Urban Food Crop Production Capacity and Competition with the Urban Forest

Jeffrey J Richardson^{1*} and L. Monika Moskal¹

¹School of Environmental and Forest Sciences, University of Washington, Seattle, WA USA

* Corresponding Author

Keywords: Forest; Agriculture; Remote Sensing; LiDAR

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 [1], there is a growing interest in the long-term sustainability of urban and peri-urban ways of living [2]. 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 [3-5] and the security of the food supply [6, 7]; 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 [8], 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 [9, 10]. 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 [11], areas of grass and bare soil within residential parcels that may be suitable have been mapped in Philadelphia [7], the land area available for vegetable production has been assessed in New York City [12] and globally at the country level [10], 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 [13-15]. 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 [16]. 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 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.

Methods

Study Area

Seattle, WA has a 2010 population of 608,660, a land area of 217.2 km² [17], 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 19th century. The greater Puget Sound Region has experienced rapid urbanization in the last several decades [18]. 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.

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 (Figure 1). Details of this classification can be found in a recent study [19], 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 [19] 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.

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 ($<1 \text{ kWh/m}^2/\text{day}$), part sun ($1\text{--}2.5 \text{ kWh/m}^2/\text{day}$), and full sun ($> 2.5 \text{ kWh/m}^2/\text{day}$) (Figure 2). We assume that full sun is necessary to provide reasonable yields of the crops modeled in this study.

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 200km of Seattle [20]. Yield information for each crop was provided by the National Agricultural Statistics Service [21]. 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 [22] , 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 Figure 3. Reference diets were computed using the Interactive DRI for Health Care Professionals [23] 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.

Computing the Maximum Food Production Capacity

We used ArcGIS to determine the areal extent of each of the five land uses in Seattle (Figure 2) that coincided with the “full sun” class from Figure 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 hectare 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 one hectare 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.

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.

Results and Discussion

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 6,000 people if conversion occurred on SFR lands alone (Figure 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 Figure 3. If tree canopy shading was not present, food production could be increased by 35% in SFR zones and 19% for the non-SFR 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 [24, 25]. 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 [26]. 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" [27-29]. 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 [21], 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 [12], but future research is necessary to assess the range of yields possible in urban environments.

Seattle Foodshed

Figure 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 Figure 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 Figure 5 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 [3, 30]. 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 that may not be viable if transportation costs become very expensive.

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

The authors would like to acknowledge the contribution of feedback and support from Dale Blaha and Kathy Wolf. Funding and support provided by the USDA Forest Service PNW Research Station and the American Recovery and Reinvestment Act.

References

1. United Nations Food and Agriculture Organization, *Food, Agriculture and Cities: Challenges of food and nutrition security, agriculture and ecosystem management in an urbanizing world*, 2011.
2. Grimm, N.B., et al., *Global Change and the Ecology of Cities*. Science, 2008. **319**(5864): p. 756-760.
3. Born, B. and M. Purcell, *Avoiding the Local Trap: Scale and Food Systems in Planning Research*. Journal of Planning Education and Research, 2006. **26**(2): p. 195-207.
4. Slow Food USA. Available from: <http://www.slowfoodusa.org/about-us>.
5. Feenstra, G.W., *Local food systems and sustainable communities*. American Journal of Alternative Agriculture, 1997. **12**(01): p. 28-36.
6. Godfray, H.C.J., et al., *Food Security: The Challenge of Feeding 9 Billion People*. Science, 2010. **327**(5967): p. 812-818.
7. Kremer, P. and T.L. DeLiberty, *Local food practices and growing potential: Mapping the case of Philadelphia*. Applied Geography, 2011. **31**(4): p. 1252-1261.
8. United Nations Development Programme, *Urban Agriculture, Food, Jobs, and Sustainable Cities*, in *Publication Series for Habitat II*, 1996.
9. Orsini, F., et al., *Urban agriculture in the developing world: a review*. Agronomy for Sustainable Development, 2013. **33**(4): p. 695-720.
10. Martellozzo, F., et al., *Urban agriculture: a global analysis of the space constraint to meet urban vegetable demand*. Environmental Research Letters, 2014. **9**(6).

- 232 11. Taylor, J.R. and S.T. Lovell, *Mapping public and private spaces of urban agriculture in Chicago*
233 *through the analysis of high-resolution aerial images in Google Earth*. Landscape and Urban Planning,
234 2012. **108**(1): p. 57-70.
- 235 12. Ackerman, K., et al., *Sustainable Food Systems for Future Cities: The Potential of Urban*
236 *Agriculture*. Economic and Social Review, 2014. **45**(2): p. 189-206.
- 237 13. Peters, C.J., et al., *Mapping potential foodsheds in New York State: A spatial model for*
238 *evaluating the capacity to localize food production*. Renewable Agriculture and Food Systems, 2009.
239 **24**(1): p. 72-84.
- 240 14. Morrison, K.T., T.A. Nelson, and A.S. Ostry, *Methods for mapping local food production capacity*
241 *from agricultural statistics*. Agricultural Systems, 2011. **104**(6): p. 491-499.
- 242 15. Giombolini, K.J., et al., *Testing the local reality: does the Willamette Valley growing region*
243 *produce enough to meet the needs of the local population? A comparison of agriculture production and*
244 *recommended dietary requirements*. Agriculture and Human Values, 2011. **28**(2): p. 247-262.
- 245 16. Grewal, S.S. and P.S. Grewal, *Can cities become self-reliant in food?* Cities, 2012. **29**(1): p. 1-11.
- 246 17. U.S. Census Bureau, *United States Census 2010*, 2010.
- 247 18. Alberti, M., R. Weeks, and S. Coe, *Urban land-cover change analysis in Central Puget Sound*.
248 Photogrammetric Engineering and Remote Sensing, 2004. **70**(9): p. 1043-1052.
- 249 19. Richardson, J.J. and L.M. Moskal, *Uncertainty in urban forest canopy assessment: Lessons from*
250 *Seattle, WA, USA*. Urban Forestry & Urban Greening, 2014. **13**(1): p. 152-157.
- 251 20. Washington State University Skagit County Extension, *2013 Skagit County Agricultural Statistics*,
252 2013.
- 253 21. National Agricultural Statistics Service, *Data and Statistics*, U.S. Department of Agriculture,
254 Editor 2013.

- 255 22. U.S. Department of Agriculture, A.R.S., National Agricultural Library, Nutrient Data Lab,, *National*
256 *Nutrient Database*, 2013.
- 257 23. U.S. Department of Agriculture. *Interactive DRI for Health Care Professionals*. 2014; Available
258 from: <http://fnic.nal.usda.gov/fnic/interactiveDRI/>.
- 259 24. Ciecko, L., et al., *Seattle's Forest Ecosystem Values: Analysis of the Structure, Function, and*
260 *Economic Benefits*, 2012, Green Cities Research Alliance. p. 32.
- 261 25. Wolf, K.L., *Strip Malls, City Trees, and Community Values*. Arboriculture & Urban Forestry, 2009.
262 **35**(1): p. 33-40.
- 263 26. *Beacon Food Forest*,. 2014; Available from: <http://www.beaconfoodforest.org/index.html>.
- 264 27. Walker, R.E., C.R. Keane, and J.G. Burke, *Disparities and access to healthy food in the United*
265 *States: A review of food deserts literature*. Health & Place, 2010. **16**(5): p. 876-884.
- 266 28. Kato, Y. and L. McKinney, *Bringing food desert residents to an alternative food market: a semi-*
267 *experimental study of impediments to food access*. Agriculture and Human Values, 2015. **32**(2): p. 215-
268 227.
- 269 29. Weatherspoon, D., et al., *Fresh vegetable demand behaviour in an urban food desert*. Urban
270 Studies, 2015. **52**(5): p. 960-979.
- 271 30. Selfa, T. and J. Qazi, *Place, taste, or face-to-face? Understanding producer-consumer networks in*
272 *"local" food systems in Washington State*. Agriculture and Human Values, 2005. **22**(4): p. 451-464.

273

274

275

Table 1: Statistics related to nine crops used in modelling 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%

291 Table 2: The areal extent of land in Seattle within four different land use classes and three solar
 292 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)		
	<i>Shade</i>	<i>Part Sun</i>	<i>Full Sun</i>	<i>Shade</i>	<i>Part Sun</i>	<i>Full Sun</i>
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

293

294

295 Table 3: Table 2: The areal extent of land in Seattle within four different land use classes and three solar
 296 radiation classes in a scenario when the shading from trees is removed. Extents are given for parcels
 297 zoned single family residential and for all lands in Seattle.

Land Use	Single Family Residential Land Area (ha)			All Land Area (ha)		
	<i>Shade</i>	<i>Part Sun</i>	<i>Full Sun</i>	<i>Shade</i>	<i>Part Sun</i>	<i>Full Sun</i>
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

298

299

300 Figure 1: Categorical raster of land use for Seattle, WA. The white box in the Northeast corresponds to

301 the enlarged inset.

302 Figure 2: Solar insolation modeled as three categories of sun intensity. Insolation is shown for the
 303 current landscape (tree) and with all trees removed (no tree). Insets show the area of the white box
 304 (same as Figure 1).
 305

306

307

308

309 Figure 3: The proportion of the population of Seattle fed by converting grass land cover in full sun in
310 Seattle to intensive agriculture under different scenarios (the area of the chart is proportional to the
311 population of Seattle). The green section represents the proportion of the population fed if Single Family
312 Home zoned land is converted to intensive agriculture and the blue section represents all other lands.
313 The dark green and dark blue sections represent the additional population that could be fed if the
314 shading from trees was eliminated

315

316

317 Figure 4: Land uses derived from the National Land Cover Database for areas surrounding Seattle. The

318 boundary of the City of Seattle is shown in the middle, and the four white isolines show percentage of

319 Seattle fed if the Pasture/Hay and Crops land uses are converted to intensive agriculture.