GEOSPATIAL ANALYSIS OF URBAN TREE DISTRIBUTION AND EFFECTIVENESS OF ECOSYSTEM SERVICES IN WASHINGTON, D.C. WITH RELATION TO TRAFFIC VOLUME

by

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Graduate Faculty
of
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of
Master of Science
Biology

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Geospatial Analysis of Urban Tree Distribution and Effectiveness of Ecosystem Services in Washington, D.C. with Relation to Traffic Volume

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By

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DEDICATION

I dedicate this thesis to my grandfather, an avid naturalist, teacher, leader, and lover of God’s gift of Earth.

ACKNOWLEDGEMENTS

I conducted this research after brainstorming and collaborating with the National Parks Service and Casey Trees. This research was funded by the Trees Virginia Academic Scholarship for 2021. Dr. Travis Gallo guided this research through every stage, giving advice and encouragement along the way, and I am incredibly grateful for his help.

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Geographic Information System .... GIS

ABSTRACT

GEOSPATIAL ANALYSIS OF URBAN TREE DISTRIBUTION AND EFFECTIVENESS OF ECOSYSTEM SERVICES IN WASHINGTON, D.C. WITH RELATION TO TRAFFIC VOLUME

Angela R. Gaal, M.S.

George Mason University, 2021

Thesis Director: Dr. Henry Travis Gallo

Ecosystem services – and their economic role in providing goods to humans – is discussed as a critical planning focus for urban sustainability. Incorporating nature-based solutions provides a holistic approach to environmental policy that apply to economic, social, and ecosystem disciplines per geographic location. Chapter 1 explores publicly available tree point data to categorize street tree species according to their efficiency in providing stormwater protection, shade, carbon sequestration, air purification, and aesthetic value. The distribution of ecosystem services was determined using ArcGIS Pro 2.4.0. Chapter 2 determines the focal correlation between mean traffic volume data (2016-2019) and air purification services provisioned by public street trees using ArcGIS Pro 2.4.0 and R. Not all cities have the same demographic, climate, geography, etc., therefore environmental policy should be case-specific. Results indicate that geographic information systems (GIS) serve a key purpose to provide policy makers visual representations of geographic locations

and a big picture view for creating policies that promote long term urban sustainability through cost-effective prowess and strategic management.

CHAPTER ONE

Introduction

As the human population continues to grow, the idea of improving urban sustainability has increasingly become more important to address. Thus, decisions we make to ensure our population's safety and health is of utmost importance. How we approach environmental issues as a society has changed dramatically over the past 100 years. The battle raging in the 1960s and 1970s between urban growth and conservation, however, diverged into an overwhelming movement toward promoting nature synchronously for human and environmental well-being (Tallis, 2011). The approaches taken by politicians, agencies, nongovernmental organizations (NGOs), and the public, however, differ in response to the issue of urban sustainability and effective natural resource management. Involvement in these areas provides hopeful progress toward balance between conserving natural resources and using ecosystem services provided by nature, but we must be clear on the criteria for "effective" policy making.

Ecosystem services play a significant role in people's views about nature and what goods and benefits nature provides. In 2005, the Millennium Ecosystem Assessment evaluated how the world's ecosystems have changed over time (Reid, 2005). This assessment was a stock of the world's natural resources and provided insights for how ecosystems can be managed effectively to promote growing biodiversity and greater natural output for urban development. As the human population grows, the demand for clean water, food, and clean air increase. Thus, necessities depend on the efficiency with which ecosystem services are rendered (Millennium Ecosystem Assessment Board, 2003).

Efficiency, or effectiveness, can be defined as "the achievement of stated objectives… in utilitarian, economic terms as maximizing total welfare" (Martin et al., 2014). Longer term monitoring of ecosystem services redefines the term "efficiency" to extend past short-term outcomes and focus more on core motivation for sustainability and conservation action (Martin et al., 2014). When we consider the effectiveness of ecosystem services in terms of public street trees, we focus not only on the outputs of chemical materials, physiology, cultural benefits to society, etc. but on how those processes and materials can be maximized to last for years to come and more importantly, the why. Why should our society work vigorously to put in place systems that last for 50, 100, 200 years? Why should our culture care about the environment, and how do differing cultural interpretations impact how we treat the earth holistically? To propose a foundational motive for conservation actions is to give this stewarding work greater value.

Urban tree canopies, specifically, support nutrient cycling and oxygen regulation, promote climate resilience through shade provision and carbon sequestration, provide protective soil barriers against erosion, influence symbiotic relationships with other species through habitat provision, and maintain aesthetic, cultural fulfillment to humans (Mills et al., 2016; Mexia et al., 2018). As urban development continues, planners look toward incorporating stand-alone trees along streets to mitigate climate change and provide ecosystem services that promote urban sustainability for future generations to enjoy.

Differing Value Measures

The responsibility of decision makers is to be aware of the current social conditions when creating changes to policies that would otherwise disrupt the equilibrium of the system. Scientific evidence presented through mapping ecosystem services available in a geographic area can serve as a guideline or measurement of city health (Parkhurst, 2017). However, a difficulty in effective policy making lies with our value measure, which differs with everyone. Not every choice will lead to the same results, therefore it may be beneficial to consider multiple variables simultaneously (National Research Council, 2012).

Overall value differences throughout the local human population certainly affect the efficiency of cultural ecosystem services based on how individuals grew up, how they were taught to think about the surrounding environment, and their definition of "home." We all, however, have an innate desire to be "rooted in belonging and attachment" (Scruton, 2012). If decision makers' goal is to create an atmosphere with clean air for medical health *in addition* to an oasis where people feel a sense of place, they must divert from the tendency to view urban planning from a surface-level perspective, meaning planting trees without considering what ecosystem services might be available based on species morphology and how those available services might impact one another.

Monopolizing One Ecosystem Service Above Other Big Bucket Services

Another problem typically seen in the development of cities is visualizing environmental benefits singularly. For instance, planting trees solely for aesthetic beauty minimizes the fact that nature works as a complex framework of interactions between species and their environment (Salmond et al., 2016). Focusing on maximizing one ecosystem service above another when planting trees may result in a decline of other ecosystem services necessary to fulfill other societal needs. Without understanding the relationships between ecosystem services provided by street trees, oftentimes the result is a decline, or even elimination of one service and poor stewardship of urban spaces. This decline is especially dangerous now as urban growth continues to explode and demand for ecosystem services continues to increase (Bennett et al., 2009). Therefore, we should focus on maximizing multiple services simultaneously to build a more sustainable urban environment.

One way to approach looking at ecosystem service value is through mapping the distribution of each ecosystem service and conducting a gap analysis. A gap analysis allows us to infer where specific ecosystem services are lacking and which species to plant in those areas to increase service provisioning in the "gaps." In an ecosystem service study conducted in South Africa, Egoh et al. (2008) found that one service does not always benefit other services, but relationships may change among ecosystem services based on management, resulting in maximization of more than one ecosystem service simultaneously. It is difficult to assess correlations between ecosystem services and how policies affect these services as knowledge about these relationships remains limited, but big picture studies, such as this study, allow policy makers to infer positive action in city planning (Bennett et al., 2009). Here, I focus on public street tree management and the ecosystem services they provision to Washington, D.C. residents.

Objectives

This chapter categorizes the public street trees of Washington, D.C. by five broad ecosystem services that each species provides – 1) stormwater runoff, 2) air purification,

3) carbon sequestration, 4) shade, and 5) aesthetic beauty – and maps the distribution of each ecosystem service across the city. The two objectives of this chapter were to 1) provide a tree/ecosystem service dataset from which additional studies can build and policy makers can use as scientific evidence to support decisions about urban sustainability and 2) determine the distribution of these five broad ecosystem services provided by urban street trees and identify areas where specific ecosystem services are minimally provisioned or are completely lacking.

Methods

Species Categorization

I used the Urban Forestry Street Tree spatial data layer, maintained by the City of Washington, D.C. as a base data layer to categorize tree species in Washington, D.C. The urban forestry street tree dataset is used to log and monitor the planting of new trees and the health status of currently existing street trees in the District of Columbia. To develop a more current dataset of ecosystem services, tree records that did not indicate present, healthy trees of a specific species and tree records last edited before 2015 were excluded from this study. Each tree species (n = 273) was categorized according to the ecosystem services they provide most efficiently according to the literature (Berland 2017; Castro-Diez 2019; Salmond 2016). I chose five ecosystem service categories to focus on for this study: aesthetics, air purification, stormwater mitigation, shade and cooling, and carbon sequestration (Table 1). After each species was categorized, species-specific records were joined to the individual street tree point data in the Urban Forestry Street Tree layer. This final connection provided a spatial categorization of ecosystem services provided by public street trees across D.C.

Table 1. Tree species categorizations for five ecosystem services provided by urban street trees (Stormwater mitigation, Shade, Air Purification, Carbon Sequestration, and Aesthetics) based on the Urban Forestry Street Tree data layer maintained by the City of Washington, D.C.

ECOSYSTEM SERVICE	SPECIES	REFERENCES
Stormwater	American Elm, American Holly, American Hop Hornbeam, American Smoketree, American Sycamore, Amur Maple, Ash, Augustine Elm, Bald Cypress, Bea Schwartz Dutch Elm, Birch, Blackhaw Viburnum, Black Locust, Black Pine, Black Walnut, Blandford Dutch Elm, Blue Atlas Cedar, Bloodgood London Plane tree, Boxelder Maple, Boxwood, Buford Holly Hedge, Bur Oak, Carolina Silverbell, Cedar, Cherry, Cherrybark Oak, China Snow Lilac, Chinese Elm, Chinese Flame tree, Chinese Fringetree, Chinese Pistache, Chokecherry, Colorado Blue Spruce, Columnar English Oak, Columnare Red Maple, Columnare Sugar Maple, Cottonwood, Crimean Linden, Cypress, Dawn Redwood, Dogwood, Dogwood (Kousa), Downy Serviceberry, Dura Heat' River Birch, Eastern Redbud, Eastern Redcedar, Elm, Elm (Accolade), European Beech, European Black Alder, Flowering Dogwood, Forest Pansy Redbud, Fosters Holly, Fragrant Sumac, Freeman Maple, Ginkgo, Ginkgo (female), Ginkgo (male), Ginkgo Princeton Sentry, Glenleven Linden, Green Ash, Green Pillar Oak, Green Vase Japanese Zelkova, Greenspire Littleleaf Linden, Groenveldt Dutch Elm, Hackberry, Hardy Rubber Tree, Hawthorn Winter King, Hedge Maple, Hickory, Honeylocust, Hornbeam, Hornbeam (European)(Common), Horsechestnut, Inkberry Holly, Japanese Black Pine, Japanese Cryptomeria, Japanese Pagodatree,	American Conifer Society 2020 Anderson and Pezeshki 1999 Arbor Day Foundation 2020 Baraldi et al. 2019 Barrett et al. 1990 Bassuk Bhatta et al. 2018 Boyd Nursery Co. 2020 Buiteveld et al. 2014 (Burns and Honkala) Sluder 1990 Carretero et al. 2017 Chen et al. 2016 Claessens 2010 Connon 2020 Coulston et al. 2002 Culley and Hardiman 2007 Dineva 2017 dnr.wi.gov 2007 Drzewiecka et al. 2019 Forsyth 2007 Freeborn et al. 2012 Gillner et al. 2015 Gilman and Watson 1993 Gilman and Watson 2018 Gotsch et al. 2018 Gourdji 2018 Guries and Smalley 1990 Han et al. 2014 Horticulture Unlimited 2020 hort.ifas.ufl 2015 Hounshell 2020 Huang et al. 2004 Jeong 2010 Jo 2012 Karnosky and Myers 1982 Kiss et al. 2015 Kiyomizu et al. 2019 Kuehler et al. 2016 Landscape America 2020 Kirwan and Kane 2009 Kleczewski and Herms 2012 Kou-Giesbrecht and Menge 2019

	Japanese Zelkova, Jefferson Elm, Jujube, Juniper, Katsuratree, Kentucky Coffeetree, Leyland Cypress, Linden, Littleleaf Linden, Live Oak, Loblolly Pine, London Plane Tree, Magnolia, Magnolia (Galaxy), Maple, Marshall Green Ash, Mimosa, Moraine Honeylocust, Mulberry, New Harmony Elm, Northern Catalpa, Norway Maple, Nuttall Oak, Oak, October Glory Red Maple, Okame Cherry, Osage Orange, Overcup Oak, Paperbark Maple, Pear, Persimmon, Pin Oak, Pink-Flowering Dogwood, Pioneer Elm, Pitch Pine, Plane Tree, Pond Cypress, Possumhaw, Post Oak, Princeton Elm, Purple Leaf Plum, Red Buckeye, Red Maple, Redbud, Regen Japanese Pagodatree, River Birch, Rose of Sharon, Rotundiloba Sweetgum, Sawtooth Oak, Scotch Elm, Scots Pine, Serviceberry, Shadblow Serviceberry, Shademaster Honeylocust, Shingle Oak, Shumard Oak, Siberian Elm, Silver Maple, Skyline, Honeylocust, Slender Silhouette Sweetgum, Smooth-leaf Elm, Snowdrift Crabapple, Sourwood, Southern Catalpa, Southern Red Oak, Sovereign Pin Oak, Staghorn Sumac, Star Magnolia, Sugarberry, Summershade Norway Maple, Sunburst Honeylocust, Swamp White Oak, Sweetbay Magnolia, Sweetgum, Sweetgum (sterile), Thornless Honeylocust, Tree-of-heaven, Tupelo, Turkish Filbert, Tuscarora Crape Myrtle, Village Green Japanese Zelkova, Virginia Pine, Vitex, Washington Hawthorn, Water Oak, Weeping Willow, Winged Sumac, White Pine, Whitehouse Callery Pear, Willow, Willow Oak, Witch-hazel, Yellow Buckeye, Yellowwood, Yew, Yoshino Cherry	Kwak et al. 2020 Leopold 1980 Lou 2015 Maeglin and Ohmann 1973 Malaviya et al. 2019 Marquis Sekse 2015 McLemore (Burns) 1990 Megonigal and Day 1992 Missouri Botanical Garden 2020 Monrovia 2020 Morton Arboretum 2020 Moser et al. 2015 NC State extension 2020 Neufeld 1983 Niemiera 2009 Niemiera 2018 Nowak 1992 Nowak 1993 Nowak 1996 Nowak 2000 OSU 2020 Park et al. 2018 Peterson USDA 2018 Pietras-Couffignal and Robakowski 2019 Ranney 1994 Ranney et al. 1999 Rindy et al. 2019 Roloff 2009 Roloff 2011 Rutgers 2013 Saeed et al. 2016 Samara and Tsitsoni 2014 Sauer 2007 Scharenbroch 2011 Schooling 2015 Seiler et al. 2019 Selmi 2016 Si et al. 2018 Simon et al. 2014 Song 2013 Stirban et al. 1979 Stokes and Samuelson 2010 Takahashi et al. 2005 Taylor's Nursery 2020 Temple 2012 The Spruce 2020 TomaĐevic et al. 2004 Turk et al. 2017 UF IFAS 2020 UKY 2020 UofA Klingaman 2010 Urban Habitiats 2012 Urošević et al. 2019 Wang et al. 2016 Wang et al. 2018 Weber 1982 Woo et al. 2003 WSU 2020

		Yoon et al. 2013 Yuan 2013 Zhang et al. 2009 Zhang et al. 2016 Zhu et al. 2019
Shade	American Beech, American Elm, American Hop Hornbeam, American Linden, Amur Corktree, Amur Maackia, Arnold Crabapple, Ash, Aspen, Augustine Elm, Bea Schwartz Dutch Elm, Beijing Gold Lilac, Black Oak, Black Walnut, Blackjack Oak, Blandford Dutch Elm, Bloodgood London Planetree, Bur Oak, Cherry, Cherry (Snowgoose), Cherrybark Oak, Chestnut Oak, China Snow Lilac, Chinese Chestnut, Chinese Elm, Chinese Flame Tree, Chinese Fringe tree, Chinese Pistache, Chinese Pistachio, Chinkapin Oak, Cockspur Hawthorn, Columnare Norway Maple, Commelin Dutch Elm, Cottonwood, Crape Myrtle, Crimean Linden, Crimson Cloud Hawthorn, Crimson King Norway Maple, Cucumber Magnolia, Cypress, Darlington Oak, Dawn Redwood, Deborah Norway Maple, Dove Tree, Dura Heat' River Birch, Eastern Redbud, Elm, Elm (Accolade), Emerald Queen Norway Maple, European Beech, European Mountain-Ash, Fir, Forest Pansy Redbud, Formosan Gum, Fragrant Snowbell, Freeman Maple, Ginkgo, Ginkgo (male), Ginkgo Princeton Sentry, Glenleven Linden, Goldenrain Tree, Green Mountain Sugar Maple, Green Pillar Oak, Green Vase Japanese Zelkova, Greenspire Littleleaf Linden, Groenvelt Dutch Elm, Hackberry, Hardy Rubber Tree, Hickory, Honeylocust, Horsechestnut, Japanese Black Pine, Japanese Pagodatree, Japanese Zelkova, Jefferson Elm, Jujube, Juniper, Katsuratree, Kentucky Coffeetree, Lavalle Hawthorn, Leyland Cypress, Lilac, Linden, Littleleaf Linden, Live Oak, Loblolly Pine, London Plane Tree, Maple, Mimosa, Moraine Honeylocust, Mulberry, New Harmony Elm, Northern Catalpa, Nuttall Oak, Oak, Okame Cherry, Osage Orange, Paperbark Maple, Pear, Persimmon, Pin Oak, Pioneer Elm, Plane Tree, Post Oak, Princeton Elm, Radiant Crabapple, Red Horsechestnut, Red	Akbari 2002 Anderson and Pezeshki 1999 Arbor Valley Nursery 2020 Barker 1984 Buiteveld et al. 2014 (Burns and Honkala) Burton 1990 Burns (Smith) 1990 Carretero et al. 2017 Chen 2017 Corchnoy 1992 Coulston et al. 2002 Culley and Hardiman 2007 Dineva 2017 dnr.wi.gov 2007 Forsyth 2007 Freeborn et al. 2012 Friedman 2010 Gillner et al. 2015 Gilman and Watson 1993 Gilman and Watson 2018 Gotsch et al. 2018 Guries and Smalley 1990 Hall 2008 Han et al. 2014 Horticulture Unlimited 2020 Hounshell 2020 hort.ifas.ufl.edu 2015 Huang et al. 2004 IAState 2020 Jablonski 2017 Jeong 2010 Jo 2012 Karnosky and Myers 1982 Kirwan and Kane 2009 Kiss et al. 2015 Kiyomizu et al. 2019 Kleczewski and Herms 2012 Kuehler et al. 2016 Kwak et al. 2020 Leopold 1980 Lettl and Hýsek 1994 Liang et al. 2017 Lindell 2017 Lou 2015 Malaviya et al. 2019 Marquis Sekse 2015 McPherson 2010 Meyer 1995 Missouri Botanical Garden 2020 Monrovia 2020 Morton Arboretum 2020 NC state extension 2020 Niemiera 2009

	Maple, Red Oak, Redbud, Redmond American Linden, Regent Japanese Pagodatree, River Birch, Rock Chestnut Oak, Rotundiloba Sweetgum, Royal Paulownia, Sassafras, Sawtooth Oak, Scarlet Oak, Seneca Chief Sugar Maple, Shademaster Honeylocust, Shingle Oak, Shumard Oak, Silver Linden, Silver Maple, Skyline Honeylocust, Slender Silhouette Sweetgum, Smooth-leaf Elm, Southern Catalpa, Southern Magnolia, Southern Red Oak, Sovereign Pin Oak, Sugar Maple, Sugarberry, Summershade Norway Maple, Sunburst Honeylocust, Swamp Chestnut Oak, Swamp White Oak, Sweetgum, Sweetgum (sterile), Sycamore Maple, Thornless Honeylocust, Trident Maple, Tulip Poplar, Tupelo, Turkey Oak, Turkish Filbert, Village Green Japanese Zelkova, Washington Hawthorn, Water Oak, White, Oak, White Pine, Whitehouse Callery Pear, Willow, Wisteria, Yellow Buckeye, Yellowwood	Niemiera 2018 Nowak 1993 Nowak 1996 Nowak 2000 OSU 2020 Park et al. 2018 Pietras-Couffignal and Robakowski 2019 Ranney 1994 Ranney et al. 1999 Rindy et al. 2019 Rutgers 2013 Saeed et al. 2016 Samara and Tsitsoni 2014 Scharenbroch 2011 SelecTree 2020 Selmi 2016 Si et al. 2018 Simon et al. 2014 Smeal and Coartney 1984 Song 2013 Stirban et al. 1979 Stokes and Samuelson 2010 Takahashi et al. 2005 Taylor's Nursery 2020 Temple 2012 The Spruce 2020 TomaĐevic et al. 2004 Turk et al. 2017 UF IFAS 2020 Uhrin and Supuka 2016 UKY 2020 Urban Habitiats 2012 Wang et al. 2015 Wang et al. 2018 Weber 1982 Wondwossen 2012 Woo et al. 2003 WSU 2020 WSU 2020 WSU PNW Plants 2020 Yoon et al. 2013 Zajicek 1991 Zhang et al. 2009 Zhang et al. 2016
Air Purification	American Beech, American Elm, American Linden, American Sycamore, Arkansas Black Spur Apple, Ash, Aspen, Augustine Elm, Bay Laurel, Bear Oak, Beijing Gold Lilac, Birch, Black Locust, Black Oak, Black Pine, Black Walnut, Blandford Dutch Elm, Bloodgood London Plane Tree, Blue Atlas Cedar, Boxelder Maple, Boxwood, Buford Holly Hedge, Carolina Silverbell, Cedar, Cherry, Cherry (Snowgoose), Chinese Flame Tree, Cockspur Hawthorn, Colorado Blue	Akbari 2002 American Conifer Society 2020 Anderson and Pezeshki 1999 Arbor Valley Nursery 2020 Arora et al. 2014 Bae et al. 1986 Baraldi et al. 2019 Barrett et al. 1990 Berlizov 2007 Blonskaya 2019 Boyd Nursery Co. 2020 Burns (Smith) 1990 (Burns and Honkala) Sluder 1990

	Spruce, Columnare Norway Maple, Commelin Dutch Elm, Copper Beech, Cottonwood, Crabapple, Crabapple (Harvest Gold), Crimean Linden, Cucumber Magnolia, Cypress, Dawn Redwood, Deborah Norway Maple, Deodar Cedar, Dogwood, Dove Tree, Eastern Redbud, Elm, Elm (Accolade), Emerald Queen Norway Maple, European Beech, European Mountain-Ash, Fir, Flowering Dogwood, Forest Pansy Redbud, Freeman Maple, Ginkgo, Ginkgo (female), Ginkgo (male), Ginkgo Princeton Sentry, Glenleven Linden, Goldenrain Tree, Green Ash, Green Mountain Sugar Maple, Green Pillar Oak, Greenspire Littleleaf Linden, Groenveldt Dutch Elm, Hackberry, Hawthorn Winter King, Hedge Maple, Hemlock, Hickory, Horsechestnut, Japanese Maple, Japanese Snowbell, Jefferson Elm, Juniper, Kwanzan Cherry, Linden, Littleleaf Linden, London Plane Tree, Magnolia, Magnolia (Galaxy), Maple, Marshall Green Ash, Mimosa, Moraine Honeylocust, Mulberry, New Harmony Elm, Northern Catalpa, Norway Maple, Norway Spruce, Nuttall Oak, Oak, Osage Orange, Pawpaw, Pear, Persian Parrotia, Pin Oak, Pink-Flowering Dogwood, Pioneer Elm, Pitch Pine, Plane Tree, Pond Cypress, Poplar, Post Oak, Princeton Elm, Purple Leaf Plum, Radiant Crabapple, Red Maple, Red Oak, Red Pine, Redbud, Redmond American Linden, River Birch, Royal Paulownia, Sassafras, Saucer Magnolia, Sawtooth Oak, Scarlet Oak, Scotch Elm, Scots Pine, Seneca Chief Sugar Maple, Shademaster Honeylocust, Shingle Oak, Shortleaf Pine, Shumard Oak, Siberian Elm, Silver Linden, Silver Maple, Skyline Honeylocust, Smooth-leaf Elm, Snowdrift Crabapple, Sourwood, Southern Catalpa, Southern Magnolia, Southern Red Oak, Sovereign Pin Oak, Spruce, Staghorn Sumac, Sugar Maple, Sugarberry, Summershade Norway Maple, Sunburst Honeylocust, Thornless Honeylocust, Thundercloud Plum, Tree-of-heaven, Trident Maple, Tulip Poplar, Turkish Filbert, Tuscarora Crape	Carretero et al. 2017 Chen et al. 2016 Coulston et al. 2002 Culley and Hardiman 2007 Dave's Garden 2020 Dineva 2017 Druart et al. 2006 Drzewiecka et al. 2019 Freeborn et al. 2012 Gillner et al. 2015 Gilman and Watson 1993 Gilman and Watson 2018 Gotsch et al. 2018 Gourdji 2018 Guries and Smalley 1990 Hall 2008 Han et al. 2014 Hijano 2005 Jeong 2010 Karnosky and Myers 1982 Kiss et al. 2015 Kiyomizu et al. 2019 Kleczewski and Herms 2012 Kuehler et al. 2016 Kwak et al. 2020 Lettl and Hýsek 1994 Liang et al. 2017 Lindell 2017 Lou 2015 Maeglin and Ohmann 1973 Malaguti 2001 Malaviya et al. 2019 Martin et al. 2016 McLemore (Burns) 1990 Megonigal and Day 1992 Missouri Botanical Garden 2020 Monrovia 2020 Morton Arboretum 2020 Moser et al. 2015 NC State Extension 2020 Neufeld 1983 Niemiera 2009 Nowak 1992 Nowak 1993 Nowak 1996 Nowak 2000 OSU 2020 Ranney et al. 1999 Rindy et al. 2019 Rutgers 2013 Saeed et al. 2016 Samara and Tsitsoni 2014 Scharenbroch 2011 Seiler et al. 2019 SelecTree 2020 Selmi 2016 Sharma 2011 Si et al. 2018 Simon et al. 2014

	Myrtle, Virginia Pine, White Oak, White Pine, Whitehouse Callery Pear, Willow, Willow Oak, Yew, Yoshino Cherry	Smith 1973 Stirban et al. 1979 Stokes and Samuelson 2010 Takahashi et al. 2005 Taylor's Nursery 2020 The Spruce 2020 TomaĐevic et al. 2004 Troxel et al. 2013 UF IFAS 2020 UKY 2020 Urošević et al. 2019 Wang et al. 2015 Wang et al. 2016 Wang et al. 2018 Weber 1982 Woodland Trust 2020 Woodwell 2020 Woo et al. 2003 WSU PNW Plants 2020 Yoon et al. 2013 Yuan 2013 Zhang et al. 2009 Zhang et al. 2016 Zhu et al. 2019
Carbon Sequestration	Abrovitae, Alleghany Serviceberry, American Cranberry Viburnum, American Elm, American Hop Hornbeam, American Linden, American Sycamore, Amur Corktree, Arkansas Black Spur Apple, Ash, Aspen, Augustine Elm, Bald Cypress, Bear Oak, Birch, Black Locust, Black Walnut, Blackhaw Viburnum, Blandford Dutch Elm, Bloodgood London Plane Tree, Boxelder Maple, Bur Oak, Cedar, Cherry, Cherry (Snowgoose), Cherrybark Oak, Chinese Elm, Chinese Flame Tree, Chinese Pistachio, Colorado Blue Spruce, Copper Beech, Cottonwood, Crabapple, Crabapple (Harvest Gold), Cucumber Magnolia, Cypress, Dawn Redwood, Deodar Cedar, Eastern Redcedar, Elm, Elm (Accolade) Freeman Maple, Ginkgo, Ginkgo (female), Ginkgo (male), Ginkgo Princeton Sentry, Green Ash, Green Mountain Sugar Maple, Green Vase Japanese Zelkova, Groenveldt Dutch Elm, Hackberry Hemlock, Hickory, Honeylocust, Japanese Maple, Japanese Zelkova, Jefferson Elm, Juniper, Katsuratree, Kentucky Coffeetree, Kwanzan Cherry, Leyland Cypress, Lilac, Linden, Littleleaf Linden, Live Oak, Loblolly Pine, London Plane Tree, Longleaf Pine, Magnolia, Magnolia	Akbari 2002 Anderson and Pezeshki 1999 American Conifer Society 2020 Arbor day foundation 2020 Arora et al. 2014 Bae et al. 1986 Baraldi et al. 2019 Barrett et al. 1990 Berlizov 2007 Bhatta et al. 2018 Blonskaya 2019 Burns (Smith) 1990 Carretero et al. 2017 Chen et al. 2016 Coulston et al. 2002 Culley and Hardiman 2007 Dave's Garden 2020 Dineva 2017 Druart et al. 2006 Drzewiecka et al. 2019 Fang Liang et al. 2012 Gardenista 2020 Gilman and Watson 1993 Gilman and Watson 2018 Gotsch et al. 2018 Gourdji 2018 Guries and Smalley 1990 Hall 2008 Han et al. 2014 Hijano 2005 Horticulture Unlimited 2020 Hounshell 2020 Huang et al. 2004 Jeong 2010

	(Galaxy), Maple, Marshall Green Ash, Mimosa, Moraine Honeylocust, Mulberry, New Harmony Elm, Northern Catalpa, Norway Maple, Norway Spruce, Nuttall Oak, Oak, Overcup Oak, Pear, Persian Parrotia, Persimmon, Pin Oak, Pioneer Elm, Pitch Pine, Plane Tree, Pond Cypress, Poplar, Post Oak, Princeton Elm, Purple Leaf Plum, Radint Crabapple, Red Horsechestnut, Red Maple, Red Oak, Red Pine, Redmond American Linden, River Birch, Rose of Sharon, Rotundiloba Sweetgum, Royal Paulownia, Sassafras, Sawtooth Oak, Scarlet Oak, Scots Pine, Seneca Chief Sugar Maple, Serviceberry, Shingle Oak, Shortleaf Pine, Shumard Oak, Siberian Elm, Silver Linden, Silver Maple, Slender Silhouette Sweetgum, Smooth-leaf Elm, Snowdrift Crabapple, Sourwood, Southern Magnolia, Sovereign, Pin Oak, Spruce, Sugar Maple, Sugarberry, Summershade Norway Maple, Sunburst Honeylocust, Sweetbay Magnolia, Sweetgum, Sweetgum (sterile), Thornless Honeylocust, Tree-of-heaven, Trident Maple, Tulip Poplar, Tupelo, Turkish Filbert, Village Green Japanese Zelkova, Water Oak, Weeping Willow, White Fringetree, White Oak, White Pine, Whitehouse Callery Pear, Willow, Willow Oak, Witch-hazel, Yew, Yoshino Cherry	Jo 2012 Karnosky and Myers 1982 Kiss et al. 2015 Kiyomizu et al. 2019 Kleczewski and Herms 2012 Kuehler et al. 2016 Kwak et al. 2020 Leopold 1980 Liang et al. 2017 Lindell 2017 Lou 2015 Malaguti 2001 Malaviya et al. 2019 Martin et al. 2016 Marquis Sekse 2015 Maeglin and Ohmann 1973 Megonigal and Day 1992 Missouri Botanical Garden 2020 Monrovia 2020 Morton Arboretum 2020 Moser et al. 2015 NC state extension 2020 Neufeld 1983 Niemiera 2009 Niemiera 2018 Nowak 1992 Nowak 1993 Nowak 1996 Nowak 2000 OSU 2020 Park et al. 2018 Pietras-Couffignal and Robakowski 2019 Rindy et al. 2019 Roloff 2009 Rutgers 2013 Saeed et al. 2016 Samara and Tsitsoni 2014 Sauer 2007 Scharenbroch 2011 Sharma 2011 Si et al. 2018 Simon et al. 2014 Smith 1973 Song 2013 Stirban et al. 1979 Stokes and Samuelson 2010 Takahashi et al. 2005 Taylor's Nursery 2020 Temple 2012 The Spruce 2020 Troxel et al. 2013 UF IFAS 2020 UKY 2020 Urošević et al. 2019 Wang et al. 2018 Weber 1982 Wondwossen 2012 Woodland Trust 2020

		Woodwell 2020 Woo et al. 2003 WSU 2020 Yoon et al. 2013 Zhang et al. 2009 Zhang et al. 2016 Zhu et al. 2019
Aesthetics	Abrovitae, Alleghany Serviceberry, American Beech, American Cranberry Viburnum, American Elm, American Holly, American Hop Hornbeam, American Smoketree, Amur Maple, Arkansas Black Spur Apple, Arnold Crabapple, Aspen, Bald Cypress, Bay Laurel, Beach Plum, Beijing Gold Lilac, Birch, Black Locust, Black Pine, Blackhaw Viburnum, Blandford Dutch Elm, Bloodgood London Plane Tree, Blue Atlas Cedar, Boxwood, Buford Holly Hedge, Bur Oak, Carolina Poplar, Carolina Silverbell, Cedar, Cherry, Cherry (Snowgoose), Chestnut Oak, China Snow Lilac, Chinese Chestnut, Chinese Elm, Chinese Flame Tree, Chinese Fringetree, Chinese Pistache, Chinese Pistachio, Chinkapin Oak, Chokecherry, Cockspur Hawthorn, Colorado Blue Spruce, Columnar English Oak, Columnare Red Maple, Columnare Sugar Maple, Copper Beech, Cottonwood, Crabapple, Crabapple (Harvest Gold), Crape Myrtle, Crimson Cloud Hawthorn, Crimson King Norway Maple, Cucumber Magnolia, Cypress, Dawn Redwood, Deborah Norway Maple, Deodar Cedar, Dogwood, Dogwood (Kousa), Dove Tree, Downy Serviceberry, Dura Heat' River Birch, Eastern Redbud, Eastern Redcedar, Elm (Accolade), Emerald Queen Norway Maple, English Holly, European Black Alder, Fig, Fir, Flowering Dogwood, Forest Pansy Redbud, Formosan Gum, Fosters Holly, Fragrant Snowbell, Fragrant Sumac, Franklin Tree, Freeman Maple, Ginkgo, Ginkgo (male), Ginkgo Princeton Sentry, Glenleven Linden, Golden Chain Tree, Goldenrain Tree, Green Ash, Green Mountain Sugar Maple, Green Vase Japanese Zelkova, Greenspire Littleleaf Linden, Groenveldt Dutch Elm, Hackberry, Hawthorn Winter King, Hedge Maple, Hemlock, Hickory, Honeylocust, Hornbeam,	Anderson and Pezeshki 1999 Arbor Day Foundation Arora et al. 2014 Bae et al. 1986 Baraldi et al. 2019 Barrett et al. 1990 Bassuk Berlizov 2007 Blonskaya 2019 Boyd Nursery Co. Burns (Smith) 1990 Burton 1990 Carretero et al. 2017 Chen et al. 2016 Claessens 2010 Connon 2020 Corchnoy 1992 Coulston et al. 2002 Culley and Hardiman 2007 Dineva 2017 dnr.wi.gov 2007 Druart et al. 2006 Drzewiecka et al. 2019 Fang Liang et al. 2012 Forsyth 2007 Freeborn et al. 2012 Freilicher 2017 Gardenista 2020 Gillner et al. 2015 Gilman and Watson 1993 Gilman and Watson 2018 Gotsch et al. 2018 Gourdji 2018 Guries and Smalley 1990 Hall 2008 Han et al. 2014 Hijano 2005 Horticulture Unlimited 2020 hort.ifas.ufl 2015 Jablonski 2017 Jeong 2010 Jo 2012 Karnosky and Myers 1982 Kirwan and Kane 2009 Kiss et al. 2015 Kiyomizu et al. 2019 Kleczewski and Herms 2012 Klingaman 2010 Kou-Giesbrecht and Menge 2019 Kuehler et al. 2016 Kwak et al. 2020

	Hornbeam (European)(Common), Horsechestnut, Inkberry Holly, Japanese Apricot, Japanese Black Pine, Japanese Cryptomeria, Japanese Maple, Japanese Pagodatree, Japanese Plum, Japanese Snowbell, Japanese Stewartia, Japanese Zelkova, Jefferson Elm, Jujube, Juniper, Katsuratree, Kentucky Coffeetree, Korean Evodia, Kwanzan Cherry, Lavalle Hawthorn, Leyland Cypress, Lilac, Linden, Littleleaf Linden, London Plane Tree, Longleaf Pine, Magnolia, Magnolia (Galaxy), Maple, Marshall Green Ash, Mimosa, Moraine Honeylocust, Mountain Silverbell, Mulberry, Nannyberry, New Harmony Elm, Northern Catalpa, Norway Maple, Norway Spruce, Nuttall Oak, Oak, October Glory Red Maple, Okame Cherry, Osage Orange, Overcup Oak, Pagoda Dogwood, Paperbark Maple, Pawpaw, Peach, Pear, Persian Parrotia, Persimmon, Photinia, Pin Oak, Pink-Flowering Dogwood, Pioneer Elm, Plane Tree, Pomegranate, Pond Cypress, Poplar, Possumhaw, Princeton Elm, Purple Leaf Plum, Radiant Crabapple, Red Buckeye, Red Horsechestnut, Red Maple, Red Oak, Redbud, Regent Japanese Pagodatree, Rhododendron, River Birch, Rock Chestnut Oak, Rose of Sharon, Rotundiloba Sweetgum, Royal Paulownia, Sassafras, Saucer Magnolia, Sawtooth Oak, Scarlet Oak, Scotch Elm, Seneca Chief Sugar Maple, Serviceberry, Seven-son Flower, Shadblow Serviceberry, Shademaster Honeylocust, Shingle Oak, Shortleaf Pine, Shumard Oak, Silver Linden, Silver Maple, Skyline Honeylocust, Slender Silhouette Sweetgum, Smooth-leaf Elm, Snowdrift Crabapple, Sourwood, Southern Catalpa, Southern Magnolia, Southern Red Oak, Sovereign Pin Oak, Spruce, Staghorn Sumac, Stanley Plum, Star Magnolia, Sugar Maple, Sugarberry, Summershade Norway Maple, Sunburst Honeylocust, Swamp Chestnut Oak, Swamp White Oak, Sweetbay Magnolia, Sweetgum, Sweetgum (sterile), Sycamore Maple, Thornless Honeylocust, Thundercloud Plum, Tree-of-heaven, Trident	Landscape America 2020 Leopold 1980 Liang et al. 2017 Lou 2015 Malaguti 2001 Malaviya et al. 2019 Martin et al. 2016 Marquis Sekse 2015 McLemore (Burns) 1990 McPherson 2010 Megonigal and Day 1992 Missouri Botanical Garden 2020 Monrovia 2020 Morton Arboretum 2020 Moser et al. 2015 NC state extension 2020 Neufeld 1983 Niemiera 2009 Niemiera 2018 Nowak 1992 Nowak 1993 Nowak 1996 Nowak 2000 OSU 2020 Park et al. 2018 Peterson USDA 2018 Pietras-Couffignal and Robakowski 2019 Ranney 1994 Ranney et al. 1999 Roloff 2009 Roloff 2011 Rutgers 2013 Saeed et al. 2016 Samara and Tsitsoni 2014 Sauer 2007 Scharenbroch 2011 Schooling 2015 Seiler et al. 2019 SelecTree 2020 Sharma 2011 Si et al. 2018 Simon et al. 2014 Sluder 1990 Smeal and Coartney 1984 Smith 1973 Song 2013 Stirban et al. 1979 Stokes and Samuelson 2010 Takahashi et al. 2005 Taylor's Nursery 2020 Temple 2012 The Spruce 2020 TomaĐevic et al. 2004 Troxel et al. 2013 Turk et al. 2017 UF IFAS 2020 Uhrin and Supuka 2016 UKY 2020

	Maple, Tulip Poplar, Tupelo, Tukey Oak, Turkish Filbert, Tuscarora Crape Myrtle, Village Green Japanese Zelkova, Vitex, Washington Hawthorn, Water Oak, White Fringetree, White Oak, White Pine, Whitehouse Callery Pear, Willow, Willow Oak, Winged Sumac, Wisteria, Witch-Hazel, Yellow Buckeye, Yellowwood, Yew, Yoshino Cherry, Yucca	Urban Habitiats 2012 Urošević et al. 2019 Wang et al. 2015 Wang et al. 2016 Wang et al. 2018 Weber 1982 Wondwossen 2012 Woodland Trust Woo et al. 2003 WSU 2020 WSU PNW Plants 2020 Urban Habitiats 2012 Yoon et al. 2013 Yuan 2013 Zajicek 1991 Zhang et al. 2009 Zhang et al. 2016 Zhu et al. 2019

Ecosystem Service Analysis

To assess spatial provisioning of ecosystem services, I used the Calculate Density Geoprocessing tool using ArcMap ver. 2.8.0 (ESRI, Redlands, CA, USA). The Calculate Density tool calculates the density of points within a given cell size by dividing the total number of points by the area of the cell. I calculated the density of tree points for each ecosystem service category with a 300-m cell size. The returning vector data (shapefile) contained a value of the density of trees that provisioned the respective ecosystem service. I used this value as proxy for ecosystem service provisioning. I then converted these vector layers into rasters to assess the spatial distribution of ecosystem service provisioning.

Results

From the literature, 42.5% of tree species provisioned at least four of the five ecosystem services explored in this study (Table 1). Of the tree species studied, aesthetics

(238 species) was the most provisioned service followed by stormwater protection (175 species), shade (158 species), air purification (157 species), and carbon sequestration (151 species). All tree species provisioned at least one ecosystem service. Overall ecosystem service provisioning tended to be greatest in downtown east of the National Mall, specifically around Lincoln and Stanton Parks. Ecosystem service provisioning was also high in central and northwest Washington, D.C. Pockets of the city near the Anacostia River and directly north of Ivy City had minimal service density (Figure 1).

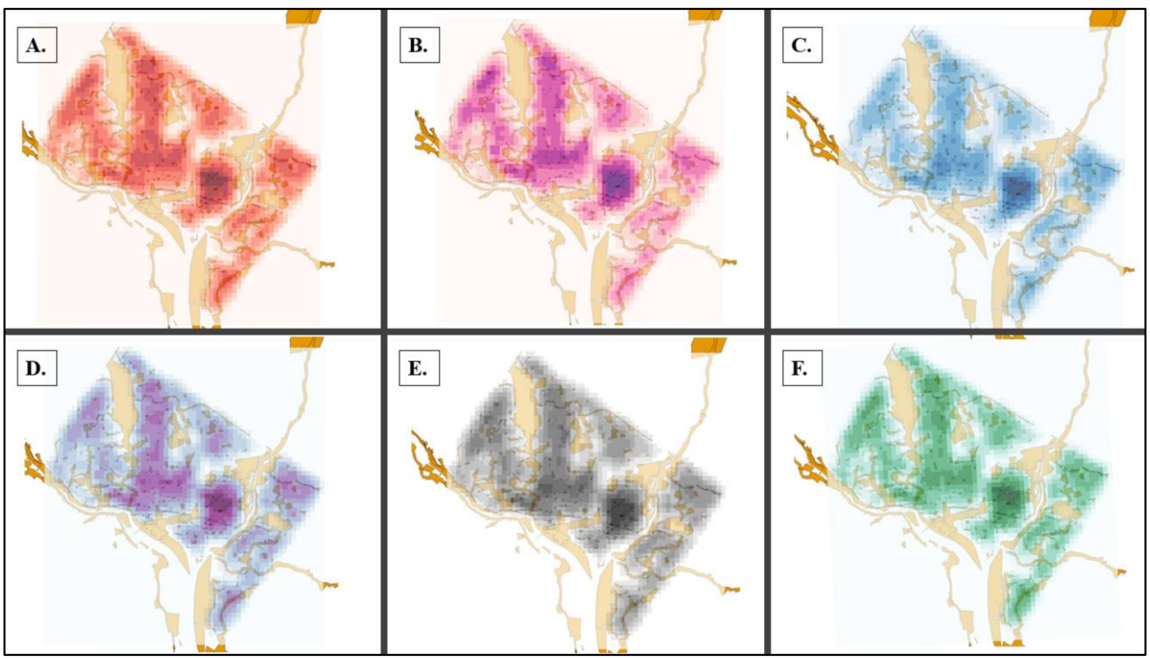

Figure 1. The provision distribution at 300-m resolution of A) aesthetics, B) air purification, C) shade, D) stormwater mitigation, and E) carbon sequestration. F) represents a GAP analysis of all 5 ecosystem services. Darker areas represent a higher overlap of multiple services in Washington, D.C. Orange areas represent areas with no data where no public tree point data was collected.

An important result of this study was a new spatially explicit tree/ecosystem service data product from which additional studies can build and policy makers can use as scientific evidence to support decisions about urban sustainability. This dataset is open access and located at George Mason University Dataverse (Gaal, 2021).

Discussion

Even with useful, high quality scientific evidence at our fingertips, we cannot simply weave data into policy decisions. With this in mind, we should address the lack of effective knowledge translation from raw data into the hands of policy makers. One way to breach this gap is using geographic information systems which provide clear visual representations of a geographic area as well as hard data that can be used contextually by policy makers. Through tree species categorization and a point density analysis, I determined where ecosystem services were provisioned across Washington, D.C. and where services might be lacking for future strategic planning. Results indicated that ecosystem service provisioning was not consistent across the District and that aesthetic beauty had the greatest density distribution.

Oftentimes trees are planted solely for artistic expression or attractiveness (Bourassa, 1988). However, planting for one purpose is not the most effective way to manage ecosystem services in urban areas, especially since interactions between tree species create a complex framework where one ecosystem service may benefit another. Some argue that because nature is already a successful working system which renews itself, we should create policies that incorporate more nature-based solutions into our city infrastructures (Lafortezza, 2018). Although my point density distributions of each ecosystem service did not show drastic differences across Washington, D.C., my analysis does identify areas lacking particular ecosystem services that should be prioritized.

Ecosystem Service Use and Effectiveness

Tree species studied did not exhibit the same number or type of ecosystem services, therefore the distribution of ecosystem services throughout Washington, D.C. was not consistent (Figure 1). Species morphology plays a large part in how effective tree species are at provisioning specific ecosystem services. For instance, some species are more suited to combatting urban heat islands which increase the local surface temperature (shade provisioning species) because of their broad canopies, large collective leaf-area, and high transpiration rates (Gillner et al. 2015). Other species, like black pine *(pinus nigra),* may still provide minimal shade provision but are better equipped to provision air purification. Black pine *(pinus nigra)* serves as an excellent biomonitor for airborne pollution and can store chemicals in its bark (Chiarantini et al. 2016). One limitation to my study was that all tree points were categorized as provisioning services equally regardless of size or age. However, younger trees with a smaller trunk diameter and smaller canopy do not provision ecosystem services as effectively. Jönsson and Snäll (2020) showed that ecosystem service functionality increases with tree age. When strategically planting, planners should consider planting adult trees or maintain the expectation that planted trees will not provision ecosystem services most effectively until grown.

Approximately 42.5% of the tree species studied provisioned four to five ecosystem services, and these species should be prioritized in planting to maximize effectiveness of ecosystem service provisioning. A few examples of specific species include the American Elm *(Ulmus americana),* Cypress *(Cupressus),* Hackberry *(Celtis),* Hickory *(Carya),* Linden *(Tilia),* London plane tree *(Platanus x acerifolia),* Moraine Honeylocust *(Gleditsia triacanthos),* Northern Catalpa *(Catalpa speciosa),* Norway Maple *(Acer platanoides),* Oak *(Quercus),* Red Maple *(Acer rubrum),* River Birch *(Betula nigra),* Turkish Filbert *(Corylus colurna),* White Pine *(Pinus strobus),* and Willow *(Salix).* Of course, some tree species are more suited to the Washington, D.C. climate than others, and some species have a higher tolerance of road salt, salt spray, and overall urban pollution than others. It is key to select tree species that meet all the criteria so that species don't have to compensate for the lack of a healthy environment by targeting their energy toward maintaining homeostasis.

Future Endeavors

Having the tools to see where we stand in regards to our "ecosystem health", provides a starting point for improvement. For example, as city foresters and planners think about how different ecosystem services interact and affect one another, we can use an integrated Ecosystem Services Review which utilizes GIS-based technology (Sieber and Pons, 2015). Five key steps should be used to approach ecosystem service management in cities: 1) identify the ecosystem services present in the city, 2) note possible adaptation, 3) think through how to optimize the existing ecosystem services, 4) identify the costs of actions and benefits of actions, and 5) develop strategies for accomplishing those benefits (Sieber and Pons, 2015). In tandem with these steps, geographic information systems provide visuals and statistics to guide planners. This framework does provide effective, positive results in ecosystem services management and can improve overall quality of life for people living in urban areas.

Limitations

This study was limited by the amount of data acquired. Some data points had to be discarded due to non-current tree point counts (recorded before 2015), unclear tree point notes from gathered data, and missing data in Washington, D.C. (as referenced in Figure 1). I also assigned each tree point a standard categorization of a specific ecosystem service regardless of the size or age of the tree when, in fact, younger trees with a smaller trunk diameter and smaller canopy do not provision ecosystem services as effectively (Jönsson and Snäll, 2020). Future research should take into consideration the age of individual trees, specifically comparing the effectiveness of ecosystem service provisioning in saplings versus full grown trees. Another study may consider the effectiveness of service provisioning based on season, whether trees provision ecosystem services more effectively in spring than winter and if there is a significant difference in the focal correlation between seasons and traffic volume. Finally, future research may consider how socioeconomic variables like population density or net income in local neighborhoods impacts the distribution and effectiveness of ecosystem service provisioning.

Conclusion

As urban development continues to grow, city planners and policy makers need management tools to help them know where ecosystem services are currently distributed and where those services are lacking. Of special concern is the decline of regulating services which affect the maintenance of other ecosystem services (Carpenter et al. 2009). The findings from Chapter 1 clearly indicate that not all ecosystem services are provisioned equally, and areas with lower ecosystem service provisioning seem to be around the edges of the city (Figure 1). Chapter 1 provides a complete dataset of current tree species planted in Washington, D.C. since 2015 and is a valuable tool for strategic future planting (Table 1).

CHAPTER TWO

Introduction

A Lack of Effective Information Transfer to Policymakers

There exists a “language” barrier between scientists and policy makers regarding how scientific evidence is applied in policy. Haskins and Margolis, (2015) clearly differentiate between the technical, systematic nature of scientific evidence and generalized, broad applications to policy from decision makers. Both are beneficial, just in different ways. For decision makers elected by the people in a democratic society, policy staff have little technical training of broader issues targeted to the district they serve and little time to become experts in an issue area before their superior steps onto the floor for a congressional hearing. For instance, staffers covering multiple issue, such as agriculture, natural resources, energy, etc. in one portfolio are forced to gain quick knowledge and grasp the broad scope of the issues to present to the representative. In this way, broader knowledge visualized by GIS allows them to highlight critical information for their superior’s decision-making (Haskins and Margolis, 2015).

But how do they know that the evidence they are using as support for their claim is valid, usable, and sufficient? In the past, the use of scientific evidence in policymaking was simply thought of as knowledge transfer, but simply adding more scientific evidence to a policy position doesn't address underlying political bias (Parkhurst, 2017). In the case of ecosystem services, data showing that planting more trees of a specific species improves air quality by filtering out molecules that pollute the air would be valuable evidence used to support urban sustainability locally. As Parkhurst (2017) states, "Nothing can be said to simply 'work' to inform policy when the policy involves more than a simple technical exercise." Each policy decision must be taken case by case.

Representatives' interest in environmental issues depends on the geography and business types in their district or state. For example, in Texas the logging industry provides employment for individuals and revenue for local logging businesses. Effective natural resource legislation allows for proper use and conservation of the lumber available in the region and is regulated locally by bodies such as the Texas Logging Council (Texas Forestry Inc, 2020). Representatives in Congress communicate with these local government bodies for feedback on what is important in the district economically, environmentally, and socially. For this reason, a standardized approach to lawmaking for all environments cannot be adopted. External validity applies in few scenarios and must be carefully considered.

Value-Driven Action

The more conflicting the core beliefs of decision makers, the more crucial the role of science in policy as a neutral marker and as a strategic tool (Ingold, 2014). In this way, science facilitates policy making and breaches the conflict gap. However, a trade-off exists in that when scientific knowledge is used strategically in policy, scientific credibility tends to decrease. The issue of trust oftentimes arises if policy makers take a political angle. So even if scientific evidence is used in policy, the complexity of variables that contribute to policy output may yield subpar results in finalized decisions (Ingold, 2014). Still, it has been noted that science does play a significant role in policy decisions because decision makers value expertise in the issue area in which they deal (Ingold, 2014).

Breach the Gap Between Science and Policy

But what else could contribute to effective policy making that otherwise would lie stagnant and motionless in the movement toward a more sustainable society? The answer is twofold: communication and relationships. When speaking of communication, knowledge is discovered, transferred, and used in such a way as to enable "evidence-informed" decision making for a specific scenario (Bednarek et al. 2018). Researchers oftentimes lack the resources and time to dedicate to thoughtful consideration of how their research fits into the policy realm (Bednarek et al. 2018). Therefore, a critical gap exists between knowledge acquired in the field and its place in policy. This must be breached by boundary spanning.

Effective communication is important but not sufficient to meeting the goal. It takes frequent collaboration to translate key scientific knowledge into something policy relevant (Bednarek et al. 2018). GIS helps breach the gap between science and policy by effectively communicating research through visuals to urban planners and policy makers. I sought to use the current street tree database I created to explore tangible policy-relevant scientific questions. From there, I considered how the distribution of air purification trees correlate with local traffic volume and told a story. By knowing where air purification trees were lacking spatially, urban foresters and planners can know where to plant specific tree species in Washington, D.C.

Objectives

The main objectives of this chapter were to 1) calculate the density of air purification provisioning trees in Washington, D.C., 2) assess the distribution of air purification provisioning trees and relate their distribution to local traffic volumes, and 4) develop policy-relevant maps from which to make recommendations to policy makers on future public tree planting.

Methods

The categorized street tree dataset was uploaded to ArcGIS Pro 2.4.0, and five new feature layers, one for each ecosystem service, were created by selecting attributes from the categorized street tree data table. I created a point density layers of trees that provision air purification at three spatial scales (120m, 300m, and 900m) for each ecosystem service by converting the point features to raster data through the point density tool. I chose output cell sizes of 120-m, 300-m, and 900-m to create density rasters at the three different spatial scales.

Traffic volume in Washington, D.C. for each 2016-2019 was downloaded from OpenData DC as shapefiles. Using R version 4.0.5 (R Core Team, 2021), each shapefile was converted to a raster and aggregated to 120-m, 300-m, and 900-m resolutions. During the aggregation processes the mean was taken for overlapping data values. For each spatial scale the mean of the 4 years was calculated for each cell. I then used a masking layer to convert raster cell values where public street trees were not sampled (large National Parks, cemeteries, university campus, etc) to NA to indicated “no data”. The reason for doing this was because these areas appear to have low tree density, when in fact, trees were not recorded in these areas and there were no data points for these locations. By converting these cells to NA, it removed them from our subsequent analyses.

I calculated the overall correlation between mean traffic volume and the density of air purification provisioning trees in Washington, D.C. at each 120-m, 300-m, and 900-m resolutions using the *cor* function in R, making sure to load the masking layer to block out areas where trees were not sampled (NA). I also calculated a focal spatial correlation between mean traffic volume and density of air purification provisioning trees at each spatial scale using the *corLocal* function in R. Focal analysis calculates the correlation of each cell within a moving window of the three nearest neighboring cells, offering more localized relationships between mean traffic volume and air purifying trees. The purpose of conducting this analysis at three resolutions was to provide city planners with density values based on need. This includes small-scale projects such as a city sidewalk where more existing data is needed per area or large-scale projects like a city greenspace where a courser value will suffice.

Results

At all three spatial scales I found low negative correlation (120-m, 300-m, and 900-m scales) between mean traffic volume data and density of air purification provisioning street trees. At 120-m resolution I found -0.17, at 300-m resolution -0.18, and at the 900-m scale -0.24. While the focal spatial correlation results do not give an overall value, I found high negative correlation between mean traffic volume and air purification provisioning trees along the central and west areas of the District near Rhode Island Ave NW and near Oxon Run Park and high positive correlation in parts of northwest Washington, D.C. surrounding Rock Creek Park (Figure 3).

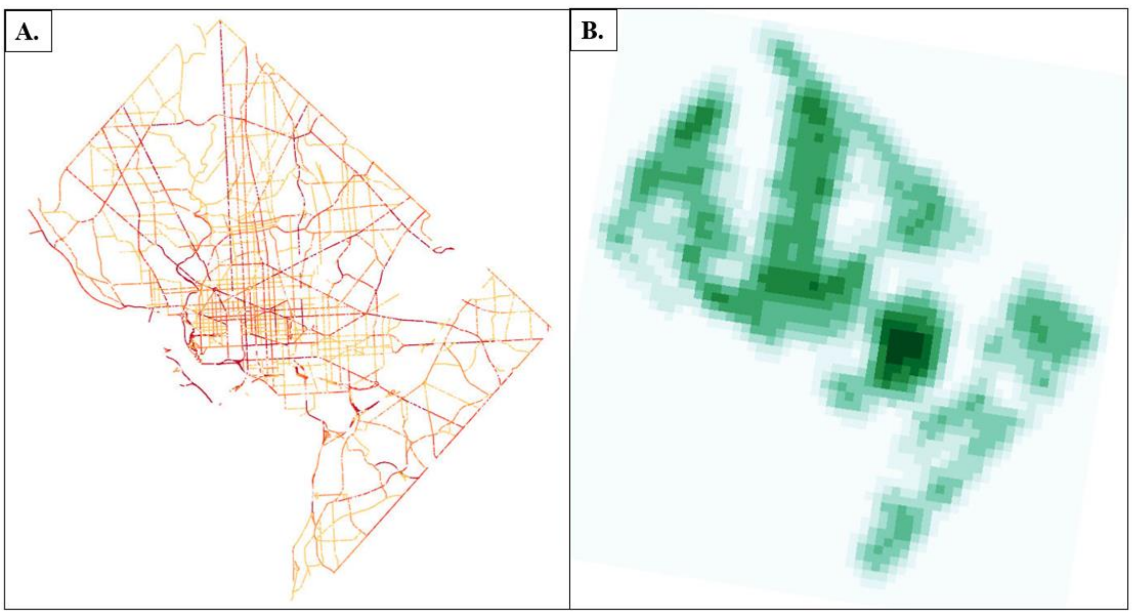

Figure 2. A) Mean traffic volume data for 2016-2019. Warmer colors indicated higher traffic volume. B) Density of air purification provisioning public street trees throughout Washington, D.C. White areas indicate areas with minimal or no data. Darker shading represents greater tree densities.

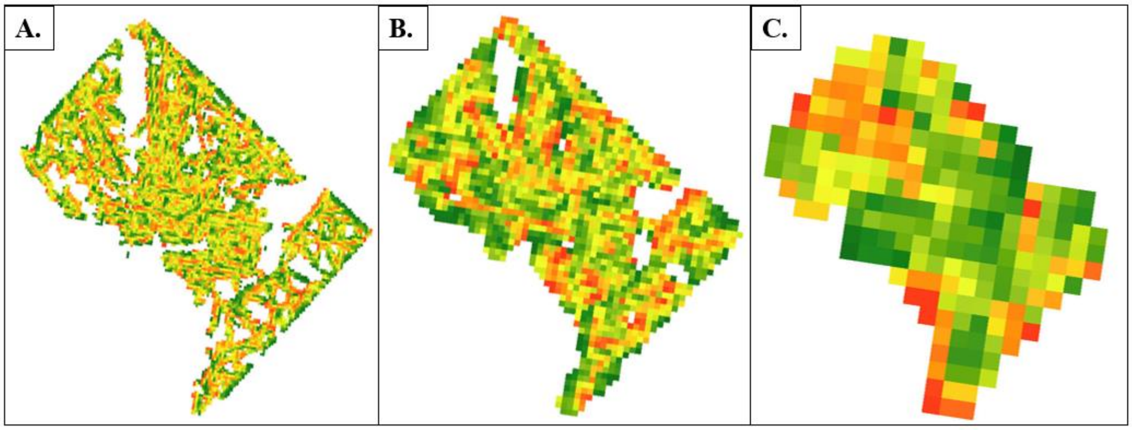

Figure 3. Focal correlation at A) 120-m resolution, B) 300-m resolution, and C) 900-m resolution of traffic volume and air purification provisioning in Washington, D.C. Green shades represent low or negative correlation and red shades represent high or positive correlation. White areas in maps A and B indicate areas with no data.

Discussion

Although urban environments continue to flourish, with a projected population growth of 1.2 billion people by 2030, research on environmental sustainability in urban settings has been limited in recent years (McDonald et al. 2020). Washington, D.C. serves as a clear example of study due to its aesthetic value as the capitol of the United States of America and as a location of urban growth. Using the ecosystem service categorization provided in Chapter 1, I explored whether the distribution of air purification services specifically correlates with local traffic volume. Results indicated slight negative correlation between tree distribution and local traffic volume at the 120-m, 300-m- 900-m scales. These results indicate that there is little to no relationship between trees that purify air and those areas in D.C. that likely have higher air pollution. Thus, there is potential for explicit tree planting guidelines that could help alleviate air pollution issues through nature-based solutions.

In urban environments, trees are oftentimes planted primarily for aesthetic beauty instead of air purification services or climate resiliency which could result in a decline of critical service provisioning for long term sustainability (Bennett et al. 2009). This could be the reason that most tree species exhibited aesthetic value (238 species) rather than air purification services (157 species) and why there existed a lower density distribution of air purification services with which to conduct the focal correlation with traffic volume. I found that the 120-m scale resulted in the least negative correlation (-0.17) compared to the focal correlation at the 900-m scale (-0.24) most likely because a finer scale resolution allowed for higher spatial accuracy in relation to traffic volume. With no positive correlation between traffic volume and air purification provisioning, it is likely there is no intentional effort in place to combat urban pollution using public trees. Washington, D.C. planners should explicitly plant tree species that provide air purification services in areas of high traffic volumes. Planners can use these maps as guidelines for where to prioritize future planting of specific tree species that may help reduce pollution in Washington, D.C. as it relates to traffic volume (Table 1). Although this study provides a focal correlation analysis for air purification provisioning alone, this type of analysis approach could be applied to other ecosystem services.

Identify Action Costs and Benefits with a Focus on Urban Sustainability

The planning of green infrastructure requires a chess-like approach, where planners consider all costs and benefits of vegetation with the goal of providing multifunctionality of vegetation in cities (Cameron and Blanuša, 2016). Management and planning of tree planting are difficult because species may differ in their effectiveness to provide desired ecosystem services based on their morphologies and age. For instance, tree growth rates and tree decomposition rates determine the rates of carbon sequestration and carbon release, respectively (Zhao and Sander, 2015). Though trade-offs exist, non-native species are often imported because they better provide fundamental services such as climate resiliency, air regulation, and soil erosion prevention than some native species and (Castro-Diez, 2019; Hoyle et al. 2017). Hoyle et al. (2017) recommends incorporating non-native species into urban environments as the climate continues to change, and this study provides an extensive list of designated native and non-native tree species found in Washington, D.C. that provide specific ecosystem services. One caveat, however, is that non-native species do not provide benefits to local urban wildlife and may reduce local habitat quality (Narango et al. 2018).

While urban trees provide an array of benefits to urban residents, they are likely not distributed equally across cities (Mexia et al., 2018). Factors such as species type, elevation, climate, etc. contribute to the distribution of ecosystem services throughout a geographic area, thus policy decisions related to urban sustainability should be contextually driven. More specifically, scientific evidence portrays internal validity, where one working system cannot be applied generally to all (Parkhurst, 2017).

To properly weigh the costs and benefits of planting in a specific way, policymakers must display comprehensive rationality, in which they gather all necessary information pertinent to the problem at hand (in the case we discuss here urban sustainability through green infrastructure) and concisely communicate their preferences based on the values they hold dear as a representative (Cairney, 2016). With these two ingredients, clear decisions can be made.

The Opportunities for Urban Planting

To promote urban sustainability, continued research on ecosystem services focusing on geographic mapping will provide planners a visual overview of what services are currently being provisioned in specific areas of cities and their correlation to socioeconomic variables. Planners will see the gaps to target specific service provisioning. As seen with this study, planners should strategically plant tree species which efficiently provide air purification in mid and southeast Washington, D.C. broadly (Figure 3) as well as in local neighborhoods where the correlation between high traffic volume and air purifying trees are low.

Limitations

The traffic volume dataset I used was missing data for specific areas within D.C., because traffic readers which collect data are moved every 1-3 years. I used traffic volume data for 2016-2019 to maximize the number of areas that data was collected and took the mean for same-location data over multiple years. However, data did not cover every road in D.C. Because of the lack of some data points for years within 2016-2019, the traffic volume dataset may not provide a true representation of where pollution exists in Washington, D.C., and the study was limited in its range of current data.

This study was also limited in the extent of recommendations that can be provided to city planners in Washington, D.C. While this study provides an overview of the extent of value of air purification service in the District, this study does not provide extensive explanation regarding other ecosystem services and how those service impact or are impacted by air purification changes. However, research indicates that increasing the provisioning of one service may elevate other ecosystem services depending on the types of relationships involved (Bennett et al. 2009; Nesshőver et al. 2017).

Conclusion

As urban development continues to expand, we need to adopt ways to shift our current management system to become more sustainable in all facets of society, including economically, culturally, and societally. One way to accomplish this goal is through nature-based solutions, including effective management of street trees (Nesshőver et al. 2017). The findings from Chapter 2 demonstrate that 1) air purification provisioning street trees are distributed throughout Washington, D.C. and 2) there is a low correlation between the density of air purification trees and local traffic volume. My findings provide guidance for city planners to plant more street trees that effectively provision air regulation (Table 1) in areas with low or negative correlation. To better understand the complexity of interactions between ecosystem services in Washington, D.C., similar focal correlation studies should be conducted for stormwater protection, shade, aesthetics, and carbon sequestration. Urban sustainability requires a shift toward nature-based solutions which result in a more cost-effective, renewable, and value-driven way of life for future generations (Frantzeskaki 2019; Lafortezza et al. 2018; Martin et al. 2014; Nesshőver et al. 2017).

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