Assessing Urban Community Gardens' Impact on Net Primary Production using NDVI

Tammy E. Parece and James B. Campbell

CORE IDEAS

- Urban agriculture can make positive impacts on the physical urban landscape.

- We explore the use of vegetation indices commonly used in commercial agriculture and forestry in assessing environmental benefits from urban agriculture.

- Cultivating a vacant lot for urban agriculture increases Normalized Difference Vegetation Index (NDVI).

- Urban agriculture's increasing NDVI correlates with an increase in net primary production.

- Urban agriculture contributes to ecosystem services.

ABSTRACT

Community gardens are one form of urban agriculture–growing of food and non-food products for sale or consumption within urban and peri-urban areas. Urban community gardens provide many benefits, including provisioning of fresh and nutritious foods, supporting environmental education, nurturing social interaction and community building, and contributing to sustainability. In many cities worldwide, urban agriculture is now integrated within urban planning programs. Although social, community, and nutritional benefits of community gardens are well documented, few quantitative assessments of their environmental benefits exist. None have applied Normalized Difference Vegetation Index (NDVI) as an environmental metric. NDVI is widely used in forestry and agriculture to track changes in vegetation phenology, assess vegetation stress and health, and, in urban areas, to separate vegetation from impervious surfaces. NDVI has a positive relationship with net primary production. We used NDVI product from U.S. satellites–Landsats 5, 7, and 8–to assess urban community garden sites. We conducted a time series analysis over the 2007 to 2015 growing seasons (May–September) for three eastern U.S. cities–Roanoke, VA; Pittsburgh, PA; and Buffalo, NY. Our results show that establishment of community gardens alter seasonal NDVI trajectories, sometimes with initial declines, but then increasing over time. Furthermore, NDVI profiles reveal the vigorous character of urban agriculture.

Today, worldwide conversion of natural and agricultural lands to urban land is occurring faster than at any other time in history and is the most extensive of land use changes (Deelstra and Girardet, 2000; Pickett et al., 2001). Effects of conversion from natural and agricultural vegetation to urban infrastructure include sealing of soils by impervious surfaces, alterations of hydrologic cycles (through reduced evapotranspiration and ground infiltration, increased stormwater runoff, and degraded rivers and streams), and the urban heat island effect (higher air temperatures as compared to adjacent rural areas) (Pickett et al., 2001). Although more than half of the world's

T.E. Parece, Dep. of Social and Behavioral Sciences, Colorado Mesa Univ., 1100 North Avenue, Grand Junction, CO 81501 USA; J.B. Campbell, Dep. of Geography, Virginia Tech, 220 Stanger Street, 115 Major Williams Hall, Blacksburg, VA 24061 USA. Received 28 July 2016. Accepted 14 Dec. 2016. *Corresponding author (tparece@coloradomesa.edu).

population now lives in urban areas (a rate expected to continue increasing) (United Nations, 2014), the rate of conversion to urban land far exceeds related increases in urban populations (Lincoln Institute of Land Policy, 2015).

Environmental effects of urban areas extend well beyond urban boundaries, as basic needs of urban populations require importation of food, energy, and clean water and exportation of waste products by air, land, and water (Deelstra and Girardet, 2000; Pickett et al., 2001; Aitkenhead-Peterson et al., 2010). To mitigate adverse effects of urbanization, researchers and urban officials are assessing and implementing sustainability initiatives, including low impact development (LID), smart growth, and expansion of green infrastructures (Hirschman and Battiata, 2016). Urban agriculture provides a green infrastructure that supports urban populations with food provisioning, cultural and social services, and mitigation of adverse environmental effects (World Bank, 2013; McClintock and Simpson, 2014; Huang and Drescher, 2015). However, while extensive research has documented social, cultural, and food provisioning services, little empirical research has documented urban agriculture's environmental benefits.

In this paper, we explore the application of a widely used vegetation index derived from remotely sensed imagery to analyze environmental benefits from one form of urban agriculture– the community garden. In our background section, we present varied forms of urban agriculture and explain our choice of community gardens for this analysis. Additionally, we review empirical research on ecosystem services derived from urban agriculture and briefly introduce our evaluation. Our materials and methods section provides details of how we identified and selected the community gardens used for our study. We then provide background on the satellite imagery and the analytical strategies we used to examine vegetation in natural and agricultural environments. We include in this section an introduction to the vegetation index used for our analysis–Normalized Difference Vegetation Index (NDVI), and research supporting its use in such analyses. Finally, we provide results and answer the following questions: Is NDVI, a common index for analyzing the health of vegetation, appropriate for examining urban agriculture? Can we identify a specific NDVI signature related to urban agriculture? Does NDVI increase in response to implementing urban agriculture, thus demonstrating urban agriculture's impact as a positive contribution to urban sustainability plans? Further, we hope that our exploratory study directs and promotes additional quantitative analyses of urban agriculture using remotely sensed imagery.

BACKGROUND

Urban Agriculture

Urban agriculture is the growing and processing of food and non-food products for sale or consumption within urban and peri-urban areas (Mougeot, 2000). Urban agriculture is a productive urban greenspace and takes many forms, from plants in small containers on patios or balconies to large farms, and, while each form has distinct characteristics, the characteristics are not unique to its form (Doron, 2005). Urban agriculture takes many different forms; e.g., home gardens–usually constituting an individual or family growing food for consumption next to their residence (Drescher et al., 2006); urban farms–usually commercial operations, including greenhouses, rooftop gardens, and community-supported agriculture (Smit et al., 2001; Doron, 2005); orchards–consisting of trees providing a source of food (fruit or nut-bearing trees), fuelwood, or building materials (Smit and Nasr, 1992; Smit et al., 2001); and community gardens, informal gardens, school gardens, or allotment gardens–all characterized by land divided into plots and the garden site is usually not owned by the people working it (Lawson, 2005).

Home gardens are the most common form, but, because they are positioned adjacent to residences, are difficult to identify on aerial images. Farms, normally the largest in areal extent, are infrequently found within city boundaries. School gardens can be easily located on aerial images since they are located on school grounds, but, like home gardens, their adjacency to buildings can create a problem in satellite image analysis (discussed in more detail below). With informal gardens, land is cultivated without the permission of the land owner (Hardman and Larkham, 2014), and while they might be present in one growing season, their ephemeral nature produces difficulty when doing a time series comparison. Allotment gardens are sponsored and managed by the local government and most frequently found in Europe and Japan (Matsuo, 2000; Petts, 2001). Community gardens are quite ubiquitous in the U.S., easily recognizable on aerial images from the combination of individual plots and walkways, and the form most frequently mentioned in urban sustainability plans because of their community and social building characteristics. Thus, for this study, we examine community gardens.

Ecosystem Services

Ecosystems are communities of organisms interacting with each other and their surrounding physical environment, creating a functioning system (Odum, 1969). "Ecosystem services are the benefits people obtain from ecosystems" (Millennium Ecosystem Assessment, 2005, p. vii). These benefits include provisioning services, e.g., food, fiber, and fresh water; regulating services, e.g., air quality, and climate and disease mitigation; cultural services, e.g., a sense of place, and locales for education and social activities; and supporting services, e.g., soil formation, primary production, and nutrient and water cycling (Millennium Ecosystem Assessment, 2005).

Within urban systems, agriculture creates an ecosystem because plants, insects, soils, and soil organisms interact to form a food provisioning service (Bolund and Hunhammar, 1999). Urban agriculture's food provisioning services are well documented by Alaimo et al. (2008), Gittleman et al. (2012), and Pourias et al. (2015), among others.

Furthermore, ecosystem services provided by urban agriculture extend into other service areas. Saldivar–Tanaka

and Krasny (2004), Dunlap et al. (2013), Li et al. (2013), and Taylor and Lovell (2015) document cultural services when immigrants cultivate familiar plants from their home countries to maintain their cultural ties. Drescher et al. (2006), Agustina and Beilin (2012), Dunlap et al. (2013), and Cohen and Reynolds (2015) document community building and social interactions. Supporting services are illustrated by use of harvested rainwater (e.g., Redwood et al., 2014; Parece et al., 2016) and waste water (e.g., Faruqui, 2002; Rojas-Valencia et al., 2011; Kihila et al., 2014; Makoni, 2014) for irrigation, and by increased nutrient cycling from use of waste water for irrigation (e.g., Rojas-Valencia et al., 2011; Makoni, 2014) and composting solid waste (e.g., Adam-Bradford, 2006; Njenga and Karanja, 2006; Eriksen-Hamel and Danso, 2009; Sotamenou and Parrot, 2013).

Less common are studies supporting urban agriculture's contribution to regulating services. Such studies include calculating greenhouse gas reductions related to reduced food miles when producing food locally (e.g., Propersi, [2009] and Hardoy and Ruete [2013] for Rosario, Argentina; Albright [2013] for upstate New York; Kulak et al. [2013] for London).

Our study specifically appraises urban agriculture as a supporting service and evaluates changes in net primary production when converting a vacant parcel to a community garden. To accomplish this evaluation, we use well documented methods developed for evaluation of (for example) vigor of forests and productivity of agricultural systems, but not yet applied to urban agriculture. In the next section, we first discuss our study sites and identification of data derived from satellite images for individual community gardens, then provide more detail on remote sensing methods for evaluating change in net primary production.

MATERIALS AND METHODS

Study Sites

We selected three U.S. cities for our analysis– Roanoke, VA; Buffalo, NY; and Pittsburgh, PA. For Pittsburgh and Buffalo, we identified community gardens and their addresses with internet searches, using the words "Buffalo New York/ Pittsburgh Pennsylvania Community Gardens," setting up a spreadsheet file. We then reviewed websites for each of the gardens for details on the garden including length of gardening time and formal organization. For Roanoke, because of our extensive research on this urban agriculture setting, we were familiar with all community gardens for this study. None of the selected community gardens were school gardens nor did any of the gardens appear to be established without permission of the landowner. Within geographic information system software (ArcMap), we geocoded the addresses. This process provided point shapefiles for exact locations of community gardens. We converted this shapefile to the appropriate file format for Google Earth (KML). We added it within a Google Earth window to make sure each point identified the actual location of the community garden (e.g., not the street in front of the community garden).

Buffalo, NY

Buffalo has a very large urban agriculture community, with over 72 community gardens identified from the internet. The Grassroots Garden website (http://www.grassrootsgardens. org) provides an interactive GoogleMap with points plotted for each garden and designations for their gardens as school gardens, food only gardens, flower/ornamental gardens, and combination of food and ornamental. We eliminated the majority of these community gardens as unacceptable for satellite image analysis for multiple reasons. The largest community garden (Growing Green) includes many buildings, greenhouses and aquaponics, and thus very little outdoor gardening space. Additional locations eliminated were rooftop gardens, gardens designated as school gardens located adjacent to buildings, purely flower/ornamental with plantings such as roses, and very small gardens between multi-story buildings which were difficult to identify even on aerial photos.

Pittsburgh, PA

For Pittsburgh, our initial internet search took us to the *Grow Pittsburgh* website (http://www.growpittsburgh.org/ [accessed 20 Apr. 2017]), which provided a list of urban agriculture sites categorized by urban farm, school garden, and community gardens. We, again, looked at each of these gardens for suitability in a satellite imagery analysis, eliminating those very small gardens difficult to see even on aerial photos. We had less difficulty with Pittsburgh locations (as compared to Buffalo), as some were constructed on large, previously vacant lots.

Roanoke, VA

For Roanoke, it was unnecessary to conduct an internet search because of our familiarity with the urban agriculture scene, including frequent contact with the local urban agriculture community. The Roanoke Community Garden Association (RCGA) was established in 2008 and has six active community gardens. One garden is adjacent to a house and difficult to identify because of its proximity to a building and Roanoke's extensive tree canopy cover. The two most recently established gardens (in 2015) were not included in this study as they are still under development.

By using the *Historical Image* sliding bar in Google Earth to review historical photographic coverage of each site, we documented the cultivation process for each community garden (i.e., we identified dates of images acquired prior to cultivation, dates of images with new cultivated areas, and dates of images with substantial vegetative growth). Figure 1 shows an example of an historical sequence for Hurt Park Community Garden in Roanoke, VA. From our internet searches, we documented an establishment date for each garden. We do note that large urban farms were located in each of our study sites but as noted above, urban farms have

Fig. 1. Historical sequence illustrating establishment and growth of Hurt Park Community Garden (within cyan polygon), Roanoke, VA. (Sources– 2006 and 2011: Virginia Base Mapping Program; 2012: National Agriculture Imaging Program; 2010 and 2015: source unknown but displayed in Google Earth).

different characteristics than do community gardens and, therefore, are not included in this analysis.

Satellite Imagery and Vegetation Analytic Methods

Satellite Imagery

Of the many land observation satellites currently orbiting the earth, for this analysis, we used Landsat. Landsat offers researchers the opportunity to make temporal comparisons over intervals of just a few days to decades (USGS, 2016b). Specifically, Landsat is a system of eight U.S. land-observation satellites–the first launched in 1972, the most recent in 2013 (of these, currently Landsats 7 and 8 are in service). These satellites follow orbits that permit repetitive observation (assuming cloud-free conditions) of any given portion of the earth's surface, at the same local sun time about every 16 d. Each orbital path slightly overlaps a prior path and thus, for some locations, the satellite revisits edges of the same scene on subsequent passes–an opportunity present for both Pittsburgh and Roanoke.

Sensors aboard the Landsat satellites measure electromagnetic radiation from the sun that is reflected off objects/features on the earth's surface. The portion of radiation reflected and captured by Landsat's sensors depends on many factors– extent of cloud cover, atmospheric interference and, most importantly, spectral properties of each feature. The unique spectral properties of varied features provide the basis for distinguishing objects from each other and tracking characteristics of individual features over time, and thereby form the basis for remote sensing analyses. Sensors collect spectral values for different portions of the electromagnetic spectrum and within Landsat, each portion is called a band (for example- Landsat 8's Band 4 covers 0.64–0.67 µm and Band 5 covers 0.85–0.88 µm (the red visible and the near-infrared portions of the electromagnetic spectrum, respectively) (USGS, 2016a). Although sensors aboard different Landsat satellites differ in their sensitivity to regions of the electromagnetic spectrum, they have been cross-calibrated, enabling comparison of vegetation indices over time (e.g., Teillet et al., 2001; Steven et al., 2003; Mishra et al., 2014).

Vegetation Indices

Healthy vegetation provides insights into the vigor of an ecosystem, represented by vegetation indices–ratios calculated from pixel values in separate bands of satellite imagery. A pixel represents a footprint of a specific area on the earth's surface and the area's size varies by satellite system. For Landsat, each pixel represents an area of 900 m^2 for the red and near infrared bands (a 30 m × 30 m square area on the earth's surface). The value of each pixel provides a digital number based on the observed brightness of the landscape within that pixel, and the set of values across all bands represent the spectral signature(s) of that particular area. However, an individual pixel could represent homogenous land cover (e.g., a loblolly pine forest, the top of a building, or a golf course fairway) or heterogeneous land cover (e.g., a mixture of sidewalk, grass, and a portion of a building roof). When a pixel images a heterogeneous mixture, it is called a mixed pixel, and mixed pixels are difficult to match to one specific landscape feature; this is a situation which occurred frequently when we evaluated the Buffalo community gardens.
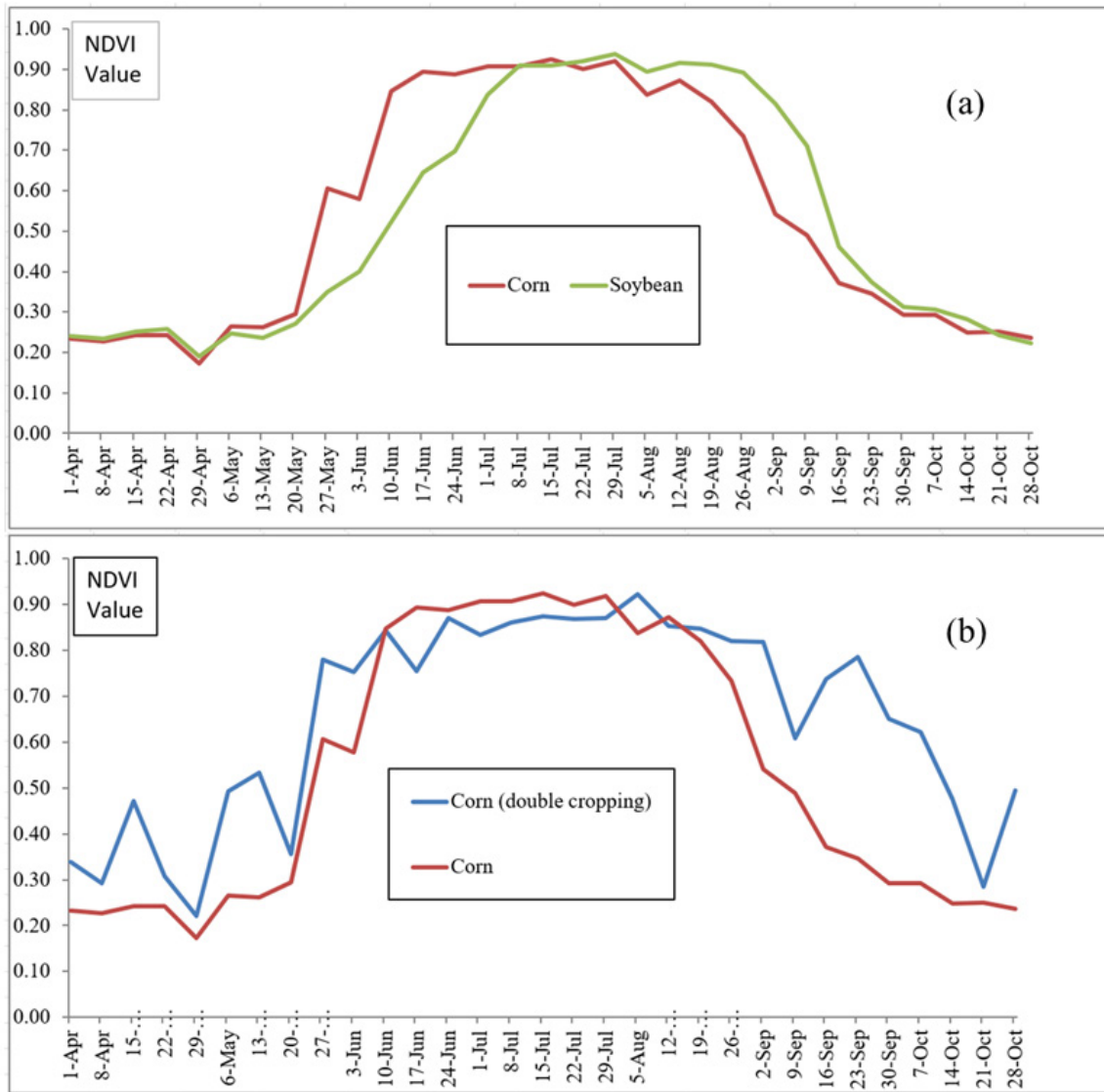
Fig. 2. Comparison of Normalized Difference Vegetation Index (NDVI) signatures for pure pixels of corn and soybeans (top) and, on bottom, a pure pixel of corn (brown line) compared to a mixed pixel of corn (blue line) with double cropping. Source: Dr. Jie Ren, Virginia Tech, with permission.

The NDVI is widely used to track vegetation phenology, identify vegetation stress, and assess vegetation health in forestry and agriculture (Huete et al., 1994), and, in urban areas, to distinguish vegetation from impervious surfaces (Weng, 2012). NDVI is based on the spectral values from the red and near infrared (NIR) portions of the electromagnetic spectrum, gathered either in situ with hand-held spectrometers or with sensors onboard satellites such as Landsat (Tucker, 1979). NDVI values are real numbers between −1 and +1, and the formula is

$$\frac{NIR - Red}{NIR + Red}$$

NDVI is sensitive to photosynthetically active vegetation (Tucker, 1979) and provides a positive linear relationship with the fraction of absorbed photosynthetically active radiation (fAPAR) by plant tissue (Myneni and Williams, 1994). fAPAR increases with ground cover and plant leaf area and productivity of vegetation is positively related to fAPAR (along with other factors such as nutrient availability, solar insolation, etc.) (Myneni and Williams, 1994). In agriculture, NDVI fluctuates throughout a growing season–increasing as a photosynthetic activity increases (a seed sprouts, grows stems, leaves, and fruit), peaks at plant maturity, and then declines as crops are harvested and vegetation dies off (photosynthetic inactivity). Different plant species have different NDVI values that peak at different times during the growing season and are highly dependent on the characteristics of specific plants– when it was sown, when it started growing, when it matures, and its leaf structure (i.e., erectophile or planophile) (Tucker, 1979; Justice et al., 1985; Huete et al., 1994; Myneni and Williams, 1994).

NDVI values closer to +1 equate to more mature and healthy vegetation, and to more complete vegetative cover of soil surfaces. Figure 2 provides an example of sequential

NDVI values for two different agricultural crops–corn and soybean. The graph (a) demonstrates, for a single growing season, differences between pure, single-cropped, pixels of corn and soybean NDVI signatures. The graph (b) illustrates NDVI differences between a pure pixel of corn, and a mixed pixel of corn with double cropping, with the latter illustrating a variable NDVI profile suggestive of a community garden, with multiple plantings, often of different plants throughout the growing season, where productivity extends well into the autumn.

Thus, because of its relationship to fAPAR, NDVI values have the potential to estimate primary production and to monitor phenological changes (Huete et al., 1994). For urban areas, few studies have used NDVI from remotely sensed imagery to quantify primary production (e.g., As-syakur et al. [2010] for gross primary production, Davies et al. [2011] for above-ground carbon storage for a single city, and Wu and Bauer [2012] for net primary production of turfgrass). In addition, two studies have quantified decreases in net primary production from urbanization at a broad scale– Milesi et al. (2003) for the southeastern United States and Imhoff et al. (2004) for the United States as a whole. We could not identify studies that have applied the NDVI to assess either positive or negative changes in primary production related to urban agriculture.

Urban agriculture adds complexity to NDVI analyses. In large agriculture plots, an individual pixel will typically represent a single crop species (as seen in Fig. 2). Urban agriculture, however, is typified by polyculture, i.e., multi-cropping, and intercropping (Smit et al., 2001). Multi-cropping is defined as two or more crop species cultivated within the same unit area and intercropping as two or more species grown at the same time in close proximity (Gliessman, 1980). Such practices are commonly used in community gardens as documented in studies by Yadav et al. (2012) and Li et al. (2013). Thus, any application of remote sensing to examine urban agriculture will likely encounter multi-cropping and intercropping, and record plots as mixed pixels (pixels representing integration of several different spectral features), preventing direct application of conventional remote sensing analyses.

Satellite Imagery Selections

Landsat products are available, without charge, through the U.S. Geological Survey's internet search engines- GLOVIS (https://glovis.usgs.gov/ [accessed 21 Apr. 2017]) or EarthExplorer (https://earthexplorer.usgs.gov/ [accessed 21 Apr. 2017]). We chose Landsat 5, 7, and 8 surface reflectance NDVI images for the months of May through early October (years 2007–2015) for each study site. Surface reflectance products correct for atmospheric interference of reflected radiation (for specifics, see Department of Interior [2015]). The NDVI surface reflectance product is delivered with NDVI values from -10,000 to +20,000. (NDVI values should range from –1 to +1 but to reduce storage space, USGS creates NDVI images with integer values and advises use of a scaling factor [0.0001] to correct to actual NDVI value [Department of Interior, {2015}]).

Community Garden Identification within the Satellite Image

We identified each Landsat pixel intersecting with a community garden. To accomplish this task, for each city, we first created a polygon file (using the "Create Fishnet" tool within ArcMap; Environmental Systems Research Institute, 2015) that matched exactly to the boundaries of each pixel in a Landsat image. We then selected those polygons containing each community garden point, and converted those selected polygons to KML files. We added this KML polygon file to Google Earth to verify that each selected polygon covered a community garden, in whole, or in part. In instances where community gardens were positioned within several polygons, we returned to ArcMap to select additional polygons.

Once we identified all polygons that covered a community garden, either in whole, or in part, we exported those selections into a new KML file to evaluate each individual polygon. We viewed each polygon in Google Earth, using current and historical imagery to check for specific situations:
- Features of the community garden were clearly visible within the pixel, e.g., cultivated rows,
- The community garden occupied at least 50% of the pixel,
- No tree canopy was found in more than 20% of the pixel, and
- The community garden was not shadowed by buildings.

We removed from the analysis any polygon representing a Landsat pixel that did not meet any of these qualifications. Within Fig. 3 and Fig. 4, the cyan polygon represents the area covered by one Landsat pixel. Figure 3 illustrates examples of unacceptable pixels; we deleted any community garden points found within unacceptable pixels. Figure 4 provides examples of pixels we considered acceptable for our study. These steps permitted us to verify that each point selected as a community garden in fact matched to an identified community garden, that the sensor had a clear view of the garden plot, and that we could match each plot to a pixel representing the spectral properties of the garden plot.

Identification of Satellite Images

Each Landsat NDVI surface reflectance scene was loaded into ArcMap, one scene representing one specific date for one specific garden. Figure 5 demonstrates examples of Landsat surface reflectance NDVI images. We evaluated each scene for clarity and cloud cover. For scenes with clouds or haze covering all community gardens, we eliminated the entire scene from consideration. We eliminated data relative to specific community gardens when clouds were covering only that garden or if the garden fell on a pixel with missing data (in 2003, a partial failure of the sensor on Landsat 7 created data gaps, illustrated in Fig. 5 [USGS, 2015]).

In ArcMap, we used the *Spatial Analyst Tools > Extraction > Extract Multi Values to Points* to extract all NDVI values for each community garden point from each scene, for all years (2007–2015), creating a separate shapefile for each year. We

Fig. 3. Examples of unacceptable matches between pixels and different community gardens in Buffalo, NY (community garden is identified by the white arrow). Such matches were not suitable for use in this study. Cyan polygons represent footprints of Landsat pixels. (Source: Google Earth).

Fig. 4. Examples of acceptable matches between pixels and community gardens. Left: Farmer's Garden Patch, Buffalo; Center: Bandi Schaum Field, Pittsburgh; Right: Hurt Park Community Garden, Roanoke. Cyan polygons represent footprints of Landsat pixels. (Source: Google Earth).
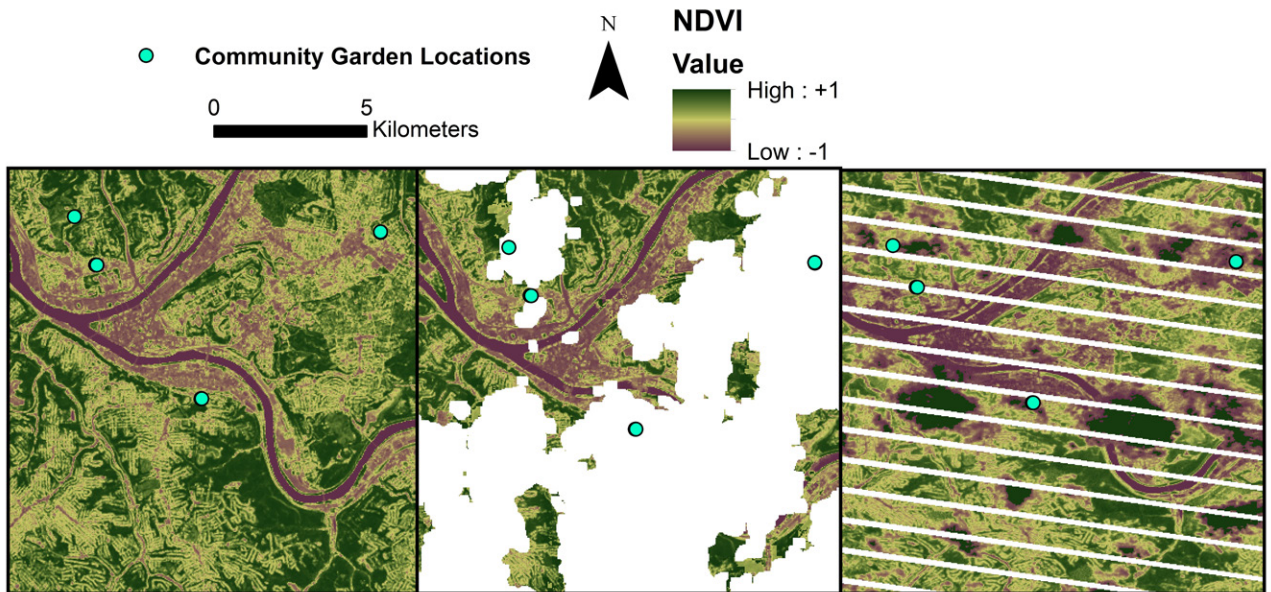
Fig. 5. Examples of Normalized Difference Vegetation Index (NDVI) Landsat Images for Pittsburgh. Left: Landsat 8, no interference within image; Middle: Landsat 8- clouds covering portions of image; Right: striping caused by Landsat 7's SLC-off missing scan line anomaly.

Table 1. City and state, community garden with neighborhood description (as identified from GoogleEarth images), establishment date, and number of viable Landsat pixels.

City, state	Community garden and neighborhood description	Date established	Number of Landsat pixels
Buffalo, NY	Serenity Garden- high density residential	2011	1
	Farmer's Garden Patch- medium/high density residential	2012	1
	Old First Ward- medium density residential	2012	1
	Esser Avenue- medium/high density residential	2013	1
Roanoke, VA	Frank Roupas– high density residential	2009	3
	Hurt Park- medium/high density residential	2012	2
	MountainView- medium/high density residential	2013	2
Pittsburgh, PA	Olde Alleghany– high density residential	1982, aerial images show garden expansion between 2010 and 2012	2
	Larimer Avenue–medium/high density residential	2010	2
	Ballfield Farm†- abandoned baseball field surrounded by trees	2008, but cultivation does not show on 2008 aerial photos	1
	Bandi Schaum Field- abandoned baseball field surrounded by trees	2012	2

† Although called a farm, this site is operated similarly to a community garden.

Table 2. Number of viable Landsat scenes by year, satellite, and city.

Year	Satellite	Roanoke, VA	Buffalo, NY	Pittsburg, PA
2007	Landsat 5	7	2	8
	Landsat 7	9	7	7
2008	Landsat 5	5	4	10
	Landsat 7	11	5	5
2009	Landsat 5	7	2	2
	Landsat 7	6	3	8
2010	Landsat 5	8	6	9
	Landsat 7	7	1	5
2011	Landsat 5	6	5	6
	Landsat 7	7	3	3
2012	Landsat 7	8	5	10
2013	Landsat 7	6	2	6
	Landsat 8	9	4	6
2014	Landsat 7	6	1	4
	Landsat 8	8	5	8
2015	Landsat 7	10	7	10
	Landsat 8	7	4	11
Total by city		121	61	114

name and neighborhood description, date established, and number of Landsat pixels covering that site.

Numbers of viable Landsat scenes for each year (during the growing season only), and for each garden, varied (Table 2). The number of scenes for gardens located in Roanoke, VA and Pittsburgh, PA exceeded those of Buffalo because these two cities are covered by two Landsat paths; 16 and 17 cover Roanoke, and 17 and 18 cover Pittsburgh. With the exception of 2012, two active Landsat satellites were in orbit each year.

Does Urban Agriculture Produce a Unique NDVI Signature?

Our results show that urban agriculture does not produce a unique NDVI signature, such as you would see for rural agriculture— as noted above, urban agriculture is typified by multi-cropping and/or intercropping, and thus produces a mixed pixel of spectral signatures. Furthermore, as demonstrated by Fig. 6 (Olde Alleghany Community Garden, Pittsburgh, PA), the mixed pixel integrates spectral signatures of neighboring roads, buildings, and grassy areas between cultivated rows within a community garden.

Nonetheless, our results show that urban agriculture is characterized by distinctive spectral signatures during the growing season (i.e., NDVI values demonstrating growth [increasing] and harvest [decreasing]) and unique NDVI patterns when assessed over the growing season (May–September). We demonstrate these results with a selection of NDVI graphs for one community garden within each city– Olde Alleghany Community Garden (established 1982); Frank Roupas Community Garden, Roanoke, VA (established 2009); and Old First Ward, Buffalo, NY (established 2013). Figure 7 shows the tangle of individual lines depicting the varied growth and senescence of plants within the gardens throughout the growing season—intricate, because of intercropping and multi-cropping inherent to a community garden over the course of the growing season. We note that each garden serves a multiplicity of gardeners, each with

then exported each attribute table into a text file and imported the text file into Microsoft Excel. Within Excel, we scaled the NDVI value using the scale factor (0.0001, as noted above), so our NDVI values then ranged from +1 to −1 for each image. We graphed each point's value over the growing season to compare NDVI values before and after cultivation.

RESULTS AND DISCUSSION

We identified eighteen Landsat pixels to examine in our study. Although we geocoded 72 community gardens for Buffalo, NY, once we evaluated each site, we identified only four Landsat pixels that met our criteria (largely due to small sizes of the Buffalo gardens, as illustrated in Fig. 3). Table 1 provides details for each city and community garden site, including
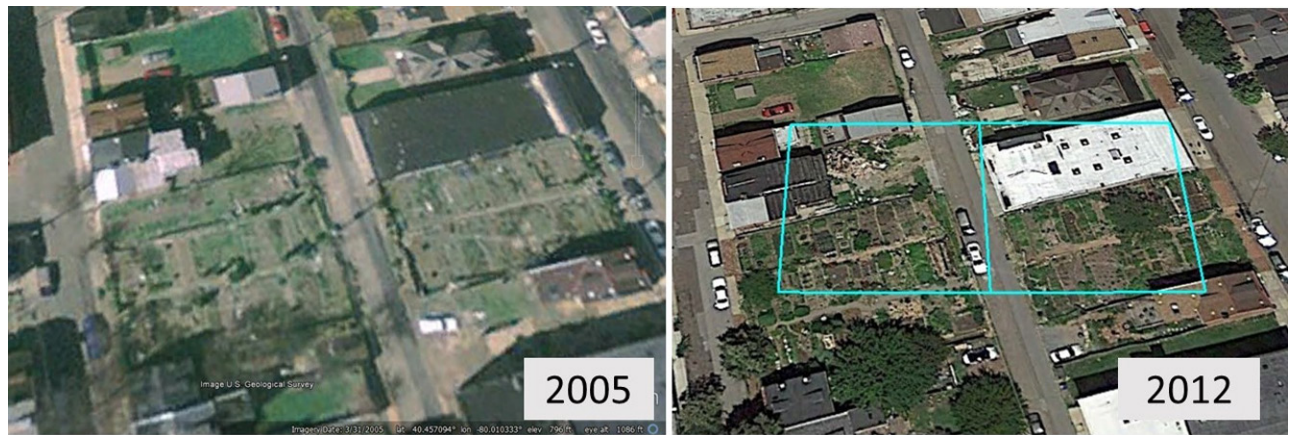
Fig. 6. Olde Alleghany Community Garden, Pittsburgh, PA. Cyan polygon represents the footprint of the Landsat pixels.

individual interests, adding to variability inherent to any such garden. In contrast, Fig. 2 illustrates the well-structured NDVI curve of a large, mono-cropped field, with a single crop observed over a single growing season. Thus, the intricate NDVI pattern forms a kind of signature for the community garden, varying not just throughout the growing season but from year to year dependent on the timing of planting, the various species grown, and the physical conditions of the area (e.g., temperature).

Variation of peak NDVI values between different gardens is of particular importance; the landscape around the community garden influences the garden's NDVI because it contributes to the NDVI profile for that pixel. NDVI peaks multiple times within the same growing season and peak values appear to be concordant with those of the landscape around the garden. To highlight these findings, we start with an examination of Frank Roupas Community Garden (Roanoke). The three pixels within this community garden show a wide variety of values, from dense vegetation in the west pixel (showing peak NDVI values at >0.9), grassier areas between garden plots in the middle pixel (peak NDVI values ~0.8), and inclusion of impervious surfaces in the east pixel (peak NDVI values ~0.7) (Fig. 8).

All community gardens produced NDVI values similarly. For example, Olde Alleghany (Fig. 6) is in a higher density residential area and its peak values run ~0.5 or less in the west pixel and between 0.5 and 0.55 in the east pixel (greater vegetation growth seen in the east pixel). Larimer Avenue, Esser Avenue, and Farmer's Garden Patch are situated on corner lots, thus two sides are adjacent to impervious surfaces (streets) and produce similar peak NDVIs, ~0.55. MountainView Community Garden is likewise situated on a corner lot, but is also adjacent to a parking lot on a third side; its peak NDVI values are slightly less, ~0.5. Table 3 provides peak NDVI details for each community garden.

Does NDVI Increase after Cultivation?

To answer this question, examining line graphs in Fig. 7 is difficult; as such, our comparison consisted of two steps: (i) examining average NDVI before and after cultivation, and (ii) examining NDVI values for the same date before and after cultivation.

We illustrate annual average NDVI (values averaged over the growing season, May through September) for the years 2007 through 2015 in Fig. 9–14. We have grouped pixels for gardens similar to the trend we noted in Table 3. For example, we graphed the annual average NDVI for Bandi Shaum east, Frank Roupas west, and Ballfield Farm in Fig. 9. In Table 3, we noted that the highest NDVI value after cultivation for these three locations was greater than the other locations; we found a similar situation with average annual NDVI. Additionally, as Fig. 9 illustrates, average annual NDVI shows an increasing trend (as seen by the graphed trend line) for Bandi Schaum east and Frank Roupas west. Ballfield Farm does not show an increasing trend, but Ballfield Farm was established in 2008, so we do not have a clear picture of average annual NDVI for multiple years prior to cultivation.

With three exceptions, average annual NDVI increases after cultivation for all other gardens–Frank Roupas middle pixel and Bandi Shaum west pixel (Fig. 10), Hurt Park south pixel and Larimer north pixel (Fig. 11), Larimer south pixel and Frank Roupas east pixel (Fig. 12), Serenity Gardens and Hurt Park north pixel (Fig. 13), and MountainView west and east pixels, Esser Avenue, and Old First Ward (Fig. 14). The three exceptions are Farmer's Garden Patch (Fig. 12) and both Olde Alleghany pixels (Fig. 13). The average annual NDVI for Farmer's Garden Patch (established 2012) demonstrates almost no change in NDVI before and after cultivation, but it does show an extreme drop in NDVI value the year of cultivation and then a significant increase in the following year.

For newly-established gardens, our graphs demonstrate that NDVI initially decreases during the transitional process from grassy plot to community garden, a trend noted for all the Buffalo gardens (Farmer's Garden Patch, Esser Avenue, Old First Ward, and Serenity), Bandi Shaum in Pittsburgh, and MountainView in Roanoke. The trend for Olde Alleghany Community Garden (Fig. 13) shows decreasing NDVI from 2007 through 2015, but Olde Alleghany was established in 1982 so we do not have data prior to its establishment.
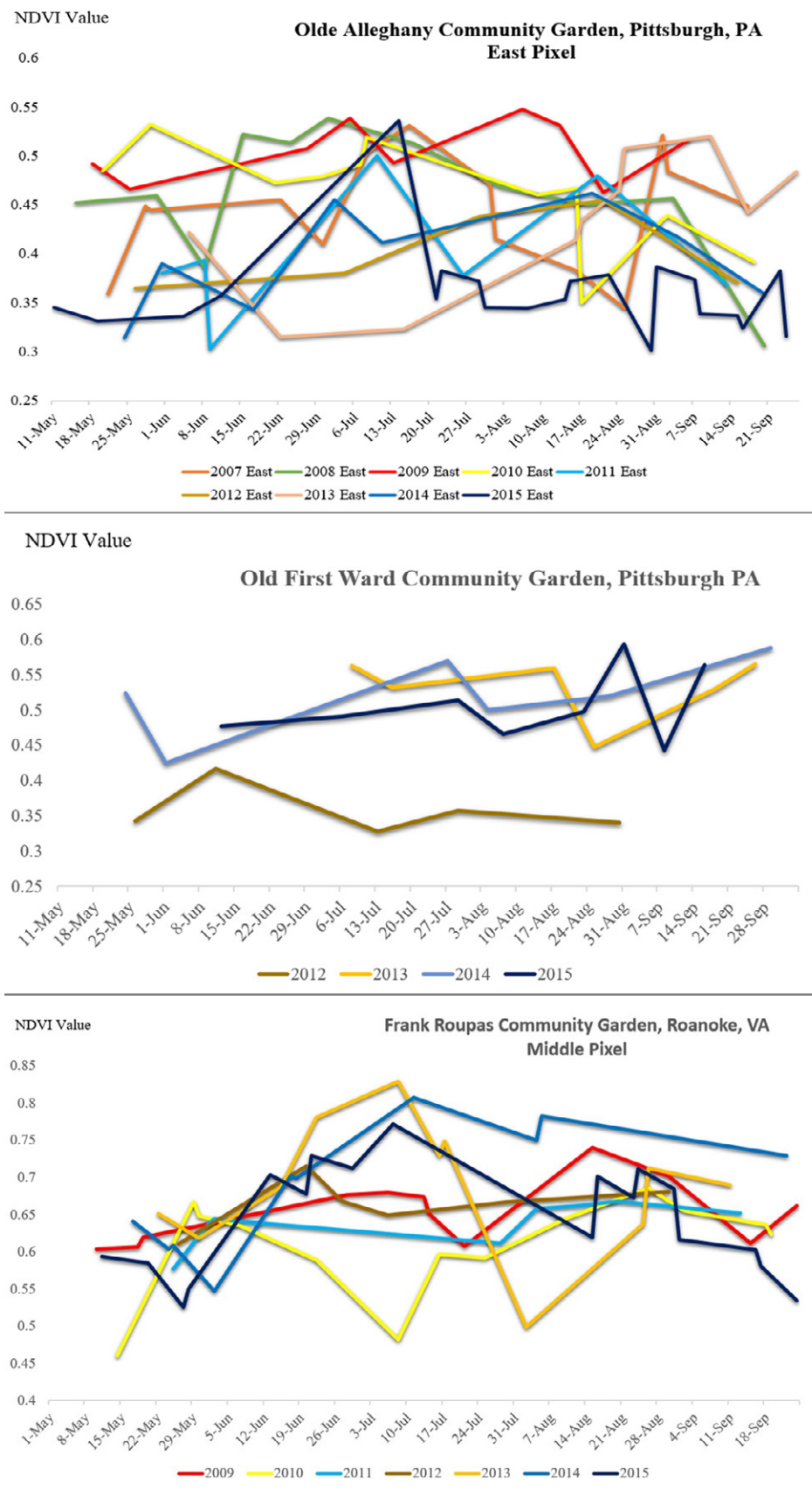
Fig. 7. Sample of line graphs mapping Normalized Difference Vegetation Index (NDVI) changes for the growing season (May–September) for three different mixed pixels (representing one community garden for each city). These lines capture the complex, dynamic sequences of multi-cropping and intercropping that characterize NDVI profiles for urban agriculture throughout the growing season.

Fig. 8. Frank Roupas Community Garden, Roanoke, VA. The west pixel (left) shows denser vegetation, the middle pixel more evident walkways between plots, and the east pixel (right) some impervious surfaces included in the mixture of spectral values.

Table 3. Peak Normalized Difference Vegetation Index (NDVI) by community garden, after cultivation.

Garden	Peak NDVI values after cultivation	Notes
Frank Roupas	>0.9 (west pixel) ~0.8 (middle pixel) ~0.7 (east pixel)	Vegetation within the garden changes from more dense vegetation on the west to inclusion of impervious surfaces in the east
MountainView	~0.5 (both pixels)	Surrounded on three sides by impervious surfaces (streets and parking lot)
Hurt Park	~0.8 (south pixel) ~0.7 (north pixel)	North pixel includes some sidewalk and is next to a street
Bandi Schaum	~0.85 (east pixel) ~0.83 (west pixel)	Composition of both pixels is equally mixed with garden plots, grassy areas (the garden is on former baseball field). No impervious surfaces within either pixel.
Ballfield	~0.8	Pixel composition similar to Bandi Schaum (garden is on former baseball field)
Old First Ward	Between 0.5 and 0.6	Garden plots surrounded by grassy areas, small area of sidewalk and street included in the pixel. Area under cultivation is less extensive than Hurt Park and Frank Roupas.
Larimer Avenue, Esser Avenue, and Farmer's Garden Patch	~0.55	Corner lot, thus two sides are impervious surfaces (streets). Cultivated areas similar in size for all three gardens, but less than Hurt Park.
Serenity Garden	~0.5 to 0.55	While only one side is adjacent to a street, this garden is typified by many walking paths

The table in Appendix A (available online with this article) provides a comparison of NDVI values for specific dates. In most instances, we were able to identify one date per month during the growing season (May–September) when a Landsat scene was acquired in years both before and after cultivation. In a few instances, we identified three scenes for one date. In others, we were unable to identify scenes from two different years acquired on the same date, but we were able to identify scenes taken on contiguous dates in different years (e.g., Bandi Schaum– 23 and 24 May; Ballfield– 15 and 16 July; and Serenity, Esser, and Farmer's Garden Patch– 18 and 19 May). For most gardens, acquisitions on the same date (or the very next day) of the growing season, show that NDVI was higher after cultivation than before cultivation. For six of the ten community gardens,

in May, NDVI was lower after establishment than before, but this effect is likely related to gardeners' turning of soils at the beginning of the planting process.

CONCLUSIONS

NDVIs for all gardens were extremely variable throughout the growing season. In rural agriculture, NDVI normally peaks once during a growing season because pixels typically represent large, homogenous fields. Urban agriculture, specifically the community gardens in this study, consists of many different species of plants cultivated within the same location and (for this study) within a single Landsat pixel. Different crops sprout, mature, and are harvested variably within a growing
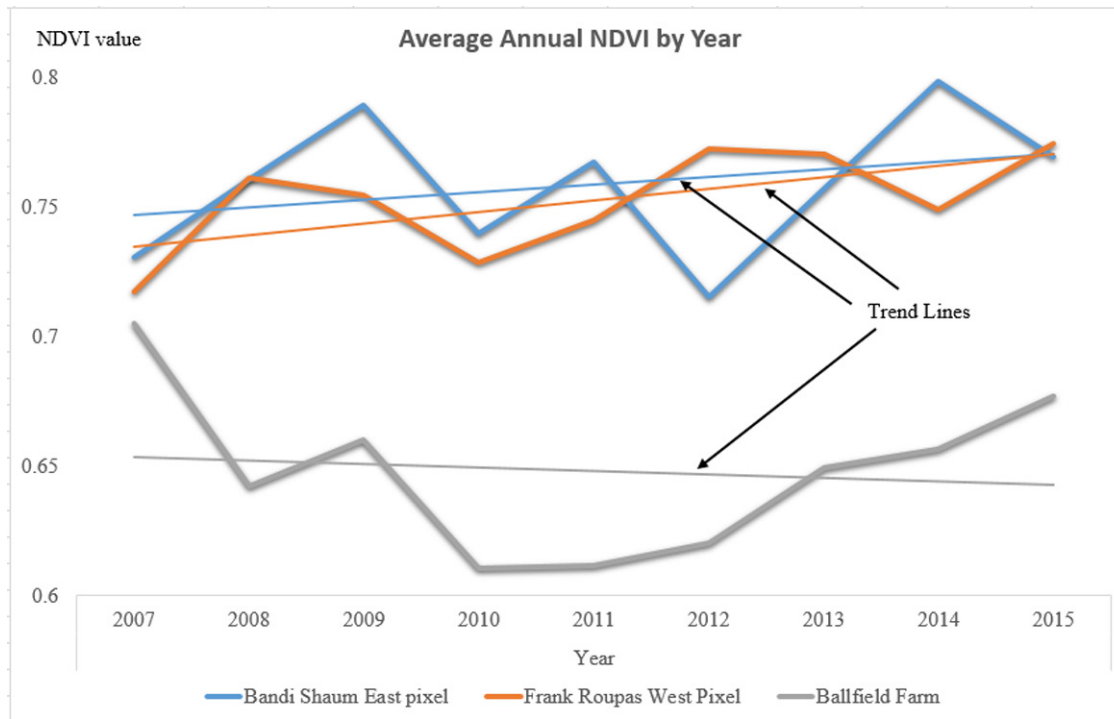
Fig. 9. Average annual Normalized Difference Vegetation Index (NDVI) for 2007 through 2015, Frank Roupas Community Garden west pixel (est. 2009), Roanoke, VA; and Bandi Schaum east pixel (est. 2012) and Ballfield Farm (est. 2008) in Pittsburgh, PA.
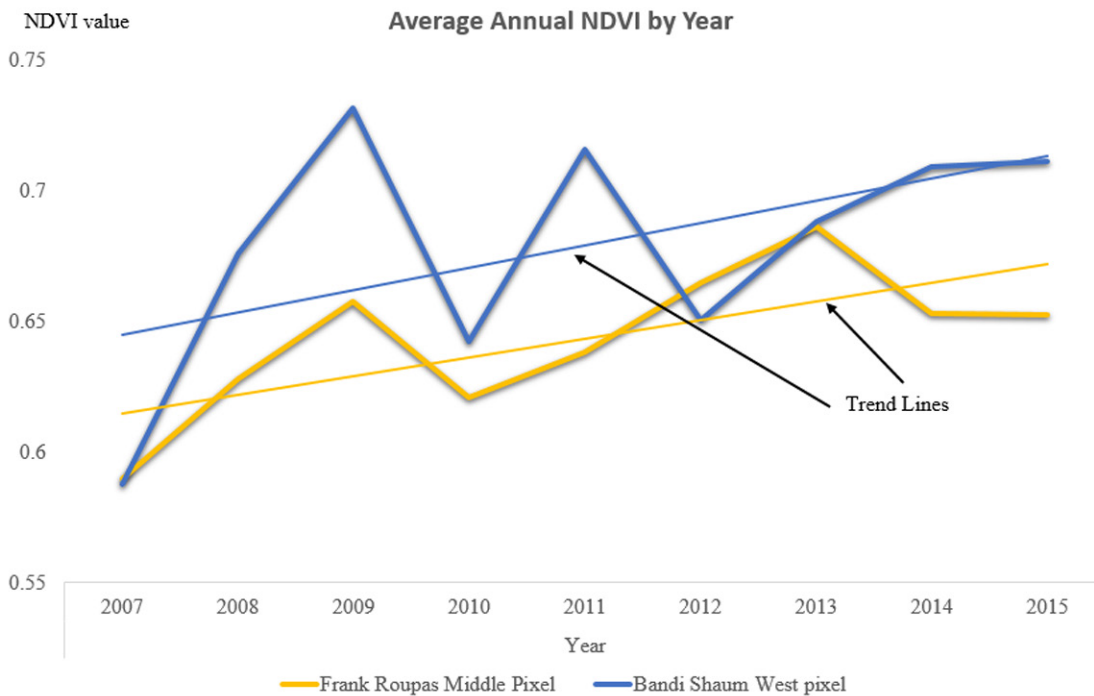

Fig. 10. Average annual Normalized Difference Vegetation Index (NDVI) for 2007 through 2015, Frank Roupas Community Garden middle pixel (est. 2009), Roanoke, VA, and Bandi Schaum west pixel (est. 2012), Pittsburgh, PA.

season, thereby creating highly variable NDVI profiles. For all of our NDVI sequences, community gardens were located within highly variable landscapes immediately surrounding the garden. Those community gardens adjacent to impervious surfaces had NDVI values significantly lower than those areas adjacent to non-agricultural green spaces (e.g.,

Frank Roupas community garden, Ballfield Farm, and Bandi Schaum garden).

Our NDVI graphs are consistent with NDVI graphs of mixed agriculture collected over large expanses (e.g., Justice et al., 1985). Although our peak NDVI values vary, each community garden has an individual story related
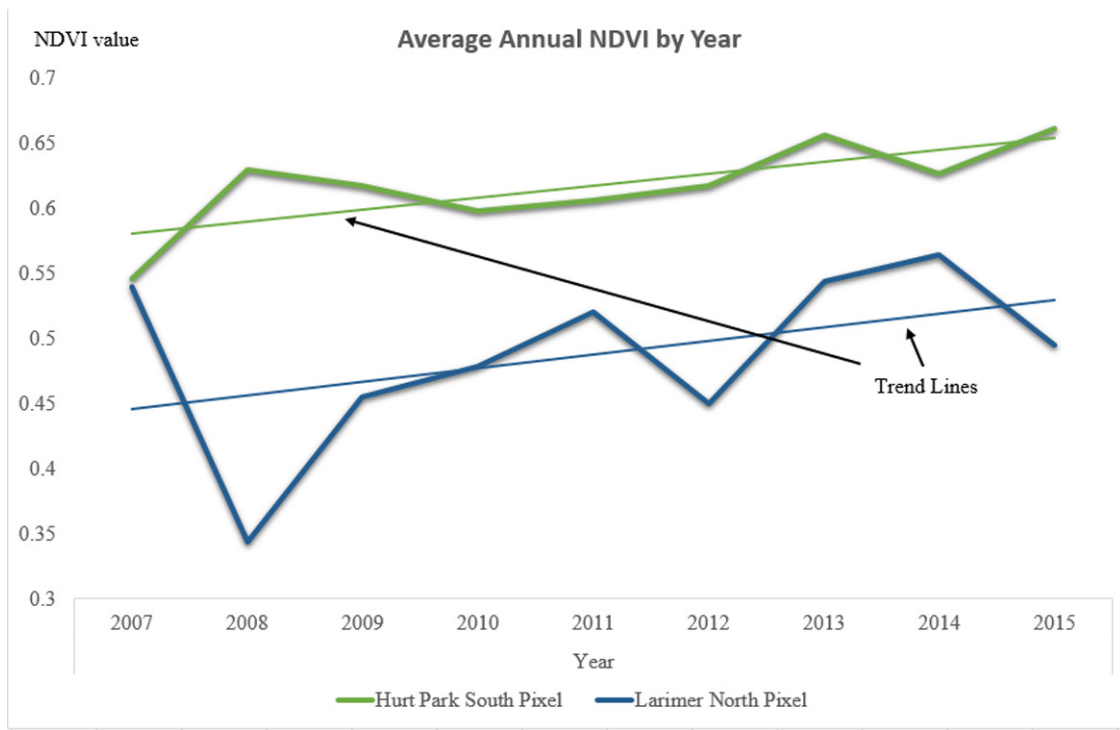
Fig. 11. Average annual Normalized Difference Vegetation Index (NDVI) for 2007 through 2015, Hurt Park Community Garden south pixel (est. 2012), Roanoke, VA, and Larimer Community Garden north pixel (est. 2010), Pittsburgh, PA.
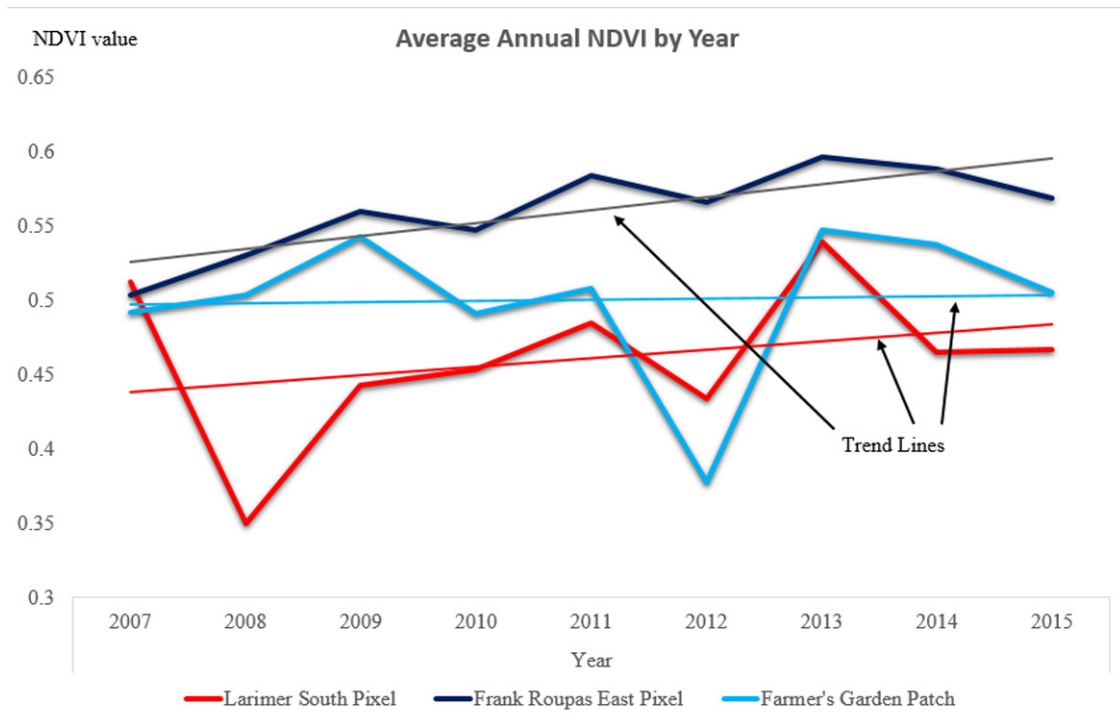

Fig. 12. Average annual Normalized Difference Vegetation Index (NDVI) for 2007 through 2015, Larimer Community Garden south pixel (est. 2010), Pittsburgh, PA; Frank Roupas Community Garden east pixel (est. 2009), Roanoke, VA; and Farmer's Garden Patch (est. 2012), Buffalo, NY.

to its location, plant species, adjacent landscape variables, and (although not examined within this study), regarding thepatrons of the specific gardens and the plants that they choose to cultivate. As we continue to analyze urban agriculture's NDVI signatures– including subsequent years in the gardens examined herein, other urban areas, and NDVI for urban farms–we will be able to more specifically identify distinctive NDVI sequence patterns and use NDVI analyses to identify urban agriculture locations and their contributions to urban greening efforts.
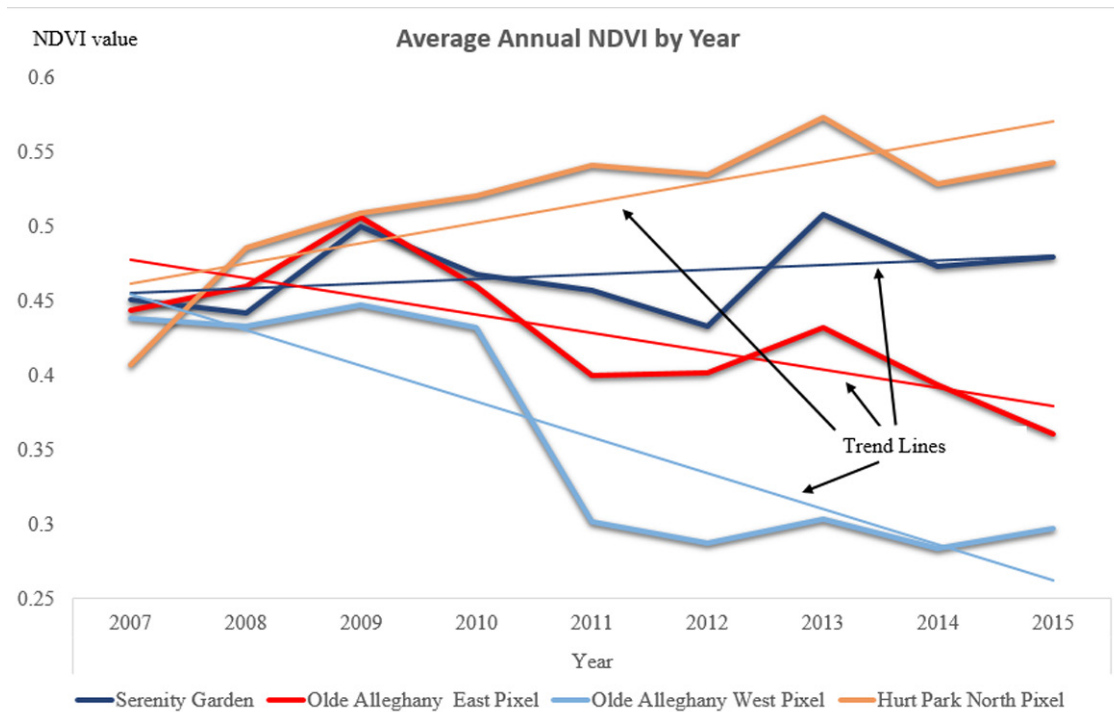
Fig. 13. Average annual Normalized Difference Vegetation Index (NDVI) for 2007 through 2015, Serenity Garden (est. 2011), Buffalo, NY; Olde Alleghany Community Garden both pixels (est. 1982), Pittsburg, PA; and Hurt Park Community Garden north pixel (est. 2012), Roanoke, VA.
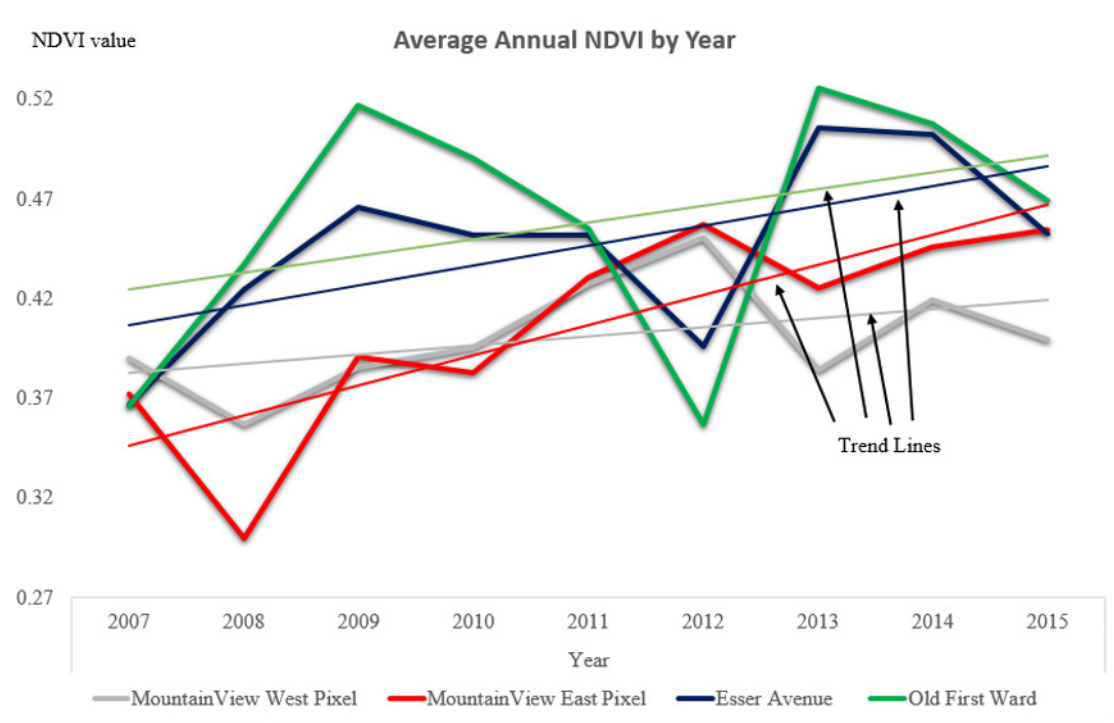

Fig. 14. Average annual Normalized Difference Vegetation Index (NDVI) for 2007 through 2015, MountainView Community Garden both pixels (est. 2013), Roanoke, VA, and Old First Ward (est. 2012) and Esser Avenue Community Gardens (est. 2013), Buffalo, NY.

Although NDVI can vary from year to year in response to temperature and precipitation differences, our data covered multiple years after cultivation for most of our gardens, which was sufficient to demonstrate that average annual NDVI was higher after cultivation than before. Even though some locales experienced a drop in NDVI after initiation of cultivation, average annual NDVI thereafter increased. Because NDVI and fAPAR have a positive relationship, our analysis demonstrates

these community gardens provide positive contributions to urban net primary production. Increases in net primary production reflect a healthier and more vital ecosystem.

This study has outlined a strategy for interpreting NDVI responses of urban agricultural activities as captured by satellite imagery. Such a capability offers opportunities both for local governments and community programs promoting and managing local community gardening activities. The ability to interpret NDVI in urban settings provides the opportunity to develop tools supporting analyses that can address questions or problems specific to individual communities or organizations. Local governments, who may have interests beyond the community gardens discussed here, may find the ability to observe net primary production in a broader context (beyond community gardens), such as monitoring green-up projects across cities; assessing effectiveness of projects in progress; identifying areas that are effective in supporting or buffering greenways, parks, or riparian buffers from neighboring heat island effects; and identifying locations that would benefit from such projects. For community organizations such as neighborhood associations and community gardening associations, the ability to monitor net primary production seasonally, or annually, can become a management tool to better understand responses to weather and climate, changes in crops and/or cultivation practices, and to identify unused sites that might be used for development of new community gardens.

With the methodologies outlined here, local organizations can examine Landsat satellite imagery, freely available to the public without special equipment or training, with online resources readily accessible, and tutorials available at minimal cost. Therefore, few obstacles exist for implementation of the strategies outlined here, and, likely, many opportunities in fact exist to refine and expand particle applications once others have the opportunity to experiment from the very basic ideas suggested here.

Looking forward, the context for these procedures will favor their use, through acquisition of NDVI data at shorter intervals, and at finer detail. At present, the European Space Agency satellite Sentinel-2A acquires imagery comparable to USGS Landsat imagery, but with characteristics that enhance effectiveness for NDVI monitoring. Sentinel-2A, launched in 2015, attained operational status in mid-2016 (too recent to provide an archive sufficient for application of this procedure). An identical satellite, Sentinel-2B, launched in March 2017, follows an orbital track offset to offer repeat coverage of a given site every 5 d (assuming cloud-free conditions). Sentinel's sensors view the same spectral regions as does Landsat, but at finer spectral and spatial detail, so can provide the basis for calculation of NDVI. This improved capability, together with the Sentinel system's 5-d revisit capability, will greatly improve the ability to observe NDVI. Sentinel's data distribution polices, like Landsat's, provide for open distribution of imagery, so these data are also available to the public without cost. Therefore, urban planners interested in applications of NDVI will find continuing, and improved, access to data to calculate NDVI at finer detail, and at more frequent intervals. These circumstances provide a context enabling a broad range of organizations and individuals to apply, and to evaluate, methods outlined here in a wide variety of locations and circumstances.

Conflict of Interest Disclosure

The authors declare there to be no conflict of interest.

References

Adam-Bradford, A. 2006. Container composting in peri-urban Kumasi, Ghana. In: R. Van Veenhuizen, editor, Cities farming for the future: Urban agriculture for green and productive cities. RUAF, Ottawa, Canada. p. 234–237.

Agustina, I., and R. Beilin. 2012. Community gardens: Space for interactions and adaptations. Proc. Soc. Behav. Sci. 36(0):439–448. doi:10.1016/j.sbspro.2012.03.048

Aitkenhead-Peterson, J.A., M.K. Steele, and A. Volder. 2010. Services in natural and human dominated ecosystems. In: J. Aitkenhead-Peterson and A. Volder, editors, Urban ecosystem ecology. Vol. 55. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI. p. 373–390.

Alaimo, K., E. Packnett, R.A. Miles, and D.J. Kruger. 2008. Fruit and vegetable intake among urban community gardeners. J. Nutr. Educ. Behav. 40(2):94–101. doi:10.1016/j.jneb.2006.12.003

Albright, L. 2013. Peri-urban horizontal greenhouses. Resour. 20(2):6.

As-syakur, A.R., T. Osawa, and I.W.S. Adnyana. 2010. Medium spatial resolution satellite imagery to estimate gross primary production in an urban area. Remote Sens. 2:1496–1507.

Bolund, P., and S. Hunhammar. 1999. Ecosystem services in urban areas. Ecol. Econ. 29:293–301.

Cohen, N., and K. Reynolds. 2015. Resource needs for a socially just and sustainable urban agriculture system: Lessons from New York City. Renew. Agric. Food Syst. 30(01):103–114. doi:10.1017/S1742170514000210

Davies, Z.G., J.L. Edmondson, A. Heinemeyer, J.R. Leake, and K.J. Gaston. 2011. Mapping an urban ecosystem service: Quantifying above-ground carbon storage at a city-wide scale. J. Appl. Ecol. 48(5):1125–1134. doi:10.1111/j.1365–2664.2011.02021.x

Deelstra, T., and H. Girardet. 2000. Urban agriculture and sustainable cities. In: N. Bakker, M. Dubbeling, S. Gündel, U. Sabel-Koschela, and H. deZeeuw, editors, Growing cities, growing food: Urban agriculture on the policy agenda. Deutsche Stiftung für

Internationale Entwicklung Feldafing, Germany. p. 43–66.

Department of Interior (DOI). 2015. Product Guide Landsat 4–7 Climate Data Record (CDR) Surface Reflectance. Version 6.0. http://landsat.usgs.gov/CDR_LSR.php (accessed 25 Apr. 2017).

Doron, G. 2005. Urban agriculture: Small, medium, large. Archit. Design 75(3):52–59.

Drescher, A.W., R.J. Holmer, and D.L. Iaquinta. 2006. Urban homegardens and allotment gardens for sustainable livelihoods: Management strategies and institutional environments. In: B.M. Kumar and P.K.R. Nair, editors, Tropical homegardens: A time-tested example of sustainable agroforestry. Springer, The Netherlands. p. 317–338.

Dunlap, R., J. Harmon, and G. Kyle. 2013. Growing in place: The interplay of urban agriculture and place sentiment. Leisure/Loisir 37(4):397–414. doi:10.1080/14927713.2014.906173.

Environmental Systems Research Institute. 2015. ArcMap version 10.2. ESRI, Redlands, CA.

Eriksen-Hamel, N.S., and G. Danso. 2009. Urban compost: A socio-economic and agronomic evaluation in Kumasi, Ghana. In: M. Redwood, editor, Agriculture in urban planning: Generating livelihoods and food security. Earthscan, Ottawa, Canada. p. 35–48.

Faruqui, N. 2002. Greywater reuse in urban agriculture for poverty alleviation: A case study in Jordan. Water Int. 27(3):387–394.

Gittleman, M., K. Jordan, and E. Brelsford. 2012. Using citizen science to quantify community garden crop yields. Cities Environ. 5(1):4.

Gliessman, S.R. 1980. Multiple cropping systems: A basis for developing an alternative agriculture. Paper presented at the Workshop on Innovative Biological Technologies for Lesser Developed Countries, Washington, DC.

Hardman, M., and P.J. Larkham. 2014. Informal urban agriculture: The secret lives of guerrilla gardeners. In C. Aubry, E. Duchemin, J. Nasr, editors, Vol. 1, Urban agriculture. Springer, London.

Hardoy, J., and R. Ruete. 2013. Incorporating climate change adaptation into planning for a liveable city in Rosario, Argentina. Environ. Urban. 25:339–360.

Hirschman, D., and J. Battiata. 2016. Urban stormwater management: Evolution of process and technology. In: T. Younos, T.E. Parece, editors, Sustainable water management in urban environments. Book Series: The Handbook of Environmental Chemistry, Volume 47. Springer, Switzerland. p. 83–120.

Huang, D., and M. Drescher. 2015. Urban crops and livestock: The experiences, challenges, and opportunities of planning for urban agriculture in two Canadian provinces. Land Use Policy 42:1–14.

Huete, A., C. Justice, and H. Liu. 1994. Development of vegetation and soil indices for MODIS-EOS. Remote Sens. Environ. 9:224–234.

Imhoff, M.L., L. Bounoua, R. DeFries, W.T. Lawrence, D. Stutzer, C.J. Tucker, and T. Ricketts. 2004. The consequences of urban land transformation on net primary productivity in the United States. Remote Sens. Environ. 89(4):434–443. doi:10.1016/j.rse.2003.10.015

Justice, C.O., J.R.G. Townshend, B.N. Holben, and C.J. Tucker. 1985. Analysis of the phenology of global vegetation using meteorological satellite data. Int. J. Remote Sens. 6(8):1271–1318. doi:10.1080/01431168508948281

Kihila, J., K.M. Mtei, and K.N. Njau. 2014. Wastewater treatment for reuse in urban agriculture: The case of Moshi municipality, Tanzania. Phys. Chem. Earth, PT. A/B/C 72–75:104–110.

Kulak, M., A. Graves, and J. Chatterton. 2013. Reducing greenhouse gas emissions with urban agriculture: A life cycle assessment perspective. Landsc. Urban Plan. 111:68–78.

Lawson, L.J. 2005. City bountiful: A century of community gardening

in America. University of California Press, Berkeley, CA, USA.

Li, L., L. Weller, Y. Tao, and Z. Yu. 2013. Eco-vegetation construction of the community gardens in US and its implications. Asian Agric. Res. 5(7):92–96.

Lincoln Institute of Land Policy. 2015. Atlas of urban expansion. http://www.lincolninst.edu/subcenters/atlas-urban-expansion/. Lincoln Institute of Land Policy, Cambridge, MA, USA.

Makoni, F.S.N. 2014. Characterisation of treated domestic wastewater and its potential use for small scale urban agriculture in Bulawayo: Balancing health and environmental needs. (Philosophiae Doctor), Univ. of the Free State, Bloemfontien, South Africa.

Matsuo, E. 2000. Japanese perspectives of allotment and community gardens. Acta Horticulture, International Society for Horticulture Science. XXV International Horticulture Conference Part 13:143–148. http://wwwlib.teiep.gr/images/stories/acta/Acta%20523/523_19.pdf (accessed 26 Apr. 2017).

McClintock, N., and M. Simpson. 2014. A survey of urban agriculture organizations and businesses in the US and Canada: Preliminary results. Urban Studies and Planning Faculty Publications and Presentations, Portland State University. http://archives.pdx.edu/ds/psu/12615 (accessed 26 Apr. 2017).

Milesi, C., C.D. Elvidge, R.R. Nemani, and S.W. Running. 2003. Assessing the impact of urban land development on net primary productivity in the southeastern United States. Remote Sens. Environ. 86:401–441.

Millennium Ecosystem Assessment. 2005. Island Press, Washington, DC.

Mishra, N., M.O. Haque, L. Leigh, D. Aaron, D. Helder, and B. Markham. 2014. Radiometric cross calibration of Landsat 8 Operational Land Imager (OLI) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+). Remote Sens. 6:12619–12638. doi:10.3390/rs61212619

Mougeot, L.J.A. 2000. Urban agriculture: Definition, presence, potentials and risks. In N. Bakker, M. Dubbeling, S. Gündel, U. Sabel-Koschela, and H. deZeeuw, editors, Growing cities, growing food: Urban agriculture on the policy agenda. Deutsche Stiftung für Internationale Entwicklung Feldafing, Germany. p. 1–42.

Myneni, R.B., and D.L. Williams. 1994. On the relationship between FAPAR and NDVI. Remote Sens. Environ. 49(3):200–211. doi:10.1016/0034–4257(94)90016–7

Njenga, M., and N. Karanja. 2006. Community-based composting production for urban agriculture in Nairobi. In: R. Van Veenhuizen, editor, Cities farming for the future: Urban agriculture for green and productive cities. RUAF, Ottawa, Canada. p. 238–242.

Odum, E.P. 1969. The strategy of ecosystem development: An understanding of ecological succession provides a basis for resolving man's conflict with nature. Sci. 164(3877):262–270.

Parece, T.E., M. Lumpkin, and J.B. Campbell. 2016. Irrigating urban agriculture with harvested rainwater: Case study in Roanoke, Virginia, USA. In: T. Younos, T. E. Parece, editors, Sustainable Water Management in Urban Environments. Book Series: The Handbook of Environmental Chemistry, Vol. 47. Springer, Switzerland. p. 235–264.

Petts, J. 2001. Urban agriculture in London. WHO, Copehagen, Denmark.

Pickett, S.T.A., M.L. Cadenasso, J.M. Grove, C.H. Nilon, R.V. Pouyat, W.C. Zipperer, and R. Costanza. 2001. Urban ecological systems: Linking terrestrial ecological, physical, and socioeconomic components of metropolitan areas. Annu. Rev. Ecol. Syst. 32:127–157.

Pourias, J., E. Duchemin, and C. Aubry. 2015. Products from urban collective gardens: Food for thought or for consumption? Insights from Paris and Montreal. J. Agric. Food Syst. Community Dev. 5(2):1–25. doi:10.1007/s10460–015–9606-y

Propersi, P.S. 2009. The health impacts of farming on producers in Rosario, Argentina. In: M. Redwood, editor, Agriculture in urban planning: Generating livelihoods and food security. Earthscan, Ottawa, Canada. p. 167–180.

Redwood, M., M. Bouraoui, and B. Houmane. 2014. Rainwater and greywater harvesting for urban food security in La Soukra, Tunisia. Int. J. Water Resour. Dev. 30(2):293–307.

Rojas-Valencia, M.N., M.T. Orta de Velásquez, and V. Franco. 2011. Urban agriculture, using sustainable practices that involve the reuse of wastewater and solid waste. Agric. Water Manage. 98:1388–1394.

Saldivar-Tanaka, L., and M.E. Krasny. 2004. Culturing community development, neighborhood open space, and agriculture: The case of Latino community gardens in New York City. Agric. Human Values 21:399–412.

Smit, J., and J. Nasr. 1992. Urban agriculture for sustainable cities: Using wastes and idle land and water bodies as resources. Environ. Urban. 4:141–152.

Smit, J., J. Nasr, and A. Ratta. 2001. Urban agriculture: Food, jobs and sustainable cities. Publication Series for Habitat II. United Nations Publications.

Sotamenou, J., and L. Parrot. 2013. Sustainable urban agriculture and the adoption of composts in Cameroon. Int. J. Agric. Sustain. 11(3):282–295. doi:10.1080/14735903.2013.811858

Steven, M.D., T.J. Malthus, F. Baret, H. Xu, and M.J. Chopping. 2003. Intercalibration of vegetation indices from different sensor systems. Remote Sens. Environ. 88:412–422.

Taylor, J.R., and S.T. Lovell. 2015. Urban home gardens in the global north: A mixed methods study of ethnic and migrant home gardens in Chicago, IL. Renew. Agric. Food Syst. 30(01):22–32. doi:10.1017/S1742170514000180

Teillet, P.M., J.L. Barker, B.L. Markham, R.R. Irish, and G. Fedosejevs. 2001. Radiometric cross-calibration of the Landsat-7 ETM+ and Landsat TM Sensors Based on Tandem Data Sets. NASA Publications 13. http://digitalcommons.unl.edu/nasapub/13 (accessed 26 Apr. 2017).

Tucker, C.J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8:127–150.

USGS. 2015. Landsat Enhanced Thematic Mapper Plus (ETM+). U.S. Geological Survey. https://lta.cr.usgs.gov/LETMP (accessed 26 Apr. 2017).

USGS. 2016a. Frequently asked questions about the Landsat missions. U.S. Geological Survey. http://landsat.usgs.gov/band_designations_landsat_satellites.php (accessed 26 Apr. 2017).

USGS. 2016b. Landsat missions. U.S. Geological Survey. http://landsat.usgs.gov/ (accessed 26 Apr. 2017).

United Nations. 2014. World urbanization prospects: The 2014 revision. Dep. of Economic and Social Affairs, Population Division, New York.

Weng, Q. 2012. Remote sensing of impervious surfaces in the urban areas: Requirements, methods, and trends. Remote Sens. Environ. 117:34–49.

World Bank. 2013. Urban agriculture: Findings from four city case studies. The World Bank, Washington, DC.

Wu, J., and M.E. Bauer. 2012. Estimating net primary production of turfgrass in an urban-suburban landscape with QuickBird imagery. Remote Sens. 4:849–866. doi:10.3390/rs4040849

Yadav, P., K. Duckworth, and P.S. Grewal. 2012. Habitat structure influences below ground biocontrol services: A Comparison Between Urban Gardens and Vacant Lots. Landsc. Urban Plan. 104(2):238–244. doi:10.1016/j.landurbplan.2011.10.018