattle's annual food needs based on 2006 NLCD land use and the yield assumptions from Fig. 3 and Table 1. The majority of food production capacity is concentrated in a few fertile river valleys: the Skykomish, Stillaguamish, Snohomish, White, and Puyallup. Note that Fig. 4 does not include the contribution of food production from urban food crops, as the NLCD did not classify any raster cells within the City of Seattle as cropland or pasture. A buffer of 58 km around the City of Seattle was required to meet 100% of the population's food needs; the area within this buffer is 1,509,264 ha. The non-Seattle population within this area is approximately 2.9 million, which means that an additional, larger area would be required to meet the food needs of these residents. While the assumptions used to produce the Seattle foodshed are overly simplistic, likely underestimating the contribution from urban and urban open space land covers, and overestimating the contribution that pasture/hay land used could provide, the overall size and land requirements of the foodshed is a reminder that cities such as Seattle cannot easily rely on locally produced food to sustain their population. Previous research and commentary focused on questions regarding the framing of locality and food security point out that local food may not be inherently better, more sustainable, or contribute to food security (Born and Purcell, 2006; Selfa and Qazi, 2005). The definition of "local" also plays a factor; the majority of agricultural land in Washington State is on the East side of the Cascade Mountain Range, where a large portion of the U.S.'s tree fruit and wheat is produced. Relying on these lands, which are more than 230 km away from Seattle, enlarges the foodshed to a size than may not be viable if transportation costs become very expensive.

3. Conclusions

We have produced a comprehensive a method for estimating the MFCPC of a city that utilizes remotely sensed data and geospatial analysis. In the case of Seattle, the MFCPC is likely near 4% of the population's food needs based on the most likely land uses for conversion to food crops. Thus we conclude that urban food crops in Seattle can play a small role in supplying Seattle food needs, but achieving food security in Seattle is dependent on sources outside the city limits. Our methodology is easily transferrable to other cities where LiDAR data and a categorical raster map of land cover are available. A new suite of crops should be chosen, though, to best match local growing conditions, and these crops could be chosen to emphasize vegetable production or other food goals if the MFCPC is not a statistic that of principle importance. For instance, researchers and/or planners could use these methods to evaluate the potential of urban agricultural production to produce a specific target quantity of vegetables or fruit. Future research focused on sustainability of urban food supplies, at least in cities similar to Seattle, should focus on the necessity and thus the consequences of importing large amounts of food from regional and potentially global sources.

Acknowledgments

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