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LETTER

Attenuation of urban agricultural production potential and crop water footprint due to shading from buildings and trees

Mark S Johnson[1,2], **Michael J Lathuillière**[1], **Thoreau R Tooke**[3] and **Nicholas C Coops**[3]

[1] Institute for Resources, Environment and Sustainability, University of British Columbia, 418-2202 Main Mall, Vancouver, British Columbia V6T 1Z4, Canada
[2] Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, BC, Canada
[3] Faculty of Forestry, University of British Columbia, 2424 Main Mall, Vancouver, BC V6T 1Z4, Canada

E-mail: mark.johnson@ubc.ca

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Abstract

Urban agriculture requires local water to replace 'hydrologic externalities' associated with food produced outside of the local area, with an accompanying shift of the water footprint (WF) for agricultural production from rural to urban areas. Water requirements of urban agriculture have been difficult to estimate due to the heterogeneity of shading from trees and buildings within urban areas. We developed CityCrop, a plant growth and evapotranspiration (ET) model that couples a 3D model of tree canopies and buildings derived from LiDAR with a ray-casting approach to estimate spatially-explicit solar inputs in combination with local climate data. Evaluating CityCrop over a 1 km^2 mixed use, residential neighborhood of Vancouver Canada, we estimated median light attenuation to result in 12% reductions in both reference ET (ET_o) and crop ET (ET_c). However, median crop yields were reduced by only 3.5% relative to potential yield modeled without any light attenuation, while the median crop WF was 9% less than the WF for areas unimpeded by shading. Over the 75 day cropping cycle, median crop water requirements as ET_c were 17% less than that required for a well-watered grass (as ET_o). If all lawns in our modeled area were replaced with crops, we estimate that about 37% of the resident population could obtain the vegetable portion of their diet from within the local area over a 150 day growing season. However doing so would result in augmented water demand if watering restrictions apply to lawns only. The CityCrop model can therefore be useful to evaluate trade-offs related to urban agriculture and to inform municipal water policy development.

1. Introduction

Agriculture forms the basis of human societies, yet population growth and dietary changes coupled with environmental impacts from agriculture suggest that the sustainable provision of food remains an unresolved global challenge (Keating *et al* 2014). Recent studies have recognized urban areas as an important and practically ubiquitous zone of agricultural production, with 98% of cities in the world containing at least some area of cropland (Thebo *et al* 2014). However, current approaches to conducting global inventories of urban agriculture are unable to identify opportunities and trade-offs for agricultural production at spatial scales that are useful for municipal planners and others. There is also growing interest in how the urban water balance can be influenced by urban design, land use and management (Fletcher *et al* 2013).

Interest in urban agriculture has increased greatly in recent years (Barthel and Isendahl 2013, Ernwein 2014, La Rosa *et al* 2014), and the number of urban farms is rising (Rogus and Dimitri 2015). Despite concerns regarding the potential of urban agriculture to contribute significantly to food security (Badami and Ramankutty 2015), urban agriculture is strongly linked to social benefits including community building, greening of cities, and provision of fresh foods within areas where access can be difficult (Badami and Ramankutty 2015). At present, there are few tools available for scientists, planners and decision makers to evaluate trade-offs that ensue when considering the resource requirements and production potential of urban agriculture (Surls *et al* 2015), particularly within dense urban spaces.

Advances in remote sensing such as airborne light detection and ranging (LiDAR) provide a means for deriving fine-scale input data for modeling and decision making purposes that can be coupled with ground-based climatological and demographic data. LiDAR derived buildings and trees compare well with field-based measurements and estimates from aerial photography (Goodwin *et al* 2009). While detailed remote sensing data is not available at present for all areas, spatial coverage is rapidly expanding. When coupled with crop models and water use data, analysis based on LiDAR or other remote sensing data can provide highly detailed spatial estimates of agricultural production potential in conjunction with physical limitations to crop production resulting from shading and crop water needs.

Sunlight for plant growth is impeded in urban areas due to shading from trees, buildings, and other structures. However, light that filters through tree canopies and/or reflects off physical surfaces such as walls and windows augments direct and diffuse sunlight, with the combined light inputs permitting production of numerous crops within dense urban areas. Recognition of the production potential of areas that may appear limited by light inputs is one way to identify opportunities for increasing urban agriculture. Several other features of urban environments can be physiologically advantageous for crop growth, including warmer nighttime temperatures, higher daytime CO_2 and lower overall wind speeds (Wagstaff and Wortman 2015).

Crop water requirements for agricultural production in urban areas (e.g. evapotranspiration (ET) of urban farms and vegetable gardens) are met via a combination of direct rainfall recharging soils and application of supplemental irrigation. The potential trade-off of increased demand on municipal water supplies due to urban agriculture must be considered for areas that are seeking to increase local food production, particularly for jurisdictions for which water supplies are not metered, although municipal sources can be augmented through rainwater collection for subsequent use as irrigation. Determination of ET within urban areas is essential to closing the urban water balance, and is central to water management within the urban environment (Fletcher *et al* 2013).

In this paper, we provide a first approximation of the agricultural production potential of an urban area that highlights water management decisions that would be required to achieve this potential. The primary objectives of this research were to provide a spatially detailed evaluation of (i) direct and diffuse light inputs to an urban neighborhood; (ii) agricultural production potential within a developed urban area; and (iii) the crop water use requirements to achieve this crop production potential. We developed a coupled plant growth—ET model for urban environments (CityCrop) in support of these objectives, and applied it to a neighborhood within Vancouver, Canada that contains a variety of building forms, parks and other features typical of urban areas within North America.

2. Materials and methods

2.1. CityCrop: a plant growth—ET simulation model for urban environments

The CityCrop model provides estimates of ET and crop productivity based on (i) input data from ground-based measurements of meteorological parameters and (ii) solar inputs attenuated by shading due to tree canopies and building structures. In its present form, we assume that crop growth is not water limited in order to evaluate water inputs needed to achieve crop production potential as a function of light attenuation. We estimate water use for theoretical food production (as defined by Fischer *et al* 2009) by combining models of solar radiation obtained from LiDAR inputs with theoretical biomass growth and crop water use (figure 1). In this study, we evaluated the production potential of areas classified as open vegetated ground surfaces, but rooftops, parking garages and other structures currently of interest for augmenting cropping areas within cities (Thomaier *et al* 2015) could also be modeled based on input data availability. Briefly, a solar radiation model is used within CityCrop to condition a theoretical crop growth model and a crop water use model. Crop growth occurs as a function of intercepted light and a thermal index, which allows light constraints to impede crop growth. The solar radiation model also conditions reference ET, which is used to estimate crop ET. In this form, CityCrop can be used to estimate light attenuation impacts on potential crop productivity, and the water use required to achieve this potential (e.g. maximum) crop productivity.

2.2. Solar radiation model

LiDAR remote sensing data acquired with vegetation in full leaf-on condition is used to derive the 3D structure of trees and buildings and to classify surfaces as vegetative versus solid (Tooke *et al* 2012). Secondary LiDAR returns are used to differentiate trees and above ground vegetation from hard surfaces (e.g. buildings) since solid surfaces tend to reflect the entire laser signal as a single return. LiDAR intensity values were further used to identify ground vegetation since vegetation typically produces a high reflectance in the near-infrared region of the electromagnetic spectrum characteristic of the LiDAR signal. For CityCrop, tree canopies and buildings are used to attenuate sunlight available for potential crop growth on areas classified as lawns (figure 2). LiDAR-derived surfaces are coupled with a solar position model that projects

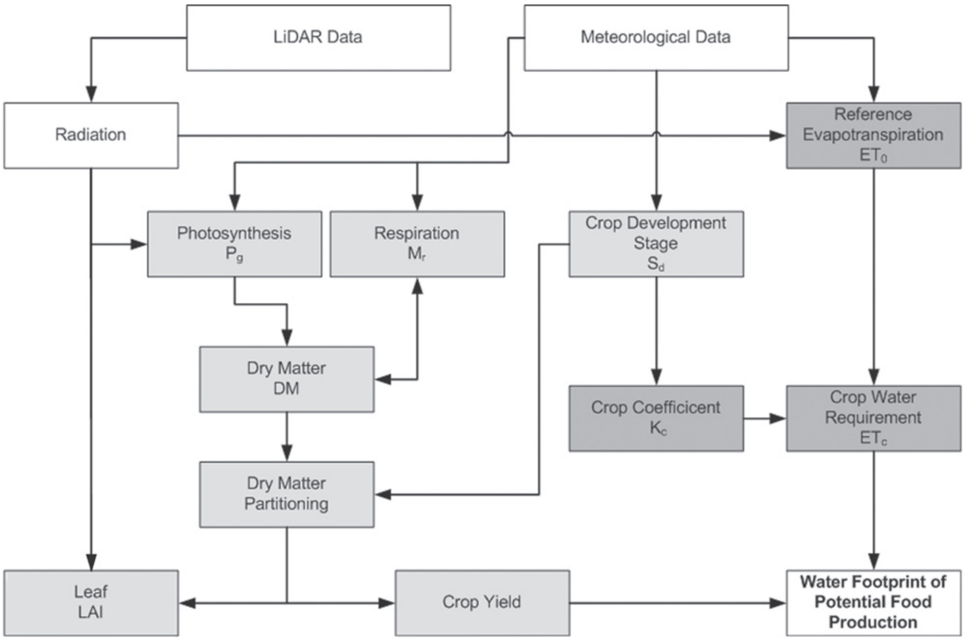

Figure 1. CityCrop model schematic detailing model input data (white boxes), submodel components (light gray boxes) and model outputs (dark gray boxes).

Figure 2. Overview of 1 km^2 study area within Vancouver, Canada. Crop production and evapotranspiration determined for areas classified as open vegetative surfaces and shown in figure in light green. Trees and impervious surfaces (buildings and roads) shown in dark green and white, respectively.

Table 1. Crop model stage of development (S_d) and corresponding crop coefficients (K_c) used to estimate theoretical crop growth, and associated water use.

Stage name	S_d	K_c	Description
Initial	<1	K_{ini}	From planting to shoot emergence
Development	<1	K_{dev}	Following shoot emergence, crop develops until flowering
Mid-season	$1 \leqslant S_d < 2$	K_{mid}	Post-flowering, crop matures and enters senescence
Maturity	2	K_{end}	Crop is mature and vegetables/fruit are harvested

direct sunlight as a function of day, time, and latitude (Grena 2008) and diffuse light, which is further conditioned based on skyview fractions (Tooke *et al* 2013). Solar radiation transmission through urban vegetation is determined using a vegetation attenuation algorithm described in Tooke *et al* (2012), providing irradiance estimates that are sensitive to small variations in the local urban form as input data to the CityCrop model. Due to limited information on the spectral properties of features surrounding buildings, reflected radiation is calculated assuming a static albedo for all urban surfaces.

2.3. Theoretical crop growth model

CityCrop uses growing degree days as a thermal time metric to simulate crop growth to estimate theoretical food production. The crop cycle is separated into initial, development, mid-season and maturity stages (table 1) based on the planting date, shoot emergence and flowering times using equation (1) (before flower, i.e. GDD < GDF) and (2) (after flowering, i.e. GDD > GDF) and (Costa *et al* 2009), as:

$$S_d = \frac{\mathrm{GDD}}{\mathrm{GDF}}, \tag{1}$$

$$S_d = 1 + \frac{\mathrm{GDD} - \mathrm{GDF}}{\mathrm{GDT} - \mathrm{GDF}}, \tag{2}$$

where S_d is the crop's stage of development (dimensionless), GDD is the accumulated growing degree days, GDF is the flowering day (in accumulated growing degree days) and GDT is the total accumulated growing degree days for the entire crop development cycle.

For each growth day, we define maximum plant growth proportional to photosynthetically active radiation using equation (3) (Monteith and Moss 1977):

$$C_m = qI, \tag{3}$$

where C_m is the maximum daily plant theoretical growth (g CO_2 m^{-2} d^{-1}), q is the crop quantum efficiency (g CO_2 MJ^{-1}) and I is the daily incident photosynthetically active radiation flux intercepted by the crop canopy (MJ m^{-2} d^{-1}) which changes as leaves grow through the crop development phase.

Leaf development allows for further interception of radiation described by equation (4) (Goudriaan and Van Laar 1994):

$$I = \mathrm{PAR}\left(1 - e^{-k\,\mathrm{LAI}}\right), \tag{4}$$

where PAR is the photosynthetic active radiation determined by the solar model attenuated by LiDAR-derived buildings and tree canopies (MJ m^{-2} d^{-1}), k is the radiation extinction coefficient of the crop canopy, and LAI is the leaf area index (m^2 m^{-2}). For each daily time step, a portion of dry matter is allocated to leaf growth as per equation (5) (Goudriaan and Van Laar 1994):

$$\frac{\mathrm{dLAI}}{\mathrm{d}t} = \mathrm{SLAI}p_l\frac{\mathrm{dDM}}{\mathrm{d}t}, \tag{5}$$

where DM is the accumulated dry matter (g), SLAI is the specific leaf area (m^2 g DM^{-1}) and p_l is the fraction of dry matter allocated to leaves (% m^{-2}). SLAI and p_l are assumed to be constant throughout the crop development cycle.

During photosynthesis, crops produce dry matter with some dry matter lost to maintenance respiration (Penning De Vries 1975, Amthor 2000, Costa *et al* 2009) as shown in equation (6):

$$\frac{\mathrm{dDM}}{\mathrm{d}t} = \left(P_g - M_r\right)r_c, \tag{6}$$

where r_c is the conversion efficiency of carbohydrates into dry matter (g CO_2 g DM^{-1}), P_g is the gross photosynthesis rate (g CO_2 m^{-2} d^{-1}) and M_r is the maintenance respiration coefficient (g CO_2 m^2 d^{-1}). P_g is estimated from the maximum photosynthetic rate (P_{gmax}) using equation (7) (Thornley 1998):

$$P_g = \frac{C_m + P_{gmax} - \sqrt{\left(C_m + P_{gmax}\right)^2 - 4\theta C_m P_{gmax}}}{2\theta}, \tag{7}$$

where θ is the shape factor of the P_g versus PAR curve with $0 \leqslant \theta \leqslant 1$. Extreme values of θ represent a rectangular ($\theta = 0$) and a non-rectangular hyperbola ($\theta = 1$). Finally, as per Goudriaan and Van Laar (1994) as cited in Costa *et al* (2009), P_{gmax} is expressed as a function of the maximum photosynthesis rate ($P_{gmax,t}$) at a reference temperature (T_r), base temperature (T_b) and daily temperature (T) as shown in equation (8):

$$P_{gmax} = P_{gmax,t}\frac{T - T_b}{T_r - T_b}. \tag{8}$$

The maintenance respiration coefficient M_r (g CO_2 m^{-2} d^{-1}) is corrected for temperature following equations (9) and (10) (McCree 1974):

$$M_r = m_r \mathrm{DMQ}_{10}^{(T_{mean}-T_b)/10}, \quad (9)$$

where M_r is the temperature dependent maintenance respiration coefficient (g CO_2 g^{-1} DM d^{-1}), Q_{10} is the relative increase in M_r for a 10 °C increase in temperature, and T_{mean} is mean air temperature (°C). M_r can be obtained from a maintenance respiration coefficient for a reference temperature, $M_{r,t}$ (g CO_2 g^{-1} DM d^{-1}) in equation (9) after Goudriaan and Van Laar (1994) as cited in Costa *et al* (2009):

$$m_r = m_{r,t}\frac{T - T_b}{T_r - T_b}. \quad (10)$$

Using equations (8) and (10), the values of P_{gmax} and M_r reported at a given temperature, or reference temperature T_r, can be redefined for the new temperature T throughout the crop development cycle.

2.4. Crop water use

Crop water requirements are estimated by separating climate from crop conditions. First, daily reference crop ET (ET_o in mm) is calculated based on meteorological information to represent ET of a theoretical crop of 0.12 m height, albedo of 0.23 and surface resistance of 70 s m^{-1} (Allen *et al* 1998). As per equation (11):

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma\frac{900}{T + 273}u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)}, \quad (11)$$

where Δ is the slope of the vapor pressure to temperature curve (kPa $°C^{-1}$), R_n is the net radiation conditioned by light impedance determined with the LiDAR model (MJ m^{-2} d^{-1}), G is the ground heat flux (MJ m^{-2} d^{-1}) and assumed to be zero for daily calculations (Allen *et al* 1998), γ is the psychrometric constant (kPa $°C^{-1}$), u_2 is the wind velocity 2 m above the crop canopy (m s^{-1}) and e_s and e_a are respectively the saturated and actual vapor pressure (kPa). The daily crop water requirements (ET_c in mm) are then determined following equation (12):

$$ET_c = K_c ET_o, \quad (12)$$

where K_c is the daily crop coefficient (unitless) and varies with the crop development stage (table 1). Values for K_c are typically close to 0.7 initially, before reaching 1.0 during mid-season and dropping to 0.9 at harvest (Allen *et al* 1998). The sum of ET_c through the season then represents the total crop water use. Crop yield can then be estimated based on dry matter production from harvest index values obtained from the literature.

It should be noted that empirical studies often estimate K_c based on measurements or calculations of ET_c and ET_o as $K_c = \frac{ET_c}{ET_o}$, where K_c can be related to different crop development parameters (e.g. de Medeiros *et al* 2001, Williams and Ayars 2005). However, the upper limit of potential crop ET (ET_c) is approximated by the product of ET_o and K_c (Allen *et al* 2011) as expressed in equation (12). We thus opted to characterize spatiotemporal differences in ET_c by varying ET_o as a function of shading in space and time (e.g. shading reduces net radiation in equation (11)), and varied K_c temporally as a function of the thermal index (as given in equations (1) and (2)) but kept it spatially constant across the study area to avoid excessive complexity in the model. Spatial variations in the intensity and duration of shading are captured in the solar radiation component of the model. However, a lack of empirical data on the shading effect on crop development (e.g. K_c as a function of shading) prevented us from incorporating this as a model feature in the present version. As such, the effect of shading on ET_c is currently implemented simply as a reduction to the ET_o term in equation (12) via a reduction to net radiation in equation (11).

2.5. Model application

We applied CityCrop to a neighborhood located in Vancouver, British Columbia, Canada using beans (*Phaseolus vulgaris* L.) as a model crop due to its common cultivation in the region and availability of crop parameters (Moore 2011). The City of Vancouver aims to reduce per capita water consumption for the year 2020 by 33% from 2006 levels while also increasing city food assets such as urban gardens within the city by 50% by 2020 (City of Vancouver 2012). These goals provided the motivation for developing CityCrop in order to determine the food production potential and associated water use requirements for densely built areas of the city. Further, Vancouver has a Mediterranean climate characterized by warm, dry summers and cool, wet winters. As such, the growing season intersects with the dry season, and the city typically imposes water use restrictions during summer periods. Most years, lawn watering is restricted to designated periods, while use of municipal water supplies for gardening and urban farming is not presently constrained by city policy or by-laws.

A 1 km^2 mixed use, primarily residential area within the City of Vancouver, Canada centering on a long-term climatological station located at 49.226°N, −123.078°W was selected as the study area. LiDAR data were collected using a Leica ALS60 laser scanner with an average point density of 4 points m^{-2}. Ground and non-ground signal returns were classified in-house by the LiDAR provider, with further details on LiDAR data provided in Tooke *et al* (2012). To estimate crop productive potential and associated water fluxes, daily averages of meteorological data (temperature, relative humidity, wind speed, incoming long-wave radiation and atmospheric clearness) were obtained for 2008–2013, which were then averaged for each day of year to approximate a 'climate normal' for recent years.

Theoretical bean production was modeled from above ground dry matter based on crop development observations made at the Center for Sustainable Food Systems at the UBC Farm (Moore 2011) to derive crop developments stages in growing degree days (table 1). Input parameters for plant photosynthesis and maintenance respiration for *Phaseolus vulgaris* L. were taken from Costa *et al* (2009). We assumed potential crop development based on ideal watering and environmental management conditions (e.g. no nutrient limitations, water stress, or pest pressures) and constant LAI post-flowering. In order to compare our model with empirical data and literature values, we evaluated beans grown to full maturity (e.g. dry beans). Beans were modeled as being planted on 1st May, with thermal time accumulating to the end of the crop cycle at 75 days after planting (Allen *et al* 1998). We estimated crop yield (g m^{-2}) as a function of modeled plant biomass (dry matter) (g m^{-2}) based on published relationships between yield and dry matter for *Phaseolus vulgaris* L. (Scully and Wallace 1990). Calories produced (kcal m^{-2}) were then estimated from yield based on 337 kcal per 100 g of dried beans (USDA 2014), where kcal refers to a dietary calorie. Finally, water use efficiency (WUE, as g DM kg^{-1} water) and the water footprint (WF) of potential food production (L water kg^{-1} food produced, equivalent to m^3 water ton^{-1} food produced) were calculated using the total ET_c during the 75 day crop cycle to estimate water utilized to produce a crop through to harvest.

2.6. Statistical analyses

Model components were executed in Python with statistical analyses performed using R (version 3.1.2) (R Core Team 2015) with R packages raster (Hijmans and van Etten 2014), rasterVis (Perpiñán-Lamigueiro and Hijmans 2014) and rgdal (Keitt *et al* 2014). Because model output data was not normally distributed, summary statistics for model-derived parameters were computed for quartiles for the entire study area and compared against parameter values derived for unimpeded areas conditions.

3. Results

3.1. Crop water use and reference ET

Crop water use (ET_c) and reference ET (ET_o) were estimated for all areas classified as having a vegetated ground cover. Within the 1 km^2 study area, these amounted to 28.8% of the total area (figure 2), with just over half of this located on private land (15.8% of total area) and the remainder on public areas including parks and other municipal land (13.0% of total area).

Reference ET (ET_o) for areas unimpeded by shading totaled 368 mm over the 75 day model run. For all open, pervious areas (e.g. areas classified as having vegetated ground cover), median ET_o was found to be 325 mm for the 75 day period. Median ET_o values for public areas were 5% higher than the overall median, and median values of private land holdings were 2.5% lower than the overall median (table 2). ET_c for the 75 day model run for unimpeded areas was 305 mm, compared with overall median ET_c of 269 mm for all open areas. These values are within the range of observed ET_c for beans receiving irrigation (Barros and Hanks 1993). For public and private areas, ET_c values were slightly above and below the overall median, respectively (table 2). Overall, the impact of sunlight due to building interception and tree canopy attenuation caused a 12% reduction in the median values of both ET_o and ET_c compared to unobstructed areas. The spatial variability in ET_c is presented in figure 3.

Table 2. Median values of evapotranspiration for reference crop (ET_o) and crop ET (ET_c) in mm per 75 day crop cycle for areas classified as open vegetative surfaces. Here, grass is the reference crop and beans (*Phaseolus vulgaris* L.) are the modeled crop. Open vegetative areas were subdivided into areas without any light impedance (unimpeded), as well as by land tenure (public or private).

Water fluxes	Unimpeded	Open (all)	Public	Private
ET_o (mm 75 d^{-1})	368	325	341	317
ET_c (mm 75 d^{-1})	305	269	282	263

3.2. Urban crop production and water footprint

Accumulated dry matter for the modeled bean crop (*Phaseolus vulgaris* L.) was estimated to be 411 g m^{-2} at the end of the 75 day growing period for open areas unobstructed by light interception from buildings or trees. This compares to a median value of 391 g m^{-2} for all potentially cropped areas (e.g. those classified as having vegetated ground cover), a reduction of only 5% relative to accumulated dry matter produced in unobstructed areas. As a result, the spatial variability in crop growth (figure 4) was less than that of ET_c. This is indicated in the relative differences between quartiles for crop production metrics compared to the interquartile range for water fluxes (table 3).

The median accumulated dry matter value of 391 g m^{-2} corresponds to a crop yield of 233 g dry beans m^{-2} based on literature values for the relationship between dry matter production and crop yield for *Phaseolus vulgaris* L. (Scully and Wallace 1990). The crop yield can also be considered in calorie terms, which corresponds to a median caloric production of 784 kcal m^{-2}.

WUE was found to be 1.45 g dry matter per kg water (median value), where each mm of ET_c is equivalent to 1 L m^{-2} or 1 kg m^{-2}. WUE varied within the study area with quartile values ranging from 1.62 to 1.38 g DM kg^{-1} (table 3). The WF for dry beans was found to correspond a median value of 1157 L kg^{-1} (equivalent in units to m^3 ton^{-1}), also with a substantial interquartile range (WF values of 1012 and 1223 L kg^{-1} for the 1st and 3rd quartiles, respectively).

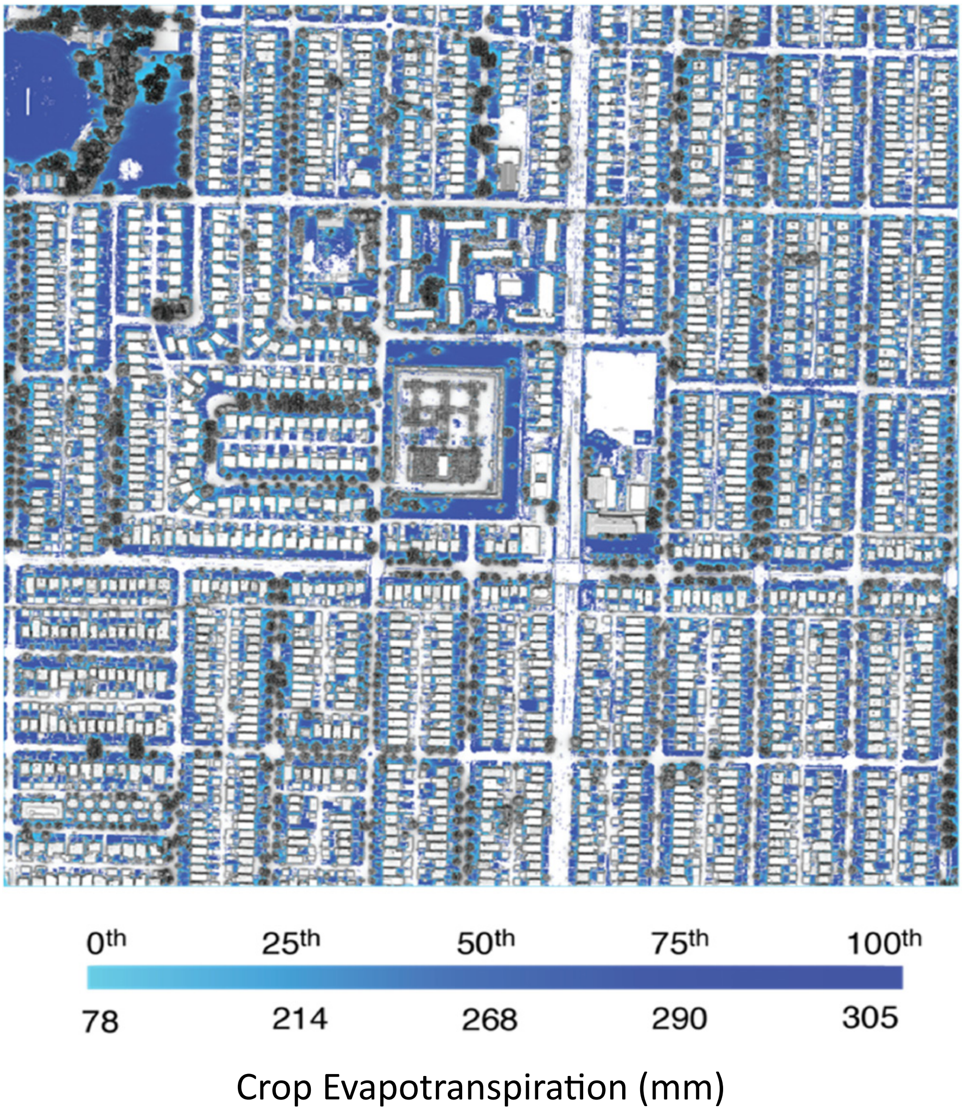

Figure 3. Crop ET (ET_c) for the study area, aggregated over the 75 day modeled cropping period. Values for minimum (0th), maximum (100th), and quartiles (25th, 50th and 75th) are given in units of mm per 75 days.

This is slightly lower than the 1351 m^3 ton^{-1} literature value for WF reported for dried beans produced in British Columbia (Mekonnen and Hoekstra 2011).

4. Discussion

4.1. Urban food production potential in densely developed areas

Light impedance due to buildings and tree canopies led to a median reduction of about 12% in modeled reference ET and crop ET compared to the fluxes estimated for an unimpeded open area. However, the impact of light attenuation on potential crop productivity led to a reduction in median dry matter production of 5% and a median yield reduction of only 3.5% (table 3). Combing these metrics, we found that crop WUE was highest for areas that had high degree of light attenuation. For example, WUE was 20% greater for areas in the 25th percentile of accumulated dry matter compared to unimpeded areas. Correspondingly, the WF of potential production was 20% less in the 25th percentile of accumulated dry matter compared to unimpeded areas. While light interception does affect potential yields, the impact on water fluxes was greater than the impact on yields, and resulting water use metrics were found to improve for increasing light attenuation (table 3).

The food production potential of urban areas has been suggested to be one of the keys to future food security (Satterthwaite *et al* 2010). While there are many millions of hectares of cropland located within the municipal boundaries of cities (Thebo *et al* 2014), the food production potential of densely built areas needs to be carefully considered so as to not be overstated (Badami and Ramankutty 2015). Here, we are not considering extensive farms located within city boundaries or peri-urban areas such as are found in many municipal districts and incorporated areas; rather, we are looking to evaluate the food production

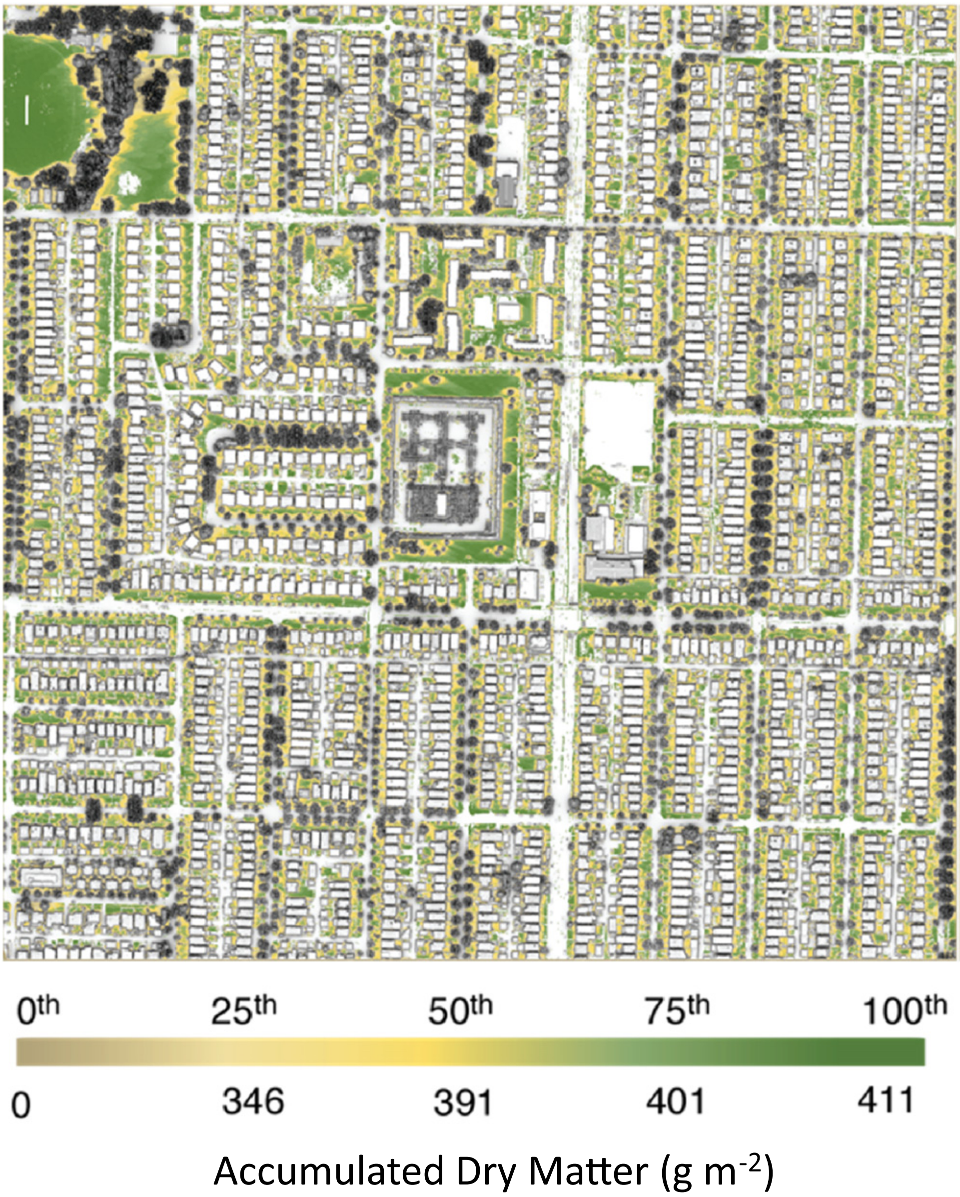

Figure 4. Accumulated dry matter (DM) for the study area, aggregated over the 75 day modeled cropping period. Values for minimum (0th), maximum (100th), and quartiles (25th, 50th and 75th) are given in units of g DM m^{-2} per 75 days.

Table 3. Crop production (accumulated dry matter and crop yield) and water use metrics (water use efficiency and water footprint of production) for 25th, 50th (median) and 75th percentiles of all areas classified as open vegetative surfaces within the study area relative to open areas without any light impedance (unimpeded). Columns are ordered from left to right by declining light attenuation (e.g., areas corresponding to the 25th percentile column are significantly more shaded than areas corresponding to the 75th percentile column).

Crop production and water use metrics	25th	Median	75th	Unimpeded
Accumulated dry matter (g m^{-2})	346	391	401	411
Yield (g m^{-2})	211	233	237	241
ET_o (mm 75 d^{-1}, also L m^{-2} per 75 d)	259	325	350	368
ET_c (mm 75 d^{-1}, also L m^{-2} per 75 d)	214	269	290	305
Water use efficiency (g dry matter per kg water)	1.62	1.45	1.38	1.35
Water footprint (L water per kg food produced)	1012	1157	1223	1266

potential within a highly urbanized form with a population density of ~5000 residents per km^2.

Using beans as a model crop, we estimate a median value of 784 calories produced per square meter. Taking the crop production potential of all open vegetated surfaces as an upper bound for potential urban food production in our study area, this suggests that something on the order of 5% of the total caloric needs of the resident population of the study area could be produced within the study area. This estimate assumes

Figure 5. Photograph of urban micro-farm within Vancouver neighborhood. Note the areas receiving direct and diffuse light due to shading from buildings and tree canopies. (Photo credit: MSJ).

that two crops can be produced per year during a combined 150 day growing season, and that all areas achieve their production potential. This would also require crops to be grown within all parks, as well as replacing all lawns and other open pervious areas. While not all open pervious areas could or should be converted to agriculture, many residents within the study area have converted their lawns into micro-farms (figure 5), a practice that is consistent with food policy within the study area (City of Vancouver 2012).

Another way to conceptualize the impact of the crop production potential on food security is to evaluate it in terms of the ability to provide the vegetable component of the average diet, in which vegetables are estimated to represent about 6.5% of total caloric intakes in North America (Block 2004). By this metric and assuming a 2300 kcal d^{-1} diet, we find that about 37% of the aggregate vegetable dietary requirements for 5000 people could be produced within the 1 km^2 study area if all private open vegetated surfaces (15.8% of the total land surface consisting primarily of lawns) were to produce two crops per year.

4.2. Water use considerations of urban agriculture

The CityCrop model computes reference ET based on FAO guidelines, which indicates the amount of ET that would be expected for a well watered, short-statured grass subject to local climatic conditions (Allen *et al* 1998). In this way, ET_o provides an opportunity to consider water use policy for local areas. The model output indicates that median crop ET is about 17% less than that of a well watered grass (computed from median values of ET_o and ET_c in table 3). These ET values can be supplied via soil water recharged from rainfall, or via supplemental irrigation.

Median ET_o for light impeded areas was 88% of the value of ET_o for unimpeded areas (325 mm versus 368 mm, table 2). This was on par with impact on ET_o for whitened greenhouses in Spain compared to ET_o for greenhouses without whitening, where ET_o of whitened greenhouses was 88% of ET_o for non-whitened greenhouses (Fernández *et al* 2010). Whitening of greenhouses (e.g. covering greenhouses with white material or paint) is a practice utilized in these systems to reduce radiation inputs to greenhouses thus reducing evaporative demands during spring and summer periods. This suggests that the magnitude of the influence of light attenuation on ET_o within the CityCrop model is reasonable.

The impact of shading in the urban environment is somewhat different from shading that occurs in screenhouses used in hot climates to reduce evaporative demand and plant stress. A screenhouse with 10% shading was found to reduce ET_c for table grapes by 34% (Pirkner *et al* 2014), which is more than the median 12% reduction in ET_c for beans within the urban area compared to unimpeded areas, but similar to the 30% reduction for at the 25th percentile (table 3). In addition to impacting the radiation balance, screenhouses and greenhouses reduce wind speed and turbulent transfers of water vapor and heat (Pirkner *et al* 2014), thereby affecting ET_c in complex ways compared to impacts on ET_c for crops grown in open areas including urban environments (where aerodynamic roughness is larger than rural areas (Brazel and Quatrocchi 2005)). For example, studies have long shown that shading can increase relative humidity and decrease temperature, with the combined reduction on plant water demand offsetting crop developmental effects due to shade (Schou *et al* 1978).

In the present case study, rainfall is limited during Vancouver's growing season, and residents commonly water both lawns and gardens. Under dry conditions free of watering restrictions, lawns would require significant additional irrigation compared to crops over the course of the 75 day crop cycle. However, as local policy currently permits unlimited watering of gardens but restricts lawn watering, it would likely be the case that replacing all lawns with micro-farms would lead to an increased demand for municipal water if alternative watering strategies were not considered. Returning to the upper bound for urban crop production within the study area, if all of the 28.8% of open vegetated surfaces were converted to crop production, then domestic water demand could increase 63% compared to a no-watering condition. This calculation assumes a base demand of 312 L per capita per day (Statistics Canada 2013) that is augmented by ET_c averaged over the cropping cycle. Clearly, such an increase in water demand would be undesirable, and so decision makers need to consider impacts of food policy in concert with studies of future water availability and policies to encourage water saving measures such as the use of subirrigated planters (Sullivan *et al* 2015), mulching, timers on sprinklers, drip irrigation, and rainwater harvesting.

Finally, a full consideration of water use in urban agriculture must also address post-harvest water use. That is, local food production as urban agriculture should be evaluated in terms of 'hydrologic externalities' that would need to be provided locally. For example, produce purchased in a supermarket carries with it a water footprint that includes crop ET as well as any water used to wash and prepare the produce for shipment. In discussions with local urban farmers, we learned that post-harvest water use can greatly exceed the amount of water applied as irrigation during the cropping cycle (C Dumont, Inner City Farms, pers. comm, 2014).

5. Conclusions

We developed the CityCrop model to assess the influence of light attenuation from buildings and tree canopies within an urban area on crop production and crop water requirements. Applying CityCrop to model the crop production potential of beans (*Phaseolus vulgaris* L.) and associated crop water fluxes over a 1 km^2 mixed use, primarily residential area within the City of Vancouver, Canada, we found that median crop water use was 17% less than that expected for a well watered lawn. However, light reductions due to the urban setting impacted crop productivity less than expected, with a modeled yield about 5% less for the 25th percentile relative to the median yield (50th percentile), and median yield only 3% less than that of open areas without any light impedance. Local water use policy and regulations need to be considered to evaluate if urban agriculture would increase water demand relative to other land uses. The model provides a framework to evaluate trade-offs related to land use management and water demand within moderate to dense urban environments where light attenuation can impact ET. Policies to encourage urban agriculture should be considered in concert with estimated impacts on water demand under current and future climatic conditions.

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