Geospatial Analysis to Site Urban Agriculture

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Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
Geospatial and Environmental Analysis

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Feb. 18, 2016
Blacksburg, Virginia

Keywords: urban agriculture, geospatial technologies, food insecurity, ecosystem services, impervious surfaces, urban microclimates, urban catchments, Roanoke, Virginia

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SCIENTIFIC ABSTRACT

The rapid expansion of urban systems in both area and population represents the most significant landuse/landcover change occurring in the world today. Urbanization is often accompanied by increasing environmental degradation. This degradation is related to stormwater runoff, air temperatures greater than surrounding rural areas, increased air and water pollution, losses of vegetated lands, and lack of access to sufficient and healthy foods in lower-income areas. Urban agriculture (UA), a practice long established in previous eras but neglected for many decades, can mediate such concerns by providing greenspaces to improve ecosystem services. Successful practice of UA requires recognition of interactions between social and environmental patterns. Neglect of these interactions leads to failure in spatially integrating social and environmental dimensions of the urban landscape, limiting the success of UA. This study investigates siting of UA within Roanoke, Virginia, a compact urban region characterized by social and environmental conditions that can be addressed by effective siting and practice of UA.

This research takes a broader perspective than prior studies on UA and urban greenspaces. It proposes innovative applications of geospatial technologies for urban assessment. Studies on UA have typically focused on food insecurity, while studies on greenspaces focus on parks and tree canopy cover, without investigating interactions that promote synergies between these two efforts. Research over the past few years is now recognizing potential contributions for urban agriculture to alleviate environmental issues such as stormwater runoff, soil infertility, and the urban heat island effect. Little of this research has been devoted to the actual siting of urban agriculture to specifically alleviate both socio-economic and environmental issues. This research applies geospatial technologies to evaluate spatial patterns characterizing both environmental and socio-economic disparities within the City of Roanoke, Virginia. This approach has identified specific locations that are open and available for urban agriculture, and has appraised varying levels of socio-economic and environmental parameters. This research identified, at the census block group level, areas with varying levels of degradation. Thus, those locations in which a new urban agriculture greenspace can contribute to both socio-economic and environmental reparation. This research has identified spatial dimensions in which UA will assist in restoring ecosystem services to guide various food production activities. These results can be generalized to other urban locations and contribute to efficient use of urban land and space, improving the three pillars of worldwide sustainability – economic, environment, and social.

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GENERAL ABSTRACT

This research evaluated physical and socio-economic conditions within the City of Roanoke Virginia to identify locations that would best be served by new greenspaces – specifically urban agriculture. Firstly, this research analyzed physical dimensions of the city – extent of man-made impervious surfaces, urban-impacted soils and tree canopy cover, current locations of parks, home gardens, community gardens and urban farms, and areas of warmer temperatures. This physical assessment outlined the setting that would most benefit from new greenspaces and assist in mitigation of adverse environmental effects from urbanization. Secondly, this research analyzed socio-economic variables – poverty rates, locations offering healthy and nutritious food options, areas lacking greenspaces for recreation and exercise, and those areas with greatest exposure to poor health conditions. This assessment identified those locations that would benefit, socio-economically, from addition of new urban agriculture greenspaces. The third and final analysis intersected the first two assessments to identify those locations that could address both poor physical and socio-economic conditions. The third analysis included an evaluation of the environmental and socio-economic changes that might occur from the addition of urban agriculture –1) reduction in stormwater runoff, energy usage and greenhouse gas emissions from rainwater harvesting, 2) increases in social and community building, 3) improvements in soils and net primary production; and 4) increased access to fresh and nutritious fruits and vegetables from locally produced food.

Acknowledgements

I thank the following organizations and individuals for contributing to my research. Without their assistance, I would not have been able to complete this complex urban analysis.

Funding Agencies: This research was financially supported by the Virginia Chapter of the American Water Works Association Scholarship (2012), the Virginia Chapter of the Water Environment Federation Sonny Roden Memorial Scholarship (2012),Virginia Tech's Graduate Student Assembly's Graduate Research Development Program Grant (2012), Sidman P. Poole Endowment for Research in Geography at Virginia Tech (2013), the Sigma Xi Graduate Award for Doctoral Degree Students (2013-2014), U.S. Geospatial Intelligence Foundation Doctoral Scholarship (2013), Cabell Brand Center First Freedom Scholarship (2013), U.S. Environmental Protection Agency STAR Fellowship (2014 – 2016), Virginia Space Grant Consortium 2014 – 2015 Graduate Research Fellowship, Virginia Space Grant Consortium 2015 – 2016 Graduate Research Fellowship, and American Society for Photogrammetry and Remote Sensing - Paul R. Wolf Memorial Scholarship (2014).

Institutional Review Board (IRB): #13-106 – for the food desert evaluation and #14-001 for the on-line survey of U.S. community gardeners.

My lab and field assistants: Thank you to every person who assisted me in data collection and analysis, without you, the details provided in my research would not have been accomplished in a timely manner. Sam Weber assisted me with generating random points and my reference data set used in accuracy assessments. Those who assisted with field temperature collection include Mesonet Drivers: Sam Freeman, Mario Garza, Chris White, Dr. Mike Hyer, Dave Carroll, Paul Miller, Hans VanBenschoten, Eric Guenther, Stewart Scales, Anthony

Phillips, Sarah Phillips, Dr. Emily Smith-McKenna, Adam Oliphant; Mesonet Helpers – Thomas Tutchings, Ash Elmelick, and Erika Cropp. Meteorology students who assisted with software installation for the fixed weather stations installed in the Roanoke City Public Schools are Bonnie Long, Michael Marston, Mario Garza, Paul Miller, Anthony Phillips and R.J. McNally. In-situ food desert data collection completed in 2013 and 2014 was accomplished by Amal Almohanna, Georgianna Mann, Alisha Farris, Lindsey Kummer, Sarah Misyak, and Melody Bowen. Phenological observations from February through May 2014 were conducted by Richard Kelly with Roanoke Valley Master Naturalists; Shannon Ritter with New River Valley Master Naturalists; Clark BeCraft and Lauran Beltran from Virginia Western Community College; Roanoke Master Gardeners – Sharon Burnham, Jane Wallace and Ann Sauls; Roanoke Valley Master Naturalists – Diana Hackenburg, Sharon Vest, Laurie and Scott Spangler, Mary Harshfield, Pat Taylor; Roanoke Tree Steward – Lori Morrey; Roanoke Community Garden Member – Diana Kevorkian; private citizens - Jon Polk, Donna Haley, Scott Whitacker, Paul Finney; Roanoke City Public Schools' teachers – Mark Levy, Joanna Reese (and her students in the Addison Middle School Environmental Club), Melissa Martin, Steven Villers, Anna Delgado, Christine Neal, Claire Guzinski, Lissa Armentrout, and Matt Newton. Thank you to Virginia Tech Undergraduate students - Lynn Wormeli and Olivia Jancse, who downloaded and categorized weather data from Weather Underground and the mesonet units, researched data on community gardens, downloaded and organized the phenological field data, organized the food desert data, and downloaded multiple Landsat and MODIS images. My further thanks to Malayshia Lumpkin for her work on rainwater harvesting and RJ McNally for working with the Roanoke City Public Schools in using weather data in their school lessons.

Other Individuals: Thank you to Dr. Jie Li, Department of Statistics, identifying the best method to analyze the temperature data. Thanks to Dr. Yang Shao for promoting use of undergraduate research assistants, and assisting me with MatLab and ENVI; Dave Carroll and Dr. Andrew Ellis for their recommendations on appropriate dates for using the mobile mesonet units and advice on the appropriate weather stations to purchase for Roanoke City Public Schools; Robin Reed and Brent Watts at WDBJ, CBS Channel 6 in Roanoke for their advice on working with the Roanoke City Public Schools; Thomas Fitzpatrick, Science Coordinator at the Roanoke City Public Schools for his support on purchasing and installing fixed weather stations for the city schools and promoting the phenological field data collection in the spring of 2014, and the many teachers, administrators, principals, and secretaries at individual schools who accommodated our many visits to trouble shoot the weather station software. Thank you to Nathan Kinzie and James Crawford of the Roanoke Cooperative Foods Association and Mark Powell and David Maxey of the Roanoke Community Garden Association for supporting my research and being accessible for my repeated questions on their associations and food production and visits to garden sites. Thank you to Frederick Williams, owner of Lick Run Urban Farm for answering my many questions on the operations of his farm. Thank you to Maureen Deisinger, Department of Geography, for her advice on identifying the best individuals as research assistants for different aspects of my research. Thank you to Karen Bland, Department of Geography, for managing and keeping track of my grant funds. In addition, thank you to the many City of Roanoke officials for talking with me about my research and providing data to be used in my analysis - David Deering - City Engineer, Chris Chittum - Planning, Building and Development, Dan Henry – Urban Forester, Tracey Leet – GIS Specialist. And thank you to Les Fuller, CNRE IT, for supporting my computer and software needs.

Last but most important - my committee: Many thanks to James B. Campbell, my committee chair, for his support and availability for long discussions on my dissertation research and the numerous letters of recommendations in my search for funding. Thank you to Elena Serrano for assisting in providing research assistants for my food desert data collection and her advice in developing my social analysis. Thank you to John McGee for his support during my research and promoting my outreach activities, and to Steven Hodges for keeping me on track when evaluating ecosystem services. Furthermore, I would like to thank all of my committee members, along with Dr. Lynn Resler and Dr. Bill Carstensen, for providing me with recommendation letters.

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1 Chapter - Introduction, Statement of Purpose, Dissertation Outline, and Literature Review

1.1 Introduction

Urbanization is arguably the most significant landuse/landcover trends occurring in the world today (Deelstra and Girardet 2000, Pickett et al. 2001). Although urban expansion is often attributed to increasing populations, rates of conversion to urban land uses exceed rates of urban population increases (Lincoln Land Institute 2015). Prevalent issues accompanying urban expansion are food insecurity for low income residents, increasing environmental degradation, conversion of vegetated land to urban land, and in some areas of the developed world (e.g., the United States) increasing numbers of vacant properties in inner cities.

Urban environments offer unique challenges that conventional analyses cannot address, including disrupted anthropocentric ecosystems, complicated by interactions between humans, nature, and the physical and built environments (Pickett et al. 2001). Understanding these interactions is vital for developing solutions to environmental, social, and economic problems prevalent in existing and expanding urban areas.

Urban agriculture, through its varied manifestations, can offer multiple dimensional solutions -- it can improve access to healthy and nutritious fresh food, revitalize inner cities, promote social interactions, improve urban hydrology, and mitigate adverse climatic effects. However, siting of existing urban agriculture within the urban landscape has largely occurred through fortuitous availability of sites. Development of more systematic siting strategies could enhance optimization of benefits derived from urban agriculture.

This research applies geospatial analysis to provide more strategic placement of urban agriculture in its physical and social contexts. This complex task requires integrative approaches that can blend spatial and temporal perspectives, bringing socio-economic and environmental data together into a common analytical framework. Geospatial technologies provide powerful, and flexible, tools for assimilating diverse data and providing a spatial context for analysis at multiple scales and levels of detail, which can match to the challenges of urban analyses. Geospatial technologies are already established as tools for urban planners to evaluate changes in landuse, locate stormwater best management practices, and assess extent of urban tree canopies. As such, geospatial analyses provide structure for evaluating the urban landscape to strategically site urban agriculture, such that it can provide multi-dimensional benefits.

Some municipalities are beginning to use geospatial technologies to identify vacant public properties as potential locales for urban agricultural greenspaces. However, such applications have often focused on very specific, isolated, facets of the urban landscape, neglecting their potential to integrate the environmental, social, and economic dimensions of urban areas, to strategically site urban agriculture. Implementing an effective and integrative urban agriculture system based on geospatial analysis may alleviate urban environmental problems, and support solutions to long-term, persistent, food insecurity and malnutrition for the chronically hungry, many of whom now live in urban areas.

1.2 Statement of Purpose and Broad Significance of Research

This research applied geospatial technologies to analyze existing data and to assimilate data acquired in the field and via remote sensing analyses. This research ultimately defined a hierarchy of locations, suitable for agricultural production, which will help improve urban ecosystem services. This hierarchy included multiple components. First, it identified locations that can accommodate agricultural production from the micro-scale to the macro-scale. Second, the hierarchy identified those locations where urban agriculture may alleviate (from optimal to negligible levels) urban environmental problems. Third, it identified locations (from optimal to negligible levels) where urban agriculture will contribute to the well-being (economic, social, and health) of low-income neighborhoods.

Specific objectives of this research included:

1) Investigation of spatial patterns of urban physical landscape, hydrology, and climates to identify locales where siting urban agriculture would help to alleviate environmental degradation;
2) Investigation of spatial dimensions of demographic characteristics of urban populations, to identify locations for urban agricultural production that can best contribute economic, social, and health benefits for low-income neighborhoods; and
3) Assimilation of the spatial dimensions developed in Objectives 1 and 2 through development of an integrative geospatial model.

Therefore, this study investigated key spatial characteristics of a city to define its physical and socio-economic dimensions and constraints that might define the spatial context to support the practice of urban agriculture.

Key outcomes of this study include: 1) identification of all open areas within a urban area that could accommodate urban agriculture; 2) identification of areas where special care is required for selection of plant form and species; 3) spatial dimensions of urban microclimates; 4) calculation of reductions in stormwater runoff and greenhouse gas emissions provided by rainwater harvesting for irrigation, thus reducing the urban ecological footprint; 5) identification of strategies for applying geospatial data to examine many different parameters of urban assessment; 6) assessment of ecosystem services provided by urban agriculture; and 7) identification of locations for strategically siting urban agriculture within a specific city, to assist in alleviation of environmental, economic, social, and health issues faced by urban populations.

1.3 Dissertation Outline

The research was organized around the three objectives -- investigating the varied spatial characteristics of an urban area to define physical and social parameters that define the spatial context for practice of urban agriculture. The next section of this chapter reviews literature pertinent to urban research, urban agriculture, and geospatial analyses of urban greenspaces, to identify gaps in urban agriculture research and to present the rationale for selection of the study site, the City of Roanoke, Virginia.

Chapter 2 focuses upon Objective 1 -- assessing the significance of environmental conditions (temperature, hydrology, soils, and vacant lands) of the study site. This chapter reviews the literature pertinent to environmental aspects of urban agriculture, identifies the data used, discusses methodology for data created for these analyses, and reports results. The result has two hierarchal components – 1) locations for the different urban agriculture forms, including identification of areal extent, and 2) the locations with varying contributions to restoring ecosystem services and alleviation of urban environmental issues. This chapter includes references to original publications resulting from preparation for and conducting this research.

Chapter 3 addresses Objective 2 and analyzes the spatial dimensions of demographic and economic characteristics of an urban population, including income, education, food desert locations, employment status, and health data. This chapter reviews the literature pertinent to urban agriculture's contribution to the health and welfare of human populations, identifies the existing data used, discusses the methodology for the data created for this analysis, and provides the results. The result is a hierarchy of locations for urban agriculture that best contribute economic, social, and health benefits for low income neighborhoods. This chapter includes the reference to an original publication resulting from preparation for and conducting this research.

Chapter 4 considers the spatial dimensions of the first two objectives to identify relative environmental and socio-economic needs of locations (greatest to least) for new urban agriculture greenspaces. In addition, to confirm environmental, economic, social and health benefits derived by urban agriculture, the chapter provides ecosystem services evaluations for Roanoke and for additional U.S. urban agriculture sites. The evaluative methods, reported in original publications, are applicable to other cities.

Chapter 5 presents the conclusions, which identifies obstacles and barriers to urban agriculture's ability to address urban problems, and identifies avenues for future urban agriculture research. This chapter includes a discussion on community outreach projects developed during the course of this research.

1.4 Literature Review

1.4.1 Urban Expansion

The United Nations estimates the world's population will rise to 9.6 billion people by 2050 (United Nations 2015). In 2009, for the first time in history, the percent urban population exceeded 50% and is estimated to rise to 66% by 2050 (United Nations 2014). The proportion of people living in urban versus rural areas varies across the world – an average of 75% for developed countries and 45% for less developed countries. However, both are predicted to increase by 2050 (total in North America, Latin America and Europe of >80%, in Asia of 64%, and in Africa of 54%), with urban areas expected not only to form the center of natural population growth but also to increase in size because of rural to urban migration (United Nations 2014).

Humans have modified over 50% of the Earth's land surface (Hooke and Martin-Duque 2012), but landscape change due to accelerated urbanization is the fastest growing trend in the world (Lord, Strauss and Toffer 2003). Urban areas are increasing in size, with respect to both land area and human population (Deelstra and Girardet 2000, Pickett et al. 2001, Lincoln Land Institute 2015). In developing countries, urban land area increases are largely related to increasing populations. In many areas of the developed world, some urban areas are expanding because of population growth and expansion as people move to the urban fringes, and yet others are experiencing land abandonment in inner cities (Gallagher 2010). Regardless of reasons for these changes, the ultimate demographic and environmental effects across the world have similar impacts.

These effects include losses of vegetated lands, expansion of impervious surface cover, increasing demands on existing infrastructure, higher air temperatures as compared to adjacent rural areas (the urban heat island effect), and increasing demands on municipal services such as potable water and waste management (Pickett et al. 2001). Urban areas import food, energy, and clean water to meet the basic needs of their populations and export waste products, as such, adverse effects of urbanization extend well beyond political boundaries (Deelstra and Girardet 2000, Pickett et al. 2001, McGranahan and Satterthwaite 2003, Aitkenhead-Peterson, Steele and Volder 2010, Despommier 2010).

Many urban areas in the U.S. also experience property abandonment as people move to urban fringes and commercial enterprises relocate either out of the city or out of the country entirely. Certain urban locales, such as Detroit Michigan and Cleveland Ohio, have experienced abandonment rates that exceed the government's ability to administer abandoned properties, thereby accelerating degradation. Additionally, governments lose tax revenues and the ability to provide services to the rest of the community causes a feedback loop - more people leaving, more abandonment, increasing degradation (Armar-Klemesu 2000, Nordahl 2009, Gallagher 2010).

1.4.2 Health and Welfare of Urban Populations

Worldwide, one in nine people suffers from chronic malnutrition due to food insecurity (FAO, IFAD and WFP 2014). In the U.S., more than one in ten households suffers from food insecurity (Brown et al. 2002, Coleman-Jensen et al. 2014), and this rate increases to almost one in five (19.5%) in households with children (U.S.D.A. 2015). Low-income urban residents face many barriers in overcoming obstacles to food insecurity, thus their health and well-being is adversely affected (Power 1999, Brown et al. 2002). In addition, urban areas are characterized by internal structural and social differences that lead to variations in their abilities to support the health and environmental well-being of their citizens (Barton 2009).

With lower incomes, a greater portion of income is spent on food and housing and, in order to afford adequate food, it is necessary to buy less nutritious food (Brown et al. 2002). This dynamic manifests itself spatially because grocery stores and supermarkets locate in more affluent neighborhoods, creating food deserts (areas with limited access to affordable and nutritious foods) (Mougeot 1999, Brown et al. 2002, Rose and Richards 2004). In addition, food insecurity can be associated with health issues, such as higher rates of obesity (Robert and Reither 2004, Riva et al. 2009), some infectious diseases, as well as school and work absenteeism (Brown et al. 2002).

Urban populations also have greater exposure to heat-related illnesses, deaths, and infectious disease because of the urban heat island effect (Patz et al. 2005). Increased air pollution can also increase susceptibility to asthma and other respiratory illnesses, especially in children (Gern 2010, Malik, Kumar and Frieri 2012). These effects can be further exacerbated in lower-income populations who can ill afford increased energy costs, or have limited access to medical care (Malik et al. 2012).

1.4.3 Urban Sustainability and Greenspaces

Urban initiatives to reduce ecological footprints and move towards sustainability involve reducing energy use, decreasing pollution, and increasing greenspaces. A greenspace is defined as “land that is partly or completely covered with grass, trees, shrubs, or other vegetation” (U.S. EPA 2015). Greenspaces positively affect the health and welfare of both human and wildlife populations residing in urban areas (Wheater 1999, Nowak 2006, Beer 2010, Kuo 2010, Volder and Watson 2010). As an example, these positive benefits include:

- Generation of ecosystem services (Bolund and Hunhammar 1999, van Leeuwen, Nijkamp and de Noronha Vaz 2010);
- Maintaining and increasing biodiversity (Botkin and Beveridge 1997, Beer 2010, van Leeuwen et al. 2010);
- Reducing air pollution and increasing air circulation (Botkin and Beveridge 1997, Aitkenhead-Peterson and Volder 2010, Beer 2010, van Leeuwen et al. 2010);
- Reducing stormwater runoff, increasing groundwater recharge, and improving water quality (Botkin and Beveridge 1997, Aitkenhead-Peterson et al. 2010, Beer 2010, van Leeuwen et al. 2010);
- Reducing the urban heat island effect (Beer 2010, van Leeuwen et al. 2010);

- Generation of health benefits from environmental improvements but also from increased physical exercise and stress reduction (Beer 2010, Kuo 2010, van Leeuwen et al. 2010); and
- Increasing social interaction between urban residents (Beer 2010, Kuo 2010, van Leeuwen et al. 2010).

Expanding the urban tree canopy and incorporating green roofs on buildings are major foci of many urban sustainability plans.

1.4.4 Urban Agriculture is a Beneficial Greenspace

Within an urban area, a greenspace "functions as productive green areas that are able to deliver useful products (wood, fruits, compost, energy, etc.) as a result of urban green maintenance or construction" (van Leeuwen et al. 2010). Urban agriculture is "the growing, processing, and distribution of food and nonfood plant and tree crops and raising of livestock, directly for the urban market, both within and on the fringe of an urban area" (Mougeot 2006, p. 4). Urban agriculture is a productive use of green areas, but is rarely recognized for its potential environmental benefits and productive use of vacant urban lands (Bourque 2000, Kaufman and Bailkey 2000). Thus, incorporation into the urban planning process is still extremely limited (Hodgson, Campbell and Bailkey 2011, Pollans and Roberts 2014, Surls et al. 2015, Huang and Drescher 2015).

Because environmental benefits of urban agriculture are rarely acknowledged (Nordahl 2009, Iaquinta and Drescher 2010), they need further investigation (Wortman and Lovell 2014). In many situations, especially in distressed urban settings, urban agriculture does clearly provide benefits beyond those provided by other greenspaces, for example - contribution to food security through production of fresh and nutritious fruits and vegetables, economic opportunities from selling agricultural products or from releasing income which can be used elsewhere (Smit, Nasr and Ratta 2001, Bellows, Brown and Smit 2003), and a sense of place (Mok et al. 2014, White 2014).

Furthermore, although urban agricultural productivity is dependent upon the same variables as rural agriculture, i.e. soils, length of growing season, water availability, and insolation, studies have shown that urban agriculture's output is greater in pounds per unit area than rural agriculture (Wade 1987, Gittleman, Jordan and Brelsford 2012). Urban agriculture's higher production rates are related to more efficient use of space and water (e.g., horizontal and vertical spaces, smaller plots), shorter life cycle crops, and multi-cropping (Smit et al. 2001).

Urban agriculture is not a new phenomenon; agriculture has been practiced within urban areas since humans first established them (van Leeuwen et al. 2010). In the United States, its history exceeds 100 years (Lawson 2005), intensifying during periods of national crisis, such as both World Wars and the Great Depression (Deelstra and Girardet 2000, Nordahl 2009, Gallagher 2010, Iaquinta and Drescher 2010). Today, it is experiencing a revival because of current economic conditions, recognition of benefits of locally grown food, the ability to contribute to urban sustainability, and the potential to alleviate food insecurity in poor urban areas (Patel 1996, Nordahl 2009, Gallagher 2010).

Urban agriculture takes many forms, extending from containers on balconies and patios to urban farms (Pearson, Pearson and Pearson 2010). While the urban farm accounts for the greatest areal extent, the most common form of urban agriculture is the home garden (Smit et al. 2001). One popular form of urban agriculture is the community garden, which consists of an area of land divided into gardening plots shared by members of a community (Lawson 2005). With urban agriculture's recent resurgence, the number of community gardens in the developed world have increased dramatically (Table 1.1), and the concept is spreading to the developing world (Table 1.2).

Table 1.1. Community gardens in a selection of developed countries

Location	Estimated number	Source (website)
US and Canada	18,000	American Community Garden Association https://communitygarden.org/resources/faq/
Australia	579	Australian City Farms and Community Gardens Network http://directory.communitygarden.org.au/data
Japan	3,382	ShiftEast http://www.shifteast.com/city-farming-blooms-with-baby-boomers/
United Kingdom	>1,000	Federation of City Farms and Community Gardens https://www.farmgarden.org.uk/about-us

Table 1.2. Community garden websites for a selection of developing countries

Location	Organization (Website)
Africa	The Footprints Network (http://www.footprintsnetwork.org/project/68/Community-food-gardens-KwaZulu-Natal.aspx) Women International for a Common Future (http://www.wecf.eu/english/articles/2013/05/ewa_garden_blikkiesdorp.php) Slow Food Foundation for Biodiversity (http://www.slowfoodfoundation.com/pagine/eng/orti/cerca.lasso?-id_pg=265) Garden Africa (http://www.gardenafrica.org.uk/)
Indonesia	Islamic Relief Worldwide (http://www.islamic-relief.org/wells-latrines-and-community-gardens/)
Argentina	Agenda De Ideas: Huertas comunitarias en Rosario Argentina (https://republicavirtual.wordpress.com/2008/05/06/huertas-comunitarias-en-rosario-argentina/)
Perú	RUAF (http://www.ruaf.org/publications/community-gardens-villa-maria-del-triunfo-lima-peru-huertas-comunitarias-en-villa-maria)
Brazil	City Farmer (http://www.cityfarmer.info/2008/01/13/cities-without-hunger-community-gardens-sao-paulo-brazil/)
Haiti, Malawi, Kenya	Muse D.Territories: Développement local et RSE (http://www.musedt.com/lagriculture-urbaine-un-levier-de-developpement-pour-les-bidonvilles-du-sud/)

Ownership of the land, upon which urban agriculture is located, varies. For instance, community garden land is rarely owned by those gardening. Typically, it is owned by a variety of stakeholders – landlords, local, regional and federal governments, non-profit organizations, or churches – who have granted gardening access (frequently temporarily) to the community. The gardens, themselves, are run by non-profits or community organizations such as churches (Kaufman and Bailkey 2004, Iaquinta and Drescher 2010).

1.4.5 Urban Greenspace Geospatial Applications

In the past, locating urban greenspaces has occurred with a specific purpose in mind - a city park for recreational use, an abandoned parcel for the placement of a community garden, a green roof as an academic research project or the efforts of a corporation/municipality to mitigate energy costs of a building (Beer 2010). Some municipalities have used geospatial technologies to identify vacant public lands which might be suitable for urban agriculture (e.g., cities of Portland OR [2012] and Oakland, CA [2009]). Little attention has been devoted to optimally siting of urban agriculture spaces (Deelstra and Girardet 2000, Gallagher 2010) to maximize both environmental and socio-economic benefits.

In addition, the literature on geospatial analyses of urban greenspaces is limited, e.g., identification of existing greenspaces or expanding urban tree canopies (Table 1.3). One study did assess quality of life using greenspaces and socioeconomic variables. Another, and very comprehensive study, has incorporated environmental, health and economic variables in separate analyses, e.g., New York State Energy Research and Development Authority (2013). However, few have applied geospatial technologies in the urban agricultural context to realize their full analytical potential by exploiting the synergistic effects of employing all three tools, GPS, GIS and remote sensing, in a comprehensive and integrative analysis. This research incorporated all of these.

Table 1.3 A Selection of Geospatial Analyses of Urban Greenspaces

Topic	**Year and Author**
Identifying UA changes over time in developing countries	Rieley and Page (1995), Dongus and Drescher 2006, Omomoh and Adeofun (2005)
Urban tree canopy cover analyses	Dwyer and Miller (1999), McPherson et al. (2011), McGee III et al. (2012)
Use of Geospatial tools to evaluate peri-urban agricultural planning for market linkages in Hanoi, Vietnam	Thapa et al. (2004)
Use of GIS to identify buildings for green roofs	Kaplan (2006)
Quality of life assessment	Li and Weng (2007)
Estimation of urban leaf area index	Jensen and Hardin (2007)
Analyzing data on allotment garden sites obtained through surveys, discussions groups, and community mapping in the Philippines	Guanzon et al. (2007)
Foodshed analyses[1]	Schuble, Bowen and Martin (2011), Martellozzo et al. (2014)
Report on food desert mapping by students at Michigan State University	Phillips (2011)
Identification of existing urban agricultural locations in Chicago	Taylor and Lovell (2012)
Identification of vacant or under-utilized public lands that would be available for urban agriculture	McClintock, Cooper and Khandeshi (2013)
Identification of vacant lands and rooftops available for urban agriculture, locations of existing community gardens, also production capabilities and benefits to urban populations	New York State Energy Research and Development Authority (2013)
Identification of existing urban farm locations in the United States	Rogus and Dimitri (2015)

1.4.6 Urban Ecosystem Services

The benefits that people receive from ecosystems are called ecosystem services (Millennium Ecosystem Assessment 2005) (Figure 1.1). Although in the past, urban areas were considered sterile environments incapable of providing ecosystem services, recent research has

[1] A foodshed is the area of land needed for cultivation to provide a sufficient food supply for people in a specific area (http://msue.anr.msu.edu/news/what_is_a_food_shed).

shown this is not true (Pickett et al. 2001, Lord, Strauss and Toffer 2003). Although urban ecosystems are disrupted and do not function as efficiently as do rural ecosystems, they do provide ecosystem services (Bolund and Hunhammar 1999, Effland and Pouyat 1997, Pouyat et al. 2010, Setälä et al. 2014). And, within the urban setting, social and ecological processes are intertwined, and as such, we should direct equal attention to interactions between social and physical processes to understand urban ecosystem services (Ernstson 2013, Lehtonen 2004, Psarikidou and Szerszynski 2012). Urban agriculture provides a context for evaluation of these interactions.

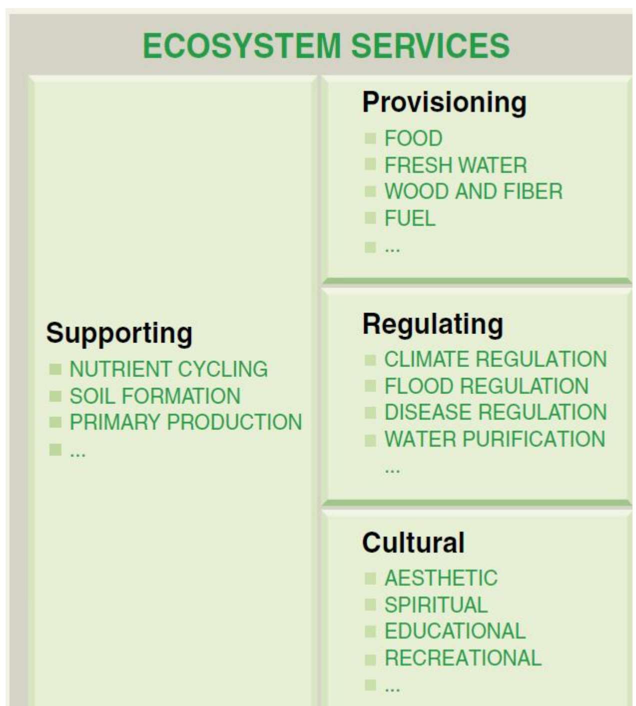

Figure 1.1 Ecosystem Services (Source: Millennium Ecosystem Assessment 2005, p VI)

Multiple factors complicate assessment of ecosystem services provided to urban residents:

1) they may not be solely provided by the local urban area in which the residents live -- most services (e.g., food production and potable water) are provided by non-

urban areas (Bolund and Hunhammar 1999, Jansson 2013), i.e. the urban area's ecological footprint extends well beyond its boundaries;

2) they are not evenly distributed within an urban area, e.g., their locations vary amongst the more affluent and less affluent neighborhoods, and by variations in the built environment (Ernstson 2013);
3) benefits from ecosystem services may not be equally accessible to all residents because of spatial and social constraints (Ernstson 2013); and
4) most ecosystem services are currently being used unsustainably (Jansson 2013).

Rising world populations behoove us to pursue strategies to reduce urban areas' footprints and to increase the potential of ecosystem services within urban areas (Jansson 2013), such as urban green spaces (Andersson, Barthel and Ahrné 2007), and, most specifically urban gardening (Barthel, Folke and Colding 2010, Connolly et al. 2013, Ernstson 2013, Jansson 2013).

1.5 Study Site – the City of Roanoke, Virginia

The City of Roanoke, Virginia has important qualities that favor its use as a setting to illuminate and investigate the practice of urban agriculture. Roanoke is the largest metropolitan region in southwestern Virginia (Figure 1.2). It is characterized by a variety of urban land uses with a history as a transportation hub for rail and road traffic, and services and industries supporting the rail system, as well as finance, distribution, trade, manufacturing, and healthcare industries (Figure 1.3).

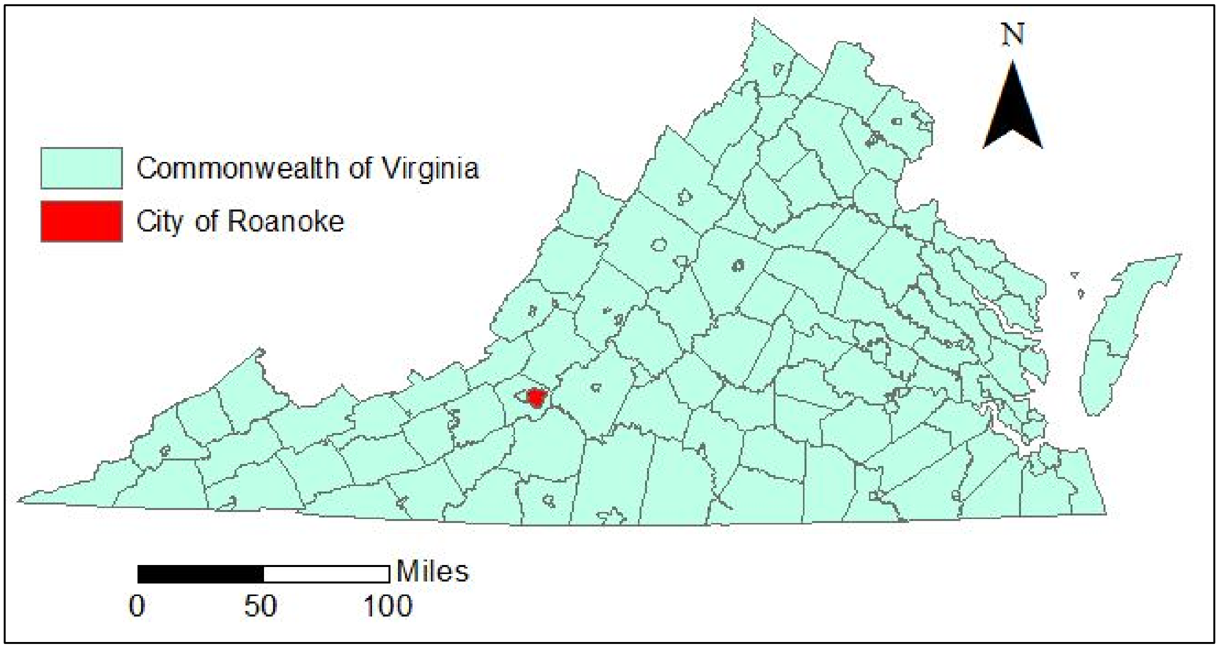

Figure 1.2 Reference Map, City of Roanoke, Virginia (Source –TIGER/Line® Shapefiles, 2014)

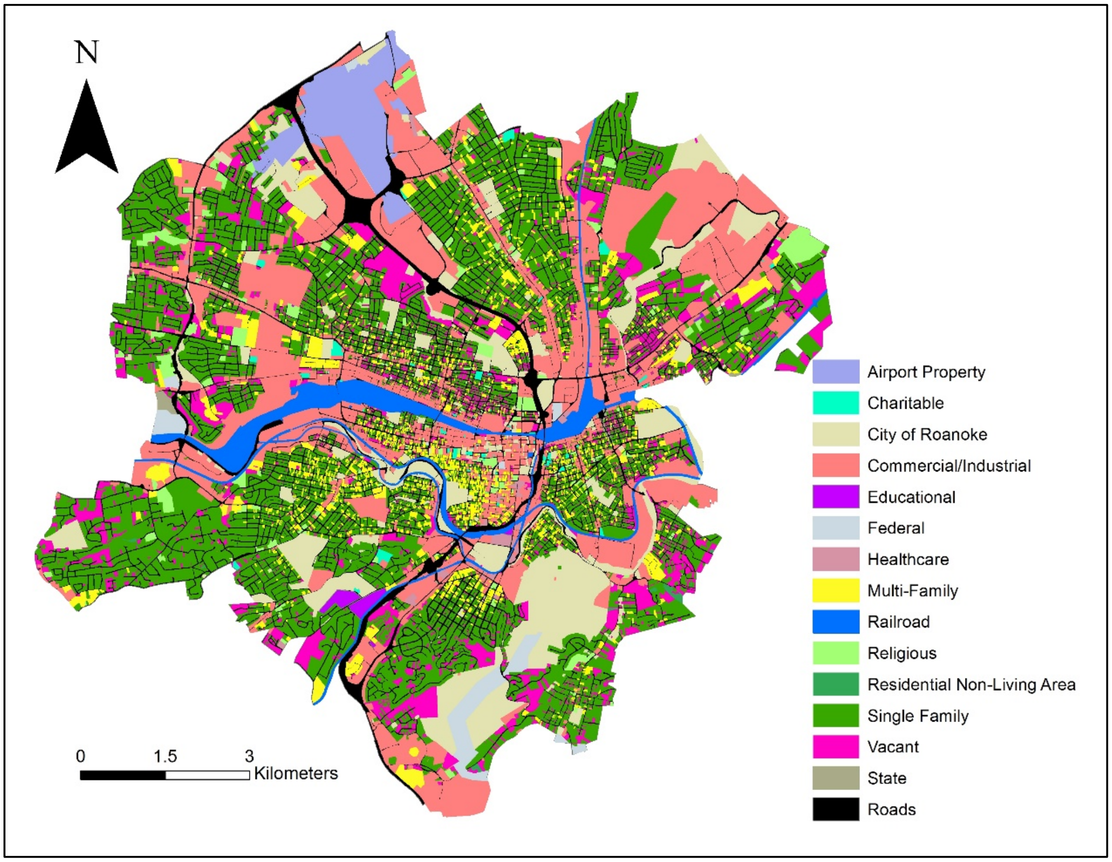

Figure 1.3 City of Roanoke, Virginia Land Use Map (Source – generated from City of Roanoke, Parcels Shapefile using Property Type Categories, 2015)

Over recent decades, Roanoke has been the focus of substantial urbanization, economic stress, and land use change. These changes have resulted in many environmental issues that extend beyond it boundaries, e.g. CO_2 emissions were estimated at 2.1 million tons in 2012 (Roanoke 2013). In addition, although it is a small urban area (42.6 mi^2), Roanoke is intensely urbanized with a population density (2,279.8 persons per $mile^2$) comparable to larger population centers such as Virginia Beach, Virginia and Raleigh, North Carolina (Table 1.4).

Table 1.4 Comparison of Roanoke to Larger Urban Areas (U.S. Census Bureau 2014)

Location	Area ($miles^2$)	Total Population	Population Density	Percent of population living below federal poverty level
Roanoke, VA	42.6	97,032	2279.8	20.9
Raleigh, NC	142.9	403,892	2826.3	14.6
Virginia Beach, VA	249.0	437,994	1758.9	6.8

City officials estimate impervious surface cover at 28% (Roanoke 2011). However, this research found that impervious surface cover is actually closer to 31.9% and not evenly distributed across the city (see Chapter 2 for further discussion). Due to the variations in extent of impervious surfaces, Roanoke has localized areas with severe drainage issues; experiencing frequent flooding due to its proximity to the Roanoke River and its tributaries, and from urban stormwater. Many segments of the Roanoke River system within the city are listed on the Virginia Department of Environmental Quality's impaired waters list, due to contaminants such as *Escherichia coli*, high water temperatures, and heavy metals (Virginia 2010).

Roanoke also forms an appropriate locale for addressing food insecurity as its poverty rate and food insecurity rates are higher than state and national percentages (Table 1.5). In addition, none of Roanoke City Public Schools have earned *The Governor's Nutrition and Physical Activity Scorecard Award*, which "recognizes and rewards schools for encouraging healthy habits" (Virginia 2012). According to the USDA (2014), a majority of the lower-income census tracts within the city have limited access to food (distance to food access at least ½ to 10 miles); Figure 1.4 depicts these USDA designations as encompassing almost all of the city. Furthermore, a study completed for 2014 by the University of Wisconsin ranked the City of Roanoke 127th out of 133 counties and cities in Virginia for health factors such as obesity, diabetes, and physical inactivity (2015).

Table 1.5 Comparison of Roanoke to Virginia and United States

	Roanoke	Roanoke County	VA	United States
Households below Federal Poverty Level (US Census 2014)	22.4%	5.1%	11.3%	15.4%
Food Insecurity Rates (Feeding America 2014)	16.9%	8.3%	12.1%	14.3% (USDA 2015)
National School Lunch Program (Virginia 2015)	68.0%	25.0%	39.7%	42.9% (USDA 2013)

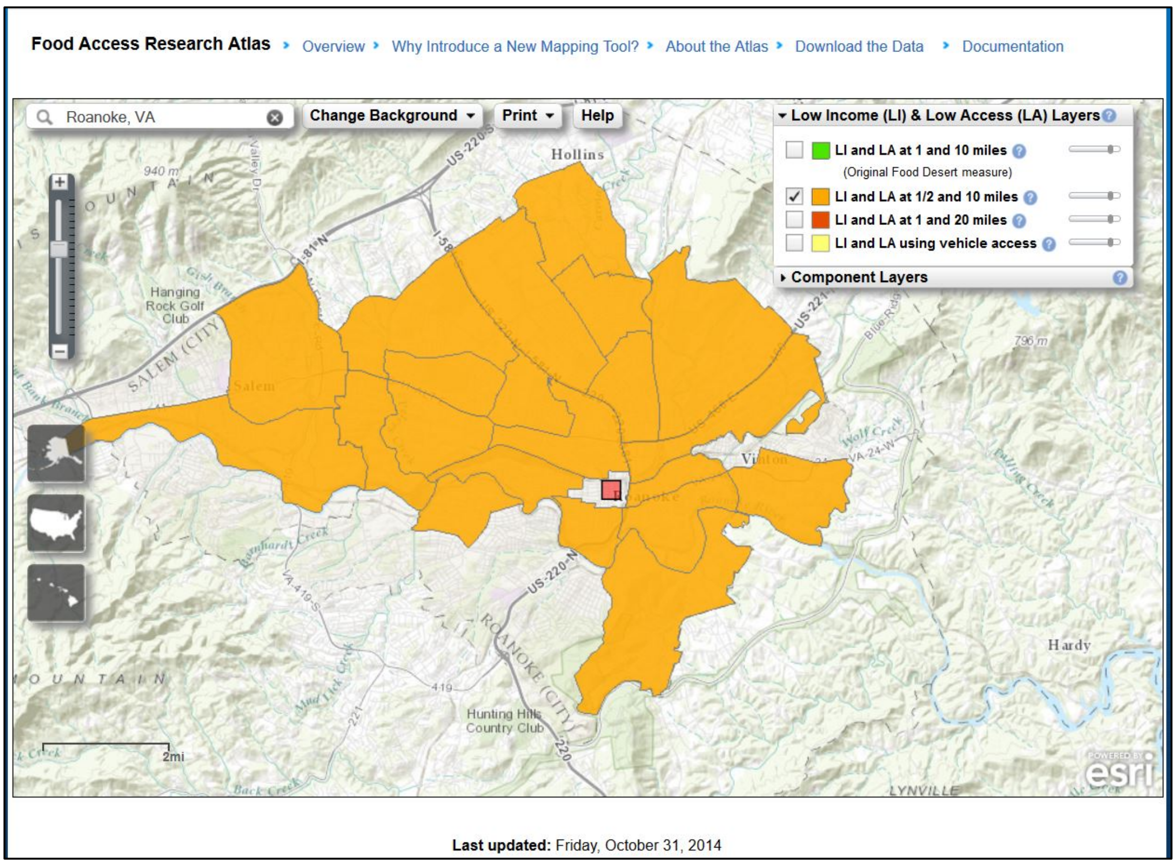

Figure 1.4 USDA designated food desert locations within the City of Roanoke, Virginia (Source: USDA 2014)

1.5.1 Urban Agriculture in Roanoke, Virginia

Many forms of urban agriculture exist within the City of Roanoke. The number of backyard gardens had not been documented previously, but were identified as part of this research (see Chapter 4). In addition, the city has two very active local-food organizations - The Roanoke Community Garden Association (http://www.roanokecommunitygarden.org/home.htm) and the Roanoke Natural Foods Co-op (http://roanokenaturalfoods.com/). Figure 1.5 shows the locations of two urban farms and several community gardens sites, as demonstrated from this image, these locations are not well-distributed across the City.

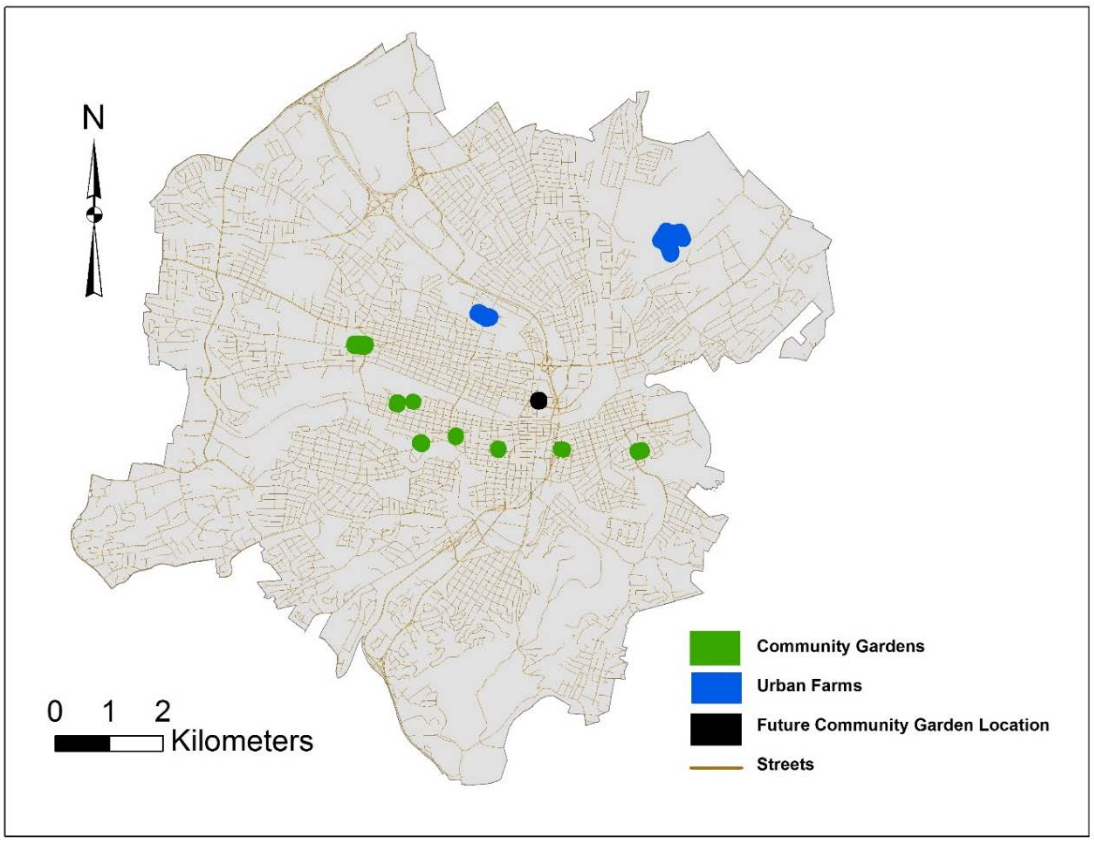

Figure 1.5 Site of two urban farms and community gardens (current sites in green, future site in black) within the City of Roanoke (note – polygon size has been enhanced for visualization purposes)

The Roanoke Community Garden Association (RCGA), established in 2008, has multiple locations across the city (green polygons in Figure 1.5). Some gardens are owned by RCGA, some are provided by local property owners, one is leased from the City, and one is operated on land owned by Goodwill Industries of the Valleys. Gardens are organic only and RCGA harvests rainwater at most of its locations (Figure 1.6). The two most recent gardens are MountainView Community Garden (established 2013), and Growing Goodwill Garden (established 2014). Land for MountainView is owned by the City but leased to RCGA (a five year lease that began in 2013); food production started in 2014. Growing Goodwill Garden is under development, with plans that include a food forest[2]. Thirty percent of RCGA gardeners are either immigrants or refugees. RCGA has plans for future sites across the city (Powell 2013), the next to be sited on land owned by a church (Powell 2015).

Figure 1.6 Rainwater harvesting system at Hurt Park Community Garden (Photo by James B. Campbell 2013)

[2] A food forest is a food garden primarily consisting of fruit or nut bearing trees and bushes and designed to mimic a natural ecosystem. (http://www.permaculture.org/demonstration-site/food-forest/)

The Roanoke Natural Foods Co-op operates the urban farm at Heritage Point in northeast Roanoke (larger blue polygon in Figure 1.5 and Figure 1.7). The land, purchased by the Co-op in 2012, covers approximately 18 acres and is located near an industrial park. In addition, the Co-op has leased an additional 3.5 acres from the city and adjacent to the farm (Ress 2013).

Figure 1.7 Heritage Point Urban Farm in northeast Roanoke (Photo by Tammy Parece 2013)

A second urban farm is located at the site of a defunct nursery (smaller blue polygon in Figure 1.5 and Figure 1.8). The location was purchased by a private citizen in 2010 with the intention of starting an urban farm and farmer's market. The site was used as a dumping ground for trash and tires after the nursery closed in 2002. Since its purchase in 2010, the current owner has cleaned up the property and renovated the building located on the site (Nair 2012), and started food production.

Figure 1.8 Privately-owned Lick Run Farm in central Roanoke (Photo by James B. Campbell 2015)

1.6 Summary

Roanoke's physical setting, mix of social and environmental challenges, and existing systems of urban agriculture present an opportunity to explore the value of geospatial analysis to evaluate strategic placement of urban agriculture in its physical, economic, and social contexts. This task requires integrative strategies that can blend spatial and temporal perspectives to bring social and environmental data together into a common analytical framework.

Together the next three chapters provide a comprehensive schema for other urban areas to accomplish a similar evaluation. Furthermore, this research contributes to the literature on urban agriculture as one comprehensive evaluation of an urban area. This research also provides a stepping stone for future urban agriculture research, temporally, to track the success (environmentally and socio-economically) of any new agriculture greenspaces established because of this geospatial analysis.

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2 Chapter - The Physical Environment for Urban Agriculture

2.1 Introduction

This chapter focuses on evaluation of urban physical dimensions for siting urban agriculture. The research investigated the spatial patterns of urban terrain, hydrology, and microclimates within the City of Roanoke, Virginia. The objective was to identify open areas available for crop production, to determine if those locations are suitable for crop production, and to identify those areas that have the greatest need, environmentally, for the mitigating effects of a greenspace. The research attempted to answer the following questions:

1. Are there areas within the City of Roanoke that are available for agriculture?
2. Can these areas support crop production, or are the areas so degraded that it is counter-intuitive to place agriculture in those locations?
3. Do variations in terrain, hydrology and microclimates overlap, to help identify which locales provide a hierarchy of locations (at the census block group level) that demonstrate greatest to least need for a new green space to assist in improving urban environmental problems?

Ultimately, this research provided multiple results and identified:

- areas within the City of Roanoke, Virginia that are available for agricultural production;
- the appropriate urban agriculture form for each of those sites;
- any barriers to cultivation related to contamination, aspect and slope;
- census block groups with the highest percent of impervious surfaces and, thus, greatest exposure to water quantity and quality issues;
- census block groups that are most affected by higher air temperatures;

- areas with soils that could be improved with the addition of a new greenspace; and
- census block groups with the least amount of greenspaces.

By overlaying each of these physical attributes and assimilating this data within ArcGIS™, a hierarchy of census block groups resulted demonstrating those locations with the greatest need for the addition of a new greenspace. In addition, this research provides methodology that urban municipalities, environmental advocates, researchers, and other stakeholders can follow in identifying locales to strategically site urban agriculture for the greatest contribution to environmental sustainability.

2.2 Chapter Structure

Initially, this chapter presents a brief review of the literature on greenspaces' contribution to mitigating urban areas' environmental problems. Then, this chapter is structured around each of the different physical aspects of the study site, the City of Roanoke, Virginia (but is applicable to any urban area) – land cover/land use, soils, hydrology, and microclimates. Each of these sections discuss the pertinent literature, the gaps present within the literature, the existing data used, the methodology for creating new data and for analysis of the data, and the results of that specific physical evaluation. The final section of this chapter presents the assimilation of each section's results. The final product presents a hierarchy of locations, at the census block group level, that show a need (from greatest to least) for mitigation of urban environmental problems.

2.3 Urban Greenspaces and Environmental Impact

A greenspace is defined as "land that is partly or completely covered with grass, trees, shrubs, or other vegetation" (U.S. EPA 2015). Greenspaces positively affect the health and welfare of both human and wildlife populations residing in urban areas (Wheater 1999, Nowak

2006, Beer 2010, Kuo 2010, Volder and Watson 2010). These positive effects include reducing air pollution, reducing stormwater runoff, mitigating the urban heat island effect (Bowler et al. 2010), and reuse or revitalization of vacant lands and brownfields (Yokohari and Bolthouse 2011, Orsini et al. 2013).

The majority of greenspace studies focus on expanding the urban tree canopy (UTC) because, of all types of greenspaces, trees provide the greatest environmental benefit (e.g., McPherson 1994, Booth et al. 2002, Cappiella et al. 2005, Chen and Jim 2008, Volder and Watson 2010, McPherson et al. 2011). However, urban locales are not amendable to extensive urban tree planting, nor to maintaining existing trees because of problems such as limited space, limited tree lifespan, impervious surfaces, management costs (Volder and Watson 2010), and unfavorable soil conditions (Bartens et al. 2012). In addition in many urban areas, the high value of land precludes reforestation (Kaplan 2006, van Leeuwen et al. 2010).

Other greenspaces such as recreational parks are limited in their ability to alleviate environmental problems. Their predominant vegetation is grass/lawns and many are monocultures and intensely managed, which promote an environment with limited biodiversity (Cook and Ervin 2010), and may contribute to increased soil compaction (Pouyat et al. 2010). Grass surfaces are cooler than impervious surfaces such as asphalt and concrete (Bonan 2002, Bowler et al. 2010), however, these grassy surfaces do require regular management such as consistent mowing (Bolund and Hunhammar 1999), which contributes to poor air quality. The nature of this greenspace – for recreational use – means stormwater must be removed to make the park usable. Impervious surfaces are usually constructed near or in the park for parking and walking (Figure 2.1), and, in many cases, the park’s lawn area suffers compaction which generates additional stormwater flow.

Figure 2.1 Example of parking area for patrons next to a greenspace (left), and asphalt walkway for pedestrians within an urban greenspace. These locations are within the Roanoke River Greenway, City of Roanoke, Virginia. (Source: Virginia Base Map Program aerial photos from 2008).

Although urban agriculture qualifies as a greenspace, little recognition is given to urban agriculture as contributing to environmental benefits (Bourque 2000, Kaufman and Bailkey 2000). Use of urban agriculture as a greenspace avoids many of the problems faced by urban trees and recreational parks, e.g., limited space, potential for damage to infrastructure such as sidewalks, or soil compaction. Urban agriculture as a greenspace also assists in regulating air, in stormwater management, in soil remediation by increasing organic content, reuse of brownfields or other areas of soil contamination through use of raised beds, and where spaces are limited – smaller crops such as herbs or vertical farming techniques can be used (Despommier 2010, New York State Energy Research and Development Authority (NYSERDA) 2013).

2.4 Terrain

2.4.1 Land Inventory for Potential Urban Agriculture Locations

The first step in urban agriculture analysis is identifying those areas within the city that are available for agriculture production (Dongus and Drescher 2006, Dubbeling and Merzthal 2006, Dubbeling et al. 2010), and such efforts have begun in many areas of the United States and Canada. These efforts are defined as a *land inventory* for urban agriculture but include a wide variety of variables in the analysis. All use GIS and, a few include some remote sensing in their analysis.

Two publications arose from the land inventory analysis (both found in the Appendix). Since the first step in a land inventory is eliminating those land covers not open and available for urban agriculture (impervious surfaces, water, tree canopy cover), the first publication relates to identification of impervious surfaces. For the *land inventory*, impervious surfaces were manually delineated for the city using 2011 Virginia Base Mapping Program aerial photos as a guide. But, this procedure is very time intensive. Since many municipalities do not have the budget nor manpower to accomplish such a feat, a comparison of this method to remote sensing classification algorithms for impervious surface extraction using Landsat imagery is found in the original publication cited below. The Appendix contains this publication.

Parece, T.E. and Campbell, J.B. 2013. ***Comparing Urban Impervious Surface Identification Using Landsat and High Resolution Aerial Photography****. Remote Sensing. 5(10): 4942-4960. doi:10.3390/rs5104942. (http://creativecommons.org/licenses/by/4.0/)*

The second publication relates to the entire land inventory procedure, most specifically evaluating land cover and then land use, and identifying the sites open and potentially suitable for urban agriculture. This second publication also includes an analysis of the urban agriculture form -- community garden, urban farm, orchard or home garden -- appropriate for each site. The Appendix contains this original publication.

Parece, T. E. and Campbell, J.B. Pending Publication 2017. ***Geospatial evaluation for urban agriculture land inventory: Roanoke, Virginia****. International Journal of Applied Geospatial Research 8(1). This paper appears in the International Journal of Applied Geospatial Research edited by Dr. Donald Alpert. Copyright 2017, IGI Global, www.igi-global.com. Posted by permission of the publisher.*

2.4.2 Slopes and Aspect

This portion of the analysis involved identification of slopes and aspect for the *land inventory* accomplished in the prior section. The question evaluated pertained to whether or not slopes and/or aspect would limit or prohibit cultivation for those areas identified as open and available for urban agriculture. Within ArcGIS™, the *Spatial Analyst/Surface* tools and the U.S.G.S. 10 meter digital elevation model were used for this analysis.

2.4.2.1 Slopes

Steep slopes can be a prohibiting factor in urban agriculture (Smit and Nasr 1992), but literature on urban agriculture *land inventory* analyses rarely include slopes as a prohibitive variable;

- McClintock et al. (2013) eliminated all locations with slopes greater than 30%;
- Balmer et al. (2005) eliminated slopes over 10% but acknowledged that slopes really should not be an issue; and
- NYSERDA (2013) stated slopes were not an issue in New York because of its' relative flatness.

While slopes could be prohibitive for agriculture, the proper urban agriculture form could help stabilize slopes, i.e. *orchards*. To determine slopes within the city, the *Surface* tool was set to percent slope. Within the City of Roanoke, slopes range from flat to 189.9%, but the majority of slopes are less than 20% (Figure 2.2). The steepest slopes (over 30%) are in the southeastern part of the city, which contain the Mill Mountain Park, Yellow Mountain Park, National Park Service lands, e.g., areas of extensive tree canopy cover.

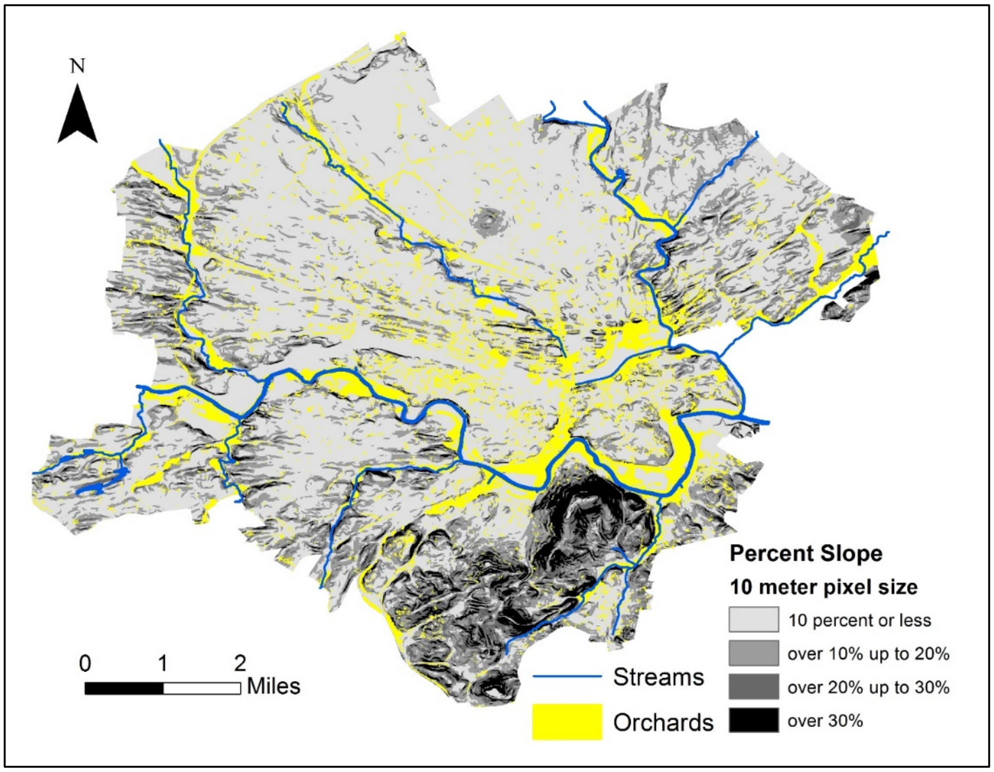

Figure 2.2 Percent slope distribution for the City of Roanoke, as calculated from the 10-meter U.S.G.S. digital elevation model.

For those open areas potentially suitable for urban agriculture, identified under the land inventory analysis, *Spatial Analyst/Zonal/Zonal Statistics* calculated the slopes for each form – *orchards, community gardens, home gardens* and *urban farms*. As Table 2.1 shows, for each form, the smallest slope is 0% or flat. The average slope is less than 8.2% across all forms. The maximum slope (112.9%) and the maximum average slope (8.2%) correspond to *orchards*, thus the steep slopes that exist in Roanoke and are exposed to possible erosion, could be stabilized from the implementation of urban agriculture (such as example is shown in Figure 2.3).

Table 2.1 Slopes by urban agriculture form for the *land inventory*

UA Form	Minimum Slope	Maximum Slope	Average Slope
Community Garden	0%	66.7%	7.5%
Home Garden	0%	75.8%	8.2%
Orchards	0%	112.9%	5.7%
Urban Farm	0%	63.6%	7.8%

Figure 2.3 An area in Roanoke that experiences considerable erosion from stormwater runoff and could be an area where terracing for urban agriculture could help alleviate the soil loss (Photo by Author 2013).

Can slopes be a barrier for urban agriculture within Roanoke? From the 2011 Virginia Base Mapping Program aerial photos, areas under active cultivation were examined. Home gardens and one of the urban farms are actively cultivating steep slopes (≥ 30%), hence for residents participating in urban agriculture, slopes are not considered a barrier within the city. Furthermore, evidence of terracing was discovered in several home gardens (Figure 2.4); further demonstrating that slopes may not be an issue.

Figure 2.4 Google Earth™ image (2012 NAIP aerial photos) of areas in southwest Roanoke with significant slopes, 33.8% (right) and 30.4% slope (left), as calculated from the 10-m digital elevation model, backyards of the residences have been terraced to allow for landscaping and vegetation.

2.4.2.2 Aspect

Aspect governs the different types of crops planted. Southern slopes are tilted towards the sun (in the Northern hemisphere), they receive greater solar radiation and will be warmer and drier (higher evapotranspiration). Northern slopes will receive less insolation and, as such, will be cooler and moister, thus amenable to plant damage from mold and mildew. McClintock, et al. (2013) is the only researcher that included aspect into his urban agriculture *land inventory* analysis; for one of his food production scenarios, he eliminated any location with a North, Northwest, or Northeast aspect.

Zonal Statistics as a Table tool extracted aspect for urban agriculture form identified in the *land invento*ry (Table 2.2). Only 10.5 hectares acres fell into the "Flat" aspect, mostly pertaining to the form - *orchards*. Total acreage located within the northern aspects (North, Northwest, and Northeast), where the solar radiation received is much less than other aspects, equals 779.2 hectares (33.8% of all potential locations for urban agriculture within Roanoke). The other aspect types – south, southeast, southwest, east, west – are warmer and can be more amendable to agriculture. However, because they are also warmer, these locations could benefit from the addition of a new greenspace. In general, aspect will not be a barrier to extensive urban agriculture within Roanoke, as appropriate crop selection is required for all aspects.

Table 2.2 Aspect by urban agriculture form identified in the *land inventory*

Aspect direction	Form (number of locations)	Total area (hectares)
Flat	Community Garden	1.0
	Home Garden	0.1
	Orchards	9.4
	Total	10.5
North	Urban Farm	43.4
	Community Gardens	99.5
	Home Garden	149.6
	Orchards	67.6
	Total	360.1

Northwest	Urban Farm	21.7
	Community Garden	52.0
	Schoolyard (1)*	0.1
	Home Garden	91.7
	Orchards	23.8
	Total	189.2
Northeast	Urban Farm	13.7
	Community Garden	71.7
	Schoolyard (1)*	1.0
	Home Garden	105.5
	Orchards	38.9
	Total	229.9
East	Urban Farm	32.2
	Community Garden	73.0
	Schoolyard Garden (2)*	0.7
	Home Garden	88.8
	Orchards	42.9
	Total	236.9
South	Urban Farm	63.1
	Community Garden	139.7
	Schoolyard (4)*	3.7
	Home Garden	195.7
	Orchards	70.0
	Total	468.5
Southeast	Urban Farm	42.3
	Community Garden	128.7
	Schoolyard (10)*	8.3
	Home Garden	138.4
	Orchards	38.1
	Total Acres	347.5
Southwest	Urban Farm	28.2
	Community Garden	72.2
	Schoolyard (4)*	2.0
	Home Garden	139.7
	Orchards	28.9
	Total	269.0
West	Urban Farm	33.9
	Community Garden	53.9
	Home Garden	77.5
	Schoolyard (1)*	0.3
	Orchards	29.1
	Total	194.4
Total Overall		2306.0

*schools were not included in total hectares

Neither slope nor aspect appear to be a limiting or prohibiting factor within the city for any existing urban agriculture form. As such, neither are considered as an environmental problem that needs to be addressed by the addition of a new greenspace, so were not included within the hierarchal assessment.

2.4.3 Urban Soils

Urbanization disturbs the heritage of existing soils, and current pedological processes, by truncating or burying soil profiles, sealing soils through construction of impervious surfaces, and reshaping the terrain by filling in depressions or suppressing topographic irregularities (Effland and Pouyat, 1997; Galbraith, 2003; Scheyer and Hipple, 2005). This disruption negatively impacts soils in many ways, i.e. higher bulk densities, loss of soil horizons, loss of organic matter, higher soil temperatures, lack of moisture, contamination, and disruption of natural cycling of nutrients and water (Effland and Pouyat, 1997; Galbraith, 2003; Scheyer and Hipple, 2005). As such, most soils found within urban areas are commonly classified as *urban land or urban land complexes* (Effland and Pouyat, 1997; Scheyer and Hipple, 2005). Such designations indicate aforementioned disturbances from non-agricultural human activities (Effland and Pouyat, 1997; Galbraith, 2003; Scheyer and Hipple, 2005).

Urban agriculture researchers consistently recognize poor urban soil quality, especially possible contamination (e.g., Webb 1998, Brown and Jameton 2000, Kaufman and Bailkey 2000, Smit et al. 2001, Kaethler 2006, Scheyer and Hipple 2005, Buerkert et al. 2009, Pouyat et al. 2010, Attanayake 2014, LaCroix 2014, Wortman and Lovell 2014, Clarke et al. 2015). The literature is prolific on recognizing or recommending urban agriculture as useful for remediating soils either through increasing organic matter (Brown and Jameton 2000, Smit et al. 2001, Cofie et al. 2006) or phytoremediation capability (Brown and Jameton 2000, Kaufman and Bailkey 2000, Smit et al. 2001).

For this section of the physical evaluation of the City of Roanoke, soils were assessed to answer two questions:

1) Do farming quality soils exist within the city, if so where?
2) Does the city contain any soils classified as *urban land or urban land complexes*, and thus could possibly benefit by increasing organic matter from urban agriculture?

For this evaluation, the Soil Survey Geographical (SSURGO) shapefile for Commonwealth of Virginia soils was downloaded from the National Resource Conservation Service (NRCS). This data contains soil information collected as part of the National Cooperative Soil Survey, prepared in part by field observation (NRCS 2015a). This shapefile delineates, and labels, areas ("mapping units") of soils observed by field survey and aerial photography (including some mapping units that are composed of unlike soils too small to separate at the scale of the map). Intersecting this shapefile with the *potential urban agriculture sites* shapefile identified soils by mapping unit (MU) within each potential urban agriculture site. Then, for each MU, soil was identified (e.g., 18B = Frederick silt loam 2 – 7% slope) and documentation for that specific soil reviewed for its suitability for agriculture.

Each mapping unit was categorized into one of six categories, as follows:

- *Prime Farmland*. Prime farmland "is land that has the best combination of physical and chemical characteristics for producing food, feed, forage, fiber, and oilseed crops and is available for these uses. It could be cultivated land, pastureland, forestland, or other land, but it is not urban or built-up land or water areas" (NRCS 2015b). The NRCS designates certain mapping units as prime farmland (which varies by region), for southwestern

Virginia, this would include 18B – Frederick silt loam 2 – 7% slope; 2B – Allegheny loam 2 – 7% slope, or 39B Shottower loam 2 – 7% (NRCS 2015c). Any areas with soils in this category would, generally as compared to the other categories below, have the least need for amendments to improve its quality;

- *Farmlands of Statewide Importance for Virginia* – mapping units designated as a soil for farmland which is considered important in the Commonwealth of Virginia, e.g., 40C – Shottower cobbly loam 7 – 15% slope, 47C Thurmont sandy loam 7 – 15% slope, or 49C – Tumbling loam 7 – 15% slope (NRCS 2004);
- *Not Suitable* – mapping units which correspond to water (W) and pits and quarries (35);
- *Slopes Possibly too Steep* – mapping units with the letter E, that identify the steepest slope category for an individual soil type;
- *Urban Lands or Urban Land Complexes* – urban lands consist of urban infrastructure such as buildings, streets, parking lots, etc., and are considered disturbed soils. Urban land complexes could include natural soils along with the aforesaid urban infrastructure or be found adjacent to such urban infrastructure. For a conservative assessment, this category contains any mapping unit containing the word *urban* in its title, e.g. 29C – Hayesville urban land complex, 53 – Urban land, or 21C – Frederick urban land complex. Any soils within in this category, generally as compared to the other categories, would likely benefit from increases of organic matter that could result from urban agriculture; and
- *Not Prime Farmland but Cultivatable* – these mapping units are designated by the NRCS as “not prime farmland,” however, within the Official Series Descriptions (NRCS 2015c) use and vegetation is described. For example, Shottower (MU 39C and 39C) and

Sequoia (MU 37C and 37D) are both noted under *Use and Vegetation* with different forms of agriculture. Any of those soil series with either agriculture or other vegetation use notes were placed into this category. Even those noted as suitable for forest or woodlands under vegetation (for example, Grimsley, MU 23C) were placed under this category as urban agriculture is not limited to ground crops but can include fruit and nut bearing trees.

This classification revealed that soils for the majority of the *land inventory* sites (i.e. areas open and potentially available for new urban agriculture) fall into the *Urban Lands or Urban Land Complexes* category – 54.7%, followed by *Not Prime Farmland but Cultivatable* - 17.3%, then *Farmland of Statewide Importance* – 14.8%, and *Prime Farmland* - 6.5%. Very minute areas classified as *Not Suitable* – 0.4% and as *Slopes Possibly too Steep* – 6.2% (Table 2.3).

Table 2.3 Soils summary for the *land inventory*

Farmland Suitability	Soils	Hectares	% of potential sites
Prime Farmland	2B, 8A, 18B, 39B, 42A, 43A, 47B, 48B, 49B, 56A, 56B	150.8	6.5
Farmland of Statewide Importance	2C, 16C, 16D, 18C, 18D, 24C, 25C, 25D, 26C, 26D, 40C, 47C, 49C, 49D	340.9	14.8
Not Suitable	35, W	8.1	0.4
Slopes Possibly too Steep	5E, 15E, 16E, 17E, 19E, 20E, 28E	144.0	6.2
Urban Lands or Urban Land Complexes	6C, 6D, 21C, 21D, 29C, 29D, 41C, 44A, 51C, 52, 53, 57A	1261.1	54.7
Not Prime Farmland, but Cultivatable	5C, 5D, 13A, 15C, 15D, 20C, 22C, 23C, 26B, 37B, 37C, 37D, 39C, 40D, 9B	399.8	17.3

2.1.1 Block Group Ranking from Terrain Analysis

As noted above, *urban land and urban land complexes*, as compared generally to the other categories, is likely those areas with the greatest need for a new greenspace to potentially increase soil organic matter. The category identified as having the best agricultural soils - *Prime Farmland* – is likely those areas with the least need for a new greenspace. As such, to assimilate soils into the assessment for those block groups that would benefit the greatest from a new urban agriculture greenspace, the block groups were ranked as follows:

5 – 90% of soils in the block group are *Urban Land and Urban Land Complexes* or *Slopes Possibly Too Steep;*

4 – Between 50% and 90% of soils in the block group are *Urban Land and Urban Land Complexes;*

3 – Less than 50% *Urban Land and Urban Land Complexes* and greater than 50% are *Not Prime Farmland but Cultivatable;*

2 – Less than 50% are *Urban Land and Urban Land Complexes* and less than 50% are *Not Prime but Cultivatable*;

1 – Less than 50% are *Urban Land and Urban Land Complexes* and greater than 50% but less than 90% are *Prime Farmland*; and

0 – 80% or more of soils in block group are *Prime Farmland, Farmland of Statewide Importance*, or *Not Suitable.* The *Not Suitable* category was placed in this ranking because this land is not suitable for cultivation, thus could not be improved with urban agriculture.

2.5 Hydrology

The hydrological analysis began with a literature review on the applicability of geospatial technologies, particularly remote sensing, in a land cover and land use evaluation, and most specifically to a hydrological evaluation of any area. The Appendix contains this original publication.

Parece, T.E. and Campbell, J.B. 2015. ***Land use/land cover monitoring and geospatial technologies: An overview****. In Advances in Watershed Science and Assessment. T. Younos and T.E. Parece, eds. Book Series: The Handbook of Environmental Chemistry, Volume 33; Springer. DOI 10.1007/978-3-319-14212-8_1. "With Permission of Springer"*

2.5.1 Urban Catchment Delineation

The first step in an urban hydrologic evaluation is recognition of the unique characteristics of urban watersheds and includes correct definition of urban catchments. Such evaluation should include those urban characteristics that differ greatly from those of natural environments -- man-made urban infrastructure including impervious surfaces and storm drain networks (Jacobson 2011). However, the city of Roanoke's GIS files are incomplete for documentation of their storm drain infrastructure (David Dearing – City of Roanoke Engineering Department, personal communication, March 6, 2013). As such, the original publication related to urban hydrological analysis covers an urban area in Fairfax County, Virginia. The Appendix contains the original publication.

Parece, T.E. and Campbell, J. B. 2015. ***Identifying Urban Watershed Boundaries and Area, Fairfax County, Virginia****. Photogrammetric Engineering and Remote Sensing 81(5):365-372. Reproduced with permission from the American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, asprs.org.*

2.1.2 Block Group Ranking from Hydrology Analysis

Within the analyses for the prior two publications, impervious surfaces were the primary significant factor affecting the hydrology results. Delineation of all impervious surfaces within the city, under the terrain analysis, allowed for calculation of the percent impervious surface for each block group. The higher the percent impervious surface for a block group creates the greater potential for stormwater runoff and greatest adverse impact on water quality, thus the greater need for mitigation efforts. Therefore, the ranking for each block group follows:

0 – less than or equal to 10%

1 – greater than 10% but less than or equal to 25%

2 - greater than 25% but less than or equal to 40%

3 - greater than 40% but less than or equal to 50%

4 - greater than 50% but less than or equal to 75%

5 – greater than 75%

2.6 Climate

Urban areas are warmer than surrounding rural areas, thus resulting in a phenomenon – the Urban Heat Island Effect. But, within urban areas, variations within the built environment create unique microclimates because of diversity in the landscape, especially thermal properties of surface materials (Arnfield 2003, Geiger et al. 2003). Evaluating this intra-urban microclimate variability presents an opportunity to evaluate spatial dimensions of an urban environment, and identify those locations which are warmer and heat up faster than other locales over the course of a day, and maintain this heating effect over spring, summer, and fall. Identifying such warmer locales also provides an opportunity to strategically site urban agricultural greenspaces and help mitigate this heating effect.

2.1.3 Intra-Urban Temperature Variation

The first aspect of the climate evaluation involved predicting temperatures across the entire city by utilizing landscape variables and temperatures measured at different locales. The Appendix contains this original publication.

Parece, T.E., Li, J., Campbell, J.B., and Carroll, D. 2016. ***Assessing urban landscape variables' contribution to microclimates.*** *Advances in Meteorology***.** *Article ID 8736263.* http://dx.doi.org/10.1155/2016/8736263. *(http://creativecommons.org/licenses/by/4.0/)*

2.1.4 Intra-Urban Phenology Variation

Phenology is the recurring seasonal activity of plants and animals, i.e. mating, birth and death in animals; germination, flowering and fruit production in plants (Denny et al. 2014). The timing of phenological stages (phenophases) vary by species, age within an individual species, local climate, and many biotic and abiotic conditions (Denny et al. 2014). Evaluating plant phenology - start of season, length of season and end of season - within an urban area is a companion to a microclimate evaluation, as it can assist in identifying locations that are typified by higher temperatures.

The original publication related to this analysis has been drafted and is under review by the dissertation chair. A copy of the manuscript is located in Appendix.

Parece, T.E. and Campbell, J.B. In draft. ***Urban Heat Islands Effect on Urban Phenology***

2.1.5 Block Group Ranking from Climate Analysis

The above assessments provided locations within the city that had warmer temperatures. The next step was identifying those census block groups with the greatest need for a new greenspace to assist in mitigation of higher air temperatures. Within ArcMap™, first *Selection by Attribute* identified the highest 25% of temperatures on the dates of data collection. Then, *Selection by Location* identified those block groups with those highest temperatures. Ranking for each block group related to how many higher temperature points each block group contained over all of the days, ranked 0 – 5. Those census block groups with the greatest number of higher estimated temperatures for all days received a rank of 5. Those areas with no higher estimated temperatures received the rank of 0. All other block groups were divided evenly into quarters, and ranked as follows:

0 Census block groups never having highest temperatures across all days;

1 Census block groups with the lowest 25% of number of high temperatures;

2 Census block groups with between 26% and 50% of number of high temperatures;

3 Census block groups with between 51% and 75% of number of high temperatures;

4 Census block groups with between 75% and 99% of the number of high temperatures; and

5 Census block group(s) having the greatest number of high temperature points across all days.

2.7 Locations of Existing Greenspaces

For the final step in the physical evaluation of Roanoke, one additional component was considered – existing greenspaces - including existing city, state and federal parks and existing community gardens and urban farms. Within ArcMap™, *Selection by Location* identified block groups containing the aforementioned greenspaces, and *Selection by Attribute* identified the size of the greenspace. The block groups were ranked (5 – no greenspace present, thus the greatest need for a new greenspace, 0 – greenspace is present and of significant size so that a new greenspace is not needed) using the following parameters:

5 - Block groups with no current urban agriculture site and no parks (thus no greenspace is present);

4 - Block groups with current urban agriculture production but no parks;

3 - Block groups with no current urban agriculture production and have parks, but park area is less than 1 hectare;

2 - Blocks groups have no current urban agriculture but have parks over 1 hectare;

1 - Block groups with existing urban agriculture and existing parks but the area of the parks is less than 10% of the overall area of the block group; and

0 - Block groups with existing urban agriculture and existing parks with area that exceeds 10% of the overall area of the block group.

2.2 Final Data Assimilation – Physical Analysis

Identifying which environmental issue is most important to an urban area can be a subjective decision. Hydrologists and people living in the areas of most frequently flooding might identify stormwater runoff as the most important variable during an intense rainstorm, but may change their opinion during a period of drought. Whereas during extreme heat events, people without air conditioning might rate temperature mitigation as more important. As such, the different environmental variables received equal weighting in the final total ranking.

One additional field was added to the *Attribute Table* of the census block group shapefile titled “total ranking”. The ranking was calculated as the sum total of each individual variable’s ranking number. A block group could receive a number ranking from 0 (demonstrated no need in any of the four categories) to 20 (demonstrating the greatest need in all four categories).

All block groups demonstrated some level of need, the lowest score was a three (two block groups). No block group received a perfect score of 20, but three block groups scored 18 and two block groups scored 17 – all within the inner portion of the city. Figure 2.5 shows the rankings of the block groups from the greatest need (in darkest green) and least need (in darkest red) for a new greenspace that can assist in mitigation of adverse environmental effects of urbanization. All block groups have land open and potentially suitable for urban agriculture -- the number within each block group represents the percentage of the block group area available for a new urban agriculture greenspace.

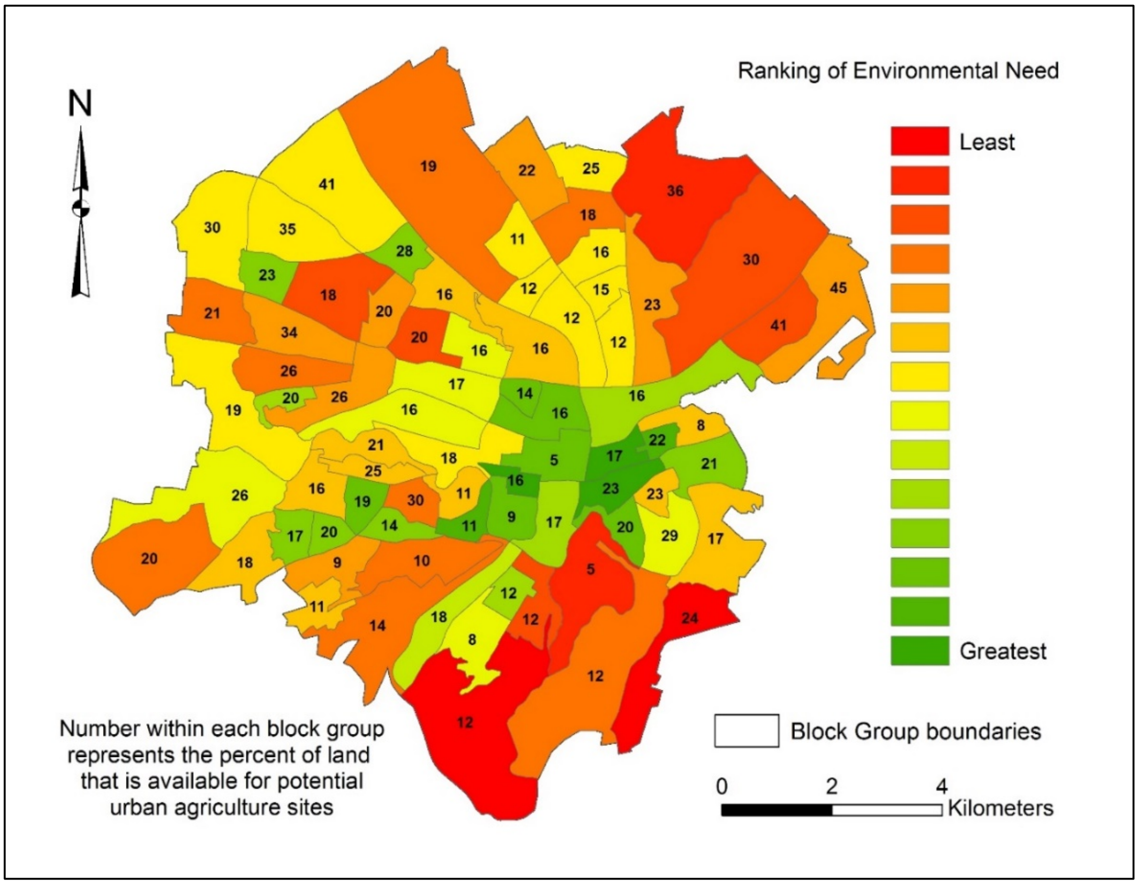

Figure 2.5 Ranking of each census block group for environmental need, least to greatest

2.8 Conclusions

Correlating the different properties of the above assessments allowed identification of those block groups with the greatest need for mitigation of adverse urban environmental effects.

Completing a land inventory, simultaneously with an evaluation of adverse physical effects of urbanization, allowed demonstration that each block group has ability to accommodate a new greenspace, albeit the percent of land available varies. Yet, if a new urban agriculture greenspace were implemented in these locations in order of the hierarchal need, some benefits may not be achieved. In addition, the level of environmental benefits would vary dependent upon urban agriculture form, the size of the plot and the exact nature of the environmental problem. For example by weighting all variables equally, an area suffering substantial impact from stormwater runoff might not also be an area suffering from the highest air temperatures.

Specifically the Blue Hills Industrial Park (northeast Roanoke) has large expanses of impervious surfaces resulting in substantial erosion and flooding of roadways located downhill from the park. But the area demonstrates cooler temperatures and is the site of the largest urban farm in the city. The census block groups in this area ranked very low as areas needing a new greenspace, thus runoff would continue to occur and water quality continue impaired. Whereas, if we provided more weight to hydrology, this area would likely gain a higher ranking and other block groups with higher air temperatures and no existing greenspace would receive a lower ranking.

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3 Chapter – The Socio-Economic Dimensions of Urban Agriculture

3.1 Introduction

This chapter focuses on the evaluation of the social, economic, and demographic aspects of the study site for siting urban agriculture. This aspect of the research investigated the socio-economic spatial patterns for income, education, household organization, food access and availability (including locations of retail food outlets and existing urban agriculture sites), health, and other nutritionally related health issues. The research objective was to identify any co-variation between these socio-economic parameters to determine which locations would have the greatest need for a new urban agriculture greenspace.

3.2 Publication

The manuscript related to this chapter was accepted for publication on 3 February 2016 and is found in the Appendix.

Parece, T. E., Serrano, E. L. and Campbell, J.B. Pending Publication. ***Strategically siting urban agriculture: A socio-economic analysis of Roanoke, Virginia.*** *The Professional Geographer. "This is an Accept Manuscript of an article to be published by Taylor & Francis in THE PROFESSIONAL GEOGRAPHER."* (ID: 1157496 DOI:10.1080/00330124.2016.1157496)

4 Chapter - Urban Agriculture and Ecosystem Services

4.1 Introduction

This chapter focuses on the assimilation of the previous two chapters and strategically siting urban agriculture, optimizing both physical and socio-economic benefits. Analyzing the spatial covariation of these patterns helped identify those block groups with the greatest need for a new greenspace, both environmentally and socio-economically. Then each census block group was ranked as to its need, greatest to least. An ecosystem services evaluation identified urban agriculture's ability to provide specific ecosystem services, and thus to assist in alleviation of the environmental, social, health, and economic issues prevalent in urban environments. The research within this chapter attempted to answer the following questions:

1. Will the geospatial models developed in Chapters 2 and 3 intersect to identify locales within Roanoke that provide optimal locations for urban agriculture to meet environmental, health, economic, and social needs for the population?
2. Will the identified locations for urban agriculture within Roanoke contribute to urban ecosystem services? Specifically, the research attempted to determine if urban agriculture supports improvements in supporting, provisioning, regulating and cultural services.

4.2 Chapter Structure

Initially, this chapter presents a brief review of urban areas and ecosystem services. Then this chapter is structured around the two research questions. Methods are discussed separately for each section.

4.3 Urban Ecosystem Services

The first human settlements were likely healthier and safer than surrounding natural areas but as industrialization expanded urban areas, cities became unhealthy places (Barton 2009). Modern urban planning arose from the need to counteract unhealthy conditions (Barton 2009) but nonetheless as urban areas continued to grow, they were constructed around social and economic development (Su, Fath, and Yang 2010) with little thought (until very recently) to the link between environmental health and human health and well-being (Barton 2009). With this recognition, especially after the release of the Millennium Ecosystem Assessment (2005), discussions have focused upon assessment of the diverse abilities of regions across the world to provide ecosystem services (Andersson, Barthel, and Ahrné 2007, Costanza 2008, Gómez-Baggethun and Barton 2013, Jansson 2013), particularly in urban areas where "the notion of urban ecosystem services is quite new" (Ernstson 2013, p 2).

What are ecosystem services? According to the Millennium Ecosystem Assessment (2005) "ecosystem services are the benefits people obtain from ecosystems" (p. V). These services are divided into four categories **–** *supporting, provisioning, regulating,* and *cultural* (Figure 4-1). Ecosystem services are not just limited to provision of services to sustain natural processes (i.e. nutrient cycling, climate regulation) but also provide for social processes (i.e. spiritual or educational) (Figure 4-1). Current research on urban ecosystems services mainly focus on a single service (Gómez-Baggethun and Barton 2013). However within an urban area, social and ecological processes are intertwined, and as such, equal attention should be given to both social and physical processes when performing ecosystem services analyses (Lehtonen 2004, Psarikidou and Szerszynski 2012, Ernstson 2013). Furthermore, with a rising world population, it behooves us to pursue strategies to reduce urban areas' footprint and increase the potential of ecosystem services within the urban area (Jansson 2013), such as urban green spaces (Andersson, Barthel, and Ahrné 2007), and specifically urban gardening (Barthel, Folke, and Colding 2010, Connolly et al. 2013, Ernstson 2013, Jansson 2013).

Figure 4.1 Ecosystem Services
(Millenium Ecosystem Assessment 2005)

4.4 Integrated Model

4.4.1 Methods

For this section, the analysis is limited to the study area, the City of Roanoke, Virginia. Using a GIS, the parameters for each of the prior two assessments were combined. As a reminder, the environmental model combined four separate parameters – percent of impervious surfaces; locations and sizes of existing parks, community gardens, and urban farms; soils; and temperature -- ranking each variable from 0 (no need) to 5 (greatest need); a block group ranking could range from 0 to 20. For the socio-economic analysis, ten parameters were evaluated using a binary ranking, 0 or 1, thus, the total ranking for the socio-economic could range from 0 (least need) to 10 (greatest need). A physical scientist would argue that physical variables are more important and thus deserve more weight when combining with socio-economic variables. Whereas, a social scientist would argue the opposite. As discussed in Section 1.4.5, social and ecological processes are interweaved and should be granted equal attention, so to provide equal weight to the ranking of the environmental parameters with the socio-economic assessment, the environmental score was divided by two.

4.4.2 Results

Table 4-1 provides the results of the integrated assessment. Blocks groups received total scores from four (least need) to 18 (greatest need). One block group (dark green in Figure 4-2) received the highest score – 18. Almost 80% of the block groups demonstrated a significant need for a new urban agriculture greenspace (score of 10 or greater). Figure 4-2 shows the distribution of the block groups by score, those locations with the greatest need (shades of green) are located within the central part of the city. The block group with the greatest need also has a significant percentage of open land (23% – as identified in Chapter 2), available for new greenspaces.

Table 4.1 Number of block groups for each score

Score	Number of block groups
18	1
17	1
16	5
15	4
14	3
13	4
12	17
11	5
10	20

9	3
8	5
7	3
6	4
4	1
Total	76

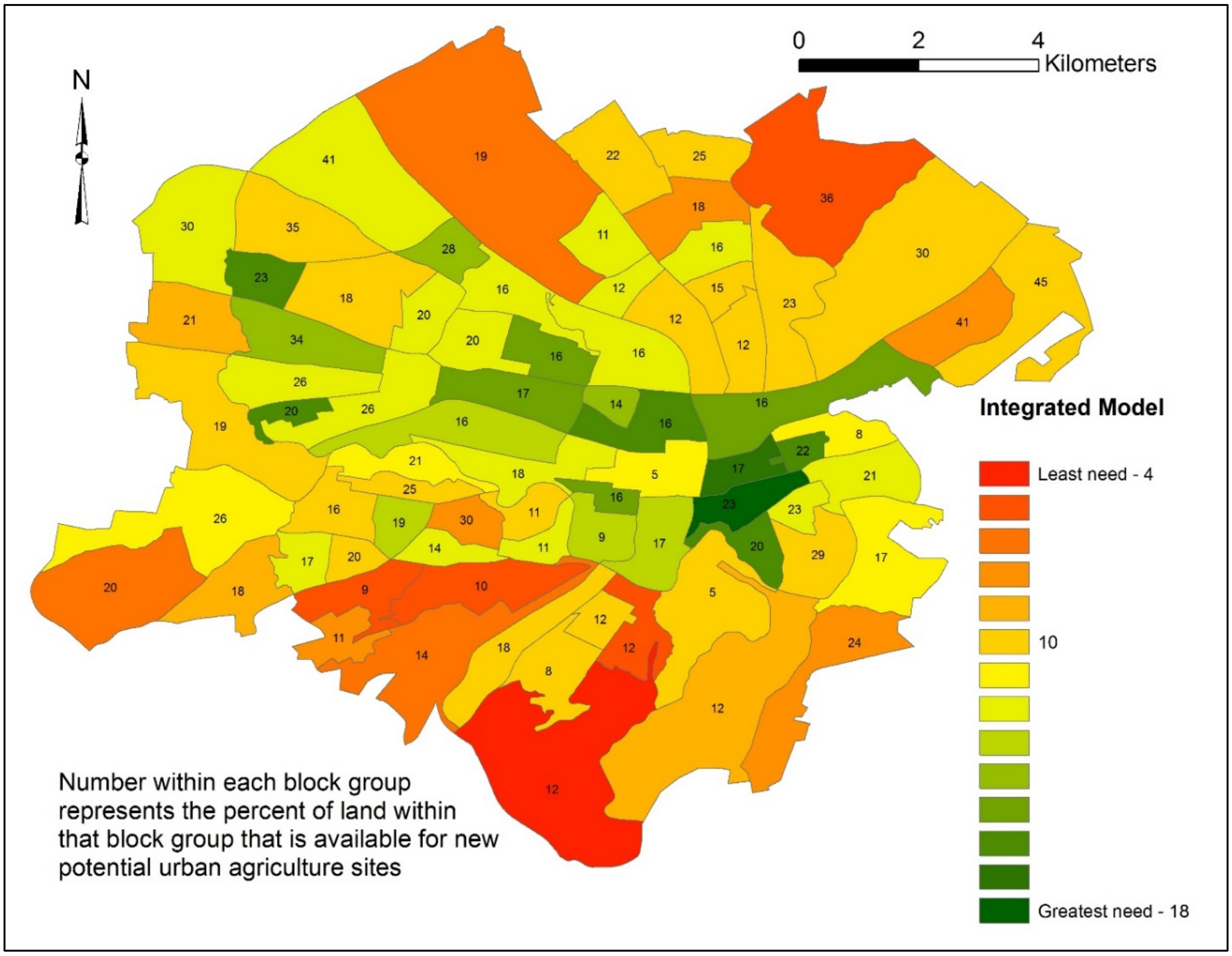

Figure 4.2 Final ranking of greatest need (18 – dark green) to least need (4 – red) for a new urban agriculture greenspace

4.5 Ecosystem Services Analysis

The analysis of urban agriculture's ability to contribute to ecosystem services was addressed with a separate evaluation for each type of ecosystem service – *cultural, regulating, supporting, and provisioning*.

4.5.1 Cultural Services

This portion of the research was accomplished through an on-line survey distributed to community garden associations and garden clubs throughout the United States. The Appendix contains the original publication.

Parece, T.E. and Campbell, J.B. "A Survey of Urban Gardeners", provisionally Chapter 17, In: Global Urban Agriculture: Convergence of Theory and Practice between North and South being edited by Antoinette Winkler-Prins. With permission of CABI.

4.5.2 Regulating Services

This portion of the research involves a rainwater harvesting evaluation. The Appendix contains the original publication.

Parece, T.E. Lumpkin, M., and Campbell, J.B. In press. ***Integrating Harvested Rainwater in Urban Agriculture****. In Sustainable Water Management in Urban Environments. T. Younos and T. Parece, eds. Book Series: The Handbook of Environmental Chemistry, Volume 47; Springer. "With Permission of Springer"*

4.5.3 Supporting Services

This portion of the research involves evaluating Normalized Difference Vegetation Index (NDVI) for select locations of urban agriculture to determine if urban agriculture positively contributes to net primary production. The Appendix contains the draft of the original publication submitted to an academic journal for review on January 7, 2016

Parece, T. E. and Campbell, J.B. Under review. ***An Analysis of the Ecological Impacts of Community Gardens using NDVI***

4.5.4 Provisioning Services

This portion of the research involves an estimation of food production potential for the locations identified above in *Section 2.4.1 - Land Inventory for Potential Urban Agriculture Locations*. The draft of the original publication for this analysis is found in the Appendix. It is currently under review by two committee members.

Parece, T. E., Campbell, J. B. and Hodges, S. C. ***A Comparative Analysis of Methods to Calculate Urban Agriculture's Production Potential***

4.6 Conclusions

All census block groups within Roanoke demonstrated some type of need, physical or socio-economically, for new greenspaces. No one parcel showed only physical needs and no one parcel showed only socio-economic needs. The ecosystem services evaluation demonstrates that implementing urban agriculture within Roanoke can provide benefits in each of the different ecosystem services categories and contribute to Roanoke's sustainability. Furthermore, the ecosystem services evaluation methods, outlined in each manuscript, can be applied to identify and quantify urban agriculture ecosystems services for other urban areas.

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5 Chapter – Conclusions

Agriculture has formed a part of urban systems since humans first formed cities thousands of years ago (van Leeuwen, Nijkamp and de Noronha Vaz 2010). Research on urban agriculture has been present for decades. But, with increasing world populations, the majority now residing in urban areas, and increasing sizes of urban areas, questions have arisen as to how to alleviate food insecurity present for ~ 800 million people worldwide. Thus, within the past few years, urban agriculture research has expanded exponentially.

However, the research into siting urban agriculture is limited, and is often restricted to identification and assessment of vacant lots for new urban agriculture sites (e.g., Balmer et al. 2005, Kaethler 2006, Horst 2008, Taggart, Chaney and Meaney 2009, Colasanti and Hamm 2010, Grewal and Grewal 2012, Meenar and Hoover 2012, McClintock, Cooper, and Khandeshi 2013). These *land inventories* utilize GIS, sometimes with limited remote sensing, and, rarely, include socio-economic analysis. Furthermore, by identifying vacancy as the first qualification, the *land inventories* are analyzing land use when, logically, a land cover analysis should be conducted first. The research conducted herein, first accomplished a land cover analysis, next analyzed land use, and included a socio-economic analysis.

Furthermore, this *land inventory* went beyond prior analyses by categorizing all areas identified as open and available for urban agriculture into a hierarchy of need for new greenspaces to help alleviate physical and socio-economic disparities. This hierarchy evaluated variations in physical attributes (Chapter 2) and socio-economic factors (Chapter 3), and identified those areas that have greatest to least need for new urban agriculture greenspaces (Chapter 4). In addition, the research included identification of potential ecosystem services that these new urban agriculture greenspaces could provide (Chapter 4). This research's methods are outlined, individually, in several published manuscripts, providing researchers, urban officials, or other urban sustainability stakeholders the ability to replicate any portion of this research.

Many barriers existed for this research. For Chapter 2, geospatial data was not available for all impervious surfaces within Roanoke, nor for the city's stormwater management infrastructure. So the research required investment of a substantial amount of time to manually delineate impervious surfaces, necessary to identify areas open and available for new greenspaces, and to identify those areas most exposed to stormwater runoff. Due to unavailability of data, accurately delineating watersheds in Roanoke incorporating stormwater infrastructures was not possible, so a method was developed using another location that is represented by complete infrastructure data. The impervious surface, watershed, and terrain identification and analysis would have greatly benefited from finer resolution data, such as lidar, but such data was not available during the course of this research, nor were funds available to obtain new data. Lidar has been recently flown for Roanoke, now providing data to support a new analysis that could form the basis for comparing results.

Further, in Chapter 2, collection of temperature data was problematic at times because of changing weather patterns – mesonet driver and helper lists were compiled weeks in advance, and volunteers were constantly on standby, with sometimes only a day's notice for field collection. Additionally, the goal was to collect temperature data with the mobile units during Landsat flyover dates and times in order to conduct a comparative analysis. But in most cases, calm, clear weather patterns did not correspond with Landsat flyover dates and times. Software difficulties with the new fixed weather stations in the city's public schools created many instances when some fixed weather stations were not transmitting on mobile mesonet dates and times. Eventually, for most new fixed stations, these problems were eliminated and relationships developed between Virginia Tech and either an individual school official or teachers with whom future communication can occur when the RCPS weather stations are not transmitting on-line.

A large number of citizen scientists volunteered for the *in-situ* phenological data collection (Chapter 2). But, yet again, weather interfered with data collection. The spring of 2014 was cooler than normal, thus start of season was delayed, and in some cases, volunteers were not available when bud burst began to occur. Further, while a large number of people volunteered to assist, most of the monitoring occurred in the eastern and southern part of the city.

Although the physical analysis was based upon a 30 meter resolution level, most of the data was aggregated at the census block group level because much of the socio-economic data is not available at a finer scales (Chapter 3). The greatest socio-economic barrier that arose during this research related to health data. No health data was available at a scale finer than the city-level. Thus, use of an appropriate proxy for health data – student eligibility rate by school for the National School Lunch Program (Houston, Marzette, Ames, and Ames, 2013; The Brookings Institute as referenced by Smit, Nasr, and Ratta 2001) — was necessary.

A greenspace can assist in mitigating higher air temperatures, reducing stormwater flow, and increasing ground water infiltration – assisting in urban sustainability efforts. Additionally, greenspaces provide areas where residents can participate in recreation, exercise and social activities. An urban agricultural greenspace adds additional benefits – increased access to fresh and nutritious foods, lowering food budgets, and opportunities for income from selling food and non-food products (as identified in Chapters 3 and 4). An urban agricultural greenspace can also be used to mitigate waste generated by an urban area by using organic matter for composting, by harvesting rainwater, or by recycling waste water for irrigation (as identified in Chapter 4). Furthermore while any greenspace provides an area for social interaction, an urban agricultural greenspace provides the opportunity for nearby residents to feel a sense of inclusion in their community when they take ownership of their greenspace through cultivation of the land and food production (as identified in Chapter 4).

This research is not a complete analysis of urban agriculture – barriers still exist to its implementation, for example

- appropriate zoning ordinances for each urban agriculture form;
- general education of citizens on urban agriculture - popular media in Roanoke – newspaper articles and TV news reports - show that many residents of Roanoke lack a clear understanding of urban agriculture, its purpose and dimensions;
- agricultural education - including plant cultivation, harvesting and food preparation - for those who are lacking such knowledge, to include cooperative extension involvement;
- including resident input into future development plans; and
- a need for trust between local residents and city officials regarding sustainability of any new urban agriculture greenspaces.

Furthermore, those areas the *land inventory* identified as open and available require individual physical site analysis (as noted in Chapter 2). Additional research can include:

- documenting production totals for those existing locations of urban agriculture within Roanoke;
- testing soils at new sites for contaminates, organic matter, soil organisms, and nutrients (both macro- and micro-);
- comparing soils from new sites to those active agriculture sites for differences – improvements or other changes;
- documenting flora and fauna diversity within the sites;

- comparing flora and fauna diversity within sites to areas within differing buffer zones around the site to determine the exact distance of the site's impact zone;
- determining the exact volumes of harvested rainwater captured and used at existing sites;
- testing harvested rainwater for its quality;
- comparing plants irrigated with harvested rainwater to those using potable water to determine if any chemicals in potable water impact growth of the plants or food products; and
- comparing plants at different locations within a specific urban agriculture site – do plants on the outskirts fare better or worse than those on the interior.

Additional research questions that could be asked include:

- Does intercropping actually result in greater production capacity?
- What intercropped plants produce the greatest production levels?
- If non-food plants are included in cultivation, which plants generate the greatest benefit to food production?
- How much income can be generated for an individual within a year?
- How much financial impact does producing one's own food generate, i.e. how much of the food budget is actually reduced?
- Does this reduction occur only during the growing season?

The completion of this research is just a beginning to expand urban agriculture research.

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Appendix – Publications related to this Research

Remote Sens. **2013**, *5*, 4942-4960; doi:10.3390/rs5104942

OPEN ACCESS

Remote Sensing

ISSN 2072-4292

www.mdpi.com/journal/remotesensing

Article

Comparing Urban Impervious Surface Identification Using Landsat and High Resolution Aerial Photography

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Received: 10 July 2013; in revised form: 14 September 2013 / Accepted: 25 September 2013 / Published: 10 October 2013

Abstract: This paper evaluates accuracies of selected image classification strategies, as applied to Landsat imagery to assess urban impervious surfaces by comparing them to reference data manually delineated from high-resolution aerial photos. Our goal is to identify the most effective methods for delineating urban impervious surfaces using Landsat imagery, thereby guiding applications for selecting cost-effective delineation techniques. A high-resolution aerial photo was used to delineate impervious surfaces for selected census tracts for the City of Roanoke, Virginia. National Land Cover Database Impervious Surface data provided an overall accuracy benchmark at the city scale which was used to assess the Landsat classifications. Three different classification methods using three different band combinations provided overall accuracies in excess of 70% for the entire city. However, there were substantial variations in accuracy when the results were subdivided by census tract. No single classification method was found most effective across all census tracts; the best method for a specific tract depended on method, band combination, and physical characteristics of the area. These results highlight impacts of inherent local variability upon attempts to characterize physical structures of urban regions using a single metric, and the value of analysis at finer spatial scales.

Key Words: impervious surfaces; urban; Landsat; high-resolution imagery; landuse classification; Roanoke; Virginia

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1. Introduction

Urbanization is arguably one of the most significant landuse/landcover change occurring in the world today [1,2]. Sizes and distributions of urban areas are dynamic because of rising populations. In 2009, for the first time in history, the percentage of human population that lived in urban areas exceeded 50%—the United Nations estimates this percentage will increase to 69% by 2050 [3]. Although urban expansion is often attributed to increasing population, the rate of conversion to urban land uses far exceeds the rate of urban population increase, a phenomenon common across the world [3].

Conversion to urban land—losses of agricultural and forested lands, coupled with increasing impervious surface cover—has direct effects on natural temperature regulation [4,5] and alters the hydrologic cycle [5–7]. Decreasing vegetative cover and increasing impervious surface cover alters thermal processes in urban regions, thus creating warmer temperature regimes relative to rural areas (urban heat island effect) [5,8,9]. Alteration of the hydrologic cycle represents the most significant urban water quality issue present today [5,6,10] because stormwater runoff from impervious surfaces creates water quality problems including higher water temperatures and elevated levels of contaminants in surface waters [5,11]. A better understanding of such impacts is required to effectively address these adverse issues [5,10,12].

Mapping impervious surfaces is essential for evaluating these impacts and implementing effective environmental and urban management planning [5,10,12–17]. Since the 1970s, remote sensing has been widely used for analyses of urban areas [5,13,18,19]. The earliest research specifically devoted to impervious surface identification began in the 1990s, but was limited in scope until high-resolution imagery and increased computing power became available (in the mid-2000s) [13].

High-resolution imagery provides the spatial detail necessary to record the fine-scale heterogeneity present within an urban area [12,13,15,18,20–22]. Researchers readily acknowledge that this fine-scale heterogeneity is a problem for remote sensing, especially with regards to creating mixed pixels (pixels influenced by the variation in spectral values present within its dimensions). Ultimately, the solution to this issue lies in identification of analyses capable of resolving this fine detail. However, acquisition and analysis expenses, limited spatial extent, and high costs of sequential coverage limit routine applications.

Because of this heterogeneity, a wide variation in remote sensing techniques, image sources, and effectiveness exists from study to study [5,13,18], and creates a lack of uniformity that limits our ability to make comparisons between studies [5,18]. Furthermore, the success of each of the approaches is often evaluated in different ways, for example—accuracy assessments, root mean square error, absolute error, which presents obstacles for other researchers to effectively interpret the findings and identify the most effective method(s).

Despite the relatively coarse spatial resolution of Landsat imagery in the context of urban analysis (30 m by 30 m pixel size), it offers advantages of affordability, accessibility, multispectral coverage, sequential acquisition, and the spatial scope to represent complete urban systems. Much literature is specifically devoted to applications of Landsat imagery to derive impervious surfaces, however, assessing and comparing even this body of literature is very difficult. A selection of this literature is presented in Table 1 ([10,19,23–48]), which does not attempt a comprehensive review, but rather presents an illustration of the variety of techniques applied in many different areas. Only one of these studies evaluates the effectiveness of a multi-scale approach (from a finer scale to increasingly larger scales—see [23]). Very few have compared applications of alternative techniques within the same milieu (see [49–51]).

Table 1. Selected Studies, using Landsat imagery, that illustrate the variety of classification techniques to identify impervious surfaces.

Method as Identified in Paper	**Location (Image Date) [Reference]**
Artificial neural networks	State of Connecticut, USA (1995) [10]; Central New York State, USA (2001) [24]
Linear segmentation	Bangkok, Thailand (1987) [25]
Subpixel analysis	Charleston, SC, USA (1990) [26]; DuPage and Cook Counties, IL, USA (1997) & East Greenwich, RI, USA (1997) [27]; State of Missouri, USA (1980, 1990 & 2000) [28]
Linear mixture analysis	Columbus, OH, USA (1999) [29]
NDVI	Atlanta, GA, USA (1979, 1987, &1997) [30]; Fairfax County, VA, USA (1990, 1995, & 2000) [31]; Montgomery County, MD, USA (1990–2001) [32] Tampa Bay, FL, USA (1991–2002) [33] Seattle-Tacoma, WA, USA (1986 & 2002) and Las Vegas, NV, USA (1984 & 2002) [34]; Cixi County, China (1987, 2000, 2002 & 2009) [35]
Regression tree	Sioux Falls, SD, USA (2000), Richmond, VA, USA (1999), and the Chesapeake Bay, USA (1999–2001) [23]; Western Georgia, USA (1993 & 2001) [36] Washington DC-Baltimore, MD, USA (1984–2010) [37]
Spectral mixture analysis	Columbus, OH, USA (1999) [38]; Marion County, IN, USA (2000) [39]; Lake Kasumigaura, Japan (1987, 2000, & 2007) [40] Franklin County, OH, USA (1999) [41]
Regression analysis with tassel cap	Twin Cities Metropolitan Area, MN, USA (1986–2000) [19]; State of Minnesota, USA (1990 & 2000) [42]; Franklin County, OH, USA (1999, 2000, & 2003) [43]
Support vector regression using sub-pixel classification	Germany (1999–2001) [44]
Object oriented classification and Normalized Difference Built-up Index	Jiaozuo, China (2007) [45]
Multi-layer perceptron neural network with support vector machine	Beijing, China (2009) [46]
Normalized Impervious Surface Index	Xiamen City, China (2009) [47]
Linear spectral unmixing	Pearl River Delta, China (1998, 2003 & 2008) [48]

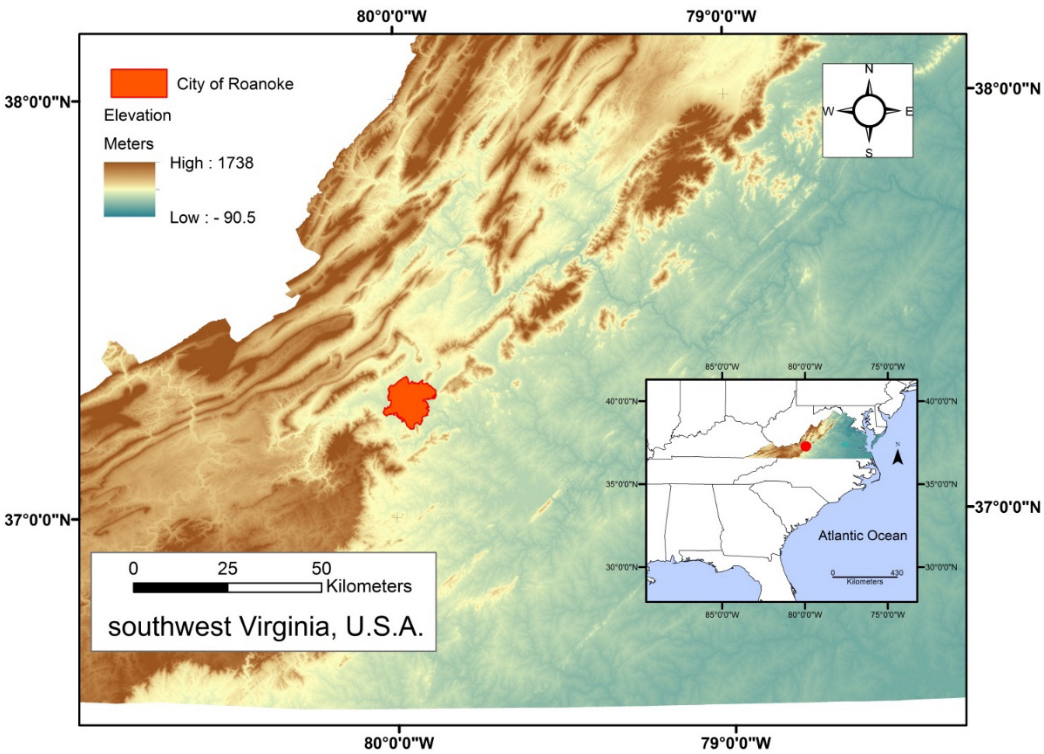
Therefore, the objective of this paper is to evaluate accuracies of selected image classification strategies, as applied to Landsat imagery. It will assess the effectiveness of Landsat data for mapping urban impervious surfaces by using a reference data set manually delineated from high-resolution aerial photos. We then evaluated the robustness of these strategies at a finer scale. Our goal is to identify the most effective method(s) for delineating impervious surfaces using Landsat imagery, and to determine if finer scale analyses are needed, thereby guiding applications for selecting cost effective delineation techniques for urban regions.

2. Methods

2.1. Study Site and *Data*

The study site is the City of Roanoke, Virginia, USA, a small city (110 square kilometers) located in a valley in southwest Virginia (Figure 1). Roanoke is the largest city in Virginia, outside of the major metropolitan areas in the eastern part of the Commonwealth. Although small in area, Roanoke has a population density comparable to much larger cities in the USA.

Figure 1. City of Roanoke, Virginia, USA Reference Map.



Over recent decades, Roanoke has been the focus of substantial urbanization, economic stress, and landuse changes. Roanoke has substantial drainage problems and experiences frequent flooding due to its proximity to the Roanoke River, the river's tributaries, and urban stormwater runoff from impervious surfaces. Many segments of the Roanoke River system within the city are on the Virginia Department of Environmental Quality's impaired waters list, due to contaminants such as *Escherichia coli*, high water temperatures, and heavy metals [52]. In addition, its CO_2 emissions were estimated at 2.3 million tons in 2009 [53], and city officials estimate impervious surface cover at 28% [54]. For our analysis, Roanoke offers the advantage of a compact urban region with a range of land uses and urban environments that permit evaluation of alternative analytical strategies.

2.2. Delineating Impervious Surfaces from Aerial Photos

GIS shapefiles—roads, buildings, and parcels—for our study site were downloaded from Roanoke's geospatial data gateway and the US Census Tigerline data gateway. We accessed aerial photos through the Virginia GIS server with ESRI's ArcCatalog® GIS server connection. The Virginia Base Mapping

Project 2011 flyover for the city occurred between 4 March 2011 and 10 March 2011 [55], completed with 6 inch resolution [56].

We overlaid the city's boundary, parcels, and building shapefiles on the 2011 aerial photos, and, using them as guides, impervious surfaces were delineated in GIS. Many urban researchers have conducted their analyses using landuse or landcover boundary delineations, (see [9,57,58]; this strategy seems to be fruitful for studies that focus upon analysis of urban heat island, but is less well-matched for studies that must consider other dimensions of the urban landscape. For our analysis, impervious surface delineation was accomplished separately by each census tract because: (a) each census tract is spatially compact and contains different landuse/landcovers with varying percent impervious, (b) subdividing the study area provides the ability to evaluate intra-urban variations at a fine scale, and (c) providing impervious surface data individually by census tracts allows for consideration of impervious surfaces' relationships with demographic data. Census tracts are spatial subdivisions delineated by the United States government for which statistical data is collected during the decennial census [59]. After editing roads and buildings shapefiles, we joined these using GIS, creating a single polygon for each census tract, then calculated percent impervious for each.

2.3. Landsat Image Processing

A cloud-free Landsat TM 5 scene (path 17, row 34, dated 13 March 2011) was obtained from the US Geological Survey's GloVis server. The US Geological Survey provides the scenes with georeferencing already complete. The image was cloud-free and LEDAPS [58,60] preprocessing removed remaining atmospheric effects during preparation of the surface reflectance image. A histogram adjustment was conducted to ensure no negative reflectance values.

The image was subset to form multiple band combinations—bands 5, 6 and 7; bands 1, 5, and 7; and bands 2 through 6. We chose to include the thermal channel (band 6) because of impervious surfaces contribution to UHI [20–22], and bands 1, 5, and 7 as band 1 is useful for distinguishing soil from vegetation, and the spectral properties of impervious surfaces can mimic soil surfaces [61,62]. Supervised classification was performed on the entire scene for these three images and an image with all seven bands.

Training Areas of Interest (AOIs) were created separately for each band combination using a binary classification—*impervious* and *other*. Locations for the impervious surfaces' training areas were identified using the aerial photos, typically including man-made objects such as the airport runways, parking lots, US Interstate highways, and large buildings—shopping malls/centers. Training areas for the *other* category included all pervious landcovers—agriculture, forests, water, and included several golf courses. We did not limit our training areas to Roanoke City but used the entire Landsat scene to avoid including mixed pixels, which were often problems near roads and for the city's urban forest. We created AOIs for the *other* category using forested areas in the Jefferson National Forest (west and southwest of the City). We created AOIs for the impervious surfaces related to roads by using wider segments of the Interstate 81 corridor where the pavement has four or more lanes in each direction with little to no adjoining vegetation.

Using a feature space created separately from each image, we assessed the training data for normality, separability, and partitioning, and combined selected areas of interest as needed. These assessments ensured that brightness values for our different categories were not highly correlated, were mutually independent between bands, and that spatially separate pixels were not spectrally similar to each other. Our final signatures represented multiple different and distinct spectral classes for each of the two landcover categories—*impervious* and *other*. Four supervised classifications were performed on each image—parallelepiped, maximum likelihood, minimum distance, and Mahalanobis' distance.

2.4. Validation Points and Accuracy Assessment

We created a validation dataset by generating a shapefile of random points for each census tract. The total number of random points for the entire city was 1,877—the numbers of samples positioned within census tracts varied from 50 in the smallest census tract to 115 in the largest. We overlaid these point files individually on the 2011 aerial photos and identified each point as either *impervious* or *other*.

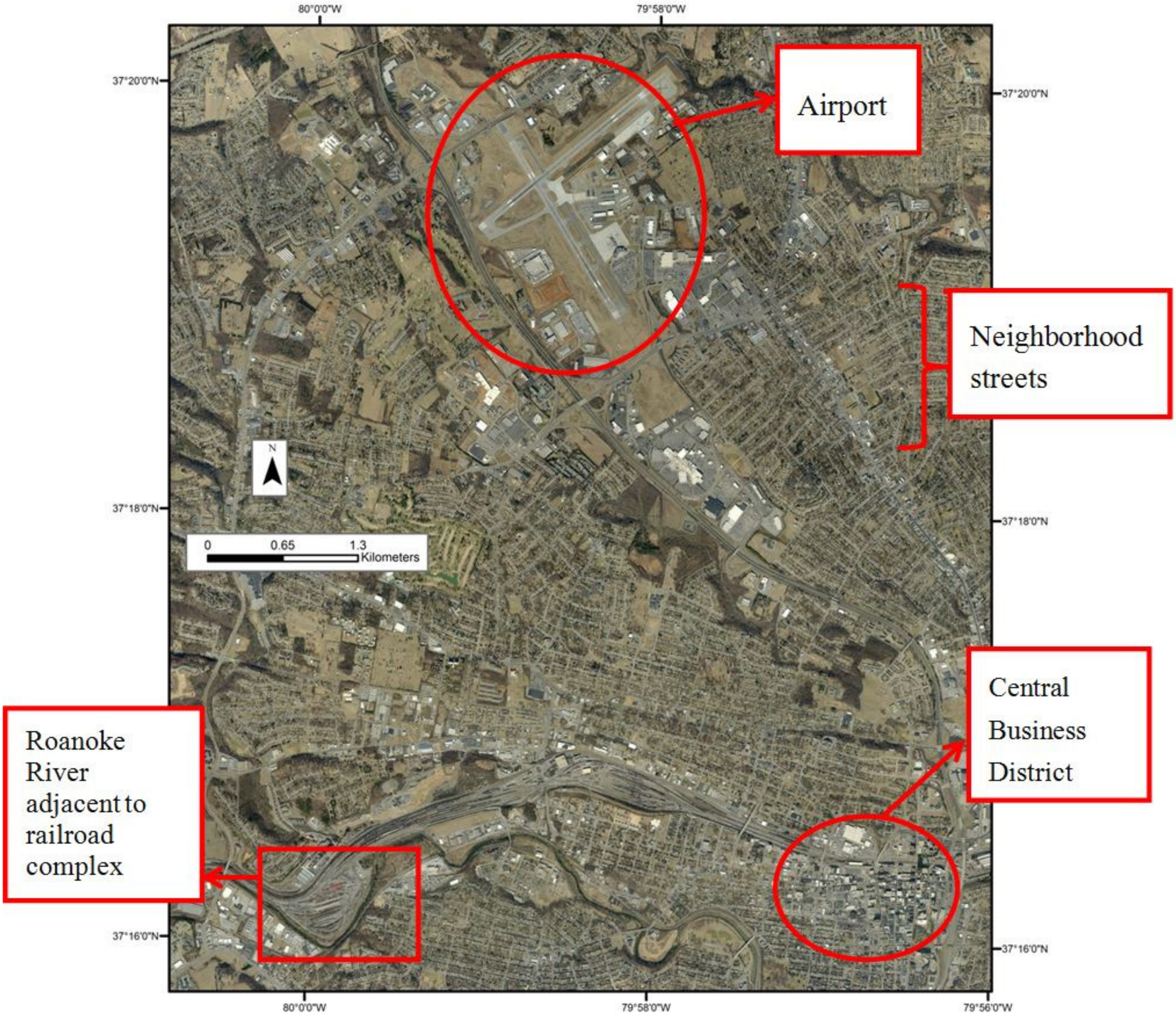
The most widely utilized data set in the USA for impervious surfaces was developed by the Multi-Resolution Land Charateristics Consortium (MLRC) as part of the National Land Cover Database (NLCD). This raster dataset was developed to identify "percent developed imperviousness" for the coterminous USA [63]. The dataset was derived by means of regression tree software using both leaf-on and leaf-off Landsat images and images from NOAA's Defense Meteorological Satellite Program [63]. The National Land Cover Database Impervious Surfaces (NLCD IS) dataset presents a continuous layer with a gradient of imperviousness from 0 to 100 percent for each 30 m by 30 m pixel [64], *i.e.*, the value of each pixel is identified as the percent of impervious surfaces present within that pixel. Accuracy assessments have been performed on the full NLCD with resulting overall accuracies ranging from 59.7% to 80.5% [65], 43%–83% [66], and 78%–85% [67]. We were unable to locate a similar accuracy assessment performed specifically on the NLCD IS dataset.

Using the random points, we performed an accuracy assessment of the NLCD IS dataset representing our study area. After downloading the dataset from the MRLC website, we used GIS to generate several binary files with varying impervious thresholds from 10% to 75%, masking the extent to the city's political boundary. We added each NLCD threshold file to the attribute tables of our random points shapefile, and calculated user's accuracy, producer's accuracy and overall accuracy for each threshold. We performed this assessment to establish a base threshold for overall accuracies of our classified Landsat images. Our method for this assessment differs from those employed by other researchers because we are assessing the presence or absence of impervious surfaces, whereas they calculated accuracies for all landcover/landuse categories (see [65–68])

The datum for Landsat Imagery is WGS 1984 and the datum for the NLCD is NAD 1983 Albers. So, for each classified image, we changed the spatial reference from WGS 1984 to NAD 1983 Albers so our accuracy assessments would be comparable to that of the NLCD IS data. We added the value of each pixel (*impervious* or *other*) for each classified image for each point to the random points' attribute table, and then calculated overall accuracy for each image.

Our objective is to determine the most effective method(s) for identifying impervious surfaces from Landsat imagery. As such, as explained below and in table in Section 3.3, we chose the four classified images with the highest overall accuracies and compared those images to the aerial photos. We examined them visually to assess their effectiveness in delineation of specific landmarks, such as the airport, river, railway complex, neighborhood streets, and central business district (Figure 2) by comparing the results to our aerial photos.

Figure 2. Specific locations for visual accuracy.



2.5. Assessment of Accuracy at the Census Tract Scale

After choosing the images with the greatest overall accuracy for the entire study site, we then assessed accuracy variations within the urban system, using census tracts as units. Although census tracts form somewhat arbitrary units for investigating impervious surfaces, their use here supports related analyses in our study area, and provides boundaries with which governments and institutions are increasingly defining their urban space within the USA. We chose eleven contiguous census tracts within our study site to accomplish the assessment. These included the census tract with the smallest area (also the most highly developed as it comprises the central business district—Number 11), the largest in area (6.01), and the census tract with the least amount of development (28).

3. Results

3.1. Aerial Image Delineation of Impervious Surfaces

The percent impervious, as delineated from the aerial photos, for the eleven census tracts used in the finer scale analysis ranged from 13.3% (Tract 28) to 89.5% (Tract 11) (Table 2). The smallest census tract (11), 105.3 ha, representing the central business district, has the largest percent impervious at 89.5%. Census Tract 28, with the smallest percent impervious (13.3%), is the second largest in area (1,077.5 ha).

Table 2. Percent impervious (IS) delineated from aerial photos and total area of census tract.

Census Tract No.	3	4	5	6.01	6.02	11	23	24	26	27	28
Percent IS	44.5	37.4	44.2	22.5	32.0	89.5	24.3	26.7	39.6	35.5	13.3
Hectares	883.3	359.6	354.3	1,106.1	599.8	105.3	789.7	283.9	159.2	415.1	1,077.5

3.2. Accuracy Assessments of the NLCD IS Data Set

For pixel impervious values ≥ 10%, the accuracies of the several binary classifications of the NLCD IS data resulted in overall accuracies ranging from 53.5% (pixel impervious value ≥ 10%) to 72.8% (pixel impervious value ≥ 45%) and kappas from 0.21 to 0.43 (Table 3). Accuracy and kappa increase as the threshold of impervious percent increases until about 40%–50%. Overall accuracies range between threshold values of 35% and 75%, and are consistently close to 70% or above. These results are consistent with the overall accuracy assessments completed on the general NLCD performed by other researchers (see [65–69]), and thus, form our baseline with which to compare our different classifications on the Landsat Images.

Table 3. Overall accuracy and kappa of Roanoke's NLCD IS dataset at varying thresholds of percent impervious.

Impervious Threshold	**Overall Accuracy**	**Kappa**
10%	53.5%	0.21
35%	68.6%	0.39
40%	71.4%	0.42
45%	72.8%	0.43
50%	72.6%	0.39
75%	70.6%	0.25

3.3. Accuracy Assessments of the Supervised Classifications

Overall accuracies for all sixteen supervised images ranged from 50.8% (Mahalanobis' distance: all bands) to 72.1% (parallelepiped: bands 2–6) (Table 4). Our kappa values for these classified images ranged from 0.16 (Mahalanobis' distance: all bands) to 0.40 (minimum distance: bands 1, 5, and 7) (Table 4). All the classification methods using the band combination of channels 2–6 produced results similar to the NLCD IS standard. The results for ten of our sixteen classified images were comparable to results achieved for the NLCD IS (*i.e.*, for pixel impervious values ≥ 10%, NLCD IS overall accuracies remained steady around 70% and the kappas for the NLCD IS around 0.40).

Since our objective was to identify the most effective method(s), we selected parallelepiped—bands 2–6; minimum distance—bands 1, 5, and 7; and minimum distance—all bands to include in our finer scale assessment at the census tract level. These three images had the highest overall accuracies and highest kappas. In addition, we had other several classified images that achieved results similar to the NLCD IS standard, so, we also chose to include the image which attained the highest overall accuracy and highest kappa—Mahalanobis' distance—bands 5, 6, and 7. These selections gave us one classified image from each band combination and the four images for our finer scale assessment.

Table 4. Overall accuracy (OA) and kappa of all sixteen classified Landsat images *.

Image and Classification	OA	Kappa	Image and Classification	OA	Kappa
All Bands			**Bands 2–6**		
maximum likelihood	56.5%	0.22	maximum likelihood	68.3%	0.38
minimum distance	**70.8%**	**0.39**	minimum distance	67.6%	0.33
parallelepiped	64.4%	0.32	**parallelepiped**	**72.1%**	**0.33**
Mahalanobis' distance	50.8%	0.16	Mahalanobis' distance	68.6%	0.38
Bands 1,5, & 7			**Bands 5, 6, & 7**		
maximum likelihood	59.8%	0.28	maximum likelihood	67.7%	0.35
minimum distance	**71.1%**	**0.40**	minimum distance	55.1%	0.18
parallelepiped	67.3%	0.36	parallelepiped	67.2%	0.32
Mahalanobis' distance	61.8%	0.31	**Mahalanobis' distance**	**69.4%**	**0.38**

Notes: *classified images in red were chosen for the finer scale analysis.

3.4. Comparison of Aerial Photos to Supervised Classifications

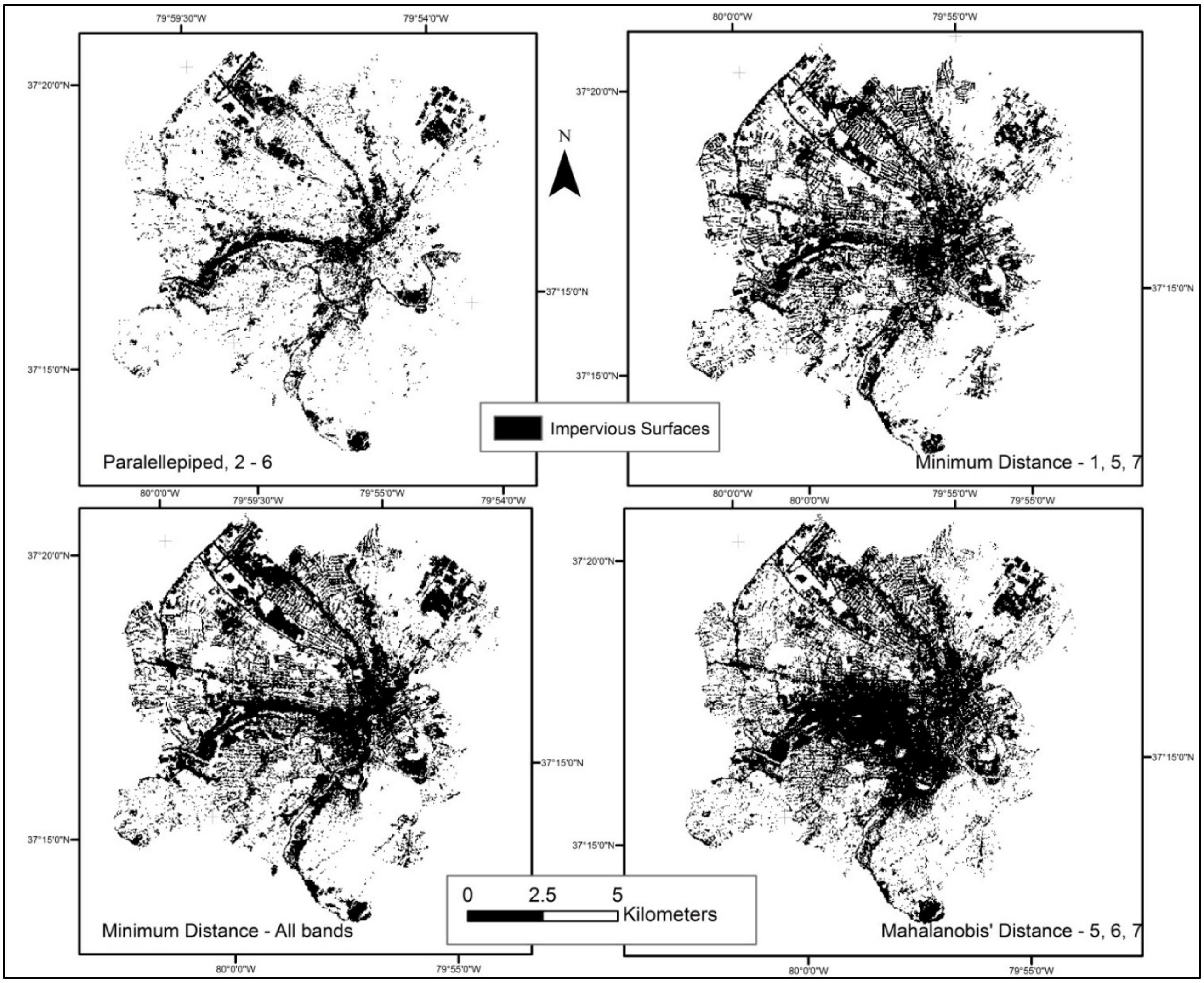
In this section, we are only reporting our visual assessment of the four classified images chosen in Section 3.3 above. Each of the images (Figure 3) provided sharp detail for the airport area, the major roads and highways, the railway complex, and a large shopping center near the airport. Minimum distance—bands 1, 5, and 7; minimum distance—all bands; and Mahalanobis' distance—bands 5, 6, and 7 provide additional detail including most of the neighborhood streets. Minimum distance—bands 1, 5, and 7; minimum distance—all bands; and parallelepiped clearly record the high concentration of impervious surfaces within the central business district. Minimum distance—all bands performed the best in separating the river from the surrounding impervious surfaces, an area which can cause difficulty because of the many bridges crossing the river and sediments within the river from stormwater runoff. The neighborhood streets can cause difficulties with different classification algorithms because of shadowing from buildings and some trees, along with variations in width and types of adjoining vegetation.

3.5. Supervised Classification Results—Finer Scale

Table 5 encapsulates the results from the manual delineation of the percent impervious for each census tract, and the percent impervious per census tract for each of the four chosen classified images

(Figure 3). The divergence of the classified image percent from the manual delineation percent is enumerated in Table 6 (negative values indicate under estimates). Parallelepiped—bands 2–6 consistently under-estimated the percent impervious in all census tracts (a range in differences from −21.5 to −5.2) (Table 6). The other three methods over-estimated percent impervious for all census tracts (a range in differences from 1.0 to 27.5) (Table 6). No single method produced consistent under- or over-estimates in all the census tracts.

Figure 3. Impervious surfaces as classified by four algorithms.



When examined at finer scale, no one method consistently provided the highest accuracies and kappas in all tracts. Overall accuracies and kappas for each of the four images by census tract were variable (Table 7), consistent with the percent impervious comparisons in Tables 5 and 6. However, in six of the census tracts, all four methods achieved accuracies similar to the NLCD IS standard. Two of our census tracts had accuracies that exceeded those standards—Tracts 11 and 28. Census Tract 11 has the highest percent impervious and both minimum distance images achieved accuracies in excess of 80.0%. Census Tract 28 has the lowest percent impervious; all methods achieved accuracies in excess of 78%. We did find two census tracts (4 and 27) where the overall accuracies were lower than the NLCD IS standard.

Table 5. Percent impervious for the manual delineation of aerial photos and percent impervious for each of the four chosen classification methods (Figure 3), and listed by census tract.

Census Tract No.	Method				
	Aerial Photos	**Parallelepiped (Bands 2–6)**	**Minimum Distance (Bands 1, 5 & 7)**	**Minimumdistance (All Bands)**	**Mahalanobis' Distance (Bands 5, 6, &7)**
	% IS *	% IS	% IS	% IS	% IS
3	44.5	36.4	49.5	59.1	53.7
4	37.4	19.3	55.3	52.5	52.4
5	44.2	25.2	59.8	58.1	69.3
6.01	22.5	17.3	24.6	30.1	29.3
6.02	32.0	23.0	39.2	39.8	39.0
11	89.5	84.0	93.8	96.6	92.7
23	24.3	12.8	33.6	33.5	26.2
24	26.7	5.2	40.4	36.8	53.4
26	39.6	29.0	61.2	61.3	67.1
27	35.5	24.3	56.4	52.2	58.6
28	13.3	7.5	18.2	14.3	17.9

Notes: * IS = impervious surface.

Table 6. Difference in percent imperious between aerial photo delineation and classified images, listed by census tract *.

Census Tract No.	Method			
	Parallelepiped (Bands 2–6)	**Minimum Distance (Bands 1, 5 & 7)**	**Minimum Distance (All Bands)**	**Mahalanobis' Distance (Bands 5, 6, &7)**
3	−8.1	5.0	14.6	9.2
4	−18.1	17.9	15.1	15.0
5	−19.0	15.6	13.9	25.1
6.01	−5.2	2.1	7.6	6.8
6.02	−9.0	7.2	7.8	7.0
11	−5.5	4.3	6.9	3.2
23	−11.5	9.3	9.2	1.9
24	−21.5	13.7	10.1	26.7
26	−10.6	21.6	21.7	27.5
27	−11.2	20.9	16.7	23.1
28	−5.8	4.9	1.0	4.6

Notes: *a negative value indicates an under-estimate.

All classification methods produced overall accuracies equal to or exceeding results of the city-wide NLCD IS in the majority of the census tracts (parallelepiped bands 2–6 and minimum distance all bands in eight of eleven tracts, and the other two methods in seven of eleven tracts). The methods also produced overall accuracies in 18 of 44 assessments that exceed the city-wide NLCD IS standard (≥75%), and at least one kappa higher than the NLCD IS standard (≥0.43). In most cases, the highest overall accuracy and highest kappa for a specific census tract was from the same method, with three exceptions—Census Tracts 6.01, 6.02 and 28.

Table 7. Overall accuracy (OA) and kappa (k) for each of the four chosen classified images, listed by census tract.

Census Tract No.	Method							
	Parallelepiped (Bands 2–6)		Minimum Distance (Bands 1, 5 & 7)		Minimum Distance (All Bands)		Mahalanobis' Distance (Bands 5, 6, &7)	
	OA	k	OA	k	OA	k	OA	k
3	76.7%	0.52	60.2%	0.21	66.0%	0.33	64.1%	0.29
4	57.9%	0.18	61.8%	0.23	56.6%	0.12	65.8%	0.31
5	70.7%	0.41	61.3%	0.21	68.0%	0.35	66.7%	0.31
6.01	81.7%	0.38	75.7%	0.31	75.7%	0.36	75.7%	0.39
6.02	76.7%	0.44	71.1%	0.40	74.4%	0.45	72.2%	0.39
11	78.0%	0.23	88.0%	0.34	86.0%	0.17	78.0%	0.03
23	78.4%	0.29	79.4%	0.49	73.5%	0.39	77.5%	0.38
24	69.1%	0.09	75.0%	0.47	73.5%	0.44	69.1%	0.40
26	64.9%	0.12	71.9%	0.47	68.4%	0.40	68.4%	0.41
27	65.8%	0.24	64.6%	0.28	65.8%	0.30	60.8%	0.24
28	85.8%	0.31	78.8%	0.21	82.3%	0.28	85.0%	0.47

4. Discussion

For our study site, at least four of the supervised classification methods performed as well as the NLCD IS data set with respect to overall accuracy and kappa value at the coarser city scale. Three of our four most effective classifications were based in part upon the TM's thermal channel, an effect that is consistent with reports of other researchers who have noted the contribution of the thermal channel to classification of impervious surfaces to the UHI [5,13,16,70]. Because our leaf-off imagery records a time with little to no vegetation growth (winter season), Band 1 was useful for distinguishing soil from vegetation especially in instances where impervious surfaces—roads, highways, parking lots—exhibit properties similar to bare earth (no vegetative cover) [5,61]. Visually, these four classifications did vary in effectiveness for identifying distinguishable features (especially neighborhood streets, the river, and the central business district) in various parts of the city. In certain heterogenic urban areas, such as these specific locales, the classification algorithms vary in their latitude to assign mixed pixels to specific spectral categories.

When examined at the finer detail of the census tract, internal heterogeneity within the city greatly impacted the results. Except for a few census tracts, our classifications produced variable results within and across the census tracts. Census tracts are defined by demographic criteria, so are not comparable to each other with respect to composition and variation in landuse/landcover.

With larger average parcel sizes, our accuracies are higher but in areas with wide variability in parcel sizes (thus greater heterogeneity) our accuracies were more variable across the methods.

Consideration of average parcel size within the census tract, spatial patterns of the parcels, percent impervious, and interactions with the classification algorithm, contribute to variability of results (Table 8):

Parcels

- Parcel sizes, range of parcel sizes within a specific tract, the percent impervious, and the spatial pattern of land uses all affect accuracy;
- Units with very high and very low percent impervious show high accuracies for all methods (Census Tracts 11 and 28); and
- Units with the highest percentages of impervious surfaces (Census Tract 11), show low kappa values; the more variability in range of parcel sizes within a census tract and the higher percent impervious, the greater variability in accuracy of classifications between the methods.

Classification Strategy

- At least one classification method achieved an accuracy of over 70% in nine of the eleven census tracts;
- Parallelepiped classification—bands 2–6 proved the most effective method in tracts with moderate percentages of impervious surfaces and larger average parcel sizes;
- In some census tracts, multiple methods achieved accuracies higher results greater than the city-wide NLCD IS standard; and
- For all census tracts, the most effective method included either the thermal channel (band 6) or the blue visible channel (band 1).

Table 8. Summary of census tract characteristics and best classification method for that census tract.

Census Tract No.	% IS Aerial Photos	Average Parcel Size (ha)	Range of Parcel Sizes (ha)	Highest Overall Accuracy	Highest Kappa	Best Classification Method
3	44.5	0.39	234.5	76.7%	0.52	parallelepiped, bands 2–6
4	37.4	0.14	6.0	65.8%	0.31	Mahalanobis' distance (bands 5, 6, & 7)
5	44.2	0.12	6.3	70.7%	0.41	parallelepiped, bands 2–6
6.01	22.5	0.33	79.2	81.7%	0.39	parallelepiped, bands 2–6
6.02	32.0	0.26	26.7	76.7%	0.45	parallelepiped, bands 2–6
11	89.5	0.11	2.1	88.0%	0.34	minimum distance(bands 1, 5 & 7)
23	24.3	0.27	47.1	79.4%	0.49	minimum distance (bands 1, 5 & 7)
24	26.7	0.11	14.7	75.0%	0.47	minimum distance (bands 1, 5 & 7)
26	39.6	0.08	28.9	71.9%	0.47	minimum distance (bands 1, 5 & 7)
27	35.5	0.12	26.3	65.8%	0.30	minimum distance (all bands)
28	13.3	0.33	82.9	85.8%	0.47	Mahalanobis' distance (bands 5, 6, & 7)

Our analysis is subject to several sources of uncertainties:

Although we avoided bias in our random points dataset by retaining an independent party to complete it, human error still could have been a factor and some points misidentified between *impervious* or *other*;

Shadowing from buildings and coniferous trees could have altered brightnesses of some pixels resulting in misclassification between *impervious* and *other*;

For our finer scale analysis, we chose the best four methods from the broader scale analysis; so, it is possible that another method, which we did not consider, could have performed equally well or better at the finer scale analysis.

Some imprecision can occur when comparing point values to pixel values—our pixels cover a 90 square meter area; in urban settings, this area could encompass several different surface covers whereas a random point has no area and could be located anywhere within a pixel with different surface covers. Additionally, many studies have pointed out the problems encountered with mixed pixels within urban areas and have developed alternative methods in attempts to solve the mixed pixel dilemma [5,13]. However, our analysis indicates that more complicated methods in delineating impervious surfaces from Landsat imagery may not be necessary for this study site. Our overall accuracies at the coarser city-wide scale for several of our images were comparable to the overall accuracy of the widely used NLCD IS dataset, and to accuracies achieved by many of the more complex methods referenced in Table 1. At finer census tract scales, and even though no one method was effective across all census tracts, different methods and band combinations produced accuracies in excess of 70% and 80%.

5. Conclusions and Future Outlook

Based on our analysis, Landsat imagery is effective in delineating urban impervious surfaces using standard classification methods but the best specific method is highly dependent on the internal heterogeneity within a specific site. Most of our classifications at the city scale provided accuracies equivalent to that of the US National Land Cover Database. Our study shows that, for our study site and similar urban areas, a finer scale analysis using spatially compact boundaries can overcome this internal heterogeneity and provide higher accuracies. The best method will depend on physical characteristics of the finer-scale compact area.

The literature on identification of impervious surfaces is abundant, with the majority of the studies analyzing urban areas at coarse scales. To properly manage impacts of urbanization, such as stormwater mitigation and temperature regulation, analyses must account for the heterogeneity within urban regions. We encourage applications of more robust, and more detailed, reference data to permit analysis and validation at finer spatial scales to provide improved assessment, and to permit analysis of the detailed spatial fabric of the urban landscape.

Many developed countries have high-resolution aerial photos available to aid in identification of impervious surfaces. However, these analyses are not uniformly effective and derivation of impervious surfaces from high-resolution aerial photography is time-intensive and costly, a practical concern for developing countries. In contrast, the Landsat image archive is free, readily available for most regions of the world, and covers many decades. And, as our study reveals, standard classification methods can be quite effective especially when completed at finer scales.

Acknowledgments

We would like to thank Yang Shao of Virginia Tech's Department of Geography for his advice on this paper, and Sam Weber, an undergraduate student in Virginia Tech's Department of Geography, who prepared our random points validation data set. We also acknowledge the constructive contributions of the Journal Editor and three anonymous reviewers.

Conflicts of Interest

The authors declare no conflict of interest.

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Geospatial evaluation for urban agriculture land inventory: Roanoke, Virginia USA

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Abstract:
Urban agriculture is recently being recognized as a distinctive urban land use contributing to greenspaces and food security. The land inventory forms the critical first step in identifying sites for urban agriculture. Our analysis greatly expands on prior land inventory strategies, first analyzing land cover to identify all open areas available for siting urban agriculture. Then in GIS, we completed a land use suitability analysis, and finally a demographic analysis to assess potential sites for contribution to food security of lower income populations. Results show that Roanoke includes 2,312 hectares suitable for schoolyard gardens, urban farms, community gardens, orchards, and home gardens, of which 189.4 hectares are found in neighborhoods with extremely high rates of poverty. Our inventory strategy can be implemented elsewhere without special data or software. A detailed inventory offers opportunities for long-range planning, and broadening participation of stakeholders.

Key Words: *Food Insecurity, Urban Agriculture, Land Inventory, Roanoke Virginia USA, Geospatial Analysis*

Recently, research on urban agriculture has expanded exponentially because of widespread food insecurity and expanding urban areas across the world. Although urban expansion is attributed to increasing populations, rates of conversion to urban land uses exceed rates of urban population increases (Lincoln Land Institute, 2015). Expanding urbanization causes loss of vegetated lands, expansion of impervious surface cover, increasing demands on existing infrastructures, warmer air temperatures as compared to adjacent rural areas (the urban heat island effect), and increasing demands on municipal services such as waste management and provision of potable water (Pickett et al., 2001). Urban areas also must reach well beyond their political boundaries to import food, energy, and clean water to meet basic needs of their populations and, as such, adverse effects of urbanization reach into regions outside the urban setting (Aitkenhead-Peterson, Steele, & Volder, 2010; Deelstra & Girardet, 2000; Pickett et al., 2001; McGranahan & Satterthwaite, 2003).

Urban agriculture, through its varied manifestations, can offer a multi-dimensional solution to these adverse effects. It improves access to healthy and nutritious fresh food, revitalizes inner cities, promotes social interactions, improves urban hydrology, and mitigates adverse climatic effects. The first step in establishing new urban agriculture sites requires identifying open, available, and suitable locations - a *land inventory* (Dongus & Drescher, 2006; Dubbeling & Merzthal, 2006; Dubbeling, van Veenhuizen, & de Zeeuw, 2010).

Although urban agriculture studies include land inventories to identify potential urban agriculture sites, most inventories are limited in scope, often emphasizing identification of vacant lands. In addition, most researchers conduct them to assist local municipalities wishing to incorporate urban agriculture into their planning and/or sustainability initiatives, so tailor their methods to that specific locality. Although some incorporate other stakeholders (i.e. local non-profits or local urban farmers) into their inventory process by asking them what characteristics require inclusion, these results, again, often focus upon specific local characteristics. Although a local perspective is valuable in recognizing unique dimensions of natural, social, and built landscapes, use of geospatial analysis allows us to develop a more generally applicable methodology. Such a framework can be relevant for any urban area, and can include a wider suite of data that nonetheless permits incorporation of those specific parameters necessary when examining an individual locale.

We expand on prior land inventory analyses by incorporating, first - land cover, second - land use, third – urban agriculture form, and finally – demographics, into our evaluation. In our literature review, we introduce and define urban agriculture in its several forms. Next, we identify existing land inventories and parameters researchers included in their geospatial analysis. We then describe our study site and highlight why it forms an appropriate locale for developing our inventory strategy. We step the reader through our analysis, and report results. These results identify locations within the city for siting different forms of urban agriculture (and, at different scales). Our results also include an evaluation of the extent these potential sites are proximally located to assist lower income residents with food security. Our conclusions discuss the significance of our procedures, and their relevance for other urban areas.

Urban Agriculture

Urban agriculture is the production of agricultural products (for food, fuel, and other uses) and rearing of livestock in urban and peri-urban areas (Mougeot, 2000). It is not a new phenomenon; people began producing agricultural products within urban areas when first establishing them thousands of years ago (van Leeuwen, Nijkamp, & de Noronha Vaz, 2010). In the United States, its history exceeds 100 years (Lawson, 2005), intensifying during periods of national crisis, such as both World Wars and the Great Depression (Deelstra & Girardet, 2000; Iaquinta & Drescher, 2010).

Urban agriculture is now increasing in a context driven by parallel trends of expanding urbanization and increasing food insecurity. Worldwide, one in nine people suffers from chronic malnutrition due to food insecurity (FAO, 2014). In the United States, more than one in ten households suffers from food insecurity (Brown et al., 2002; Coleman-Jensen, Nord, Andrews & Carlson, 2011), and this rate increases to almost one in five (19.5%) in households with children (USDA, 2015). Since, the majority of people now live in urban versus rural areas (in 2009, the percentage of people living in urban areas exceeded 50%, and estimates place this percentage at 66% by 2050 (United Nations, 2014)), many of the food insecure live in urban areas.

Although income factors, significantly, into food choices (Hofferth & Curtin, 2005; Rose, 1999), disparity exists over access to healthy and nutritious foods. This disparity manifests itself spatially as access appears related to differing socio-economic status and types of neighborhoods, i.e. segregated by race or ethnicity (Moore & Diez Roux, 2006; Morland, Diez Roux, & Wing, 2006; Seaman, Jones, & Ellaway, 2010). A lack of supermarkets and commercial food establishments offering healthy choices complicates accessibility to healthy and nutritious foods (Bader, Purciel, Yousefzadeh, & Neckerman, 2010; Eisenhauer, 2001; Galvez et al., 2008; Moore & Diez Roux, 2006; Morland et al., 2006; Rose & Richards, 2004). Urban agriculture is well-documented as contributing to alleviation of food insecurity in lower income urban populations (Eisenhauer, 2001; Mougeot, 2000; RUAF, 2010; Smit, Nasr, & Ratta, 2001).

In addition, urban agriculture forms a greenspace, and as a greenspace, it provides a wide range of benefits. For example, urban agriculture makes productive use of vacant lands (Balmer et al., 2005; Grewal & Grewal, 2012; McClintock, Cooper, & Khandeshi, 2013; New York State Energy Research and Development Authority (NYSERDA), 2013), or idle public lands (Smit & Nasr, 1992); increases economic stability for gardeners, from selling agricultural products or from releasing income which can be used elsewhere (Bellows, Brown, & Smit, 2003; Smit et al., 2001); reduces stormwater runoff, increases groundwater recharge, and improves water quality (Aitkenhead-Peterson, Steele, & Volder, 2010; Beer, 2010; Botkin & Beveridge, 1997; van Leeuwen at al., 2010); reduces urban heat island effects (Beer, 2010; van Leeuwen et al., 2010); generates health benefits from increased physical exercise and stress reduction (Barton, 2009; Botkin & Beveridge, 1997; Kuo, 2010); increases social interactions between urban residents (Beer, 2010; Kuo, 2010; van Leeuwen et al., 2010); promotes environmental knowledge of urban residents (Fuller, Irvine, Devine-Wright, Warren, & Gaston, 2007; Lehmann, 2012; Seaman et al., 2010; Viljoen, Bohn, & Howe, 2005); provides residents with a sense of place (Mok et al., 2014; White, 2014); and generates ecosystem services (Bolund & Hunhammar, 1999; van Leeuwen et al., 2010). The extent that urban agriculture produces these benefits depends on its scale and form.

Urban Agriculture Forms

Urban agriculture ranges in size from micro-gardening (i.e., containers on balconies and patios), meso-scale (i.e., shared garden plots) and macro-scale (i.e., urban farms) (Pearson, Pearson, & Pearson, 2010). Each of these scales possesses specific characteristics, but not exclusively and overlaps exist. For instance, urban farms normally operate for profit, but people gardening in containers on patios and balconies can sell their products and some urban farms exist as part of non-profit food banks. While differing scales are significant as they relate to production capability, start-up costs, and man-power, when conducting a land inventory for sites appropriate for urban agriculture, discussing form is important.

Home gardens are the most common form (Smit et al., 2001). Home gardens are usually referred to as backyard gardens, but they include side yards and front yards, and consist of micro-gardening in containers on windowsills, patios and balconies (Pearson et al., 2010). A home garden’s major characteristic is an individual or family growing food for household consumption in an area adjacent to their residence (Drescher, Holmer, & Iaquinta, 2006).

Community gardens exist as a very popular form of urban agriculture in the Americas (Lawson, 2005), are found in some European cities (Hardman & Larkman, 2014), and are expanding in Asia and Africa (Parece & Campbell, *forthcoming*). A community garden consists of an area of land divided into plots shared by members of a community (Lawson, 2005). Community members share some type of relationship – e.g. church, neighborhood, school, or employer. Each member works their own plot but contributes to maintenance and care of common areas. While the land upon which the garden is located can be owned by a community garden association, normally, another entity (governments, churches, non-profit organizations) owns the land and grants gardening privileges, sometimes for only a limited period of time (Drescher et al., 2006; Iaquinta & Drescher, 2010; Smit & Nasr, 1992).

Informal gardening is closely related to community gardens although opportunistic in nature (in some locations, deemed *guerilla gardens*). Local residents engaged in informal gardening find a vacant lot, clean it up, cultivate it, revitalize the area with agriculture – all accomplished without permission of the land owner (Hardman & Larkman, 2014). This form of urban agriculture is prevalent in the rapidly expanding urban areas of the Global South. In many cases, the property owner or municipal authorities, later, reclaim the land (Hardman & Larkman, 2014). Figure 1 shows such an example for the City of Roanoke, Virginia USA.

Figure 1. Left: 2011 Virginia Base Mapping Program aerial photo shows a grassy area. Center: 2012 National Agriculture Imagery Program (NAIP) aerial photo shows a garden in this lot; Right: 2015 street-level photo shows the area reclaimed for grass (Photo – second author 2015).

Allotment gardens are similar to community gardens, practiced extensively in Europe (Andersson, Barthel, & Ahrné, 2007; Hardman & Larkman, 2014; Petts, 2001) and Japan (Matsuo, 2000). Allotment gardens, also a community project, differ from community gardens because the local government usually sponsors and manages the garden. Initially started as food production sites for the lower income working class, the demographics for those now using allotment gardens varies much more broadly (Petts, 2001).

School gardens are located on public and private school properties. The food produced usually supports school lunch programs, or supplements students' home food supplies. School gardens are also used for student education. In rare instances, community gardens are located on school properties (Moore, Wilson, Kelly-Richards, & Marston, 2015; Pudup, 2008; Smit et al., 2001).

Urban farms account for the greatest areal extent of urban agriculture (Smit et al., 2001). Urban farms include greenhouses, rooftop gardens, and community-supported agriculture, and in most instances, operate for-profit by families or commercial enterprises. Because of start-up and maintenance costs of green roofs and greenhouses, operators produce and sell higher-priced or specialized products to restaurants and florists. In the practice of community-supported agriculture, members purchase a share of produce grown by a farmer, rarely participating in the growing process (Doron, 2005; Smit et al., 2001).

Orchards, consisting of fruit or nut-bearing trees, are also a form of urban agriculture; in the Global South, orchards provide sources of fuelwood and building materials (Smit & Nasr, 1992; Smit et al., 2001). Orchards are rarely discussed within the literature as a form of urban agriculture. Nor are fruit- or nut-bearing trees discussed within the literature specific to expanding urban forests.

Land Inventory Analyses

Incorporating urban agriculture into a specific urban area begins with a *land inventory* - identifying those areas within a city available for agricultural production (Dongus & Drescher, 2006; Dubbeling & Merzthal, 2006; Dubbeling, Veenhuizen, & Zeeuw, 2010). Such efforts have begun in many areas of the United States and Canada (Table 1). Most *land inventories* are accomplished specifically to identify sites for urban agriculture, but some inventories are accomplished as part of studies to quantify urban agriculture production capability within a specific locality (indicated in Table 1 by an *). All studies use geospatial technologies for their analysis, most using just GIS, but some also incorporating remote sensing (e.g. Colasanti, 2010; McClintock et al., 2013; Nipen, 2009; NYSERDA, 2013).

Table 1. Land Inventory Analyses for Potential Urban Agriculture

Author (date)	Location	Variables included in analysis
Balmer et al. (2005)	Portland, Oregon	Land tenure, water access, slope, accessibility, proximity to existing agriculture
Kaethler (2006)	Vancouver, British Columbia	Land tenure, under-utilized lands, tree canopy cover, sunlight, impervious surfaces, soils, proximity to existing agriculture, accessibility, opportunity for community buildings, size (only those areas over 1000 square meters)
MacKenzie & Cohen (2007)	Portland, Oregon	Further evaluation of sites identified by Balmer et al., (2005). Excluded protected natural resource sites, areas of open spaces for recreation, locations of springs and steep slopes. Included portions of parks for community gardens.
Horst (2008)	Seattle, Washington	Lands classified as vacant, unused, or excess right of way, utility right of ways, public schools and parks, evaluated only those suitable for community gardens (> 2,000 feet^2)
Nipen (2009)	Halifax, Nova Scotia	Eliminated impervious surfaces and areas shaded from buildings, through use of lidar data. Identified those areas without structures.
Taggart, Chaney, & Meaney (2009)	Cleveland, Ohio	Vacant lands, proximity to existing agriculture, access to water and transportation, prime farmland soils, and eliminated forested and riparian areas.
Colasanti (2010)*	Detroit, Michigan	Vacant lands identified from city datasets and cross referenced against 2005 aerial photos. Excluded lands owned by City of Detroit Recreation Department.

MacRae et al., (2010)*	Toronto, Canada	Zoning regulations, then overlaid on aerial photos for size, shape, site coverage, accessibility, proximately to water courses, to roads, use of park space, and rooftops.
Grewal & Grewal (2012)*	Cleveland, Ohio	Vacant lots, commercial and industrial rooftops and residential areas. Calculated a portion of each of these identified areas in their production capability study.
Meenar & Hoover (2012)	Philadelphia, Pennsylvania	Number of vacant lands identified within each Census Tract.
Patel &MacRae (2012)	Toronto, Canada	Follow up to MacRae, et al., (2010), identified locations greater than 1 acre, large enough for Community-Supported Agriculture.
McClintock, et al. (2013)*	Oakland, California	Identification of vacant and under-utilized locations, included access to water, slopes, aspect, proximity to schools and transportation, and used aerial photos to visually inspect and eliminate areas that appeared in use or with dense vegetation.
NYSERDA (2013)*	New York, New York	Comprehensive evaluation – see below for more details.

One of the most notable inventories is the extremely complex New York State Energy Research and Development (NYSERDA) (2013) study. A production capability report, like some other studies, it presents the most comprehensive land inventory completed, including ground, rooftop, and indoor capabilities. Researchers, for this report, identified vacant public and private lands, roof tops, under-utilized open spaces, surface parking areas, open areas in public housing developments, and existing community gardens. They eliminated wetlands, heavily forested areas, areas adjacent to landfills, and vacant lands that appeared to be in “active use” via overlays on aerial photos and satellite imagery. They also noted other possible available locales - traffic islands and median strips for fruit trees, and yard space as home gardens, but did not quantify these areas. They identified areas of possible soil contamination, but did not eliminate these as potential sites. They discussed many other factors, e.g., slopes, hydrology, energy consumption or reduction, but these were not factors affecting their land inventory.

These studies are much more limited in scope than our study because they conduct a land use analysis, whereas we start with land cover and then proceed to a land use evaluation. Land cover represents the surface features of a parcel of land such as forest, water, or impervious surfaces. In contrast, land use refers to the economic utility that society makes of the same land area, for instance the land use of a forest cover might be for the production of fuel or for recreational purposes (Parece & Campbell, 2015). Our approach screens to eliminate parcels with land cover unsuitable for the practice of urban agriculture as the first step, then we consider land use.

We acknowledge and evaluate current and past land uses, (e. g., commercial locations in active use cannot provide sites for urban farms nor home gardens, but can be actively cultivated as community gardens for business owners and employees). We also include orchards and schoolyard gardens in our urban agriculture form evaluation. Through this inventory strategy, we deliver a comprehensive, multifaceted, perspective on the resources potentially available to a municipality for urban agriculture. In addition, we also identify potential sites in lower income areas to assist in alleviating food insecurity – schools in proximity to urban farms, orchards and community gardens, and locales in high poverty rate census block groups -- a factor that only one study considered (e.g. Meenar & Hoover, 2012).

Study Site

Important qualities highlight the City of Roanoke, Virginia USA as a setting to illuminate and investigate potential sites for urban agriculture. Roanoke is the largest metropolitan region in southwestern Virginia (Figure 2). It is characterized by a variety of urban land uses, with a history as a transportation hub for rail and road traffic, and services and industries supporting the rail system, as well as finance, distribution, trade, manufacturing, and healthcare industries. The City of Roanoke's land cover includes 47.9% tree canopy (Pugh, 2010), and 31.9% impervious surfaces (as calculated by first author).

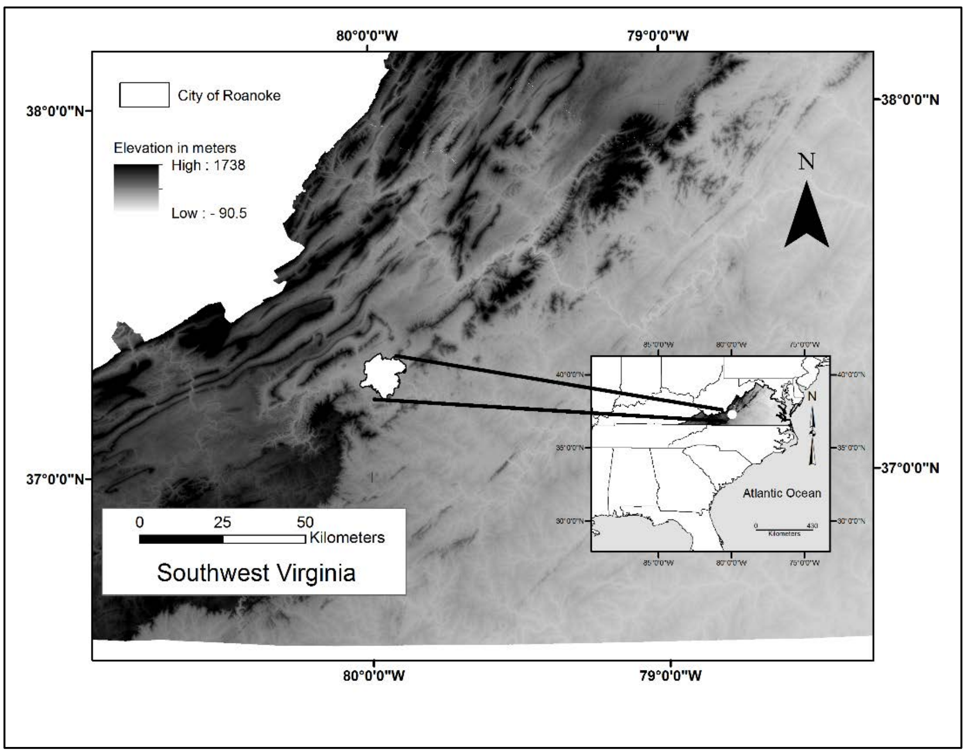

Figure 2. Reference Map, City of Roanoke, Virginia USA (Sources – Virginia Geographic Information Network, 2004; TigerLine® Shapefiles, 2014)

Roanoke's demographics favor examination of relationships between urban agriculture and its potential to address food insecurity; its poverty rate, K-12 student qualification for a free or reduced price school lunch, and food insecurity rates are all higher than the surrounding county, and both state and national percentages (Table 2). The USDA identifies most census tracts within the city as having limited access to food, i.e. a food desert (USDA, 2014). Furthermore, a study completed by the University of Wisconsin ranked the City of Roanoke 115th out of 133 counties and cities in Virginia for health factors such as obesity, diabetes, and physical inactivity (2014).

Table 2 Comparison of City of Roanoke to Roanoke County, Virginia, and United States

	Roanoke	Roanoke County	VA	United States
Households below Federal Poverty Level (U.S. Census, 2012)	20.9%	5.1%	10.3%	13.8%
Food Insecurity Rates (Feeding America, 2014)	16.9%	8.3%	12.1%	14.3% (USDA, 2015)
National School Lunch Program qualification (Virginia, 2015b)	74. 8%	26.5%	42.0%	42.9% (USDA, 2013)

Urban Agriculture in Roanoke, Virginia

Roanoke's urban agriculture scene embraces many forms – community gardens, urban farms, and includes two very active local-food organizations - Roanoke Community Garden Association and Roanoke Natural Foods Co-op. However as Figure 3 demonstrates, these two urban agricultural forms are not well-distributed across the city.

The Roanoke Natural Foods Co-op operates one urban farm at Heritage Point in northeast Roanoke. The land, purchased by the Co-op in 2012, is approximately 7.2 hectares and located near an industrial park. In addition, the Co-op has leased another 1.4 hectares from the city, adjacent to the farm (Ress, 2013). The second urban farm is located at the site of a defunct nursery (almost center in Figure 3), and located within a residential neighborhood. This land was purchased by a private citizen in 2010 with the intention of starting an urban farm and farmer's market. This site was used as a dumping ground for trash and tires after the nursery closed in 2002. Since its purchase in 2010, the current owner has cleaned up the property and renovated the site's building (Nair, 2012).

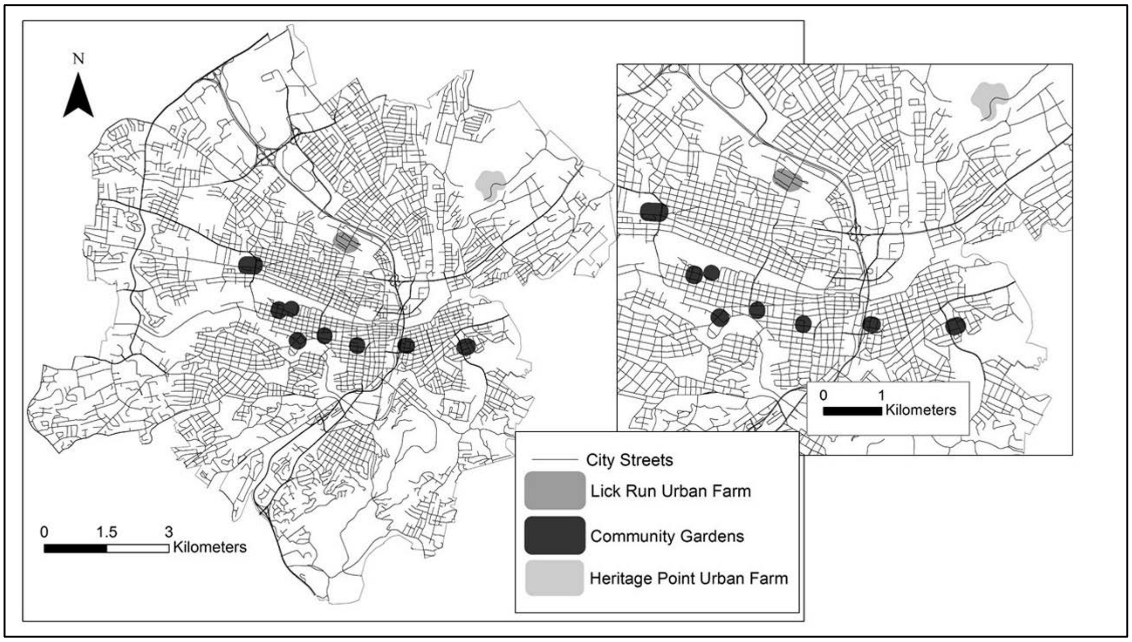

Figure 3. Sites of two urban farms and several community gardens within the City of Roanoke (Please note the size of the polygon does not represent the size of the garden or farm -- symbology has been enhanced.)

The Roanoke Community Garden Association (RCGA), established in 2008, operates multiple locations across the city (Figure 3). RCGA owns some gardens, leases one from the city, and operates on land provided by local property owners - with one on land owned by Goodwill Industries of the Valleys. RCGA requires that members garden organically, and RCGA harvests rainwater at most of its locations. The two most recent gardens established include Mountain View Community Garden (2013), and Growing Goodwill Garden (2014). Growing Goodwill Garden, currently under development, embraces planting an orchard. Immigrants or refugees comprise 30% of RCGA gardeners (Powell, 2013). RCGA plans additional sites across the city (Powell, personal communication, 2015).

Methods

This section describes our strategy for extracting those areas that are unsuitable or impractical for agricultural uses to produce our final inventory of land. Our goal is to distill, from existing information about Roanoke's landscape, those sites likely to form suitable opportunities for urban agriculture. In brief, our strategy systematically identifies, from varied sources outlined below, areas unsuitable for use as urban agriculture because of existing land cover and land uses, e.g., contamination, impervious surfaces, and other reasons, then eliminates these locations from consideration. The remaining areas identify prospective sites for the practice of urban agriculture.

Our data came from several sources (Table 3). Each source provided data downloading capability, in most cases in shapefile format, then we analyzed the data using Esri's ArcMap™ GIS software (Esri, 2015). The spatial extent of some files exceeded the boundaries of the City of Roanoke (those designated with an ••), so we clipped this data using the city's boundary shapefile. The US EPA and the National School Lunch Program provided data in spreadsheet files, which we spatially joined to specific shapefiles (further details are outlined below). In addition, the authors created one new dataset, discussed in more detail below.

Table 3. Data and Sources

Data	Source
Vector shapefiles for buildings, parcels, parks, greenways, streams, flood plains, city boundary, airport	City of Roanoke FTP site (2015)
Impervious Surfaces	Created by first author
Tree Canopy Cover, raster file••	Virginia Department of Forestry (2015d)
Aerial Photos, 2011, 15 cm resolution	Virginia Geospatial Information Network (VGIN) (2015e)
Vector shapefiles for Conservation Lands••	Virginia Department of Conservation and Recreation (2015a)
Brownfields, Superfund, RCRA, and other potentially polluted sites••	US EPA (2015a, 2015b, 2015c) and Virginia Department of Environmental Quality (2015c)
Poverty Rates	U.S. Census Bureau (2012)
National School Lunch Program	Virginia Department of Education (2015b)

Land Cover Analysis

The first step in a land inventory analysis is to identify the different types of land cover - impervious surfaces, tree canopy cover, water, and open areas (land not covered by the other three).

Impervious surfaces are a non-permeable land cover, usually man-made; examples include asphalt and concrete roads, walkways, parking lots, and buildings. A variety of remote sensing methods have been used to identify impervious surfaces (Parece & Campbell, 2013). For this study, we manually delineated impervious surfaces, starting with the city's shapefiles for buildings and parcels (parcels provide a basic outline for roads). We overlaid the shapefiles on the 2011 aerial photos via the Virginia Geographic Information Network's GIS server. In some instances because of intense shadowing, either from buildings, trees, or the camera's field of view, we used 2008 aerial photos or Google Earth™ to clarify the land cover. Once completed, we employed this new shapefile to erase all impervious surfaces from the city's boundary shapefile, resulting in a new a shapefile representing all of the city's pervious surface cover.

We converted the tree canopy cover raster file (one-m^2 resolution) to a vector polygon shapefile and then erased the canopy cover from the pervious surface cover shapefile. With the city's stream shapefile, we added polygons for other areas of open water – ponds, and stormwater retention and detention areas. We likewise erased the water bodies from the pervious surface cover shapefile. The resulting shapefile contained one land cover - open areas, utilized in our land use analysis.

Land Use Analysis

We identified land uses, not available as potential sites for urban agriculture greenspaces, from several files. From the city's shapefiles, we identified and eliminated locations for the Roanoke-Blacksburg Regional Airport, quarries, the wastewater treatment facility, and all railroad yards. The conservation land shapefiles included The Nature Conservancy lands, National Park Service (NPS) land, easements, National and State Forests, U.S. Fish and Wildlife areas, Department of Defense lands, and scenic rivers; the city only contained NPS and easements lands. We eliminated NPS lands, but not easements.

The city contains sixty-two parks within its boundaries, ranging in size from 0.1 to 247.4 hectares. We evaluated each park to determine if it was in active use either with sports fields, playground equipment, or walking trails. We looked closely at the larger city parks, examining the parks for open areas accessible for community garden sites.

We identified four golf course locations from the city parcel's file. Two of the golf courses are actively operating so we eliminated any open areas within them. The city designated the other two golf courses as vacant, and thus open areas within these two locations remained as potential urban agriculture sites.

Schoolyards are viable locations for urban agriculture, however, recognizing that school children need outside space for recreation, we decided not to include all of these open areas as potential urban agriculture sites. The open areas ranged from schoolyard to schoolyard, from 731 m^2 to 14.9 hectares. As such, for those schoolyards with more than 7.7 hectares of open area (n = 3), we designated 0.8 hectares (2 acres) as potential areas for urban agriculture. For those schoolyards of between 1.3 and 7.7 hectares of open areas (n = 14), we designated 0.4 hectares (1 acre) of potential land for urban agriculture. For the rest of the schoolyards (n = 12), we calculate 50% of the open area as available for urban agriculture. We exported the open schoolyard areas from the potential urban agriculture shapefile into its own shapefile named *schoolyard gardens*.

Other Land Use Considerations

We also evaluated prior land uses and potential soil contamination, most specifically, pollution sites noted by regulatory authorities (the US EPA and the Virginia Department of Environmental Quality). The data from the US EPA included the Toxic Relief Inventory (TRI), Superfund sites, and Resource Conservation and Recovery Act (RCRA) sites. Files from the Virginia Department of Environmental Quality contained shapefiles for solid waste facilities, petroleum release sites, and Virginia locations that qualify under the National Pollutant Discharge Elimination System Program (NPDES). Explanation for review of this data is provided as follows.

US EPA's Toxic Relief Inventory (TRI) "tracks the management of over 650 toxic chemicals that pose a threat to human health and the environment" (US EPA, 2015c). TRI data is available as a downloadable spreadsheet. US EPA Superfund identifies sites with uncontrolled hazardous waste; the US EPA evaluates the sites, identifies clean-up requirements and can place prohibitions and site restrictions before and after completion of clean-up activities (US EPA, 2015b). RCRA gives the federal government authority for involvement in regulation of hazardous solid waste disposal sites, including provisions for site evaluation and placement of use regulations if deemed hazardous to human health (US EPA, 2015a).

The Virginia Department of Environmental Quality (DEQ) tracks releases of petroleum products, the locations, and clean-up status. Virginia DEQ also documents locations for all active Virginia locations that qualify under the National Pollutant Discharge Elimination System Program (VPDES). The Clean Water Act (Section 402) established the National Pollutant Discharge Elimination System Program, which limits pollutant discharges into streams, rivers, and bays for industrial activities, municipal separate storm stormwater systems (MS4s), and construction activities qualifying as point sources of stormwater discharge to surface waters (Virginia, 2012).

For each of the above data categories, we identified locations (if any) within the city, through query of the parcel's shapefile or by joining the spreadsheet file with the parcels shapefile. Then, for each location, we reviewed the documentation from the US EPA or Virginia DEQ for the type of contaminant, status of clean-up, any use restrictions or regulations placed on the site, and the status of the land use (i.e. active or inactive). For any location that was designated as hazardous to human health, we erased those open areas from our potential urban agriculture sites.

The final areas requiring our consideration were floodways and floodplains identified by Federal Emergency Management Agency (FEMA), available as a shapefile from the city. FEMA defines a floodway as a stream and any adjacent land that must be reserved to discharge a base line flood; development on this adjacent land can be restricted (2014a). FEMA defines floodplains as all land areas with the potential to be overcome by floodwaters, regardless of the source (2014b). While development of land with these designations faces limitations, they offer viable opportunities for expanding the urban forest with fruit or nut bearing trees. We used the *select by location query* for those potential urban agriculture sites contained within the FEMA flood zone locations, then exported this selection into a new shapefile named *FEMA Orchards*. We then switched the selection and exported the remaining areas to a new potential urban agriculture open areas shapefile.

Urban Agriculture Form Analysis

Since urban agriculture takes multiple forms, the next step of the evaluation considered urban agriculture form. We located specific property descriptions within the city's parcels shapefile to consider in this part of the evaluation – vacant, commercial/industrial, multi-family, residential-non-living areas, and single family. We intersected the potential urban agriculture open areas shapefile with city's parcel shapefile to determine the property type description/land use categories for each parcel's open area.

However, intersecting with the parcel's shapefile excluded open areas not within any parcels, i.e. lands within highway cloverleaves, median strips, areas between sidewalks and streets. As such, we created another shapefile (erasing the parcel areas from the potential urban agriculture open areas shapefile), and named this shapefile *non-parcel open areas*.

We evaluated each of the previous two shapefiles (*open parcel areas* and *non-parcel open areas*) for location, property type, and size in meters^2 or hectares, and assigned the following urban agriculture form categories:

- Too Small - less than 1.0 m^2 – for vacant parcels, non-parcel land or occupied commercial/industrial properties;

- Urban Farm - greater than 0.4 hectares for vacant parcels, non-parcel land (with exceptions noted below), or residential non-living areas; all highway cloverleaves, and areas less than 0.4 hectares adjacent to highway cloverleaves;
- Community Garden – areas equal to 1000 m^2 but less than 0.4 hectares for vacant parcels or non-parcel lands in non-residential neighborhoods, any non-parcel lands greater 0.4 hectares within residential neighborhoods, all multi-family residential and non-residential living areas (regardless of size), and all commercial/industrial property greater than 1.0 m^2;
- Home Garden – for occupied parcels that are single family residential and all-non-parcel lands within 6 meters of a residential parcel;
- Schoolyard Garden – as described previously; and
- Orchards – FEMA floodways and flood plains, highway or major road way median strips, non-parcel grassy areas next to roadways/streets in commercial/industrial areas greater than 1.0 m^2, all vacant areas greater than 1.0 m^2 but less than 1000 m^2.

Demographic Analysis

We joined the spreadsheet reporting the rate of qualification for the National School Lunch Program (NSLP) for each school to the corresponding school's point shapefile. We added a field to this shapefile for size of potential schoolyard gardens. We evaluated these two attributes, asking the question – can those schools with the highest NSLP qualification rates install a schoolyard garden and contribute to food security for its students? In addition, we completed a spatial analysis query to determine the proximity of each school to potential agriculture sites for urban farms, community gardens, and orchards.

Finally, we overlaid the urban agriculture form shapefiles (*open parcel areas, non-parcel areas, and FEMA Orchards*) with the shapefile for the 2010 Census data for poverty rate by block group, to identify potential urban agriculture sites within those block groups with high poverty rates (and therefore, at greatest risk for food insecurity). We defined high poverty as any rates above national level.

Results and Discussion

Potential Urban Agriculture Sites

After the land cover analysis, i.e. elimination of impervious surfaces, tree canopy cover, and water, Roanoke contains 2,774.4 hectares of open areas (25% of total area) that may be suitable for urban agriculture.

As previously described in the land use analysis discussion, we erased any opens areas that were contained within the airport, quarries, National Park Service land, the two golf courses, and the wastewater treatment plant. For city parks, it was determined that the majority of the open areas within these parks are in active use, either with sports fields, playground equipment, or walking trails. The two largest parks – Mill Mountain Park (247.4 hectares) and Yellow Mountain Park (118.7 hectares) are adjacent to the National Park Service and tree canopy covers all but minute areas of these parks. Thus, we eliminated open areas within all city parks.

The US EPA Toxic Relief Inventory (TRI) file contained fifteen sites within the city boundaries and the city's parcel's shapefile noted all sites as active commercial or industrial locations. We considered each location inappropriate for food production.

The US EPA listed five Superfund sites for the city of Roanoke, we reviewed each location but only three were actually within the city boundaries:

- US EPA designated one site as a threat to public health (1998);
- US EPA found a second site with soil contaminated from multiple chemicals, and of immediate threat to public health, welfare and environment (1994); and
- US EPA noted the final site with elevated lead (in excess of 1,000 ppm) in soil, and because of its proximity to the Roanoke River, also deemed it a threat to aquatic life and water quality (2000).

We deemed any open areas within these three sites as inappropriate for agriculture and, thus, erased these areas from the potential urban agriculture sites shapefile. In addition, because of the notes in the report from the US EPA for the third site (i.e. the aquatic threat from runoff), we eliminated any non-parcel areas adjacent to this site and any locations with the *FEMA Orchards* shapefile as potential urban agriculture sites.

The US EPA identified four sites under the Resource Conservation and Recovery Act (RCRA) for the City of Roanoke; while evaluating these locations, we determined one site was outside of the city boundaries. For the other three sites, one site was already eliminated as part of the TRI evaluation. The US EPA noted that a second site should remain solely as industrial/commercial use and required that the company institute a management plan (US EPA, 2010). US EPA specifically restricted the third site from any residential use or as a public garden space (2009). We eliminated any open areas within these parcels as potential urban agriculture sites.

The Virginia DEQ solids waste facility shapefile noted two facility sites within the city, but both of these are offices not actual landfills, so those open areas were not erased. The shapefile for petroleum release sites designated all but three sites -- resolved and closed; none of the open incidents intersected with any potential urban agriculture location. The VPDES shapefile contained six such locations but did not provide any additional details if a specific pollutant was in the stormwater discharge. None of these locations required elimination from the open areas – four already eliminated and the final two noted as vacant properties by the city.

After the schoolyard evaluation, open areas on school properties totals 80.6 hectares. But, referring back to our methods on schoolyards, the total potential urban agriculture area on schoolyards equals 6.9 hectares. We did not identify the specific section of open area for agriculture as this would be a decision made by local school principals and teachers.

After categorization for urban agriculture form, excluding the *Too Small* category and reduction in schoolyard open areas, we identified 2,311.6 hectares (20.8% of total area) with potential for urban agriculture. Of these total hectares, we designated 179 potential sites for urban farms (278.5 hectares), 6,247 potential sites for community gardens (691.7 hectares), 986.9 hectares of potential home gardens, and 347.6 hectares for potential orchards (Figures 4 and 5).

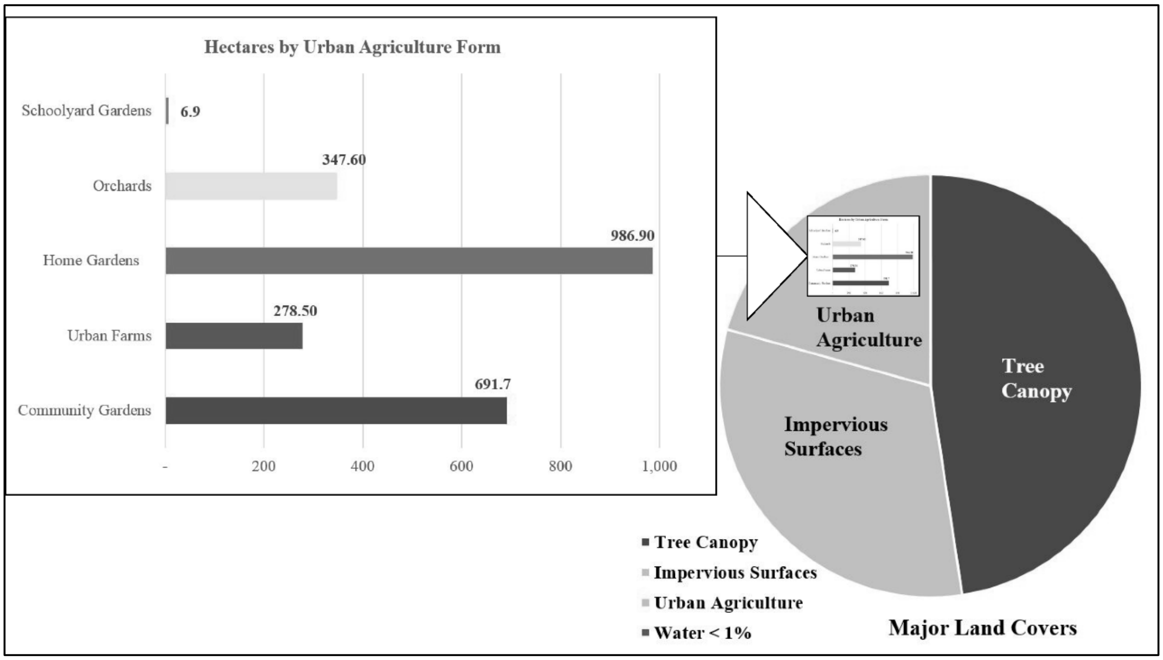

Figure 4. Major land cover classifications, including urban agriculture. Within the urban agriculture classification, the bar chart indicates amount of hectares for each urban agriculture form.

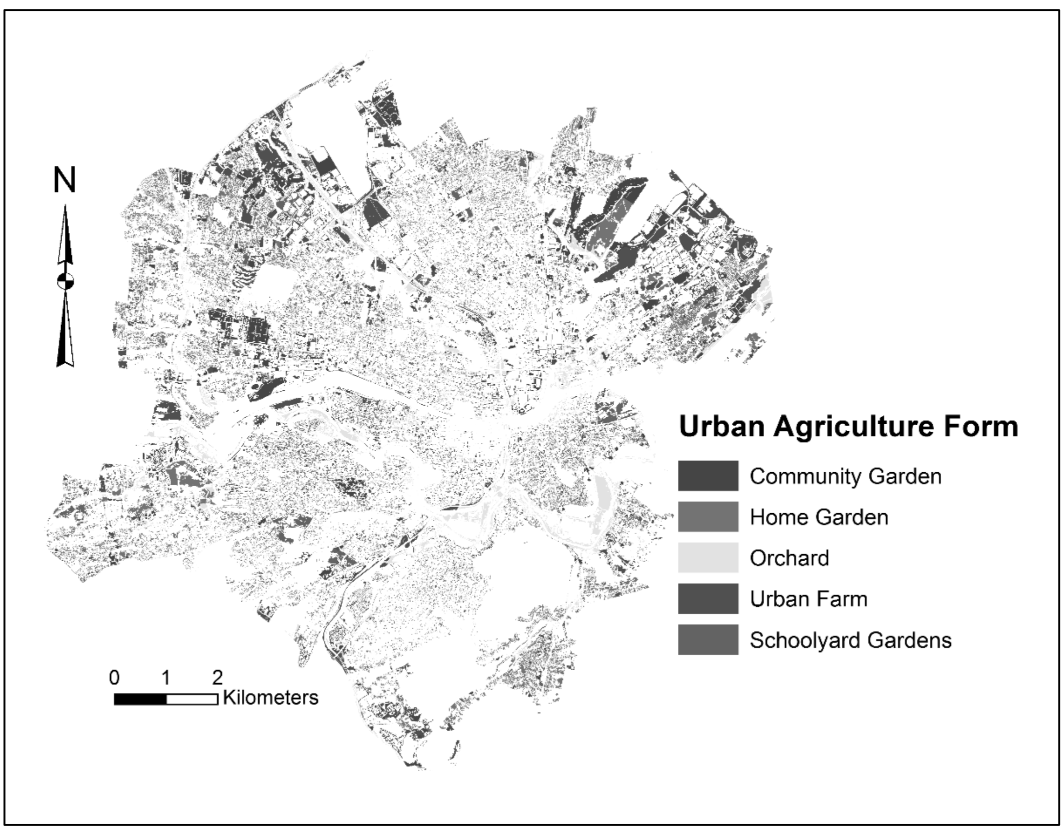

Figure 5. Locations of potential urban farms, community gardens, backyard gardens, orchards, and schoolyard gardens within Roanoke, Virginia

Site Contribution to Food Security

While the city average rate for students qualifying for the National School Lunch Program (NSLP) is 74.8%, only two city public schools fall below national average qualification, one at 18% and one at 38% (note - some schools within the city boundaries are not part of the Roanoke City Public Schools system). All other city public schools qualify at 53% or greater - 17 schools exceed 75% and eight schools qualify at 90% or greater. After evaluating the schoolyard open areas with the percentage of students within each Roanoke City Public School that qualify for the NSLP, all schools have the potential to contribute to their students' food security by implementing a schoolyard garden. Two of the schools with potential plots of 0.8 hectares, have NSLP rates of 77.5% and 90%. For those schools with potential plots of 0.4 hectares, nine have NSLP rates over 75% and all but one of these schools (a private school) have rates in excess of 53%. The eight schools, with 90% or greater rate of NSLP qualification, have enough open areas for potential urban agriculture plots from 364 m^2 to 0.8 hectares; four with potential plots of 0.4 hectares each.

All schools within the city have access to other potential urban agriculture sites. For potential community gardens sites, eighteen schools are within 100 meters, twenty-five schools are within 150 meters, and all schools but one are within 250 meters. For potential urban farm sites, three schools are within 100 meters, four schools within 150 meters, eight schools within 250 meters, thirteen schools within 500 meters, and twenty-three schools within 1 kilometer. For potential orchard sites, twenty schools are within 100 meters, twenty-six schools - 150 meters, and all schools are within 250 meters.

We identified the Household Federal Poverty Rate for each census block group (Figure 6), as a reminder the national average is 13.8%. For Roanoke, twenty block groups have high poverty rates, rates greater than 15% but less than 25%; 24,431 people live within these block groups. Ten block groups have very high poverty rates - greater than or equal to 25% but less than 35% (13,514 people). Eleven block groups have extremely high rates of poverty, 35% or more (15,178 people), and these rates range from 35.5% to 53%. As such, 55% of the city's population live within high poverty census block groups (97,032 people live in the city).

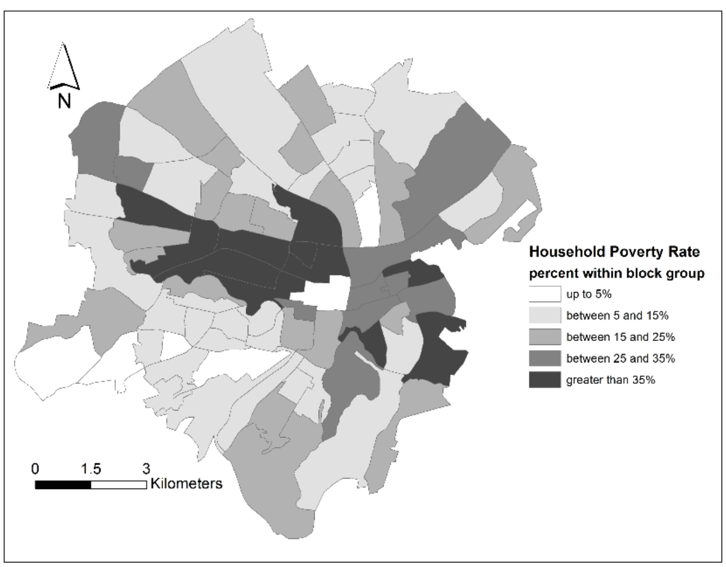

Figure 6. Percent of households within each block group whose income was below the Federal Poverty Rate

Potential urban agriculture sites exist within all block groups. For those block groups with high rates of poverty, five contain potential sites for urban farms and all twenty contain potential sites for community gardens and orchards. For those block groups with very high rates of poverty, three contain potential sites for urban farms and all contain potential sites for community gardens and orchards. For those block groups with extremely high rates of poverty (≥ 35%), all eleven contain potential locations for community gardens (108.9 hectares) and orchards (69.1 hectares), and six contain potential locations for urban farms (11.5 hectares) (Figure 7). Of note, the Roanoke Community Garden Association successfully sited six community gardens within these extremely high poverty rate block groups, and the privately owned urban farm is also located within one.

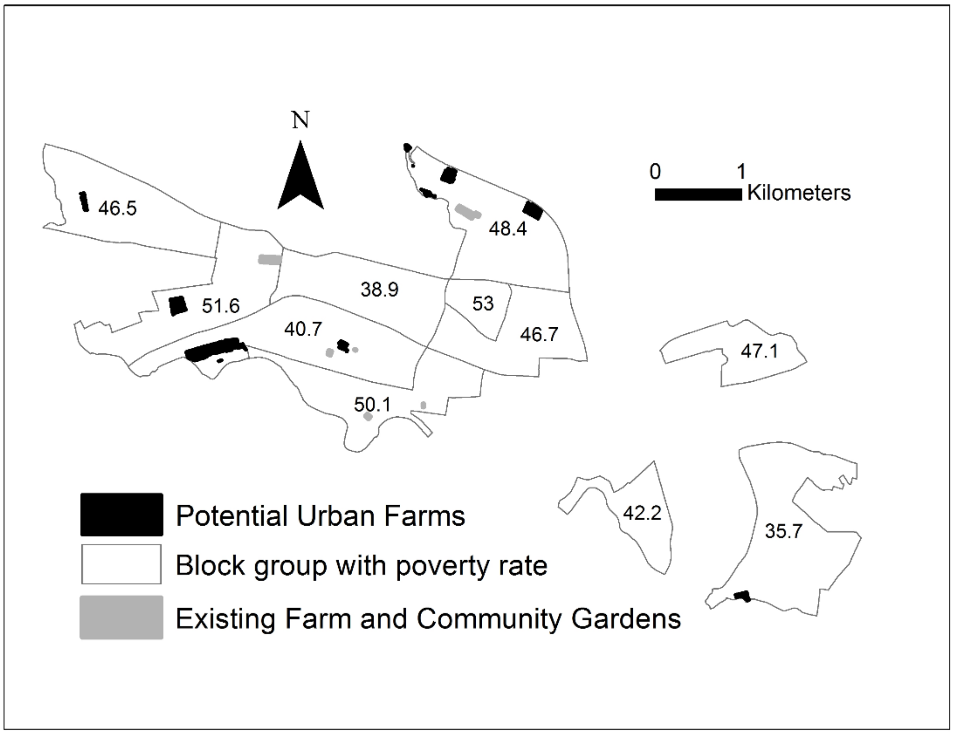

Figure 7. Block groups with extremely high rates of poverty (≥ 35%), black represents sites of potential urban farms and gray represents the locations of an existing urban farm and community gardens. The number within the block group shows the percent of households within that block group that exceed the Federal Poverty Rate.

Conclusions

The premise for our evaluation is that we constructed our land inventory with a land cover analysis, followed by a land use assessment. Our procedure is contrary to most inventories that start with identification of vacant land uses and then evaluate these vacant lands for other characteristics – i.e. adjacency to existing agriculture, proximity to water, dense vegetation. This strategy ignores the basic fact that vacant lands are not the only locations that could support urban agriculture.

Our strategy eliminated areas that would not be available for new greenspaces without substantial alteration of surface cover – impervious surfaces, tree canopy cover and open water.

We eliminated areas of national security concern (airport and railways) and areas where current land use is not amenable to agricultural production (wastewater treatment facilities, active recreational areas, National Park Service land, and quarries). While we eliminated all open areas with city parks, these sites could support gardens, provided that local residents have input. We included easements. We also included the final two VPDES sites that were designated by the city as vacant properties; although these locations are permitted pollutant discharge locations, this status does not especially mean that a human health toxic pollutant is located on the site. These two sites would require specific *in-situ* analysis, but should not be excluded as potential sites.

We also included FEMA floodways and flood plains. Some urban agriculture could be problematic within these areas, as during times of flood, plants could be washed away and pollutants, i.e. chemicals and sediments, could wash into the streams during normal rainfalls. However, these opens areas are amenable to trees. Although, rarely discussed as a form of urban agriculture, orchards form a viable source of food production for urban areas, and a form which requires discussion more often because most urban areas include expansion of urban forests in their sustainability plans.

We did not limit our analysis to the larger urban agriculture forms – community gardens and urban farms. We also included home gardens, schoolyard gardens and orchards. We did ignore rooftops as potential sites, although easily identifiable, these locales are problematic as their structural integrity requires assessment. We also did not place a lower size limit on all forms, as no site is too small for a home garden. As a result, our land inventory reveals that a significant portion of land (21% of total area) within the City of Roanoke is available as potential urban agriculture sites, with many potential sites available to the food insecure. Our analysis has only provided a brief and limited socio-economic analysis, other factors, e.g., locations of existing greenspaces and food deserts, should be included in identification of optimal sites for urban agriculture. Our analysis shows that the Roanoke Community Garden Association effectively chooses low-income neighborhoods for community garden sites.

These results report only hectares, and locations, of open areas available for urban agriculture, not production capability. Also, we do not comment on specific site qualities, such as soil properties, nor capabilities to support growth of specific crops. Each site would require an individual assessment (prior to cultivation), for soils, and for needed amendments, and length of growing season for plant species. Such evaluations are standard practice in any agriculture or development setting prior to land use implementation. We also recognize that, while we have identified 2,311.6 hectares as available for urban agriculture, this entire land area would not be cultivated as areas would be needed for site access, equipment, and other infrastructure, such as containers for storing harvested rainwater.

Although our analysis shows results for a specific municipality – the City of Roanoke, Virginia USA, our analysis can be implemented for any urban area, both in the Global North and Global South. While existing GIS data is not available for all characteristics for every urban area, shapefiles can be created using GIS software and remotely sensed images – both aerial photos and satellite imagery – ubiquitous for all land areas of the world. Furthermore, additional data can be acquired using unmanned aerial systems, which are low cost, becoming abundant, and in certain locales more easily flown than other aerial systems (Parece and Campbell, 2015).

Our inventory strategy provides a framework for understanding social and ecological contexts for urban agriculture. It offers an informational resource enabling examination of relationships of existing and prospective sites for contribution to ecosystem services, e.g., temperature and water regulation. Likewise, from a social perspective, an inventory allows communities to examine relationships between potential sites and their social settings; for example, between neighborhood demographics, proximity to schools, farmer's markets, parks, and walkways. With this information, communities are better prepared to employ less of a "target of opportunity" strategy for siting of community gardens, and instead undertake more extensive long-range planning that can consider a broader suite of informational resources, and involve a broader range of organizations and stakeholders. Because these data are already prepared in a geospatial context, they can seamlessly integrate with data used by planning agencies and community organizations.

Acknowledgements: We recognize the contributions of the *IJAGR* reviewers for their careful attention, comments, and insights that have strengthened this paper. This research was financially supported by The Virginia Space Grant Consortium 2014/2015 Graduate Research Fellowship. This publication was developed under STAR Fellowship Assistance Agreement No. FP-91769301-0 awarded by the U.S. Environmental Protection Agency (EPA). It has not been formally reviewed by U.S. EPA. The views expressed in this publication are solely those of Tammy Erlene Parece and U.S. EPA does not endorse any products or commercial services mentioned in this publication.

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Land Use/Land Cover Monitoring and Geospatial Technologies: An Overview

Tammy E. Parece and James B. Campbell

Contents

Abstract Accurate and detailed land use and land cover information forms an important resource for hydrologic analysis; remote sensing forms a critical resource for acquiring and analyzing broad-scale land use information. Although aerial photography is an important resource for land use information, it was the availability of multispectral satellite data beginning in 1972 that significantly advanced the

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T. Younos, T.E. Parece (eds.), *Advances in Watershed Science and Assessment*, The Handbook of Environmental Chemistry 33,
DOI 10.1007/978-3-319-14212-8_1

ability of remote sensing researchers to systematically monitor and evaluate land use/land cover changes and their impacts on water quality and quantity. In that context, practitioners developed classification schemes specifically tailored for use with remotely sensed imagery and for systematic assessment of land use change. Since then, land observation technologies have evolved to allow extensive and intricate land use monitoring techniques, and now, in the twenty-first century, include the use of lasers for 3-D analyses and unmanned aerial systems. Such technologies have enabled land use assessment to contribute not only to its original focus in urban and regional planning but to a broad range of environmental and social issues. This chapter provides an overview of remote sensing, its technological evolution, and remote sensing applications in land use and land cover mapping and monitoring, with a focus upon implications for watershed assessment and management.

Keywords Electromagnetic spectrum • Land cover • Land use • Remote sensing • Water resources

1 Introduction

Land use and land cover mapping date back to Egyptian and Babylonian civilizations thousands of years BC [1] and have long formed essential components to understanding Earth's resources including water, its most vital resource. Approximately, 70 % of Earth's surface is covered with water versus 30 % land cover. And, it's estimated that, over time, humans have modified over 50 % of the natural land cover [2], thereby creating conditions that affect natural water resources and its quality.

Key land use changes that adversely impact water resources include deforestation, desertification, and urbanization. Deforestation outcomes typically change to either agricultural or urban land uses. Although land conversion from forests to agriculture impacts water quality, the level of impact is highly dependent on agricultural practices (i.e., tillage technique, chemical use versus organic practices, or size and type of conservation easements). Current agricultural practices have a greater impact on water quantity because of over-withdrawal from groundwater supplies (estimated up to 35 %) or diversion of water into water-poor areas for irrigation purposes [3, 4].

Urbanization is the most extreme form of land cover and land use changes as it results in losses of agricultural and forested lands coupled with notable expansion of impervious surface cover [5, 6]. These effects, combined with associated decreases in vegetative cover, result in significant local hydrologic modifications [7–9] and habitat destruction [10]. Hydrologic modifications represent the most significant water quality and quantity issues present today [7, 9, 11]. Stormwater runoff from impervious surfaces in urban areas degrades water quality through higher water temperatures, increased runoff volume and rate, and elevated levels of contaminants in surface waters [8, 9, 12, 13]—effects which extend well beyond specific urban regions, vitiating downstream waterbodies [14].

Remote sensing techniques can be used to map and monitor changes in land use and land cover locally and over large expanses and to evaluate impacts of these changes. Remote sensing techniques involve collecting data from a distance, then analyzing and interpreting collected data for specific purposes. In this chapter, remote sensing refers to collection and analysis of information using aerial photography and/or satellite imagery for the purpose of monitoring the Earth's surface. With the capacity to remotely sense the Earth's surface, the science of land use/land cover mapping has gained the ability to evaluate large areas at economical costs.

In this chapter, we present methods for classifying land use and land cover and sources of land use and land cover data; discuss remote sensing principles and use of the electromagnetic spectrum in classification and analyses of land use and land cover; provide a brief history of remote sensing and introduce two types of imagery—aerial photos and satellite imagery; present how remotely sensed land use and land cover is used in hydrological analyses; and finally introduce the newest remote sensing technologies and their applications for land use and land cover monitoring.

2 Land Use/Land Cover Classification

2.1 Definition of Land Use and Land Cover

Land use and *land cover* are terms frequently used interchangeably. However, these terms have significantly different meanings and applications. Land cover refers to physical features on the surface of the Earth—vegetation, water, the built-up land. Whereas, land use specifically refers to the human (economic) utility of what is on the Earth's surface. In some instances, terms used to describe land cover can also describe land use, for example, forest describes the type of vegetated cover but also describes a use for industries such as forest products. Although remote sensing can be used to identify both, often we can think of broad-scale imagery (e.g., satellite imagery) as primarily portraying land cover, whereas the fine detail of aerial photography or similar imagery might be required for identification of land use.

Land use mapping is accomplished by partitioning an image into units, usually polygons, and then assigning each unit to a specific category. Land use/land cover classifications are strictly naming systems such that each classification contains a description defining uses falling within a system of mutually exclusive categories. As an example—a definition for a water classification is *Open Water—all areas of open water, generally with less than 25 % cover of vegetation/land cover* [15].

2.2 Land Use and Land Cover Classification Systems

The precision in a land use classification (known as *taxonomic detail*) should match to the intended use of the analysis and is usually defined by the map user. For example, in Fig. 1, the left-hand image shows fine detail subdividing forest cover to represent forested wetlands (light green) and deciduous forest (dark green), as might be required to support ecological or hydrological analyses. The right-hand image, representing a coarser classification, symbolizes forest cover as a single class, as might support an analysis of regional land use.

Thus, the value of land use and land cover information resides in application of a systematic classification system with a structure organized to support the user's application of the information for its intended purpose. An important modern milestone marks the beginnings of systematic uses of geospatial data for land use information, when in the 1960s, the State of New York (USA) recognized the importance of mapping land use and its natural resources. In conjunction with researchers at Cornell University, the Land Use and Natural Resources Inventory (LUNR) mapping project was completed with one hundred different land use classes [16]. Significant detail was required for this mapping project as it was subsequently used for urban planning, economic development, and environmental planning. In the early 1970s, the State of Minnesota (USA) also completed a state-wide land use map but only for nine different land use categories (Orning and Maki 1972, as referenced in [17]). Such projects introduced important advances in systematizing the classification of land use data for large areas, but retained a local, often ad hoc, character that inhibited application to multi-temporal analysis or to applications that encompass broad-scale land areas.

In 1976, Anderson et al. [17] introduced a framework for standardization of land use and land cover tailored for remote sensing classification. The Anderson classification system, the most widely used classification scheme today, consists of multiple levels of classification designed to be compatible with remotely sensed imagery acquired at varied scales and levels of detail. It is comprised of a hierarchal

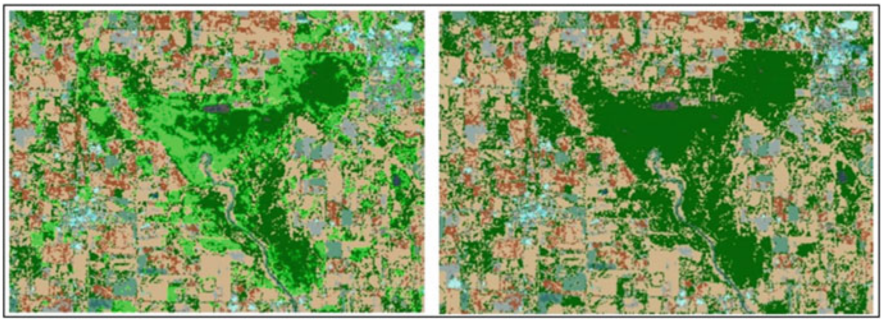

Fig. 1 Effects of taxonomic detail in land use classification—fine detail (*left*) and coarse detail (*right*). *Source*: Landsat 5 imagery from the United States Geological Survey, processed by the second author for specific land cover/land use classes

Table 1 Samples of classification Levels 1, 2, and 3 from [17]

Level 1	Level 2	Level 3
1 Urban or built-up land	11 Residential	111 Single-family units
		113 Group quarters
		116 Transient lodging
	13 Industrial	
	17 Other urban	
2 Agricultural land	21 Cropland and pasture	211 Cropland
		212 Pasture
	23 Confined feeding operations	
4 Forestland	41 Deciduous forestland	
	43 Mixed forestland	
5 Water	51 Streams and canals	511 Intracoastal waterway
		512 Canals associated with residential development
		513 Canals associated with utility, commercial, or industrial development
	52 Lakes	521 Freshwater ponds
	54 Bays and estuaries	541 Tidal marshes
		542 Open water

grouping of three levels, allowing for applicability at multiple resolutions. Level 1 can be used when finer details are not needed, such as for national or regional scales, and is more appropriate for land cover identification. Yet, Level 3 is available when finer detail is needed at a local scale and can be more readily described as land uses (Table 1).

Without a standard classification framework, it is difficult to identify changes occurring over time, compare between places, and to avoid duplication of efforts. As such, the Anderson system has been used as the basis for many other classification systems in the United States. For instance, classifications used by the Multi-Resolution Land Characteristics Consortium (MRLC) for the National Land Cover Database (NLCD) for the coterminous United States is a modified Anderson system [18]. One difference between the Anderson system and the NLCD scheme is that water is defined in three categories under Anderson (Table 1), but the NLCD limits it to one—open water [15].

Caution should be exercised when comparing datasets from the same source as classification methods may have changed over time. NLCD data have been prepared from analysis of satellite data (specifically Landsat Thematic Mapper, discussed later in this chapter) for 1992, 2001, 2006, and 2011. The history of the NLCD forms an example of the hazards of changing classification methods, as improvements implemented to prepare the 2001 data prevent systematic comparison of results between the 2001 and the 1992 datasets. Therefore, changes made for the 2001 classification mean that the 1992 and 2001 classes are not compatible for compiling land cover change [19–21]. More generally, land use change studies, or regional mosaics, require compatibility with respect to the classification system, level of detail, spatial scale, date, and projection. Analysts, therefore, should devote special attention to consistency in land use classification in such situations.

2.3 Sources of Land Use/Land Cover Data

For any specific region, there are likely to be several sources for acquiring land use or land cover data derived from remotely sensed imagery, with alternative dates, coverage, and classification systems. For the United States, the NLCD (mentioned above) provides land cover data with broad-scale coverage (e.g., national, regional, or state levels). For finer scales, such as cities or comparable local areas, more detailed data completed from sensors with finer spatial resolution is readily available in most jurisdictions. However, the data, likely organized by political or administrative boundaries, will not match to drainage basin (watershed) boundaries.

Data for other countries each follow procedures and classification strategies specific to local needs and traditions. In considering national land cover mapping systems, the analyst will encounter wide variations in costs, dates, availability, classification, and completeness of coverage. Some examples:

The Canada Land Inventory, available for rural Canada, provides data covering land use and cover categories for agriculture, forestry, wildlife, and recreation. The maps were generated in the 1960s, 1970s, and early 1980s and many Canadian jurisdictions still use them for land use planning [22].

The European Environment Agency provides downloadable land use and land cover data for Pan-European urban areas with populations greater than 100,000 people. The Urban Atlas was completed using multispectral data, and the categories are based on the European Coordination of Information on the Environment (CORINE) classification system [23].

The Centre for Ecology and Hydrology provides land cover mapping data for the United Kingdom (for 1990, 2000, and 2007 [24]), but each of these three maps has been produced as a number of different products with varying data formats and spatial resolutions. The United Kingdom also has generalized land use data available through their generalized land use website [25].

Land cover maps for Africa have been generated by both the US Geological Survey [26] and the European Space Agency [27].

3 Electromagnetic Radiation Use in Remote Sensing

Sensors that measure the sun's electromagnetic radiation provide the foundation for obtaining and analyzing aerial photographs and other imagery used to monitor the Earth's surface. Electromagnetic energy from the sun that is reflected off the Earth's surfaces and that portion which is absorbed and reradiated as thermal energy are both used in remote sensing analyses. The reflective portion of the spectrum (0.38–3.0 μm[1] wavelengths) has direct application in remote sensing analyses, and different wavelength ranges have different applications. Sensors record this data as images for scientific analysis. Remote sensing methods that measure the sun's electromagnetic radiation form the basis for *passive remote sensing*. In *optical remote sensing*, sensors record reflected solar energy as brightness values, thereby detecting features (both natural and man-made) on the Earth's surface.

In *active remote sensing*, instruments transmit man-made radiation to illuminate the Earth's surface. The man-made energy reflects off features (both natural and man-made) and is received and analyzed to form an image. Sonar, radar, and Lidar are examples of such remote sensing systems. The main focus of this chapter is on passive remote sensing, i.e., optical remote sensing.

A major consideration for optical remote sensing is atmospheric interference with incoming radiation—scattering. Scattering specifically refers to radiation reflected by particles in the atmosphere before it reaches the surface of the Earth. The level of interference depends on many factors, including:

- The altitude of the aircraft or satellite, i.e., sensors on low-flying aircraft have less atmosphere to penetrate.
- The wavelength of the radiation—the shorter, blue wavelengths are scattered about four times as much as the longer, red wavelengths (specifically designated Rayleigh scattering, caused by larger atmospheric molecules).
- The presence of dust, pollen, water droplets, and smoke (designated Mie scattering).
- The presence of larger airborne particles (designated non-selective scattering).

All factors noted above cause scattering but the form and magnitude of the scattering vary.

Another key consideration is the amount of reflected radiation from the features (both natural and man-made) on the surface of the Earth. When energy reaches the Earth's surface, it is either reflected, retransmitted, or absorbed. Different objects and features reflect or re-emit radiation in various ways. Observing or measuring these properties establishes spectral properties of individual objects (their spectral signatures). A particular object's spectral properties vary either over the course of a day, from night to day, over the course of a year, or over the course of several years. Variation in spectral properties allows remote sensing analysis to distinguish objects/features from one another and compare changes between the same object/feature over time.

Figure 2 shows the spectral properties of two features—healthy vegetation and clear, calm water. The *y*-axis represents percent of reflected energy. The *x*-axis

[1] All wavelength ranges discussed within this chapter are approximations. Different disciplines define the specific divisions of the electromagnetic spectrum in various wavelengths. Most definitions are extremely close in value.

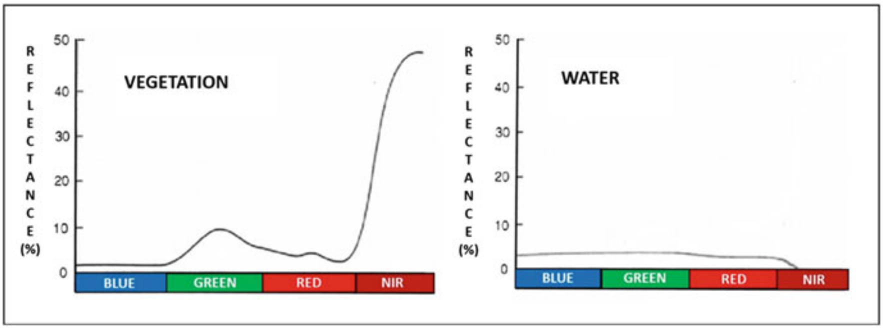

Fig. 2 Spectral signatures of vegetation and water [28] (Permissions, Campbell_Guilford_4_June_2014)

represents four segments of the electromagnetic spectrum—blue visible, green visible, red visible, and the near infrared (NIR). As this figure demonstrates, the percent of radiation that is reflected from water is very low across all portions of the visible spectrum. Whereas for vegetation, reflectance has a slight peak in the green, drops off in the red, but substantially increases in the near infrared (NIR).

As stated earlier, optical sensors measure returned energy and record it as a brightness value for the object. In the case of absorption, the energy recorded is greatly reduced. The brightness of the object also depends on many other factors. For instance, the surface of the object (rough or smooth) as is related to the wavelength of the energy will redirect the energy in different ways. If the surface is rough, the energy will be redirected in multiple directions; if smooth, the energy is redirected mostly in the same direction. This redirected energy may or may not be in the direction of the sensor and thus affects the amount of returned energy recorded by the sensor.

Figure 3 is an example of how a passive or optical sensor records the brightness values of different objects/features. This is a portion of a satellite image, Landsat 5 (natural color image, Path 17, Row 34), acquired over the Commonwealth of Virginia (USA) on April 4, 2010. The dark object in the lower right is Smith Mountain Lake. Since water absorbs and re-emits only a very small percent of energy that reaches it, the lake shows as an object darker than the surrounding vegetation. Urban areas (the City of Roanoke is in the upper left) are very bright because they reflect strongly across the entire visible spectrum and because the smooth surfaces of roads and some roofs are reflecting more energy directly back to the sensor.

The first remotely sensed images acquired were aerial photos. Early aerial photos were produced as black and white images, formed from brightness across the three visible portions of the electromagnetic spectrum. Prevailing technology allowed display only as a single black and white image (a one-band image).

Fig. 3 Natural color scene, Smith Mountain Lake (*lower right*) is much darker than the surrounding vegetation. The City of Roanoke, Virginia (USA) (*upper left*), and smaller urban areas appear very bright. *Source*: Landsat 5 imagery acquired on April 4, 2010, from the United States Geological Survey and processed by first author as a natural color image

As technology improved, sensors were not only able to collect the data in multiple bands[2] (initially just across the visible spectrum—blue, green, and red) but also able to display images as natural color. These multispectral images advanced remote sensing analyses by using spectral signatures of different features, as defined by individual spectral bands.

Additional advances in technology permitted sensors to collect radiation outside the visible spectrum, first in the near infrared (NIR) and later the longer wavelengths, mid (MIR) and far infrared (FIR). Human eyes cannot see these portions of the spectrum, but cameras and other image sensors can measure this radiation and record it as brightness values. These brightness values can then be represented using the colors of the visible spectrum. Thus, we can use visible radiation to display the nonvisible. Specialized software is used for this display and the user chooses which bands are displayed in the software's view screen. Specific images will be discussed in later sections of this chapter.

Software used to display remotely sensed images is also used for analyzing the images for specific applications. Each pixel of an individual band of an image has a set of brightness values, representing a feature's spectral signature within that pixel. These values can be enhanced in various ways, which forms the basis of remote sensing analyses. The features can be analyzed within an individual band but multiband analyses are more robust. Some of the most frequently used techniques in spectral enhancement are spectral ratios and indices. For example, when using

[2] The number of bands of an image refers to how many divisions of the electromagnetic spectrum were used to create that image. For the exact electromagnetic spectral divisions for each band, you must refer to the metadata that accompanies the image.

Landsat imagery, dividing band 4 (NIR) by band 3 (red) enhances the presence and vigor of vegetation.

Aerial cameras typically collect up to four bands (blue, green, red, and NIR). Sensors for other multispectral images can be located on satellites or placed on an aircraft for a specific collection campaign. Further advances in the design of imaging systems permit separation of finer subdivisions of the spectrum to form hyperspectral imagery by using more than 200 very specifically defined segments of the electromagnetic spectrum. Hyperspectral applications are discussed later in this chapter (Sect. 6.2).

4 History of Mapping and Remote Sensing

4.1 Background

Land use and land cover mapping in our current understanding dates at least to the late 1600s when estate managers in Western Europe began to map landowners' forests, fish ponds, croplands, and pastures [29]. Such maps were prepared through direct ground surveys and manual drawings. Many significant mapping projects were accomplished with these methods. The mapping of the Americas during the European Age of Exploration (1400s–1800s) and the mapping of the western United States by Lewis and Clark in the early 1800s form two major examples. These missions were undertaken to explore, identify, and map land areas, but ultimately these maps were used to determine the land's potential uses for settlements, transportation hubs, agriculture, and natural resource extraction.

Systematic mapping, specifically for land use inventory, began in the early twentieth century. L. Dudley Stamp produced the Land Utilization Survey for Britain in the 1930s [30]. This broad-scale inventory was generated from information provided by volunteers who reported land use information for their home regions. With technological advances, i.e., the development of cameras, computers, and space exploration, by mid-century remote sensing potential and applicability became the primary avenue of land use/land cover mapping and monitoring.

Initially, availability of suitable aerial photography focused applications of remote sensing mainly to urban settings, most often, to support planning and economic development programs. However, over time, improved access to higher-quality imagery, and especially the routine availability of satellite imagery, expanded applications to include rural regions and wildland landscapes, enabling acquisition of broad-scale land use data to support hydrologic analysis.

4.2 Mapping Using Aerial Photography

Aerial photography has been in existence for over 100 years using kites, balloons, airplanes, and most recently unmanned aerial vehicles (commonly called drones).

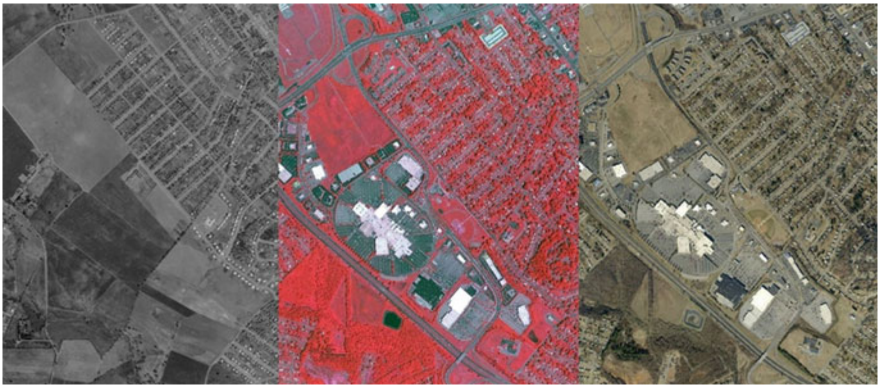

Fig. 4 1960 panchromatic image (*left*), 2008 color infrared image, bands 4-3-2 (*middle*), and 2011 natural color image (*right*) of northwest Roanoke, Virginia, USA. Sources identified in text

During the 1930s, scientists at the Tennessee Valley Authority (TVA) in the United States developed methods for systematic interpretation of aerial photography to extract land use and agricultural information, as well as rural settlement patterns [31, 32]. Those methods are no longer used but form the foundation for extracting land use information from aerial photographs.

Aerial photos can be taken in three different forms. Panchromatic is a one-band image; the visible portion of the electromagnetic spectrum is combined to produce a black and white image. A natural color image is taken using the three visible portions (**r**ed, **g**reen, and **b**lue—abbreviated RGB) of the spectrum, each in a separate band, and then overlaid to produce a color photo. A color infrared (CIR) photo is taken with the green and red visible bands and also the near infrared section of the spectrum; such photos are displayed as color infrared photos. Applications for these three different types of aerial photos vary but all are useful for mapping land use.

Figure 4 provides a side-by-side comparison of the three types of aerial photos for the northwest region of the City of Roanoke, Virginia (USA). On the far left is a panchromatic image from 1960 acquired by the United States Geological Survey (USGS). The CIR image (middle) was obtained by the United States Department of Agriculture (USDA) as part of its National Agricultural Imagery Program (NAIP) in 2008. For this image, NIR is being displayed in red, the red portion of the spectrum as green, and the green portion as blue. Since NIR is being displayed as the red band (as stated in Sect. 3, vegetation has the highest reflection in NIR), vegetation shows as red in the image. CIR imagery is extremely useful for evaluating and analyzing vegetation land cover. The 2011 natural color image (on right) was taken as part of the Virginia Base Mapping Program, which acquires annual aerial photos of the Commonwealth of Virginia (USA).

Developing a land use map from an aerial photo is accomplished in different ways. In the 1930s TVA project, it was accomplished with hand-drawn annotations on the aerial photos. As technology changed, this process also changed. A combination of photo-overlay technique and a computer database was used in the LUNR

Fig. 5 An example of the photo-overlay technique in GIS, delineating man-made surface cover (cyan polygons) to help identify a transportation land use within an urban area. Completed within GIS using high-resolution (15 cm by 15 cm pixel size) 2008 aerial photos from the Virginia Base Mapping Program. Area location is northwest Roanoke, Virginia, USA; the airport dominates the photo. *Source*: Image provided by the first author

project (mentioned earlier in Sect. 2.2); most specifically, mapping of land use and identification of natural resources for New York State (USA) were accomplished by using Mylar transparencies overlaid on aerial photographs [33], for 1 km^2 cells [28], and hand-drafted [17]. The land use identified from the aerial photos was then combined with reference data from other sources (public records, direct observation, etc.); a computerized map was produced from the results [1, 17].

With the increase in computing power, hand delineation of land use from aerial photos is no longer necessary, and it can be accomplished in either of two ways. One technique employs computer software that uses specialized algorithms to evaluate the spectral properties of the image, looking for similarities. Simply put, once these similarities are identified, the program will assign all pixels with these spectral values to specific classes. The algorithms will also assign unidentified pixel values to a specific class, depending on the algorithm's parameters. Specifics of these algorithms' methodologies are beyond the scope of this chapter (see [28] for some specifics).

Another technique employs computer software to apply the photo-overlay method. Aerial photos, georeferenced[3], are added to the program, and each land use polygon is delineated by the user within a geographic information system (GIS) using the aerial photo as a guide. Figure 5 is such an example; man-made objects (impervious surface land cover) are represented as cyan polygons to assist in

[3] Georeferencing means to define a specific location on the surface of the Earth for an image, usually with a specific geographic coordinate system.

identification of a specific land use class (transportation) within an urban region (City of Roanoke, Virginia, USA).

In addition to identifying specific land use classes, aerial photos enable time series mapping of land use changes, an important analysis to identify how land use has impacted water quality and quantity. Figure 3 (noted earlier) shows a comparison of the northwestern part of the City of Roanoke from 1960 to 2011. The 1960 photo shows some urban development for residential areas but also large expanses of agricultural lands.

The two later images in Fig. 3 (2008 and 2011) show that urban land has replaced former agricultural lands and includes additional residential areas throughout the region, an airport, a large shopping mall, and other commercial areas. This time series shows that permeable land surfaces have been extensively replaced by impervious surfaces, greatly altering the hydrologic characteristics of the land. These changes, agriculture to urban, have greatly degraded the water quality of streams within the Roanoke River watershed. The City of Roanoke has substantial drainage problems and experiences frequent flooding due to increased stormwater runoff from impervious surfaces. The Virginia Department of Environmental Quality has listed several segments of the Roanoke River system within the city as impaired, i.e., they do not meet established water quality standards due to the presence of contaminants such as *Escherichia coli*, heavy metals, and high water temperature [34].

4.3 Mapping Using Satellite Imagery

The 1950s was the beginning of a race into space as governments across the world established satellite systems for telecommunications, defense initiatives, and weather monitoring. During the 1960s, astronauts from the US' Gemini and Apollo missions created a large archive of photos of the Earth from space. In the late 1960s, one of the first broad-scale land cover maps was created from these photos [35]. This map, of the southwestern United States, demonstrated the capability of remotely sensing land cover employing imagery acquired from outside the Earth's atmosphere.

Weather satellites can be used to monitor the Earth's surface, but their major purpose is monitoring weather patterns using data at coarse spatial resolutions, relative to the needs for land surface analysis. The first land observation satellite was launched in 1972 (Landsat 1), a joint project of the USGS, the USDA, and the US National Aeronautics and Aerospace Administration (NASA). With the advent of land observation satellites, land use/land cover mapping and monitoring changed dramatically. This system established the utility of satellites to acquire imagery over large areas, to provide a continuous stream of images, and to record multitemporal images over the same area.

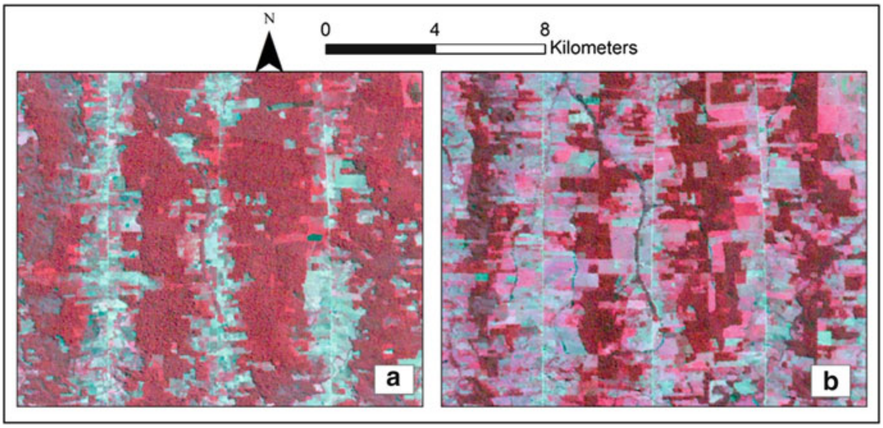

Fig. 6 Portions of two Landsat 5 TM scenes acquired over the same region of the Amazon rainforest in 1992 (**a**) and 2002 (**b**). *Dark red* is the forested area and the images show substantial deforestation from 1992 to 2002. *Source*: United States Geological Survey, processed by the first author and displayed as CIR (bands 4-3-2)

Figure 6 shows portions of two Landsat 5 Thematic Mapper (TM) scenes (Path 231, Row 68) acquired over the same region of the Amazon rainforest in 1992 (a) and 2002 (b). The images are displayed as CIR (bands 4-3-2) to enhance the presence of vegetation. The darkest areas of red are dense forest, the white areas are settlements including roads, and the light red or pink areas are agriculture. A stream is visible in the middle of the image. Comparing 2002 to 1992, a substantial reduction in forest area has occurred. The stream is more prominent in the 2002 image as much of the forest canopy, which would have reflected the radiation, is now gone and the radiation is being absorbed by the water.

Landsat is the longest continuous program of land observation satellites in the world. The most recent Landsat satellite (Landsat 8) was launched in February of 2013. Sensors aboard each satellite have been improved as technology has advanced and new uses for the imagery established. Landsat images (and images from other land observation satellites) are acquired, again, using the electromagnetic spectrum and most are equipped with passive remote sensors. The Landsat satellites have acquired more than 3.5 million images of the Earth's land surfaces since 1972. The USGS manages the Landsat imagery archives and all Landsat images are freely available to the public since 2009 [36].

France, in collaboration with European partners, launched its first land observation satellite (SPOT) in 1986. SPOT is a series of satellites with the most recent launch in 2012. Many other countries today have land observation satellites in orbit, each with specific characteristics and capabilities; Table 2 provides an outline of characteristics for a selection of these satellites. The nature of the images varies with respect to sensors, numbers of bands and bandwidths, spatial resolutions (pixel size), and land area covered in a single scene (image swath).

Table 2 A select listing of land observation satellites

Satellite (launch year)	Sponsoring entity (website)	Resolution (pixel size) (m)	Image swath (km)
Landsat system (1972–present)	United States [37]	15–120	170
IKONOS (1999)	Satellite Imaging Corporation [38]	1 and 4	11.3–13.8
SPOT system (1986–2012)	France [39]	10 and 20	3,600
CBERS (1 and 2) (1999)	China/Brazil [40]	260	890
DEIMOS 1 (2009)	Elecnor [41]	22	600
MODIS (1999)	United States [42]	250, 500, and 1,000	2,330

These satellites can carry one or more sensors, and sensors from satellite to satellite can vary in design and capabilities. Satellite sensors can be either active or passive (see Sect. 3). Passive sensors can be multispectral (acquiring images across several different segments of the electromagnetic spectrum) or hyperspectral (acquiring images across hundreds of segments of the electromagnetic spectrum—see Sect. 6.2). Passive sensors collect reflective shortwave radiation or emitted longwave (thermal) radiation. Active sensors can include sonar or radar (both beyond the scope of this chapter) or Lidar (see Sect. 6.1). The characteristics of a specific sensor depend on the purposes of the satellite system for which it is being designed. Multispectral sensors can be designed to acquire reflected radiation in a very limited range of the electromagnetic spectrum (e.g., blue, green, and red visible) or a much wider range (the blue visible through the far infrared).

Different models of passive sensors acquire images, basically, in the same way. The sensor records the energy from either the reflected or re-emitted radiation over a specific area of the Earth's surface. Such an area is defined by two parameters—the image swath, which represents the area of land covered in one orbital pass of the satellite, and the pixel size, which represents the smallest area that forms an individual brightness value on the image. This returned energy is directed by a mirror onto instruments that focus and transmit the energy to detectors. The detectors record the energy as brightness values in the form of digital numbers. Sensors vary in their capability to record a range of brightness values; brightness values are in binary format. For example, Landsats 4–7 use 8 bits, and Landsat 8 uses 12 bits. (An 8-bit sensor can record up to 256 different brightness values for each pixel, whereas a 12-bit sensor can record up to 4,096.)

The data is transmitted to ground stations positioned in different areas of the world, depending on the satellite system. The images are rectangular arrays of pixels. Most images are available for a fee. Processing of Landsat or any other satellite image requires specialized imaging software. Governments, corporations, and educational institutions each use a variety of software packages to display and analyze satellite images. Two private corporations—Google and ESRI—have each processed a complete set of all Landsat images for land use/land cover changes, which are readily available for time series viewing over the Internet.

Table 2 provides only a selection of existing systems; many other land observation satellites are in orbit. The specifics listed in Table 2 are important when choosing imagery for a specific application. Larger pixel sizes facilitate faster processing, especially with analyses over large areas. However, a larger pixel size means that the land use spatial detail within that pixel is more likely coarser, and it represents a mixture of land uses or land covers, especially in urban areas.

5 Significance of Land Use/Land Cover Mapping for Hydrologic Studies

Land use impacts hydrology largely through its influence upon the natural hydrologic cycle. Vegetated surfaces, especially during the growing season, will redirect rainfall through the ability of leaves, branches, and trunks to intercept raindrops and to delay water movement to the soil surface. Forest soils act like sponges, retaining water so that it is slowly released to groundwater or to flow to streams and rivers over days, weeks, and months. Open, grassy surfaces likewise capture and slow the movement of water and retain soil moisture. In contrast, pavement and compacted or indurated soils impede infiltration and increase surface runoff. Runoff from impervious surfaces consequently flow to streams, rivers, and storm sewers and contribute to flooding and contamination of surface waters.

5.1 Land Use and Curve Numbers

Land use impact is significant for hydrologic analysis because it is a key variable in hydrologic models that predict surface runoff from precipitation events. In traditional hydrologic analysis developed by the USDA Natural Resources Conservation Service (NRCS), this relationship is described by the runoff *curve number* (CN), an empirical approximation of the runoff from a precipitation event in a specific drainage basin.

Curve numbers have been derived for a variety of surfaces and categorized by climate and by land use (both broadly and specifically defined) (Table 3) [43]. For each drainage area examined, analysts examine aerial imagery (often aerial photography, although uses of other forms of imagery may soon increase as their availability increases) to characterize surface conditions and hydraulic properties of local land cover, on a parcel-by-parcel basis. Analysts select curve numbers for each parcel of interest using methods outlined by NRCS, including:

- Land use (from designated classes)
- Hydrologic soil group, defined to identify hydrologic behavior of local soils (as selected from tables that represent soil units)

Table 3 Selected land use classes and NRCS curve number designations [43]

Land use	Runoff curve numbers by hydrologic soil groups			
	A	B	C	D
Rural				
Fallow	76	85	90	93
Row crop (contoured)	65	75	82	86
Small grain	63	75	83	87
Pasture	49	69	79	84
Close-seeded legumes or rotation meadow	64	75	83	85
Meadow	30	58	71	78
Woods	43	65	76	82
Impervious surfaces (paved)	98	98	98	98
Urban				
Residential housing	46	65	77	82
Commercial and business	89	92	94	95
Industrial	81	88	91	93
Streets and roads	98	98	98	98
Open areas	49	69	79	84
Connected impervious areas	98	98	98	98
Arid/semiarid				
Herbaceous	–	71	81	89
Oak-Aspen	–	48	57	63
Pinyon-juniper	–	58	73	80

Curve numbers were selected from a much larger set of options for local conditions and usually represent median conditions/designations when possible. Curve number values are for specified land use classes and hydrologic soil groups (larger values for CNs indicate faster runoff [44])

- Additional specifics of each site (such as soil parcel size, characteristics of impervious surfaces, climate, local condition of the surface, or hydrologic condition)

From such analyses, hydrologists can model the hydrologic behavior of landscapes to form the basis for maintaining water quality and management of runoff.

Two examples of using remotely sensed imagery to identify land use in hydrologic analyses are provided below.

Carlson [45] used Landsat 5 TM images to extract land use for the Spring Creek Watershed in central Pennsylvania (USA) for two separate years—1986 and 1996. He used these classified images in an urban growth model to project land use for 2025. Then, using CNs for each land use classification, he calculated actual runoff coefficients, urban flood ratios, and peak flow rates (using a 25-year storm) for each year—1986, 1996, and 2025.

In a second example, Melesse and Wang [46] used Landsat imagery to extract land use to document changes over time in comparing two different hydrologic models. For one study site—the Red River, North Dakota (USA)—Landsat images (1974–2001) were used to classify land cover to determine that urban extent had increased by 54 %. Monthly precipitation data was then used to determine river discharge for two time frames, 1974–1992 and 1993–2002. The results showed a higher runoff to precipitation ratio for the later period. For their second study site, Simms Creek watershed in Florida (USA), they used Landsat imagery (2000 and 1984) to identify urban land use. This time, they used Manning's roughness coefficient, SCS-CNs, and simulated rainfall. They found more areas of 100 % impervious surfaces in 2000 than in 1984 and also found an increase in peak discharge and reduced time to peak in 2000 as compared to 1984.

5.2 Urban Land Use and Hydrology

Hydrology of urban areas is extremely complex [47]. Urban hydrology includes stormwater runoff from impervious surfaces, less evapotranspiration, less groundwater infiltration, treatment and distribution of potable water, and wastewater treatment and discharge. The initial focus of urban hydrology planning was identification of the most efficient ways to redirect stormwater flow in the shortest amount of time [48]. This strategy increased impervious surface area designations beyond those designed for roadways and buildings, and which channelized streams above and below the ground surface (Figs. 7 and 8).

Urbanization, therefore, often creates unfavorable hydrologic regimes characterized by rapid runoff, urban flooding, and reduced water quality. Urban planners, hydraulic engineers, and environmentalists agree that the spatial distribution of impervious surfaces has significant effects on water quality [49]. Thus, managing and reducing urbanization's impacts, identifying runoff volumes and rates, identifying the extent of contaminant sources, and tracking temporal changes in urban hydrology are first addressed by evaluating the extent of impervious surfaces [48].

One of the most extensive remote sensing analyses of impervious surfaces was completed by the Multi-Resolution Land Characteristics Consortium (MLRC) as

Fig. 7 Reedy Creek, Richmond, Virginia (USA). Impervious surfaces have replaced the natural stream channel and habitat. The channel was designed to remove stormwater from residential, commercial, and industrial land uses (Photo by the first author)

Fig. 8 Stroubles Creek, Blacksburg, Virginia (USA). The stream channel is redirected underground beneath the town's central business district and the university (Virginia Tech) campus (Photo by the first author)

part of the NLCD (mentioned in Sect. 2). This dataset is the most widely utilized in the United States for impervious surfaces and was developed to identify "percent developed imperviousness" [50]. The 2006 dataset was developed using regression tree software from both leaf-on and leaf-off Landsat images and images from National Oceanic and Atmospheric Administration's (NOAA) Defense Meteorological Satellite Program [50]. The National Land Cover Database Impervious Surfaces (NLCD IS) dataset is a continuous layer with a gradient of imperviousness from 0 to 100 %, whereby the value of each 30 m^2 pixel is the percent of impervious surfaces present within that pixel [21]. A new NLCD IS was released in April 2014 after a 2011 update and subsequent validation (for specifics on the update—see [19]). Figure 9 shows the extent of impervious surfaces for northwest Roanoke, Virginia (USA), in 2006 (a) and 2011 (b), and the areas of change between the two datasets (c).

Individual researchers have developed different methods for extracting impervious surfaces from remotely sensed imagery. As previously mentioned, pixel size varies from sensor to sensor, and within an urban environment, land use/land cover is extremely variable and creates a fine-scale heterogeneity in spectral values due to mixed pixels.[4] In most case studies, researchers are evaluating the extent or change in impervious surfaces and the resultant impact on water quantity and quality.

For example, one study evaluated changes in impervious surface cover in three sub-watersheds in Atlanta, Georgia (USA)—the Line, Flat, and Whitewater Creek sub-watersheds—to determine if increasing urbanization was impacting the freshwater mussel population [51]. Investigators used three Landsat images (1979, 1987, and 1997) to calculate changes in impervious surfaces. They also conducted four mussel inventories in the 1990s and used pre-1992 historical records to determine if any change occurred in mussel populations over time. They then used changes in

[4] A mixed pixel means that more than one land use/land cover type is present within the spatial extent of the pixel; as such the spectral value cannot be matched to one specific feature.

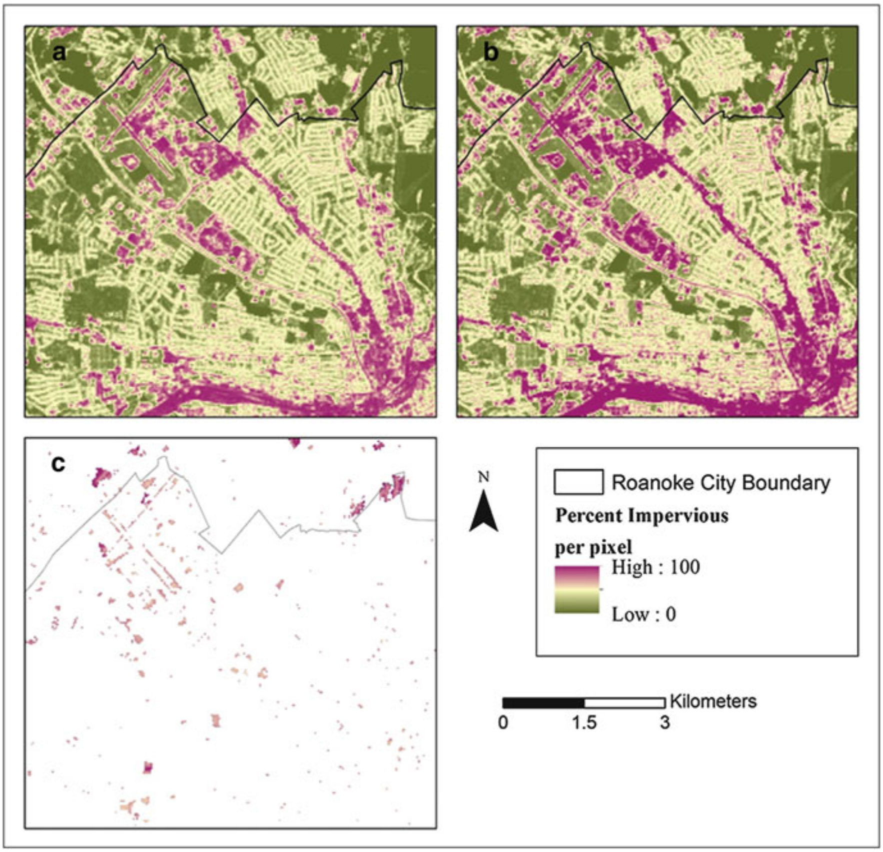

Fig. 9 The NLCD IS for Roanoke, Virginia (USA), and the per pixel impervious percent, from 0 to 100. (**a**) Impervious surfaces in 2006, (**b**) impervious surfaces in 2011, (**c**) the locations of change in per pixel percent imperviousness from 2006 to 2011. Source identified in text

impervious surfaces as an ecological indicator to assess the impacts on water quality and mussel populations. Their study of fourteen different sites determined that the sub-watershed with the highest rate of change in impervious surfaces also had the highest decline in mussel species diversity.

For the second example, researchers using Landsat 5 TM images from 1987, 1999, 2000, and 2007 analyzed impervious surface changes as an environmental health indicator for Lake Kasumigaura Basin, Japan (Lake Kasumigaura is the second largest lake in Japan) [52]. Their results showed that, by 1987, the watershed had already been impacted by land use change (all sub-basins had at least 10 % impervious surfaces). They also found that, by 2007, nine of the 22 sub-basins had greater than 25 % imperviousness and qualified as a degraded watershed. They concluded that if the trend continues, by 2017 more than 50 % of the Lake Kasumigaura Basin will fall into the degraded category.

6 Future Applications

Accurate and timely land use data, and land use change data, form important components of addressing land use planning and land use policy for the twenty-first century. Remote sensing provides one of the most important tools for acquiring and analyzing such data. In this context, we can expect changes to current strategies. Changes may promote integration of information and target acquisition of imagery to acquire land use data of smaller regions at greater spectral and spatial detail. For example, investigations of the urban heat island can benefit from integration of land use data with detailed thermal data to better define the role of land use in urban temperatures (e.g., see [53, 54]). Likewise, hyperspectral data, not normally employed for land use survey, can play a role in detecting regions where there is a legacy of contaminated soils, environmental hazards, and related risks to public health.

This section will explore three nascent technologies for remote sensing of land cover—Lidar, hyperspectral images, and unmanned aerial systems. The technologies, themselves, are not new, but researchers are exploring new applications in the context of land use/land cover assessment.

6.1 Lidar

Lidar (light detecting and ranging) is a form of active remote sensing. Lidar technology is based on applications of lasers (Fig. 10). Light is generated by the laser (1) which travels through fiber optic cables to a rotating mirror (2). The light is directed through bundled optical cables (3), which are twisted to provide a directed beam through lenses to the feature(s)/object(s) of interest. Reflected light is returned to the sensor (4), through a separate set of bundled fiber optic cables, to a second rotating mirror, and then transmitted (5) via fiber optic cables to the receiver (6). The transmission of the laser beam and the registration of the returns are controlled by the electronics.

The Lidar sensor records the time it takes for the returned (reflected) light to reach the sensor and translates the time delay as distance to the object. After processing of the returns, in aerial systems this distance then determines the height of that particular feature above ground. In ground-based (terrestrial) systems, the measurement is the distance from the sensor. Analysis of these distances, using appropriate software, results in surface elevation models, forest modeling, and other applications. The Lidar sensors are also equipped with geographic referencing equipment so the returns can be spatially located on the Earth's surface. Lidar sensors can be placed on aircraft, satellites, in ground-based vehicles, or on a stationary tripod on the ground (Fig. 11).

Because Lidar transmits light energy, as photons, the pulses penetrate even the smallest openings. The number of pulses per second and time delays between pulses

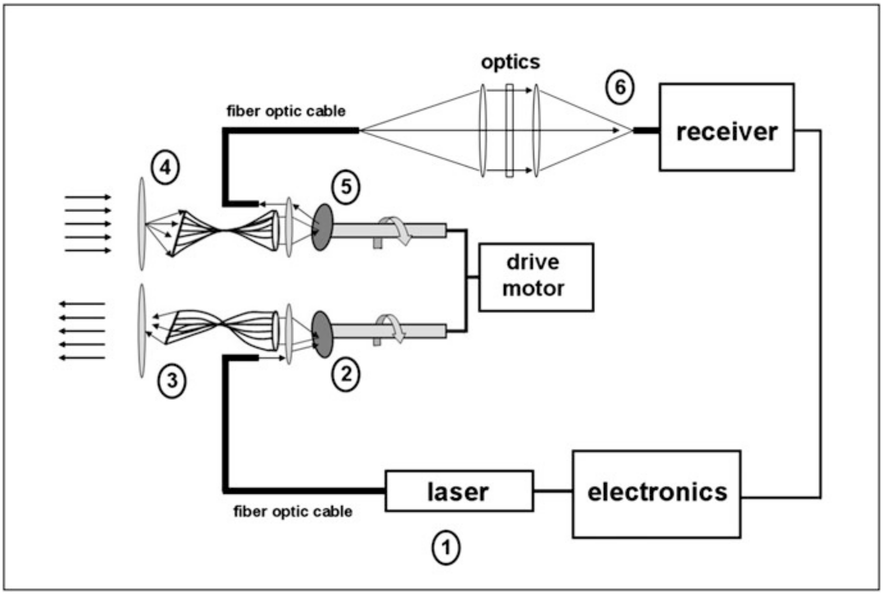

Fig. 10 A schematic of a Lidar scanner [28] (Permissions, Campbell_Guilford_11_August_2014)

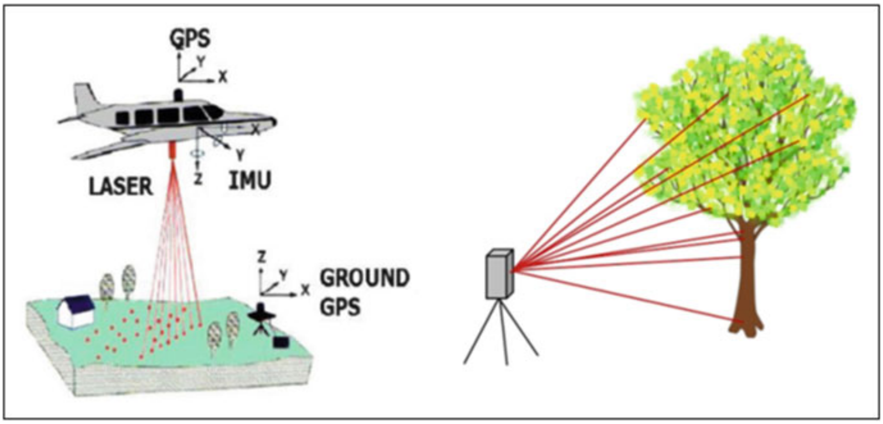

Fig. 11 Airborne Lidar system on the *left*. Terrestrial Lidar system on the *right*. *Sources*: left, USGS; right, second author

depend upon the design of each individual sensor. Sensors can be designed to either transmit light as waveform or as discrete returns. For discrete returns, sensors record the time and intensity of individual returns (from 1 to 5) of each pulse. The number of returns depends also on the complexity of the terrain, i.e., in an open area, only one return may be recorded after the pulse hits the ground, whereas a

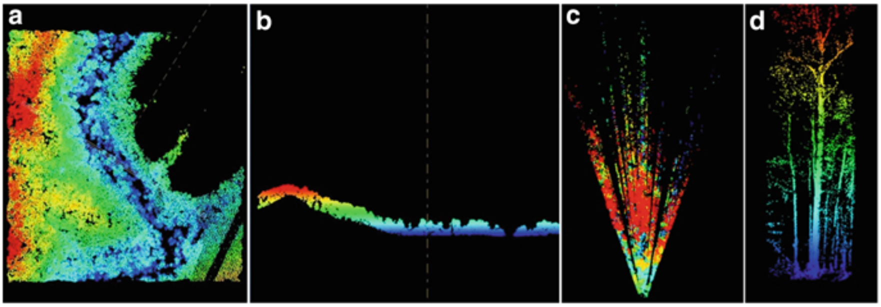

Fig. 12 Lidar point clouds over a Canadian region of the boreal forest. Images (**a**) and (**b**) are airborne Lidar, (**a**) point cloud from above and (**b**) point cloud as seen from the side. Images (**c**) and (**d**) are ground-based acquisition, (**c**) point cloud from above, and (**d**) point cloud as seen from the sensor's origin (*Credit*: First author using V. Thomas data)

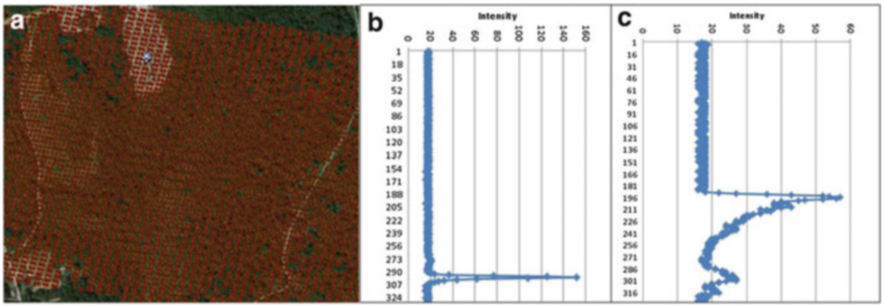

Fig. 13 LVIS waveform Lidar acquired over the Patuxent Watershed, Maryland, USA, (**a**) overhead view displays as a point cloud, (**b**) represents a pulse that hit a road, and (**c**) represents a pulse for a forested area (*Credit*: First author using data downloaded from LVIS website [55])

forest could have multiple returns after hitting leaves and branches of trees, underlying shrubs, and then the ground.

Figure 12 shows examples of discrete-return Lidar of a Canadian segment in the boreal forest. Images (a) and (b) are airborne Lidar, (a) point cloud from above and (b) point cloud as seen from the side. Gaps in the point cloud are areas where pulses were absorbed by water. Images (c) and (d) are ground-based Lidar acquisitions, (c) point cloud viewed from above, the energy originates from sensor (bottom of the image) and spreads out the farther it gets from the sensor. Gaps in this image are areas where the pulse hit an impenetrable object—tree trunks. Image (d) is the point cloud as seen from the ground-based Lidar sensor. The colors within each image represent differing elevations, as assigned by the software user.

For waveform Lidar, the sensor records the entire returned pulse; the image of the waveform is dependent on the terrain. The return's pulses appear as a point cloud when displayed with software (Fig. 13a), but when examining an individual pulse, the terrain is displayed as a wave with varying intensities, as portions of the pulse returns to the sensor after hitting features on the surface of the Earth. Figure 13 shows the display of Laser Vegetation Imaging Sensor (LVIS) [55] waveform Lidar which was acquired over the Patuxent Watershed, Maryland (USA), in 2003 and 2004. Overhead view displayed as a point cloud (a). When viewing the data for a specific point, it displays as one wavelength—(b) represents a pulse that hit a road (a low, flat surface), and (c) represents a pulse for a forested area (several vegetation layers at different elevations).

Because of Lidar's ability to show differing heights, it is useful for three-dimensional modeling, for distinguishing between different tree species, to see into areas shadowed from nearby taller features/objects, and for providing fine-scale delineation between features (the latter is dependent upon the density of the point cloud). Some examples of applications of Lidar for land use or land cover identification include:

In coastal mapping for Camp Lejeune, North Carolina (USA), researchers fused elevations extracted from Lidar with IKONOS imagery to classify roads, water, marshes, roofs, trees, and sand [56]. Investigators opined that fine-scale classification was needed to distinguish features with similar spectral characteristics. They found that using Lidar surface elevations along with the multispectral imagery increased their accuracy for these classifications.

In applications to distinguish features within shadowed areas, researchers have used Lidar data with aerial images to extract land use for rural Spain [57]. These researchers found that the combination of these two types of data allowed extraction of land uses within shadowed areas. In a second study, researchers successfully used aerial photos and Lidar to identify land use in shadows within an urban area—the City of Alcalá, Madrid, Spain [58].

For another urban study, researchers used the combination of Lidar and aerial photos to enhance urban land use analysis for Austin, Texas (USA) [59]. Most specifically, they used a building detection algorithm to identify buildings from Lidar data and then used seven spatial characteristics of these buildings to help classify varying residential land uses.

In a watershed study, for the Garonne and Allier River watersheds in France, researchers used airborne Lidar and SPOT images for land cover classification [60]. Nine separate land cover types were classified—five different types of riparian forests, along with gravel, low vegetation, water, and bare earth.

6.2 Hyperspectral Imagery

Hyperspectral remote sensing is the collection of spectral data forming images with hundreds of bands, each band no more than a few nanometers wide. Hyperspectral data does not necessarily cover a broad region of the electromagnetic spectrum, but divides the spectrum into smaller segments. As an example, Fig. 14 shows differences in bandwidths and total wavelength coverage between images acquired with Landsats 7 and 8—multispectral sensors and Airborne Visible/Infrared Imaging

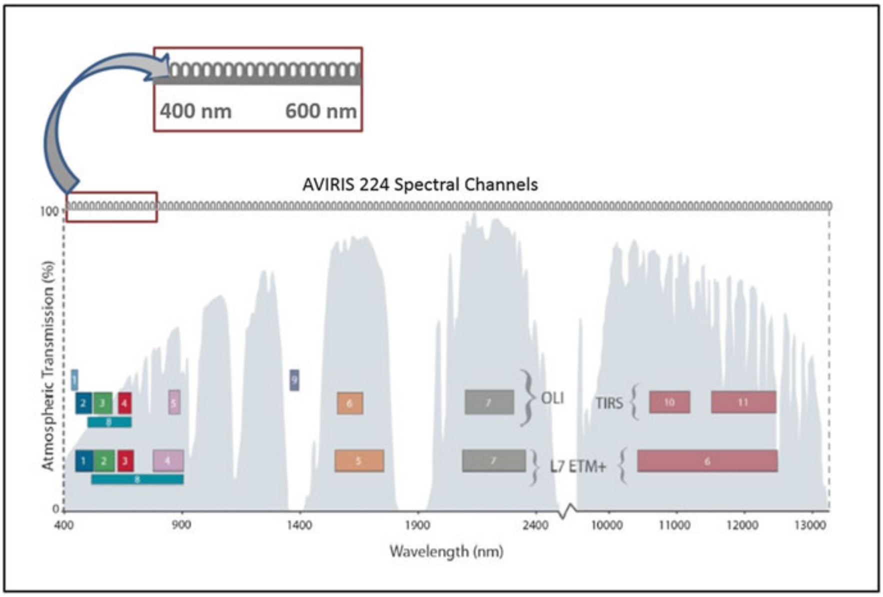

Fig. 14 Comparison of spectral channels for Landsat (multispectral, depicted by colored shapes, *bottom*) and AVIRIS (a hyperspectral sensor with 224 narrow channels, *top*). *Shaded patterns* represent wavelengths where the atmosphere will transmit electromagnetic radiation. Inset represents detail of hyperspectral channels (Landsat diagram credit: USGS; AVIRIS annotations by second author)

Spectrometer (AVIRIS) [61]—a hyperspectral sensor. Landsat acquires images using only 11 noncontiguous bands: nine bands between 0.43 and 2.29 μm and two bands from 10.6 to 12.51 μm. In contrast, AVIRIS acquires images in 224 contiguous bands from 380 to 2,500 nm (or 0.38–2.5 μm), each band only 10 nm wide.

Dividing the electromagnetic spectrum into smaller divisions allows for comparison of spectral properties gathered for specific features to match to spectra gathered in the field (many such spectra are already recorded in spectral libraries). Such comparisons permit detailed analyses of specific biophysical properties, which characterize land use or land cover to permit more precise identification. Hyperspectral evaluations have long been used by energy companies to identify landforms characteristic of mineral-rich regions. Some examples of using hyperspectral imagery in very detailed land use analyses are described below.

One study, of two different regions in Italy, analyzed Multispectral Visible and Infrared Imaging Spectrometer (MIVIS) imagery [62]. For the Tessera region near Venice, researchers differentiated several types of cultivated vegetation—soybeans, corn, sugar beets, alfalfa, wheat stubble, along with mixed woods, water, and urban. For the second location, the Pollino Mountain of Basilicata, they differentiated between several uncultivated vegetative areas—mixed beech forest, fir wood, pine wood, holm oak wood, along with high mountain prairies, xerophilous prairies, and barren and urban lands.

Two different studies in Greece used Hyperion imagery [63]. For an area north of Athens, Greece, researchers differentiated several forest types—conifers and broad-leaved—and identified transitional woodland/scrubland, heterogeneous agricultural areas, scrubland to herbaceous vegetation, sparsely vegetated areas, bare rocks, urban, burnt areas, and sea [64]. For the island of Crete, researchers differentiated between sparsely vegetated areas, permanent crops, heterogeneous agricultural areas, sclerophyllous vegetation, natural grasslands, bare land, and sea [65].

And, for a specific hydrologic analysis, a study for the Woluwe catchment in Belgium [66] analyzed CHRIS-Probe imagery [67]. Researchers differentiated eight land cover classes—forest, agriculture and grassland, water, bare soil, construction site, white buildings, city buildup, and dark buildings. In this study, the color of man-made objects can affect the accuracy of the land cover classification schemes and, as such, the resultant hydrologic model. These researchers used the land cover results as inputs into the WetSpass model to evaluate groundwater recharge.

6.3 Unmanned Aerial Systems

Unmanned aerial systems (UAS) are lightweight aerial vehicles (both fixed and rotary winged, commonly called drones) that carry cameras or other imaging sensors (either passive or active). The vehicles are piloted from a remote location and, typically, the ground-based pilot uses a wireless link to visually monitor the imaged area in real time. UAS origins are found from military uses (dating back to World War I) and from radio-controlled model airplanes used by hobbyists. Images acquired by UAS are saved on a storage device contained within the airborne vehicle and then downloaded after landing or streamed live to the remote operator. Figure 15 is an example of UAS using a fixed-wing aircraft, sensors are located on the wings of the aircraft.

Fig. 15 Fixed-wing UAV (Photo by the second author)

In some situations, UAS offer many advantages over other aerial (aircraft and satellite)-borne sensors:

- Rapid deployment [68], e.g., fine-scale inspection of hydrologic behavior of varied land use classes, associated storm drains, and drainage systems during and immediately after rainfall/snowmelt events.
- More economical mapping [69, 70], especially over small areas [71–73], e.g., spot updates of areas within broader surveys (such as the NLCD) believed to have changed since original compilation.
- Flown at very low altitudes (as low as a several hundred millimeters) and thus obtain extremely fine detail of a specific area [74].
- Used as a substitute for manual field data collection, such as animal surveys [48], situations harmful to human life [75], or validation of information derived from the coarser detail acquired from higher altitudes.
- Used to investigate problematic areas not clearly identifiable on conventional imagery, e.g., flown under cloud cover [70, 76] or in areas masked by shadows or large buildings.

Some specific examples of existing UAS remote sensing applications include:

- Slope and small stream mapping within Universiti Teknologi Malaysia precinct [71].
- Elephant population survey in Burkina Faso, Africa. Researchers found that UAVs were extremely useful in monitoring elephant populations, and of special importance, the elephants seemed to ignore the UAS as they were flying overhead [77].
- Marine mammal survey in Shark Bay, Western Australia. Researchers were able to identify several species of mammals, fly the UAS repeatedly within the same flight time over multiple altitudes, and repeat the flight pattern over the course of several consecutive days [69].
- Test flights over Mt. Etna, Italy. Researchers analyzed gas composition of volcanic plumes (where gaseous plumes are fatal to humans) [75].
- Orthoimages and digital surface model development at an 11 cm spatial resolution for an agricultural region in Córdoba, Spain. Researchers used the resultant images to classify two types of agricultural land uses—terraces and non-terraces [78].
- Rangeland vegetation species classification in southern New Mexico (USA) [79].

We anticipate that future applications of UAS technology in environmental and land use observations will be especially useful in urban areas, where the use of manned vehicles is restricted due to space and safety concerns, for imaging large-scale agricultural fields (where locating a small area of insect infestation may be difficult at higher altitudes), and in forest evaluations (where a tree canopy may prevent observation by sensors from above).

7 Conclusions

Monitoring the health of water—Earth's most precious resource—relies upon an astute understanding of the land surfaces which supply, transport, filter and store water, and regulate water temperatures as it flows to lakes, rivers, and aquifers. Remote sensing's use of airborne and satellite sensors forms the foundation of our ability to monitor large expanses of the Earth's surface and, in fine detail, to record variations in water resources.

These capabilities provide a better understanding of the impacts of human alterations to the Earth's surface upon water quality and water supply. The spatial perspective of remotely sensed imagery provides insight into interactions between varied land covers and land uses. It allows anticipating threats of hazardous materials for water quality, forecasting variations in water supply, and assessing diversions for agriculture, industry, recreation, and other confining impacts of hazardous spills along with mitigating such threats. Remote sensing technologies have significant potential for understanding climate change impacts.

The land use and land cover analyses outlined in this chapter provide some of the most important tools for sustaining, and improving, our ability to monitor the extent and quality of water resources. Employed in coordination with other capabilities described in this chapter, remote sensing can form a framework for understanding interrelationships between the many dimensions of water resources and for illuminating their spatial and temporal variations.

With continued launching of land observation satellites, our ability to map and monitor the Earth's changing surface will become more robust. As sensor technologies continue to change and additional analyses of existing imagery are identified, the ability to classify land cover and land use will be accomplished in even finer detail across broader regions, with greater flexibility in timing, and in acquiring sequential coverage. Greater computing power will allow us to store greater volumes of data over time, acquire larger volumes of data in the future, and fuse various data sources with imagery to perform superior evaluations of water quantity and quality. Looking forward with these advances, as outlined in Sect. 6, Lidar will enhance our ability to visualize and analyze in three dimensions, hyperspectral imagery will allow us to identify spectral signatures of features/objects at finer details, and unmanned aerial systems will be able to map land cover and identify land uses in areas previously not accessible to humans.

Acknowledgement We thank Dr. Valerie Thomas, Virginia Tech, Department of Forest Resources and Environmental Conservation, Blacksburg, Virginia, for providing the Lidar data mentioned in Sect. 6.1 Lidar.

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Identifying Urban Watershed Boundaries and Area, Fairfax County, Virginia

Tammy E. Parece and James B. Campbell

Abstract

Urban hydrology differs from that of natural environments, and thus urban watersheds require innovative evaluation techniques. Typical geospatial evaluation of urban hydrology begins with identification of water flow and watershed boundaries. This study identifies steps to delineate a highly urbanized watershed in Fairfax County, Virginia. Using standard techniques for natural watersheds and one-meter2 resolution lidar, watershed and flow accumulation raster datasets were derived. Then, modifications encountered within urban landscapes i.e., impervious surfaces, stormwater inlets, pipes, and retention ponds along with high-resolution aerial photos and lidar-derived contour lines were integrated into the analysis. Regions redirecting water flow from stream channels and areas redirecting water flow into the stream channels were identified. These areas were removed or added, reducing the area by almost 17 percent, and the watershed boundary was significantly altered. This analysis illustrates the significance of the distinctive characteristics of the urban landscape in accurate delineations of urban watersheds.

Introduction

Substantial literature, dating back decades, has been devoted to urban hydrology; most specifically to evaluation, management, and engineering of urban hydrologic systems to address changes the built environment has wrought on the natural hydrologic cycle (e.g., McPherson and Schneider, 1974; Debo and Day, 1980; USDA, 1986; Sample *et al.*, 2001; Debo and Reese, 2003; Lhomme *et al.*, 2004; Leonhardt *et al.*, 2014). With the advent of GIS, research has become much more robust in modeling water flow and evaluating water quality issues (Rodriguez *et al.*, 2008). Yet, a better understanding of hydrologic impacts of urbanization is required as current best management practices implemented to address urban stormwater runoff are proving to be inadequate (Burton Jr. and Pitt, 2002). Effective management of urban stormwater runoff and water quality issues can only be accomplished once drainage areas and flow networks in urban settings are identified, with careful attention paid to the urban landscape's distinctive features (McPherson and Schneider, 1974; Burton Jr. and Pitt, 2002; Quinn, 2013).

Urban hydrologic characteristics are unique i.e., quite unlike those of natural environments (Kaufman *et al.*, 2001; Sample *et al.*, 2001; Debo and Reese, 2003; Rodriguez *et al.*, 2003). Anthropogenic changes from land grading, channelization, impervious surfaces, and stormwater sewer systems direct water flows from one catchment area to another (McPherson and Schneider, 1974). Yet, geospatial evaluation of hydrologic impacts begins with identification of overland water flow and watershed boundary areas, and evaluative techniques applied are based on similar techniques used in natural landscapes (Sample *et al.*, 2001; Rodriguez *et al.*, 2003). These conventional approaches fail to account for transfers of runoff across topographic divides, creation of sinks, and disruption by built topography, which modify original natural surfaces and invalidate conventional delineations of drainage systems.

Water bodies experience changes from stormwater runoff with as little as 10 percent impervious surface cover within its watershed (Center for Watershed Protection 2003). Anthropogenic landscape changes due to removal of vegetative cover and increased impervious surfaces have reduced infiltration, amplified stormwater runoff volume and rate, diminished groundwater tables, and decreased evapotranspiration (DeBusk *et al.*, 2010; Welker *et al.*, 2010). Stormwater runoff from impervious surfaces in urban regions degrades water quality through higher water temperatures, and elevated levels of contaminants in surface waters (Slonecker *et al.*, 2001; Davis *et al.*, 2010; Welker *et al.*, 2010). Stormwater runoff not only effects water quality within a specific urban region but also vitiates downstream waterbodies (Bhaduri and Minner, 2001).

On-the-ground surveys in an urban area can produce watershed boundaries that do not compare to those of a natural watershed because they account for grading, and slope changes from impervious surfaces. However, field surveys cannot account for water inflows or outflows without evaluating the stormwater network's inlets, pipes (including location and flow direction), and retention ponds. In large urban areas, field surveys can be quite complex, expensive, and disruptive to daily human activities.

Many researchers recognize that stormwater networks and impervious surfaces have altered urban water flows, and the need to include these and aerial photographs with raster based-delineations (Kaufman *et al.*, 2001; Debo and Reese, 2003), yet few researchers alter standard geospatial methods when delineating an urban watershed. In *Urban Drainage Catchments* (Maksimovíc and Radojkovíc, 1986), when identifying watershed/catchment area, most authors recognized that the built environment changed the natural water flow, and therefore, included these changes in their delineations. However, these delineations were all accomplished without using geospatial software and were completed for relatively small areas. We located four articles evaluating stormwater flow, which included stormwater networks and field data collection with GIS to delineate catchments (Table 1).

While published research is sparse, many government agencies and personnel, and other professionals have long recognized the deficiencies in applying routine methods in identifying urban catchment areas. As such, many of these entities are including impervious surfaces, stormwater networks, and remotely sensed data in analyses in local areas (Mauldin, personal communication, 2014; Quinn, personal communication, 2014). In addition, as more urban infrastructure is recorded as

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Photogrammetric Engineering & Remote Sensing
Vol. 81, No. 5, May 2015, pp. 365–372.
0099-1112/15/365–372

doi: 10.14358/PERS.81.5.365

Table 1. Research including Stormwater Network Systems in Their Identification of Urban Watershed Boundaries

Author Year	Method
Sample *et al.*, 2001	Gathered vector based data from an on-the-ground analysis for a 43 acre neighborhood.
Rodriguez *et al.*, 2003	Used a land-based survey to delineate three specific catchment areas (between 18 and 180 hectares) and then added stormwater sewers to analyze water flow.
Lhomme *et al.*, 2004	Established a DEM delineated flow path, overlaid the stormwater drainage system and calculated the change in flow path
Amaguchi *et al.*, 2012	Vector-based urban landscape delineation and divided study area into city blocks to evaluate water flow within each block. Also split water flow into above surface and below surface, eventually all flowing into the river channel.

digital data, ArcHydro (an add-on data modeling application for GIS) has the potential to integrate stormwater infrastructure with terrain models and other geospatial layers, which will boost analytic power of urban watershed evaluation, planning, and management (Maidment, 2004; Nelson, 2009).

This study presents an analysis of an urban drainage system to illustrate the impact of urban development upon conventional delineation involving natural drainage systems. The approach addresses urban watershed delineation and integrates stormwater network systems and aerial photos with geospatial techniques, using both vector and raster analysis. We hypothesize that using these additional techniques, for a complete evaluation in urban settings, would produce a watershed area and boundary that varied significantly from that defined by applying techniques accepted for delineation of natural watersheds. Thus, our study illustrates specific examples of how application of standard geospatial techniques developed, for identification of watershed and water flow in natural areas, is insufficient in urban environments.

Study Area

A case study for a small urban watershed in Fairfax County, Virginia illustrates the value of applying different methods to delineate the watershed and flow network, and forms the basis for comparative analysis. The Flatlick Branch of the Cub Run watershed in Fairfax County, Virginia is our study site. This stream and watershed are located in the extensively urbanized northern Virginia area, just outside of Washington, D.C. Specifically, the stream is in northwestern Fairfax County, very close to Washington Dulles International Airport (Figure 1).

Figure 2 depicts the spatial distribution of general land use categories within the watershed. Land use in the watershed is generally residential (64 percent) represented by single family homes with a mixture of low and medium density. The watershed's second major land use is categorized as open space (23 percent), however, a golf course (center of the image) represents almost half of the open space category. The watershed has smaller areas of commercial and industrial land uses; dispersed forest patches are present in all land use categories.

Extensive data are available for Fairfax County watersheds, as the US Geological Survey (USGS) has numerous streams gauged in this area for water quantity and quality assessments. The USGS office in Richmond, Virginia provided the data used in this analysis:

- 2009 natural color aerial photos at 15 cm resolution, acquired by the Virginia Base Mapping Program through a contract with the Sanborn Map Company. Virginia acquires orthoimagery across different locations over the Commonwealth on a four-year rotating basis. The 2009 flyover included the northern Virginia metropolitan area and the imagery was acquired using North American 1983 HARN Datum (Virginia Geographic Information Network 2011).
- Raster dataset for an elevation model generated from lidar with one-meter2 resolution. The lidar acquisition was accomplished in 2009 and delivered to Fairfax County as several preprocessed datasets including the elevation model used in this analysis.
- Line shapefile for field documented above-ground locations of the stream channel(s), completed by Fairfax County in 2008.
- Polygon shapefile, for the watershed, digitized by analysts at the USGS from their hand delineation completed from a topo map.
- Point shapefile for the location of the USGS-Flatlick Branch stream gauge; the gauge was installed in 2007 by the USGS.
- Shapefiles for all known or surveyed stormwater pipes (lines), inlets - manholes and curbside (points), and retention ponds (polygons) for Fairfax County, completed by Fairfax County in 2005.
- General land use in a polygon shapefile, created by Fairfax County in 2007.

Methods

First, comparing the lidar-watershed delineation to the USGS-derived watershed was considered necessary to determine which watershed model would be the best to use for our analysis. The *Spatial Analyst Hydrology* toolset in Esri's ArcMap® was used to process the lidar-elevation model into watershed and flow accumulation raster datasets. Figure 3 shows the process, each tool used, and the resulting raster layer. The USGS-stream gauge (point) shapefile was used as the pour point input in the final step of the watershed delineation. Several flow accumulation datasets, with varying thresholds, were created with *Raster Calculator* to help evaluate the flow of water across the watershed landscape. A contour line file was also created using the *Spatial Analyst/Contour* tool, with contour spacing of one meter.

In GIS, the point, line, and polygon stormwater network shapefiles were overlaid on the lidar-derived watershed, along with the lidar-contour lines, stream channel shapefile, and lidar-derived flow accumulation raster datasets, to evaluate how the stormwater networks would influence and impact water flow within the watershed. We were specifically looking for three situations:

1. stormwater networks that do not connect to surface drainage ways, thus are not part of the "naturally" delineated watershed and act as isolated catchment areas;
2. stormwater pipes that discharge outside the watershed (de facto decrease in drainage area); and
3. stormwater pipes that drain into the watershed (de facto addition to drainage area).

The aerial photos were added to our map as the bottom layer of the ArcMap® window, and layers were turned on and off as needed to assist with the visual analysis.

First, the stormwater facilities were evaluated under situation 1 (above), i.e., for detention versus retention ponds (detention ponds are designed to only slow the flow of water into natural stream channels, whereas retention ponds hold water and prevent the flow going into natural channels). For any locations determined as detention ponds, no changes were made to the original lidar-watershed delineation. Any areas identified as retention ponds, thus acting as isolated catchment areas, were selected and exported into a new polygon shapefile. Since the pour point (the ArcGIS term for the

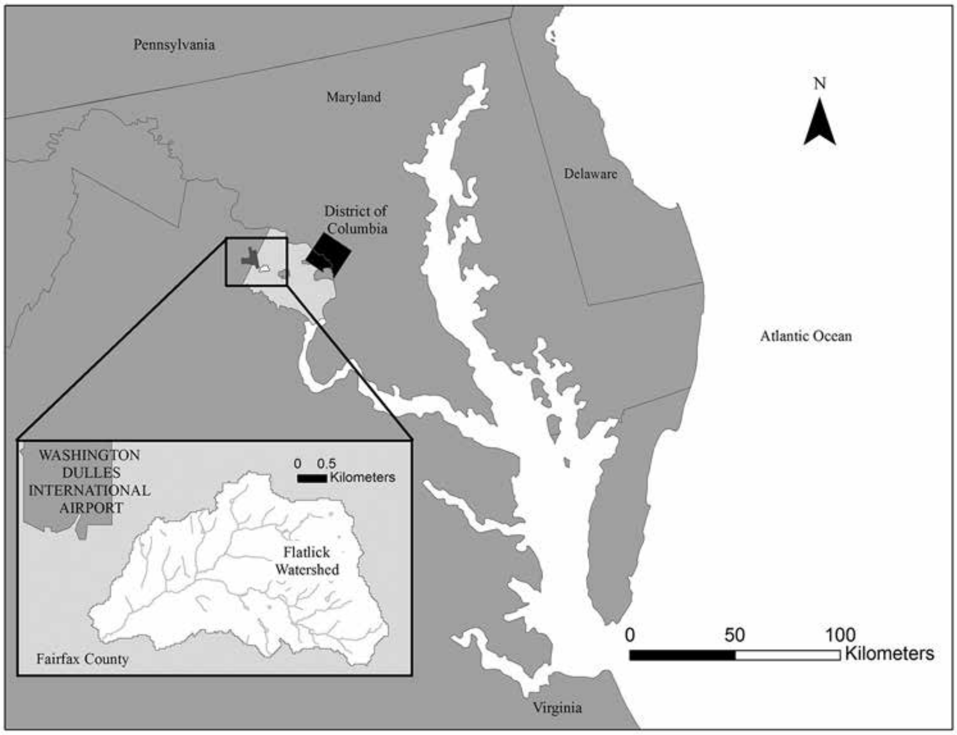

Figure 1. Location of Flatlick Branch of the Cub Run Stream, Fairfax County, Virginia.

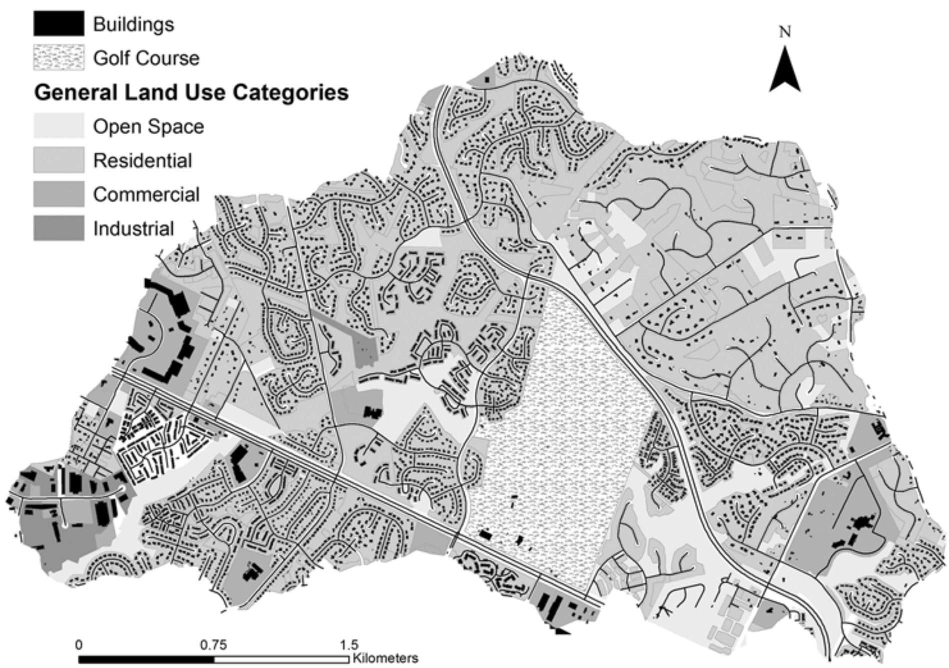

Figure 2. Land use distribution within the boundaries of the US Geological Survey-delineated watershed.

location of concentrated water flow exiting a specific catchment (Esri, 2012)) input for the watershed tool can be a point shapefile or a raster dataset, the stormwater network facilities (polygons), identified as retention ponds and exported into the new shapefile, were converted to a raster dataset using the *Conversion/Polygon to Raster* tool. The land area draining into these specific locales was identified, again using the *Spatial Analyst/Hydrology/Watershed* tool with the new raster datasets (the pour point) and the lidar-derived flow direction raster as the inputs to the tool. In this manner, the land area for each of these individual isolated catchments was delineated.

In each step, our visual analysis continued, using all shapefiles, the raster datasets, and the aerial photos, i.e., turning on and off layers as needed to evaluate the flow direction. This step was essential to ensure that these "isolated" stormwater facilities were, in fact, isolated, and not eventually draining into the main stream channel or a buffer zone around the main stream channel.

Impervious surfaces or drainage pipes can also bring additional water flow into the retention ponds: in some cases

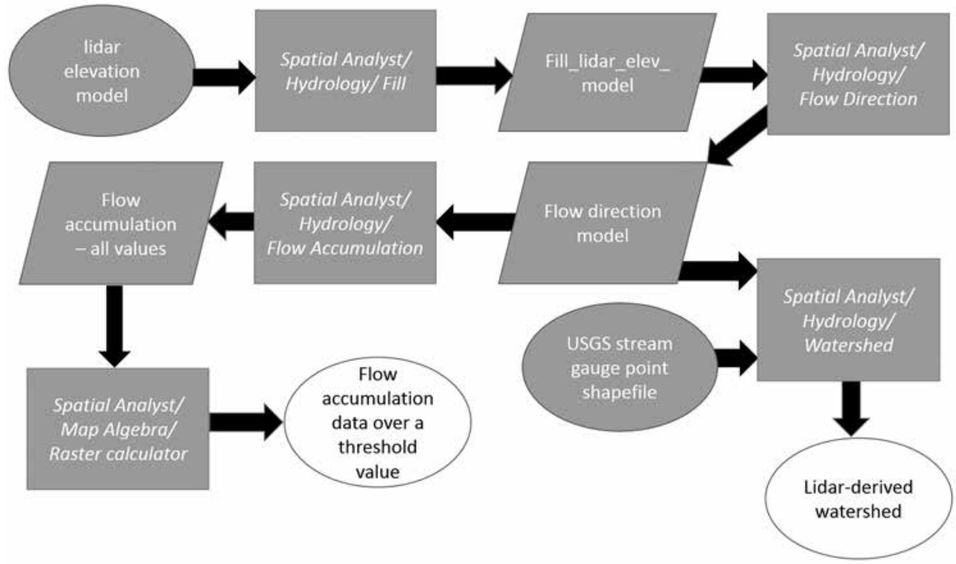

Figure 3. Steps using the *Spatial Analyst/Hydrology* toolset to delineate watershed and flow accumulation raster datasets from the lidar-elevation model. Gray ovals represent original raster dataset or shapefile input. Rectangles represent the GIS tool. Parallelograms represent the output from the tool and also the input raster dataset into the next tool. White ovals represent the final datasets.

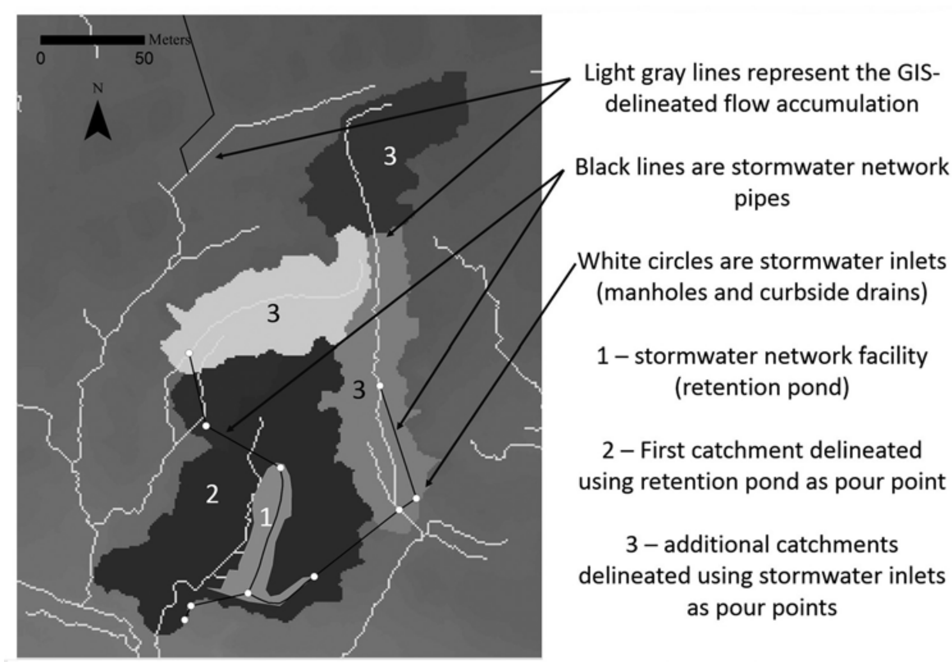

Figure 4. Stormwater drain pipes adding additional land area to a retention pond's watershed.

with stormwater inlets and in other areas by the grading of impervious surfaces. For example, in Figure 4, polygon 1 is a stormwater network retention pond and polygon 2 is the watershed delineated for this retention pond (using the retention pond area in raster form as the pour point). In this figure, the stormwater inlets (curbside drains and manholes) are represented by small white circles, the stormwater network pipes represented by black lines, and the light gray lines represent the lidar-flow accumulation raster dataset. Stormwater inlets (white circles) were clearly installed for stormwater flow locations as they are placed directly on the flow accumulation. The stormwater network pipes were installed to allow stormwater flow straight into the stormwater retention pond. This additional land area covered by these flows needed to be included in this delineation, so these specific stormwater inlets served as additional pour point inputs into the *Watershed* tool. This evaluation and delineation was conducted multiple times, for all isolated stormwater network facilities within the watershed, and any stormwater inlets connected to stormwater pipes clearly allowing additional water flow into the retention pond. Each time we verified our decisions by visual evaluation using the lidar-elevation model, lidar-contour lines, and aerial photos.

The next step was evaluation of any stormwater pipes that cross the lidar-delineated boundary of the watershed under situations 2 and 3 (above) and as depicted in Figure 5. For each of these locales, we carefully examined each with the lidar-elevation model, lidar-contour lines, and aerial photos to determine if the stormwater pipes were connected to the

Figure 5. Stormwater network pipes that cross the boundary of the lidar-derived watershed. Dark gray lines and polygons represent stormwater network pipes and facilities. Within the bold black outlines are examples of stormwater pipes and facilities that cross the lidar-watershed delineated boundary.

stream channel, retention or detention ponds, or discharged into buffer zones around the above-ground stream channels. For each of these locations, the land area draining to these points was determined, again using the stormwater inlets (points) and facilities (polygons) as the pour point input of the *Watershed* tool.

For the final step of our analysis, *Raster Calculator* was used to build equations that added the new land area and subtracted land area from the original lidar-derived watershed raster.

Results

Figure 6 shows results of delineating the watershed from the lidar-elevation model; elevation within the watershed ranges from 78 to 150 meters. Overlaying the USGS-derived watershed (bold black outline) on the lidar image reveals that the watershed shapes are very similar but also reveals impacts of roads and other impervious surfaces and sharpening some of the edges of the lidar-watershed. The area measured in hectares is very similar, i.e., 1,089 ha for the USGS-derived watershed and 1,086.6 ha for the lidar-elevation model. However, the lidar-watershed was the most appropriate to use in the next two steps of our analysis because of its finer one-meter^2 resolution, and because it appears to include the influence of impervious surfaces in some areas of the watershed delineation.

When overlaying the stormwater network shapefiles on the lidar-elevation model several areas that met the criteria under each situation listed above in Methods were identified : (a) stormwater network facilities isolated from the stream network, including retention ponds either not located on water flow channels or connected only to each other by stormwater network pipes (Plate 1), (b) stormwater pipes that discharge outside the watershed, and (c) stormwater pipes that drain into the watershed area.

To reiterate, we carefully evaluated each stormwater facility with all map layers, raster datasets, and the aerial photos to ensure accuracy in identifying it as a retention pond or a detention pond. Some areas were clearly visible on the lidar-elevation model as separate catchment areas (please refer back to Plate 1, Box 2 - darker shading represents higher elevations, thus watershed divides). In some instances, stormwater pipes and a section of the above-ground stream channel designed to drain into a retention pond and not into the main stream channel were identified (Plate 2, Box 1). In yet other cases, we discovered stormwater pipes that actually connected two unconnected stream channels, and then directed water flow into a buffer zone around the main stream channel (Plate 2, Box 2).

Twenty-four areas of water flow disconnected from the stream channel because of the stormwater network facilities were identified. The total area of these independent catchment areas (delineated for the stormwater network facilities isolated from the stream channel) is 162.4 hectares, and constitute locations subtracted from the Flatlick Branch lidar-derived watershed.

Ninety-four locations where stormwater inlets were connected to pipes crossing the watershed boundary (again for an example see Figure 5) were identified. Of these, 32 stormwater inlets outside of the watershed boundary were connected to pipes adding stormwater flow into the watershed, thus adding land area; and 41 stormwater inlets inside the watershed boundary were connected to pipes that removed stormwater flow from the watershed, thereby removing land area from the drainage basin.

In addition, the direction of the water flow (into or out of the watershed) for one of the stormwater pipes could not be determined (Figure 5). The remaining locations of stormwater network pipes that crossed the watershed boundary had no impact as they were already removed from the watershed when the individual catchment areas (see above paragraphs on isolated catchment areas) were identified.

Figure 7 represents the final watershed overlaid with the boundary of the original lidar-delineation. The original

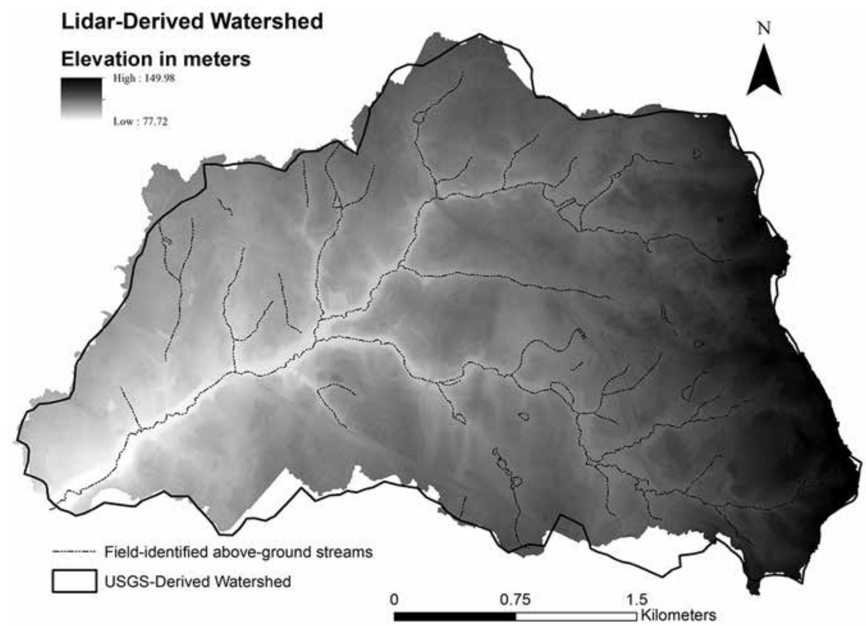

Figure 6. USGS-derived watershed (bold black outline) overlaid on the lidar-derived watershed.

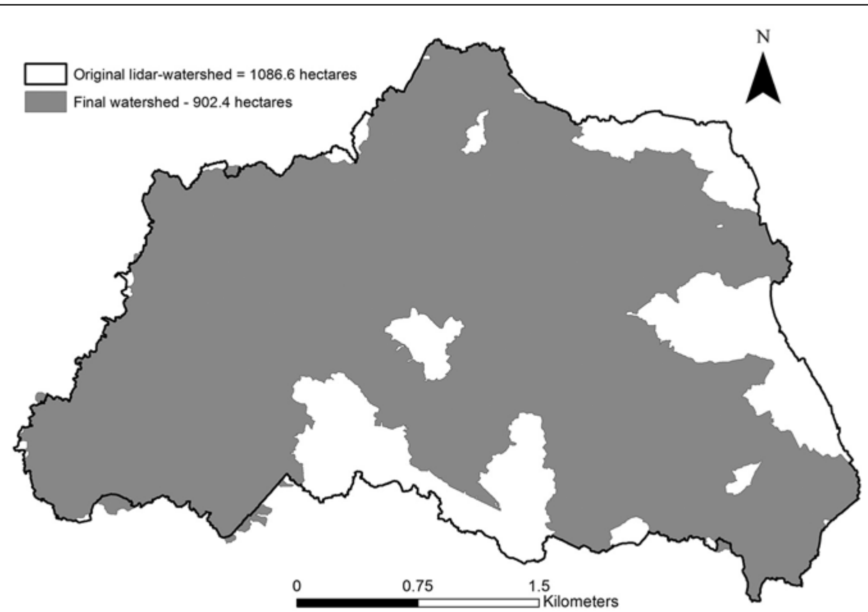

Figure 7. Watershed area (gray) after removal of catchment areas delineated from stormwater network facilities, pipes, and inlets, and adding additional land areas contributing water flow from outside the original lidar-derived watershed boundary. Bold black outline is the original lidar-derived watershed.

lidar-derived watershed area was 1,086.6 hectares. After adding and subtracting land area throughout this analysis, the total corrected area is 902.4 hectares, a difference of 16.9 percent. More important than total watershed land area is the alteration of the watershed boundaries; boundaries determine the actual land area necessary for stormwater management and other best management practices related to urban water quality.

Some areas of the watershed still needs field analysis. In several locations, the watershed boundary crossed over rooftops, both flat commercial buildings and angular roofs of residential buildings. Even with our high-resolution aerial photos, we were unable to determine how stormwater was collected or redirected from each of these rooftops. As such, each building would need to be evaluated for its management of stormwater flow. In addition, it is not clear from the stormwater network shapefiles and aerial photos whether or not one specific area actually added or removed land area from the watershed (Figure 5, the northwest-pointing U-shaped stormwater facility, represents a parking lot). We were unable to address this specific area within our remote geospatial analysis.

Conclusions

For our small, highly urbanized watershed, one-meter^2 resolution lidar-delineation of a watershed only slightly changed the watershed area as compared to the USGS manual interpretation using a topographic map. The difference in area was only 2.6 hectares. For those locales, with physical characteristics similar to the Flatlick Branch of the Cub Run watershed, that do not have lidar available, this result demonstrates very little difference in area between ten-meter^2 and one-meter^2 resolution elevation models. Thus, lidar, although preferred,

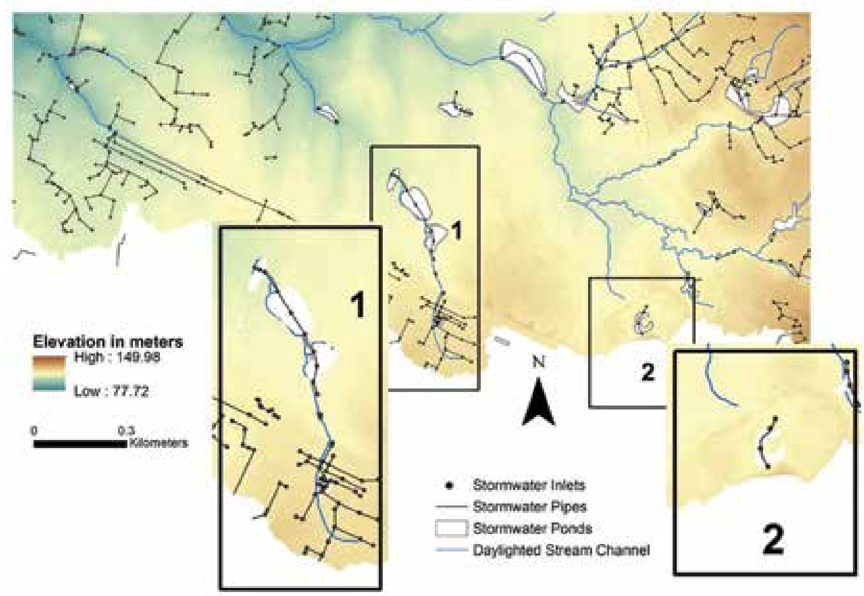

Plate 1. Examples of areas disconnected from the stream channel (blue lines). In Box 1, retention ponds (white) are connected to each other by stormwater pipes (black lines) and inlets (black dots). In Box 2 stormwater inlets and pipes flow into a single retention pond.

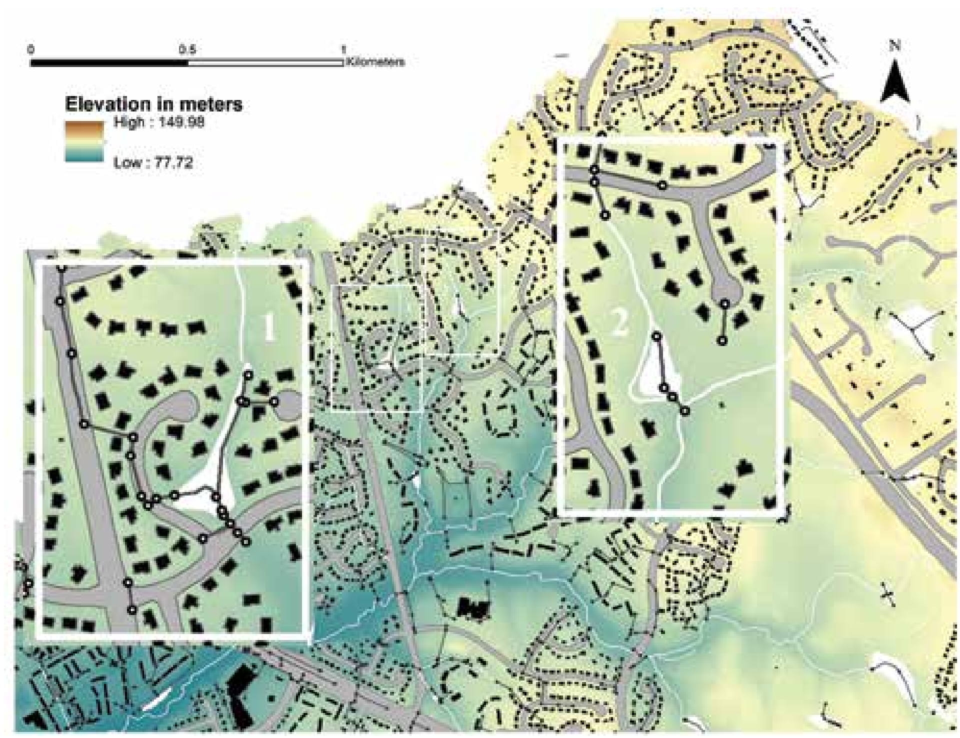

Plate 2. Box 1 shows a stream channel (white lines) and stormwater pipes (black lines) directing water flow into a stormwater retention pond (white polygon) and away from the main stream channel. Box 2 shows an area of a stormwater detention pond as the stormwater pipes actually join disconnected stream channels to the main stream channel.

may not be a requirement for urban watershed delineation for a location with similar terrain and land use.

Actual boundary differences were more pronounced and may have more influence on the water flow in an urban area. The lidar-delineated watershed appeared to provide a better account of impervious surfaces than did the coarser resolution USGS-derived watershed model. The lidar resolution, at only one-meter^2, was based on final returns of the lidar for the surface elevation. However, neither delineation accounted for additions or subtractions from the watershed resulting from stormwater network inlets (curbside drains and manholes), pipes, and retention facilities. After subtracting isolated networks from the watershed, and adding and subtracting the land area with redirected flow because of the stormwater network system, the area decreased by almost 17 percent. We further note that additions and subtractions to the area of the lidar-derived watershed caused by mis-definition of watershed boundaries not only alters the size of catchment, but also, by adding and subtracting different land uses, can alter the hydrologic character of the watershed, further misrepresenting its nature.

We recognize our analysis has many limitations. Data sources may be inaccurate or incomplete in ways that analysts cannot understand, due to incomplete documentation and the unknown number of parties who can alter local drainage. Further, local jurisdictions, such as Fairfax County, must respond to requirements to change drainage infrastructure, especially in light of new federal and state stormwater management regulations. In addition, other drainage infrastructure, e.g., drainage tiles, homeowner drainage modifications, or rainwater harvesting systems, may not be visible, or documented by the local government. Such changes can further complicate urban watershed delineation.

This geospatial analysis has supported the original contention that using GIS in delineating watersheds in urban areas is not as simple as it is in natural settings, and that anthropogenic alterations to land cover and landscape create complex hydrologic geometries. The greatest complications are stormwater sewer networks and impervious surfaces, which are designed to redirect water flow. With the stormwater drain networks, lidar and high-resolution aerial photography, geospatial evaluation can include these features in delineating the watersheds.

However, despite the ability to include stormwater networks in our analysis, impervious surfaces, such as roads and parking lots, interfere with use of ArcGIS *Hydrology* toolset, require repeated delineation to capture all the land area that drained into a specific locale (either stormwater inlet or stormwater facility), and thus ground assessment may still be necessary. Rain collection from roof areas also needs further evaluation to determine its inclusion or exclusion from surface flow and in the main stream channel and watershed area. In addition, relationships between natural and built drainage systems require further evaluation.

Surface runoff in urban regions has significance for local climates, water quality, transport and concentration of contaminants, flood control, and public health. The complex hydrologic characteristics of urban landscapes, including complex patterns of impervious surfaces, vegetation, structures, and compacted soils, present immense challenges for hydrologic analysis. The complexity of urban systems are further challenged by climate change and the increasing intensities of precipitation. Still, the biggest challenges for urban hydrology is the inability of conventional tools and strategies, transferred from rural and natural landscapes, to describe hydrologic processes prevalent in urban systems.

Acknowledgments

We thank John Jastram, Hydrologist, US Geological Survey, for providing the geospatial files used in this analysis. We also thank members of the audience attending our paper presentation at the 2014 ASPRS Conference, Louisville, Kentucky, for their encouragement to submit this research as a journal article. Further, we recognize the contributions of the *PE&RS* reviewers for their careful attention, comments, and insights that have strengthened this paper. The Virginia Space Grant Consortium provided partial support for this project.

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(Received 29 April 2014; accepted 05 December 2014; final version 16 Dacember 2014)

Hindawi Publishing Corporation
Advances in Meteorology
Volume 2016, Article ID 8736263, 14 pages
http://dx.doi.org/10.1155/2016/8736263

Research Article

Assessing Urban Landscape Variables' Contributions to Microclimates

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Received 2 July 2015; Accepted 16 September 2015

Academic Editor: Stefania Bonafoni

The well-known urban heat island (UHI) effect recognizes prevailing patterns of warmer urban temperatures relative to surrounding rural landscapes. Although UHIs are often visualized as single features, internal variations within urban landscapes create distinctive microclimates. Evaluating intraurban microclimate variability presents an opportunity to assess spatial dimensions of urban environments and identify locations that heat or cool faster than other locales. Our study employs mobile weather units and fixed weather stations to collect air temperatures across Roanoke, Virginia, USA, on selected dates over a two-year interval. Using this temperature data, together with six landscape variables, we interpolated (using Kriging and Random Forest) air temperatures across the city for each collection period. Our results estimated temperatures with small mean square errors (ranging from 0.03 to 0.14); landscape metrics explained between 60 and 91% of temperature variations (higher when the previous day's average temperatures were included as a variable). For all days, similar spatial patterns appeared for cooler and warmer areas in mornings, with distinctive patterns as landscapes warmed during the day and over successive days. Our results revealed that the most potent landscape variables vary according to season and time of day. Our analysis contributes new dimensions and new levels of spatial and temporal detail to urban microclimate research.

1. Introduction

As early as the 1800s, observers recognized that urban regions are warmer than their rural surroundings, an effect known as the urban heat island (UHI). The UHI is well understood through a multitude of studies documenting its relationship to landscape differences between rural and urban areas [1, 2]. Land cover and land use changes—removal of vegetative cover and increasing amounts of impervious surface cover—will intensify and expand UHIs [3]. Urban areal extent expands as urban populations grow, and with over 50% of the world's population now living in urban areas, the UHI is expected to intensify [4].

Furthermore, urban areas are internally heterogeneous, from spatial variation of urban surfaces and construction, along with their economic and historic development. Such differences within urban landscapes create microclimates generated by unique combinations of surface materials' thermal properties, vegetative cover, landscape design, and remnants of the natural environment [5, 6]. Understanding the spatial patterns of urban microclimates requires assessment of local relationships between air temperatures and urban landscape features, at fine spatial scales [7]. Practical implications for improved knowledge surrounding spatial detail of urban temperatures include impacts for human health and safety, forecasting variations in energy use, and municipal administration.

This paper assesses those distinctive combinations of urban landscape features that create microclimates within a specific urban area, the city of Roanoke, Virginia, USA. We use these distinctive combinations to estimate temperatures across the entire city and address gaps in research investigating fine-scale microclimate variations within an UHI.

2. Urban Microclimate Literature

While UHI literature evaluating differences between rural and urban temperatures dates back over a century (as referenced by [1, 9]), research evaluating intraurban microclimate differences date back only a few decades. Much of this research evaluates temperature differences related to land use, that is, low-density residential, high-density residential, industrial, commercial (e.g., [1, 10–17]). Some recent research has investigated land cover and related thermal differences (e.g., [18–22]). However, evaluative techniques for microclimate assessments vary widely.

Extensive research has been accomplished using only satellite imagery to evaluate urban thermal patterns (e.g., [11, 15, 16, 23, 24]). Some satellite studies attempt to extrapolate specific land surface temperatures from remotely sensed images of varying resolutions (i.e., Landsat or MODIS) [25]. These studies report specific temperature values derived from radiative values (from the satellite images) and, in some cases, validating these estimated temperatures with data from a limited number of field sites [2]. But satellite imagery does not accurately represent all ground surface characteristics because in some regions it records thermal conditions of building roofs [5, 6].

Because satellite imagery cannot capture all ground conditions, some researchers utilize mobile mesonet units to record air temperatures along specified transects in conjunction with remotely sensed imagery (e.g., [12–14]). Although mobile units are effective in collecting data across the range of urban landscapes, they are restricted to roadways and parking areas and have a limited temporal scope. Further, because temperatures are changing while mobile collection is underway, data should be segmented into shorter temporal intervals to minimize mixing of temporal and spatial variation.

In contrast, fixed weather stations deliver a constant stream of data from established locations. As such, some researchers acquire temperature data from fixed weather stations or temporarily place stationary weather stations in designated areas (e.g., [1, 14, 26–28]). But, in most urban areas, the number of fixed stations is limited, with sparse distributions relative to place-to-place variation of local temperatures. Combining both approaches provides advantages in capturing local spatial and temporal variations.

Some urban microclimate studies only use a network of fixed stations and site units in specific locations across an urban area (e.g., [29–31]). But, again, the number and placement of fixed stations are not able to capture the detail created by unique combinations of urban landscape characteristics.

The aims of urban microclimatic research are variable. For example, Gaffin et al. [29] assessed temporal patterns over the past 100 years, seasonally and diurnally. Bourbia and Boucheriba [30] specifically examined urban street canyon variables. Holmer et al. [19], bencheikh and Rchid [22], and Asgarian et al. [32] examined effects of vegetation on cooling in an urban environment. Yahia and Johansson [31] examined differences in heating and cooling between parks, urban canyons, and open residential areas.

A few researchers have examined the unique combinations of landscape characteristics, although the number of temperature sites is often limited or temporary, the time period of collection is limited, and distances (within which the landscape characteristics are captured) differ.

(i) de Andrade et al. [33] used five sites, collected data over six days, and used descriptive variables to categorize the landscape (bare soil, green areas, arboreal areas, built-up areas, and water bodies) within a 450-meter radius of each station;

(ii) Shahrestani et al. [34] used six sites (but the radius around each site is unclear), including street orientation, built surfaces: walls, roads, and other pavements, vegetation, and elevation, collecting data for one month during the summer;

(iii) Sodoudi et al. [35] used three permanent stations and 31 sites using hand-held equipment, for one day over two different collection times; variables were soil type and texture, building dimensions, vegetation type, and impervious surface type, but again it is unclear what radius around the equipment was used to identify the specific variables;

(iv) Bourbia and Boucheriba [30] used seven stations, collecting data every two hours for two weeks during summer; variables included skyview factor, street orientation, street widths, and building heights, but again buffer distance is not clear.

Rarely do researchers use these variables to extrapolate temperature patterns across entire urban areas. Only one such study was found—Hart and Sailor [28] collected afternoon temperatures for six days, no more than one hour at a time, over a two-month summer period. They chose dates when temperatures were predicted to be higher than normal. They used mobile transects (employing one to four vehicles), collecting data every 2 seconds and eliminating duplicate data collected when stopped. They normalized temperatures for elevation using data from the permanent weather station located at the nearby airport. Landscape variables included land use, tree canopy cover, impervious surface cover, ground vegetation, loose surface cover, total length of roads, and total floor space as captured within 300 meters for each of their temperature readings. They used a regression tree model to extrapolate temperatures across the entire city of Portland Oregon for two categories—weekdays and weekends.

Our research resembles that of Hart and Sailor [28] but refines and expands upon their (and other researchers') efforts by employing finer spatial and temporal detail. We use mobile collection units, with a network of fixed stations, and include landscape variables collected at a finer spatial scale (30 × 30 m), for multiple data collection periods across two years, and used Random Forest to estimate temperatures across our entire study site. We refer readers to our *Methods* section for complete details.

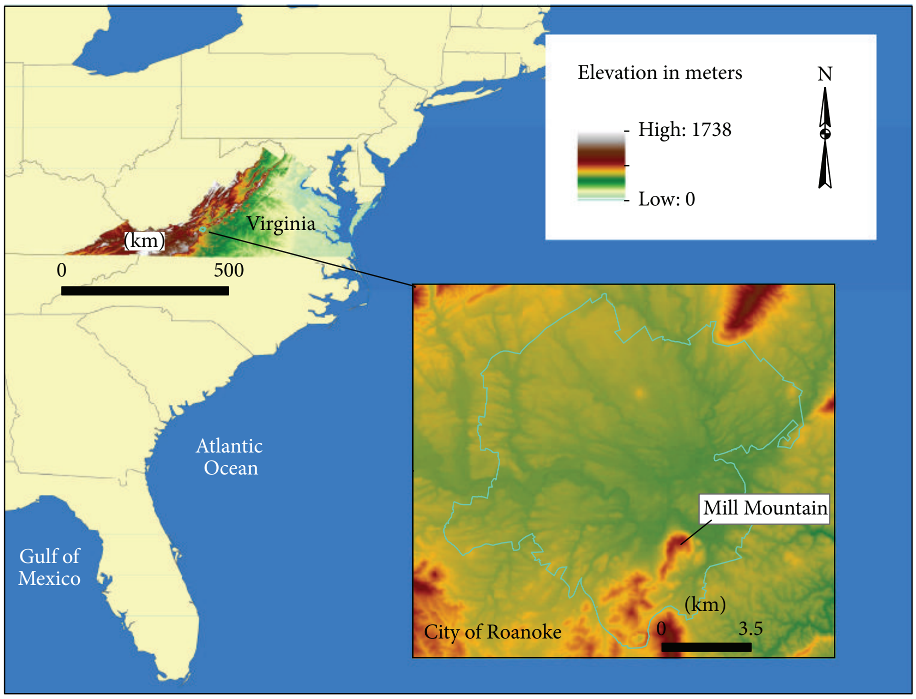


Figure 1: City of Roanoke, Virginia, reference map.

3. Study Area

The City of Roanoke, Virginia, USA, is located in Virginia's Central Valley, between the Blue Ridge Mountains and the Alleghany Highlands (Figure 1). It is southwest Virginia's largest metropolitan region, and although small in area (110 km^2), it is intensely urbanized, with respect to both population density (880 persons per square kilometer) and area. It has a variety of urban land uses, with an historical focus as a hub for rail and road traffic with industries supporting the rail system, as well as supporting services: finance, distribution, trade, manufacturing, and health care.

Roanoke's elevation ranges from 269 to 531 meters. As noted in inset in Figure 1, Roanoke's elevation is relatively uniform throughout the city, with the exception of Mill Mountain (southeast). Although Mill Mountain's relief is documented well in the elevation map, Figure 2 clearly illustrates its notable elevation, rising out of the valley as a considerable landscape feature.

Roanoke's land cover includes 31.9% impervious surfaces (as calculated by first author) and 47.9% tree canopy [36], although the distribution of both is not uniform across the entire city (Figure 3). The streams and river within the city's boundaries are on the US EPA's Total Maximum Daily Load list for PCBs, high water temperatures, and *Escherichia coli* [37].

4. Methods

4.1. Temperature Collection. Air temperatures were collected using both mobile mesonet units and fixed weather stations.

Figure 2: The base of Mill Mountain in southeastern Roanoke; the mountain is a significant landscape feature in Roanoke, rising straight up out of the valley (photo, first author, 2014).

The data collection period extended from April through November of 2013 and June through August of 2014.

4.1.1. Fixed Stations. At the beginning of our collection campaign, the fixed stations existing within Roanoke included four K-12 schools, the local airport (National Weather Service), Virginia Western Community College, a few private residences, and a local TV station. Each station reported their data via the internet either through WeatherBug or Weather Underground.

Both internet sites provide access to current and historical data, but in remarkably different ways. For WeatherBug, users must download their app and for historical data a "Plus" app. Even with the "Plus" app, temperature data is only displayed

Table 1: Davis Vantage Vue Wireless Weather Stations Model number 6250 specifications [8].

Characteristic	Details
Collection time	Every 2.5 seconds
Outdoor to indoor transmission capability	Wireless via FCC-certified radio transmitter, up to 1000 feet (304.8 meters)
Outdoor equipment	Rain collector (inches) Temperature (°Fahrenheit)/humidity (%), sensor mounted within a passive solar radiation shield Anemometer (miles per hour) Wind vane (16 divisions)
Transmission distance, outdoor to indoor datalogger	Within 1000 feet (304.8 meters)

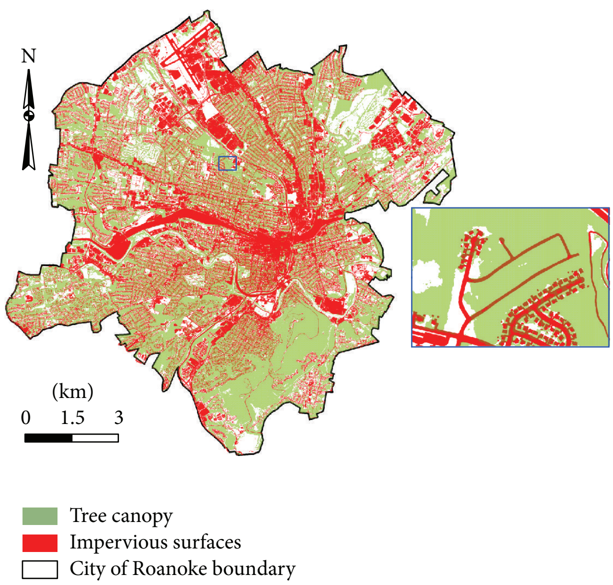


Figure 3: Roanoke's impervious surface and tree canopy cover; both are not uniformly distributed. The inset illustrates that tree canopy and impervious surfaces can occupy the same area (reddish-brown color).

Figure 4: Davis Vantage Vue Wireless Weather Station at Westside Elementary School (photo, first author, 2013).

as hourly reports for the preceding 30 days and only the high and low temperatures for another 90 days. Their data is not downloadable so it must be manually recorded.

Weather Underground, however, provides complete historical data (for as long as the weather station has been reporting to the site), downloadable as a .csv file. The data is collected as frequently as set (by the weather station owner) to record data. In addition, data can be downloaded as daily, weekly, monthly, or yearly reports. For both WeatherBug and Weather Underground the data is only accessible if the weather station is actually online.

The equipment for WeatherBug sites is unknown. But, WeatherBug does have specific equipment requirements to qualify as a WeatherBug location. Weather Underground provides equipment information (as entered by the weather station's owner) and does monitor the equipment for consistency with other reporting stations. Station type, its maintenance, and siting are issues across most weather station networks, as they can enter bias.

As part of our research, eleven new fixed weather stations were purchased, and, with the assistance of Roanoke City Public Schools (RCPS), sited at middle and elementary schools. We chose the public schools for new stations because schools are distributed across the city. Careful selection was made for the new instruments after consulting with meteorology experts: faculty and local meteorologists. All new stations are Davis Vantage Vue Wireless Weather Stations (Model number 6250) with Davis WeatherLink data loggers and software. Table 1 provides instrument specifications.

These stations' outdoor instruments were installed by RCPS facilities personnel, on school roofs in locations not easily accessible (Figure 4) to unauthorized personnel. Our university's meteorology students linked indoor consoles with data loggers to outdoor equipment, set data reporting (timed for every five minutes), installed computer software, and connected stations to Weather Underground (Figure 5). We were then able to monitor the fixed weather stations remotely.

4.1.2. Mobile Temperature Collection. Our university's mobile mesonet units (Figure 6) are Campbell Scientific mobile meteorological units. Table 2 provides the instruments' specifications, which were configured by the fourth author for vehicular use.

Table 2: Campbell Scientific specifications.

Equipment	Notes on variable being measured, including units
RM Young wind monitor	Miles per hour, direction (in degrees)
CSL temperature/RH probe (shielded and aspirated)	Temperature (°Fahrenheit) (humidity (%))
Sentra 278 barometer	Millibars
Garmin GPS receiver	Registering latitude and longitude in WGS1984
CR800-ST-SW-NC Measurement & Control Datalogger	Set for data collection every 2 seconds, capturing date and time (24-hour clock), but programmable for other time periods

Figure 5: Paul Miller (Virginia Tech MS student), Tom Fitzpatrick (RCPS science coordinator), and Rob Moorefield, (RCPS IT specialist) at Westside Elementary School (Photo, third author, 2013).

Figure 7: Three mobile mesonets (photo, first author, 2013).

Figure 6: One of Virginia Tech's Campbell Scientific mobile meteorological unit (photo, third author, 2013).

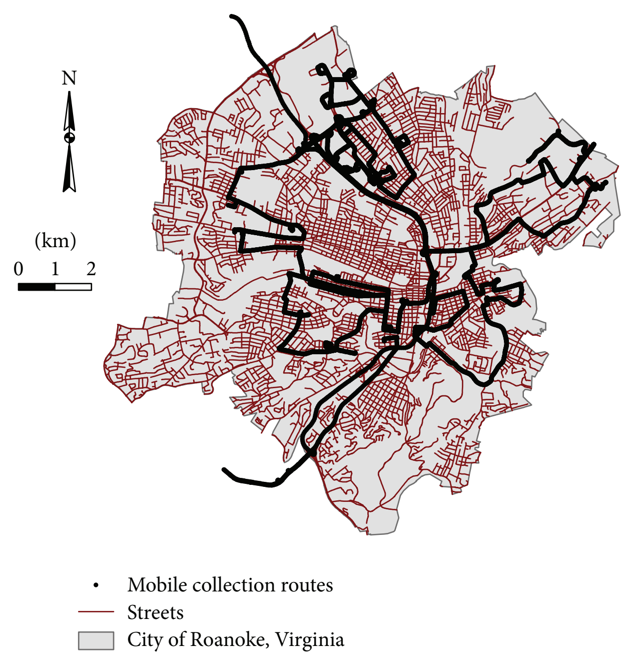


Figure 8: Routes 1, 2, 3, and 4 July 2014.

The units were mounted on roofs of Chevrolet Cobalts (Figure 7) and driven into and around Roanoke for transect data collection. Data collection campaigns were organized using volunteer drivers and navigators to follow routes covering a range of landscapes and land uses (Figure 8 shows routes driven on 1, 2, 3, and 4 July 2014). As previously noted, our collection campaign included multiple dates in 2013 and 2014 and, in some cases, covered consecutive dates (Table 3).

We chose these dates to capture a range in seasonal temperature regimes: green-up during spring, summer heating, and the onset of autumn frosts. We coordinated our plans

Table 3: Mobile transect collection schedule.

Year	Day	Synoptic condition	Times	Number of mobile units
2013	21 April	Stable, cool	09:32–10:50	3
			15:36–16:52	3
	22 April	Stable	09:37–10:56	3
			14:54–15:50	3
	23 April	Stable, warmer than previous two days	09:21–10:15	3
			14:46–16:00	3
	23 July	Increasing instability	09:10–12:06	2
			14:30–15:48	2
	5 August	Stable, hot	06:57–09:10	1
			11:17–11:48	1
			13:28–13:59	1
			15:39–17:36	1
	14 August	Front passed, hot	09:00–11:30	3
			13:28–16:23	3
	6 September	Stable, hot	10:20–13:10	3
			14:03–16:14	3
	26 October	Stable, frost warning	01:04–05:00	1
	4 November	Stable, frost warning	03:08–06:12	1
	8 November	Possible instability	22:27–00:30	1
	9 November	Stable, cool	01:01–02:11	1
	25 November	Stable, cold	06:39–08:29	1
			11:07–12:24	1
			13:22–14:39	1
	28 November	Warmer, possible rain	11:20–12:07	1
2014	27 June	Front passed, hot	13:39–14:01	1
			14:41–16:07	1
	1 July	Hot, possible instability	09:47–11:41	3
	2 July	Hot, possible instability	07:37–09:41	1
			09:42–11:07	3
	3 July	Hot, afternoon instability	09:37–11:28	3
	4 July	Stable, cooler than prior days	09:49–11:18	3
	12 July	Stable, hot	14:09–14:49	1
			18:14–18:35	1
			19:38–19:45	1
	15 July	Hot, instability	13:27–13:50	1
			15:43–16:08	1
	26 July	Front passed, hot	14:22–15:14	1
			21:31–22:13	1
	28 July	Possible instability	07:32–08:15	1
	4 August	Stable, hot	08:09–09:14	1
			10:36–11:14	1
	16 August	Front passed, hot	08:26–10:04	1
			11:23–13:38	1

with local meteorologists to select days when we could expect calm, clear weather as cold air/warm air advection would override local conditions. In most cases, we successfully targeted days when the synoptic pattern was quiet. The exceptions were a few days in the summer, when synoptic patterns are sometimes unstable, a normal summer condition within Virginia. Although we collected some daytime data during the autumn season, our principal goal was to capture onset of early season frosts—routes driven during nighttime hours usually beginning just before or just after midnight and ending just after sunrise.

At the conclusion of each campaign, the data file was downloaded as a .dat file, which can be imported into Excel. Latitude and longitude are collected as degrees and,

*	Date	TIMESTAM	Time_EST	RECORD	BP_mbar	WindDir	WS_mp	latitude_a	latitude_b	Latitude	longitude_	longitude1	Longitude	AirTF	RH	NLCD_IS	ELEV	TCC_30	slope_per	TCC_per	Aspect	ASP_Na
	6/27/2014	12:00:00 AM	12:00:00 AM	81716	1019	354.5	35.07	37	19.2711	37.32118	-79	-58.1012	-79.96835	87.8	52.06	61	353.4039	257	0	29	-1	Flat
	6/27/2014	12:00:00 AM	12:00:00 AM	81717	1019	2.872	34.52	37	19.2882	37.32147	-79	-58.1001	-79.96833	87.7	51.8	82	353.4039	74	0	8	-1	Flat
	6/27/2014	12:00:00 AM	12:00:00 AM	81718	1019	0.646	33.21	37	19.3051	37.32175	-79	-58.0986	-79.96831	87.7	51.61	79	353.4039	0	0	0	-1	Flat
	6/27/2014	12:00:00 AM	12:00:00 AM	81719	1019	0.096	32.33	37	19.3217	37.32202	-79	-58.0974	-79.96829	87.7	51.51	80	353.4039	0	0	0	-1	Flat
	6/27/2014	12:00:00 AM	12:00:00 AM	81720	1019	0.096	34.96	37	19.3382	37.32230	-79	-58.096	-79.96826	87.6	51.92	81	353.4039	0	0	0	-1	Flat
	6/27/2014	12:00:00 AM	12:00:00 AM	81721	1019	353.9	37.59	37	19.3545	37.32257	-79	-58.0945	-79.96824	87.6	52.12	48	353.4039	0	0	0	-1	Flat

Figure 9: Screenshot illustrating of a portion of the GIS attribute table for mobile temperature collection date 27 June 2014.

separately, decimal minutes, so we combined these into one reading as decimal degrees. The time was noted as Mountain Time (stamped as hours : minutes : seconds on a 24-hour clock), so we converted to Eastern Standard Time (added two hours). The spreadsheet file was then loaded into GIS software and a point shapefile created for all collection points, maintaining all recorded data within the corresponding attribute table.

Throughout the mobile collection campaigns, the number of fixed stations reporting at a given time varied—some went offline completely, some were only reporting on certain days, and some private residences installed new weather stations. A spreadsheet file was created for all fixed weather stations' data (temperature only) for the same dates and times as the mobile weather stations' collection. A point shapefile was also created in GIS for each fixed station, again, maintaining each recorded parameter within the attribute table.

We thought some residual effect from heating the day before may influence morning temperatures. So, a spreadsheet was created for the daily high, low, and average temperatures for all fixed stations reporting for the day before each of the mobile unit collection dates.

Because siting of individual stations can enter bias into our analysis (as a reminder—we did not control actual installation of the fixed station equipment either for new stations or preexisting stations), we compared data from the fixed stations to the Campbell Scientific equipment mounted on the vehicles. As such, we completed a spreadsheet for dates for all mesonet data collection campaigns, noted exact times we were driving near a fixed weather station, and entered temperatures for both the mobile unit and the fixed station at that specific time and the straight line distance between the mobile unit and the fixed station. We then conducted a correlation analysis between the fixed stations' and the mobile units' temperatures.

4.2. Landscape Metrics. Our final step was documenting landscape characteristics within a 30 × 30 meter grid cell around each fixed weather station and all mobile units' data points. A ten-meter digital elevation model (DEM) was downloaded from the USGS Seamless Server. The National Land Cover Database 2006 Percent Developed Imperviousness (*NLCD IS*, 30-meter resolution raster file) was downloaded from the Multi-Resolution Land Characteristics Consortium website. During the course of our analysis, when a new NLCD (2011) was produced, we compared the 2011 dataset to the 2006 version and noted very little change in reported impervious surfaces, so we continued our use of the 2006 data. A one-meter resolution tree canopy cover (*TCC*) raster dataset was provided by the Virginia Tech's Geospatial Extension specialist. Using ArcMap, *aspect* and *percent slope* were derived from the 10-meter DEM. The one-meter *TCC* was aggregated to 30 meters and percent *TCC* for each 30-meter grid cell was calculated.

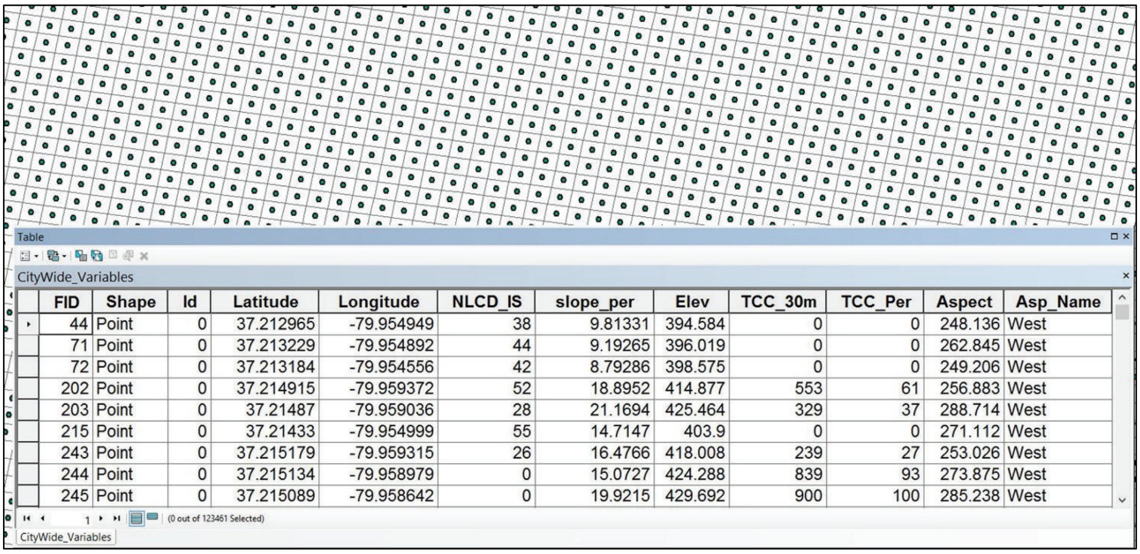
We added to the attribute table for each mobile data collection point and each fixed weather station values for *elevation, TCC, NLCD IS, aspect,* and *percent slope* using *extract multiple values to points* tool in ArcMap (Figure 9).

Finally, a fishnet of 30 × 30 meter grid cells was created for the entire city ($n = 123{,}461$). This tool within ArcMap also creates a point shapefile, placing a point at the center of each grid cell. Using this point shapefile, we extracted all the same landscape metrics, thus ensuring we knew these metrics for every 30 × 30 meter area over the entire city (Figure 10).

4.3. Data Analysis Using Random Forest. We incorporated data collected from fixed stations and mobile mesonet units to build a model that can estimate temperatures at 30 m resolution for the entire city. Our data has a complex structure characterized by high correlations among covariates, spatial correlations among observations taken at different locations, and nonlinear relationships between covariates and the microlevel temperatures that we want to estimate. To overcome these challenges, a predictive model based on Random Forest [38] was used.

Random Forest is a machine learning method widely used for classification and regression analysis. In our study, we use Random Forest to build a large number of regression trees (e.g., 500) derived from bootstrap samples (random sampling with replacement) of the full dataset; then the final prediction/estimation is made based on the average of the outputs of all the regression trees. This practice is also known as *bagging* in machine learning literature, which improves stability and accuracy of the regression tree. Another feature of Random Forest is that it builds each regression tree slightly different than a standard regression tree. In Random Forest, each tree node is split using the best split among a random subset of predictors. For a standard regression tree, each node is split using the best among all predictors. This additional layer of randomness makes it robust against overfitting [38]. Hence the results from Random Forest are generally preferred to those from regression trees.

Our predictive model was built for a selection of collection dates listed in Table 3. We used 90% of the mobile readings as our training set while retaining the remaining 10% as our validation test set. Variables *elevation*, *TCC*, *NLCS IS*, *aspect*, and *percent slope* were used in the model to account for spatial heterogeneity of the microlevel temperature distribution. Another variable included in the model was the predicted temperature at 30 × 30 m detail based upon fixed station readings, considered as the "basis" temperature at locations designated as *predicted basis temperature*.



Table

CityWide_Variables

FID	Shape	Id	Latitude	Longitude	NLCD_IS	slope_per	Elev	TCC_30m	TCC_Per	Aspect	Asp_Name
44	Point	0	37.212965	-79.954949	38	9.81331	394.584	0	0	248.136	West
71	Point	0	37.213229	-79.954892	44	9.19265	396.019	0	0	262.845	West
72	Point	0	37.213184	-79.954556	42	8.79286	398.575	0	0	249.206	West
202	Point	0	37.214915	-79.959372	52	18.8952	414.877	553	61	256.883	West
203	Point	0	37.21487	-79.959036	28	21.1694	425.464	329	37	288.714	West
215	Point	0	37.21433	-79.954999	55	14.7147	403.9	0	0	271.112	West
243	Point	0	37.215179	-79.959315	26	16.4766	418.008	239	27	253.026	West
244	Point	0	37.215134	-79.958979	0	15.0727	424.288	839	93	273.875	West
245	Point	0	37.215089	-79.958642	0	19.9215	429.692	900	100	285.238	West

(0 out of 123461 Selected)

CityWide_Variables

Figure 10: Screenshot of a portion of the GIS attribute table containing landscape variables for each 30 × 30 m grid cell for the entire city, illustrating also a portion of the grid.

The predicted basis temperature is obtained using Kriging [39], where a variogram model is determined based on temperature readings and spatial locations of the training set and those of the fixed stations.

The last variable included in our model is called predicted *lag-1 average temperature* (hereinafter referred to as *lag-1*), which is based on average temperature readings at fixed stations and mobile unit readings of previous day. The predicted lag-1 at each spatial location is obtained in a similar fashion as the predicted basis temperature, that is, using Kriging as the interpolation strategy.

We ran our model twice for some time periods—once with only the data collected for that date and a second time including the lag-1. We experimented with including predicted lag-1 because we wanted to evaluate effectiveness of including a measure of heat absorbed by the ground during the previous day to see if it had a residual effect the next day.

Once the model was built for each time period, we evaluated its performance using the validation test set. Then the model is used to predict temperature at each location (30 × 30 m resolution) for the entire city for the same time period. At each location, the covariate values (*elevation*, *TCC*, *NLCD IS*, *aspect*, and *percent slope*) are obtained by landscape metrics as noted above, while the *predicted basis temperature* and *predicted lag-1* are obtained using the Kriging method as mentioned above.

In order to assess which variables contribute most to temperature prediction, we used the importance matrix [40] from Random Forest. For each variable, the importance matrix depicts the percentage increase in prediction mean square error (MSE), based upon random permutations of that variable's values using out-of-bag cases in Random Forest. The variable that results in largest increase in MSE will be identified as the most important variable for the Random Forest model.

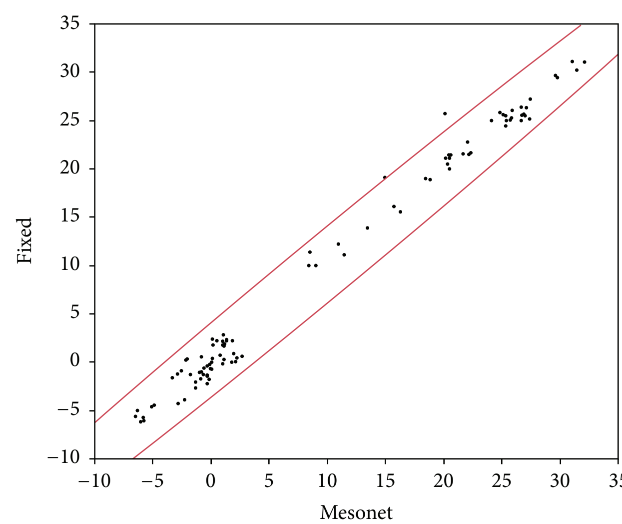


Figure 11: Correlation between the temperatures (°C) of fixed weather stations and mobile mesonet units.

5. Results and Discussion

In 2013, we drove within 300 meters of a fixed weather station 94 times and twice within 500 meters, when the fixed stations were active. For those 96 times, we found a 99% correlation between the fixed weather stations' temperatures and those collected by the mobile mesonet units (Figure 11). (The two temperature readings that fall outside of the 99% ellipse were readings from stations that were between 300 and 500 meters from our mobile unit.) These results provide confidence in reliability of the two temperature measurement systems (fixed and mobile) for recording air temperatures (at least for weather conditions selected for our project) and provide that differences in siting weather stations, motion of

Table 4: Random Forest fit results.

Date	Test set MSE °C	% variability explained	Variable importance (from most important to least important)
22 April 2013, morning	0.13	70.57	Basis, elevation, NLCD IS, slope, aspect, and TCC
22 April 2013 morning includes *lag-1*	0.14	68.92	Basis, elevation, NLCD IS, TCC, slope, aspect, and lag-1
22 April 2013, afternoon	0.03	82.36	Elevation, basis, NLCD IS, aspect, TCC, and slope
23 April 2013 morning	0.09	60.50	Basis, elevation, NLCD IS, slope, aspect, and TCC
23 April 2013 morning includes *lag-1*	0.06	71.59	Elevation, basis, lag-1, NLCD IS, slope, aspect, and TCC
23 April 2013 afternoon	0.06	65.82	Basis, elevation, NLCD IS, aspect, slope, and TCC
2 July 2014	0.09	84.53	Basis, elevation, NLCD IS, slope, aspect, and TCC
2 July 2014 includes *lag-1*	0.05	90.77	Basis, lag-1, elevation, NLCD IS, slope, TCC, and aspect
3 July 2014	0.14	72.12	Basis, elevation, slope, NLCD IS, aspect, and TCC
3 July 2014 includes *lag-1*	0.10	78.96	Basis, elevation, lag-1, aspect, NLCD IS, slope, and TCC
4 July 2014	0.04	78.89	Basis, NLCD IS, slope, elevation, TCC, and aspect
4 July 2014 includes *lag-1*	0.03	85.92	lag-1, basis, elevation, NLCD IS, slope, aspect, and TCC
26 October 2013, 01:00–02:00	0.03	76.08	Elevation, basis, slope, aspect, TCC, and NLCD IS
26 October 2013, 02:00–03:00	0.05	88.45	Basis, elevation, aspect, slope, NLCD IS, and TCC
26 October 2013, 03:00–04:00	0.03	73.25	Elevation, basis, NLCD IS, slope, TCC, and aspect
26 October 2013, 04:00–05:00	0.04	87.58	Basis, elevation, slope, aspect, NLCD IS, and TCC
25 November 2013, early morning	0.04	87.16	Basis, elevation, slope, NLCD IS, TCC, and aspect
25 November 2013, noon	0.03	80.64	Basis, elevation, NLCD IS, slope, aspect, and TCC
25 November 2013, midafternoon	0.04	88.7	Basis, elevation, aspect, NLCD IS, TCC, and slope

the mobile units, and other operational details are not likely creating significant variability within our dataset.

A total of 107,065 mobile mesonet readings were obtained in 2013 and 53,741 readings in 2014. A total of 4,325 fixed station temperatures were collected for 2013 and 2,352 for 2014. We collected 268 daily readings for high, low, and average temperatures from the fixed stations for the day before the mobile collection date.

Here, we are reporting results of our Random Forest predictive model for one collection campaign for each season (Table 4). As a reminder, each predictive model used just one hour of data since we wanted to minimize any temporal effects in temperatures created by normal daily heating. Seasonal campaigns include morning and afternoon comparisons, comparisons between predictive models before and after including the lag-1 variable, four separate early morning campaigns on one date, and three different time periods over the course of one day.

As Table 4 shows, we have very small mean square errors (MSE) for all dates. The model performs worst on 22 April 2013 (using the lag-1 variable), but the MSE is only 0.14 and percent of variation explained is 68.92%. The model performs best on 4 July 2014 (with lag-1 variable), the MSE is 0.03, and percent of variation is 85.92%. For all dates, except 22 April, when we added the lag-1 variable, the percent of variation increased. Table 4 also lists the importance of each variable in explaining temperature variation in hierarchical order of their influence (i.e., the first row in the table, 22 April 2013 morning, basis temperature (fixed station) had the most influence and tree canopy cover had the least influence).

5.1. Discussion—Spring Campaign. The spatial distribution of our spring collection campaign predictive results is shown in Figure 12 (22 April 2013) and Figure 13 (23 April 2013) for both morning and afternoon campaigns. The morning images are before (left image) and after including the lag-1 variable (middle image) and the afternoon predictions (right image). Patterns within the city are similar in both morning images—the southeastern mountain (Figure 2) is warmer during the mornings, as are densely built-up areas of the city (consistent with the patterns of impervious surfaces in Figure 3). For 22 April 2013, the three most important variables do not change after including the lag-1 variable, and our MSE and percent explanation changed minutely, but the mountain area is not quite as warm as the built-up areas.

The estimated afternoon temperature images (right) show that as the city warmed throughout the day, the patterns changed; warmer areas now coincide with greater built-up areas of the city (again, consistent with patterns of impervious surfaces as presented in Figure 3). The afternoon patterns also demonstrate that the mountain (and area of greatest tree canopy cover) is cooler. Temperatures for the afternoon on 23 April are slightly higher than on 22 April, which highlights the more densely built-up central business district as much warmer than the rest of the city.

5.2. Discussion—Summer Campaign. Morning summer temperature patterns (Figures 14 and 15) are similar to April; the mountain is warmer, as are major roadway areas. 2 July and 3 July 2014 were much warmer than 4 July (by at least 6°C), so major roadways and intersections are more prominent in

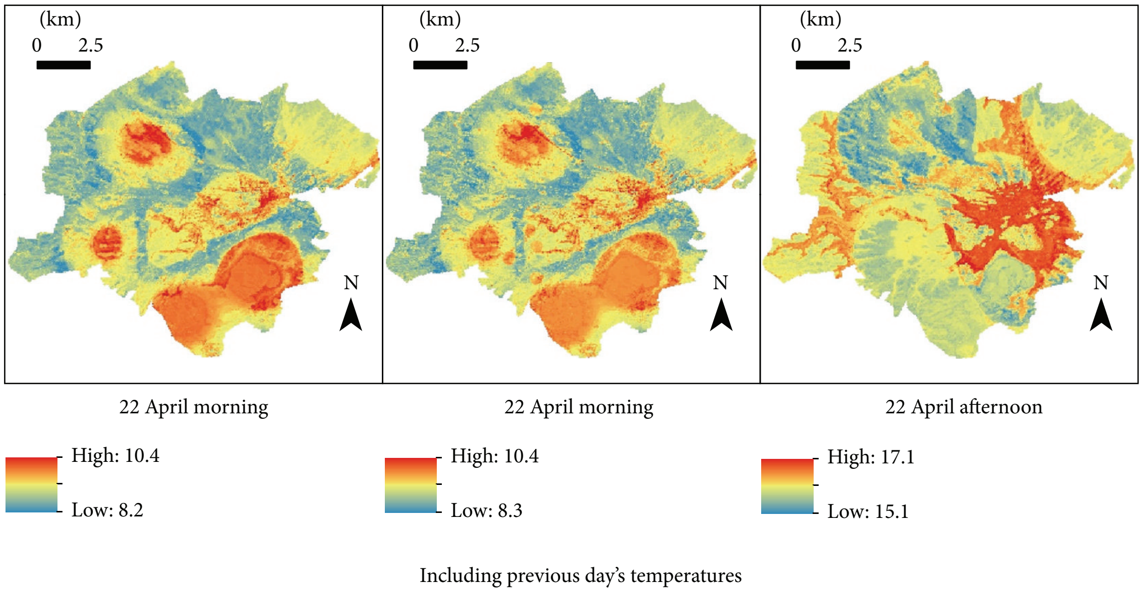


FIGURE 12: Estimated temperatures (°C) across the entire city for 22 April 2013. Left image does not include lag-1 variable, middle image includes lag-1 variable, and image on right depicts afternoon temperatures.

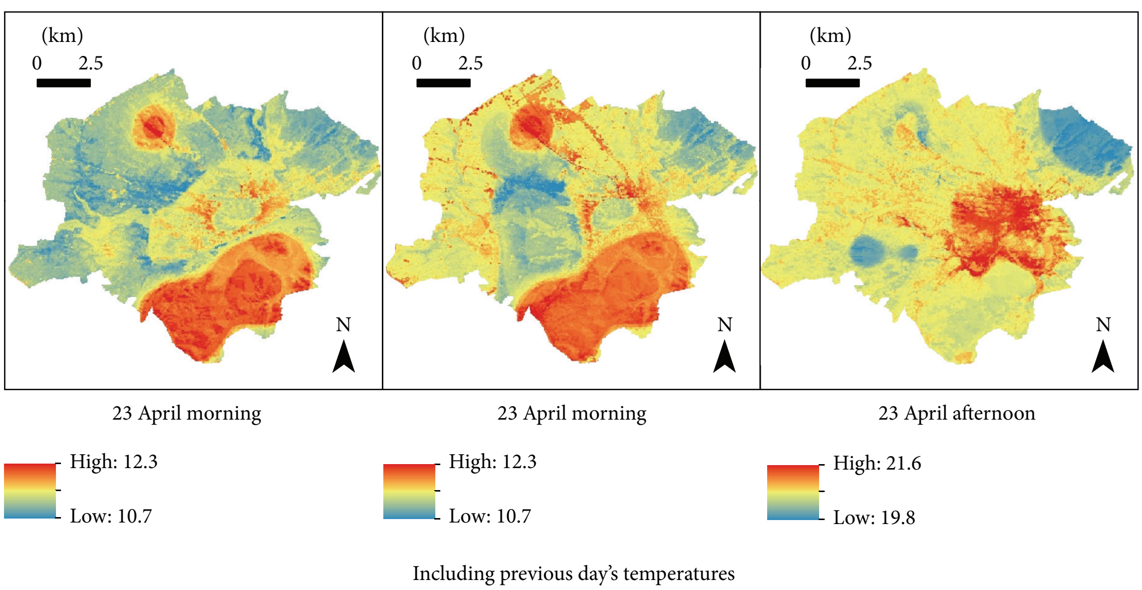


FIGURE 13: Estimated temperatures (°C) for 23 April 2013. Left image does not include lag-1 variable, middle image includes lag-1 variable, and image on right depicts afternoon.

the 3 July image than the 4 July image. Including the lag-1 variable increased our percent explanation to almost 80% for 3 July and over 85% for 4 July. While there appears to be an anomaly in the southwestern part of the city on the 4 July image, this area is actually a built-up area, including a substantial railroad yard, which retained heat from two prior hot days (2 and 3 July).

5.3. Discussion—Autumn Campaign. Figure 16 shows estimated temperatures (°Celsius) for three different time periods on 25 November 2013—early morning, late morning, and afternoon. 25 November is an autumn day but temperatures on this date were closer to Roanoke's normal winter-time temperatures. The temperature patterns demonstrate that the southern area, along with those areas of greatest impervious

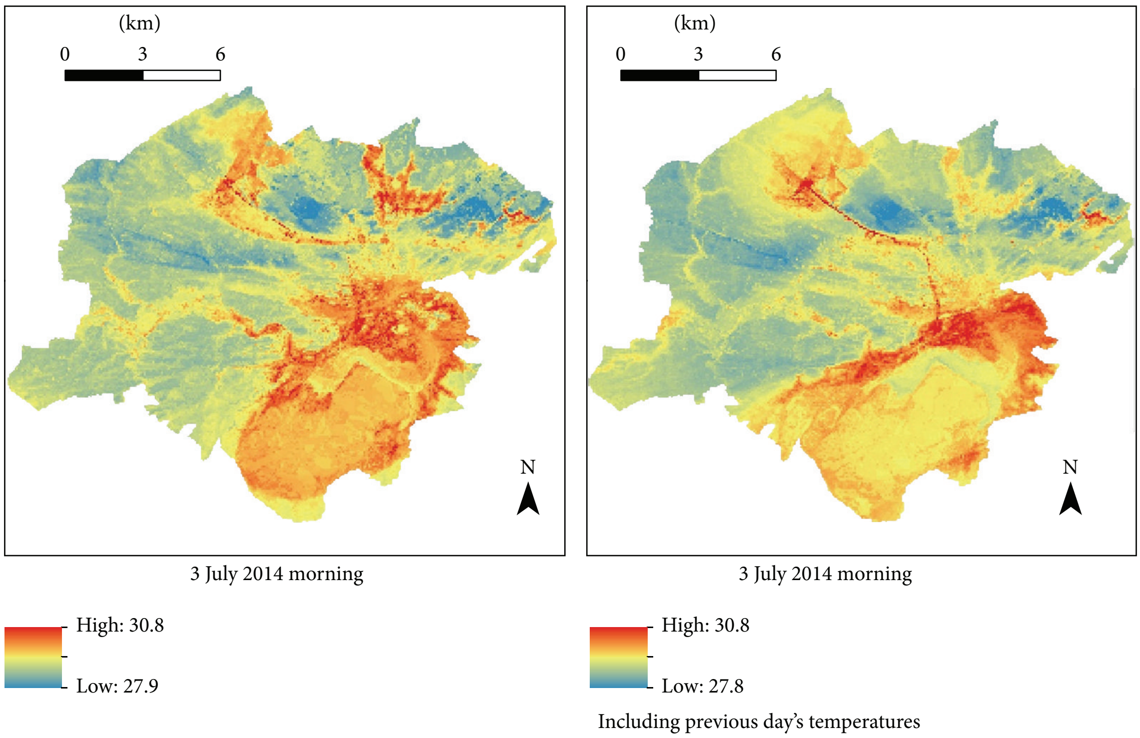


Figure 14: Estimated temperatures (°C) for 3 July 2014 morning. Left image does not include lag-1 variable and right image includes lag-1 variable.

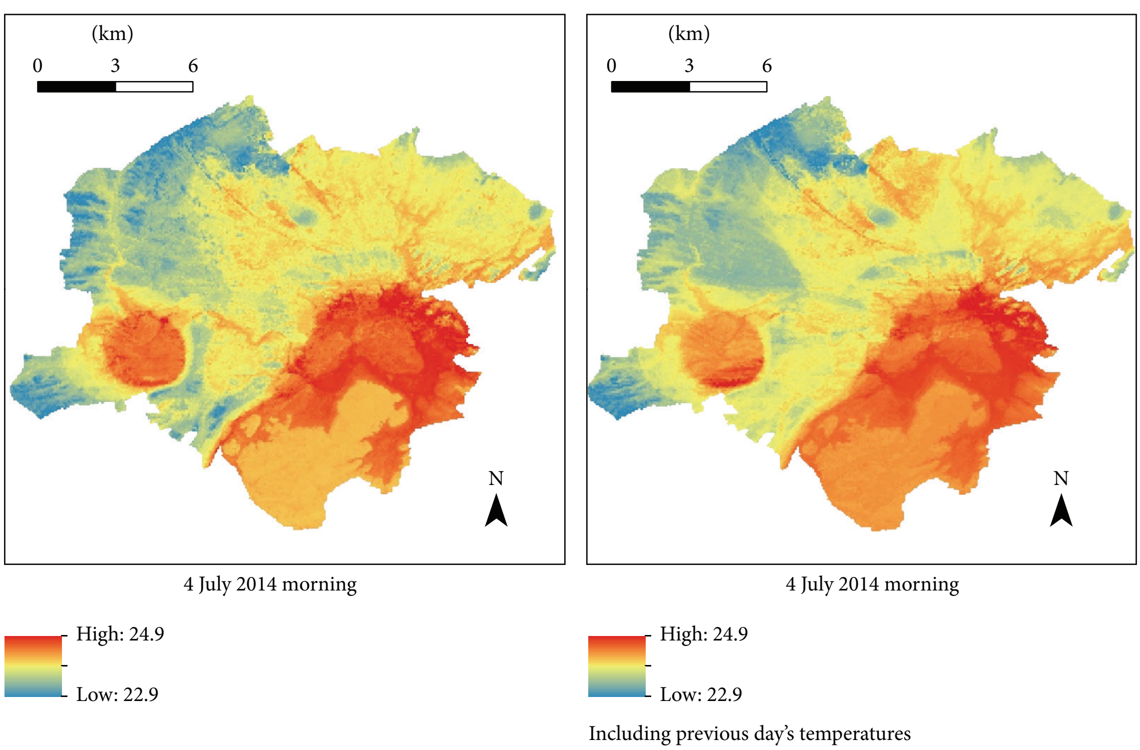


Figure 15: Estimated temperatures (°C) for 4 July 2014 morning. Left image does not include lag-1 variable and right image includes lag-1 variable.

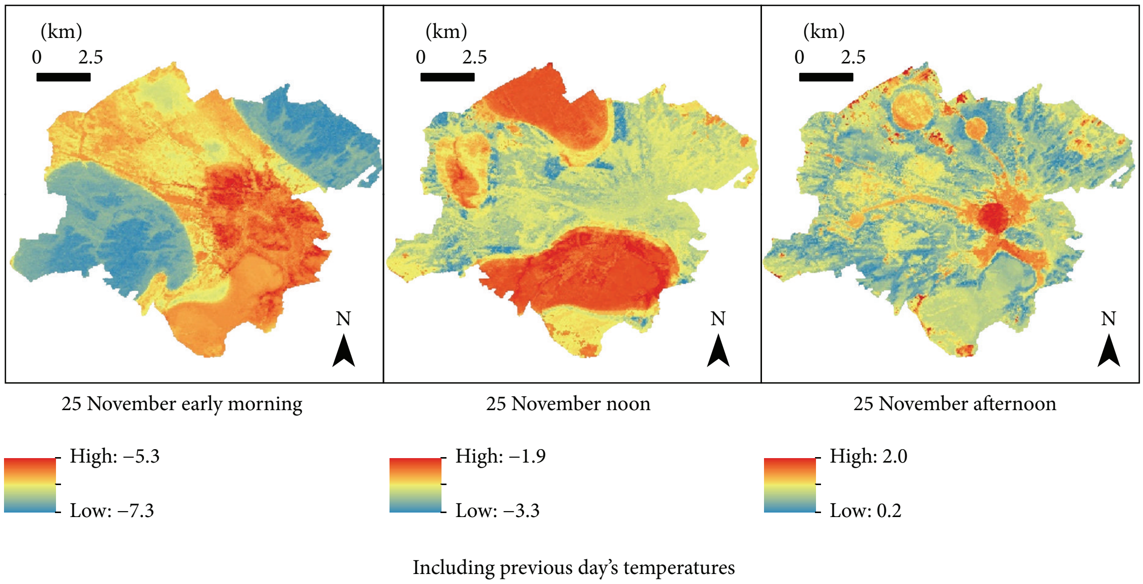


Figure 16: Autumn estimated temperatures (°C) for three different time periods on 25 November 2013—early morning, around noon, and afternoon.

surfaces, is warmer in the morning (left); the patterns change as the day warms (middle); and, by midafternoon, areas that are the warmest are those greatest built-up locales: the central business district, major roadways and associated businesses, the airport (northeastern area), and a large mall.

6. Conclusions

Combining data collected from both mobile mesonet units and fixed weather stations with landscape metrics into our model, we were able to estimate air temperatures across the entire city for each period of our data collection. Furthermore, our estimated values demonstrated distinct temperature patterns (warmer versus cooler areas) related to landscape metrics.

Our patterns show warmer morning temperatures in southeastern area of the city (the mountain area) and larger roadways. These patterns changed as the city warmed throughout the day or warmed over the course of several days. The patterns also changed when a cold front passed through (on the afternoon of 3 July) when built-up areas retained heat from the previous days. In each of our estimated temperature maps, Mill Mountain is a distinctive feature because of the substantial elevation change, substantial forest cover, and the extensive roadway around the mountain's base (Figure 2).

Future climate research for Roanoke will examine additional temperature collection for multiple contiguous days over each of the four seasons, including data for both morning and afternoon. Research to track the thermal properties for different surfaces can employ additional data from handheld infrared thermometers to record both morning and afternoon pavement temperatures. Additional metrics to include in our Random Forest model include physical geometry (building heights and street widths), land cover albedo (especially for roofs and other impervious surfaces), thermal conductivity of different surfaces, shadowing (skyview factor), and sources of anthropogenic heat. In addition, some of our collection dates were timed to coincide with Landsat overpasses, so we plan to investigate relationships between estimates based upon our mesonet data and those derived from analysis of satellite observations.

This research offers a glimpse on how detailed representations of temperatures vary within the urban landscape and how they can inform our understanding of the urban thermal landscape. Although additional work will be required to understand the full merits and shortcomings of the strategies that we have applied here, our results provide estimates that reveal the spatial patterns and their temporal variations. Landscape data are available or can be easily constructed from other data, for most urban areas, although in some regions dates of data layers may not match well (e.g., for our study, dates of the impervious surface and canopy cover differed by 4 years). Larger cities may require larger efforts—more fixed stations, more mobile units, and longer routes to collect the required samples. Although we have not experimented to assess the influence of sample size upon accuracy, it may be feasible to design routes that collect more concise sample numbers that will provide accurate results.

Disclaimer

The views expressed in this publication are solely those of Tammy Erlene Parece and EPA does not endorse any products or commercial services mentioned in this publication.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This research was financially supported by Virginia Tech's Graduate Student Assembly's Graduate Research Development Program Grant (2012), Sidman P. Poole Endowment for Research in Geography at Virginia Tech (2013), Sigma Xi Graduate Award for Doctoral Degree Students (2013-2014), U.S. Geospatial Intelligence Foundation Doctoral Scholarship (2013), Cabell Brand Center First Freedom Scholarship (2013), and Virginia Space Grant Consortium 2014/2015 Graduate Research Fellowship. This publication was developed under STAR Fellowship Assistance Agreement no. FP-91769301-0 awarded by the U.S. Environmental Protection Agency (EPA). It has not been formally reviewed by EPA. The authors thank the following people for their assistance with this research: Dr. Andrew Ellis, Dr. Mike Hyer, Brent Watts, Robin Reed, Sam Freeman, Mario Garza, Chris White, Paul Miller, Hans VanBenschoten, Eric Guenther, Anthony Phillips, Sarah Phillips, Dr. Emily Smith-McKenna, Adam Oliphant, Thomas Tutchings, Ash Elmelick, Erika Cropp, Bonnie Long, Michael Marston, R.J. McNally, Lynn Wormeli, Olivia Jancse, and the employees of the National Weather Service, Blacksburg Office.

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Intra-Urban Microclimatic Effects on Phenology

Version date 1 March 2016

Abstract: 150 to 250 word

The urban heat island effect is commonly defined as the thermal differences between cooler rural and warmer urban areas. But the urban heat island effect also refers to microclimatic differences within an urban area arising from varied combinations of vegetation and impervious surfaces related to different land uses. Microclimatic variations should also produce intra-urban differences in vegetation phenophases, although few studies have investigated urban phenology. Most phenological studies are usually regional to continental in scale and predominantly track changes in start of season related to the Earth's changing climate. This study reports on using MODIS NDVI 250 m resolution data to identify intra-urban differences in start of season. We then compared these results to *in-situ* temperature collection campaign which we used to predict temperatures across an entire city. In addition, we completed an *in situ* start of season data collection by observing select tree species across our city. Our results demonstrate that MODIS, processed by TIMESAT software, successfully identified intra-urban start of season variations and these variations are consistent with differing intra-urban microclimates and our *in-situ* start of season observations. Our study demonstrates that MODIS imagery can be used to track historical changes in start of season within an urban area or evaluate changes as they relate to climate change. Furthermore, results from such analyses can aid plans for increasing the urban tree canopy or in cultivating locations for urban agriculture – i.e., warmer areas with a longer growing season could accommodate warmer weather trees and crops.

Keywords: 4 – 6

Urban Heat Island, urban phenology, TIMESAT, MODIS, urban agriculture

1 Introduction

Phenology is the recurring seasonal activity of plants and animals, i.e. mating, birth and death in animals; germination, leaf bud burst, flowering and fruit production in plants (Denny et al. 2014). The timing of phenological stages (phenophases) vary by species, age within an individual species, local climate, and many biotic and abiotic conditions (Denny et al. 2014). Phenology studies are numerous, most involving temporal analyses of remotely sensed images, having documented advancing start of season at large regional or continental scales, an effect possibly related to climate change (Neil and Wu 2006). Monitoring and documenting phenological changes across the world are important to evaluate climatological impacts on ecological functioning and potential complications for the world's future food supply (Luo et al. 2007).

Urban areas are warmer than their rural surroundings. A plethora of studies document urban heat island (UHI) effects originating from differences in land cover and land use between rural and urban landscapes (Hedquist and Brazel 2006). More specifically, areas with larger areas of impervious surfaces and lower vegetative cover tend to be warmer. Urban heat island studies also analyze remotely sensed images for phenological comparisons between urban and rural areas, and along the urban-rural gradient (e.g. (Zhang et al. 2004; Gazal et al. 2008; Walker et al. 2015; Roetzer et al. 2000). These studies have documented earlier start of season within urban areas compared to surroundings rural areas.

Within an urban area, distinct landscape combinations in the built environment create unique microclimates (internal heat islands) generated by differences in surface materials' thermal properties, by absence of vegetative cover, and by alteration of the hydrologic cycle (Geiger et al. 2003). Since landscape differences create microclimatic variations, plant phenophases -- start of season, length of season and end of season -- should also vary within an urban area. Thus, intra-urban phenological evaluations should accompany microclimate evaluations because such analyses assist in identifying effects of intra-urban heat islands.

Since more than 50% of the world's population now live in urban areas (United Nations 2014), intra-urban studies are as important as regional and continental scale evaluations for many reasons – to aid in urban sustainability initiatives, to assist in creating healthy environments where people live, and to plan for changes relative to increasing urbanization and climate change (Neil and Wu 2006; Luo et al. 2007). Yet, few evaluations of phenological differences within the urban landscape exist (Neil and Wu 2006).

Our study evaluates differences for start of season within an urban area – the City of Roanoke, Virginia, but we go beyond the methods used in other intra-urban studies. Within this paper, we first review these studies and then introduce our study area. We describe our methods in detail and our use of MODIS NDVI imagery within TIMESAT software to identify start of season over five years (2010 – 2014). We then compare the 2013 TIMESAT results to an *in-situ* temperature data collection campaign using both mobile mesonets and a network of fixed weather stations, processed along with landscape metrics, to predict temperatures across the entire city. Finally, in 2014 citizen scientists conducted *in-situ* phenological data collection and we compared results with 2014 TIMESAT results.

2 Intra-Urban Phenological Evaluations

We located only a few studies looking at intra-city phenological variations. One study, Luo et al. (2007), analyzed 43 years of existing phenological and meteorological data for Beijing, China. This study found that temperatures within the city had increased and start of season had advanced.

Two studies completed *in-situ* analyses to determine if start of season varied within cities. Mimet, et al. (2009) studied intra-urban phenological differences for start of season at six sites from Rennes' (France) inner city to the peri-urban zone. Researchers set up 17 weather stations to track temperature variations during their study period, and found the inner city site had earliest bud burst, but noted other sites were inconsistent in bud burst variations. However, their weather stations were positioned uniformly - open to the south and west, so did not capture microclimate variations from the landscape. Jochner et al. (2012) studied phenological differences within three German cities using *in-situ* phenological sites. They attempted to address landscape variations by using a two-km buffer around each phenological station to establish an urban index (extent of built up land use). They tracked start of season, 1980 – 2009, finding a progressive earlier start of season related to an increasing urban index, but they noted that altitude and higher temperatures could have also been a factor.

A fourth study included remotely sensed imagery in the analysis. Dhami et al. (2011), collected *in-situ* data and Landsat imagery to compare differences in date of budburst between New York City (high density) and Ithaca, New York (lower density) for the London Plane Tree over two years (2007 and 2008). They assessed results using land surface temperature (LST) and fractional vegetation indices derived from Landsat imagery. They found that leaf budburst occurred earlier in New York City. They also noted that leaf bud burst in Ithaca had occurred earlier in 2007 than 2008, but did not discuss whether this could have been attributable to warmer spring temperatures.

3 Study Site

Our study site, the City of Roanoke, Virginia is located in the valley between the Blue Ridge and Alleghany mountains and is the largest city in southwest Virginia (110 km^2 and almost 100,000 residents) (Figure 1). The city is characterized by two major land covers – tree canopy cover (47.8%) (Pugh 2010) and impervious surface cover (31.9%, as calculated by first author); and numerous land uses including industrial, commercial, a major railway hub and healthcare industry, and low to very high density residential neighborhoods. Roanoke also exhibits spatial patterns related to both types of urban heat islands – warmer as compared to the surrounding rural areas, and warmer islands within the city because of its varied land cover and uses (Figure 2).

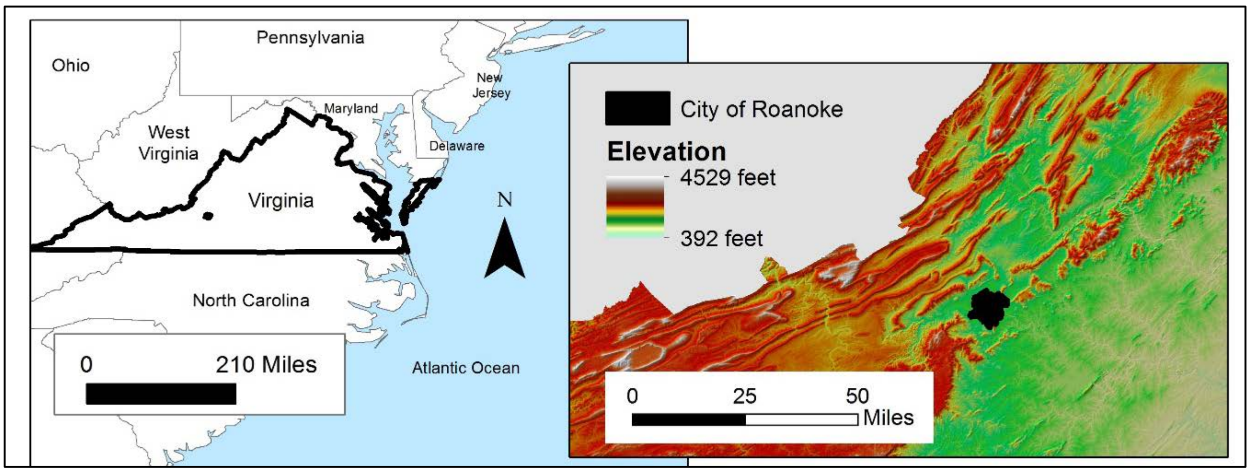


Figure 1. City of Roanoke, Virginia Reference Map (image on right generated from the Virginia digital elevation model)

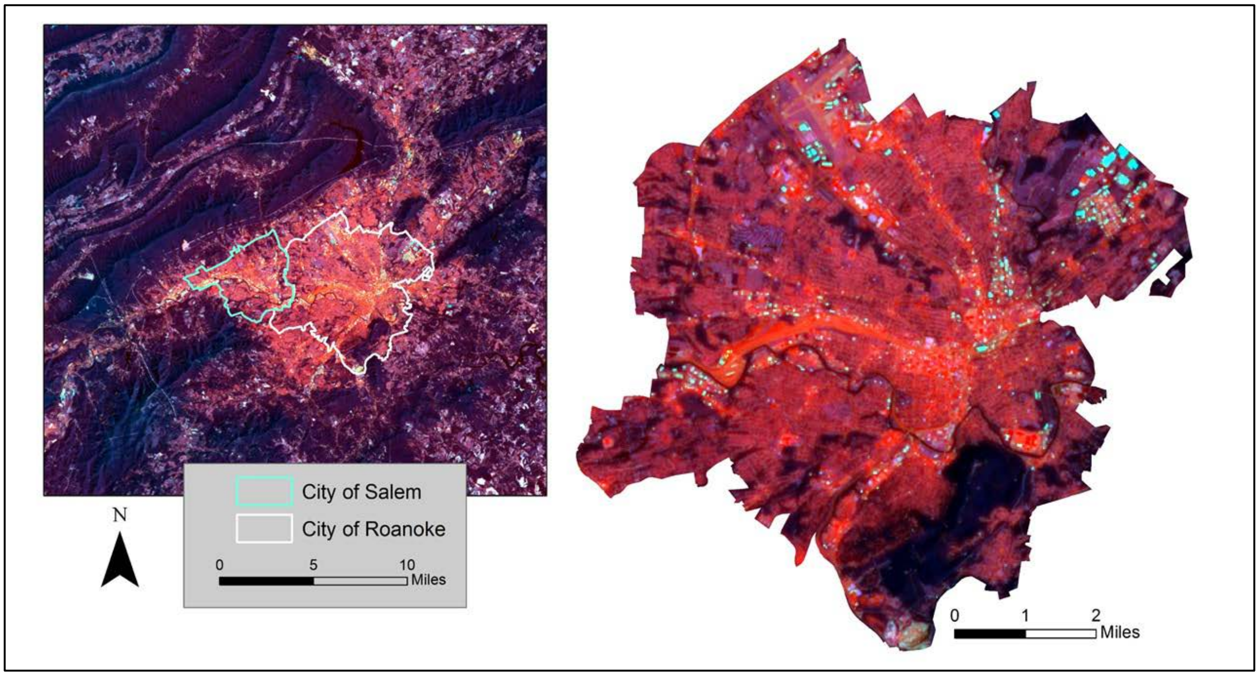


Figure 2. Landsat 8 thermal image (bands 10-7-6) of a portion of southwest Virginia (left) and zoomed into the City of Roanoke (right). Image acquired May 24, 2014, illustrating urban heat island urban to rural differences (left), and internal variations within the city (right). Darker areas are much cooler; much warmer areas are very bright red (roadways) and very bright cyan areas (building roofs).

4 Materials and Methods

4.1 Satellite Imagery - MODIS

MODIS (Moderate Resolution Imaging Spectroradiometer) vegetation indices are frequently used when tracking phenological changes at the regional or continental scale and involves a time-series analysis of satellite imagery (Zhang et al. 2003). MODIS is an instrument aboard the *Terra* and *Aqua* satellites. Terra's sun-synchronous orbit passes from north to south across the equator in the morning and captures images of the entire Earth's surface every 1 to 2 days (Aqua has a similar orbit, but passing south to north over the equator in the afternoon)

(NASA 2015). MODIS images are available over many spectral bands and resolutions and downloadable from *http/reverb.echo.nasa.gov*. For this study, we used MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V005. While MODIS imagery is acquired almost daily, this product extracts the best data acquired over the 16 day window, and is already processed for several different vegetation indices — 23 images cover an entire calendar year (NASA 2015).

Of the vegetation indices, we used the Normalized Difference Vegetation Index (NDVI) product for this analysis. The NDVI formula is:

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

The near-infrared (NIR) and visible red wavelengths of the electromagnetic spectrum are more sensitive to photosynthetic activity than other wavelengths (Tucker 1979). Each pixel's NDVI values represent stage of growth and/or health of vegetation within that pixel (the closer to +1, the more healthy or mature). NDVI values can also be used, over a series of images acquired during the course of a year, to determine start of the growing season, length of the growing season, and end of the growing season (herein after referred to as phenological variables) (Huete et al. 2002; Jönsson and Eklundh 2002).

We downloaded images covering Roanoke for 2001 through 2014. To process the images for phenological variables, we used TIMESAT (Jönsson and Eklundh 2004). TIMESAT, as an add-on to MATLAB software, graphs NDVI values over an entire time series. The time series can be a single year or multiple years, as defined by the user. Figure 3 provides an example of NDVI graphing (blue line) for one pixel, for the City of Roanoke, over the 14 year period. Each individual wavelength cycle represents one growing season (Roanoke has one growing season per calendar year). The peak of the wavelength is the highest NDVI value, representing maturity or peak of the growing season. The valley within each cycle is the lowest NDVI value, the period when most vegetation is dormant.

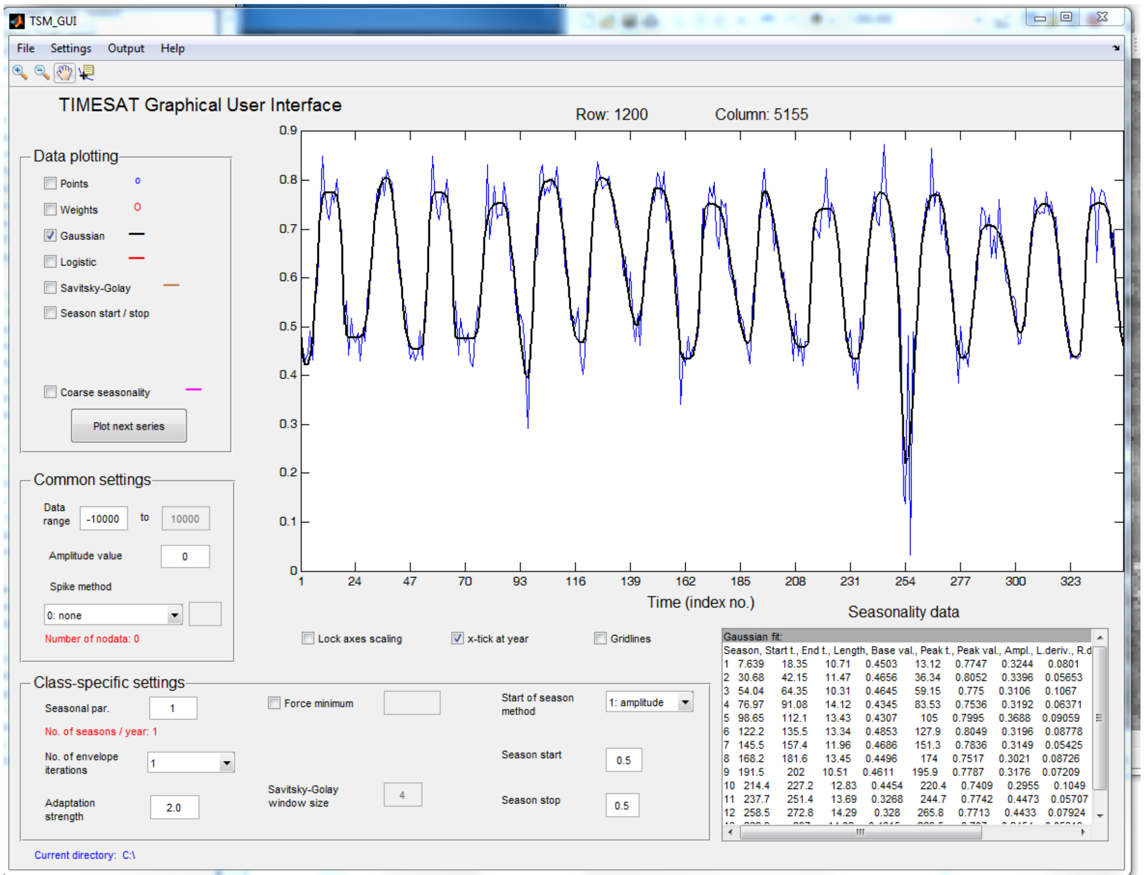


Figure 3. TIMESAT Graphic User Interface window showing the graph for one pixel's NDVI over 14 years

The black line within the figure represents a smooth line fitted to the plotted NDVI values, using a specific algorithm, chosen by the user. For this example, we have set this parameter to Gaussian. Three different algorithms are available within the TIMESAT software – Logistic, Savitzky-Golay, and asymmetric Gaussian. The specifics of each algorithm can be found within the TIMESAT Software Manual (Eklundh and Jönsson 2011), and the effectiveness for tracking phenological phases has been extensively validated (e.g., Jönsson and Eklundh 2002, 2003, 2004; Tan et al. 2011). Most of the algorithms have been evaluated for a large region, not at the scale of an individual city. To determine which algorithm best fits the City of Roanoke, we evaluated each algorithm's results for five separate years (2010 - 2014).

Once the specific algorithm is chosen, TIMESAT then calculates phenological variables using *Class-specific settings* (bottom in Figure 3). For this example, start of season is calculated as ((maximum NDVI – minimum NDVI) x 0.50) + minimum NDVI value, along the slope the fitted line. TIMESAT identifies which image for each year corresponds to this value using a real number — the input images are numbered sequentially, so for 23 images per year, year one images are numbers 1, 2…23; year two images are numbered 24, 25…46; year three images are numbered 47, 48…69; etc. The values found within the text box in the lower right of Figure 3 (*Seasonality data*) designate the image (number) for each parameter (e.g. start of season, end of season, length of season, etc.) by each year (listed in the first column of this box, on the left – year 1, 2, 3, etc.). For example using Year 3 – start of season is identified as image number 54.04, end of season as image number 64.35, length of season 10.31 images, lowest NDVI value as 0.4645, and highest NDVI value as 0.775.

TIMESAT can evaluate images over a series of many years (as in Figure 3 for 14 years), or for an individual year. But, to evaluate one individual year, TIMESAT requires three consecutive years of images – year before, year of interest, and year after. TIMESAT then defines the start of season for the year of interest. As such, our 2013 and 2014 analyses required use of images from 2012 through 2015.

In addition to an individual pixel evaluation, TIMESAT will calculate phenological variables for all pixels within an entire image (or subset of an image), producing a thematic image for the specific chosen variable (Figure 4). TIMESAT's *image viewer* includes a histogram for the range of values, and values for the minimum (27.7625) and maximum image number (39.8151). As noted above, these values represent the number of the image (in sequential order), so these values equate to a specific date. In Figure 4, 27 equates to the 4th image for that specific year (February 18) and .7625 adds 12 days (March 2); 39 is the 16th image (August 29) and .8151 adds 13 days (September 11).

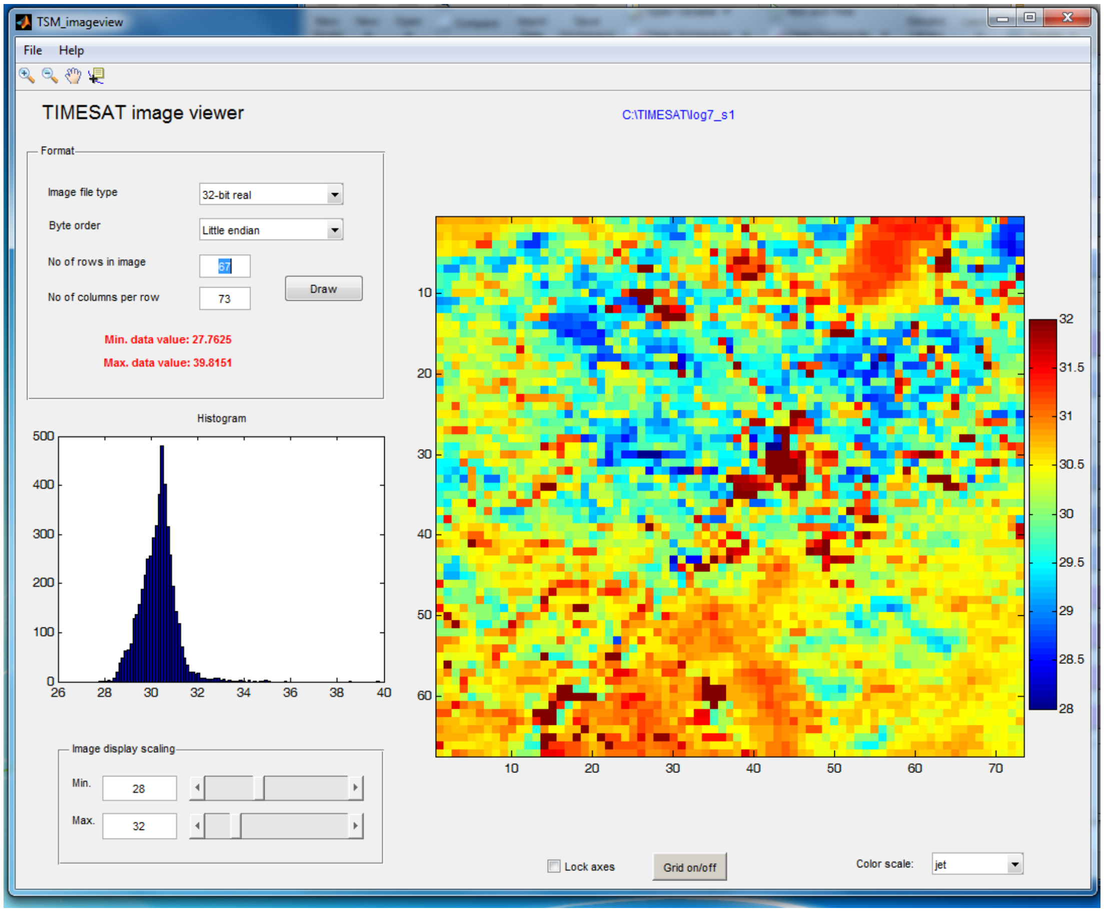


Figure 4. An example of the thematic image produced by TIMESAT for start of season.

4.2 In-Situ Data Collection - Temperature

During 2013 and 2014, we collected temperature data across the city for multiple days in the following ways:

- Driving transects across the city using our fleet of three mobile mesonets;

- Downloading fixed station temperature data from WeatherUnderground® via the internet (*www.wundeground.com*) or recording it manually in a spreadsheet from Weatherbug® using their computer app (available at *www.weatherbug.com*); and
- Obtaining historical average temperature data from the National Weather Service (http://www.erh.noaa.gov/rnk/climate/f6/html/F6.html) for February through June for 2013 and 2014, those months where temperatures can advance or delay start of season.

Our 2013 collection campaign collected temperatures across all four seasons, our 2014 collection campaign did not begin until late June and concluded in early August. To extrapolate temperatures for the entire city, we identified landscape variables for all temperature collection points within a 30 meter area around each point (e.g., percent impervious surface, percent tree canopy copy, slope, aspect, and elevation). We then identified the same landscape metrics for the entire city at the same 30 meter resolution. We used the temperature points and the landscape metrics for those points as training data for Random Forest. Random Forest used these values to predict air temperatures for the entire city based on the unique combination of landscape metrics present within each 30 meter grid cell.

4.3 In-Situ Data Collection – Vegetative Start of Season

Because a field component is highly recommended for phenological studies (Liang et al. 2011), we enlisted citizen scientists, including Master Naturalists, Tree Stewards, Master Gardeners, K-12 public school teachers, and local community college faculty and research assistants, to assist with *in-situ* monitoring of trees during the spring of 2014. We trained volunteers in February 2014 using the National Phenology Network (NPN) protocol (www.usanpn.org). Reporting to NPN is accomplished either on the web or via a downloadable mobile app. The NPN protocol includes identification of latitude and longitude using Google Maps™ for the specific tree(s) monitored, and reporting for status of leaves, flowering and fruiting, and for each feature, the extent of growth, e.g., breaking leaf buds, leaves, etc. (Figure 5).

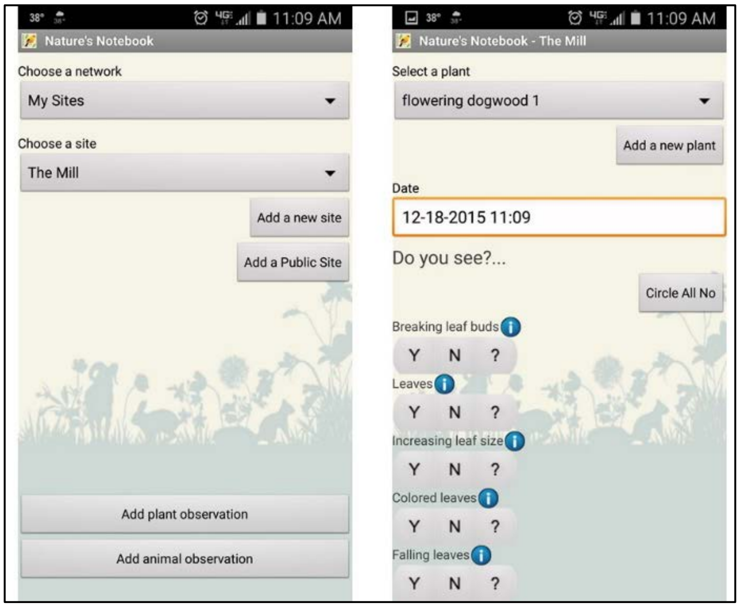


Figure 5. Screenshot of NPN Nature's Notebook Mobile App for reporting vegetation phenology

All reported data is downloadable directly from NPN website via a spreadsheet file. Our citizen scientists monitored the trees during the spring 2014 (from February through May) for leaf bud burst, leafing out, first flowers, full flowering, and full tree canopy.

4.4 Data Analysis

We compared the start of season values for each of the different TIMESAT algorithms, image date, statistical metrics (mean, range, and standard deviation) for five years (2010 – 2014). Since urban areas are highly heterogeneous, especially with intra-urban heat islands, we expected variation in start of season across the city, and looked for that algorithm that found the greatest variation in start of season values.

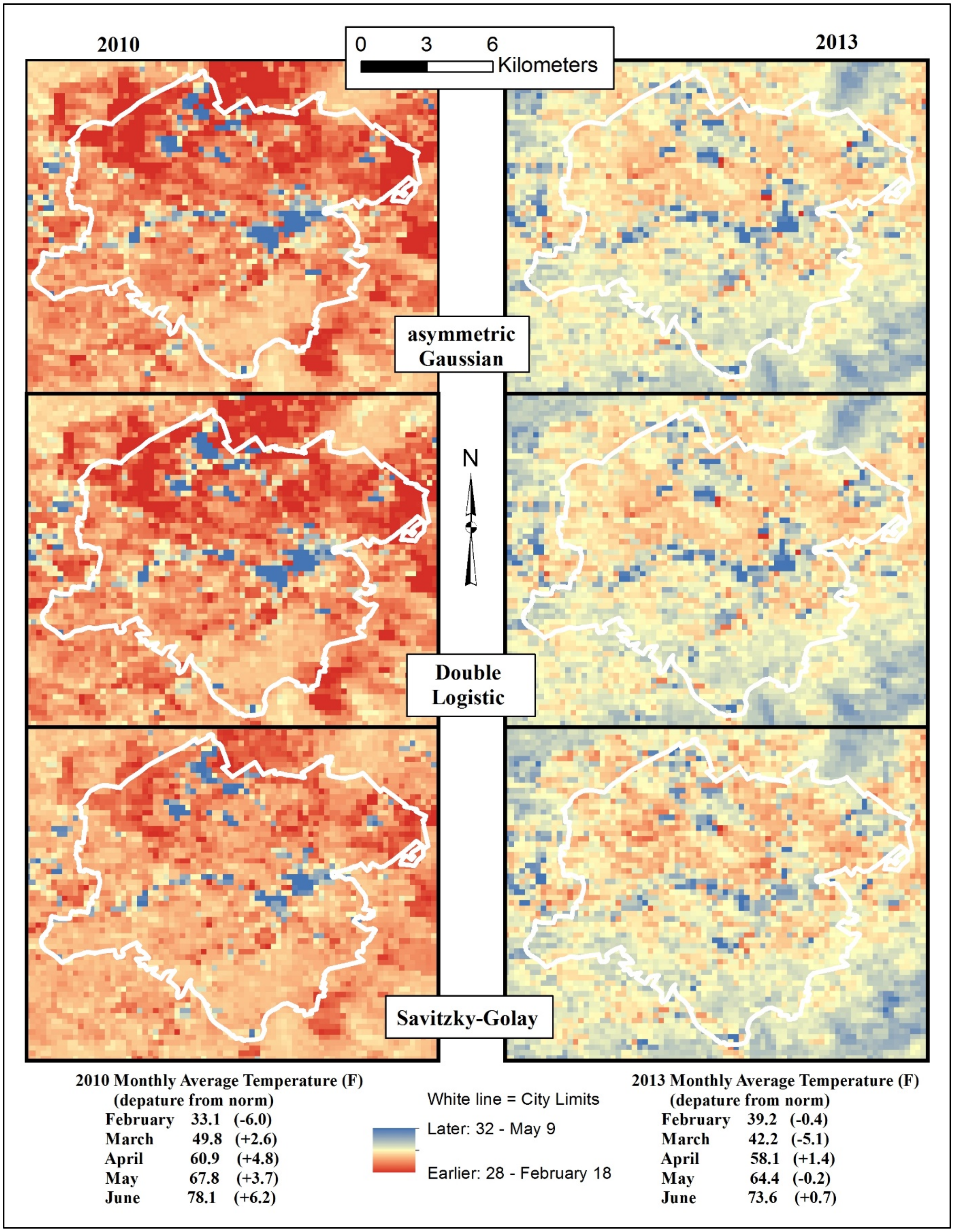
We next compared TIMESAT patterns for start of season values and our temperature patterns, looking for those TIMESAT patterns reflecting earlier start of season (lower image values) to those higher temperature patterns and those TIMESAT patterns showing a later start of season (higher image values) to cooler temperature patterns.

For each tree from our *in-situ* analysis, we first compared differences for *in-situ* observations. We only compared the same tree species to each other, e.g., red maple to red maple, black oak to black oak, etc. We eliminated any tree species that were only monitored at one location or any tree species where only a single tree was monitored. Next, we added spreadsheet downloaded from NPN to ArcGIS™ and used latitudes and longitudes to plot tree locations on our TIMESAT and MODIS NDVI images. If the same species was found multiple times within the same pixel, we verified that *in-situ* values were the same and only used one tree for thecomparison. We then extracted TIMESAT and MODIS NDVI values from each image for each tree's point. We compared *in-situ* reporting with those values extracted from the satellite images for similarities and differences. Since leaf bud burst is the primary phenophase indicative of start of season (Liang et al. 2011), we compared the leaf bud burst date of each individual tree species to the TIMESAT start of season value.

5 Results and Discussion

5.1 TIMESAT Results

Start of season clearly varies over the entire city (Figure 6 – city boundaries are white). The spatial patterns for start of season date varies depending on the algorithm but also depending on whether temperatures for a specific year were above average, average or below average (we symbolized the start of season image number for all images using the same scale). Figure 6 shows results for two years – 2010 (on left) and 2013 (on right), along with the monthly average spring temperatures for each year at the bottom of the image. Although 2010 had below normal temperatures in February, spring months were warmer than normal, facilitating an increase in vegetative growth earlier in the season. For 2010, TIMESAT identified an earlier start of season across the entire image as compared to 2013 (when temperatures were closer to normal averages).



2010
0 3 6
Kilometers
2013
asymmetric Gaussian
N
Double Logistic
Savitzky-Golay
2010 Monthly Average Temperature (F)
(depature from norm)
February 33.1 (-6.0)
March 49.8 (+2.6)
April 60.9 (+4.8)
May 67.8 (+3.7)
June 78.1 (+6.2)
White line = City Limits
Later: 32 - May 9
Earlier: 28 - February 18
2013 Monthly Average Temperature (F)
(depature from norm)
February 39.2 (-0.4)
March 42.2 (-5.1)
April 58.1 (+1.4)
May 64.4 (-0.2)
June 73.6 (+0.7)

Figure 6. TIMESAT start of season results for each algorithm for two years (2010 and 2013) and average temperatures for the spring of each year. 2010 was warmer so start of season occurred earlier.

Although the different algorithms produce slightly different patterns, the patterns show similar variations across all images -- the city and surrounding urban areas demonstrate an earlier start of season than surrounding rural areas. (We refer back to the Landsat image in Figure 2 as a reference for variations in the area's physical layout.) Even the two mountains within the image show a different start of season - Read Mountain in the northeast corner (just outside the city boundaries) shows a slightly later start of season as compared to Mill Mountain within the city (southeast).

Furthermore, distinct patterns are also present within city boundaries. The southern half of the city demonstrates a later start of season, while most of the northern part of the city demonstrates an earlier start of season (with the exception of the far northeast). The northern area of the city is more densely built, with less vegetation. The northeast corner consists of a large industrial complex – large buildings situated on large park-like parcels of land – and is located near a large urban farm and golf course.

Of specific note are areas at the middle of the city – in all images they show as the darkest blue, which would indicate the latest start of season. The actual TIMESAT values for these areas are images numbered between 33 and 39. But these are areas of extensive impervious surfaces, thus little vegetation, e.g., the railway complex in the middle of the image demonstrate very late start of season as does the airport runways in the northwest. TIMESAT could not locate an appropriate start of season. Furthermore in every year, two algorithms - Gaussian and Double Logistic - identified an image numbered 22 (December of the previous year) for start of season for a few pixels (appearing very dark red in the images in Figure 6) — likewise, areas of extensive impervious surfaces. These types of landscapes interfere with the functioning of TIMESAT algorithms, a common situation when doing remote sensing analyses in urban areas.

Which algorithm shows the greatest variation, thus is most appropriate for examing an urban area? As noted above in *Methods*, we also examined summary statistics for five years (2010 – 2014). For the pixels only within the city boundaries (n = 2342), Gaussian showed the highest standard deviations, and Double Logistic had higher standard deviations than Savitzky-Golay, for all years. But, the range of values for both Gaussian and Double Logistic, from 22 (for all years) to 39.21 (2011) (equating to dates December of the previous year and August 29), clearly reports dates that are not reasonable for start of season for Roanoke. So, after confirming these outliers were all related to areas of extensive impervious surfaces, we eliminated them from our statistical analysis. The number of deleted outliers varied by algorithm and by year -- less than 10 for all algorithms in 2012 and between 100 and 200 in 2011 — across all years, the Savitzky-Golay algorithm reported the least number of outliers. Furthermore, in no year did the Savitzky-Golay algorithm identify a pixel image number that corresponded to a date in the prior year.

When we eliminated these higher outliers, the highest image date for all algorithms was 32 (May 9; May 8 for 2012 - a leap year). In four of five years (2010, 2011, 2013 & 2014), Logistic had the lowest minimum date for start of season. For four of five years, Logistic had the highest standard deviation (2010, 2011, 2012, and 2014). For three years (2011, 2012 and 2013) means were the same for all algorithms; in 2010, the Logistic mean was the same as the Gaussian but both were 4 days earlier than Savitsky-Golay. For 2014, only 1 day separated all three means. Table 1 summarize these statistics for the years 2010 through 2014.

Table 1. Summary Statistics for 2010 – 2014 for the three TIMESAT algorithms

Year		Savitzky-Golay	Logistic	Gaussian
2010	Mean*	29.24	28.97	28.97
	Minimum – Maximum*	27.35 – 31.99	26.85 – 31.96	26.88 – 31.90
	N	2290	2242	2246
	Standard Deviation	0.65	0.76	0.71
2011	Mean*	30.03	30.00	30.00
	Minimum – Maximum*	27.70 – 31.94	27.75 – 31.99	27.90 – 31.97
	N	2238	2154	2174
	Standard Deviation	0.75	0.77	0.76
2012	Mean*	29.20	29.16	29.22
	Minimum – Maximum*	26.29 – 31.86	27.10 – 31.99	27.57 – 31.94
	N	2335	2333	2332
	Standard Deviation	0.62	0.63	0.61
2013	Mean*	29.95	30.01	30.01
	Minimum – Maximum*	27.97 – 31.95	27.19 – 32.00	27.78 – 31.99
	N	2312	2303	2290
	Standard Deviation	0.56	0.54	0.53
2014	Mean*	30.15	30.08	30.07
	Minimum – Maximum*	28.87 - 31.95	26.92 – 31.98	26.77 – 31.98
	N	2306	2294	2287
	Standard Deviation	0.49	0.58	0.58

*Number represents the image number

5.2 Comparison of Satellite Derived Start of Season to Temperature Patterns (2013)

Our temperature collection campaign included collecting consecutive days of temperature on April 21 – 23, 2013, recording both morning and afternoon temperatures. Start of season cannot be attributed to the temperatures from a particular day but, rather, an accumulation of temperatures, warming the earth over a long period of time and initiating leaf bud burst and flowering. Thus, comparing phenology to one date is not revealing as the temperature patterns change over the course of a day, and then over months, as temperatures either maintain warmth or continue to warm. For example, Figure 7 shows estimated temperature patterns for the morning of April 21, afternoon of April 21, and afternoon of April 23 — the city experienced increasing temperatures over the three days (April 21 – 23) and meteorological data showed continued warming thereafter. In Figure 7, we have included estimated temperatures for September 6 (towards the end of Roanoke's growing season), demonstrating how the patterns changed over the growing season, ultimately reflecting the same patterns depicted in the Landsat thermal image (Figure 2). For any date on which we collected temperatures in the morning, the southern areas of the city appeared warmer, then patterns changed as the day progressed.

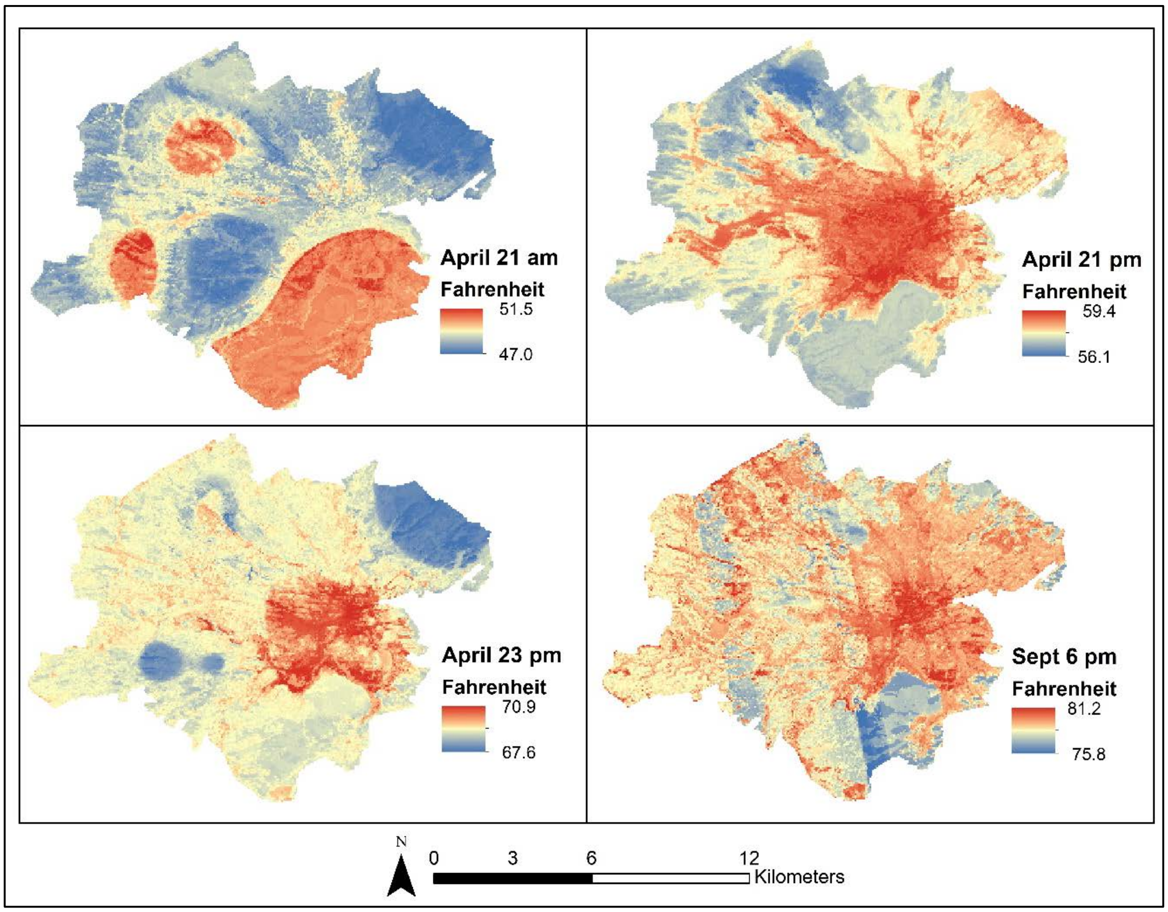


Figure 7. Estimated temperatures across the entire City of Roanoke for three time periods in April 2013 and the afternoon of September 6, 2013. Temperature data collected and processed as outlined in Parece, et al. (2016).

TIMESAT results for 2013 start of season correspond with spring temperatures from April 21 through April 23 (Figure 8). The patterns show spatial covariation – locales with later start of season correspond with areas where our estimated temperatures were cooler. Specifically, Mill Mountain (outlined by the fuchsia oval in Figure 8) shows cooler temperatures and later start of season. The northeast corner of the city (black oval) shows cooler temperatures and later start of season but progressing into warmer temperatures and earlier start of season as one moves southeast farther into the city – the cooler area (dark blue oval) is the industrial park on very large lots similar to a park like setting and the warmer areas are an older industrial park with smaller buildings spaced closer. In the eastern part of the city (gray oval), a mixture of warmer and cooler temperatures and different starts of season – areas represented by mixtures of single family residential and supporting commercial areas. The center of the city is characterized by very warm temperatures and early start of season but also by extensive impervious surfaces for the railway complex and associated infrastructure (where TIMESAT cannot accurately calculate start of season for such surfaces, so identifies the start of season for these pixels as very late). We do note that resolution of these two images are different — MODIS phenology data have a resolution of 250 meters, whereas, our temperatures are predicted at 30 meter resolution.

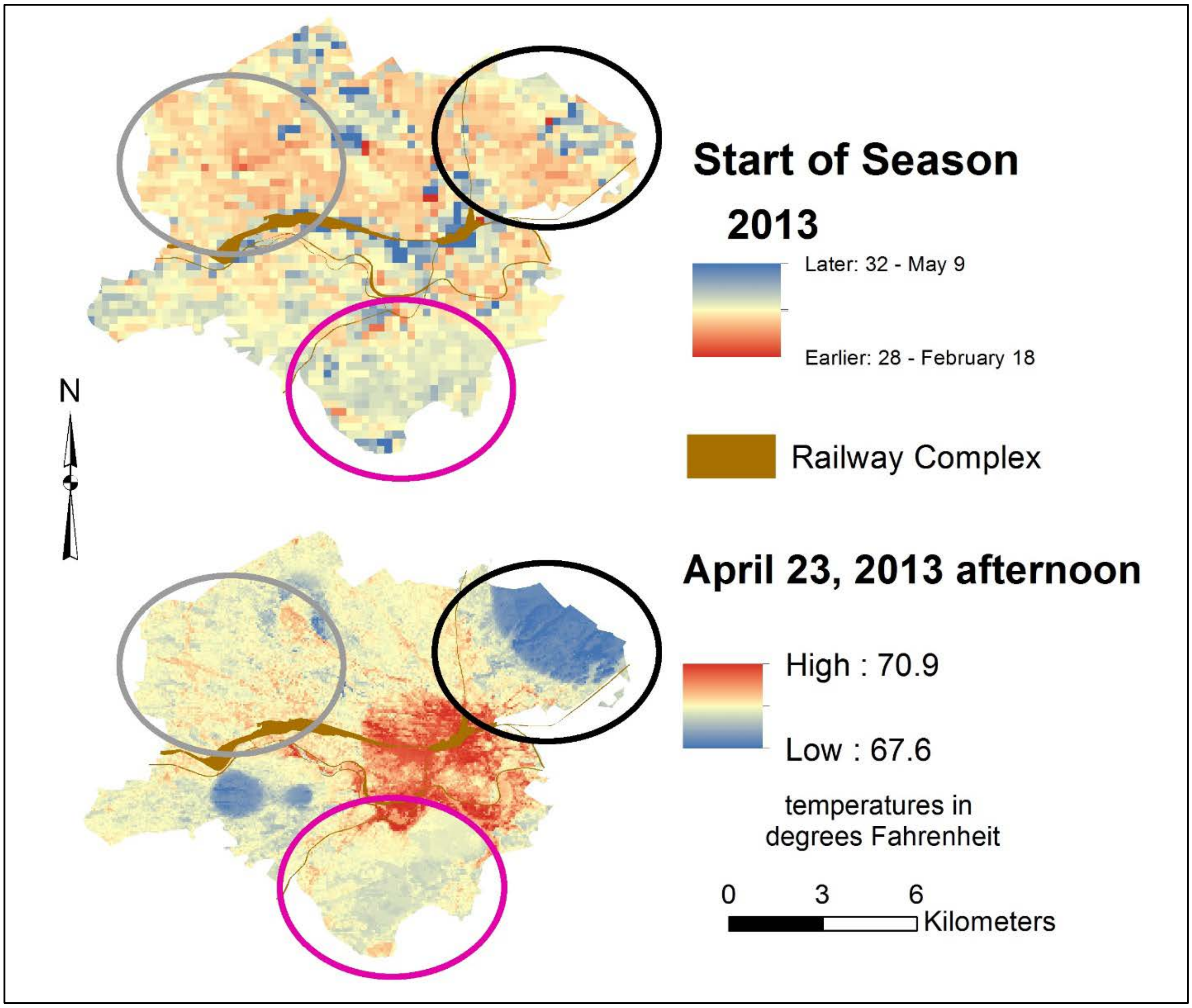


Figure 8. Comparison of TIMESAT results for 2013 (250 m resolution) with estimated temperatures for the afternoon of April 23 2013 (30 m resolution as derived from microclimate analysis completed by Parece, et al., 2016).

5.3 Comparison of Satellite Derived Start of Season to In-Situ Data (2014)

Our citizen scientists monitored 62 individual trees during the spring 2014 (from late February through mid-May) for leaf bud burst, first open flowers, and full tree canopy, although the trees were not monitored consistently by all observers. In addition, monitoring sometimes occurred on only an individual tree for some species, for only one observation date, some only observed leaf bud burst but did not monitor flowering, some noted flowering but not lead buds, and most failed to report when the leaf canopy reached 95% or greater. Flowering dogwood (*Cornus florida*), red maple (*Acer rubrum*), black oak (*Quercus velutina*) and white oak (*Quercus alba*) are the species with the greatest number of individual trees and most consistent monitoring, thus are the trees we used for this portion of our analysis. For three species – flowering dogwood, red maple and white oak - multiple trees were monitored at each location. As noted above in *Methods*, if multiple trees fell on the same MODIS pixel and the *in-situ* information gathered was the same for each, we only report on one tree.

The trees are distributed across the city - five each for flowering dogwood (*Cornus florida*), red maple (*Acer rubrum*), white oak (*Quercus alba*) and three black oak (*Quercus velutina*) - a total of 18 trees. The trees are located in distinctive landscapes – a large industrial park (Blue Hills), on Mill Mountain (southeast Roanoke), a cemetery, three schools (one near the city's center), a park, and residential neighborhoods (Figure 9).

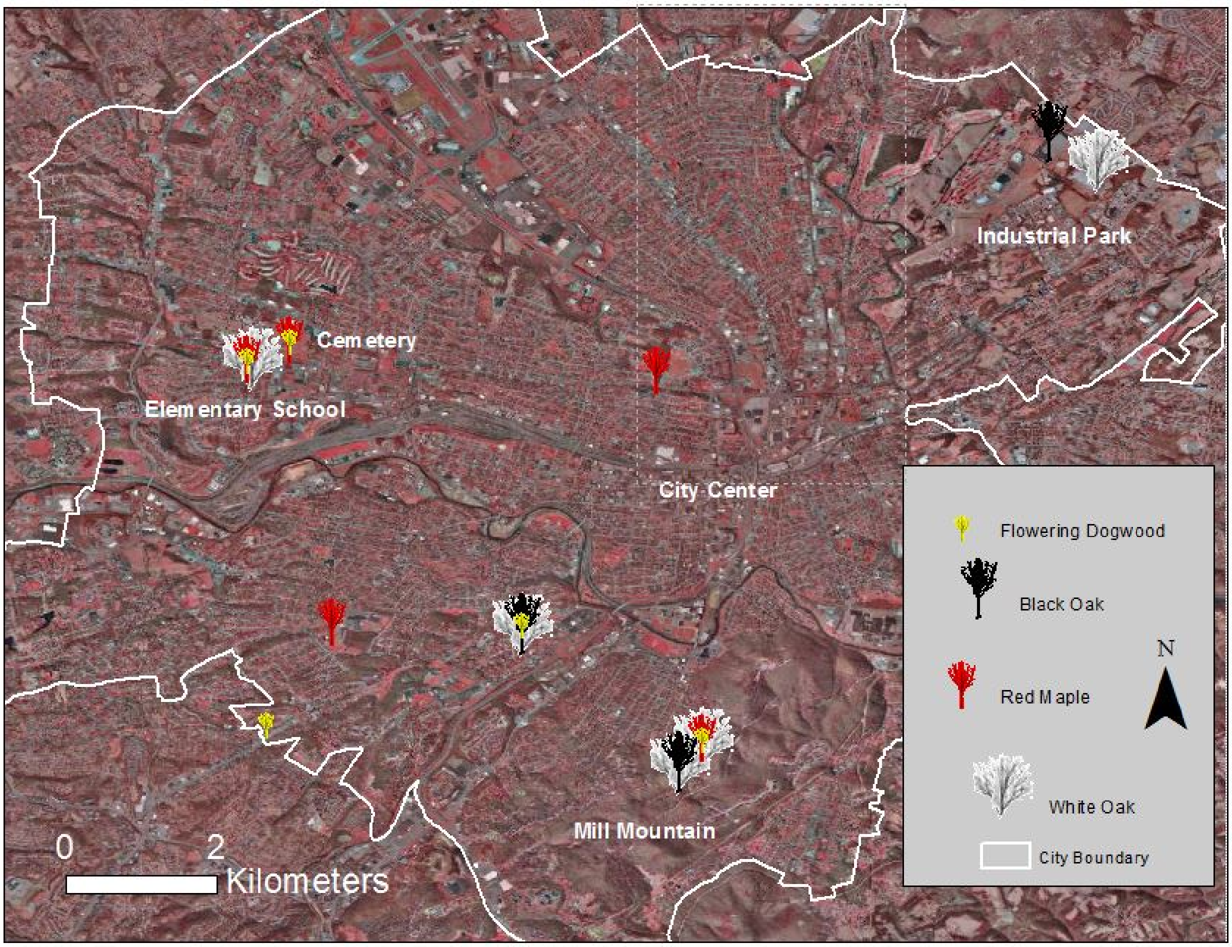


Figure 9. Locations of trees monitored by citizen scientists and reported in this study, overlaid on color-infrared aerial image from the Virginia Base Mapping Program

We used dates of breaking leaf buds to compare to TIMESAT-derived start of season dates for all three algorithms. No algorithm performed the same for all sites nor for all trees of a single species. Table 3, categorized by tree species, provides results for first date of observed breaking leaf buds, location and the date ranges identified as start of season by TIMESAT's algorithms. Three locations' field observations fell within the range of dates identified by the three algorithms – the black oak in Fern Park, the red maple and flowering dogwood at Fairview Cemetery, and the flowering dogwood on Robin Hood. Another four locations fell within one or two days of the range – both trees in the two Black Hills' locations, the white oak in Fern Park, the red maple on Robin Hood, and the white oak at Fairview Elementary School.

Our greatest disagreement was the Oakwood location – all field observations deviated from TIMESAT by 13 days to one month. Oakwood was the location with the lowest elevation, so elevation was not a factor for the later date of bud burst, i.e. higher elevations are cooler and thus start of season begins later. When examining historical imagery in GoogleEarth™ for Oakwood, the area is predominantly conifers and likely the cause of the earlier start of season identified by TIMESAT. The red maples at Addison Middle School and Patrick Henry High School also deviated significantly - 1 month and 13 days, respectively. Addison Middle School only provided one observation at their location -- if more observations had been submitted, this result may have been different. For Patrick Henry High School, the field observation identified breaking leaf buds as early as March 14 and two of the algorithms did identify March dates; trees at this school are widely spaced and located in open areas and the school is typified by large expanses of impervious surfaces.

Table 3 2014 *in-situ* phenology monitoring results compare with TIMESAT

Tree species common name (Scientific name)	Site name	Date first observed breaking leaf buds	Range of TIMESAT start of season
black oak (*Quercus velutina*)	Blue Hills	April 9	April 6 - 8
	Fern Park	April 14	April 14 - 15
	Oakwood	April 17	April 2 - 4
flowering dogwood (*Cornus florida*)	Fairview Cemetery	April 4	April 2 - 9
	Fairview Elementary School	April 4	April 12
	Robin Hood	April 9	April 10 - 15
	Fleetwood	April 17	April 11 - 13
	Oakwood	May 2	April 2 - 4
red maple (*Acer rubrum*)	Addison Middle School	March 5	April 2 - 9
	Patrick Henry High School	March 14	March 29 – April 4
	Fairview Elementary School	March 31	April 12
	Fairview Cemetery	April 2	April 2 - 9
	Robin Hood	April 14	April 10 - 15

white oak (*Quercus alba*)	Blue Hills	April 9	April 11 - 26
	Robin Hood	April 9	April 10 - 15
	Fern Park	April 10	April 14 - 15
	Fairview Elementary School	April 14	April 12
	Oakwood	April 17	April 2 - 4

For the Fairview Elementary School site, all three TIMESAT algorithms identified the same date for start of season – April 12. But, the field observations of the trees did not agree with this date – flowering dogwood (April 4), red maple (March 31) and white oak (April 14). The same citizen scientist also observed trees at Fairview Cemetery (across the street from the school but within a different MODIS pixel). For the cemetery, the three algorithms produced different dates (two identified April 2 and one identified April 9), and the field observations showed breaking leaf buds for the two trees within this range – flowering dogwood (April 4), red maple (April 2). The landscape differences between the two locations, albeit across the street from each other, are significant – the cemetery's large expanses of grass with trees, the elementary school – large expanses of impervious surfaces with playgrounds, some grassy areas and some trees, the red maple was specifically identified by our monitor as being next to a sand covered playground.

Figure 10 is an overlay of the red maples on our temperatures for April 21 and 22, 2013 -- sizes of point symbols vary according to the first observation of breaking leaf buds by our monitors. While the years are different (2013 for derived temperatures and 2014 for in-situ tree monitoring), the patterns, again, show spatial co-variation. The smaller point for the red maple at city center represents the earliest leaf bud burst, and temperatures are warmer in this location. The largest red maple symbol, representing the latest date for leaf bud burst, is on Mill Mountain in the southern part of the city and its coolest area. Of specific note are the two points near each other on the western side of the city – Fairview Elementary School (smaller of the two points) and Fairview Cemetery (larger of the two points); the elementary school's red maple is situated on areas designated as warmer and the field observation showed an earlier leaf bud burst than the red maple in Fairview Cemetery (again we note that the same person was the monitor for both sites).

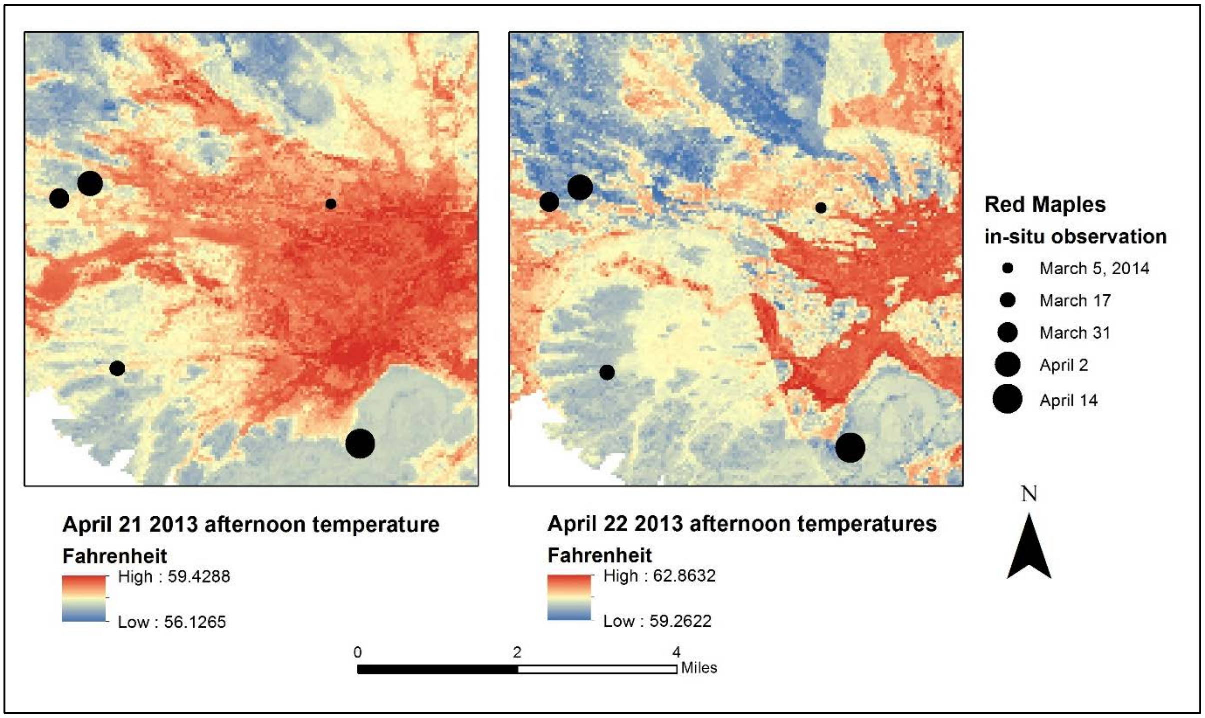


Figure 10 Patterns for estimated April 2013 temperatures and Red Maple in-situ leaf bud burst observations for 2014. Earlier bud burst is occurring in areas where temperatures are higher

6 Conclusions

Phenophases, for this study - start of season, vary within this urban area. Our study demonstrates that using TIMESAT to evaluate MODIS NDVI is an effective evaluative technique for start of season variations within the City of Roanoke, Virginia. When evaluating each TIMESAT algorithm to determine which algorithm shows the greatest variation in documenting start of season, no one algorithm proved consistent across the five years assessed

(2010 – 2014). This result is not surprising because, as with many other urban analyses, landscape variations within urban areas create a need for multiple methods of analysis.

Generally, start of season varies from year to year – even at the pixel level. Variations depend on whether the city experienced consistently warmer temperatures or cooler temperatures during the spring. Our 2013 *in-situ* temperature data collection and resultant derived temperatures using Random Forest (Parece et al, 2016), demonstrated spatial co-variation with our TIMESAT start of season results – areas of warmer temperatures showed an earlier start of season, areas with cooler temperatures showed a later start of season.

Our 2014 *in-situ* vegetative phenophase observations also demonstrated spatial co-variation with both TIMESAT results and the derived temperatures across the city. Observed earlier start of season corresponded with TIMESAT derived start of season — with one exception - our Oakwood location. However, upon examining aerial photos, we determined that this location was predominantly conifers, which likely were recorded as an earlier green-up than those observed from *in-situ* monitoring of specific deciduous trees.

Our analysis provides some support for type of plant selection for different locales within the city. However, further analysis should be completed with TIMESAT to document end of season and thus, length of season. With such additional analysis, the appropriate plants could be identified as suitable for such locations -- i.e. plants with a longer or shorter growing season. Such identification would be especially useful for evaluating locations for specific crops for urban agriculture – a longer growing season would accommodate food production for a longer period of time or for those species that require a longer time to attain maturity.

We do urge caution for future analyses for two reasons. Firstly when attempting to correlate temperatures for a specific date to phenology – as we have previously noted, direct correlation between one day's temperature and phenologic status cannot be accomplished since initiation of leaf bud burst and first flowering occurs only after multiple days of sustained warming temperatures. Secondly, MODIS provides the best image over a 16 day period, so the date of the MODIS image (or the image value identified by TIMESAT for start of season) could actually vary from those dates identified. This actually may result in closer correlation for in-situ monitoring.

Landsat imagery would likely be more appropriate satellite imagery for investigating urban phenology as its 30 meter resolution provides finer detail, rather than the 250 meter scale provided by MODIS. However Landsat's less frequent revisit interval, combined with loss of coverage due to cloud cover, limit the utility of Landsat for urban phenological analysis. If sufficient numbers of cloud-free Landsat images could be identified (within at least one year), an additional evaluation could compare TIMESAT-derived start of season for Landsat to MODIS. Such finer scale analyses may be required to accurately document start of season using satellite imagery of urban areas with a higher density of multi-family residential areas such as New York City, London or Philadelphia.

7 Acknowledgements

We would like to thank our citizen scientists who assisted in our in-situ data collection campaign. We would also like to thank our funding supporters.

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Strategically Siting Urban Agriculture: A Socio-Economic Analysis of Roanoke, Virginia

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Abstract: Food insecurity is a major concern in the United States, particularly in high poverty areas and households with children. Urban agriculture helps address food insecurity and promote recreation, aesthetics, biodiversity, and other benefits. Our paper reports a socio-economic evaluation of ten different variables, including in-situ analysis of healthy, nutritious food options, of a small, intensely urbanized city to identify neighborhoods that would benefit from urban agriculture. We produced a hierarchy of locations (using census block groups), from least to greatest socio-economic need, for new urban agriculture sites. Our results found one block group qualified in all ten variables and two-thirds demonstrated a need in at least half of the variables. The majority of these block groups were distributed within the middle of the city.

Key words*: food security, urban agriculture, GIS, Roanoke Virginia*

In the United States, more than 81% of the population live in urban areas (United Nations 2014). Within urban areas, internal variations in built environment, greenways, and socio-economic settings create disparities in quality of life, health, and well-being for residents (Eisenhauer 2001; Frank, Andresen, and Schmid 2004; Feng et al. 2010). These disparities often appear to be related to differing socio-economic status (Moore and Diez Roux 2006; Seaman, Jones, and Ellaway 2010). Impacts from such disparities include uneven access to affordable food and housing, transportation, employment, and locales for social interaction and physical activity (Freedman and Bell 2009; Richardson et al. 2012).

Urban agriculture has recently received wide attention because it offers a spectrum of benefits to urban populations, including opportunities to promote recreation, aesthetics, biodiversity, and other factors. Most researchers agree that that a land inventory is the first step in siting urban agriculture (Dongus and Drescher 2006; Dubbeling, van Veenhuizen, and de Zeeuw 2010). Urban agriculture land inventories -- the foundation for planning urban agriculture -- largely focus upon availability and physical evaluation of vacant or under-utilized lands as potential urban agriculture sites (e.g., Balmer et al. (2005); Colasanti and Hamm (2010); Meenar and Hoover (2012); McClintock, Cooper, and Khandeshi (2013)). Investigators conduct land inventories for a variety of reasons, e.g., research projects (Colasanti and Hamm 2010; Meenar and Hoover 2012), at the request of municipalities (Balmer et al. 2005) or local food/non-profit organizations (McClintock, Cooper, and Khandeshi 2013), but all are accomplished to support siting new urban agriculture. Furthermore, implementing urban agriculture on vacant or under-utilized lands allows for the productive use of otherwise non-productive spaces.

While an urban agriculture land inventory provides groundwork for sustainability efforts of an urban area as a whole, identification of under-utilized lands does not necessarily address socio-economic inequalities faced by lower income residents. An important priority should be identifying those neighborhoods with socio-economic characteristics that would best benefit from urban agriculture, scaffolded with a land inventory, which has been largely ignored. To date, only one land inventory could be identified that included data on low-income neighborhoods within the land inventory analysis (e.g., Meenar and Hoover 2012).

The goal of this study is to evaluate socio-economic factors, including landscape variables related to these factors, to identify neighborhoods that could benefit from urban agriculture's contributions to improving socio-economic qualities. The study was conducted within the small, yet completely urbanized and densely populated, City of Roanoke, Virginia. The first step was to identify socio-economic variables important for our analysis. Then, from empirical studies, we outline how urban agriculture can help address disparities in lower-income neighborhoods. Next, we outline why our study site is appropriate for such an urban agricultural analysis. We identify data applicable to Roanoke and outline our analytical methods. Finally, we review our results - a hierarchy of locations (identified spatially as census block groups) for strategically siting urban agriculture to help alleviate factors adversely affecting health and well-being of low-income urban residents.

Urban Socio-Economic Disparities

Within an urban landscape, the physical distribution of vegetation (i.e. parks, urban forest, and other greenspaces) and the built environment (buildings, roads, and other related infrastructure) varies. Such physical variations are frequently related to socio-economic factors (e.g., income, assets, education, among others) because, in most cases, money drives how and where these physical aspects are developed (Wolch, Wilson, and Fehrenbach 2005; Ernstson 2013; Anguelovski 2015). As such, those populations, with the greatest need for jobs and for affordable housing, food, transportation, and recreational facilities, are those often excluded from the decision-making process (Ernstson 2013; Cohen and Reynolds 2014). These socio-economic factors even appear to drive construction, maintenance, and enhancement of greenspaces (Wolch, Wilson, and Fehrenbach 2005; Ernstson 2013; Francis and Chadwick 2013).

Urban disparities are highlighted when we examine access to affordable and nutritious food – i.e., food security (Moore and Diez Roux 2006; USDA 2009). The United States Department of Agriculture (USDA) defines food security as access to sufficient quantities of healthy and nutritious foods for an active and healthy life (Coleman-Jensen, Gregory, and Singh 2014). Food insecurity is prevalent in the U.S. In 2014, 14.3% of U.S. households (45.6 million people) were found to be food insecure sometime during the previous twelve months (USDA 2015); this rate increases to one in five when only examining households with children. Food insecurity rates vary across the country, and across socioeconomic and demographic characteristics (Coleman-Jensen, Gregory, and Singh 2014; USDA 2015). Higher rates are found in major urban areas (16.7%), in female single-headed-households (34.4%) and households with incomes less than the federal poverty level (42.1%) (Coleman-Jensen, Gregory, and Singh 2014).

In lower-income households, a greater portion of income is spent on food and housing and, in order to afford adequate food, it is necessary to buy less nutritious food (USDA 2009; Walker, Keane, and Burke 2010). And although income constitutes a major factor in food choices (Rose 1999; Hofferth and Curtin 2005), access to healthy and nutritious foods may be complicated by factors such as vehicle ownership, availability of public transportation, local crime rates, and locations of supermarkets or commercial food establishments offering healthy choices (Eisenhauer 2001; Rose and Richards 2004; Moore and Diez Roux 2006; Galvez et al. 2008; Bader et al. 2010).

Locations without such availability (e.g., establishments offering healthy choices) are considered food deserts -- defined as areas where people have limited access to affordable fresh fruits and vegetables and other healthy foods (Bader et al. 2010). But access is more than just the presence of retail food outlets (or lack thereof) (Caspi et al. 2012); accommodation – e.g., operating hours (Caspi et al. 2012; Chen and Clark 2015), availability - the presence of sufficient quantities of healthy food for all residents (Bader et al. 2010; Caspi et al. 2012), and acceptability – people's attitudes about the food that is available (Freedman and Bell 2009; Caspi et al. 2012). In recent years, a prolific research effort has investigated specifics of designating exact locations of food deserts and defining what constitutes a true food desert (e.g., Sage, McCracken, and Sage 2013; Chen and Clark 2015; Cho and Rodriquez 2015; Thibodeaux 2015), and ways to overcome lack of supermarket access (either by providing farmers' markets or identifying locations for new retail outlets that offer nutritious alternatives) (e.g., Wang, Qiu, and Swallow 2014; Anderson and Burau 2015; Lu and Qiu 2015).

Strong evidence exists that lack of local access to foods can indicate overall dietary quality and food insecurity (Moore and Diez Roux 2006; Bader et al. 2010). Lack of food security has repercussions beyond insufficient diets (Robert and Reither 2004; Riva et al. 2009; Coleman-Jensen, Gregory, and Singh 2014); and include health issues such as higher rates of obesity (Robert and Reither 2004; Riva et al. 2009). For example, full-service restaurants, grocery stores, and direct marketing of local foods are associated, on a per capita basis, with lower rates of obesity, whereas quick-service restaurants and convenience stores are associated with higher rates (Ahern, Brown, and Dukas 2011). Presently, obesity is considered a national epidemic (Wyatt, Winters, and Dubbert 2006), as more than one-third of U.S. adults (35.7%) are considered obese (Ogden et al. 2012).

Furthermore, many studies have also tied other health issues in urban areas to a lack of greenspaces (De Vries et al. 2003; Mitchell and Popham 2007; Maas et al. 2009). Urban populations experience greater exposure to heat related illnesses, deaths, and infectious disease because of the urban heat island effect (Patz et al. 2005); a phenomena which causes urban areas to be warmer than surrounding rural areas because of reduced vegetative cover and higher amounts of impervious surfaces. Furthermore, lack of vegetation is associated with higher levels of air pollution, which can also increase susceptibility to asthma and other respiratory illnesses, especially for children (Gern 2010; Malik, Kumar, and Frieri 2012). Some studies have further tied higher health risks in lower-income neighborhoods to limited greenspace in these neighborhoods (Mitchell and Popham 2008; Seaman, Jones, and Ellaway 2010; Marcus 2012). These effects can be further exacerbated in lower-income populations who can ill afford increased energy costs for air conditioning, or have limited access to medical care (Malik, Kumar, and Frieri 2012).

In addition to providing areas for physical activity, urban greenspaces provide both emotional and psychological benefits (Kaplan 2001; van den Berg, Hartig, and Staats 2007) by reducing stress, depression and anxiety (Mitchell and Popham 2007; Mitchell and Popham 2008; Kuo 2010). People report better health, physically and mentally, when they live in greener environments (Kaplan 2001; Mitchell and Popham 2007; Mitchell and Popham 2008; Maas et al.

2009). Greenspaces also constitute a social resource where people can meet and interact, in addition to participating in physical activity (Kuo 2003; Secco and Zulian 2008; van Leeuwen, Nijkamp, and de Noronha Vaz 2010). Furthermore, decreases in attention deficit disorder, hyperactivity disorder, and propensity to crime have been reported in children after increased exposure to greenspaces (Louv 2005; Kuo 2010; Marcus 2012).

Socio-Economic Benefits of Urban Agriculture

A greenspace is defined as "land that is partly or completely covered with grass, trees, shrubs, or other vegetation" (U.S. EPA 2015). Within an urban area, a greenspace "functions as productive green areas that are able to deliver useful products (wood, fruits, compost, energy, etc.) as a result of urban green maintenance or construction" (van Leeuwen, Nijkamp, and de Noronha Vaz 2010). Urban agriculture is "the growing, processing, and distribution of food and nonfood plant and tree crops and raising of livestock, directly for the urban market, both within and on the fringe of an urban area" (Mougeot 2006, p 4). Urban agriculture forms a productive greenspace that encompasses a broad range of scales, from small containers on window sills and patios, to a commercial urban farm, as large as several hectares, and can be owned and/or operated by private citizens, business, non-governmental organizations or municipalities (Pearson, Pearson, and Pearson 2010).

Research on urban agriculture and its benefits is quite extensive. Urban agriculture provides a wide range of socio-economics benefits (as reported by a selection of such studies found in Table 1). These studies document (either quantitatively or qualitatively) urban agriculture's contribution to food security (e.g., increasing access and consumption of fresh fruits and vegetables, supplementing food supplies, and increasing knowledge about healthy food choices), health benefits (e.g. increased activity and stress relief), and community benefits (e.g.

community building, social inclusion and community revitalization), among others as identified in Table 1.

Table 1 Benefits of urban agriculture

Benefits	Author (Year)
Increased access to and consumption of fresh fruits and vegetables	Maxwell, Levin, and Csete (1998); Alaimo et al. (2008); Bleasdale, Crouch, and Harlan (2011); Corrigan (2011); Ottman et al. (2012); White (2014)
Supplementing food supplies	Reynolds (2009); Wills, Chinemana, and Rudolph (2010); Abdulkadir et al. (2012); Ottman et al. (2012); Pourias, Duchemin, and Aubry (2015); Taylor and Lovell (2015)
Reducing food expenses and generating income	Faruqui (2002); Reynolds (2009); Abdulkadir et al. (2012); McCabe (2014); Taylor and Lovell (2015)
More thorough knowledge about healthy food choices	Hatchett et al. (2015)
Knowledge about food systems	Faruqui (2002); Travaline and Hunold (2010); Hatchett et al. (2015)
Health benefits from outdoor exercise	Bleasdale, Crouch, and Harlan (2011); Hale et al. (2011); Ottman et al. (2012); Moore et al. (2015)
Stress relief	Bleasdale, Crouch, and Harlan (2011); Hale et al. (2011); Ottman et al. (2012)
Community revitalization	Reynolds (2009); Ottman et al. (2012); McCabe (2014)
Crime prevention	Ottman et al. (2012); McCabe (2014)
Increased property values	Voicu and Been (2008); McCabe (2014)
Cultural preservation	Saldivar-Tanaka and Krasny (2004); Hale et al. (2011); Ottman et al. (2012); Li et al. (2013); Taylor and Lovell (2015)
Social interactions and cultivation of relationships	Travaline and Hunold (2010); Wills, Chinemana, and Rudolph (2010); Hale et al. (2011); Ottman et al. (2012); White (2014); Hatchett et al. (2015)

Building a sense of community	Saldivar-Tanaka and Krasny (2004); Travaline and Hunold (2010); Hale et al. (2011); Ottman et al. (2012); Hatchett et al. (2015); Moore et al. (2015)
Empowerment and social inclusion	Agustina and Beilin (2012); Ottman et al. (2012); White (2014)
Leadership development	Hatchett et al. (2015); Moore et al. (2015)
Sense of connection to place	Hale et al. (2011); Ottman et al. (2012);White (2014)

Study Site

The City of Roanoke is southwest Virginia's largest city (Figure 1) and its demographic characteristics provide the opportunity to explore relationships between socio-economic variables and optimal locations for urban agriculture. Roanoke's poverty rate and food insecurity rates are higher than those of the surrounding county, state, and national averages (Table 2), and, according to the USDA (2014), residents of a majority of the lower-income census tracts within the city live in a food desert (specifically live at least one mile from a grocery store). In addition, according to the Virginia Department of Health, Roanoke's rates for poor health conditions exceed state averages (Table 3) (Virginia 2015b). A study completed by the University of Wisconsin ranked (for 2014) the City of Roanoke 127th out of 133 counties and cities in Virginia for poor health factors such as obesity, diabetes, and physical inactivity (2015). Within Roanoke, socio-economic characteristics vary from neighborhood to neighborhood. Across census block groups, the household poverty rates range from 0 to almost 53% (U.S. Census 2015b), rates of female single-headed households range from 0 to over 67% (U.S. Census 2015b), and unemployment rates range from 0 to almost 29% (U.S. Census 2015b). For each public school, rates of student eligibility for a free or reduced school lunch program, under the U.S.D.A National School Lunch Program, range from 18% to almost 98% (Virginia 2015a).

Roanoke has 62 city parks (642.5 ha) and some land associated with National Parks (96.7 ha) but the majority of these greenspaces (72.0%) are highly concentrated around the river (chief site of the railroad) or in the southeastern portion of the city.

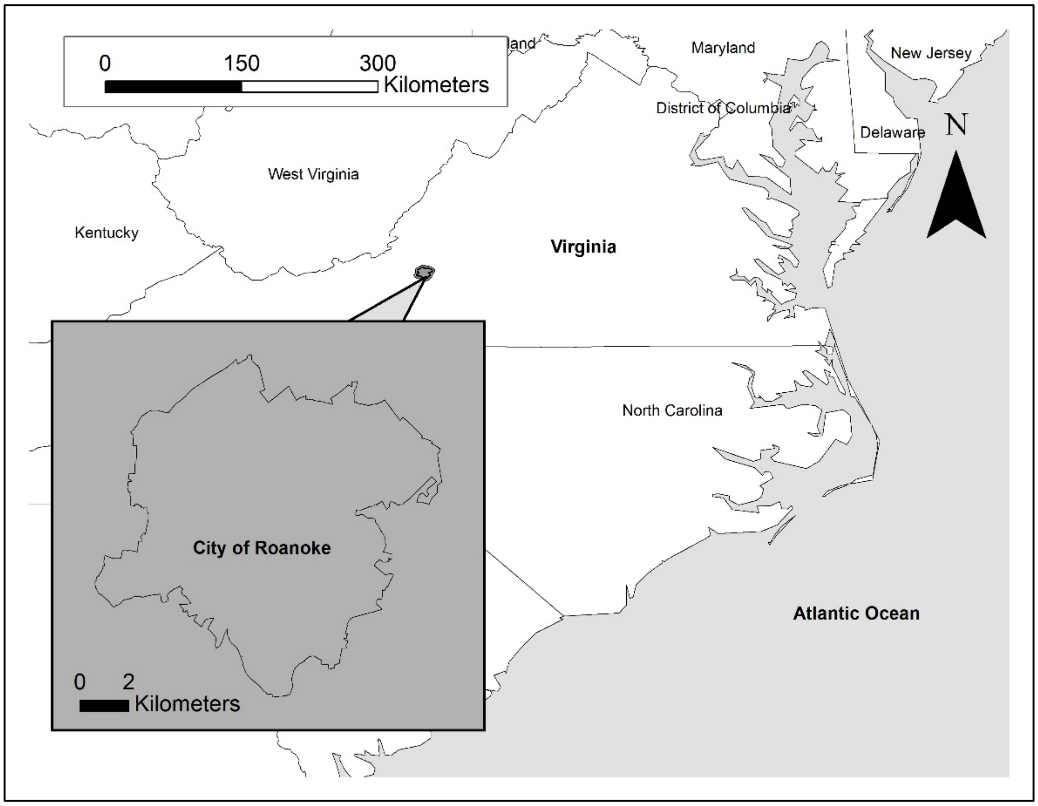

Figure 1 City of Roanoke, Virginia reference map

Table 2 Comparison of City of Roanoke to the surrounding county*, the state and the country

	City of Roanoke	Roanoke County	Virginia	United States
Households below Federal Poverty Level (U.S. Census 2015a)	22.4%	5.1%	11.3%	15.4%
Food Insecurity Rates (Feeding America 2014)	16.9%	8.3%	9.6%	14.3% (USDA 2015)
Eligibility for National School Lunch Program (Virginia 2015a)	67.96%	25.0%	39.67%	42.9% (USDA 2013)

*in Virginia, counties and cities are independent entities

Table 3 Comparison of various health condition rates, City of Roanoke to Virginia (Virginia 2015b)

Health Condition	Rate in City of Roanoke	State Average
Primary hypertension and renal disease	11.2%	7.6%
Chronic liver disease	24.0%	8.8%
Diabetes Mellitus	28.7%	18.5%
Nephritis and Nephrosis	27.6%	18.2%
Heart Disease	222.1*	157.4*
Adult Obesity (Virginia 2015c)	36.0%$^{+}$	27.2%

*per 100,000 people
$^{+}$rate was less than 30% in 2007

Urban agriculture is practiced within the city (17.3 total hectares) in a variety of locations, sizes and forms (home gardens, community gardens and two urban farms) (Figure 3). One urban farm (Lick Run – yellow polygon) is operated by a private citizen. The largest of the two urban farms (Heritage Point Farm – blue polygon, 7.1 ha), located in the northeastern part of the city in an industrial park, is operated by the Roanoke Natural Foods Co-op. The most common urban agriculture form - home gardens (red polygons) - are distributed throughout the city with notable voids around the airport, the railway complex, the aforementioned industrial park, two very large city parks - Mill Mountain and Yellow Mountain, and in inner-city residential areas. Community gardens (green polygons) are sited in these inner-city residential areas lacking home gardens.

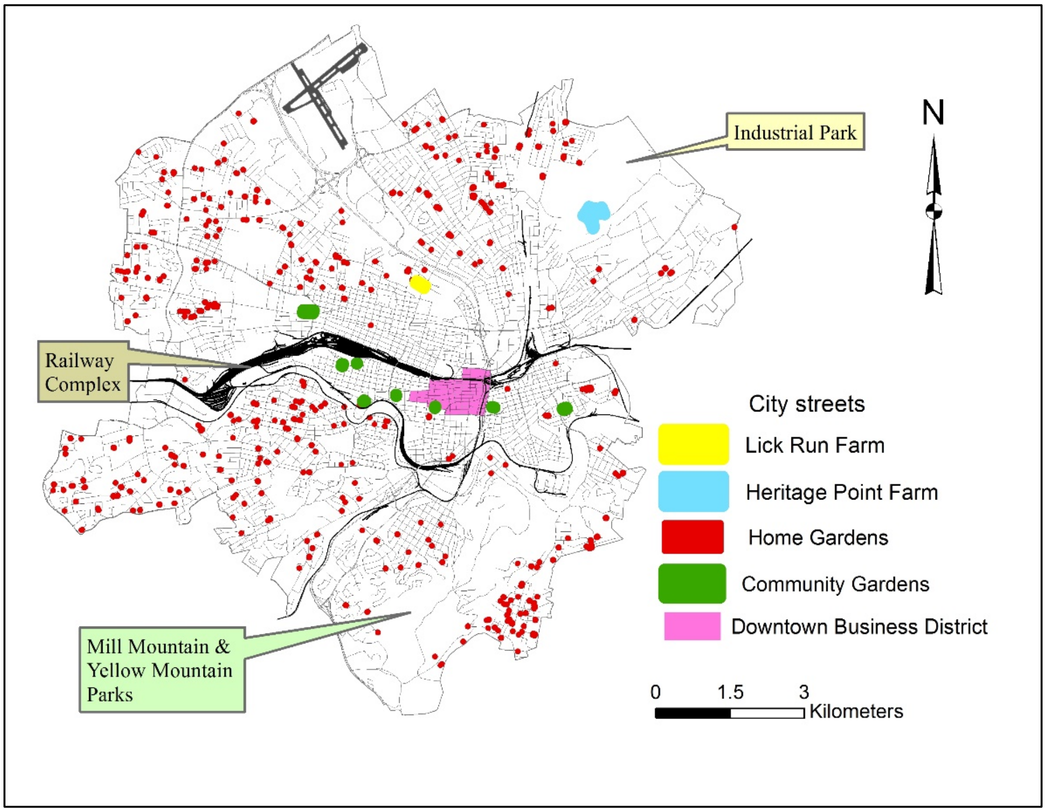

Figure 2 Locations of existing urban agriculture within the City of Roanoke (polygons are enhanced for visual reference only and do not represent the size of the garden) (shapefile for urban agriculture sites was created by first author)

Data

For this analysis, we used geographic information systems (GIS), examining demographic and geospatial data acquired from publically available sources, and from our first-hand, on-site observations as described under *Methods*. Our spatial unit of analysis is the census block group, subdivisions of census tracts and a common spatial unit for analyzing socio-economic data in most areas of the world. Using block groups as the spatial unit for our analysis provides for finer-scale examination, comparable with the scale in other studies of urban demographics. A shapefile for block group boundaries was downloaded from TIGERLine® website (https://www.census.gov/geo/maps-data/data/tiger-line.html).

Income, education, type of household, and employment status are indicators of socio-economic status, at both fine (e.g. an individual or household) and broad scales (e.g. a city or country) (Robert and Reither 2004). The U.S. Census Bureau computes poverty status for households, so instead of income level, we used household poverty status. We feel that household poverty status is a more appropriate income variable than income alone because poverty rates include the number of household members in its calculation (U.S. Census, 2015a). Poverty status records document total number of households within each block group, and also divides households into different types, e.g. couples, male-headed only, female-headed only, and notes the number of households within each group that are at or below the federal poverty level. Records of educational level (called *educational attainment* by the U.S. Census Bureau) contain data for total population - age 25 and older, along with subdivisions - male and female, and different levels of educational attainment - no high school diploma, high school diploma, bachelor's degree, etc. Employment status records contain total population over 16 years, total population in labor force over 16 years, and total population over 16 years not employed.

In addition to the above data, we obtained population data, subdivided to represent male and female, population by age group, and by means of transportation to work. The last decadal census was completed in 2010, but the U.S. Census Bureau has updated their summary profiles for the 5 year period 2009 – 2013 (U.S. Census 2015c), which we used for this analysis. Data for all variables listed above were obtained from the American Fact Finder website as a spreadsheet file (http://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml).

Health condition information is not available at a scale finer than the city level, but the rate of student eligibility by school for the USDA's National School Lunch Program (NSLP) can represent a proxy for food insecurity and health conditions related to inadequate nutrition (Houston et al. 2013; The Brookings Institute as referenced by Smit, Nasr, and Ratta 2001). This report details the percent of students within each school that qualify for a free or reduced school lunch. This data is available as a spreadsheet file, per school district and by individual school zone, from the Virginia Department of Education website (http://doe.virginia.gov/support/nutrition/statistics/index.shtml). The shapefile for school zones was downloaded from the City of Roanoke FTP website (ftp://ftp.roanokeva.gov/GIS/).

Shapefiles for parks were downloaded from the Virginia Department of Conservation and Recreation (http://www.dcr.virginia.gov/natural_heritage/cldownload.shtml) and City of Roanoke FTP site. Community gardens and urban farms were identified and assessed through personal visits. Retail food outlet locations were defined and evaluated with information from the internet (e.g., addresses of grocery stores, neighborhood convenience stores, fast food stores, etc.), from the city's parcel shapefile, and from our on-site observations (more details are found within the *Methods* section).

Methods

For each census block group (n=76), within GIS, we joined all variables from the spreadsheets downloaded from American Fact Finder. Then for each block group, we calculated the following rates:

- poverty rate (total households with income in the past 12 months below poverty level divided by total households);
- rate of female single-headed households (total female single-headed households divided by total households);
- unemployment rate (total unemployed divided by total population in the labor force);

- percent population age 25 or older with no high school diploma (total of all males and females, age 25 or older, with completed education less than high school diploma divided by total population age 25 or older);
- percent of females without a high school diploma (sum of all females with completed education less than high school divided by total population);
- percent population, in work force, using public transportation to and from work (population using public transportation divided by population in work force); and
- percent population under the age of 18 years (sum of all male and female ages under 18 years divided by total population).

Student eligibility rates by school for the National School Lunch Program was joined to the school zone shapefile (elementary schools (n= 17), middle schools (n=5), high schools (n=2)). We chose the elementary school zones since they are more numerous and student population numbers are less than middle school and high school zones (i.e., are at a finer scale). Elementary schools were selected and exported into a separate shapefile.

We intersected the parks, community gardens and urban farms areas, separately, with the block group shapefile to determine if any block groups lacked either or both of these greenspaces. We did not include home gardens in this analysis since the food produced may not be available for consumption outside the specific residence.

For our food evaluation, we first identified retail food locations from the internet, creating three separate shapefiles – retail food stores (farmer's markets, grocery stores, and convenience stores), large food retailers (supermarkets, superstores) and restaurants (fast food, sit-down, and delis). We either verified these locations from the city's parcels shapefile, using GoogleEarth™, or geocoding the addresses.

We then visited retail food stores and restaurants to evaluate the type of food (and price) available for sale. Instead of a random sample, we chose a specific area of the city as advised by a city official that Roanoke's 'food desert' existed along Melrose Avenue (personal communication, Chris Chittum, Director – City of Roanoke Planning, Building and Development; February 28, 2013). We chose the center-point of this area and created a ½ mile (1.6 kilometers) buffer to identify specific locations within which to evaluate local access to affordable and nutritious food.

Our first visit to this area was to verify the locations identified as noted above. In subsequent visits over a 12 month period, an observational checklist, adapted from the Nutrition Environment Measures Study in Restaurants (NEMS-R) (Saelens et al. 2007) and-Nutrition Environment Measures Surveys in Stores (NEMS-S) (Glanz et al. 2007), was completed to record data on availability of foods and beverages within each location. The checklist included the following food groups, including brand name, size range, price range, and comments: fruit; vegetables; frozen desserts; sugar-sweetened beverages; water; alcohol; grains/baked goods; grain-based desserts; snacks; protein/meats/beans/alternatives; and pre-packaged foods. We noted on this checklist those foods available for sale and in what form (i.e. fresh, frozen, canned, etc.). The goal of the checklist was to assess availability of nutritious foods and beverages, based on the Dietary Guidelines for Americans (USDA 2010) and the U.S. food guidance system, including whole grains, fruits, vegetables, low-fat milk, lean meats/beans/alternatives, and water; and nutrients of concern, such as saturated/solid fats, added sugars, and calories from alcohol. The assessment has been widely used to provide insight and illustrate the *quality* of food available and accessible to individuals within a targeted geographic area. It has also been shown to help predict dietary quality of community residents. Graduate nutrition students were recruited and trained as observers in direct observation; said training was conducted by the second author. The checklist was tested at restaurants and convenience stores within a different neighborhood and modified accordingly. We then compared our results to the main food groups of the US food guidance system (USDA 2010), identifying stores/restaurants that include healthy foods for sale (e.g., fresh fruits and vegetables, whole grain breads, low fat milks and cheeses).

Our final step was to rank each block group to identify locations that would gain the greatest benefits from new urban agriculture sites. For each of the following parameters, we added a field to the block group shapefile's attribute table. Then, using a query within GIS to answer the questions below, adding appropriate value to the field for that specific block group. We used a binary method, ***Yes*** and ***No***, to rate each parameter. For our first six variables, ***Yes*** equates to any parameter that exceeds the national rate (in parentheses for the following variables) and was assigned a ***1***; ***No*** equates to any parameter equal to or less than the national rate as follows, and was assigned a ***0***: 1) student eligibility rate by school for National School Lunch Program (a proxy for food insecurity and health related conditions) (national rate - 42.9%), if any block group contained more than one elementary school zone, we used the school zone representing majority of the land area; 2) poverty rate (15.4%); 3) unemployment rate (5.4%); 4) percent of population with less than a high school diploma (14.0%); 5) percent of female-headed households (19.0%); and 6) percent of children (23.3%).

For each of the following additional parameters, presence within the block group equates to less need for urban agriculture, so *presence = 0*, and *no presence = 1*: 7) presence of a park, 8) community garden or urban farm present, and 9) supermarket or superstore present? For the final variable (10), is the block group contained within the 'food desert' identified by the city official? ***Yes*** *= 1*, ***No*** *= 0*.

We added another field to the shapefile attribute table – *total score*. We then populated this field by adding the binary values (1 or 0) for all variables to produce a ranking of between 0 (no need for urban agriculture's socio-economic benefits) to 10 (the block group demonstrating need across all 10 variables). We used the final two parameters - percent of females with less than a high school diploma, and rates of public transportation use (both rated individually - ***1*** if exceeded the national rate, ***0*** if equal to or less than the national rate) to evaluate any questionable rankings, adding these two scores in separates field of the attribute table.

Results and Discussion

We start with our results for the retail outlet food evaluation. Figure 4 displays the results of our internet search; we identified 192 restaurants (dark gray circles), 144 retail food stores (light gray circles), and sixteen supermarkets or superstores (one each - Walmart, Target, Fresh Market, Piggly Wiggly, Whole Foods; five Food Lions, two Kmarts, and four Krogers) in the entire city. Within the 'food desert' identified by the city official (large circle with bold black border), we located and evaluated seventeen retail stores (including one grocery store, one discount bakery and the rest convenience stores) and eight restaurants; none of the twenty supermarket/superstores were contained within the 'food desert' evaluation area. After our food quality evaluation was completed, four additional stores were opened (three Walmart Neighborhood Markets and an additional whole foods location), for a total of 20 larger food stores (black triangles).

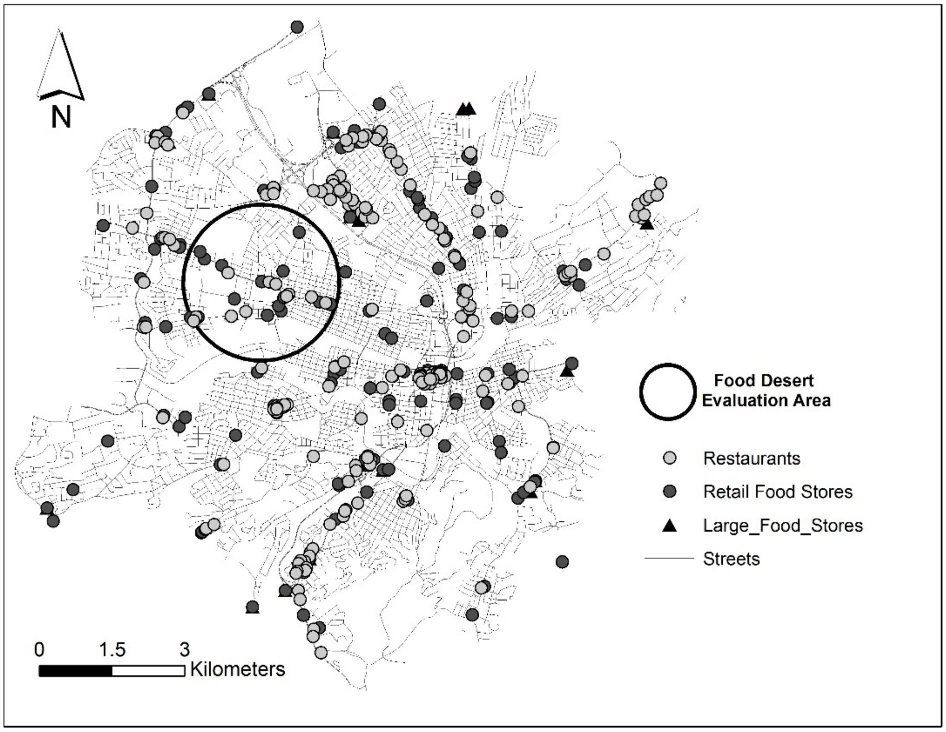

Figure 3 Locations of all food stores and restaurants in Roanoke, Virginia and the site of our food evaluation (black circle) (shapefiles for food retail locations and 'food desert' evaluation area was created by first author)

Our evaluation from the modified NEMS-S and NEMS-R, as compared to the Dietary Guidelines for Americans (USDA 2010), verified the lack of sufficient and affordable healthy options, thus confirming the location of the food desert. More specifically -- for the eight restaurants, only one had a salad bar, three had supersize options, four noted healthy options but these were identified as water, non-fried vegetables, low-fat or fat free salad dressings, diet soda, and low-fat or skim milk. Of the seventeen retail stores, very few offered fresh fruits and vegetables (and the selections were limited), and few provided healthy drink alternatives. Table 4 summarizes the selection of more healthy options and Table 5 summarizes the selection of less healthy options, as tallied from the NEMS-S for the seventeen stores. Within our evaluation area, only a small percentage of retail outlets offers healthy options, and the majority offer unhealthy options. We have not included all survey items in this summary, but based it on a similar summary found in Freedman and Bell (2009). While we evaluated only a specific buffer zone around the center point of the 'food desert' identified by the city official, the retail stores and restaurants in a larger radius, or in another area of the city (in the eastern part), the food access for Roanoke appears very closely related to that identified by the USDA (see *Study Site* above) -- most poverty census tracts within Roanoke have limited access to retail outlets selling fresh and nutritious foods.

Table 4 Summary of NEMS-S results for healthy food and beverage options

Food Group from MyPlate*		**Specific Food or Beverage**	**Food Stores Offering Item (%)**
Grains		Whole grain breads	35.3%
Fruit	To be encouraged	Apples (fresh)	11.8%
		Bananas (fresh)	5.9%
		Oranges (fresh)	11.8%
	To be limited	Fruit canned in sugar syrup	88.2%
Vegetables		Leafy Greens (fresh)	11.8%
		Onions (fresh)	17.6%
		Peppers (fresh)	11.8%
		Tomatoes (fresh)	17.6%
Protein Foods		Hot dogs	35.3%
		Low-fat hot dogs	11.8%
		Turkey dogs	5.9%
		Eggs	64.7%
		Beans	70.6%
		Tuna (canned)	64.7%
Milk	To be encouraged	2% or low fat	29.4%
	To be limited	Whole milk	88.2%
100% Fruit Juice		Orange juice only	88.2%

*Based on ChooseMyPlate.gov food categories

Table 5 Summary of NEMS-S results for less healthy food and beverage options

Specific Food or Beverage	**Food Stores Offering Item (%)**
Beer	88.2%
Other alcohol, i.e. wine or mixed drinks	88.2%
Soft drinks	100%
Potato Chips	100%

Canned Pastas	82.4%
Packaged sausage and bacon	76.5%
Candy	100%
Prepackaged deserts – cakes, pastries	88.2%

In addition, most of the elementary schools' student eligibility rate for the National School Lunch Program (NSLP) exceed the national rate; indeed, only two schools are less than the national rate (Figure 5). Moreover, in eleven of seventeen elementary schools, greater than 75% of students qualify for the program.

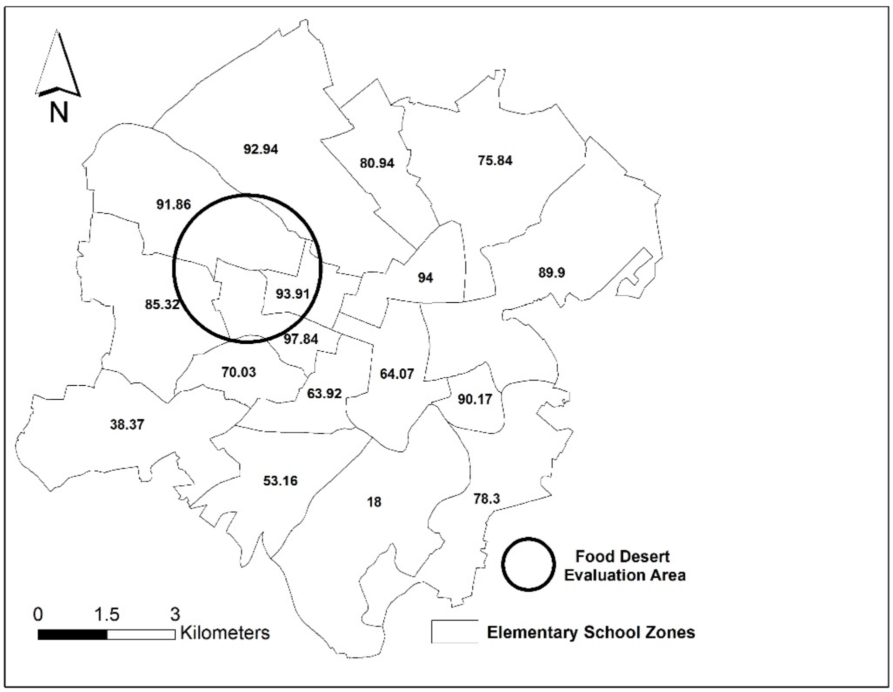

Figure 4. Elementary school zones -- number represents the percentage of students in the school eligible for the National School Lunch Program

For our individual block group analysis (as a reminder, Roanoke has 76 census block groups):

- sixty-four exceed the NSLP national rate -- 42.9%;
- forty exceed the national poverty rate of 15.4%, some have extremely high rates over 35% (Figure 6);

- thirty-two exceed the national rate of female headed-households -- 19.0%;
- forty-six exceed the national unemployment rate -- 5.4%;
- forty-six exceed the national rate of people aged 25 or older with less than a high school diploma -- 14.0%;
- in twenty-five, the percent of population that are children less than 18 years exceeds the national average -- 23.3%;
- forty have no park;
- seventy-three do not have an urban farm nor a community garden;
- sixty-five do not have a supermarket or superstore within their boundaries; and
- fourteen block groups were found within the area identified by the city official as a 'food desert', and where we confirmed a lack of healthy and nutritious options from our field data collection using the NEMS-S and NEMS-R.

After adding all binary values, only one block group demonstrated a need in all ten categories; five demonstrated a need in nine categories; nine in eight categories; eleven in both seven and six categories; fifteen in five categories; twelve in four; ten in three; two in two categories; and no block groups had only one or zero qualifications. Figure 7 shows the distribution, from least to greatest need, within the city.

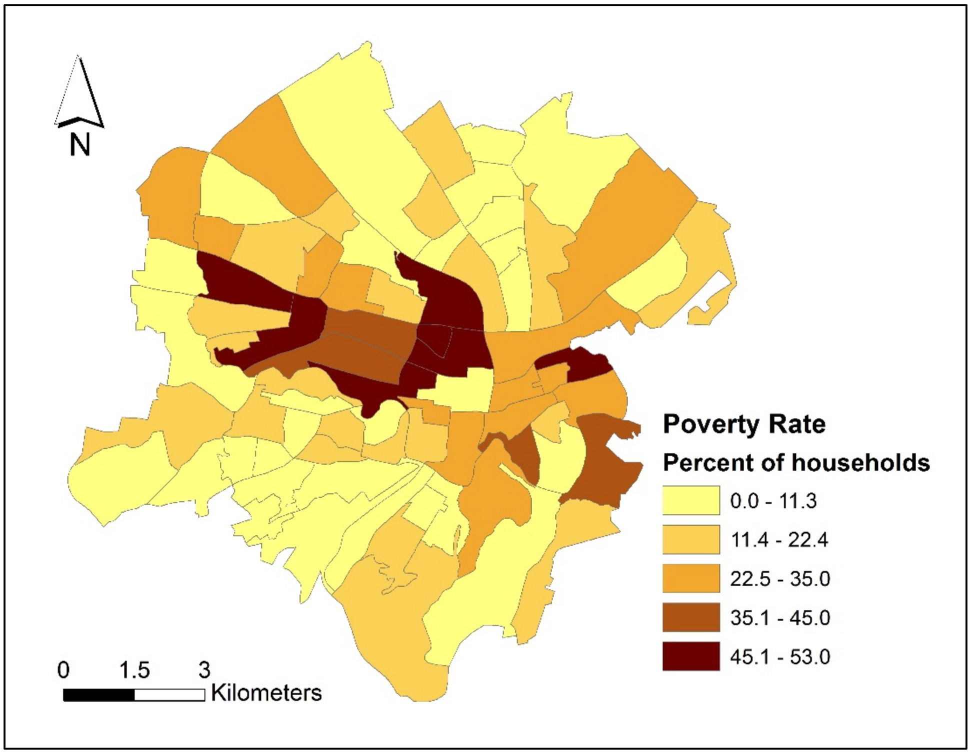

Figure 5 Percent of households, by block group, falling below the federal poverty rate

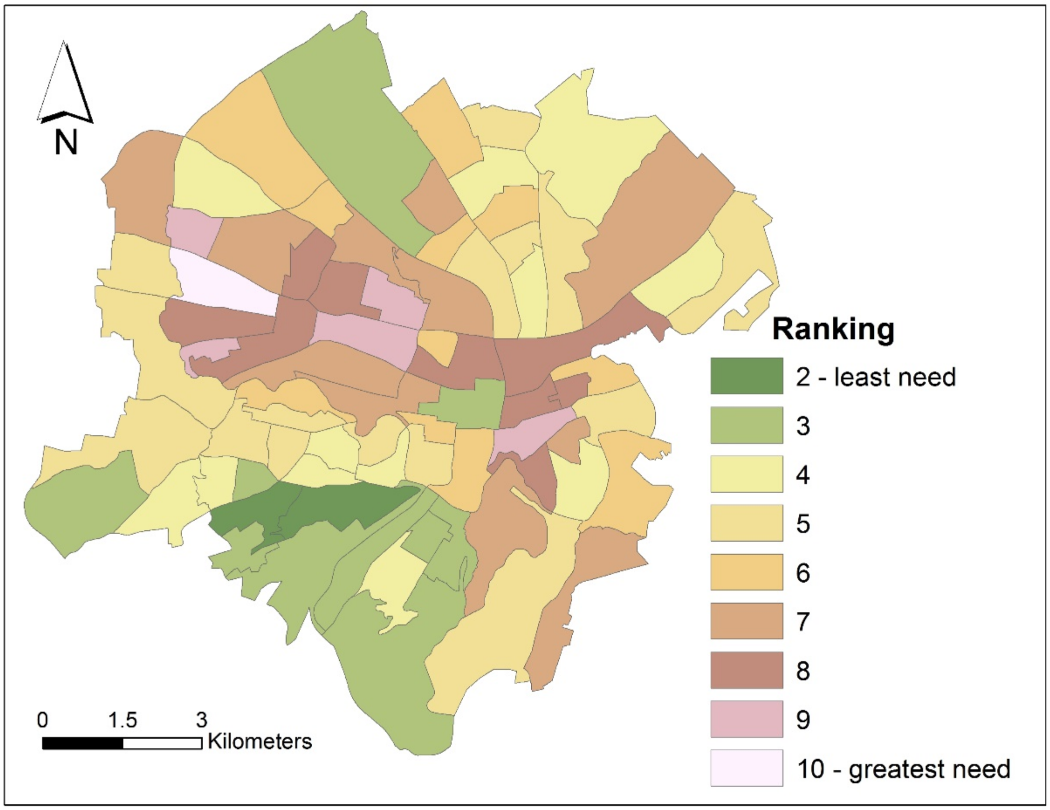

Figure 6 Ranking of each block group (from 2 – least need to 10 for the greatest need) for siting new urban agriculture locations

When we added the additional two parameters – percent of females without a high school diploma and percent of work force using public transportation, neither variable changed our final results, i.e., the order of the block groups did not change. We also looked closely at which variables were highly correlated; less than one-third of the block groups had high poverty rates and high employment rates, whereas over one-third of block groups with high poverty rates did not have a community garden, an urban farm, or a park within its boundaries.

We do note that the divergent time frames of our different parameters may have affected some of our results -- census data was averaged for a five-year period ending 2013, food evaluation was accomplished over a one-year period ending in 2014, our urban agriculture sites are current through 2015. But differences in dates do not concern us, rather when we compare our more recent data to older data, many variables for Roanoke have remained the same or worsened – the average rate of student eligibility by school for a free and reduced lunch under the National School Lunch Program remained the same, rates of obesity increased (see Table 3). Furthermore, one variable not addressed within this analysis - the number of homeless public school students within the city - rose substantially from approximately 386 (in 2012) to over 600 (in 2014) (Jackson 2014).

Conclusions

Many researchers and scholars question urban agriculture's ability to address socio-economic problems (Pollans and Roberts 2014). However, not only is urban agriculture practiced across the world, but research has documented its contribution to provisioning fresh fruits and vegetables, and many municipalities are including urban agriculture into their development and sustainability plans. Municipalities and researchers are preparing and have completed land inventories to identify vacant and under-utilized lands for new urban agriculture greenspaces.

However, referring back to our introduction, these land inventories should start with identifying locations within socio-economic disadvantaged areas and prioritize these locations for urban agriculture projects. Once these areas are identified, then vacant or under-utilized lands within these neighborhoods can be found. After these two steps are accomplished, the job is not done -- physical characteristics must be evaluated, i.e. soil's farming quality, soil contamination, are the slopes too steep, is there access to water, etc. Then, once appropriate sites are identified, the next steps involve local residents in the decision-making process, which would include assessing their desires for a new greenspace, locating, establishing and maintaining of the community garden, farm or orchard, and assessing their abilities to produce and process food.

Furthermore, support through the local-extension services will be needed to provide continuity and promote investment of local residents in ownership of the process.

Siting urban agriculture on vacant or under-utilized lands is necessary to make productive use of these non-productive areas. However, placing urban agriculture on these lands does not address whether or not lower-income residents will have access to these new greenspaces. Our GIS analysis, using publically available data, has explored, quite successfully, a socio-economic assessment as the first step in a land inventory. This social and economic analysis identified locales within the City of Roanoke, Virginia as a hierarchy of sites that will best contribute economic, social, and health benefits for under-served populations. These benefits include assisting in alleviation of food insecurity, supplementing healthy food for low income populations, increasing urban greenspace, providing opportunities for physical activity, and facilitating educational opportunities for citizens. Once urban agriculture has been implemented in such neighborhoods, it offers an opportunity for assessing its contribution to alleviating disparities and its contribution to the health and well-being of urban populations in the context of social and physical infrastructures. Our analysis, as outlined here, can be applied in any urban area.

Acknowledgements

This research was financially supported by Virginia Space Grant Consortium 2014/2015 and 2015/2016 Graduate Research Fellowships. This publication was developed under STAR Fellowship Assistance Agreement No. FP-91769301-0 awarded by the U.S. Environmental Protection Agency (EPA). It has not been formally reviewed by EPA. The views expressed in this publication are solely those of Tammy Erlene Parece and co-authors. US EPA does not endorse any products or commercial services mentioned in this publication.

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17 A Survey of Urban Gardeners

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17.1 Introduction

Across the world, urban landscapes are a heterogenetic mix of vegetation and the built environment, i.e., the ratio of greenspace to man-made structures (e.g., roads, buildings) varies from neighborhood to neighborhood. Frequently, these physical variations are correlated with socio-economic factors (e.g., education, income, assets, etc.) because how and where development occurs is controlled by wealth (Wolch et al., 2005; Ernstson 2013; Anguelovski 2015). As such, an unequal distribution of power exists and decision making processes seldom include people with the greatest needs for jobs, affordable housing, food, and recreational facilities (FAO 2007; Ernstson 2013; Cohen and Reynolds 2015). For example, larger houses, greenspaces, and large retail stores are frequently located in more affluent areas, whereas, lower income urban residents live in more densely populated areas, have less access to healthy and nutritious food, and existing greenspaces are small or poorly maintained.

Advocates of urban agriculture believe that it provides an opportunity to overcome many of the consequences of this unequal power distribution. Urban agriculture helps alleviate widespread food insecurity in lower income populations (Koc et al., 1999; FAO, 2010). It combats poverty through income generation and releasing income to be used elsewhere (Bellows et al., 2003; Draper and Freedman, 2010; Dubbeling, 2010; Hampwaye, 2013; Orsini et al., 2013). Urban agriculture also increases local productive greenspaces and provides a place for residents to congregate to form and strengthen social and community relationships (Patel 1996; Saldivar-Tanaka and Krasny 2004; Drescher et al., 2006).

However, critics of urban agriculture point out many faults with these contentions, especially because it can only provide a small portion of food needed by urban residents (Ellis and Sumberg, 1998; Hallsworth and Wong, 2013). Furthermore, it contributes to marginalization of disenfranchised populations because as soon as it improves a neighborhood, the land becomes more valuable and is reclaimed for development (Draper and Freedman, 2010; Voicu and Been, 2008), or undergoes gentrification and displaces lower income residents (Wolch et al., 2014). Additionally, financial considerations (e.g. start-up costs, delivery to markets, annual fees, and land ownership) are barriers for lower income populations (Brown, et al., 2002; Cabannes, 2012; Lee-Smith, 2010). A risk to human health exists from producing and consuming food grown in degraded environments (Bellows, 1999; Furedy et al., 1999; Gallaher et al, 2013; Wortman and Lovell, 2014), and a risk presents for further environmental degradation from chemicals used in agriculture (DeBon et al., 2010).

Who is right? Does urban agriculture face such a dicotomy? Do answers to these question vary relative to location? Many of the chapters within this book examine these questions, albeit within specific urban areas, e.g., Broadstone and Brannstrom – Houston, TX, USA; Bellwood-

Howard and Nchanki – Tamale, North Ghana; and Hammelman – Medellin Colombia. Within our chapter, we look at urban agriculture from a broader spatial perspective – across many urban areas.

Urban agriculture encompasses many forms, from plants in small containers to farms (Pearson et al. 2010). We specfically look at one form - community gardens - to examine these questions. We handle our examination in the following ways. We first define community gardens and answer the question – do they only exist in the more affluent areas of the world, i.e., the Global North? Next, we review community garden case studies to see if any specific benefits have been quantified. Then, we present methods and results of an on-line 2014 survey of urban gardeners located in many different urban areas across the United States. Finally, we discuss our findings in relation to the aforementioned questions.

17.2 Community Gardens

Community gardens are not new, dating back at least one hundred years (Bassett 1981; Waliczek et al., 1996; Lawson, 2005). In essence, a community garden is a section of land divided into small plots for use by many individuals (or families), each for their own use, usually for food production (Patel, 1996; Brown and Jameton, 2000; Brown et al., 2002; Lawson, 2005). In most cases, each gardener keeps produce for personal use, or for friends and families; infrequently, food is sold, and often excess food is given away (Brown et al., 2002). Community garden members share responsibility for common areas, e.g. paths, structures, tools (Smit et al., 2001).

The land upon which a community garden is located is rarely owned by those gardening. A specific community garden may be owned by landlords, local, regional and federal governments, non-profit organizations, or churches – who have granted gardening access (oftentimes only temporarily) to a community. The form of agriculture (plants only, plants and small animals, or larger livestock) practiced in any particular garden depends on zoning regulations, local, regional, and federal laws, and the consent of the property owner (Goldstein et al., 2011; Hodgson et al., 2011).

Frequently, community gardens are discussed in conjunction with allotment gardens and guerilla gardens, but while all three types are closely related, fundamental characteristics differ. Allotment gardens are usually sponsored and managed by local governments and were initially developed as cultivation sites for the lower income working class (Petts 2001). Allotment gardens are common in Europe (Petts 2001; Andersson 2007; Hardman and Larkman 2014), and Japan (Matsuo 2000). Guerilla gardens, or informal gardens, are opportunistic – the plots are cultivated without permission of the land owner, and are found all over the world but most frequently in the Global South (Hardman and Larkman 2014).

17.2.1 Community Gardens in the Global North and Global South

Community gardens are prevalent throughout the world, but more easily identified in the Global North. Table 17.1 provides an example of numbers of community gardens in select countries within the Global North.

Table 17.1 Numbers of community gardens in a selection of Global North countries

Location	Estimated number	Source
US and Canada	18,000	American Community Garden Association (n.d.)
Australia	579	Australian City Farms and Community Gardens Network (2015)
Japan	3,382	ShiftEast (2010)
United Kingdom	>1,000	Federation of City Farms and Community Gardens (2011)

Community gardens also exist in the Global South, although are more difficult to identify - the term “community garden” may not be used. Table 17.2 provides names of countries and sources that provide information on community gardens located within that country.

Table 17.2 Global South Community Gardens

Location	Organization (Website) or Research Study Author (date)
Africa	The Footprints Network (http://www.footprintsnetwork.org/project/68/Community-food-gardens-KwaZulu-Natal.aspx) Women International for a Common Future (http://www.wecf.eu/english/articles/2013/05/ewa_garden_blikkiesdorp.php) Slow Food Foundation for Biodiversity (http://www.slowfoodfoundation.com/pagine/eng/orti/cerca.lasso?-id_pg=265) Garden Africa (http://www.gardenafrica.org.uk/) Karaan and Mohamed (1998) Bharwani et al. (2005) Wills et al. (2010) Shisanya and Hendriks (2011) Ruysenaar (2013)
Indonesia	Islamic Relief Worldwide (http://www.islamic-relief.org/wells-latrines-and-community-gardens/)
Argentina	Agenda De Ideas: Huertas comunitarias en Rosario Argentina (https://republicavirtual.wordpress.com/2008/05/06/huertas-comunitarias-en-rosario-argentina/)
Perú	RUAF (http://www.ruaf.org/publications/community-gardens-villa-maria-del-triunfo-lima-peru-huertas-comunitarias-en-villa-maria)
Brazil	City Farmer (http://www.cityfarmer.info/2008/01/13/cities-without-hunger-community-gardens-sao-paulo-brazil/)
Haiti, Malawi, Kenya	Muse D.Territories: Développement local et RSE (http://www.musedt.com/lagriculture-urbaine-un-levier-de-developpement-pour-les-bidonvilles-du-sud/)
Phillipines, Zambia and Mexico	Wade (1987)

17.3 Community Garden Research and Case Studies

Urban agriculture research is extensive -- too extensive to summarize here. Several literature reviews discuss community gardens -- (a) those generally on urban agriculture which include community gardens (e.g. ETC 2003; Lesher, 2005; Orsini et al., 2013; Stewart et al., 2013; Hamilton et al., 2014; Mok et al., 2014), and (b) those specifically reviewing community garden research (e.g. Draper and Freedman, 2010; Guitart et al., 2012). Specific case studies accomplished for community gardens have identified many benefits. Table 17.3 outlines a selection of these studies, categorizing each by the benefits identified. Of particular note -- case studies are overwhelmingly surveys, interviews and/or participant observations, and most are limited to one specific urban area or community garden association.

Table 17.3 Benefits identified from a selection of community garden case studies

Benefit	Author (date)
Environmental	
Beautifying neighborhoods	Waliczek et al. (1996); Bleasdale et al. (2011); Hale et al. (2011); Ottmann et al. (2012)
Improvement of degraded land	Wade (1987); Patel (1996); Choo (2011)
Increases diversity of plants or insects	Saldivar-Tanaka and Krasny (2004); Agustina and Beilin (2012); Li et al. (2013); Gardiner et al. (2014)
Environmental education	Pudup (2008); Quayle (2008); Chan et al. (2015)
Economic	
Purchasing local foods	Quayle (2008)
Reduced household expenses	Patel (1996); Karaan and Mohamed (1998); McCabe (2014)
Produced income	Wade (1987); Karaan and Mohamed (1998); McCabe (2014)
Increased property values	Voicu and Been (2008); McCabe (2014)
Health	
Increased exercise	Quayle (2008); Pourias et al. (2015)
Health eating/increased fresh food intake	Patel (1996); Karaan and Mohamed (1998); Armstrong (2000); Alaimo (2008); Quayle (2008); Reynolds (2009); Wills et al. (2010); Bleasdale et al. (2011); Corrigan (2011); Ottmann et al. (2012); Pourias et al. (2015);
Improved mental health, i.e. stress relief or relaxation	Armstrong (2000); Bleasdale et al. (2010); Corrigan (2011); Ottmann et al. (2012); McCabe (2014); Chan et al. (2015);

Learning about food and healthy eating	Pudup (2008); Travaline and Hunold (2010); Bleasdale et al. (2011); Corrigan (2011); Hale et al. (2011); Ottmann et al. (2012)
Social	
Strengthening communities, community building and/or community organization	Armstrong (2000); Pudup (2008); Quayle (2008); Travaline and Hunold (2010); Beilin and Hunter (2011); Corrigan (2011); McCabe (2014); Chan et al. (2015)
Social inclusion, sense of belonging	Quayle (2008); Wills et al. (2010); Agustina and Beilin (2012); Chan et al. (2015);
Promoting community involvement, helping others	Waliczek et al. (1996); Corrigan (2011); Chan et al. (2015)
Decreased crime	Wade (1987); McCabe (2014)
Social networking/interaction	Patel (1996); Armstrong (2000); Saldivar-Tanaka and Krasny (2004); Reynolds (2009); Wills et al. (2010); Bleasdale et al. (2011); Hale et al. (2011); Agustina and Beilin (2012); Ottmann et al. (2012); Chan et al. (2015)
Maintaining cultural diversity	Saldivar-Tanaka and Krasny (2004); Li et al (2013);
Increased self-worth, empowerment	Pudup (2008); Reynolds (2009)
Learning about the community	Agustina and Beilin (2012)

17.4 Survey of Urban Gardeners

17.4.1 Our Methodology

In late 2013, we crafted an on-line survey of 32 questions, presented both in English and in Spanish, using the Qualtrics On-line Survey Platform. We drafted a solicitation email, addressed to principal contacts at community gardens and garden clubs, asking for their assistance in sending the survey link to their members. The first question was the online consent form, which advised survey participants that they could conclude the survey at any time by just closing their web browser. The questions were in three formats – free form text, yes/no, and multiple choice with an option “other” text field. We concluded the survey with optional demographic questions and provided respondents with the ability to opt out of these questions.

To locate community garden contacts throughout the USA, we utilized the American Community Garden Association website’s search engine - *Find a Garden* - with a 161 km radius (100 miles). We chose major cities, e.g. Dallas Texas; Atlanta Georgia, Des Moines Iowa, trying to identify at least one community garden in each state. We then selected community gardens from the resulting list, trying to eliminate any community garden in which the setting was noted as rural, a school garden, food pantry garden, or urban farm. In addition, we searched the Garden Clubs of America – National Map for garden clubs and their email addresses. We then sent out the solicitation email to each identified contact's email address.

We started emails for the survey on 1 February 2014, and monitored the survey platform for responses. When we observed that the response rate remained at zero for at least a week, we sent the solicitation email to new contacts. Table 17.4 provides information on the dates and number of emails sent for each date.

Table 17.4 Dates of solicitation emails, the number of community gardens and garden club contacts to which they were sent, the number of reject messages received, and the number resent to corrected email addresses

Date sent	Number of emails sent	Number of email reject messages	Number of emails resent
1 February 2014	65	11	6
23 February 2014	26	8	2
6 April 2014	49	10	0
4 May 2014	129	3	0

17.4.2 Research Methodology on Specific Community Gardens

From our survey results, we researched information for individually named community gardens, using the specific garden's website or the American Community Garden Association's website. We identified the number of plots or people served, land ownership, date established and any identified benefits specifically quantified for gardeners or the surrounding community.

17.4.3 Survey Results

In most cases, we did not receive any response from the garden contact. However, we did receive positive responses and encouragement from contacts and individual members. In some instances, the contact agreed to send the survey link to their members only if we agreed to share the results -- we responded in the affirmative.

The survey was started 223 times with 177 participants (79.4%) completing all or a portion of the survey; 222 accessed the English version and only one accessed the Spanish version. Thirteen states were represented from the 177 completed surveys (one community garden was named but the location was not identified, and we could not locate it on the internet) (Figure 17.1). Pennsylvania generated the most responses, followed by Kansas, Texas, California, Virginia, Missouri, Florida, and one response each for Iowa, Illinois, Vermont, Ohio, Maine and North Carolina.

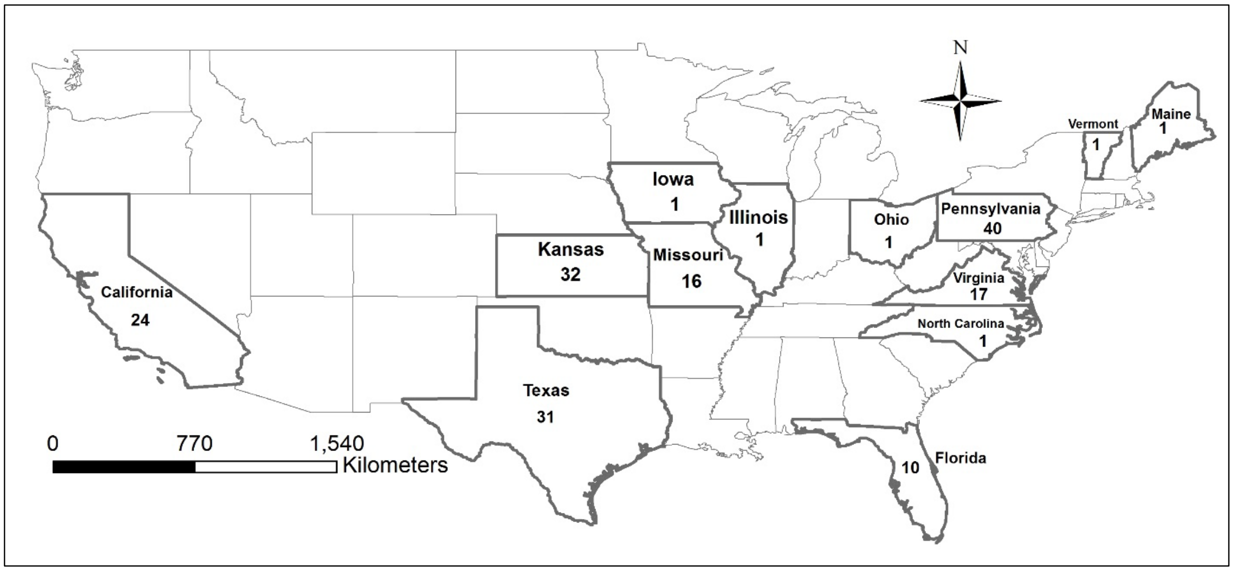

Fig. 17.1 Distribution of survey responses by state (Generated by first author using TIGER/Line® shapefiles for states' boundaries)

In most states, responses came from only one, two, or three cities, but for California and Texas, we received responses from ten and nine different cities, respectively. The community gardens named by respondents, numbered from one to 11 different gardens per state, with several respondents not naming a specific community garden. While we received the greatest number of responses from Philadelphia (40), only five community gardens were represented. Responses from other states constituted a larger number of community gardens – California (11), Texas (ten), Missouri (seven, and one urban farm). All responses from Virginia were from the same community garden. Many of our community garden participants responded that they also gardened at home (details provided below). Our one response from Illinois was from someone who only gardens at home.

For the length of time respondents have been working in the community garden, responses ranged from one month to 34 years. The average number of years across all respondents was one year (n=175; two respondents did not answer this question). Two respondents also reported how long they have been gardening at home - 9 and 45 years. Table 17.5 provides data on length of gardening time, average and range, by state. For those states with more than one respondent, the average length of gardening time was less than five years for four out of six states. Virginia had the greatest average - over 15 years. Our states with one respondent are not included in this table but their gardening time ranged from less than one year (in Ohio) to 20 years (in Vermont).

Table 17.5 Gardening time (average and range in years) by state

State	Number of community gardens named	Average number of years	Range of gardening time (years)
Pennsylvania	4	7.9	1-33
Kansas	1	4.5	1 – 26
Texas	10	4.1	0.25-32
California	11	4.8	0.17-11
Virginia	1	15.9	2-34

Missouri	7	3.9	1-15
Florida	1	2.6	0.4-5

The greatest number of respondents drive to their gardens (47%), followed by walking (41%). Only two of those who noted multiple methods of travel also stated they gardened in multiple locations. The range of travel distance was 10 feet to 20 miles, with an average of 2.2 miles. Three respondents did not answer either question.

Number of family members working in the gardens ranged from only the respondent (n=89), up to 11 (reported by one respondent). The average number of people working in the garden was 1.6 (n=174). The number of hours per week ranged from one hour to 80 hours per week, with an average of six hours per week. For those reporting that they were the only ones working in the garden, the average was 6.3 hours per week. The respondent reporting working 80 hours per week also reported working at a second community garden. Another respondent for this same community garden reported more than 20 hours per week and also reported working at a second community garden.

About half of our respondents reported that they also garden at other locations (50.5%, n=87), including their own backyards, another community garden/public garden/urban farm, their balcony or patio, or another family member's house. Of these respondents, 80% stated they also grew plants other than food (we did not ask for specifics).

The "*why do you garden?*" question was a free-form answer, with 174 respondents providing responses, from "beats watching TV," to several sentences. We reviewed each response to categorize answers under social, economic, environmental, or health categories. Most people provided answers that fit within several categories, e.g.:

> "*Love being outside, watching plants grow, enjoying nature, pleasure of growing my own fresh vegetables organically, sharing with friends and seniors in our community and also visiting with new friends I meet at the garden*" (environmental, social, and health);
>
> *"Its therapeutic, keeps my grocery bill down, its benefits people in my community who need help w supplementing"* (health, economic, and social); and
>
> *"Fresh, free produce, to be connected to the land and the food, to spend time out doors [sic], to teach the children where food comes from, to interact with soil and seasons, to learn more about gardening, to have nutrition, to be healthier and happier"* (economic, environmental, social, and health).

The most frequently stated reason was for health (96.6%, n =168); next environmental (37.9%, n = 66), social (31.6%, n = 55), with economic as the lowest (12.6%, n = 22). Relating the categories of the responses to each state, almost 100% of all states' respondents identified a health reason. Virginia had the greatest rate of respondents identifying environmental reasons (76.5%) followed by Missouri (56.3%). Texas had the greatest rate of respondents identifying economic reasons (25.8%), followed by California (16.7%). The social reason response rate was almost equal for five states – Texas (41.9%), Virginia (41.2%), Kansas (37.5%), California (37.5%) and Missouri (37.5%).

Exactly half of our respondents stated that they eat all the food they produce. For the other half, the majority stated that they gave the food to others, including local food assistance centers (97%), with only 3% either selling it or leaving it on the ground. A majority of our respondents (82%) stated they knew how to grow food prior to joining the community garden, and 65% stated that after they joined the community garden, they have taught others how to grow food.

A majority of respondents (77%) stated they have participated in activities, other than gardening, within the community garden. Their activities usually fell into three different categories – educational, social, or work. Social activities included luncheons, charity fund raisers, pot luck meals, and harvest shows/programs. Work activities included clean-up days, purchasing seeds and plants, plant sales, applying for grants, and other financial duties. Educational activities were the most frequently mentioned, to include programs on tree pruning, composting, building raised beds, raising chickens, starting an herb garden, organic gardening, preparing fresh vegetables for consumption, and children's educational programs.

One of our most comprehensive questions asked participants to identify benefits received from gardening—and to check all that apply. We provided a list, but also a free-form answer field – *other* (Table 17.6). The majority of these responses can be categorized, generally as either health or social, with meeting new people forming the number one answer.

Table 17.6 Benefits identified by respondents

Benefit choice	Number of responses (%)
I have lost weight	19 (11%)
I am eating more fresh foods	121 (68%)
I am eating less sweets	26 (15%)
My diabetes has gotten better	3 (2%)
I stopped smoking	5 (3%)
I feel better	82 (46%)
I am exercising more	79 (45%)
I have more appreciation for being outside	87 (49%)
I have more money to spend on other things	22 (12%)
I use other greenspaces in my city	28 (16%)
Crime has gone down in my neighborhood	2 (1%)
I have earned income from selling food	4 (2%)
I have met new people	142 (81%)
I have made new friends	102 (58%)
I have learned about cultures from outside the US	35 (20%)
I learned how to grow food	65 (37%)
I am now eating healthier	73 (41%)
I have been introduced to new foods and I like them	68 (38%)
Other	Relaxing/peaceful/stress relieving (most frequent), sense of community belonging lower food costs, educational

Our respondents purchase food from a variety of retail food outlets, with a large number purchasing from retail outlets that would be considered to provide healthy options (Table 17.7).

Table 17.7 Retail food outlets where our respondents purchase food.

Type of retail food outlet	Number of responses (percent)
Farmers markets	145 (82%)
Whole food stores	87 (49%)
Organic food stores	62 (35%)
Cooperative food stores	45 (25%)
Local small corner stores	66 (37%)
Large retail grocery stores	121 (68%)
Large retail supermarkets	93 (53%)
Other	24 (14%) specific named stores, international stores, directly from farmers, and multiple places

Yet, after they began gardening, their satisfaction level also varied with regard to food purchased from these locations, with 90% of our respondents noting some level of dissatisfaction (Table 17.8). Our respondents' lack of satisfaction with their food purchases did not limit itself to the local small corner store, or to large retail grocery stores and large retail supermarket stores -- it also extended to those retail food stores that would be considered to have healthy options, e.g. farmers markets, whole food stores, and organic food stores. For those who purchase at farmers' markets, whole foods, small corner and large grocery stores, 90% indicated some type of dissatisfaction with those outlets. For organic and cooperative food stores, 93% expressed some level of dissatisfaction, and for supermarkets 92% noted some level of dissatisfaction. The lowest level of dissatisfaction was 78% in the other category.

Table 17.8 Satisfaction with food from these stores since began gardening

Satisfaction level	Percent of respondents
I love the fresh food that this store sells	10%
I think the food that I grow is better but this store sells good food	40%
The food that I grow tastes better than the fresh food this store sells	35%
The fresh food that this store sells is very expensive	10%
I cannot afford the fresh food at this store	<1%
I won't buy fresh food at this store unless I have no other choice	5%

For the optional demographic questions, 146 respondents (82.4%) agreed to answer the questions, although not all respondents answered each question. The response rate by state (number agreeing to answer the demographic questions divided by the number of respondents to gardening questions) ranged from 70% of Texas and Pennsylvania respondents to 94% of Missouri respondents. All states with one respondent answered the demographic questions.

Most respondents answered they were born in the USA; three were from Canada, two each from Germany and the UK, and one each from Northern Ireland, Brazil, Israel and Estonia.

Most respondents are employed in some capacity (73%), 23% are retired, less than 1% identified themselves as unemployed, and in the other category, people identified themselves as a graduate student, stay-at-home mom, homemaker, disabled, and volunteer. Of those who are employed, only 72% responded that they received fringe benefits from their employer. The majority of our respondents (92%) reported that they owned a car.

For 2013 estimated annual income, the majority (78%) responded that they earned over $25,000 USD. The response rate by state for those in the highest income category (as compared to the total responses by state), however, varied greatly (Table 17.9)

Table 17.9 Percent of respondents, by state, in the highest income category (over $25,000 USD)

State	Percent of respondents in highest income category
States with a single response	100%
Virginia	93%
California	90%
Kansas	83%
Pennsylvania	79%
Florida	78%
Texas	59%
Missouri	53%

For other income categories - 7% earned between $20,000 and $25,000, 3% between $15,000 and $20,000, 5% less than $10,000, and 7% preferred not to provide the information. Of those who were in the lowest income category, none were employed full time, and all but two were from Texas. The two states with the lowest rate in the highest income category (Texas and Missouri) had variable rates in the other income brackets (Table 17.10).

Table 17.10 Income brackets for Missouri and Texas respondents

2013 projected annual income (in US Dollars)	Missouri	Texas
Less than 10,000	7%	22%
Between 10,000 and 15,000	0	0
Between 15,000 and 20,000	7%	0
Between 20,000 and 25,000	27%	14%
Over 25,000	53%	59%
Prefer not to say	7%	5%

Of respondents who reported income in the lowest income bracket, 71% noted an economic reason (among other reasons) for growing their own food, for example - "*lower food costs,*" "*it is nice not having to pay grocery store prices for veggitables [sic],*"*"reducing family food budgets," and "supplement my food supply*."

The type of household varied from single head of household to households with children under 18, households with children over 18 at home, multiple generational, all-adult households, and same sex partner households. We categorized these household as one-member households (29%), family households with children under 18 (15%), family households with children both under and over 18 (8%) and family households with no one under 18 (48%). The majority reported two people in their household (51%) and the total number of people in residence ranged from one to six.

The majority of respondents reported that they do not have children in their household (76%) - earlier we noted that only 23% of our respondents reported that they were retired. For the rest of the households, 13% had one child, 10% had two, and one respondent each had three and four children. For households with children, the average number was 1.6 children per household. In addition, for those households that have children, the average number of people working in the garden increased slightly to 2.2. Income levels for those households with children, 83% were in the highest income category, two respondents preferred not to respond, one respondent was in the lowest category, and two respondents reported $20,000 - $25,000.

17.4.4 Details on Named Community Gardens

Because of the large variation in community gardens, we report data for those with the greatest number of respondents to our survey, to determine if we could provide further understanding of any benefits provided by their community garden.

<u>Manhattan Community Garden, Manhattan, Kansas (n = 32)</u>: The city of Manhattan owns the land but gardens are supervised by the UFM Community Learning Center. Two different sites are available – 9th and Riley Streets (established in 1974) and 1435 Collins Lane (established 2012). Fees for individual plots are on a sliding scale based on income. A total of 260 full and half-sized plots are available, an average size 37.2 m^2. They have social events five times a season and a mentoring program for new gardeners (UFM, n.d.).

<u>Schuylkill River Park Community Garden, Philadelphia, Pennsylvania (n = 28)</u>: The city of Philadelphia and the Fairmont Park Commission own the land and lease it to the Center City Residents Association. The garden was established in 1982, then expanded in 1988. In 2009, the garden joined a program to produce food for donation to local food assistance centers and, in each year 2010 and 2011, over 500 pounds were donated. Plots are leased annually to residents for six years, at which time the gardener must give up the plot to a resident on the waiting list. A total of 70 plots are available, at sizes ranging from 9.3 to 18.6 m^2 (SRPCG, n.d.).

<u>Fort Barnard Community Garden, Arlington, Virginia (n = 17)</u>: The land is owned by Arlington County and managed by the community garden association. The garden was established in 1975 and has 70 plots up to 37.2 m^2. Fees for individual plots are established by the county. Gardeners provide fresh produce to the Arlington Food Assistance Center (Arlington Parks, 2015).

<u>Common Ground NRH Community Garden, North Richland Hills, Texas (n = 13)</u>: The land is owned by the city of North Richland Hills. Established in 2010, the association encourages families with limited income, limited space, or persons with physical handicaps. The garden has 70 plots of 7.4 m^2 each. The association promotes sharing of food with local organizations such as Meals on Wheels (Common Ground NRH Community Garden, n.d.).

17.5 Discussion

We sent emails to 129 different community garden associations and garden clubs. We received responses from at least 39 different community gardens (some gardens were not identified), and thus represents a wide range across the USA. We presented our survey in only two languages, a budget limitation. This may have affected the number of responses, however, only one person accessed the Spanish version, so we feel that the lack of responses due to language barriers is unlikely. More likely would be lack of responses from non-English language speakers because of limited internet access.

Health Benefits: Responses demonstrate that gardeners across the USA believe producing their own food provides health benefits, and offers a wide variety of health benefits, from weight loss to mental health. These positive health responses are further supported by dissatisfaction with purchased food from retail food outlets, even though some outlets provide healthy choices.

Social Benefits: Responses also show that gardeners value the social aspects of community gardens. Most of our respondents listed many social explanations for their reasons why they participate in urban food gardening, e.g. "*community involvement, extra food is donated, social interaction of other gardeners,* and *a catalyst for neighborhood and community development*." Social aspects also show up in the benefits listed by many, e.g. meeting new people, making new friends and learning about cultures from outside the United States. Finally, these social aspects are apparent in a range of community garden activities in which our respondents participate, e.g. "*picnics, opens houses for the community, offering different educational opportunities,* and *potluck dinners,*" each of these items identified by many different respondents.

Furthermore, our survey, and the data collected from the individual community garden websites, clearly shows that respondents are very much aware of the extent of food insecurity in the USA, through sharing their produce freely either with neighbors, or, for the majority, with food assistance programs. In addition, most of the garden associations recognize the need to assist lower income or disabled people beyond just food donations - either through offering a certain number of plots for lower income, sliding scale fees, or garden plots situated to support physical handicaps.

Participation: Responses also demonstrate that a variety of people participate in urban food production – disabled, a graduate student, homemakers, people employed full-time, and retired persons. This variety is also illustrated by the number of years that people have been gardening, from the novice at one month, to veterans of 45 years. Furthermore, this variety is apparent from the broad range of households participating – single person households, nuclear families, multigenerational families, and same-sex families.

Income profile: This variety is not represented in the income categories, nor in the economic reasons for gardening. Most respondents reported earnings in the highest income category, did not identify an economic reason for participating in community gardens, did not identify earning income from selling their produce, nor did they state that food at retail food outlets was too expensive. In addition, the majority of our respondents own cars and many drive to their community gardens. From these responses, we conclude that most of our respondents are middle- to higher-income earners (based on USA standards).

Environmental Profile: We do note the lack of environmental benefits identified by our community gardeners. Most did not list an environmental reason for gardening in an urban area, nor environmental education as one of the community garden's activities. Virginia had the highest response rate for environmental benefits, at 76.5%. Lack of environmental benefits can either be attributed to a failure to identify urban agriculture as a beneficial greenspace, the lack of promotion for urban agriculture's ability to alleviate environmental degradation, or perhaps the lack of connection between humans and the environment. This dimension of community gardening deserves further investigation.

Questionnaire Administration: The questionnaire's free-form text fields allowed for a wide range of answers, which complicated analysis of survey results. For instance, we had to standardize the responses to the first question – *the location where you garden, and if a community garden, its name* – by spelling out abbreviations, and organizing addresses in standard format – street, city, state and zip code. However, we feel the availability of a free-form text field was necessary to give respondents the opportunity to tell us what they wanted to say. This free-form field was especially important when we asked why they garden; respondents were able to give all of their reasons, and we were able to use categories from published literature – social, economic, environmental, and health benefits – to analyze the responses.

Our survey does have some failures. For instance, we failed to ask what barriers or problems any of our respondents faced in food gardening within their urban area, or what additional support that they need, or would like. We only produced the survey in two languages. In the future, we should provide more income categories and a better household identification scheme. We failed to ask if they use chemicals, rainwater, or if they garden organically, this may have added significantly to environmental responses. The community gardens identified by our survey respondents specifically provide opportunities for lower income populations, but our survey failed to capture responses from this segment -- perhaps related to a lack of internet access, a lack of interest, the length of our survey (46 respondents did not progress beyond the on-line consent form), or their focus on important life concerns.

Our survey is consistent with the case studies identified in Table 17.3, which list benefits from case studies for individual urban areas or community gardens. Social and health benefits are the most widely identified by individual gardeners, and our survey shows that these benefits are most highly regarded by urban gardeners. Furthermore, our survey also demonstrates that community gardening is not waxing as the economy is improving as it has in the past, the range in gardening time across all garden sites, from just a few months to decades, confirms its staying power.

17.6 Conclusions

We believe our survey results advance the literature on urban agriculture and community gardens through the number of responses received, and their distribution across the USA. The survey shows consistency in benefits identified, without a difference in spatial distribution. With regards to the specific questions identified in our introduction, neither the advocates nor the critics are 100% correct. A dichotomy does not exist. As McClintock (2014) so succinctly stated "*Urban agriculture alone cannot usher in food justice…Rather than an end unto itself, we should instead view urban agriculture as simply one of many means to an end, one of many tools working in concert towards a unified vision of food justice, and of just sustainability…*" (p. 166).

Yes, urban agriculture can only supplement food supplies, but the community gardens and gardeners in our survey recognize food insecurity and are assisting by providing food directly to food assistance centers. Furthermore, the community gardens represented within our survey also recognize financial barriers for lower income people, so provide support with reduction in fees for garden access, which also directly assists in supplementing the food supplies for those lower income residents that take advantage of this assistance.

Many economic, environmental, and human health benefits arise from all forms of urban agriculture. But community gardens provide an additional level of benefits – social benefits. Community building, interaction, sharing of knowledge, and empowerment are just a few of the social benefits identified in case studies and in our survey. These benefits of urban agriculture represent an integral part of human society, especially in urban contexts where people live and work closely together, and a world where more people increasingly live in urban than in rural areas.

17.7 Acknowledgements

This survey, all documents, emails, and solicitations, was pre-approved by the Virginia Tech Institutional Review Board, IRB No. 14-001. We acknowledge the contribution of undergraduate research assistant, Olivia Jancse, who gathered information on specifically identified community gardens. We would like to thank the Roanoke Community Garden Association for their support and advice in formulating this survey. We would also like to thank the community gardens and garden clubs who forwarded our survey request to their members, and all their members who responded to our survey.

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Irrigating Urban Agriculture with Harvested Rainwater: Case Study in Roanoke, Virginia, USA

Prepared for the book titled “Sustainable Water Management in Urban Environments,” Tamim Younos and Tammy E. Parece (editors).

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Abstract
Considered at the global scale, urbanization forms the principal source of landscape change. Worldwide, urban areas are increasing in size, both in land area and in population, causing losses of vegetated lands, increases in impervious surface cover, and increased demands on existing infrastructure and upon municipal services such as water and waste management. Urbanization, by reducing vegetative cover and increasing impervious surfaces, alters hydrologic cycles by reducing infiltration, increasing runoff volume and rates, lowering groundwater tables, decreasing evapotranspiration, and creating precipitation anomalies. Urban greenspaces are recognized as providing environmental benefits, including reduced stormwater runoff, increased evapotranspiration, and increased sub-surface infiltration which, in turn, raise groundwater tables. Urban agriculture forms a greenspace that can provide these environmental benefits, among others, in addition to contributing to food security for local populations. This chapter provides an overview of urban agriculture and its potential benefits. Then, we provide a case study based upon the City of Roanoke, Virginia, USA. We identify areas of existing urban agriculture using aerial imagery. We discuss land available for potential new urban agricultural sites. From aerial images and city geospatial data, we identify and calculate roof areas that can be used to capture rainwater. Then using precipitation data and equations identified from the literature, we calculated amounts of rainwater that could be harvested to provide irrigation water for these locations. Finally, we discuss reductions that could occur in stormwater runoff and greenhouse gas emissions if harvested rainwater were used instead of municipal water supplies. Additionally, we discuss future research areas for urban agriculture and rainwater harvesting.

Key Words urban agriculture, community gardens, rainwater harvesting, greenhouse gas emissions, Roanoke Virginia USA

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1 Introduction

Humans have modified over 50% of the Earth's land surface [1]. Modifications began thousands of years ago when humans first transitioned from hunters and gatherers to developing the land for agriculture [2]. The first urban areas developed in regions of the world amenable to food production (i.e., fertile soils adjacent to water), e.g. Mesopotamia (4000 BCE – 3000 BCE) and the Indus Valley (2500 BCE – 1500 BCE) [2, 3]. Innovations in the ability to produce and store excess food formed the capacity to sustain growing populations [2].

Worldwide human population first reached one billion in 1804, and then grew exponentially because of enhanced human welfare due to Industrial Revolution, the ability to provide potable water and sanitation services, and innovations in healthcare. Exponential growth is expected to continue with worldwide population to reach 9.6 billion by 2050 [4].

The year 2009 was a significant milestone. Prior to 2009, worldwide, the majority of people lived in rural areas; after 2009, the majority lived in urban areas. The United Nations estimates that the percentage of people living in urban areas will rise to 66% by 2050 [5]. Furthermore, the World Bank [6] predicts that, by 2050, the number of people living in urban areas will actually exceed world population totals in 2000. The proportion of people living in urban versus rural areas varies across the world – an average of 75% for developed countries and 45% for less developed countries. These trends are also predicted to increase -- North America, Latin America and Europe to >80%, Asia to 64%, and Africa to 54% -- all by 2050.

Landscape change due to accelerated urbanization is the most significant land modification occurring in the world today [7, 8]. Although urban areas are increasing in size with respect to both land area and human population [7-9], rates of conversion to urban land uses greatly exceed rates of urban population increases [9]. In developing countries, urban land area increases are largely related to increasing populations. In many areas of the developed world, some urban areas are expanding because of population growth and expansion as people move from urban centers to urban fringes, and coupled with this expansion comes land abandonment of inner cities [10].

Ultimately, effects of urbanization, demographic and environmental across the world, have similar impacts. These effects include losses of vegetated lands, expansion of impervious surface cover, disruption of the hydrologic cycle (reduction in evapotranspiration and ground infiltration, and increased stormwater runoff and flashiness of rivers and streams), increasing demands on existing infrastructures, higher air temperatures as compared to adjacent rural areas, and increasing demands on municipal services such as potable water and waste management [8]. Urban areas must import food, energy, and clean water to meet basic needs of their populations and, as such, adverse effects of urbanization extend well beyond political boundaries [7, 8, 11-13]. In order to prevent these problems from expanding and to mitigate current effects, officials are evaluating and implementing efforts to make urban areas more sustainable. Urban agriculture forms a significant greening effort gaining wide attention because of its ability to mitigate these effects as it simultaneously provides nutritional food for populations [6, 14-17].

In this chapter, we introduce urban agriculture as a functional greenspace and review its potential to assist in efforts to improve urban sustainability. Most specifically, we focus on its potential to reinvigorate the hydrologic cycle by increasing vegetation, increasing infiltration and groundwater recharge, increasing evapotranspiration, and reducing stormwater runoff and greenhouse gas emissions. We start this chapter with a brief discussion on urban greenspaces in general, then we define urban agriculture and discuss its role as a beneficial greenspace, its differing forms and its water needs. We conclude our discussion on urban agriculture with a review of the literature on rainwater harvesting for urban agriculture. Our chapter then focuses on a case study – rainwater harvesting potential for the City of Roanoke, Virginia USA. We review the state of urban agriculture in Roanoke and calculate the potential volume of rainwater that could be harvested and resultant reduction in stormwater flow and greenhouse gas emissions.

2 Urban Agriculture is an Urban Greenspace

2.1 Urban Sustainability and Greenspaces

Urban initiatives to reduce ecological footprints, i.e., the impact of human activities, and move towards sustainability, i.e., include reducing energy use, enhancing water and air quality, and increasing greenspaces. A greenspace is defined as "land that is partly or completely covered with grass, trees, shrubs, or other vegetation" [18]. Greenspaces positively affect health and welfare of both human and wildlife populations residing in urban areas [19-23]. Examples of greenspaces' positive benefits include:

- Generating of ecosystem services [24-26];
- Contributing to biodiversity [21, 25, 27];
- Reducing air pollution and increasing air circulation [21, 25, 27, 28];
- Reducing stormwater runoff, increasing groundwater recharge, and improving water quality [12, 21, 25, 27, 29];
- Reducing the urban heat island effect [21, 25, 30];
- Generating health benefits from environmental improvements and also from increased physical exercise and stress reduction for urban residents [21, 22, 25]; and
- Increasing social interaction and a sense of community among urban residents [21, 22, 25, 31].

2.2 Urban Agriculture

Within an urban area, a greenspace "functions as productive green areas that are able to deliver useful products (wood, fruits, compost, energy, etc.) as a result of urban green maintenance or construction" [25]. Urban agriculture is "the growing, processing, and distribution of food and nonfood plant and tree crops and raising of livestock, directly for the urban market, both within and on the fringe of an urban area" [32]. Urban agriculture is a productive use of green areas, and clearly provides benefits beyond those provided by other greenspaces, for example - contributions to food security through production of fresh, nutritious fruits and vegetables, economic opportunities from selling agricultural products or from releasing income which can be used elsewhere [33, 34], and nurturing a sense of place [35, 36].

Furthermore, although urban agricultural productivity depends upon the same variables as rural agriculture, i.e., soils, length of growing season, water availability, and solar insolation, studies have shown that urban agriculture's output is greater in kilograms per unit area than rural agriculture [37, 38]. Urban agriculture's higher production rates are related to more efficient use of space and water (e.g., using horizontal and vertical spaces, smaller plots), producing crops with shorter life cycle, and multi-cropping [33, 39-41].

Urban agriculture is not a new phenomenon; it has been practiced since urban areas were first established [25]. Urban agriculture history in the United States (U.S.) exceeds 100 years [42], intensifying during periods of national crisis, such as both World Wars and the Great Depression [7, 10, 43, 44]. Today, it is experiencing a revival because of current economic conditions, recognition of benefits of locally grown food, the ability to contribute to urban sustainability, and the potential to alleviate food insecurity in low-income urban areas [10, 43, 45].

Worldwide, one in nine people suffer from chronic malnutrition due to food insecurity [46]. Food insecurity also exists in the U.S. — more than one in ten households suffers from food insecurity [47, 48]. Many of the food insecure people live in urban areas since the majority of people now live in urban versus rural areas. Thus urban agriculture has become a major focus across the world [49], and it's estimated that about 800 million people participate in urban food production [50]. In a study of 15 developing countries, FAO [51] estimated up to 70% of urban households participate in agriculture (the rates vary by country – the lowest percentage, in Indonesia (around 10%) and the highest, in Vietnam (70%)). These percentages increase dramatically (5 – 40 percentage points) when one examines those households in the lowest 20% of average incomes [51]. While urban agriculture covers production of both plants and animals for food, the predominant form is plant production for household subsistence.

2.3 Urban Agriculture's Water Needs

Land availability, access to water and quality of soil are important factors for urban agriculture. The amount of water needed for urban agriculture depends on the type of food produced, but more importantly, upon form and size of production [52].

2.3.1 Urban Agriculture Forms

Urban agriculture ranges in size from micro-gardening (i.e., containers on balconies and patios – Fig. 1), meso-scale (i.e., shared garden plots) and macro-scale (i.e., urban farms) [53]. *Home gardens*, usually identified as backyard gardens, are the most common form of urban agriculture (Fig. 2) [33, 54], and usually involve a household growing food for its own consumption on land area adjacent to their residence [54].

Fig 1. Container garden on a patio in Blacksburg, Virginia USA (photo: first author, 2015)

Fig 2. Home garden in a backyard, Blacksburg, Virginia (photo: first author, 2015)

Community gardens (Fig. 3) are becoming a prevalent form of urban agriculture all over the world [54, 55], and are broadly defined as a community of people, sharing a relationship, cultivating an area of land. Each community member gardens an individual plot, and shares in maintenance of common areas. In most instances, the land is owned by an entity (local governments, churches, non-profit organizations) which allows the community to use the land for gardening [44, 54, 56]. The broad heading of community gardens can also include allotment or non-commercial gardens [54] and schoolyard gardens [31].

Fig 3. Day Avenue Community Garden, Roanoke, Virginia, USA (photo: third author, 2015)

Urban farms (Fig. 4) are the largest (in areal extent) of all urban agriculture forms [33], with an identifying characteristic as a for-profit business. This urban agriculture form can include greenhouses, orchards, rooftop gardens, and community-supported agriculture, usually owned by a family or commercial operation.

Fig 4. A Portion of Heritage Point Urban Farm, Roanoke, Virginia USA (photo: third author, 2015)

Each of these various forms does have specific characteristics, as briefly described above; however, these characteristics are not exclusive to each. For example, people gardening in containers on patios, balconies and home gardens may sell their products for profit. Orchards can be planted by municipalities for harvesting and consumption by local residents, and some urban farms exist as parts of non-profit food banks.

2.3.2 Water for Urban Agriculture

While urban agriculture is touted as a greenspace that should be included as part of urban sustainability planning, in most cases, potable water is often used for plant and crop irrigation (Fig. 5). However, with urban areas expanding, continued use of potable water for agriculture presents many obstacles — competing demands for urban water, lack of available water resources, especially in arid or semi-arid regions; and escalating costs [52]. Aiming to quantify the exact demand on municipal water supplies for expansion of urban agriculture in four Australian cities, Ward et al. [52] estimated water demand for a theoretical garden using water requirement and actual crop yield information from rural agriculture. They noted that household water demand would increase significantly, along with overall household expenses, and therefore alternative sources of water for urban agriculture should be considered. In addition, FAO [51] recommends targeting two research areas for urban agriculture water use – (1) reusing treated or partially treated wastewater, and (2) harvesting rainwater. Chapter 'Urban Wastewater Use for Sustainable Urban Agriculture in Developing Countries' (of this book) discusses uses of wastewater in the context of urban agriculture, so we do not discuss that topic here.

Fig. 5 Potable water supply for Growing Goodwill Community Garden, Roanoke, Virginia USA (photo: third author, 2015)

Rainwater harvesting collects water runoff from impervious surfaces, and in some instances, flood waters during rain events. Impervious surfaces can include rooftops, roads, and parking lots. Throughout existing urban agriculture literature, many authors cite uses of rainwater harvesting for irrigation purposes (e.g. [33, 57, 58]), yet scientific studies of rainwater harvesting for urban agriculture use are sparse.

The few studies identified on this topic vary in design and purpose, usually related to specific study sites characteristics. Three such studies are summarized here:

Lupia and Pulighe [59] performed a similar urban agriculture water need assessment as [52] above, but quantified water demand for existing home gardens in Rome, Italy. They also calculated rainwater volume that could be harvested and used as irrigation water for these home gardens. Lupia and Pulighe [59] outline procedures for calculating rainwater harvesting potential similar to what we discuss later in our case study, *Section 3*, below: rainwater harvesting from roof areas of adjacent buildings, calculating rainwater volume, and using a constant to represent the rainwater losses due to splash and evaporation. Their study estimated that (with the exception of vineyards and olive groves) harvested rainwater from roof areas would be adequate to meet water needs for all existing home gardens in Rome.

Redwood et al. [60] conducted a cost/benefit analysis of actual rainwater harvesting and greywater use (not discussed here) for urban farms in Tunisia, an arid region, and a region where recent political instability has disrupted outside food supplies. The study first evaluated the efficacy of a rainwater harvesting system, using a local school as the test site. Rainwater was collected from rooftops and greenhouses via pipes leading to a storage tank. The collected water was then pumped to greenhouses as irrigation for crops produced outside of the normal growing season. Their analysis revealed that installing such systems would create economic benefits for local urban farmers. The authors also conducted a survey of 150 urban farmers, revealing that most relied on their food production to feed their families, and more than half earned income from selling their products. Most importantly, the survey revealed that during an economic crisis, when other urban residents lost income and faced food shortages, urban farmers were able to continue to feed their families. The rainwater harvesting system was subsequently installed at 20 urban farms. Evaluation of these systems is continuing.

Richards et al. [61] constructed two vegetable raingardens (one lined and one unlined) for sub-irrigation systems, and prepared two control vegetable gardens using surface irrigation at the University of Melbourne, Burnley Campus (Australia). The objective of study was to evaluate differences in yields and the need for additional irrigation during dry periods over an 18-month period. Rainwater was harvested from a nearby roof and delivered via a pipe to raingardens where 2/3 of the harvested rainwater was directed to the vegetable gardens and the remaining 1/3 was stored in a tank for use as supplemental irrigation water. Results show that the lined raingarden needed no additional irrigation during dry periods but the unlined raingarden and the two control vegetable gardens did require more water. Production yields were comparable, except during the winter growing season, but more importantly, the raingardens reduced the volume and frequency of runoff by more than 90%.

All three rainwater harvesting studies described above use only rainwater harvested from rooftops. It's suggested that rainwater runoff from impervious surfaces such as roads, sidewalks and parking lots should be avoided in urban agriculture systems. Studies have shown that runoff from these impervious surfaces often contain contaminants such as heavy metals (common pollutants from motor vehicles); polycyclic aromatic hydrocarbons (PAHs) – contaminants originating from tires, fuels, and road surfacing materials; and biological pathogens such as fecal coliform and *Escherichia coli* originating from animal waste [57]. These contaminants present human health risks to those consuming food produced, and to urban gardeners working in contaminated soils [62-66].

3 Case Study

This section of chapter describes a case study on rainwater harvesting potential for existing and potential urban agriculture sites within the City of Roanoke, Virginia, USA. The first segment provides background information on study site. We then discuss data needs for input into the three equations that calculate (1) rainwater harvesting potential, (2) energy savings from not using municipal water supplies for irrigation, (3) reductions in stormwater runoff, and (4) reductions in greenhouse gas emissions. We next discuss methods used to identify locations of existing urban agriculture sites, new potential urban agriculture sites, and locations suitable for harvesting rainwater. Lastly, we provide study results for site identification and calculations.

3.1 Study Site

The City of Roanoke, Virginia USA, the largest city in southwestern Virginia (Fig. 6), is 111 km^2 with a population of 99,428 [67]. The city's land use and commercial sectors is influenced by its history as a transportation hub for rail and road traffic and supporting services and industries. Additional activities include finance, distribution, trade, manufacturing, and healthcare facilities. Roanoke City area contains 642.5 hectares (ha) of parks and 96.7 ha of U.S. National Park Service land. Its major land covers include 47.9% tree canopy [68], 31.9% impervious surfaces (as calculated by first author using geospatial analysis) and the remaining land cover comprised of water, grass, bare earth, and some agriculture.

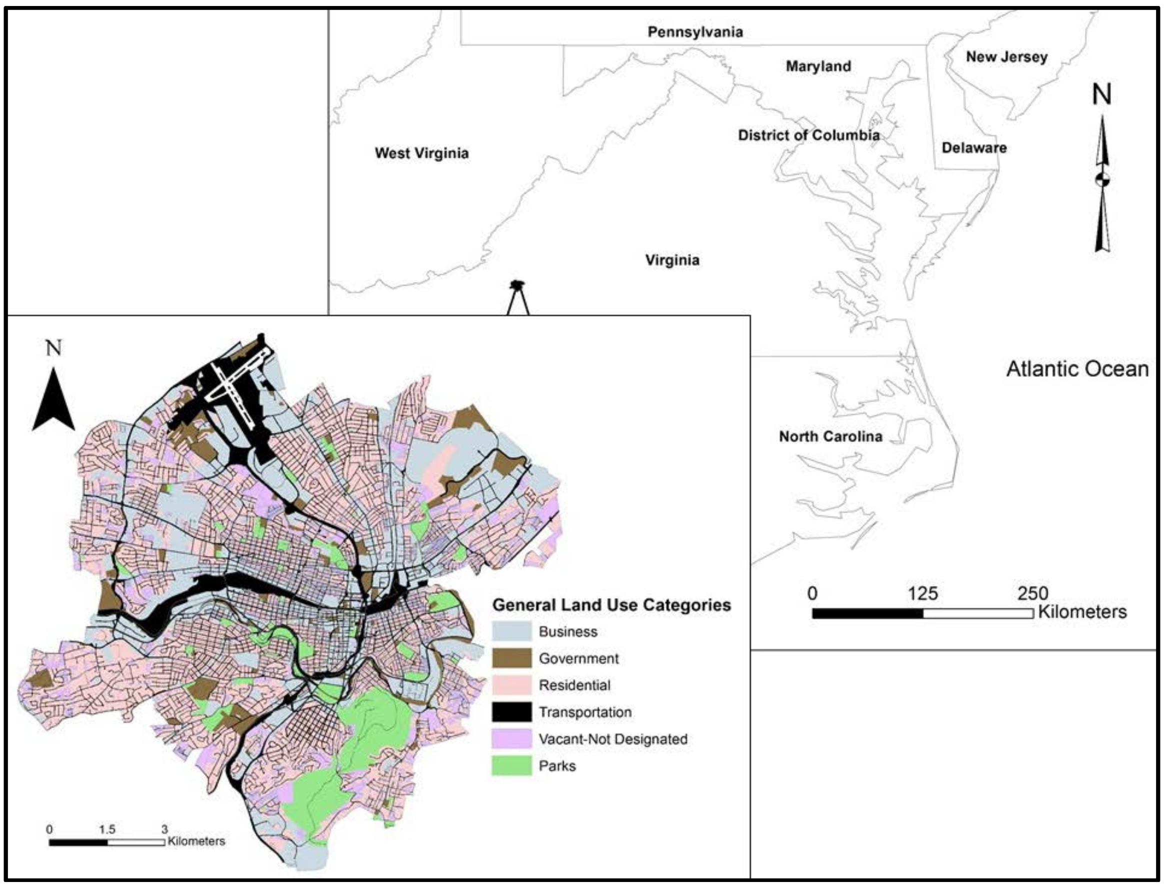

Fig. 6 Roanoke Reference and Land Use Map (*Source*: City of Roanoke Parcels Shapefile, 2015 as processed by first author)

Although, Roanoke has significant amounts of greenspace (tree canopy cover and park land), annual greenhouse gas (GHG) emissions from the city are estimated at 2,076,700 U.S. tons (~ 1.9×10^9 kg) of CO_2 for 2012 [69]. In addition, the city is frequently flooded because of its proximity to the Roanoke River and which is further exacerbated by urban stormwater runoff (Fig. 7). Many segments of the Roanoke River and tributaries flowing within the city are listed as impaired due to contaminants such as *E. coli*, high water temperatures, and heavy metals exceeding Virginia's water quality standards [70].

Fig. 7 Example of flooding (from stormwater runoff) on a major thoroughfare - US 460/Orange Avenue (downtown Roanoke is seen on the right behind the overpass) (*Source*: Public Domain, 2013, image obtained from Roanoke Civic Center Facebook site no longer in use)

The city population is supplied by a variety of water sources (Table 1). Electricity consumption for providing public water varies by water source (Table 1). Carvins Cove Reservoir's electricity use is significantly less than U.S. average as its drinking water treatment plant uses conventional water treatment methods (coagulation/sedimentation and filtration), and the city located is downhill from the reservoir which is located in the mountains northwest of the city. However, within the city, approximately 25% of Carvins Cove water is pumped uphill to some residential areas, increasing energy use about four-fold [71]. Crystal Spring uses a micro-filtration with a disinfection system which is an energy-intensive water treatment process. Spring Hollow uses a newer filtration system with less chemical use, but such systems have much higher energy needs [71]. Appalachian Power Company, Inc. provides energy for the Water Authority, the city and residents [71]. Fuels used for energy generation are coal (75.6%), natural gas (14.2%), and hydro (10.2%) [72].

Table 1 Electricity consumption versus water source [71]

Water Source	kWh/million gallons	kWh/cubic- meter
Carvins Cove	306.7 (75% of customers)	0.081
Reservoir	1306.7 (25% of customers)	0.345
Crystal Spring	1751.4	0.463
Spring Hollow	5726.4	1.513
Falling Creek	Unknown	Unknown
Private Wells	unknown	Unknown

Roanoke receives an average of 109.7 cm (43.2 in.) of precipitation per year [73]. Total rainfall per month is fairly uniform throughout the year, with just slightly more during the months of May – September, most of Roanoke's growing season (Table 2).

Table 2 Precipitation (cm) by month for Roanoke, Virginia, June 2014 – May 2015 [74]

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Year	2015	2015	2015	2015	2015	2014	2014	2014	2014	2014	2014	2014
Cm	7.4	7.3	8.8	8.6	10.3	9.7	10.3	9.0	9.9	7.3	8.6	7.5

Roanoke's urban agriculture scene includes community gardens, home gardens, and urban farms operated by two local food organizations. The Roanoke Natural Foods Co-op operates one urban farm at Heritage Point (Fig. 4) in northeast Roanoke and two local natural foods stores. The farm's land, purchased by the Co-op in 2012, approximately 10.1 ha, is located near an industrial park [75]. The second urban farm, Lick Run, is located at the site of a defunct nursery within a residential neighborhood. It was purchased by a private citizen in 2010 with the intention of starting an urban farm and farmer's market; portions are now under cultivation (Fig. 8).

Fig. 8 Lick Run Urban Farm and Community Market, area under cultivation in photo on left, farm house in photo on right (photos: third author, 2015)

The Roanoke Community Garden Association (RCGA) (established in 2008) cultivates several locations. Members of RCGA are environmentally conscious, as all gardens are organic and incorporate rainwater harvesting at most locations (Fig. 9). MountainView Community Garden (established 2013), and Growing Goodwill Community Garden (established 2014) are the most recent gardens. Land for MountainView is owned by the City but leased to RCGA for five years; food production started in 2014. The newest garden, Growing Goodwill Community Garden (Fig. 5), is located on property owned by Goodwill Industries of the Valleys; food production started in 2015 and additional cultivation plans include a food forest (i.e., orchard). Many RCGA gardeners (~ 30%) are either refugees or recent immigrants. RCGA plans for future locations across the city, the next to be sited on land owned by a church [76]. RCGA has performed exceptionally well in siting their community gardens to assist with food security in lower-income populations -- all of their community gardens are located in areas with poverty rates that exceed U.S. national and Commonwealth of Virginia averages [77].

Fig. 9 Rainwater harvesting systems at Hurt Park Community Garden, photo on left shows a 1500 gallon (5.7 m^3) barrel to the left of the pavilion; photo on the right shows a second barrel to the right of the pavilion (photos: third author 2013)

Home gardening is practiced within the city; these locations are identified in *Section 3.2 Methods*.

3.2 Methods

For our case study, we intend to show how much rainwater can be harvested for existing urban agriculture within the City of Roanoke, and for potential new urban agriculture sites. Hereinafter, we refer to the potential amount of harvested rainwater as Usable Rainwater Volume (URV).

For calculation of URV, we use the rooftop areas of all structures located within the same parcel as the urban agriculture plot. We used rooftop areas only because of concerns, noted in *Section 2.3.2,* concerning potential contaminants from impervious surfaces on the ground – such stormwater runoff could contain pollutants from vehicle emissions (e.g. roads, sidewalks or parking lots). As noted, contaminants from said runoff could accumulate in soils or crops, thus creating a potential human health hazard.

We also include scenarios for two large existing urban agriculture locations (Growing Goodwill Community Garden and Heritage Point Urban Farm) for which URV calculations include nearby commercial/industrial rooftops. For our final calculation of URV, we perform analysis based upon a land inventory of open areas for potential urban agriculture sites for Roanoke completed by Parece and Campbell [78].

In addition, we will calculate reductions in greenhouse gas (GHG) emissions that would occur from substituting harvested rainwater for irrigation instead of public water supplies. These scenarios not only calculate conservation of water and energy by harvesting rainwater, but also reductions in stormwater runoff that could be achieved.

3.2.1 Important Equations

Variables that are important to our case study include the volume of rainwater that can be harvested, roof-areas of available buildings, amount of energy used to treat and deliver potable water, and amount of greenhouse gas emissions from the fuel source for the electricity generating power plant.

To calculate the amount of usable rainwater volume, from [79], we use the following equation:

URV (m^3/time period) = Roof-Area (m^2) x Average Rainfall (m/time period) x C **(Equation 1)**

The variable C, in Equation 1, is collection efficiency -- usually 0.8 which allows for loss from splash and evaporation [79]. Again, this equation not only estimates rainwater harvesting ability, it also provides the volume reduction in stormwater runoff, and the volume reduction in potable water use.

Using the reduction in potable water use, we can also calculate the amount of energy conserved from not using treated potable water, and the resultant reduction in GHG, two very important factors in improving sustainability of urban areas. These two amounts are calculated from the following two equations ([79]:

Energy Conserved (kWh) = (Potable Water Saving (m^3) x Estimated Energy Use (kWh/m^3)) - Indoor/Outdoor Pump Energy Need (kWh) (**Equation 2**)

CO_2 emissions (grams) = Energy Conserved (kWh) x CO_2 output rate (grams/kWh) (**Equation 3**)

An input to Equation 3, is the CO_2 output rate, which depends on the fuel source for the electricity generating power plant. We are using amounts as reported in [80] (Table 3).

Table 3 Carbon Dioxide Emissions from Electric Power Generation [80]*

Fuel Type	Carbon Dioxide output rate (grams per kWh)
Coal	960.3
Natural Gas	596.0
Petroleum	868.6
Hydroelectric	10.0

*Kloss [80] reports pounds per kWh; we converted to grams per kWh (1 pound = 453.592 grams)

3.2.2 Identifying Urban Agriculture within Roanoke

First, we mapped the locations, using geographic information systems (GIS) software, of both urban farms and all community gardens, using information from the Roanoke Community Garden Association's website, 2011 Virginia Base Mapping Program (VBMP) aerial imagery, site visits to locations, and the city's parcels shapefile.

For home gardens, we examined 2011 VBMP aerial imagery displayed in GIS, creating polygons for each site identified. The VBMP imagery was obtained during early March, leaf-off [81], so it was sometimes difficult to distinguish between a dormant plot (no current crop growth) and a bare tract of land (see left of Fig. 10). So, we also used GoogleEarth™ as a cross reference. The most recent images in GoogleEarth™ are National Agriculture Imagery Program (NAIP) aerial imagery taken in June 2012, thus, for instances of actual urban agriculture, a bare plot in the 2011 March imagery was seen as rows of crops (right in Fig. 10).

Fig. 10 Example of three bare plots in residential areas -- 2011 VBMP aerial imagery (left); the same plots in GoogleEarth™ display of 2012 NAIP imagery (right) clearly show that these plots are cultivated

3.2.3 Identifying Roof Area for Existing Urban Agriculture

To identify the area of rooftop impervious surfaces within each parcel containing urban agriculture, we first intersected the shapefile for urban agriculture with the city's parcel file. Then we used the selected parcels to identify those structures (from the city's buildings shapefile) that were located within each parcel. We verified structures against the same aerial photos used in the home garden identification, to ensure that we had identified all structures; we included houses, garages, sheds, and gazebos.

In a few instances, we measured structures for rooftop areas. Most specifically, neither MountainView Community Garden (Fig. 11) nor Growing Goodwill Community Garden appear on either aerial photos (2011 and 2012) because these gardens were established (2013 and 2014, respectively), after the images were obtained.

Fig. 11 MountainView Community Garden, shed and pavilion (photos: first author, 2015)

Additionally, Growing Goodwill Community Garden has only a shed within its boundaries but is located in very close proximity to one of the Goodwill donation centers (Fig. 12 in the background). As stated under section *3.1 Study Site*, plans for this garden include a food forest, so its irrigation needs reach beyond that of a community garden that raises only cultivated crops. Larger rainwater harvesting systems (such as those discussed in *Chapter 6 – Modern Rainwater Harvesting Systems: Design, Case Studies, Impacts*) could be established for this location. As such, we used both the shed roof area and the donation center's roof area to calculate URV.

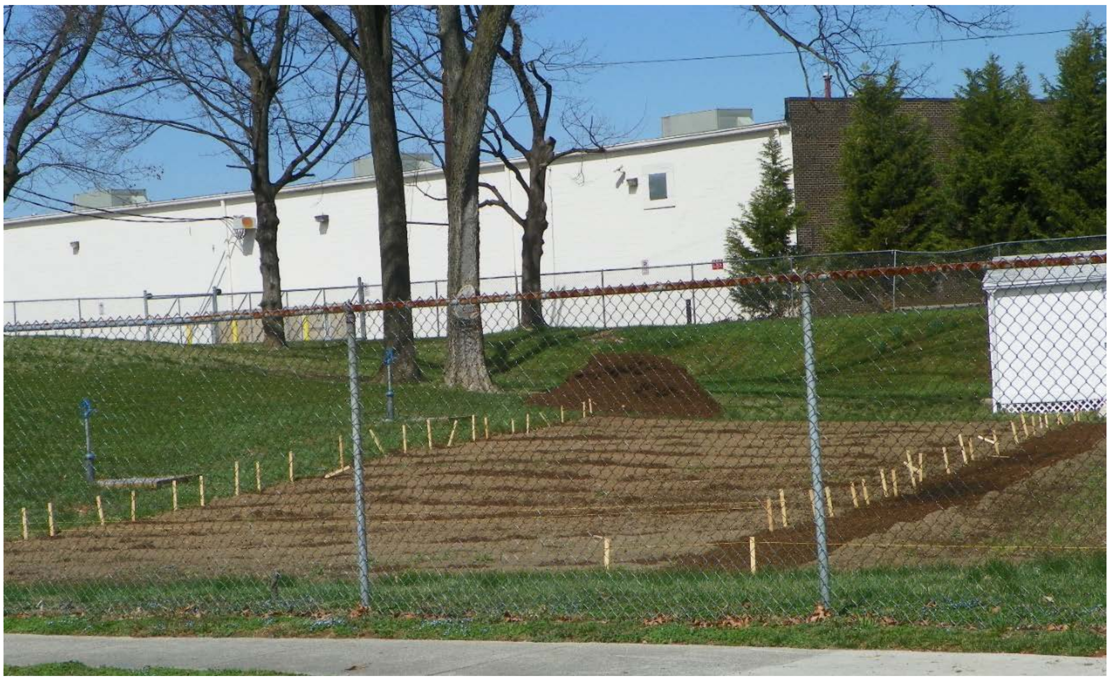

Fig. 12 Goodwill Donation Center (building in the background) near the Growing Goodwill Community Garden (photo: first author 2015)

A similar situation applies for Heritage Point Urban Farm (a very large urban farm of 10.1 ha); irrigation needs exceed what can be generated from harvesting rainwater from roofs of buildings and greenhouses on the farm's premises. But since the farm is located downhill from an industrial park, rainwater could be harvested from roofs of commercial buildings just up the road (Fig. 13). Furthermore, stormwater runoff is actually directed from this industrial park downhill towards the farm, causing considerable erosion on the farm property (Fig. 14). So, if we include the two commercial buildings closest to the farm – a ventilation duct manufacturer and a bakery -- in our calculations –URV will increase and erosion would be reduced or eliminated.

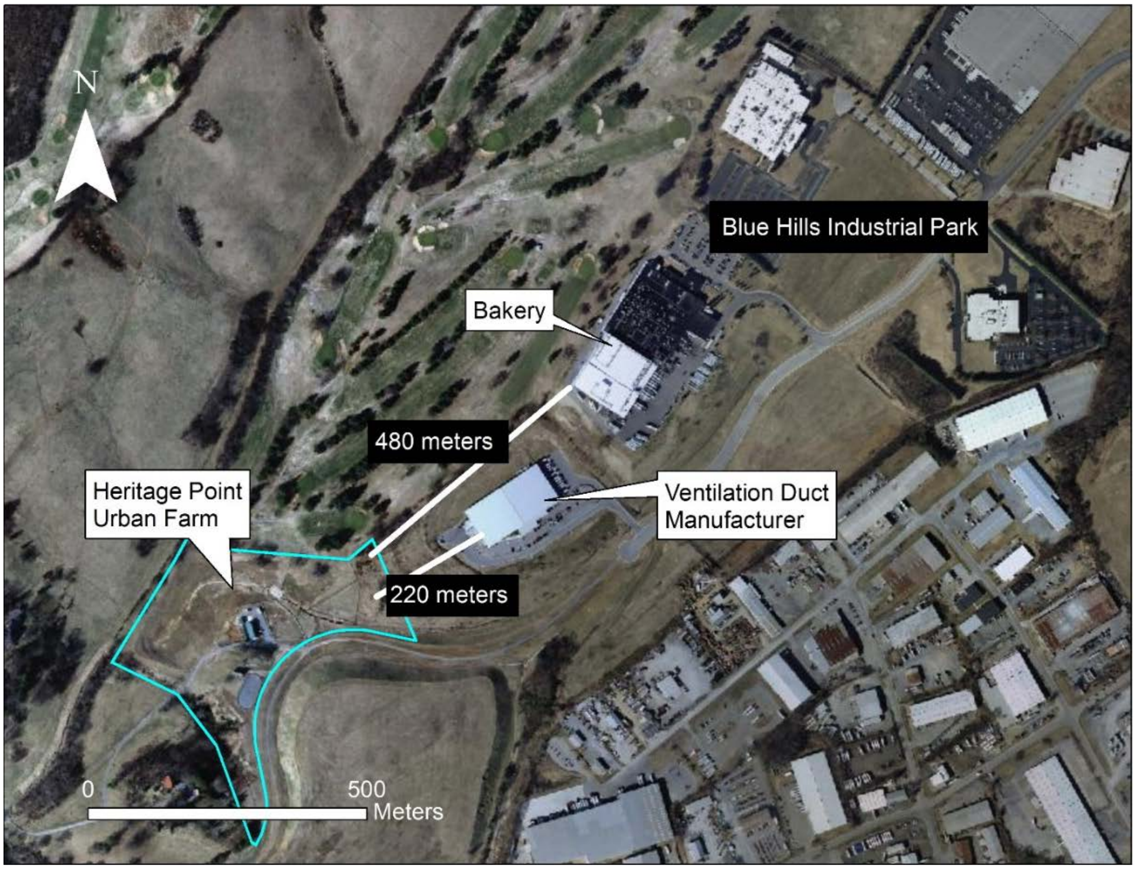

Fig. 13 Heritage Point Urban Farm and distance to commercial buildings within the industrial park (*Source*: VBMP, 2011)


Fig. 14 Erosion on Heritage Point Urban Farm's property caused from unchanneled stormwater runoff from the industrial park's buildings and parking lots (photo - first author 2013)

3.2.4 Identifying Roof Area for Potential Urban Agriculture Sites

For the City of Roanoke, Parece and Campbell [78] completed a land cover and land use analysis to determine if any land was open, available, and potentially suitable for new urban agriculture sites. From analysis, they calculated that 2,311.6 hectares of open areas have potential for home gardens, community gardens, orchards, and urban farms. However, not all of these open areas can be placed under cultivation because portions of land available for urban agriculture would need to be used for access, equipment storage, space for social interaction, and to house rainwater harvesting equipment. In addition, not all locations identified by Parece and Campbell [78] were within parcels that contained structures – many hectares were vacant parcels with no structures -- constituting highway cloverleaves, roadway and median strips, and non-parcel areas within residential neighborhoods.

As such, for this specific analysis, we use a percentage of the potential area (2,311.6 ha) to estimate the roof area from which rainwater can be harvested. To determine what percent to use, we took the total rooftop impervious surface area as calculated under *Section 3.2.2* above (including the commercial roof areas added for the Goodwill Donation Center, the ventilation duct manufacturer, and the bakery) divided by the total area of existing urban agriculture. We used all roof areas as many of the potential urban agriculture locations identified by Parece and Campbell [78] included urban farms and orchard locations that would benefit from a larger volume of harvested rainwater which could be collected from nearby commercial buildings.

3.2.5 Calculating Usable Rainwater Volume (URV)

Using roof areas (in m^2) identified under ***Sections 3.2.3*** and the amount of annual and monthly precipitation amounts (in m) identified under ***Section 3.1***, we used Equation (1) to calculate URV (in m^3) both annually and for the growing season only (April through October), for all existing urban agriculture sites.

Using the roof area (in m^2) identified under ***Sections 3.2.4*** and the amount of annual precipitation (in m) identified under ***Section 3.1***, we used Equation (1) to calculate URV (in m^3) annually for potential new urban agriculture sites.

3.2.6 Calculating Reduction in Greenhouse Gas (GHG) Emissions

To calculate reduction in greenhouse gas emissions related to energy reduction achieved from using harvested rainwater instead of public water supplies for existing urban agriculture locations, we first identified the public water source for each site. To accomplish this, we downloaded the most recent water quality report from the Western Virginia Water Authority [82]; within this document, a thematic map of the city identifies sources providing water for different areas of the city. We georeferenced this map in GIS, using the city boundary and streets shapefiles as references. We then overlaid the existing urban agriculture shapefile on this thematic map and identified each existing urban agriculture site's water source.

We identified the portion of URV (in m^3) for each water source, and using equation (2), calculated the amount of energy that would have been used had the same amount of water originated from the public water supply. Finally, we took the energy use and calculated the amount of carbon dioxide (in kg) for each fuel source (using Equation 3), based on values from American Electric Power (as noted under *3.1 Study Site* - coal (75.6%), natural gas (14.2%), and hydroelectric (10.2%)), and estimated grams per kWh for each fuel source, as noted by [80].

3.3 Results

3.3.1 Locations of Existing Urban Agriculture and Its Water Source

We identified 461 parcels with active urban agriculture within the City of Roanoke - including the two urban farms, all community gardens, and all home gardens (Fig. 15). The Carvins Cove reservoir delivers water for 306 locations, including both urban farms and all the community gardens. Spring Hollow is the source for 32 home garden locations. Crystal Spring is the source for 123 home gardens. Falling Creek is not a water source for any existing urban agriculture.

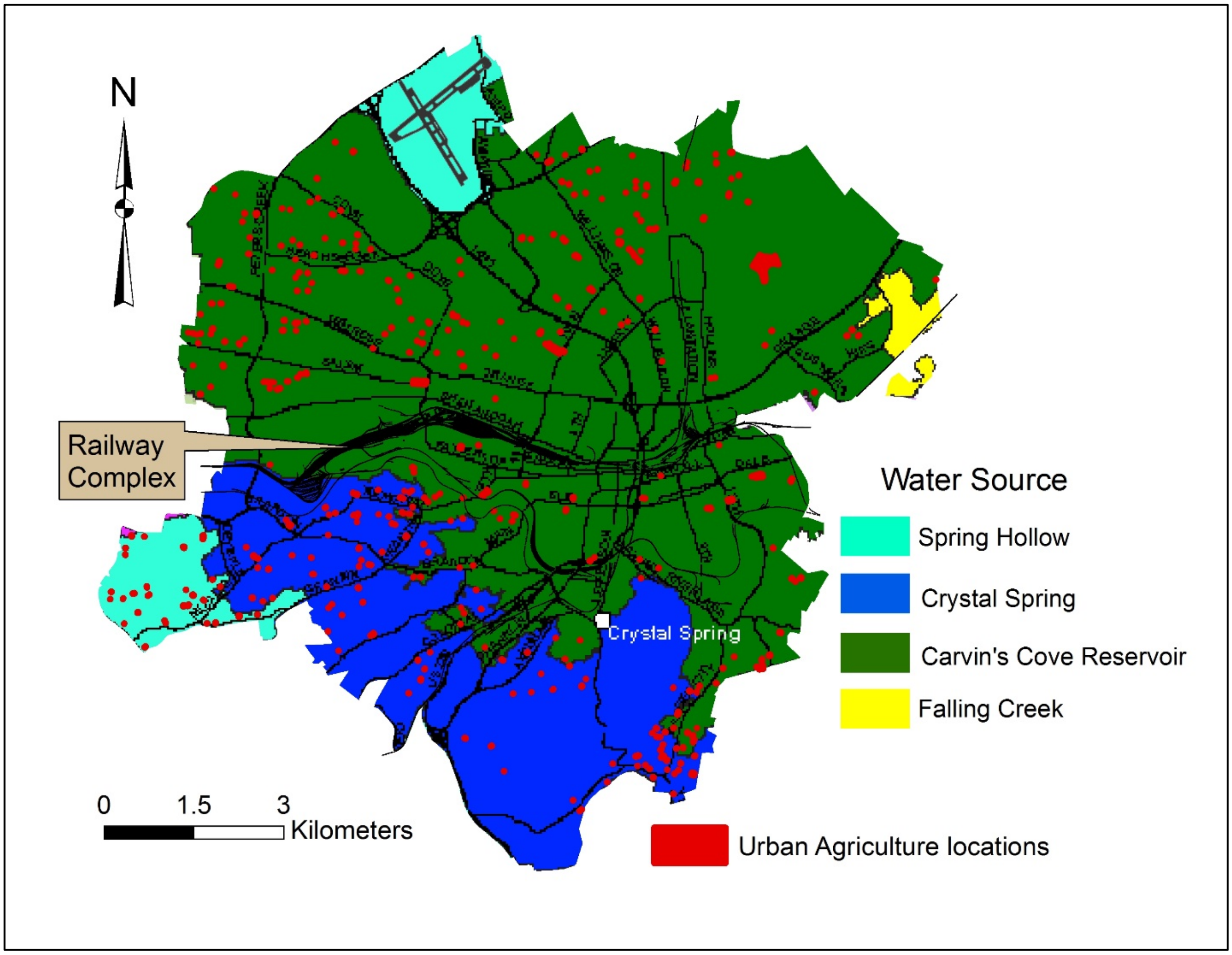

Fig. 15 Locations of existing urban agriculture and their source of water (Source of thematic water source map: Western Virginia Water Authority 2015)

3.3.2 Rooftop Area Used to Calculate Usable Rainwater Volume (URV)

As Table 4 shows, 788 structures were identified within the same parcels that contain the existing urban agriculture locations. This table also provides results of the roof area calculation (81,805.2 m^2), the division of the existing locations and structures by water source, and the total hectares of urban agriculture by water source.

Table 4 Total number of parcels containing existing urban agriculture, total hectares, number of structures, and total roof area (m^2) by water source

Water Source	No. of parcels containing urban agriculture	Area of urban agriculture in all parcels (ha)	No. of structures within each parcel	Roof area (m^2)
Carvins Cove	306	15.6	553	53,854.3
Crystal Spring	123	1.6	184	21,113.0
Spring Hollow	32	0.6	51	6,837.9
Total	461	17.8	788	81,805.2

3.3.3 Usable Rainwater Volume (URV) for Existing Urban Agriculture

For those structures contained within the same parcel as the existing urban agriculture location, Table 5 shows the URV, by water source. If harvested throughout the year, the total amount is 71,792.2 m^3, or if only harvested during the growing season (April through October), the amount is 42,604.2 m^3. Using Crystal Spring, as an example of our calculations and as inputs for Equation 1:

$$21{,}113.0 \text{ m}^2 \times 1.097 \text{ m} \times 0.8 = 18{,}528.8 \text{ m}^3 \quad \text{(Equation 1)}$$

Table 5 URV (m^3) for existing urban agriculture locations by structures contained within the same parcel as the plot

Water Source	Roof area (m^2) (from Table 4)	URV (m^3) Annually (using Equation 1)	URV (m^3) growing season only (using Equation 1)
Carvins Cove (75% of customers)	40,390.7	35,446.9	21,035.5
Carvins Cove (25% of customers)	13,463.6	11,815.7	7,011.8
Crystal Spring	21,113.0	18,528.8	10,995.7
Spring Hollow	6,837.9	6,000.9	3,561.2
Total	81,805.2	71,792.2	42,604.2

Table 6 shows the results for the additional analysis for Growing Goodwill Garden. With only the shed roof area, total annual URV is 15.9 m^3. If we add the roof area of the nearby donation center, the URV amount increases substantially to 88,502.2 m^3. Since orchards are to be included in this area, water need exists for the entire year, not just the growing season.

Table 6 URV, annually, for Growing Goodwill Community Garden

Building	Roof Area (m^2)	Annual Rainfall (m)	URV (m^3)
Shed	18.1	1.097	15.9
Donation center and shed	100,845.7	1.097	88,502.2

Table 7 provides the results for the URV potential for Heritage Point Urban Farm, annually. Since greenhouses and orchards are housed at this urban farm, water need exists for the entire year, not just the growing season. URV for just the roof area of the farm buildings is 410.3 m^3. If we include the ventilation duct manufacturer building's roof area, URV increases significantly by 77,917.2 m^3. If we include both the duct manufacturer's building's roof area and the bakery's roof area, URV increases to 282,639.4 m^3.

Table 7 URV, annually, for Heritage Point Urban Farm

	Roof area (m^2)	Annual Rainfall (m)	URV (m^3)
Farm buildings	467.5	1.097	410.3
Duct manufacturer	88,784.4	1.097	77,917.2
Bakery	232,807.6	1.097	204,312.0
Total potential URV for all roof areas			282,639.4

3.3.4 Usable Rainwater Volume (URV) for Potential Urban Agriculture Sites

Total roof area calculated for the first three scenarios above is 504,710.4 m^2; total existing urban agriculture is 17.8 hectares or 178,000 m^2. Roof area represents 25% of that total area. Potential urban agriculture totals 2,311.6 hectares or 23,116,000 m^2. It is unreasonable to assume that 280% of this area would be available as roof areas for harvesting of rainwater. As such, we will be conservative in our estimate of roof area available for potential rainwater harvesting for new potential urban agriculture sites. Using 25% as the potential roof area within the potential urban agriculture sites, we calculate 5,779,000 m^2 of potential roof area for rainwater harvesting, or a URV of 5,071,650.4 m^3.

3.3.5 Calculations of GHG Emission Reduction

Table 8 shows energy required if potable water, equal to the amount of URV, was used for irrigation. These amounts, within this table, we calculated using Equation 2, e.g., annual URV (from Table 5) for Crystal Spring equals 18,528.8 m^3. Thus, the annual kWh per m^3 for Crystal Spring is 0.463 (from Table 1).

$$8{,}578.8 \text{ kWh} = 18{,}528.8 \text{ m}^3 \times 0.463 \text{ kWh/m}^3 \quad \text{(Equation 2)}$$

Therefore, using harvested rainwater for irrigation, instead of potable water, for the Crystal Spring water source, saves 8,578.8 kWh each year. We did not calculate the energy usage for pumping of harvested rainwater as the energy could be produced using renewal sources such as wind or solar.

Table 8 Calculation of total energy conserved (kWh/m^3) by water source – annually, and for the growing season only

Water Source	URV annually (m^3) (from Table 5)	URV (m^3) growing season only (from Table 5)	kWh/m^3 (from Table 1)	Total kWh annually	Total kWh growing season only
Carvins Cove (75%)	35,446.9	21,035.5	0.081	2,871.2	1,703.9
Carvins Cove (25%)	11,815.7	7,011.8	0.345	4,076.4	2,419.1
Crystal Spring	18,528.8	10,995.7	0.463	8,578.8	5,091.0
Spring Hollow	6,000.9	3,561.2	1.513	9,079.4	5,388.1
Total	71,792.2	42,604.2	----	24,605.8	14,602.0

For all parcels with existing urban agriculture locations and structures within the same parcels, the reduction in CO_2 emissions is 11,851.56 kg for rainwater harvested only during the growing season (May – October) and 19,971.06 kg if rainwater is harvested throughout the entire year (Table 9). These amounts were calculated by using the kWh usage values from Table 8 for each fuel source (as noted under Section 3.1) and the CO_2 emissions per kWh from Table 3, as inputs to Equation 3. As an example:

Total kWh use, annually, for coal is 75.5% of 24,605.8 = 18,602.0

18,602.0 kWh x 960.3 g/kWh = 17,863.5 kg/yr. (Equation 3)

Table 9 Potential reduction in CO_2 emissions (kg) annually and for the growing season only, by fuel source, and in total

Fuel Source for Roanoke (from ***Section 3.1***)	Total kWh annually (Table 8)	CO_2 emissions (kg) annually	Total kWh growing season (Table 8)	CO_2 emissions (kg) growing season
Coal (75.6%)	18,602.0	17,863.5	11,039.1	10,600.9
Natural Gas (14.2%)	3,494.0	2,082.4	2,073.5	1,235.8
Hydroelectric (10.2%)	2,509.8	25.1	1,489.4	14.9
Total	24,605.8	19,971.0	14,602.0	11,851.6

Table 10 provides the CO_2 emissions reduction for Growing Goodwill Community Garden, for the shed roof only, and also if we include the commercial roof areas.

Table 10 Potential reduction in CO_2 emissions, Growing Goodwill Community Garden scenario, each year.

	Shed only	Shed and Goodwill Store

Fuel Source for Roanoke (from ***Section 3.1***)	Total kWh	CO_2 emissions (kg) (Equation 3)	Total kWh (Equation 2)	CO_2 emissions (kg) (Equation 3)
Coal (75.6%)	Negligible		5,420.49	5,205.30
Natural Gas (14.2%)			1,018.13	606.81
Hydroelectric (10.2%)			731.34	7.31
Total	1.29		7,169.96	5,819.4

Table 11 provides the results for Heritage Point Urban Farm, for the farm buildings only. If we include the commercial building roof areas, an additional 5,817.96 kg/yr. and 18,581.49 kg/yr., respectively, of carbon dioxide emissions is reduced.

Table 11 Potential reduction in CO_2 emissions, Heritage Point Urban Farm scenario, each year

Fuel Source for Roanoke (from ***Section 3.1***)	Farm buildings only		Farm buildings, duct manufacturer and bakery	
	Total kWh (Equation 2)	CO_2 emissions (kg) (Equation 3)	Total kWh (Equation 2)	CO_2 emissions (kg) (Equation 3)
Coal (75.6%)	25.12	24.13	17,307.71	16,620.59
Natural Gas (14.2%)	4.72	2.81	3,250.92	1,937.55
Hydroelectric (10.2%)	3.39	0.03	2,335.17	23.35
Total	33.23	26.97	22,893.79	18,581.49

4 Conclusions and Recommendations for Additional Research

Our study shows that, for the City of Roanoke, Virginia USA, a significant amount of rainwater – 442,933.8 m^3/year - could be harvested from adjacent rooftops to provide irrigation needs for existing urban agriculture. This amount also represents the volume of stormwater runoff that could be reduced if we were to use the harvested rainwater for irrigation, a significant volume in light of Roanoke's flooding problems. In addition, this effort would reduce use of municipal water supplies, energy used to provide that water, and emissions of greenhouse gases. Our methods can be used to estimate similar projections for any other urban area, as has similarly been accomplished for Rome, Italy [59].

Our study does not address if these savings are adequate to meet the water needs of urban agriculture, as agricultural needs are highly dependent upon crop type, and timing of rainfall. Estimating Roanoke's water needs for existing urban agriculture is difficult because we do not have knowledge of actual crops grown in an individual plot. Roanoke is located in a water-rich and agriculturally viable area, so the potential diversity of crops produced likely puts such comprehensive estimates for all crop production beyond reasonable capabilities. However, this task will require further consideration when addressing rainwater harvesting abilities of urban areas situated in arid and semi-arid regions.

Additionally, we have used average rainfall rates for the entire city. We should note that urban weather stations are often sparse, unevenly distributed, and that rainfall across a specific urban area can be extremely variable [83]. Thus, the effort to estimate the match between urban agriculture's water needs and availability of usable rainwater volume should be accomplished in the context of urban climatology research. Likewise, our calculations are based on local historical rainfall data and do not consider deviations that may result from climate change. Additional data quantified in conjunction with climate research could be used in identifying the right crops for the right location in order to achieve full agricultural potential.

Studies to quantify potential rainwater harvesting volume are extremely sparse. But, geospatial technologies (i.e. GIS, remote sensing, and GPS), the widespread availability of aerial imagery of world's urban regions, and of climate data allow for identification of existing urban agriculture, available rooftop areas for rainwater harvesting potential, water flows, water sources, and calculation of URV and GHG. As such, these values could be estimated for any urban area, worldwide.

Future research should be based upon implementation of rainwater harvesting systems at a variety of scales (see *Chapter 6 – Modern Rainwater Harvesting Systems: Design, Case Studies, Impacts*), to include control garden plots designed without such systems, measurements of the volume and quality of rainwater harvested, records of the volume and nutritional viability of crops produced from such systems, and reporting of actual empirical evidence of diversion of stormwater runoff from said implementation.

Acknowledgements

This research was financially supported by Virginia Space Grant Consortium 2014/2015 Graduate Research Fellowship. This publication was developed under STAR Fellowship Assistance Agreement No. FP-91769301-0 awarded by the U.S. Environmental Protection Agency (EPA). It has not been formally reviewed by EPA. The views expressed in this publication are solely those of Tammy Erlene Parece and co-authors. US EPA does not endorse any products or commercial services mentioned in this publication.

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An Analysis of the Ecological Impacts of Community Gardens using NDVI

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Submitted for publication and in peer review, 7 January 2016

Abstract: Community gardens are one of several forms of urban agriculture - the growing and processing 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, social interaction and community building, and contributing to sustainability initiatives. Currently, worldwide support for urban agriculture is so well established that many cities now include it as a component of urban planning. Although research on social, community, and nutritional benefits of community gardens is extensive, little can be identified that has quantitatively assessed its environmental benefits, and none has applied Normalized Difference Vegetation Index (NDVI). 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. For our research, we used the USGS's Surface Reflectance NDVI product from Landsats 5, 7 and 8 to assess changes in NDVI for pixels matched to urban community gardens. We analyzed Landsat scenes acquired during the growing season (May - September) from 2007 through 2015 covering three different eastern U.S. cities – Roanoke Virginia, Pittsburgh Pennsylvania, and Buffalo New York. Our results show that NDVI changes when community gardens are developed, sometimes declining initially but then increasing over time. Furthermore, NDVI reveals the dynamic character of urban agriculture over the course of a growing season and the highest NDVI for each location is impacted by landscapes immediately adjacent to the gardens.

Key words: Urban agriculture, Community gardens, NDVI, Landsat, sustainability

Highlights:

- Urban agriculture can make positive impacts on the physical urban landscape
- Developing a vacant lot for urban agriculture increases NDVI

- Urban agriculture's increasing NDVI correlates with an increase in net primary production
- Urban agriculture contributes ecosystem services

1 Introduction

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 & Girardet, 2000; Pickett, Cadenasso, Grove, Nilon, Pouyat, Zipperer & Costanza, 2001). Effects of conversion from natural and agricultural vegetation to urban infrastructure include sealing of soils by impervious surfaces, alterations of hydrologic cycle (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 population now live 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 population (Lincoln Land Institute, 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 (Aitkenhead-Peterson, Steele, & Volder, 2010; Deelstra & Girardet, 2000; Pickett et al., 2001). To mitigate adverse effects from urbanization, researchers and urban officials are assessing and implementing sustainability initiatives, including Low Impact Development (LID), Smart Growth, and expansion of green infrastructures (Hirschman & Battiata, in press). Urban agriculture provides a green infrastructure that supports urban populations with food provisioning, cultural and social services, and mitigation of adverse environmental effects (Huang & Drescher, 2015;

McClintock, 2014; World Bank, 2013). However, while extensive research has documented its social, cultural and food provisioning benefits, little empirical research has documented its environmental benefits.

This paper fills a gap in quantitative environmental analyses of urban agriculture. We employ a widely used vegetation index derived from remotely sensed imagery to analyze environmental benefits from one form of urban agriculture - the community garden. Our background section is threefold. First, we introduce urban agriculture, its forms, and empirical research on ecosystem services derived from urban agriculture. Second, we provide specifics of the remotely sensed imagery used for this study. Third, we introduce the vegetation index used for our analysis - Normalized Difference Vegetation Index (NDVI), and the research supporting its use in analysis of vegetation in natural and agricultural environments. Within our methods section, we provide details of how we identified and selected the community gardens used for our study, and on our methods of choosing and analyzing the remotely sensed images. Finally, we provide results and answer the following questions: Can we identify a specific NDVI signature related to urban agriculture? Does NDVI increase after implementing urban agriculture, thus demonstrating urban agriculture as a positive greening initiative for urban sustainability plans?

2 Background

2.1 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). Common forms of urban agriculture include:

- *Home gardens* - usually constituting an individual or family growing food for consumption next to their residence (Drescher, Holmer, & Iaquinta, 2006).
- *Community gardens, informal gardens, school gardens, or allotment gardens* - characterizing areas of land divided into plots. The garden site is usually not owned by the people working it. *Community gardens* occupy land owned by an organization (e.g., community garden associations, governments, churches, non-profit organizations), which grant gardening privileges (sometimes only temporarily) to members who share a relationship (e.g. church, neighborhood, school, or employer); members work their own plots and jointly contribute to maintenance and care of common areas (Lawson, 2005). With *informal gardens*, land is cultivated without the permission of the land owner (Hardman & Larkman, 2014). In *allotment gardens*, the project is sponsored and managed by the local government (Petts, 2001). S*chool gardens* are located on public and private school properties, are devoted to school education and contribute food to support school lunches or students' home food supplies (Moore, Wilson, Kelly-Richards & Marston, 2015; Pudup, 2008; Smit, Nasr & Ratta, 2001).
- *Urban farms* are commercial operations, including greenhouses, rooftop gardens, and community-supported agriculture (Doron, 2005; Smit et al., 2001).
- *Orchards* consist of trees providing a source of food (fruit or nut-bearing trees), fuelwood or building materials (Smit & Nasr, 1992; Smit et al., 2001). Orchards can form stand-alone initiatives, or be included as part of any of the other forms of urban agriculture.

For this study, we examine community gardens for several reasons. Home gardens are the most common form but, they are positioned adjacent to residences and, thus, are difficult to identify on aerial images. *Farms*, normally the largest in areal extent, are infrequently found within city boundaries. *Community gardens* are easily recognizable on aerial images from the combination of individual plots and walkways, and are the form most frequently mentioned in urban sustainability plans because of their community and social building characteristics.

2.2 Urban Agriculture and Ecosystem Services

Ecosystems are a set of different 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, climate, and disease; *cultural services*, e.g. education, social, and sense of place; 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). Food provisioning services from urban agriculture are undeniable, as reported by (for example) Alaimo, Packnett, Miles & Kruger, 2008; Gittleman, Jordan & Brelsford, 2012; Pourias, Duchemin & Aubry, 2015, among others.

Furthermore, ecosystem services provided by urban agriculture extend into other service areas. *Cultural services* are documented by, for example, Dunlap, Harmon & Kyle (2013), Li, Weller, Tao & Yu (2013), Saldivar-Tanaka and Krasny, (2004), and Taylor and Lovell (2015) when immigrants cultivate familiar plants from their home country to maintain their cultural ties.

Establishing community building and social interactions are documented by Agustina and Beilin, 2012; Cohen & Reynolds, 2015; Drescher et al., 2006; Dunlap et al., 2013. *Supporting services* are characterized by using harvested rainwater (e.g. Parece, Lumpkin & Campbell, in press; Redwood et al., 2014) and waste water (e.g. Faruqui, 2002; Kihila, Mtei & Njau, 2014; Makoni, 2014; Rojas-Valencia, Orta de Velásquez & Franco, 2011) for irrigation, and increased nutrient cycling from using waste water for irrigation (e.g., Rojas-Valencia et al., 2011; Makoni, 2014) and from composting solid waste (e.g., Adam-Bradford, 2006; Eriksen-Hamel and Danso, 2009; Njenga and Karanja, 2006; Sotamenou and Parrot, 2013).

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

However, providing one type of ecosystem service does not preclude contribution of other services, for example, rainwater harvesting also assists in regulating water, water purification and in decreasing erosion. Solid waste and waste water recycling assist in waste treatment and disease and pest regulation. We note that some contributions to ecosystem services (such as rainwater harvesting, cultural services, and food provisioning) generate services that can extend beyond immediate extents of the gardens and the urban area.

2.3 Landsat Satellites and Imagery

Landsat is a system of eight U.S. land-observation satellites -- the first launched in 1972, the most recent in 2013. The satellites use sun-synchronous orbits, thus passing over the same portion of the Earth's surface, northeast to southwest, at approximately the same local sun time for each overpass. Landsat orbits the Earth about 14 times in one day, and covers the entire

Earth's surface about every 16 days. Each Landsat orbit (path) permits imaging of an area approximately 185 km wide on the Earth's surface, with each orbital path slightly overlapping the prior path. Because of this overlap, for some locations, Landsat satellites revisits edges of the same scene on successive days. Landsat offers researchers the opportunity to make temporal comparisons over just a few days to decades (USGS, 2016).

Although sensors aboard the different Landsat satellites differ in their sensitivity to regions of the electromagnetic spectrum, they have been cross calibrated, enabling comparison of vegetation indices. Landsat 5's Thematic Mapper (TM) and Landsat 7's Enhanced Thematic Mapper Plus (ETM+) cross calibrated by Teillet, Barker, Markham, Irish & Fedosejevs (2001), and most specifically for the Normalized Difference Vegetation Index (NDVI) by Steven, Malthus, Baret, Xu & Chopping (2003), and ETM+ with the Landsat 8's Operational Land Imager (OLI) cross calibrated by Mishra, Haque, Leigh, Aaron, Helder & Markham. (2014). In all cross-calibrations, the difference between the two sensors' radiances was less than ± 3% (Mishra et al., 2014; Steven et al., 2003; Teillet et al., 2001), providing the ability to compare images temporally.

Landsat is considered a moderate resolution system; pixel resolution is 30 meters for the red and near infrared bands. Footprints of individual 30 m resolution pixels for all the Landsat satellites coincide, thus, offering us the opportunity to make temporal comparisons. 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 of spectral signatures, it is called a *mixed pixel* -- mixed pixels are more difficult to match to one specific landscape feature. 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.

2.4 Vegetation indices

Healthy vegetation provides insight into the vigor of an ecosystem, which can be represented by vegetation indices based upon ratios calculated from the pixel values in separate bands of satellite imagery. The Normalized Difference Vegetation Index (NDVI), one such index, is widely used to track vegetation phenology, identify vegetation stress and health in forestry and agriculture (Huete, Justice & Lie, 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 on-board satellites such as Landsat (Tucker, 1979). The formula for NDVI is $(NIR - Red)/(NIR + Red),$ providing a real number valued between -1 and +1.

NDVI is sensitive to photosynthetically active vegetation (Tucker, 1979) and provides a positive linear relationship with the fraction of photosynthetically active radiation (fAPAR) absorbed by plant tissue (Myneni and Williams, 1994). fAPAR increases with ground cover and plant leaf area, thus 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 peak NDVI values that peak at different times of the growing season, 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) (Huete et al., 1994; Justice, Townsend, Holden & Tucker, 1986; Myneni and Williams, 1994; Tucker, 1979). NDVI values closer to +1 equate to more mature and healthy vegetation. Figure 1 provides an example of sequential NDVI values for two different agricultural crops – corn and soybean. The graph on the left demonstrates, for a growing season, differences between corn and soybean NDVI signatures. The graph on the right illustrates NDVI differences between a pure pixel of corn and a mixed pixel of corn with double cropping.

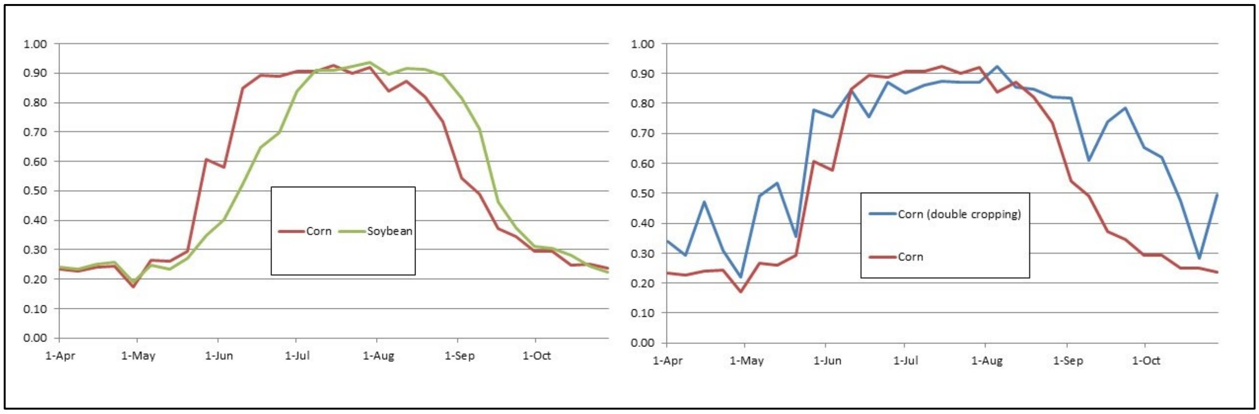

Figure 1. Comparison of NDVI signatures for pure pixels of corn and soybeans (left) and, on right, a pure pixel of corn compared to a mixed pixel of corn with double cropping.

Because of its relationship to fAPAR, NDVI values can provide 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, Osawa & Adnyana (2010) for gross primary production, Davies, Edmondson, Heinemeyer, Leake & Gaston (2011) for above-ground carbon storage for one 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, Elvidge, Nemani & Running (2003) for the southeastern United States and Imoff, Bououa, DeFries, Lawrence, Stutzer, Tucker & Ricketts (2004) for the United States as a whole. We could not identify studies that have applied the Normalized Difference Vegetation Index (NDVI) to assess either positive or negative changes 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. 1). Urban agriculture, however, is typified by polyculture, i.e., multi-cropping, and inter-cropping (Smit et al., 2001). *Multi-cropping* is defined as two or more crop species cultivated within the same unit area and *inter-cropping* 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 Li et al. (2013) and Yadav, Duckworth & Grewal (2012). Thus, any application of remote sensing to examine urban agriculture likely encounters multi-cropping and intercropping, and therefore records plots as *mixed pixels* (pixels representing several different spectral features), preventing direct application of conventional agricultural remote sensing analysis.

3 Methods

3.1 Study Sites

We selected three U.S. cities for our analysis – Roanoke Virginia, Buffalo New York, and Pittsburgh Pennsylvania. Buffalo has a very large urban agriculture community, with over 72 community gardens identified from the internet. Both Pittsburgh and Roanoke also fall at the edges of two adjacent Landsat satellite paths, thus providing the opportunity for a greater number of images to analyze.

3.2 Landsat Scenes and Data Choice

Landsat products are available, without charge, through the U.S. Geological Survey’s internet search engines - GLOVIS or EarthExplorer. The USGS provides several levels of processing, depending on the product ordered. All Landsat scenes are georeferenced, and metadata provides details documenting the georeferencing. The USGS also provides Surface Reflectance products for Landsats 4, 5, 7 and 8. Surface reflectance products are also pre-processed by the USGS using atmospheric correction algorithms (for specifics, see DOI, 2015). Furthermore, the USGS has processed some of the surface reflectance products into specific indices, such as NDVI, which we use for this study.

Using EarthExplorer, we searched for Landsat 5, 7 and 8 surface reflectance images for the months of May through early October and the years 2007 through 2015 for each of our study sites. We did not restrict our search results using any specific cloud cover setting (more specifics under *Image Analysis* below). The NDVI Surface Reflectance product is delivered as one image per date with NDVI values from -10,000 to +20,000. (NDVI values actually should range from -1 to +1 but to reduce storage space, USGS creates NDVI images with integer values and accompanying documentation to provide the scaling factor (0.0001) to correct to the actual NDVI value (DOI, 2015)).

3.3 Community Garden Identification

We identified community gardens and their addresses with an internet search. We set up a spreadsheet file with the addresses and then in ArcMap™, we geocoded the addresses. This provided us with a point shapefile for each community garden location. We then converted this shapefile to the appropriate file format for Google Earth™ (kml). We projected it within Google Earth™ to make sure each point identified the actual of location community garden, not the street in front of the community garden.

Our next step identified each Landsat pixel intersecting with a community garden. To accomplish this task, for each city, we first created a fishnet polygon file that matched exactly to the boundaries of a Landsat scene, and each individual pixel. We then selected those polygons that contained our individual community garden points, and converted those selected polygons to kml files. We projected the kml polygon file into 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 was clearly visible within the pixel, e.g. cultivated rows,
- The community garden was at least 50% of the pixel,
- No tree canopy was found in more than 20% of the pixel, and
- Shadowing from buildings was not present over the community garden.

We removed from the analysis any polygon representing a Landsat pixel that did not meet any of these qualifications. Figure 2 illustrates examples of unacceptable pixels. We then deleted any community garden points found within those polygons from the point shapefile. Figure 3 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 that could represent the spectral properties of the garden plot.

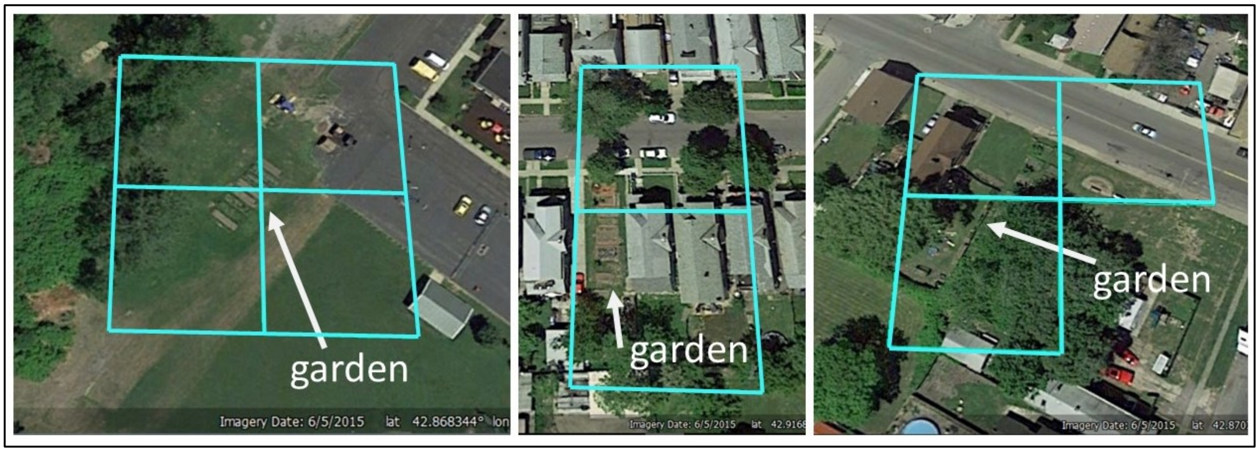

Figure 2. Examples of unacceptable matches between pixels and different community gardens in Buffalo New York (community garden is identified by the white arrow). Such matches were not suitable for use in this study. Cyan polygons represent footprints of Landsat pixels. (Source of images: Google Earth™)

Figure 3. Examples of acceptable matches between pixels and community gardens. (Farmer's Garden Patch, Buffalo – left; Bandi Schaum Field, Pittburgh – center; Hurt Park Community Garden, Roanoke – right) Cyan polygons represent footprints of Landsat pixels. (Source of images: Google Earth™)

3.4 Landsat Image Identification and Analysis

All Landsat NDVI Surface Reflectance scenes were loaded into ArcMap™. We evaluated each individual scene for clarity and cloud cover. For scenes where clouds or haze were covering all community garden points, 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 one of Landsat 7's missing scan lines (in 2003, a partial failure of the on-board satellite system created data gaps caused by missing scan lines (USGS, 2015)). Figure 4 demonstrates examples of Landsat Surface Reflectance NDVI images.

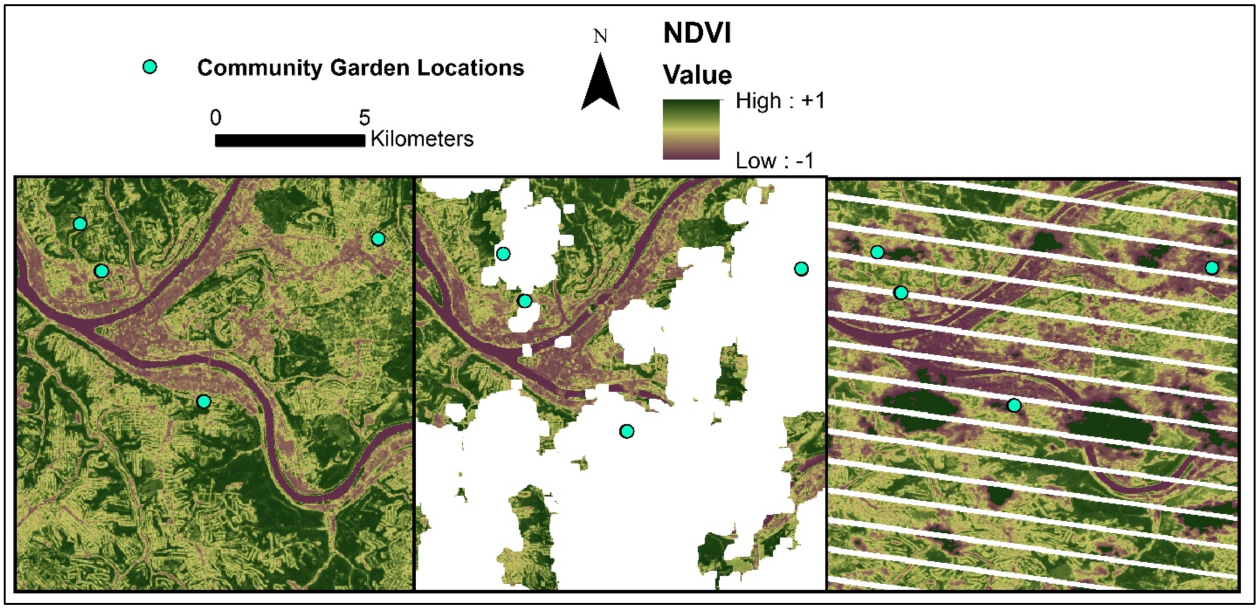

Figure 4. Examples of NDVI Landsat Images. Left – Landsat 8, no interference within image; Middle – Landsat 8 - clouds covering portions of image; Right – striping caused by Landsat 7's SLC-Off missing scan line anomaly.

In ArcMap™, we used the Spatial Analyst Tools>Extraction>Extract Multi Values to Points to extract all NDVI values for each community garden point for all years, 2007 – 2015, creating a separate shapefile for each year. We 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 a scale factor of 0.0001, so our NDVI values ranged from +1 to -1 for each image. We then graphed each point's value over the growing season to compare NDVI values before and after cultivation.

Finally, using the *Historical Image* sliding bar in Google Earth™, 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 5 shows an example of an historical sequence for Hurt Park Community Garden in Roanoke Virginia. From our internet searches, as identified above, we documented an establishment date for each garden.

Figure 5. Historical sequence for Hurt Park Community Garden (within cyan polygon), Roanoke, Virginia. (Source – 2006 and 2011 Virginia Base Mapping Program; 2012 National Agriculture Imaging Program; 2010 and 2015 source unknown but displayed in Google Earth™)

4 Results and Discussion

We identified eighteen Landsat pixels to examine in our study. Although we geocoded 72 community gardens for Buffalo, New York, once we evaluated each site, we were only to identify four Landsat pixels that met our criteria (largely due to small sizes of the Buffalo gardens). Table 1 provides details for each city and community garden site, including name and neighborhood description, date established, and number of Landsat pixels covering that site.

Table 1. City and state, community garden with neighborhood description, establishment date, and number of viable Landsat pixels

City, State	Community garden and neighborhood description	Date established	Number of Landsat pixels
Buffalo New York	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 Virginia	Frank Roupas – high density residential	2009	3
	Hurt Park - medium/high density residential	2012	2
	MountainView - medium/high density residential	2013	2
Pittsburgh Pennsylvania	Olde Alleghany – high density residential	1982, aerial images show expanded 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

Numbers of viable Landsat scenes for each year, and for each garden, varied (Table 2). The number of scenes for gardens located in Roanoke Virginia, and in Pittsburgh Pennsylvania exceed those of Buffalo because these two cities are covered by two Landsat Paths; 16 and 17 cover Roanoke, and 17 and 18 cover Pittsburgh. For each year, two active Landsat satellites were in orbit, with the exception of 2012.

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

Year	Satellite	Roanoke, Virginia	Buffalo, New York	Pittsburg, Pennsylvania
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

4.1 Does Urban Agriculture Produce a Unique NDVI Signature?

Our results show that urban agriculture does not produce a unique NDVI signature, as one often sees within rural agriculture — as noted above, urban agriculture is typified by multi-cropping and/or inter-cropping, thus produces a *mixed pixel* of spectral signatures. Furthermore, as demonstrated by Figure 6 (Olde Alleghany Community Garden, Pittsburgh, Pennsylvania), the *mixed pixel* integrates spectral signatures of roads, buildings, and grassy areas between cultivated areas within a community garden.

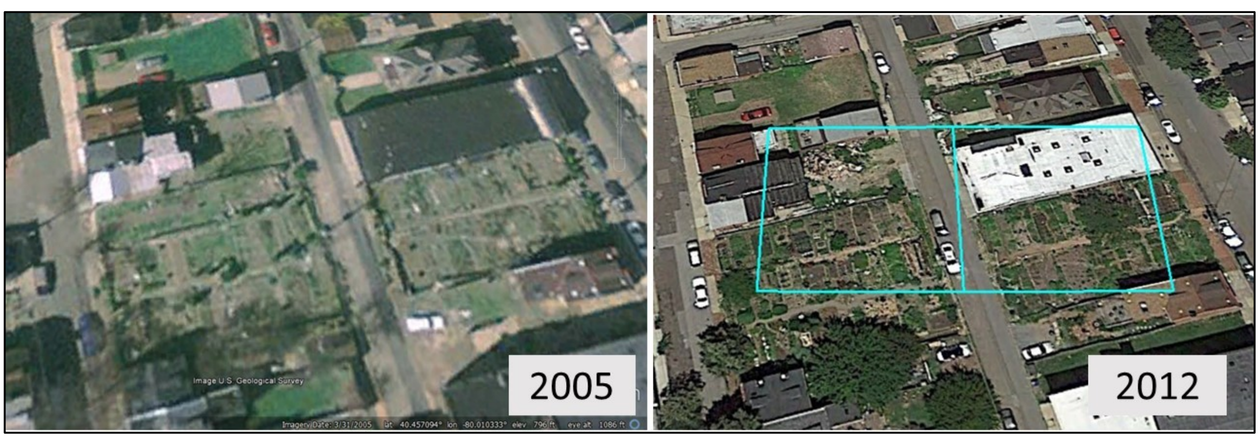

Figure 6. Olde Alleghany Community Garden, Pittsburgh Pennsylvania (left in 2005 and right in 2012); the outline cyan represents the footprint of the Landsat pixels.

Nonetheless, our results show that urban agriculture produces a unique pattern when assessing NDVI over the growing season (i.e. May - September) – the unique pattern being very dynamic. We demonstrate these results with a selection of NDVI graphs for one community garden from each city - Olde Alleghany Community Garden (established in 1982), Frank Roupas Community Garden, Roanoke Virginia (established 2009), and Old First Ward, Buffalo New York (established 2013). As Figure 7 demonstrates, NDVI varies considerably across the growing season, which reveals the different species of vegetation growing, maturing, and dying according to each's life cycle. Urban agriculture's NDVI does not exhibit a specific signature, as it would for a specific plant species, a definite single peak and low values when it first sprouts and after maturity and harvesting (Figure 1). Since community gardens are inter-cropped, as one species matures, another species is still growing and matures at a later date. It's a little more difficult to discern such patterns in the graph for Old First Ward, which we equate to the lesser number of Landsat scenes available and its shorter history as a community garden.

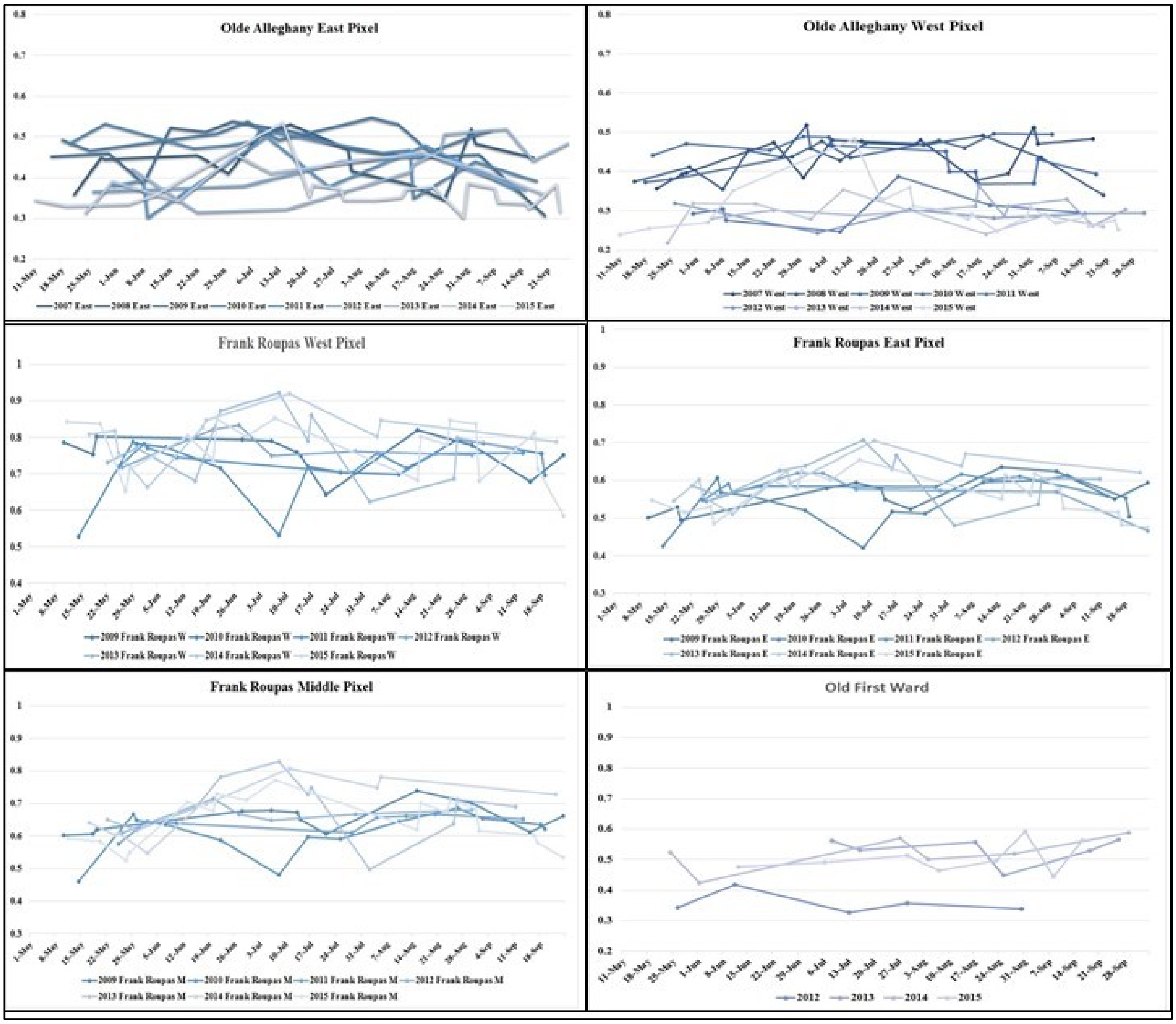

Figure 7. Sample of line graphs mapping NDVI changes for the growing season (May – September) for six different mixed pixels for three different community gardens. The lines show that NDVI profiles for urban agriculture are very dynamic throughout the growing season.

Variation of peak NDVI values between different gardens is of particular importance; the landscape around the community garden influences the garden's NDVI. NDVI peaks multiple times within the same growing season and peak values appear to correlate with 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 settings, from dense vegetation in the west pixel (showing peak NDVI values at > 0.9), more grassy 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) (Figure 8).

Figure 8. Frank Roupas Community Garden, Roanoke Virginia. The West pixel (left) shows denser vegetation, middle pixel – more evident walkways between plots, and the east pixel - some impervious surfaces included in the mixture of spectral values.

All community gardens produced NDVI values, similarly. For example, Olde Alleghany is in a higher density residential area and its peaks 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.

Table 3. Peak 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

4.2 Does NDVI Increase after Cultivation?

To answer this question, examining the line graphs in Figure 7 is difficult, as such, our comparison consisted of two steps – average NDVI before and after cultivation and NDVI values for the same date before and after cultivation.

Figures 9 presens bar graphs for average annual NDVI (NDVI averaged over the growing season – May through September), each bar representing one year, 2007 – 2015, for the Frank Roupas Community Garden in Roanoke, Virginia. (Average NDVI Bar Graphs for all other Community Gardens are located in Appendix A.) For the three Roanoke gardens (and for most of the other gardens within our study), average annual NDVI increased after cultivation began.

NDVI decreases during the transitional process from grassy plot to community garden, for example Hurt Park Community Garden (est. 2012), MountainView Community Garden (est. 2013), Frank Roupas Community Garden (est. 2009), but then increased thereafter. For Ballfield Farm (in Appendix A), we only have historical scenes for only one year (2007), and NDVI drops significantly with beginning cultivation. However, NDVI is showing an increasing trend over subsequent years.

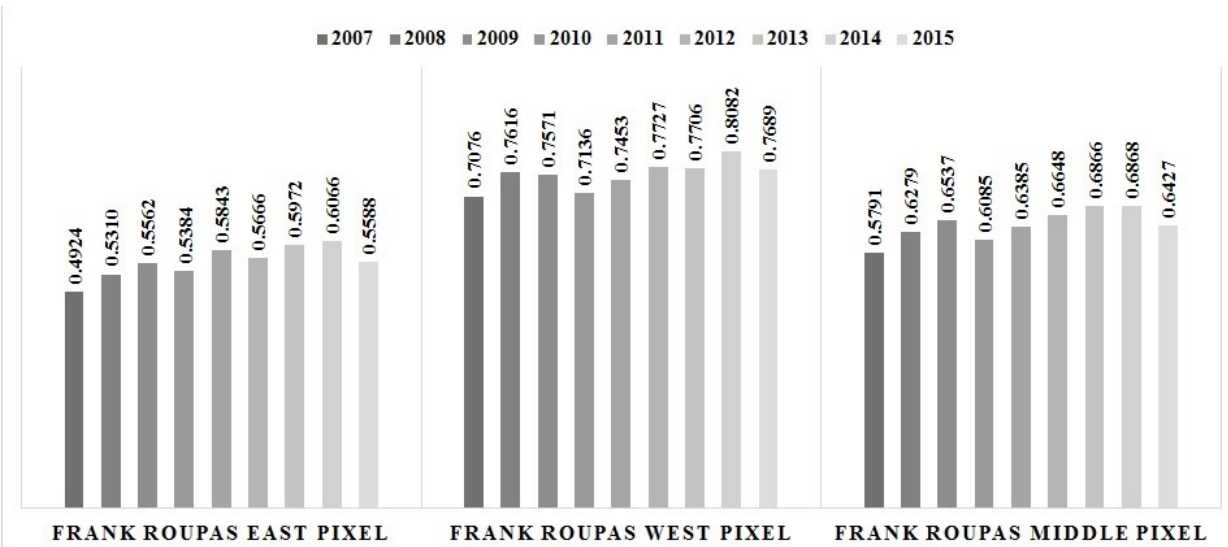

Figure 9. Average annual NDVI Frank Roupas Community Garden (established 2009), 2007 – 2015

The table in the Appendix B 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 – May 23 and 24, Ballfield - July 15 and 16, and for Serenity, Esser and Farmer's Garden Patch - May 18 and 19). For most gardens, for the same date (or the very next day), 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 is likely related to gardeners turning soils and beginning the planting process.

5 Conclusions

NDVIs for all gardens were extremely dynamic throughout the growing season. In rural agriculture, the norm shows NDVI with one peak during a growing season because pixels typically cover large homogenous fields. Urban agriculture, specifically community gardens in this study, consists of many different species of plants cultivated within the same location and within a single Landsat pixel. Different crops sprout, mature, and are harvested variably within a growing season, thus produce a highly variable NDVI profile. 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).

While NDVI can vary from year to year because of temperature and precipitation differences, our data covered multiple years after cultivation for all of our gardens 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, these community gardens provide positive contributions to urban net primary production.

Our NDVI graphs are consistent with NDVI graphs of mixed agriculture over large expanses (e.g. Justice et al, 1986). While our peak NDVI values varies, each community garden has an individual story related to its location, variation in plant species, adjacent landscape variables, and, although not examined within this study, with regard to patrons of the specific gardens and the plants that they choose to cultivate. As we continue to analyze NDVI related to urban agriculture – including subsequent years in the gardens examined herein, including other urban areas, and evaluating NDVI for urban farms, we will be able to more specifically identify specific NDVI sequence patterns and use NDVI analyses to identify urban agriculture locations and contributions to urban greening efforts, more quickly than with aerial photo interpretation.

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this article.

Acknowledgements

This research was financially supported by Virginia Space Grant Consortium 2014/2015 Graduate Research Fellowship. We thank undergraduate research assistant, Lynn Wormeli for her work on this project. We also thank Jie Ren for contributing Figure 1. This publication was developed under STAR Fellowship Assistance Agreement No. FP-91769301-0 awarded by the U.S. Environmental Protection Agency (EPA). It has not been formally reviewed by EPA. The views expressed in this publication are solely those of Tammy Erlene Parece and EPA does not endorse any products or commercial services mentioned in this publication.

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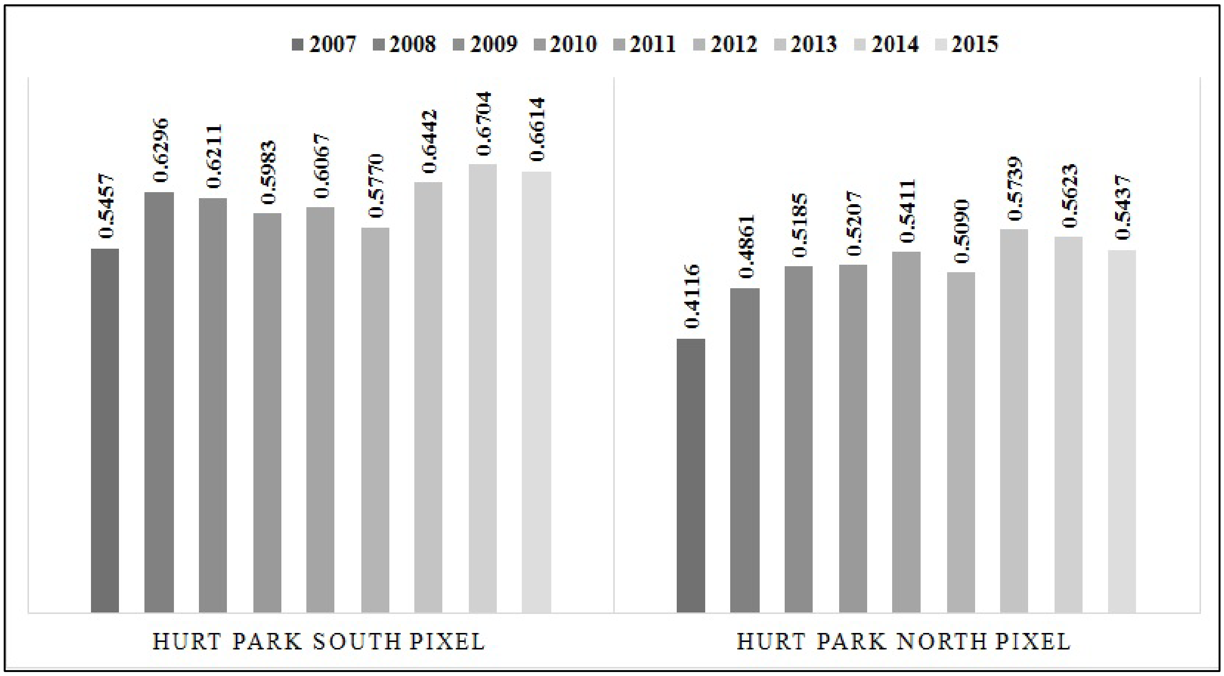
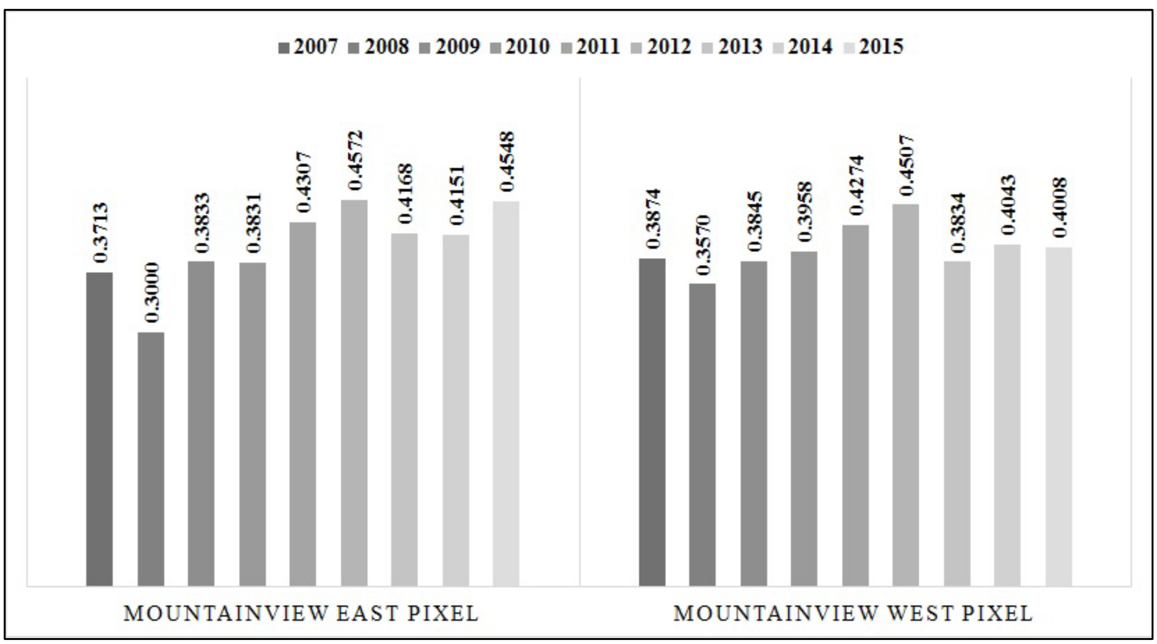
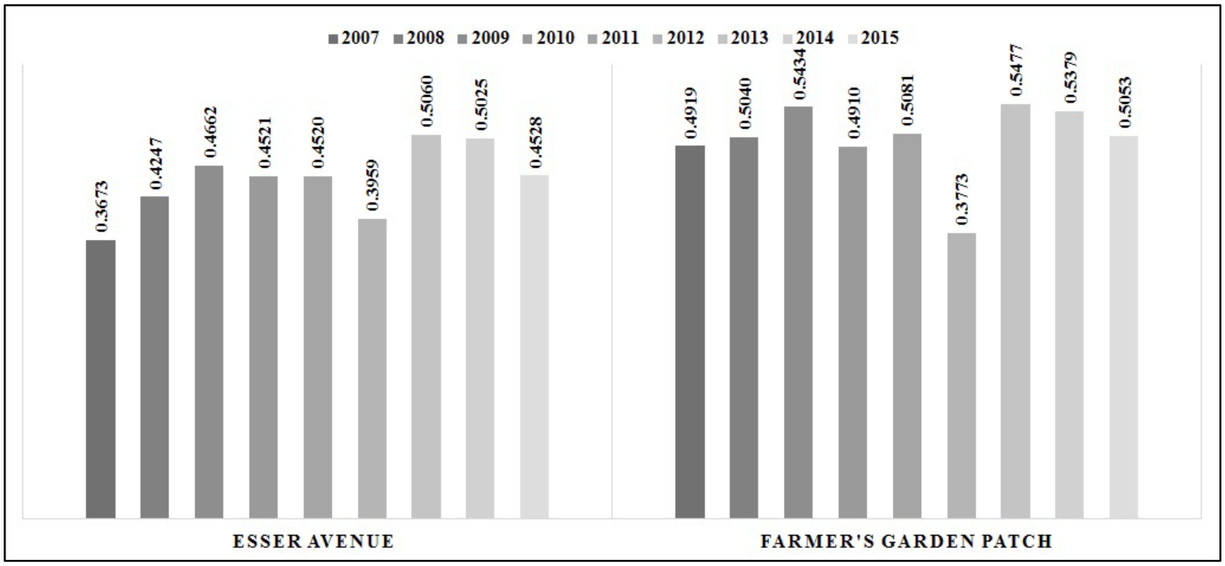
Appendix A – Bar Graphs - Average Annual NDVI 2007 - 2015



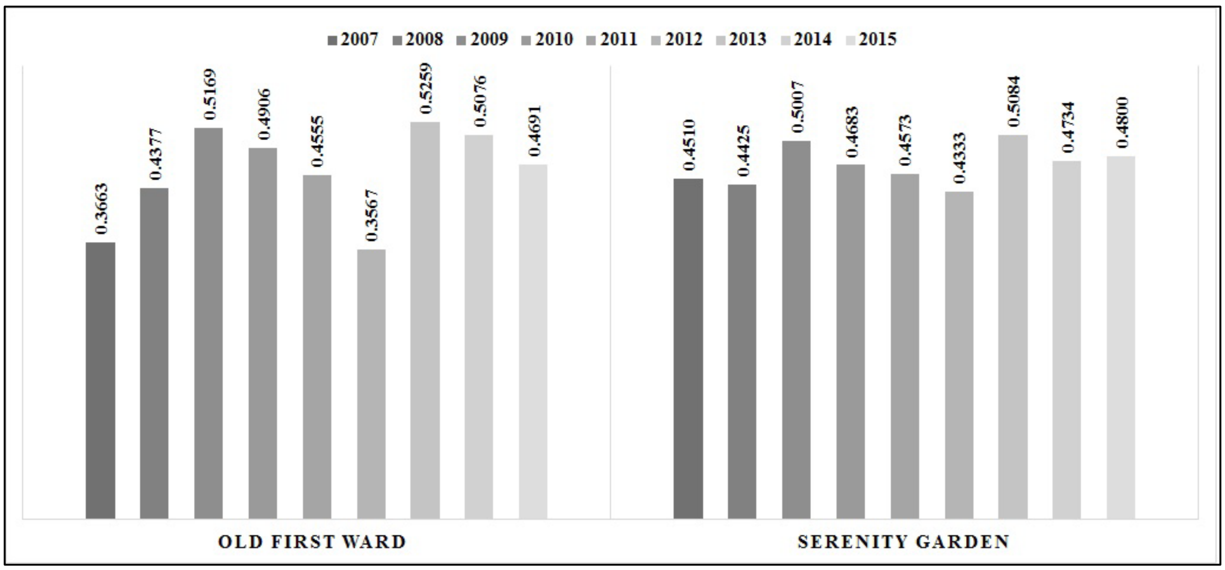
Hurt Park, established 2012



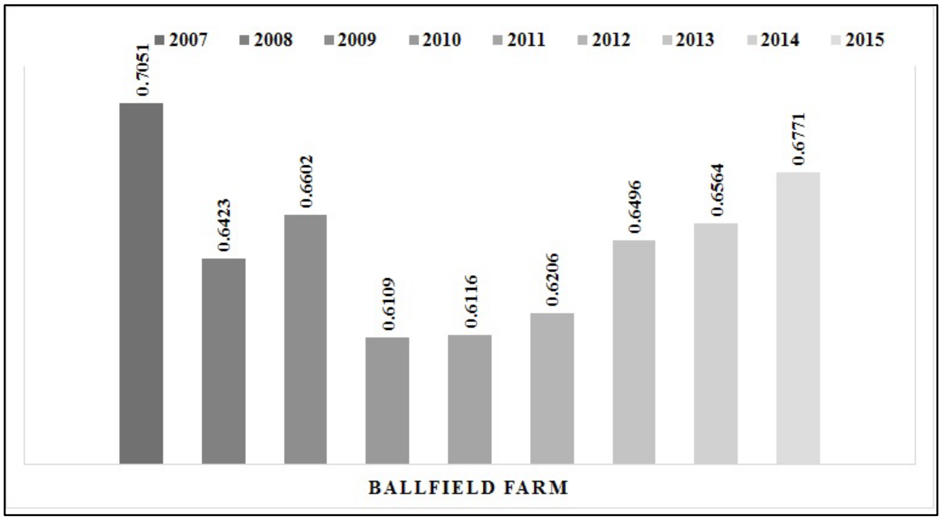
MountainView, established 2013



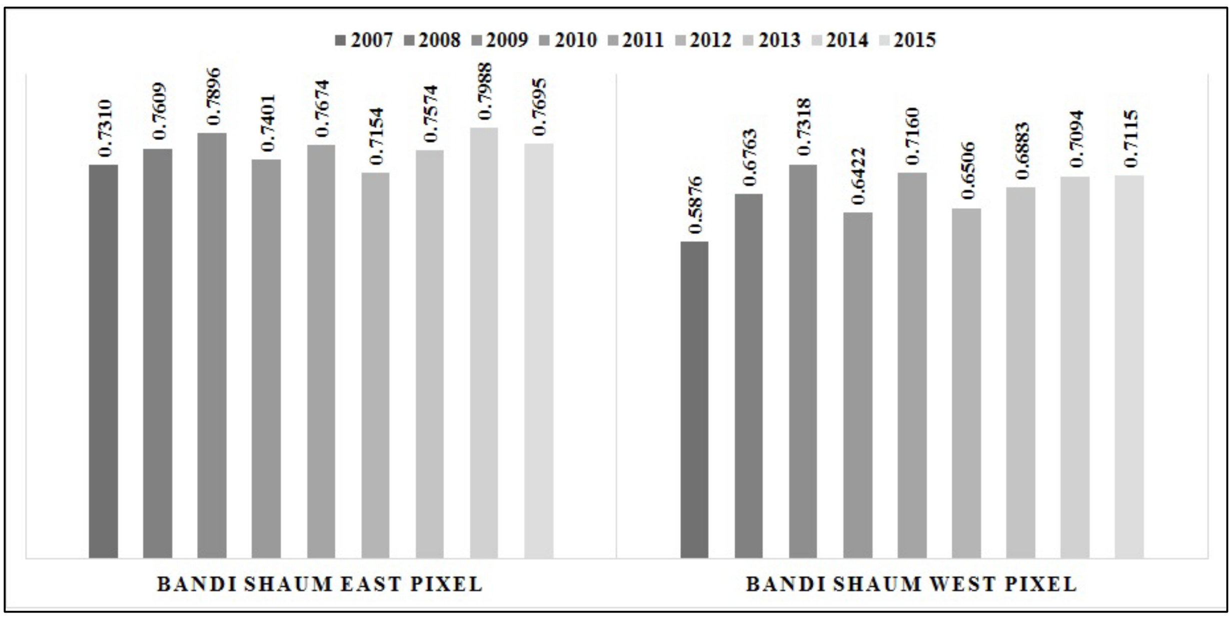
Esser Avenue, established 2013 - left, Farmer's Garden Patch, established 2012



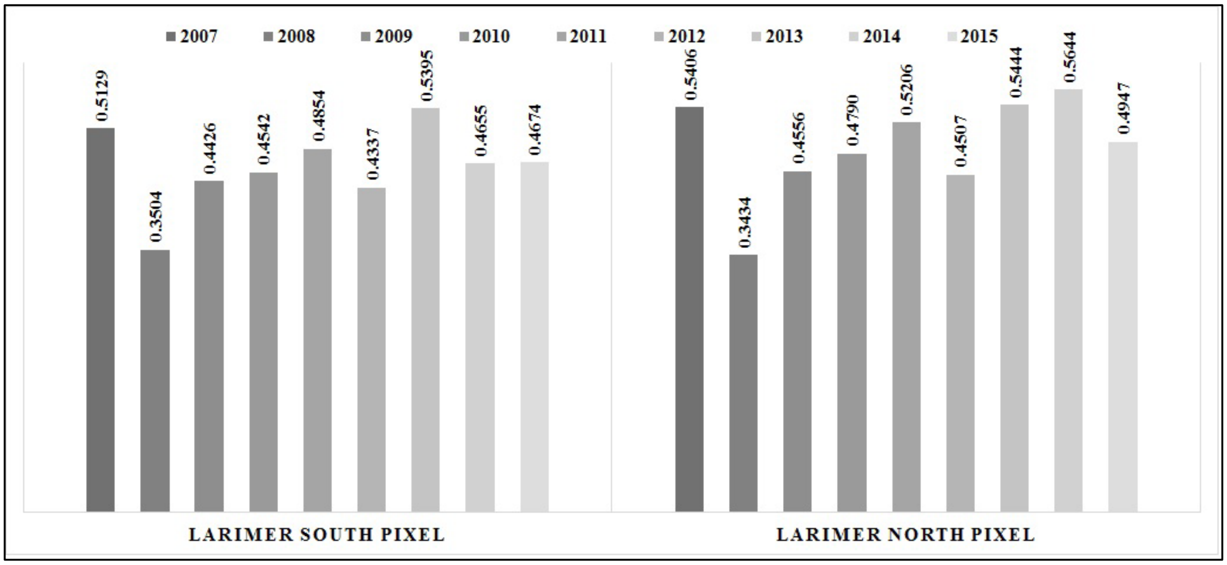
Old First Ward, established 2013 - left, Serenity Garden, established 2011 – right



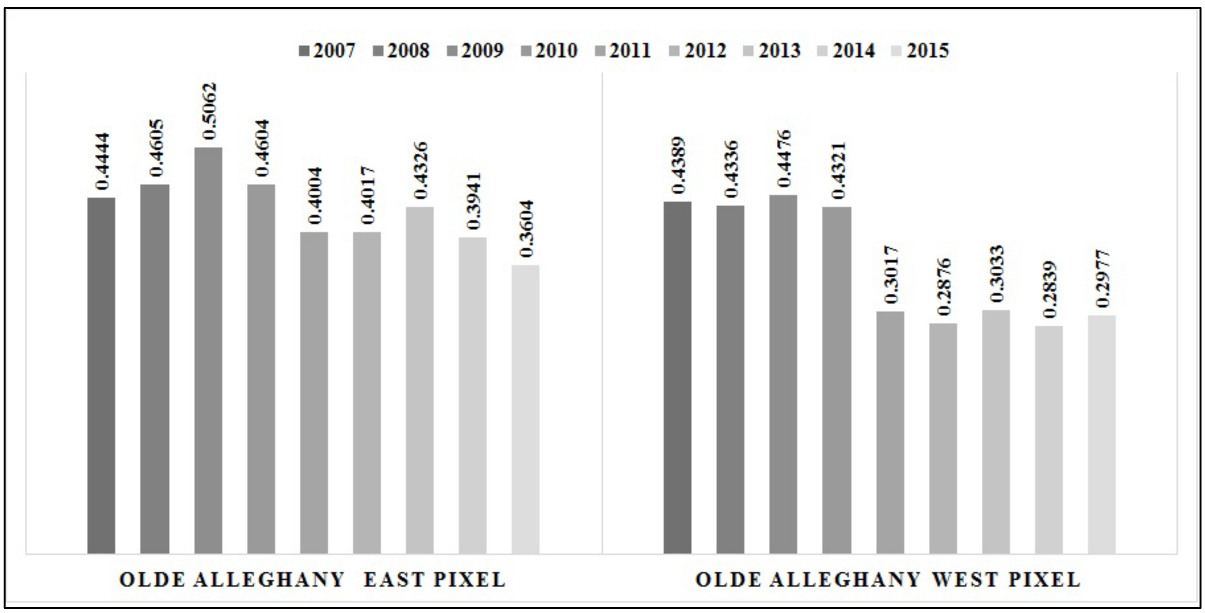
Ballfield Farm, established 2008



Bandi Schaum Community Garden, established 2012



Larimer Avenue Community Garden, established 2010



Olde Alleghany Community Garden, 2007 – 2015, established 1982

Appendix B - Table of NDVI comparisons for specific dates in years before and after cultivation

Roanoke, Virginia

Hurt Park (est. 2012), 2 pixels

25-May		17-June		17-July		15-August		24-September		
2011	2014	2008	2014	2007	2013	2009	2015	2009	2012	2015
0.5769	0.5664	0.6495	0.6729	0.5462	0.6954	0.4745	0.6351	0.7019	0.6145	0.4964
0.5621	0.4771	0.5082	0.5422	0.4437	0.6252	0.4201	0.5249	0.5649	0.4891	0.4175

MountainView (est. 2013), 2 pixels

29-May			28-June		17-July		26-August		24-September		
2007	2010	2015	2009	2015	2007	2013	2010	2013	2009	2012	2015
0.4389	0.3807	0.3460	0.3744	0.4738	0.3836	0.5605	0.4375	0.4895	0.3620	0.4095	0.3846
0.4502	0.4230	0.3338	0.3856	0.4022	0.4013	0.4274	0.4318	0.4481	0.4026	0.3638	0.3667

Frank Roupas (est. 2009), 3 pixels

29-May		22-June			17-July		25-Aug		19-Sept	
2007	2010	2007	2010	2013	2007	2013	2007	2013	2007	2013
0.5341	0.6064	0.5219	0.5210	0.6380	0.5514	0.6659	0.4261	0.5367	0.5076	0.5045
0.7339	0.7886	0.7146	0.7163	0.8739	0.7608	0.8616	0.6703	0.6876	0.7503	0.6969
0.5492	0.6667	0.6111	0.5884	0.7807	0.6416	0.7487	0.5253	0.6373	0.6265	0.6226

Pittsburgh, Pennsylvania, 2 pixels each

Bandi Schaum (est. 2012)

23-May	24-May	27-June		2-July		15-July		17-Aug		17-Sept	
2008	2014	2009	2012	2008	2014	2007	2013	2010	2013	2007	2013
0.8058	0.7765	0.7540	0.6611	0.8303	0.7948	0.8134	0.8183	0.7163	0.7873	0.7727	0.8352
0.6491	0.5751	0.6558	0.5713	0.7351	0.7438	0.5856	0.7328	0.6159	0.7203	0.6920	0.7681

Larimer Avenue (est. 2010)

29-May		22-June		5-July		16-Aug			17-Sept	
2007	2010	2007	2013	2009	2015	2007	2010	2013	2007	2013
0.4503	0.4703	0.4139	0.4221	0.4971	0.5064	0.4045	0.4154	0.5119	0.5256	0.5612
0.5037	0.5379	0.4691	0.4308	0.5261	0.5336	0.3706	0.4233	0.4778	0.6274	0.5507

Ballfield Farm (est. 2008/2009)

20-May		8-June		16-July	15-July	16-Aug			20-Sept	
2007	2010	2008	2011	2007	2013	2007	2010	2013	2008	2014
0.6175	0.6406	0.4463	0.6011	0.7726	0.7798	0.5895	0.5924	0.6376	0.6099	0.6197

Buffalo New York, 1 pixel each

Serenity Garden (est. 2011)

18-May	19-May	5-July	6-July	13-July		27-Aug	28-Aug	18-Sept	
2009	2015	2009	2015	2009	2012	2008	2013	2007	2013
0.5110	0.4746	0.4735	0.5188	0.5026	0.4254	0.3937	0.4680	0.4423	0.5618

Old First Ward (est. 2012)

1-June		8-July		27-July		17-Aug			18-Sept	
2011	2014	2010	2013	2011	2014	2007	2010	2013	2007	2013
0.4619	0.4242	0.4922	0.5624	0.4008	0.5700	0.3766	0.5422	0.5587	0.4051	0.5293

Esser Avenue (est. 2013)

18-May	19-May	14-June	12-June	27-July		17-Aug			18-Sept	
2009	2015	2007	2015	2011	2014	2007	2010	2013	2007	2013
0.4726	0.5113	0.3821	0.4853	0.3594	0.4737	0.3440	0.4023	0.5084	0.3841	0.5713

Farmer’s Garden Patch (est. 2012)

18-May	19-May	11-July		27-July		17-Aug			18-Sept	
2009	2015	2011	2014	2011	2014	2007	2010	2013	2007	2013
0.5768	0.5020	0.4879	0.5709	0.4433	0.5712	0.4344	0.5474	0.5796	0.4619	0.5718

A Comparative Analysis of Methods to Calculate Urban Agriculture's Production Potential

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A Comparative Analysis of Urban Agriculture Production Potential Methods

Abstract

Soils form an essential element of agricultural production. Urban agriculture has gained worldwide importance because of its role in contributing to food security for low income urban residents. Studies analyzing urban agriculture's production potential are numerous but rarely address production capacities of local soils. Soils within urban areas are often significantly altered through sealing, building construction, and industrial activities but recent research has demonstrated that urban soils are not as degraded as previously thought. To investigate the roles that soils play in urban agriculture's production potential, we calculate production potentials based upon a land inventory of open areas within the City of Roanoke, Virginia USA using two methods. Our first method uses production capabilities of soils; the other uses production rates for individual crops. We then compare results from the two methods. Our analysis shows that the soils' productivity method provides a viable option for estimating the potential production capacities for urban agriculture -- our results based upon the two alternative methods differ by only 4.4%.

Keywords: urban agriculture, ecosystem services, land inventory, soils agricultural capability

1 Introduction

Urban agriculture forms an increasingly significant component of efforts to address food insecurity worldwide and to support urban greening efforts. Almost 805 million people, worldwide, suffer from chronic food insecurity (FAO, IFAD, & WFP, 2014) as world populations continue to increase. Projections place the Earth's 2050 population in excess of 9.6 billion (United Nations, 2015) -- to meet needs of these 9.6 billion people, food production must increase by 60% (FAO et al., 2014). With the majority of the world population now living in urban areas (United Nations, 2014), many of the world's food insecure live in urban areas, so as a result, research to develop urban agriculture's ability to contribute to food security has grown exponentially.

FAO estimates that 800 million people, worldwide, participate in some form of urban agriculture (2015). The proportion of people participating in urban agriculture varies across the world, from 11% in Indonesia to almost 70% in Nicaragua and Vietnam but also varies according to income – a much higher participation rate in lower income families (Zezza & Tasciotti, 2010). Within the United States, the extent of urban agriculture has not been quantified, but regional estimates include over 1,000 community gardens and urban farms in New York City alone (New York State Energy Research and Development Authority (NYSERDA), 2013), approximately 226 community gardens in Philadelphia (Vitiello & Naim, 2009) and over 100 schoolyard and community gardens in Oakland, California (McClintock, Cooper, & Khandeshi, 2013) and Buffalo, New York (Grassroots Gardens of Buffalo, 2015). But despite the extent of participation in urban agriculture, its ability to contribute to food security of urban populations is still questioned (Crush, 2011; Hallsworth & Wong, 2013). Because of this dispute, numerous urban agriculture researchers have attempted to quantify an urban area's ability to produce food (e.g., Colasanti & Hamm, 2010; Grewal & Grewal, 2012; MacRae et al., 2010; McClintock et al., 2013; NYSERDA, 2013).

Methods used to quantify or estimate urban agriculture's production potential vary. *'Harvest reports'*, very important to supporting urban agriculture initiatives, include actual production results from specific farms or gardens (e.g., Gittleman, Jordan, & Brelsford, 2012; Reynolds, 2009; Vitiello & Naim, 2009). Research studies estimating production for a specific urban area utilize reports from other locales (e.g., Colasanti & Hamm, 2010; Grewal & Grewal, 2012; Haberman et al., 2014), or calculate potential production based on national or regional historical agricultural records (e.g., Desjardins, Macrae, & Schumilas, 2010; Giombolini, Chambers, Schlegel, & Dunne, 2011; MacRae et al., 2010; McClintock et al., 2013). One of the most frequently used methods considers production scenarios in *How to Grow More Vegetables:(and Fruits, Nuts, Berries, Grains, and Other Crops) Than You ever Thought Possible on Less Land than You can Imagine* (Jeavons, 2012), using specific crops suitable to their area. The methods for identifying land available for agriculture production vary, many including roof areas; rarely do production studies include production capability of soils.

Soils form the principal supporting service for net primary production, a vital ecosystem service (Millennium Ecosystem Assessment, 2005) — provisioning water, nutrients, oxygen, and stability to plants (FAO, 2015; Lal, 2009; Wall & Six, 2015). Research devoted to urban soils and urban agriculture is limited, often focusing on evaluation of soil contamination and contaminant uptake into crops (e.g., Attanayake, 2014; Clarke, Darrel, & Bain, 2015; McClintock, 2012; Sharma, Basta, & Grewal, 2015; Warming et al., 2015). Although these are important research questions, investigating soils' contribution to food production potential within an urban area is lacking.

This study investigates production potential of urban agriculture within a small urban area – Roanoke, Virginia, U.S.A. We complete a comparative analysis of food production potential in two ways: 1) using soil productivity capability based upon state agricultural documents, and 2) using estimated production for specific crops – similar to other urban agriculture studies. This paper starts with a brief introduction to urban agriculture and its contribution to urban ecosystem services, then explains why soil productivity capability should be estimated, even within an urban area. In the following sections, we introduce our study site, explain why Roanoke is an appropriate venue for such analysis, we describe our methods for the comparative analysis, and compare results provided by the two methods.

2 The Urban Agriculture Ecosystem

A functioning ecosystem consists of a set of different organisms interacting with each other and their surrounding physical environment (Odum, 1969). "Ecosystem services are the benefits people obtain from ecosystems" (Millennium Ecosystem Assessment, 2005) p. vii). Benefits include *provisioning services*, e.g. food, fiber, and fresh water; *regulating services*, e.g. air quality, climate, and disease; *cultural services*, e.g. education, social, and sense of place; and *supporting services*, e.g. soil formation, primary production, and nutrient and water cycling (Millennium Ecosystem Assessment, 2005). While in the past, urban areas were considered sterile environments not capable of providing ecosystem services, research has shown this is not true — ecosystem services are active in urban environments (Bolund & Hunhammar, 1999; Effland & Pouyat, 1997; Pickett et al., 2001; Pouyat, Szlavecz, Yesilonis, Groffman, & Schwartz, 2010; Setälä et al., 2014).

Urban agriculture is "the growing, processing, and distribution of food and nonfood plant and tree crops and the raising of livestock, directly for the urban market, both within and on the fringe of an urban area" (Mougeot, 2006) p 4). Urban agriculture takes many forms and sizes – plants in containers on balconies and patios, home gardens, community gardens and farms (Doron, 2005; Pearson, Pearson, & Pearson, 2010). Urban agriculture represents one type of ecosystem present within an urban environment — humans interact with plants, insects, soils, and soil organisms for food production (Bolund & Hunhammar, 1999).

Studies have documented ecosystem services provided by urban agriculture. *Provisioning services* include food (Alaimo, Packnett, Miles, & Kruger, 2008; Gittleman et al., 2012; Pourias, Duchemin, & Aubry, 2015) and income (Bernholt, Kehlenbeck, Gebauer, & Buerkert, 2009; Drescher, Holmer, & Iaquinta, 2006; White, 2014; Zezza & Tasciotti, 2010). *Cultural services* include community building and social interaction (Agustina & Beilin, 2012; Cohen & Reynolds, 2015; Dunlap, Harmon, & Kyle, 2013) and feelings of peace or stress relief (Hale et al., 2011; White, 2014). *Supporting services* include water cycling by using harvested rainwater (e.g., Parece, Lumpkin, & Campbell, in press; Redwood, Bouraoui, & Houmane, 2014) and recycled waste water (e.g., Barker-Reid, Harper, & Hamilton, 2010; Juarez, 2009; Makoni, 2014; Rojas-Valencia, Orta de Velásquez, & Franco, 2011), and nutrient cycling from using waste water for irrigation (e.g., Makoni, 2014; Rojas-Valencia et al., 2011) and composting solid waste (e.g., Adam-Bradford, 2006; Eriksen-Hamel & Danso, 2009; Sotamenou & Parrot, 2013). *Regulating services* are documented from indirect measures - reducing greenhouse gas emissions related to the reduction in transportation from producing food more locally in an urban area (e.g., Albright, 2013; Kulak, Graves, & Chatterton, 2013; Propersi, 2009) and from rainwater harvesting (e.g., Parece et al., in press).

3 Urban Soils

Soils, even within urban areas, are formed by climate, organisms, landforms, parent materials, and time (Pickett & Cadenasso, 2009; Scheyer & Hipple, 2005). Urbanization disturbs the heritage of existing soils, and current pedological processes, by truncating or burying soil profiles, sealing soils through construction of impervious surfaces, and reshaping terrain by filling depressions or suppressing topographic irregularities (Effland and Pouyat, 1997; Galbraith, 2003; Scheyer and Hipple, 2005). This disruption negatively impacts soils in many ways, i.e. higher bulk densities, loss of soil horizons, loss of organic matter, higher soil temperatures, lack of moisture, contamination, and disruption of natural cycling of nutrients and water (Effland & Pouyat, 1997; Galbraith, 2003; Scheyer & Hipple, 2005).

Soil survey practices have traditionally focused upon rural agriculture, so surveys of urban areas usually lack the detail, procedures, and classification systems that might best record the urban setting. As such, most soils found within urban areas are commonly classified as *urban land or urban land complexes* (Effland & Pouyat, 1997; Scheyer & Hipple, 2005). Such designations indicate the aforementioned disturbances from non-agricultural human activities (Effland & Pouyat, 1997; Galbraith, 2003; Scheyer & Hipple, 2005). Although, in the United States, soil surveys present suitability ratings that support some urban land uses, the nature and detail of the underlying classifications and delineations do not support an understanding of urban ecology.

In addition, consistent with other characteristics of an urban environment, urban soils have a heterogeneity that varies across time and space (Pavao-Zuckerman & Byrne, 2009; Pickett & Cadenasso, 2009; Pouyat et al., 2010). However, some of these differences could be amenable to agricultural production – higher amounts of organic matter can be found in residential areas, compared to commercial and industrial areas (Pouyat et al., 2010; Scharenbroch, Lloyd, & Johnson-Maynard, 2005), and natural soils, considered to be undisturbed by human activity, can be found as isolated pockets scattered throughout an urban area (Effland & Pouyat, 1997; Scheyer & Hipple, 2005).

Although today we think of agricultural soils as incompatible with urbanization, many urban soils have recent histories as productive agricultural soils, as is documented by losses of prime agricultural land to urbanization (Dillman & Cousins, 1982; Nizeyimana et al., 2001; Plaut, 1980). Furthermore, while substantial evaluation focuses on contaminants, urban soils are rarely included when evaluating an urban locale for its capacity to support agroecosystems. Only two such research studies were located - (Erickson, Lovell, & Méndez, 2013; Taggart, Chaney, & Meaney, 2009). Taggart, et al. (2009) completed a *land inventory* for vacant lands appropriate for urban agriculture for Cuyahoga County, Ohio (includes the City of Cleveland) and included soils noted as *Prime Farmland* by the U.S. Natural Resources Conservation Service (NRCS) within his evaluation. Erickson, et al. (2013) likewise inventoried an entire county – Chittenden County, Vermont (includes the City of Burlington) in his *land inventory*, but included both *Prime Farmland* and *Farmland of Statewide Importance*. Neither of these studies included production capacity. In our study, we include a *land inventory* and estimates of production potential based upon two alternative methods, one using soils, for land solely contained within one city, using geospatial analysis.

4 Study Site

Roanoke (Figure 1), southwestern Virginia's largest city (111 km^2), is located in a valley between the Blue Ridge Mountains and the Alleghany Highlands. Historically, the city has served as a regional transportation hub for rail and road traffic, with related services and industries to support its population. Although a small urban area, Roanoke is intensely urbanized – especially with respect to population density (896 persons per square kilometer).

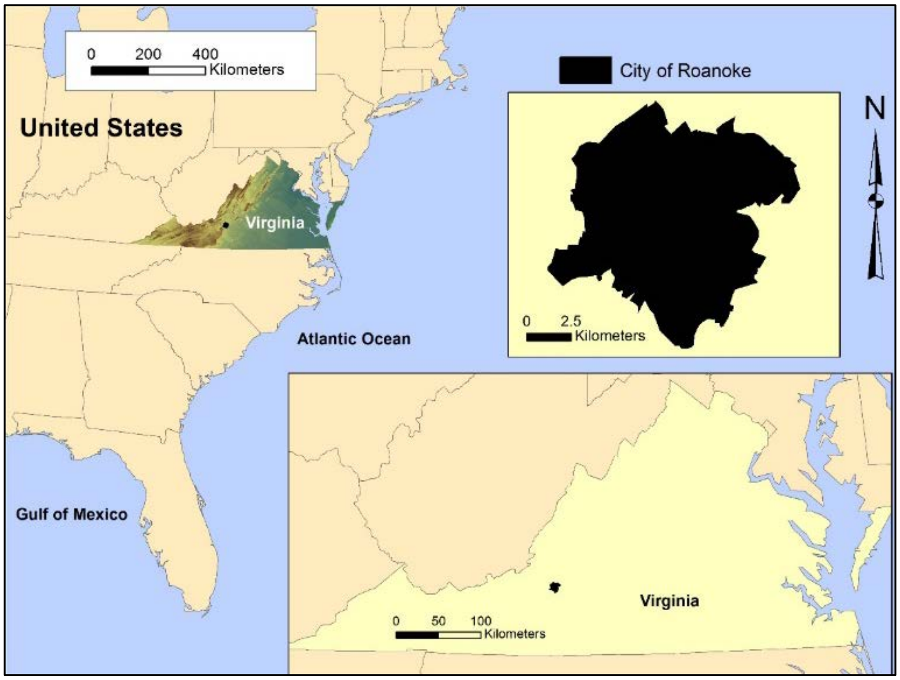

Figure 1. City of Roanoke reference map (shapefiles from the City of Roanoke and Virginia Geographic Information Network)

Roanoke's physical setting is relevant to understanding the function of its soils. Its position within the southern region of Virginia's ridge and valley physiographic province, (NRCS, 1997) where the valley encounters a sharp topographic rise of about 305 meters, situates it to receive sediments containing contrasting mineralogies from two upland branches of the Roanoke River. As a result, the valley's soils are formed less from the fertile limestone terrain of the northern ridge and valley, and more from the mixed mineralogies of sediment loads of Roanoke River's tributaries, including those of the metamorphic uplands of the Blue Ridge. Further, the narrow gorge east of Roanoke where the Roanoke River passes eastward from the ridge and valley region may have restricted eastward flowing discharge, creating numerous terrace deposits that characterize local terrain.

This complex history leaves the Roanoke region with a variable soil substratum, including some soils of limited agricultural potential and other more productive soils, often unfavorably positioned with respect to terrain. As a result, both slopes and mineralogies of the valley's soils are problematic for agricultural uses. Further, many of these soils occur in intricate spatial patterns that intermingle dissimilar soils. Thus, patterns depicted in Figure 2a provide only a rudimentary sketch of the region's soil resources. Further, as noted previously, some local soils previously used for agriculture have been modified by urbanization's alterations of the landscape.

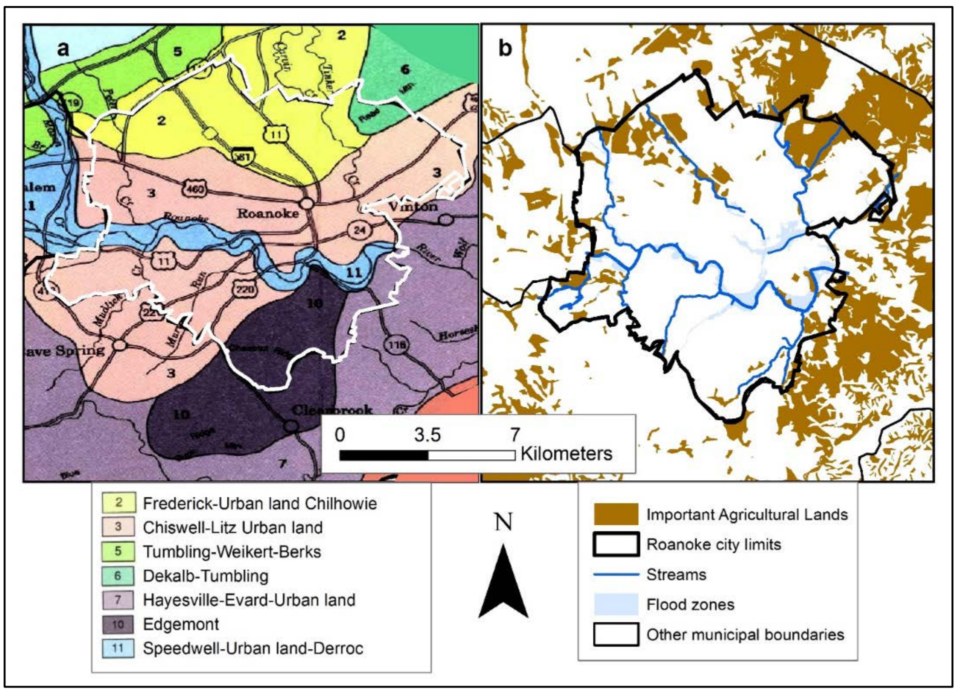

Figure 2. Soils within the City of Roanoke (Figure 2a is a georeferenced image from NRCS, 1997; Figure 2b constructed from shapefiles from the Virginia Department of Conservation and Recreation and the City of Roanoke)

Another resource helps us understand Roanoke's soils. Figure 2b shows areas designated as Virginia's agriculturally important soils (Virginia, 2007). Virginia Agricultural Model (Virginia, 2007) identifies Virginia's agriculturally important lands (prime farmlands, historic farm lands, other agriculturally suitable lands) as part of an effort to protect them from encroachment by urban land uses. This effort applied several criteria, including the NRCS's definition of prime farmland (principally, slope, land cover, and soils properties) to define five separate ratings indicating the significance of land for agricultural production. Within the City of Roanoke, the Commonwealth identified 1,457 hectares of agriculturally important land.

Furthermore, the city forms an appropriate site for our food production analysis, as many of its residents (total population – 99,428 (U.S. Census, 2015)) either suffer from, or are exposed to food insecurity – the average poverty rate is 22.4% (1/3 of block groups exceed this rate) (U.S. Census, 2015), average food insecurity rate is 16.9% (almost double the state average of 9.6%) (Feeding America, 2014), and average rates of student eligibility for the National School Lunch Program is 75%, almost double the state average (69% of schools exceed this rate) (Virginia, 2015).

Urban agriculture is practiced within the city -- two urban farms, several community gardens, and numerous home gardens. The farms and community gardens were not situated because of the soil that was available, rather they were located because of site availability – both urban farms occupy sites of formerly vacant property and the community gardens were sited because the properties were either vacant or because property owners were amenable to siting community gardens (Powell, 2013) (Figure 3). Home gardening is widely practiced within the city, scattered throughout various residential areas (Parece, et al. in press).

Figure 3. Hurt Park Community Garden in the City of Roanoke, Virginia, sited on vacant residential property. (Photo by second author 2013)

5 Methods

To analyze food production potential for the City of Roanoke, we first conducted a *land inventory* – identification of sites of current agriculture production and lands available for future agriculture production. Then we identify soils and calculate food production potential using two methods, as described below.

5.1 Land Inventory for Agriculture Production

A *land inventory* is a geospatial analysis used to identify land available within the City of Roanoke as potential sites for new urban agriculture. Within the literature, *land inventories* are conducted using a variety of methods but most start with a vacant land use analysis (e.g., Balmer et al., 2005; Horst, 2008; Kaethler, 2006; McClintock et al., 2013), among others). We started with identifying three types of land cover – impervious surfaces, tree canopy cover, and open water. Then, within GIS, we erased these areas from the City's boundary polygon shapefile; the remaining areas we identified as open lands, forming potential urban agriculture sites.

The second step of our land inventory identified historical and current land use for each potential site. We eliminated those open areas contained within the airport, railyards, active recreation areas (golf courses, a national park and city parks), quarries, and a wastewater treatment plant. We utilized data from the Virginia Department of Environmental Quality and the United States Environmental Protection Agency to evaluate those open areas within brownfields, or identified contaminated sites for their clean-up status, regulatory prohibitions in place, and any potential adverse human health exposure, and eliminated open areas contained within potentially harmful sites. After evaluating land use, we subdivided remaining open areas into five types of urban agriculture forms – urban farms, community gardens, home gardens, orchards, and schoolyard gardens (the entire step-by-step process and specifics on how the areas were categorized, we refer to Parece and Campbell, pending publication).

5.2 Food Production Potential

As noted previously, methods for estimating production potential vary. First we used a method introduced by Peters, Bills, Wilkins, & Fick (2009), hereinafter referred to as the *'soils productivity method'*. Second, we will be using a combination of state and federal agricultural records, Jeavons' (2012) estimates, along with records specific to the City of Roanoke – those from both urban farms and the Roanoke Community Garden Association, hereinafter referred to as the '*urban food production method*'. After calculating potential from both methods, we will compare them to each other.

5.2.1 'Soils Productivity Method'

Peters, et al. (2009) developed a method for assessing the production potential of agricultural land (agriculture land-use category) within New York State using soils productivity records. Peters, et al. (2009) first developed a Human Nutritional Equivalent (HNE) measure which represented a basket of food that one person would need to consume in one year to meet the requirements of My Food Pyramid (now updated and called *My Plate* - http://www.choosemyplate.gov/). Instead of calculating production rates of individual foods within this basket, for each hectare of agricultural land, Peters, et al. (2009) used proxy crops – tall hay fescue rates for perennial forage crops (to represent 19% of food within HNE) and corn silage rates for high-value annual crops (to represent 81% of food within HNE). The perennial forage crops proxy represented 52% of meat, eggs, and dairy within HNE. High-value annual crops proxy represented 100% of grains, vegetables, fruits, oils, and sweeteners and 48% of meat, eggs, and dairy within HNE. For all agricultural lands, they identified the soil type, then used soils' production rates for the two proxy crops to calculate total production capability. Finally, they used productivity rates to identify foodsheds for each New York State urban area. We note that Peters et al. (2009) used the National Land Cover Database (NLCD) records to identify agricultural lands, thus any areas of urban land cover (or land available for potential production within that urban area) were not included in their calculations.

Peters et al.'s (2009) advantage in calculating rates using this method resulted from an earlier study (Peters et al., 2007) in which they had calculated food production needs for 42 different types of diets using 41 different foods for New York State, thus creating a basis to compare productivities using proxy crops. The '*soils productivity method'* - with proxy crops -

was repeated by Smith (2014) for an Appalachian regional analysis, and by Zumkehr and Campbell (2015) in a temporal analysis for the United States.

To use this '*soils productivity method'*, we first completed a comprehensive analysis of soils and agricultural potential for the *land inventory*. Note - schoolyards were excluded from soils analysis because locations of urban agriculture on any schoolyard would be at the discretion of school officials. We used the Soil Survey Geographical (SSURGO) shapefile for Virginia soils, downloaded from the NRCS. This data contains soil information collected as part of the National Cooperative Soil Survey, prepared in part by field observation (NRCS, 2015). The shapefile delineates and labels areas ("mapping units") of soils observed by field survey and aerial photography (including some mapping units that are composed of unlike soils too small to separate at the scale of the map).

We intersected this shapefile with the *land inventory* shapefile to identify those soils by mapping unit (MU) for each location. For each MU, we identified the soil (e.g., 18B, 18C and 18B = Frederick silt loam, letter relates to different slopes) and reviewed the Virginia Nutrient Management Standards and Criteria (Virginia, 2014) documentation for that specific soil. We identified for each soil, the production potential for corn silage (kg per hectare) (Table 1 provides select examples). For those MUs that listed more than one soil, e.g., MU 25C and 25D = Groseclose-Litz complex), we used the lowest production potential of the two soils – i.e., in this case, 5,729.6 kg per hectare for Litz. For all soils listed as urban land, urban land complexes, or steep slopes (letter code E or steeper), we used the lowest production potential – 5,729.6 kg per hectare. Since urban agriculture within the United States is typified by vegetable and fruit production (infrequently for eggs, and rarely for meats), we did not include a calculation for the perennial forage proxy crop.

Table 1. Selection of soils and corn silage productivity potential (Virginia 2014)

Soil	Productivity coding	Corn silage productivity	
		tons per acre	kg per hectare
Edgemont	IIIb	20.5	7,529.3
Groseclose	IIb	22.5	8,263.9
Litz	V	15.6	5,729.6
Sindion	Ia	25.4	9,329.0

5.2.2 'Urban Food Production Method'

For this method, we consulted multiple sources. Firstly, we reviewed Jeavons' (2012) method - *'grow biointensive'* – which considers a closed, interrelated production system, focusing on soil health, high density of inter-cropped plants and no chemical inputs, among other things. Jeavons (2012) provides estimates of three different production levels – low (beginners), intermediate, and high ("excellent gardener with exceptional soil and climate" (p 177)) for individual crops including vegetables, grains, and fruits. We discussed the *Biointensive* method with urban farmers in Roanoke -- the owner of Lick Run Farm, the manager of Heritage Point Farm and Roanoke Community Garden Association board members. In addition, Lick Run Farm and one Roanoke Community Garden board member provided production records. We reviewed on-line records from U.S. Department of Agriculture National Agriculture Statistics (USDA NASS) (http://www.nass.usda.gov/Statistics_by_State/Virginia/index.php) 5-Year Crop Estimates for Virginia and the Virginia Apple Growers Association.

6 Results and Discussion

6.1 Land Inventory Analysis

We determined that the city has 2,304.7 hectares of open areas that could be potential sites for urban agriculture as community garden (691.7 hectares or 1709.2 acres), urban farms

(278.5 hectares or 688.2 acres), orchards (347.6 hectares or 859 acres), and home gardens (986.9 hectares or 2,438.8 acres).

6.2 Food Production Potential

6.2.1 'Soils Productivity Method'

Soils productivity level ranged from Ia (25.4 tons per acre) to V (15.6 tons per acre). The majority of the *land inventory* areas (77%) fell into the lowest level of productivity – 5,729.6 kg per hectare (Figure 4). The second greatest extent of the land inventory areas (15.4%) fell into the IIb (8,263.9 kg per hectare) level of productivity. Only 2.4% fell into the highest productivity level – 9,329.0 kg per hectare.

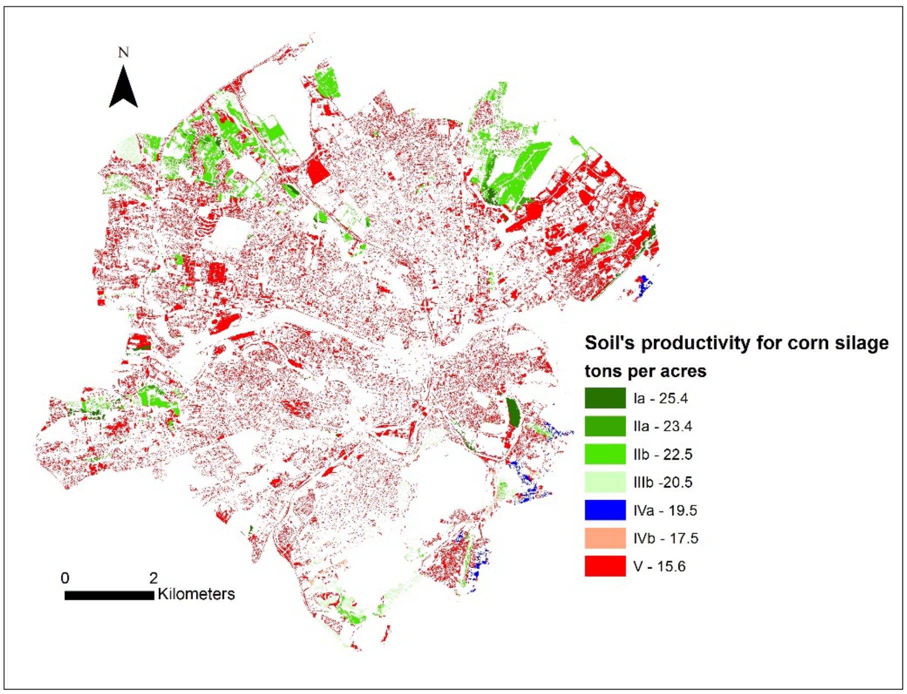

Figure 4. Soil productivity levels for the *land inventory*

Table 2 shows the estimated production using the *soils productivity method*. If all land identified under the *land inventory* as open and available for future urban agriculture sites were placed in production, gross production per growing season would be greater than 195 million pounds (88,836,532 kg) of corn silage (the proxy for annual crops), resulting in a gross production of 893.5 kg per capita. This amount does not take into account losses of crops that could be incurred at any point from harvesting to consumption, or any land that would be set aside for urban agriculture infrastructure (i.e. sheds, walkways, etc).

Table 2. Estimated Productivity using *'Soils Productivity Method'*

Urban Agriculture Form	Corn silage production potential – total kilograms	kg per capita*
Home Gardens	37,423,631	376.4
Community Gardens	27,167,400	273.2
Urban Farms	10,829,534	108.9
Orchards	13,415,967	134.9
Total	88,836,532	893.5

*Total production potential in kg divided by total population (99,428)

6.2.2 'Urban Food Production Method'

Gardeners with the Roanoke Community Garden Association sow a wide variety of crops (Powell, 2013), but actual production in pounds has not been recorded at any of the gardens (Maxey, 2015).

Both Heritage Point Farm and Lick Run Farm also grow a very wide variety of crops (Kinzie, 2015; Williams, 2016). Lick Run provided us with their production records from 2015, Heritage Point was not able to provide us with similar documentation. However, they are both extremely familiar with Jeavons (2012). Initial production levels at both locations are much lower than the low productions estimates provided by Jeavons, with a few exceptions – carrots, tomatoes and eggplant at Heritage Point (Kinzie, 2015) and carrots and leaks at Lick Run (Williams, 2016). Soils in Roanoke are so disturbed and degraded that they require extensive evaluation and amendments, especially for micro-nutrients (both farms use organic methods, although are not yet certified organic by the USDA) (Kinzie, 2015; Williams, 2016). Both farms are relatively new, and thus, are not operating at full production capacity and likely won't be for several years. Furthermore, it seems unlikely that gardens in Roanoke will ever achieve

Jeavons' highest levels of production, because the humid climate of Virginia prevents planting crops at the density recommended (Kinzie, 2015; Williams, 2016). At best, the intermediate level of production could be achievable in Virginia, after much effort to improve soils. Given soils in their current status, carrots, tomatoes and spinach were identified as the nutrient-rich crops that could achieve the highest production levels.

Mr. Maxey with the Roanoke Community Garden Association was able to provide 2011 production totals from his own personal home garden (Table 3). He has been gardening for 14 years at his home and advised that soils were definitely a barrier to production, and in some instances, certain crops do better in pots – specifically, bell peppers, banana peppers, and parsley. His production records were consistent with comments from Lick Run and Heritage Point staff to the effect that high levels of production are difficult to achieve in Roanoke, with the exception of beans. He advised that his beans were intercropped with privet hedges— a practice that increased his production totals (Maxey, 2015).

Table 3 – Home Garden Production Records from 2011 (Maxey, 2015)

Crop	Pounds produced*	Area of crop (ft^2)**	Per 100 ft^2 (9.3 m^2)	Jeavons (2012) level
Swiss Chard	10.5	8	131.25	< low
Basil	13	15	86.7	intermediate
Tomatoes	21	20	105	low
Snap Beans (Bush)	19.7	10	196	high

*one pound ~ 0.45 kg

** one square foot ~ 0.09 square meters

Using only spinach, tomatoes, and carrots, Table 4 shows the estimated production potential of our *land inventory* using the *urban food production method*, for two production levels – low and intermediate – for potential community gardens, urban farms, and home gardens (orchards are discussed separately below). Within this table, we have calculated total production at each rate, assuming that the all land was placed in production for that one crop, i.e. for carrots at 100 pounds per 100 ft^2 (45.4 kg per 9.3 m^2) for all locations, total production would be almost 248 million pounds (112,469,241 kg) or a per capita rate of 1,131.2 kg. We have estimated total production for each crop – carrots, spinach, and tomatoes –then, in the *Totals'* section, assumed a production with no intercropping, and the land area divided – 50% in spinach, 25% in tomatoes, and 25% in carrots. For the low production potential level with no intercropping, production rate is 848.4 kg per capita.

Table 4 Production Potential using *Urban Food Production Method*

Production rate pounds per 100 ft^2 (9.3 m^2)*	Total production potential		kg per capita**
	pounds	kilograms (kg)	
Carrots			
100	247,952,232	112,469,241	1,131.2
150	371,928,348	168,703,861	1,696.7
Spinach			
50	123,976,116	56,234,620	565.6
100	247,952,232	112,469,241	1,131.2
Tomatoes			
100	247,976,116	112,469,241	1,131.2
194	481,027,330	218,190,327	2,194.5
Totals – assumes no intercropping, 50% of space is spinach, 25% tomatoes, and 25% carrots			
Low	848.4 kg per capita		
Medium	1,538.4 kg per capita		

*Jeavons (2012) rates are per 100 ft^2 (9.3 m^2)
**Total production potential in kg divided by total population (99,428)

6.2.3 Orchards

We report on orchards separately. The US Department of Agriculture lists very few tree crops for Virginia with apples, by far, the largest in production (USDA 2015). The Virginia Apple Growers' Association reports apple production in Virginia at 700 bushels per acre (0.4 hectares) and ~16,000 acres in production (6,475 hectares) (Virginia Apple Growers' Association, 2015). To estimate production, using Jeavons per 100 ft^2, we multiplied 700 bushels by 40 pounds per bushel, yielding 28,000 total pounds produced per acre, or 64.3 pounds per 100 ft^2 (29.2 kg per 9.3 m^2). Jeavons (2012) reports productivity levels at 50, 75, and 100 pounds per 100 ft^2 (22.7, 34.0 and 45.4 kg per 9.3 m^2) -- low, intermediate, and high levels, respectively.

Table 5 provides results for total pounds of apples that could be produced on 347.6 hectares (859 acres) identified as orchards from the *land inventory*. If all land area identified as orchards were placed under production, at the low level of production, greater than 18.5 million pounds (8,482,020 kg) of apples could be produced, or 85.3 kg per capita. Using the rate reported by the Virginia Apples Grower Association, slightly more production occurs at 24 million pounds (10,904,368 kg) or 109.7 kg per capita.

Table 5. Potential apple production for orchard areas identified under the *land inventory*

Production rate pounds per 100 ft^2 (9.3 m^2)	Total production potential		kg per capita*
	pounds	kilograms	
50	18,699,698	8,482,040	85.3
64.3	24,040,016	10,904,368	109.7
75	28,049,547	12,723,061	128.0
100	37,399,396	16,964,081	170.6

*Total production potential in kg divided by total population (99,428)

6.2.4 Food Production Comparison

As a reminder, because urban agriculture within the United States is typified by vegetable and fruit production, infrequently for eggs, and rarely for meats, we only used corn silage as a proxy for potential production under the *soils productivity method*, and thus for comparison to the *urban food production method*. The per capita rate under the *soils productivity method* for all *land inventory* locations is 893.5 kg. Using the low production rate for the *urban food production method*, the per capita rate for community gardens, home gardens, and urban farms is 848.4 kg and adding to that figure the per capita rate for orchards - 85.3 kg for a total of 933.7 kg per capita — only 40.2 kg (4.4%) more than the *soils productivity method*. We are comparing to the low productivity level as per our urban farmers, with initial production commencing, in Roanoke, at best, we could meet Jeavons' low productivity level.

However, because soil qualities improve with continued cultivation, production rates will increase, so the *soils productivity method* may be preferred for estimation of urban food production. For example, if soils in the lowest productivity category (5,729.6 kg per hectare) were improved to the IIb capability level (8,263.9 kg per hectare), total production potential would rise by 31.0% to 256,162,680 pounds (116,194,629 kg) or 1,168.6 kg per capita. If all soils were improved to achieve maximum production capacity (9,329.0 kg per hectare) (as a reminder-- our urban farmers feel that in Roanoke, we can only achieve Jeavons' intermediate level), a 44% (or 1,284.5 kg per capita) increase could be achieved.

7 Conclusions

Results of our study demonstrate that the *soils productivity method*, introduced by Peters, et al (2009), and subsequently used by Smith (2014) and Zumkehr and Campbell (2015) is a valid and useful method for estimating initial food production capability of urban lands converted to agriculture, especially when choosing crops species that are meant to maximize initial production capacity and nutrient provision for residents. This comparison might change slightly when using a different crop, but one of the major reasons for urban agriculture is to help address food insecurity, as such it behooves gardeners and farmers to produce food that will provide the best production amounts and the best nutritional requirements for residents. As soils improve, higher production levels can be assessed, and estimates for intercropping included.

Our analysis offers one strategy for using soils productivity capacity to evaluate food production potential for urban agriculture — one that provides for a fundamental assessment. Further approaches will be needed, specifically to extend the analysis to evaluate soils for suitability of more specific capabilities, i.e. raising of other root crops, leaf crops, fruit or nut trees, and for form, i.e. rows, containers, mounding, or multi-cropping. Furthermore, although urban agriculture has a demonstrated ability to provide, and to increase many urban ecosystem services, it still remains to address social inequalities in access for all urban residents.

Our paper compares of two different methods for estimating production capability. The methods outline here are not a capability estimate for meeting daily nutritional requirements for people. We would need to adjust for the percent of land to be used for infrastructure and other supporting services for agriculture production and include a loss adjustment factor (the amount of food lost between harvesting and consumption). Once these figures are included, a comparison of the per capita production with the MyPlate Standards (or other institutional standards) should be accomplished to estimate the capability of an urban area to meet the nutritional requirements for a healthy lifestyle for all residents.

We note that procedures applied here are available to other urban regions, but the nature of the soil survey in urban regions forms a limitation because of the coarse level of spatial detail, and the lack of applicability of soil classification strategies to the urban setting. Such issues form priorities for future efforts, as projections indicate that urban populations, and the extent of urban regions will continue to increase in future.

Urban agriculture is becoming prevalent in many areas of the world. Urban soils, previously considered as degraded and unworthy of consideration as productive resources, are providing more than foundations for urban buildings -- they are generating ecosystem services by supporting urban agriculture. Since we will never have complete knowledge of all food produced within an urban area – food varieties are an individual preference and many food producing plants are cultivated within pots and planters – we are unable to track, exactly, the total production capability for all urban areas. As such, a new methods must be defined used to better estimate production in urban areas, as is now estimated for rural areas. The *soils productivity method* appears to be an acceptable measure for such production estimates.

Acknowledgements

This research was financially supported by Virginia Space Grant Consortium 2015/2016 Graduate Research Fellowship. This publication was developed under STAR Fellowship Assistance Agreement No. FP-91769301-0 awarded by the U.S. Environmental Protection Agency (EPA). It has not been formally reviewed by EPA. The views expressed in this publication are solely those of Tammy Erlene Parece and EPA does not endorse any products or commercial services mentioned in this publication.

Disclosures

The authors declare that there is no conflict of interest regarding the publication of this article.

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