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Vegetation plays an important role in regulating the health of urban ecosystems (Sanders, 2004; Jim, 2004). Riparian zones, parks, nature reserves, and other forms of urban vegetation help minimize atmospheric and hydrologic pollution and reduce the urban heat island effect (Weng, 2003). In this study I used satellite imagery to classify and quantify vegetative cover for sixteen of the most populated cities on Earth. It was found that London England had the greatest percentage of urban vegetation with 53% while Karachi Pakistan had the least at 3.06%. The highest correlating physical variables with urban vegetation were year of origin ($r^2 = -.602$), population density ($r^2=.531$) and latitude ($r^2=.215$).

Satellite imagery collected from NASA was analyzed to determine the percentage of vegetation cover in each of sixteen sample cities. The amount of vegetation recorded within the urban environments was dependent upon multiple variables. Climatic variables play a large role as habitat dictates vegetation cover. Physical independent variables including latitude, temperature, average annual rainfall, and elevation were tested for correlations with the dependent variable of urban vegetation. Further methods and analysis in this study include basic statistics, t-tests, and multiple step regression. Outside of physical variables, vegetation within the urban environment is largely determined by human decisions and behavior. Public planning, non-profit organizations, and private owners may have had more influence on the percentage of vegetation within urban environments than the restrictions of climatic variables. Further, the examination of physical and sociological variables in relation to urban vegetation is included in the discussion. The purpose of this thesis is to contribute to the academic field of geography specific to vegetation and environmental services in urban environments. Results may be a reference or guide to scholars, planners, developers, and residents of urban environments.

URBAN VEGETATION AND THE ENVIRONMENTAL HEALTH OF SIXTEEN GLOBAL CITIES

by

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Approved by

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CHAPTER I

INTRODUCTION

The earliest available records on planned urban parks date back to the 17th century. Paris France decorated its boulevards with trees, which was a practice that was adopted by many other European cities. Overcrowding and expansion of cities in Europe during the industrial revolution led to the creation of large public open spaces and the modern city park. Ultimately, the purpose of urban parks in the 18th century was to increase the sanitation of living areas in order to improve overall health (Botkin & Beverdidge, 1997). Preservation of green spaces in the United States can be traced back to the 19th century when Landscape Architect Frederick Law Olmsted was interested in creating urban green-spaces for aesthetic purposes as well as social and psychological benefits. Using both engineering and landscape design skills, Olmsted began planning New York City's Central Park in 1852. Since its inception, Central Park has served as a natural oasis amongst the concrete jungle of New York City (Small & Miller, 2003). Olmsted also played an important role in the design of San Francisco's Golden Gate Park. He advised Golden Gate Park's Landscape designer William Hammond Hall to experiment with different types of vegetation in order to transform the initially arid flora of the region into a fully productive and dynamic park space. During Olmsted's career as a landscape architect he designed many other urban parks including Boston's 'Emerald Necklace' and Franklin Park. Following Olmsted in the move towards the preservation of urban green spaces was Ebenezer Howard (Botkin & Beverdidge, 1997).

Ebenezer Howard coined the term 'Garden City' in his 1898 book *To-morrow: A Peaceful Path to Real Reform.* Howard envisioned a city that would combine the rustic health of country living and the urban activity of a residential community. Ebenezer grew up in England and travelled to Nebraska in his youth to spend time with the buffalo, as prescribed by his doctor.

While in Nebraska he found that farming wasn't for him and eventually he moved to Chicago where he began to focus on planning for the greater good. Howard then began to lecture on the practicality of starting Garden Cities around the country. The planned Garden City would be encircled by a green belt of agriculture and interspersed with parks at nine acres per thousand. The city itself was planned to be 1,000 acres with a total of 900 acres of parks. The first planned 'Garden City' was developed in Letchworth England and many more have been planned and deployed in multiple cities including Greenbelt, Maryland, Greenhills, Ohio and Greendale, Wisconsin. (Howard et al., 1965; Ward, 1992)

The next significant influential author on landscape architecture was Ian McHarg who published *Design with Nature* in 1969. *Design with Nature* provided an ecological perspective to the planning of cities. It was a step-by-step guide that served as a planning tool for the integration of landscape architecture within urban environments. After its release, urban planners began to create organizations advocating for the incorporation of vegetation within urban environments. Conferences in the late 60's and early 70's brought planners together over the topic of the integration of nature into the city. The National Institute of Urban Wildlife was established in 1973 and its first publication was a report on planning for wildlife in cities and suburbs. *Design with Nature* was the foot in the door for providing planners with a realistic approach to designing cities from an ecological perspective. Currently, zoning regulations implemented by urban planners are critical for determining how much vegetation may or may not be present in urban environments. Restrictions on building density, extent of impervious surfaces, extent of open space, and land use types can either prevent or enhance opportunities for increased vegetative quantity in developed and developing cities (Wilson et al, 2003). Currently, urban planners and advocates of the integration of nature in the urban environment have the works of Ian McHarg as a key tool and reference for claiming land and setting it aside for landscape architecture. (Bolund & Hunhammar, 1999).

The objective of this study was to quantify and compare the percentage of vegetation in sixteen of the world's largest cities (Table 1.1). The purpose of this thesis is to assist planners and developers with this analysis in support of the importance of incorporating landscape architecture and preservation of green spaces in the development and growth of cities. Without planning, the value of land in our capitalistic society can lead to overdevelopment and the loss of crucial ecological services provided by urban vegetation. Every city is an ecosystem with the interaction of living and non-living organisms.

Table 1.1. Sixteen Global Cities and Independent Variables Included in This Study

World Cities	Municipal Population	Urban Pop Dens (Sq. Mile)	Average Annual Temp (F)	Average Annual Precipitation (Inches)	Latitude	Distance to Ocean (miles)	Elevation (Meters)	Year of Origin
Beijing	19,612,368	280,057	53.2	25.00	39.90	128.1	52	1421
Shanghai	12,532,109	179,030	59.7	45.10	31.25	7.7	12	1292
Istanbul	12,573,836	165,451	57.4	24.60	41.06	1.8	93	1930
Lima	7,605,742	108,653	64.4	0.40	12.08	12.1	11	1535
Karachi	9,856,318	106,187	79.0	9.10	24.89	5.4	18	1843
Bogota	6,778,691	90,827	55.6	37.20	4.63	194.0	2568	1538
Mexico City	8,873,017	54,656	60.6	22.70	19.43	168.3	2242	1521
Bangkok	5,695,956	44,789	82.6	57.80	13.75	19.1	8	1782
Moscow	11,514,300	44,423	39.6	23.60	55.74	487.8	150	1147
Buenos Aires	2,890,151	37,350	61.9	39.60	34.62	3.5	64	1536
Tokyo	8,949,447	34,310	58.1	60.00	35.68	3.7	7	1603
Sao Paulo	11,244,369	28,264	64.9	51.30	23.58	28.0	784	1711
Santiago	4,668,473	25,965	72.5	12.30	33.48	52.4	549	1541
New York	8,175,133	24,111	52.7	48.80	40.70	3.0	25	1625
London	6,962,319	11,056	49.8	24.10	51.49	26.4	13	50
Los Angeles	3,792,621	8,665	63.5	11.90	34.00	12.8	61	1779

Trees and green space act as regulators for critical environmental issues within cities; air quality, water quality, and thermal regulation. In determining why vegetation percentage is variable across cities and political borders, climate is the most critical component in regards to the origin of urban vegetation. Lima, Peru receives only four tenths of an inch of rain on average per year. Located along the central coast of Peru, Lima is classified as a mild desert. Moscow, Russia, on the other hand is located in a forested habitat where rain levels reach 23.6 inches on average per year. Regardless of where each city is located and how much vegetation is within their respective city limits, the importance of incorporating vegetation within the urban environment is well documented. The following section is a literature review where the relationship between different types of urban vegetation and various environmental issues is explored. Atmospheric pollutants, ground water pollutants, the urban heat island, aesthetics, and other factors are all significant in the role of vegetation and its effect on urban ecosystems. The methods in this study are then outlined, followed by results, and an in depth discussion on vegetation and its role within major cities. Finally, the relationship between urban vegetation, public planning, zoning restrictions, and landscape architecture are discussed.

CHAPTER II

LITERATURE REVIEW

The environmental impacts of urban vegetation have been extensively researched by many scholars from a diverse array of academic fields. Increased vegetation within the urban environment has been correlated with the reduction of atmospheric pollution and hydrologic pollution, decreased energy demand, and decreased urban heat island effects, improved physical and psychological health, mitigated flood risks, decreased crime rates, and other factors. (Taha et al., 1997; Bolund & Hunhammar, 1999; Avissar, 1994).

Atmospheric Pollution

Vegetation in the urban environment helps to improve atmospheric composition. For example, tree cover in Chicago has been correlated with the sequestration of 155,000 tons of carbon dioxide per year as well as the removal of 6,145 tons of atmospheric pollutants per year including carbon monoxide, sulfur dioxide, nitrogen dioxide, and ozone (McPherson, Nowak, & Rowntree, 1994). Further, concentrations of C02, ozone, polycyclic aromatic hydrocarbons (PAHS), particulates, and other atmospheric pollutants can all be mitigated by the presence of urban forests. Taha & Haney (1997) studied air quality in California's South Coast Air Basin (SoCab). The area of study was Los Angeles. Due to topography, meteorology, and emissions, Los Angeles has the worst Ozone quality in the U.S. South Coast Air Quality Management District (SCAQMD) is the air pollution control agency for all of Orange County and the urban portions of Los Angeles Riverside, as well as San Bernardino counties, the smoggiest region of the U.S. SCAQMD, city planners and local companies are working together to improve atmospheric air quality by replacing low albedo surfaces such as rooftops, and other impervious surfaces with high albedo surfaces. Another option is to use concrete instead of cement in the repair of major roadways. Higher albedo surfaces reflect more light which leads to lower surface temperatures and a decreased retention of atmospheric pollutants, particularly ozone. Taha & Haney (1997) found that increased vegetation can reduce ozone concentrations if the trees are low emitters of biogenic hydrocarbons. When comparing the impacts of increasing urban vegetation as opposed to increasing high albedo surfaces, it was found that both solutions would result in net environmental impacts of similar magnitude.

Escobedo and Nowak (2009) studied the effect of urban forests on three different socioeconomic sub regions in Santiago, Chile. The Santiago metropolitan region has a population of over five million people and potentially the worst urban air quality problems in the world, specifically with particulate matter less than 10 microns (PM10). Atmospheric concentrations of PM10 accumulate in response to economic growth, motor vehicle exhaust and tire abrasion as well as suspended soil particles (Lenschow et al., 2001). Sampling was done over the course of two one-year intervals. The first year of studies was from July 1997 to June of 1998. The second set of samples was collected from July 2000 to June 2001. Results showed that air pollution removal of Particulate Matter (PM10), Sulfur Dioxide (S02), Carbon Monoxide (C0), Nitrous Dioxide (N02), and Ozone (03) occurred in all three sub regions with air pollution per square meter being greatest in the lowest socioeconomic sub region (Taha et al., 1997; Escobedo & Nowak, 2009). This was due to the result of lower socioeconomic sub regions having less vegetative cover and more industrial pollutants than higher socioeconomic sub regions. As a result vegetation samples in the lowest socioeconomic sub regions had higher densities of pollutant removal per vegetative unit than other regions.

Wagroswki & Hites (1997) researched the accumulation of Polycyclic Aromatic Hydrocarbons (PAH'S) in vegetation in different types of land cover. Residential heating, coke production, incineration, and internal combustion engines all contribute to PAH's. Samples were collected from urban, suburban, and rural areas during the fall and summer of 1995. PAH levels affect urban vegetation including local food sources. Samples included broadleaf, needle leaf, and corn. Samples were then tested and measured in order to calculate sequestration levels of PAH’s in the Northeastern United States. Site locations included Michigan, Illinois, West Virginia, and New York. It was found that broadleaf, needle-leaf, and corn have similar capabilities for sequestering PAHS. Results showed that urban maple leafs stored the greatest amount of PAHS while corn stored the least. Rural vegetation samples had on average ten times less PAH accumulation than urban samples. The results of this study also showed a strong positive correlation between PAH source levels and PAH storage levels within specimen samples.

Nowak, et al. (2006) looked in depth at pollutant removal levels for fifty five cities in the United States. The year that the study took place was 1994 and the model that they created was used to measure pollutant removal values for C0, S02, N02, PM10, and ozone (03). Cities with greater than 1000 people in the 1990 census were selected for the study. Different tree cover types had different effects on the resultant pollutant values, especially in the case of 03. Some trees are high emitters of VOC’s (Volatile Organic Compounds) which lead to the formation of 03. However, trees that are low emitters of VOC’s reduce levels of 03. The value of pollutant removal was estimated based on energy decision making studies. Results showed that Jacksonville Florida’s urban forest had the highest total levels of pollutant sequestration. This was due to the high acreage in Jacksonville’s urban area, the large percentage of forest cover, and the long leaf-on seasons. Los Angeles had the highest level of pollution sequestration per tree due to the great amount of traffic and the effect of the air basin. Minneapolis had the lowest total pollution sequestration levels, likely due to short leaf on seasons. It was found that cities with contiguous tree stands can reduce ozone levels by up to 16% with sulfur and nitrogen dioxide decreasing by up to 8 %. It was also found that 7,000 tons of atmospheric pollutants were estimated to have been removed by urban vegetation in the contiguous United States in 1994. These numbers are not absolute and many independent variables were not included in this study (Nowak et al., 2006).

Hydrology

In vegetated areas, water permeates soil and feeds the roots of trees. Conversely, when water falls on impervious surfaces it is diverted into channels and streams. Runoff from impervious surfaces can be up to 16 times greater in volume than natural areas (Schueler, 1995). This leads to higher peak flows and quicker stream degradation. In vegetated areas, only five to fifteen percent of rain water runs off the ground, the rest evaporates or is infiltrated into the ground (Hunhammar & Bolund, 1999). The strategic use of urban vegetation prevents flooding and protects the health of local, regional, and global waterways. In February of 1988, Rio De Janiero was hit by a storm that dumped the equivalent of three months of rain in just twenty four hours. Planning was limited and development was precarious; as a result, there were multiple mudslide events in which shanty towns were demolished. Since then, planning strategies have been implemented and forests have been re-vegetated in an effort to lessen the negative impacts of future flood events (Mohan et al, 1991).

Urban Heat Island Effect

One of the greatest impacts urban vegetation has on the urban environment is its ability to reduce the urban heat island effect. Shading and evapotranspiration from urban tree cover reduce surface and atmospheric temperatures leading to less risk of death from heat exhaustion and decreased energy consumption from air conditioning (Bolund & Hunhammar, 1999; Avissar, 1994). Wilson, et al. (2003) used remote sensing and the Normalized Difference Vegetation Index (NDVI) to monitor vegetative quantity and sensible heat flux in a range of individual zoning categories in Indianapolis Indiana. After concluding that higher NDVI values have an inverse relationship with urban heat island (UHI) sensible heat values, the researchers then looked into what planning factors go into increased NDVI values. Results showed that parks, agriculture, and low density dwellings resulted in the lowest mean surface temperatures and highest NDVI values.

In contrast, the central business district had the highest mean surface temperatures and lowest NDVI values (Wilson et al., 2003).

Criminology

The psychological impact of having vegetation in urban environments is wide reaching. Olmsted designed parks to increase the health and prosperity in major cities by reintroducing natural components of healthy ecosystems. While many people perceive vegetated areas in urban environments to be hostile and dangerous components of the city landscape, studies show that in many cases the opposite is true. When a random sample of people in a study to examine the relationships between perception of crime and vegetation were interviewed, it was found that pictures of well-spaced vegetation induced greater feelings of security than non-vegetated areas (Kuo & Sullivan, 2001). Crime prevention through environmental design (CPTED) has been a driving philosophy in crime reduction since introduced by criminologist C. Ray Jeffery in 1971. Well-spaced vegetation in the urban environment creates a perception of increased surveillance which deters criminals from committing crimes. In 1961 Jane Jacobs suggested ideas that eventually led to the broken windows theory stating that maintaining orderly urban landscapes diminishes precursors to crime. One study surveyed violent and property crime over a two year period across 98 apartments in Chicago. Results showed that for both calls for service and offense data, apartments with more vegetation in their immediate surroundings had less violent crime and less property crime than their less vegetated neighbors. This correlation is bolstered due to the normalization of building height, number of units occupied, and distance to police stations. Vegetation while randomly dispersed and often times implemented without planning, can be a major factor in crime reduction if placed strategically (Kuo & Sullivan, 2001).

Urban Form

Huang, et al. (2007) looked at regional differences of urban form for seventy-seven different cities around the globe. They found that major global cities vary in typology and form based upon their location and level of development. For the purpose of their study they defined and delineated urban areas based on satellite imagery. Vegetated areas and aquatic areas were not included in their classification of urban form and a maximized likelihood supervised classification was used to determine urban boundaries with a designated likelihood of 95%. Four types; residential settlement, road, industrial, and warehouses were combined to determine urban boundaries. Then a cluster analysis was performed to determine five distinct types of urban form; compactness, centrality, complexity, porosity, and density. These measures were utilized in this study to determine buffer distances for urban classifications (Table 3.1). Huang, et al. (2007) found that the most developed countries had less compactness, less centrality, more complexity, more porosity, and less density. Conversely well developed countries typically had greater compactness, greater centrality, less complexity, less porosity, and more density than 2nd and 3rd world countries. Ultimately, the more fragmented, less compact, and more complex the urban landscape mosaic, the larger the open space compared to the total urban area. Huang, et al. (2007) attributes the differences in urban form between countries to disparities in wealth. Countries with more wealth such as the United States and England have more capital to build high speed interconnected roads and maintain more open spaces. As a result, increased motorization leads to greater accessibility to work places within the city while motorists are able to maintain a home and lifestyle in a less dense and more fragmented urban fringe. Inseparable influences on urban form are the many variables that have shaped the developed land over history. Variables include early settlement, industrialization, land ownership, planning, and regulation. All of these factors go into the unique urban form specific to each global city (Huang et al 2007).

CHAPTER III

METHODS

Extent

The extent was set based on the work of Huang, et al. (2007). Prior to settling with a final extent, a variety of spatial extents were examined to determine the percentage of vegetation within each cities' boundaries. A set extent in the shape of a ten mile by ten mile square surrounding each city center was first used to determine the vegetation within the most densely developed parts of each city. This method was not suitable for this study as it did not take into account urban form. For example, the urban area of Bogota Columbia runs alongside a mountain range. In this case, a 100 square mile extent did not encompass the entirety of the urban area (Figure 3.1).

Figure 3.1 Bogota Columbia with a 100 Square Mile Extent Surrounding the City Center. Red Boundaries Within the Square Represent Areas where Clouds were Removed with a <anual Unsupervised Classification.
Projection: WGS 1984 UTM Zone 21N

Another option considered was to calculate the percentage of vegetation within the entirety of municipal boundaries. The use of municipal boundaries for determining the percentage of vegetation within major world cities was unfavorable due to the variability in area of differing major cities. For example, the municipal area of Buenos Aires is 81 square miles, whereas the municipal area of Beijing is 6,329 square miles, 78 times as large as Buenos Aires and 12 times the size of Los Angeles (Figure 3.2). If the total area of vegetation within each urban extent were the same, then the resulting ratio of vegetation to the built environment in Beijing would be much lower due to extensive vegetation within mountain ranges, agriculture, and other areas outside of developed regions (Figure 3.2). A more complex method for determining urban form was used to set the extent of study for each city.

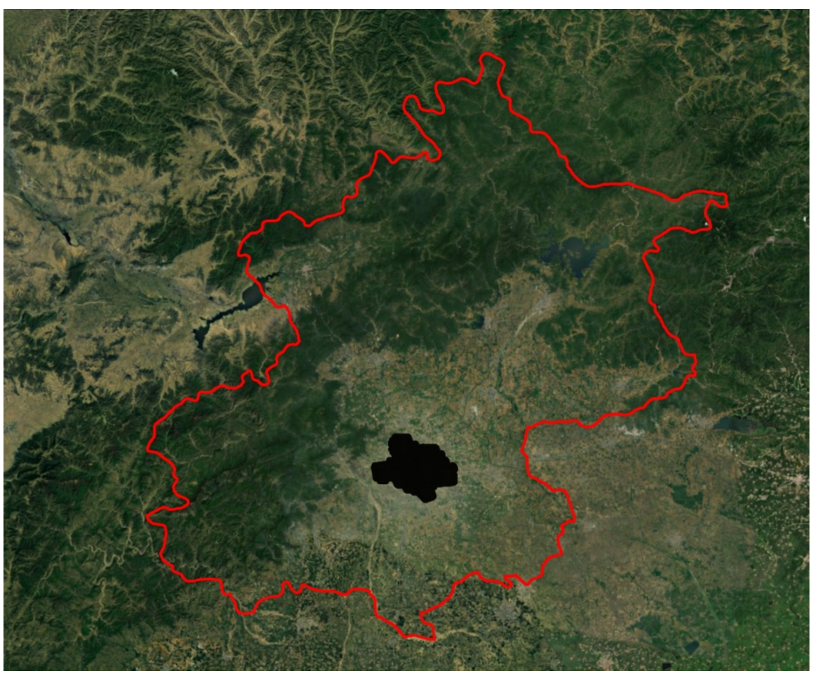

Figure 3.2. Municipal Boundary of Beijing in Red (6,329 square miles).
Urban Boundary is in Black (133 Sq. miles)
Projection: WGS 1984 UTM Zone 18

The extent of study for each city was set based upon Huang, et al. (2007) methodology. Huang, et al. (2007) were contacted for the retrieval of urban polygon boundaries in the form of a digital polygon shapefile. Results were not attainable. Instead, a shapefile with a similar classification of urban areas was obtained from a separate source (Welcome to the Data Catalog, 2010). With this shapefile, the polygon boundaries of urban development for each sample city were brought into a GIS. The next step was to obtain a polygon shapefile representing municipal boundaries in each sample city. These shapefiles were downloaded from the Country Data Index (2011). After obtaining the geographic borders of urban development and municipal boundaries for each city (Figure 3.2), the municipal area was intersected with the urban area thereby representing only developed areas within the municipal boundaries of each city (ESRI, ArcMap 9.3, 2008). The new layer for each city then represented urban development within municipal boundaries. As a result multiple open patches occurred.

Figure 3.3. Extent of Urban Form in Moscow Russia. This Boundary is a Result of the Municipal Boundary Being Intersected with the Urban Boundary.
Projection: WGS_1984_UTM_Zone_37N

The patches in Figure 3.3 exist because the new layer excluded vegetation and undeveloped areas in its classification. Patches were filled by using Huang, et al. (2007) methods and the buffer tool in ArcMap (ESRI, ArcMap 9.3, 2008). Each city was given a group number between 1 and 4 (Figure 3.4).

Figure 3.4. Shanghai (left) Group 3, Santiago (middle) Group 1, and Moscow (right) Group 4.
Source: Huang et al., 2007

The number for each city was determined based upon Huang, et al. spatial classifications of developed and developing countries. Developing countries, such as Buenos Aires and Lima Peru had very compact and densely developed cities, whereas developed countries including London and Moscow, had less compact and less densely developed cities with more large patches than developing cities. The new layer was buffered with a different radius setting for each city based upon group number and the level of compactness, centrality, complexity, porosity and density (Table 3.1) (Table 3.2). Buffers were determined based on patch size and urban form classifications. Higher compactness, higher centrality, lower complexity, lower porosity, and higher density cities had the lowest distance of a buffer as patches and gaps were smaller in these types of urban form.

Table 3.1. Regional Similarities Between Five Dimensions of Urban Form

	Compactness	Centrality	Complexity	Porosity	Density	Buffer (meters)
Group 1	Moderate	Moderate	Moderate	Moderate	Moderate	1050
Group 2	High	High	Low	Low	High	150
Group 3	High	High	Moderate	Moderate	High	600
Group 4	Low	Low	High	High	Low	1500

Note: The buffer distance was calculated based on spatial characteristics of cities' development.

Groups one to four are determined by each of five spatial metrics. Compactness measures patch shape and fragmentation. The less patches and the less fragmentation the higher the compactness. Centrality measures urban development in proximity to the central business district, the higher the centrality the closer development is to the central business district. Complexity measures the irregularity of patch shape. The less fragmented the city walls are, the less complex. Porosity measures the ratio of urban space to the total urban area, the more urban space the lower the porosity. Density is a measure of population density, where the greater the amount of people per square mile, the higher the density.

Table 3.2. Classification of Group and Buffer

World Cities	Buffer_Group	Buffer_Weight	Buffer
Bangkok	3	0.70	1,050
Beijing	3	0.70	1,050
Bogota	2	0.40	600
Buenos Aires	3	0.70	1,050
Istanbul	3	0.70	1,050
Karachi	1	0.10	150
Lima	3	0.70	1,050
London	4	1.00	1,500
Los Angeles	4	1.00	1,500
Mexico City	3	0.70	1,050
Moscow	4	1.00	1,500
New York	4	1.00	1,500
Santiago	3	0.70	1,050
Sao Paulo	3	0.70	1,050
Shanghai	2	0.40	600
Tokyo	3	0.70	1,050

Source: Huang, Lu, Sellers (2007)

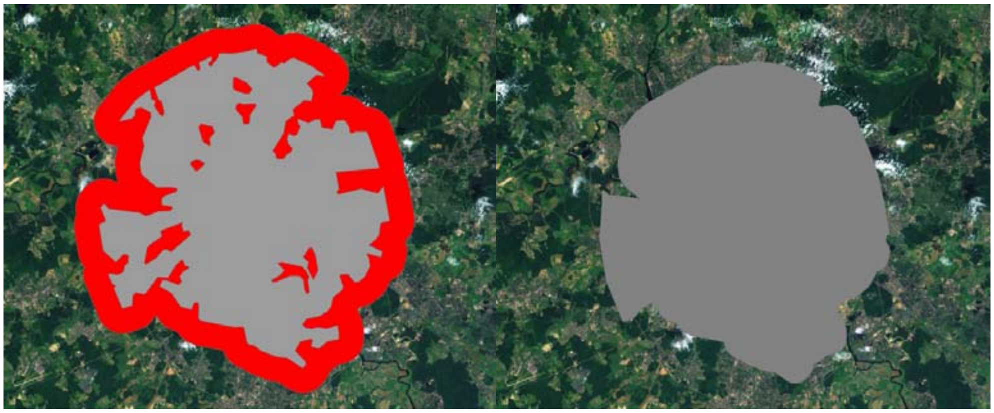

Figure 3.5. Moscow Buffered Extent (left). Moscow Final Extent (right).
Projection: WGS 1984 UTM Zone 37N

Finally, the buffered extent was clipped to each cities municipal boundary layer to only include urban areas within each city's municipal boundaries (Figure 3.5). Further modification of the extent of study included the removal of water and clouds from each urban extent to standardize all vegetation-to-land ratios (Ridd, 1995). In order to remove water from the extent of analysis, a manual supervised classification of water was performed by finding typical near infrared (NIR) spectral reflectance values within ten sample locations of water in each individual sample area (Figure 3.6).For each observed area the maximum returned brightness value of water in the NIR band was set as the maximum threshold for near infrared reflectance. All of the cells in band 4 (NIR) with brightness values less than the maximum threshold were classified as water and removed from the extent of analysis (Figure 3.6) (Wilson et al., 2003).

Figure 3.6. Urban Extent of New York City with Water Removed .
(Welcome to the Data Catalog, 2010)
Projection: WGS_1984_UTM_Zone_18N

In order to remove clouds, a manual supervised classification was performed by testing a sample of brightness values within the clouded areas of the given extent to find the most significant relationship between clouds, spectral bands, and reflectance values. A unique relationship between clouds and high spectral reflectance in the blue band emerged. As a result, all of the pixels in the blue band (1) with brightness values greater than 140 were classified as clouds and removed from the extent of the study (Figure 3.7). The shadows of the clouds are classified as water due to low reflectance values. This is due to the result NIR reflectance values below the threshold set for water.

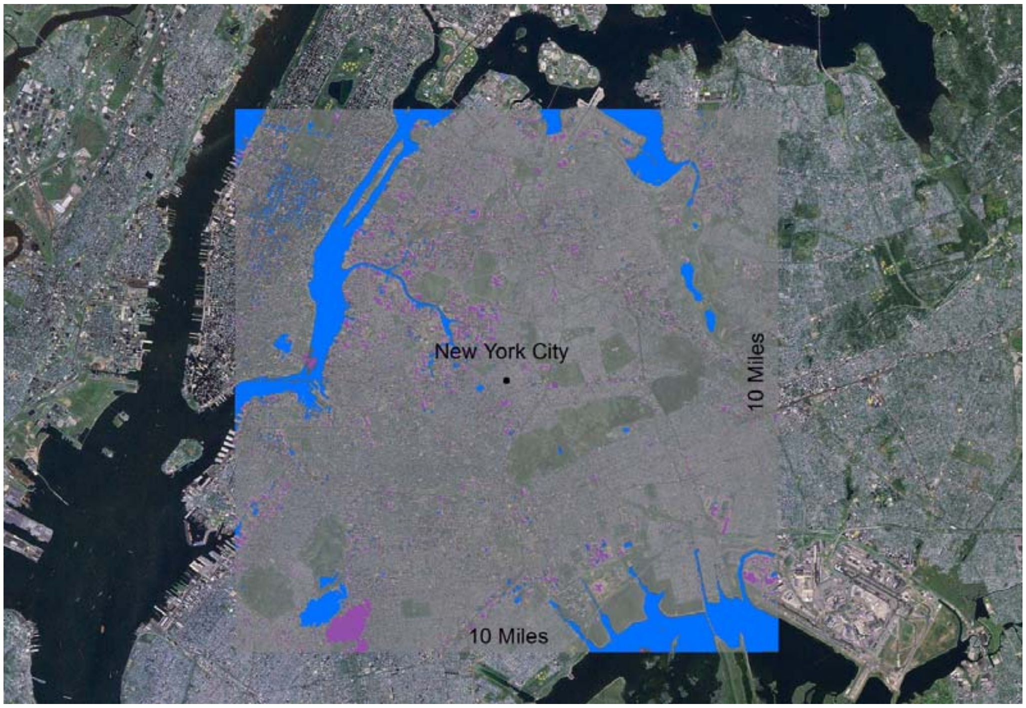

Figure 3.7. New York City with Water Classified in Bright Blue and Clouds in Purple. Clouds and Water were Removed from the Area of Extent and not Included in the Processing of the NDVI. Note: Manhattan buildings are misclassified as water due to shadowing (NW corner).

Remote Sensing

Prior to determining the extent of urban boundaries in this study, Landsat satellite imagery was collected from NASA. Imagery was sought out for the largest cities in the world by metropolitan statistical area (MSA). All of the cities observed in this study had metropolitan populations with greater than 5,000,000 people when recorded in 2010 (The World Factbook, 2011). Imagery selections were made based on the availability of peak vegetation data, as well as imagery that had minimal to no cloud cover. Measurements of near infrared reflectance at wavelengths between 760 to 900 micrometers have been examined in numerous studies to determine the presence and quantity of healthy vegetation (Jensen A., 1979; Gamon, et al., 1995; Weng, 2003). In keeping with this standard, imagery with NIR reflectance values (Landsat satellites 4, 5, and 7) were obtained using the USGS Global Visualization Viewer (U.S. Department of the Interior/U.S. Geologic Survey). Seasonality and leaf-on conditions were verified before creating spatial and temporal selections of imagery. The associated spatial, spectral, temporal, and radiometric resolutions are listed in Table 3.3. On May 31 2003 the scan line corrector aboard the Landsat 7 failed. As a result, the only ETM data used in this study were the images taken before May 2003. (U.S. Department of the Interior/U.S. Geologic Survey). Reflectance values in the red and near infrared bands recorded by Landsat MSS, TM, and ETM sensors were analyzed in this study to determine presence or absence of vegetative land cover in 16 of the world's largest 50 cities. Sixteen cities were included in this study based on availability of imagery and population size. (World Atlas, 2010; U.S. Department of the Interior/U.S. Geologic Survey; Figure 3.8

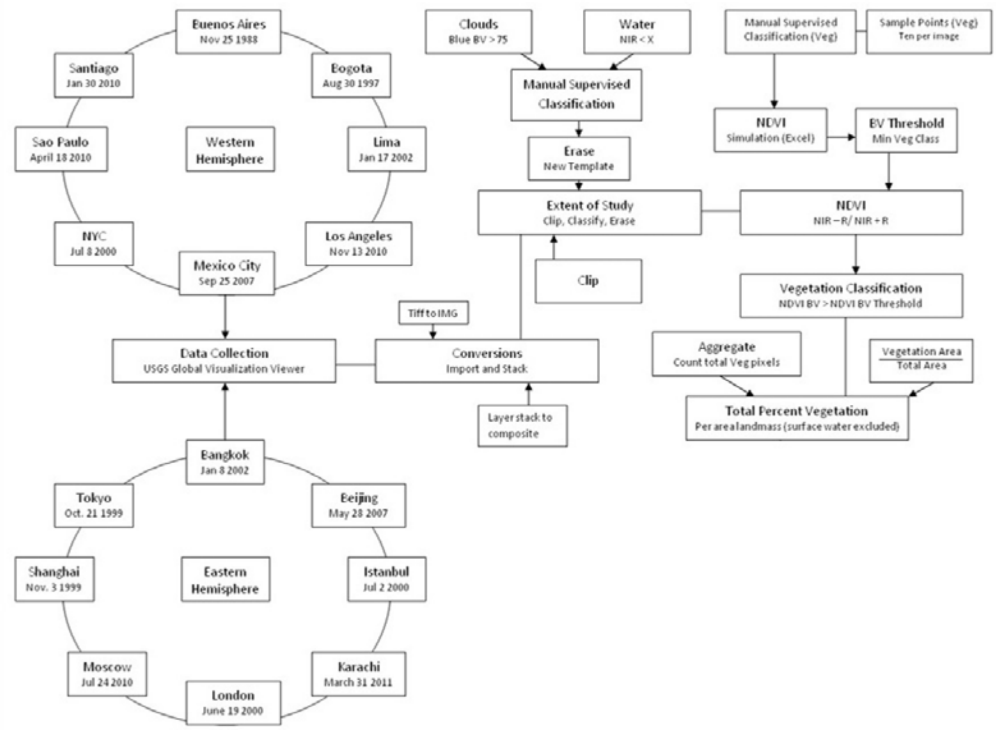

Figure 3.8. Flow chart of Methodology

Table 3.3. Satellite and Sensor Technical Specifications.

Satellite (sensor)	**Spatial**	**Spectral**	**Temporal**	**Radiometric (**per band**)**
Landsat IV (TM)	30 m X 30 m	. 5 - .9 µm	1985 – 2001	8-bit
Landsat IV (MSS)	68 m X 83m	. 5 - .9 µm	1985 - 2001	8-bit
Landsat V (TM)	30 m X 30 m	. 5 - .9 µm	1985 - 2011	8-bit
Landsat V (MSS)	68 m X 83m	.5 - .9 µm	1985 - 2001	8-bit
Landsat VII (ETM)	30 m X 30 m	.5 - .9 µm	2000 – 2003	8-bit

Source: Irons, 2011.
Note: Spectral and Temporal resolutions are listed pertaining to what was used in this study rather than what is available from NASA.

NDVI

The Normalized Difference Vegetation Index (NDVI) has been used extensively in the field of remote sensing to monitor food, fiber crops, and vegetation worldwide (Jensen A. , 1979). When an image is captured from a satellite, in this study, the Landsat TM, multiple bands of information are collected. The most important to the study of vegetative cover are the red and near infrared bands. Healthy vegetation reflects around 40% to 50% of near infrared energy and 5% of red energy. Red and near infrared bands are commonly used together to determine vegetation characteristics due to their contrasting abilities to depict vegetation. The NDVI, first created by Rouse et al. (1973), is the most commonly used metric to determine vegetation abundance and the National Oceanic and Atmospheric Administration simulates the NDVI on the entire surface of the earth on a weekly basis to show temporal snapshots of the 'greenness' of the earth (Figure 3.9).

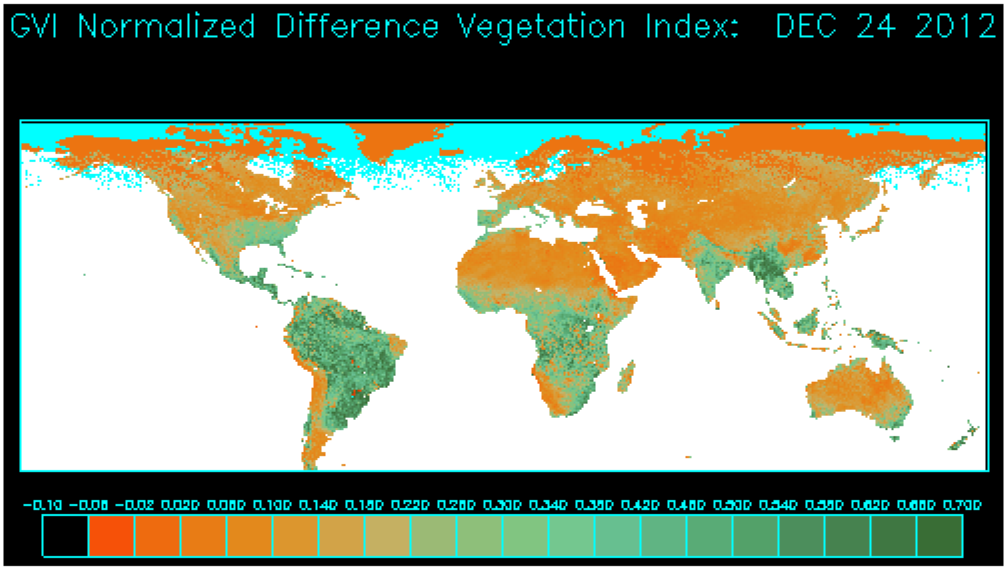

Figure 3.9. NOAA Normalized Difference Vegetation Index (NDVI) Dec 24. 2012

The equation for the NDVI is as follows:

$$\frac{\text{NIR} - \text{red}}{\text{NIR} + \text{red}}$$

The NDVI was calculated for each 30-meter cell in the bounded extent of each city in this study (Figure 3.8). Ten stratified random sample points within areas of observed vegetation were examined in each sample area and the associated NIR and red values were recorded (Figure 3.8, Table 3.4). A manual simulation of the NDVI was performed on the underlying cell at each sample point and the calculated NDVI values were then converted to brightness values (Figure 3.8., Table 3.4). NDVI values were converted to brightness values using the following equations:

$$\text{NDVI} > 0: \quad \text{BV}\ i, j, n = \text{Int}\ (128 + (128 * \text{NDVI}))$$

$$\text{NDVI} < 0: \quad \text{BV}\ i, j, n = \text{ABS}\ (\text{NDVI}) * 128$$

Where i is the cell location (x), j is the cell location (y), and n is the numeric count of the cell in comparison to the total count of cells. The minimum NDVI brightness value for each sample area was set as the minimum threshold for vegetation for each city. After determining the minimum threshold for the NDVI classification of vegetation, all of the cells for each image of each city were processed and converted into NDVI values using ERDAS (ERDAS, ModelMaker). For each NDVI, all of the cells with brightness values that were greater than the minimum threshold NDVI were classified as vegetation in ArcMap (ESRI, ArcMap 9.3, 2008). The average minimum NDVI value for all of the combined sample areas was .211 and the average minimum brightness value was 155. NDVI minimum BV thresholds varied between 129 (NDVI .007) in London and 182.15 (NDVI .72) in New York City (Table 3.5). The total amount of cells classified as vegetation were calculated and then divided by the total number of cells in the sample area to determine the percent vegetation of each city (Figure 3.8, Table 4.1). Stone (1979) proposed a minimum threshold NDVI value for vegetation at .35. However this classification was specific to Gujarat India during the months of October and September and between the years of 1972-1980. NDVI minimum vegetation thresholds were set individually for each sample site due to variability. NIR minimum thresholds are not consistent from place to place or time to time due to variation of values in location, seasonality, and elevation of the sun. (Jensen A., 1979, Figure 3.8, Table 3.4). The following table shows ten of the sample values used to calculate the minimum NDVI threshold for Tokyo Japan. This analysis was done for each city and the Average, Min, Max, and BVMin are all calculated for each cities range in NDVI values.

Table 3.4. Minimum Brightness Value Thresholds for Tokyo Japan Oct. 21 1999.

City	NIR	R	NDVI	BV
Tokyo	97	50	0.319728	168.9252
Tokyo	89	56	0.227586	157.131
Tokyo	80	54	0.19403	152.8358
Tokyo	51	36	0.172414	150.069
Tokyo	73	35	0.351852	173.037
Tokyo	120	55	0.371429	175.5429
Tokyo	69	34	0.339806	171.4951
Tokyo	65	28	0.397849	178.9247
Tokyo	74	44	0.254237	160.5424
Tokyo	83	52	0.22963	157.3926

Table 3.5. Minimum Brightness Value Thresholds for All Cities

City	NDVI MIN	BV MIN	NDVI Average	BV Average
Bangkok	0.1200	143.1398	0.1759	149.6264823
Beijing	0.2075	163.9298	0.3542	173.3407392
Bogota	0.2222	156.4444	0.4199	179.9748906
Buenos Aires	0.3103	167.7241	0.3723	175.64994
Istanbul	0.0566	135.2453	0.2553	160.6726386
Karachi	0.1592	148.3822	0.3048	167.0192682
Lima	0.1613	148.6452	0.2801	163.8474616
London	0.0078	128.9922	0.3721	176.146912
Los Angeles	0.2286	157.2571	0.4030	179.5895806
Mexico City	0.2500	160.0000	0.3822	176.9271941
Moscow	0.2340	157.9574	0.3581	173.8331556
New York City	0.4231	182.1538	0.5289	195.6938975
Santiago	0.1754	150.4561	0.4068	180.066524
Sao Paulo	0.3667	174.9333	0.5427	197.4636899
Shanghai	0.0069	128.8828	0.1758	150.4968928
Tokyo	0.1724	150.0690	0.2859	164.5895727

Statistical Analysis

Multiple statistical measures were utilized to gain a better understanding of the distribution of vegetation amongst the sixteen sample cities and to see if any significant relationships between independent variables and vegetation-to-land ratios emerged. Total population by metropolitan statistical area (MSA), municipal population, population density, average annual 24-hour average temperature, annual precipitation (inches), latitude, and distance to the ocean, elevation, and year of origin were retrieved from multiple resources to test for correlations with vegetative quantity in each sample city. Year of origin was collected from (Tokyo's History, Geography, and Population, 2010; Shanghai China, 2007; Moscow at a Glance, 2010; City District Government Karachi, 2011; Beijing History, 2011; History of Local Governance in Istanbul). MSA populations were retrieved from the World Fact book (2011). Municipal populations were obtained from Geo Hive (2011). Average temperature and average precipitation were obtained from World Climate (2005) and population density, latitude, elevation, and distance to the ocean were calculated using ArcMap (ESRI, ArcMap 9.3, 2008; ESRI, World Cities, 2006; ERDAS, Globaldem21). These independent variables were chosen to analyze physical variables (latitude, distance to the ocean, elevation, precipitation, and temperature) to see how vegetation quantities relate to constraints of climate and geographic location. Other variables included were population and the origin of year to determine how people affect vegetation quantities. Analyses done in this study included a two-sided t- test, Pearson's correlation, and multiple regressions. The basic statistics for all of the independent variables in the dataset are listed in table 3.6. Each independent variable was tested for correlations between other independent variables as well as the dependent variable using SAS statistical software.

A two-sample t-test was run to determine if vegetation quantity was statistically the same between the eastern and western hemispheres (Figure 3.8).

Ho = There is no difference between the amount of vegetation in the eastern and western hemispheres of earth.

The deviation and variance of vegetation quantity were calculated and then a test for homoskedasticity was run to determine whether or not the pooled variance or individual variance would need to be used in the calculation of the two-sided t-tests (Figure 3.8). The equation for homoskedasticity is as follows:

$$F = \sigma_1^2 / \sigma_2^2$$

$$F = 326.63/25.632$$

$$F = 12.743$$

σ_1^2 is the variance of the 1st dataset. σ_2^2 is the variance of the 2nd dataset. The calculated F value (12.743) was greater than the Fcritical values (3.79) and as a result, individual variance was used in the t-tests. In the below equation, n_1 is the size of the first sample and n_2 is the size of the second sample. X_1 is the mean of the first sample, and X_2 is the mean of the 2nd sample. The equation for the two sample t-test is as follows:

$$t = (X_1 - X_2)/\sqrt{(\sigma_1^2/n_1) + (\sigma_2^2/n_2)}$$

$$t = (17.5 - 14.6)/\sqrt{(326.63/8) + (25.623/8)}$$

$$t = .43$$

Basic statistics for the dependent and independent variables used in this study are listed in table 3.6. The percentage of vegetation in each city ranged from 3 percent in Karachi to 53 percent in London. Total MSA populations ranged from 5 million in Santiago to 36 million in Tokyo. The average annual 24-hour temperature range was calculated by averaging the temperature over 24 hours, and then averaging the 24 hour average over the course of a year. The temperature ranged from 39 degrees Fahrenheit (F) in Moscow to 82 degrees (F) in Bangkok. The average annual precipitation totals ranged from .4 inches in Lima to 60 inches a year in Tokyo. The municipal population ranged from just under 3 million in Buenos Aires to nearly 20 million in Beijing. The absolute latitude, degrees north or south of the equator, ranged from 4 degrees in Bogota to 55 degrees in Moscow, and the distance to the ocean (as the crow flies) ranged from 1.75 miles in Istanbul to 487.79 miles in Moscow. Elevation ranged from 7 meters above sea level in Tokyo to 2568 meters in Bogota. Origin year of city ranged from 50 AD in London to 1930 in Istanbul. And population density ranged from 3000 people per square mile in Beijing to over 35,000 people per square mile in Buenos Aires.

Table 3.6. Simple Statistics

Variable	N	Mean	Std Dev	Sum	Minimum	Maximum
Percent Vegetation	16	16.03875	12.85302	256.62000	3.06000	52.78000
MSA Population	16	14187188	7448783	226995000	5883000	36507000
Temperature	16	60.96875	10.71489	975.50000	39.60000	82.60000
Precipitation	16	30.84375	18.21662	493.50000	0.40000	60.00000
Municipal Population	16	8857803	4127101	141724850	2890151	19612368
Latitude	16	31.01750	13.98520	496.28000	4.63000	55.74000
Ocean	16	72.13250	127.04021	1154	1.75000	487.79000
Elevation	16	416.06250	808.73081	6657	7.00000	2568
Origin Year	16	1491	432.97712	23854	50.00000	1930
Population Density	16	207.68750	167.58310	3323	70.00000	630.00000

CHAPTER IV

RESULTS

Vegetation Percentage

The mean recorded vegetation for all sixteen cities was 16%. The median was less than the mean with a value of 13.7%. This was due to Moscow (36.3 %) and London (52.8%) both being well above the mean (table 4.1). Beijing and Karachi had the lowest levels of urban vegetation at 3.98% and 3.06% respectively.

Table 4.1. Dependent (Vegetation) and Independent Variables

World Cities	Vegetation (%)	MSA Population	Urban Population Density (People/SQ Mi)	Average Annual Temp (F)	Precipitation (inches)	Latitude	Distance to Ocean (MI)	Elevation (Meters)	Year of origin
Beijing	3.98	12,214,000	280,057	53.2	25.00	39.90	128.1	52	1421
Shanghai	5.78	16,575,000	179,030	59.7	45.10	31.25	7.7	12	1292
Istanbul	9.00	10,378,000	165,451	57.4	24.60	41.06	1.8	93	1930
Lima	5.00	8,769,000	108,653	64.4	0.40	12.08	12.1	11	1535
Karachi	3.06	13,125,000	106,187	79.0	9.10	24.89	5.4	18	1843
Bogota	16.41	8,262,000	90,827	55.6	37.20	4.63	194.0	2568	1538
Mexico City	13.81	19,319,000	54,656	60.6	22.70	19.43	168.3	2242	1521
Bangkok	20.26	6,902,000	44,789	82.6	57.80	13.75	19.1	8	1782
Moscow	36.27	15,523,000	44,423	39.6	23.60	55.74	487.8	150	1147
Buenos Aires	12.05	12,988,000	37,350	61.9	39.60	34.62	3.5	64	1536
Tokyo	8.50	36,507,000	34,310	58.1	60.00	35.68	3.7	7	1603
Sao Paulo	18.43	19,960,000	28,264	64.9	51.30	23.58	28.0	784	1711
Santiago	20.50	5,883,000	25,965	72.5	12.30	33.48	52.4	549	1541
New York	17.15	19,300,000	24,111	52.7	48.80	40.70	3.0	25	1625
London	52.78	8,615,000	11,056	49.8	24.10	51.49	26.4	13	50
Los Angeles	13.64	12,675,000	8,665	63.5	11.90	34.00	12.8	61	1779

Two-Sample T-Test

The null hypothesis that there is no difference between the amount of vegetation in the eastern and western hemispheres of earth was accepted. The T-score was .43 and the P-value was .74. Based on these findings it can be deduced that similarities in vegetation quantity between Earth's two hemispheres are not statistically significant. Larger sample sizes and further testing may be pursued to confirm this hypothesis.

Correlations

The highest correlating physical variables with urban vegetation were year of origin (r = -.776), population density (r=.722) and latitude (r=-.464). Temperature also had a strong correlation with vegetation at (r=.401). Further analysis on these results is included in the discussion.

Error Analysis

The percentage of vegetation calculated in this study was tested based on comparisons of other classifications of vegetation within urban environments. The only publically available data on urban vegetation is available through the National Land Cover Dataset (NLCD). The NLCD does not provide specific areas of vegetation; however, NLCD classifications can be grouped to determine areas of vegetation within urban environments. Error matrices were produced for both Los Angeles and New York City to check the validity of vegetation classifications (Table 4.2, Table 4.3). In New York City, the producer's accuracy of vegetation was 78.6 percent signifying that over three quarters of the cells classified in this study were also classified as vegetation in the NLCD. The user's accuracy of vegetation in New York City was 59% signifying that nearly two thirds of the cells classified as vegetation in the NLCD were also classified as vegetation in this study (Figure 4.1, Table 4.2.) The classification of vegetation in this study is more accurate than the vegetation in the NLCD due to NLCD classifications. The NLCD classifies graveyards as ‘developed low intensity’, whereas the observed vegetative cover suggests the classification should be ‘developed open space’ (Table 4.4). Other notable discrepancies between the two classifications include detailed resolution of vegetative cover including the strip of land adjacent to the railroad heading northeast/northwest. While both the NLCD and NDVI are at 30-meter resolution, the vegetation along the railroad corridor was classified in the NDVI but not in the NLCD. Overall the NDVI used in this study was much more accurate than the 2006 NLCD for classifying vegetative cover in New York City.

Table 4.2. Error Matrix: New York City

New York City (Sq. Miles)	Vegetation	Unclassified	Row Total
Vegetation	27.206	18.705	45.911
Unclassified	7.405	0	0
Column Total	34.611	0	
Producers Accuracy	0.786050678		
Users Accuracy	0.592581299		

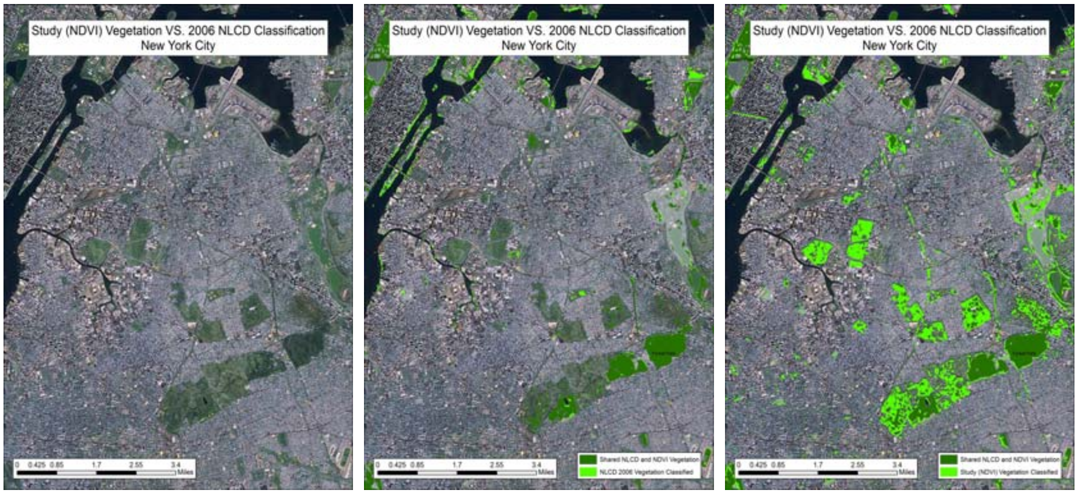

Figure 4.1. New York City Vegetation Classified with NDVI vs. NLCD

New York City shared vegetation between NDVI and NLCD compared to unclassified NDVI and NLCD imagery. Image 1 is basic imagery, image 2 shows unclassified areas found in the NDVI but not in the NLCD in bright green, image 3 shows unclassified areas found in the NLCD but not in the NDVI in bright green. Source: ESRI, 2010

Table 4.3. Error Matrix: Los Angeles

Classification area

Los Angeles (Sq. Miles)	Vegetation	Unclassified	Row Total
Vegetation	39.924	16.29	56.214
Unclassified	77.504	0	-----------------
Column Total	117.428	--------------------	-----------------

Producers Accuracy	0.339987056
Users Accuracy	0.710214537

In Los Angeles, the producer's accuracy of vegetation was 33.99% and the user's accuracy was 71 % (Table 4.3). The producer's accuracy of classified vegetation in Los Angeles was only 33.99% due to the grouped reclassifications of the ancillary data. 49% of the vegetation classified in the NLCD in L.A. is accounted for as ‘Developed Low Intensity’, which does not show up as vegetation at the 30 meter by 30 meter resolution used in this study. User’s accuracy occurred due to the inclusion of ‘Shrub/Scrub’ as vegetation (Table 4.3). Shrub/Scrub, though vegetation, has low reflectance values in the NIR band due to low primary productivity and an annual average of only 11.9 inches of rainfall per year. When looking at percentages of each of the eleven classifications included in the vegetation category of the 2011 NLCD, developed open space emerged as the most prevalent category in relationship to the NDVI. 100% of the areas classified as ‘Developed Open Space’ in the NLCD were also classified as vegetation in the NDVI for this study. The majority of vegetation (86.64%) classified from the NLCD in Los Angeles fell under the categories of either developed open space (49.04%) or Shrub/Scrub (37.6%). Other areas included in the NLCD vegetation classification besides developed open space and shrub scrub comprised less than 1 percent of the total vegetative cover (Table 4.4). The majority of vegetation classified in Los Angeles in both the NLCD and NDVI occurred in the Santa Monica mountain range. Other areas of notable vegetation were in the San Fernando Valley. While the south side of Los Angeles contrasted starkly with the NLCD and NDVI as vegetative cover was minimal and confined to small fragmented patches.

Table 4.4. NLCD Vegetation Classifications

NLCD Class	Land Cover Type
21	Developed Open Space: Lawn, Grasses, <20% impervious surfaces
41	Deciduous Forest: Trees > 5 meters tall, >20% Veg cover
42	Evergreen Forest: Trees > 5 meters tall, > 20% Veg cover
43	Mixed Forest: Trees > 5 meters tall, > 20% Veg cover
52	Shrub/Scrub: Dominated by shrubs, < 5 meters tall, >20% veg
71	Grassland/Herbaceous: >80% gramenoid or herbacious vegetation
81	Pasture/Hay: Areas of grasses or legumes, >20% vegetation
82	Cultivated Crops : annual crops, corn, soy, etc., >20% Vegetation
90	Woody Wetlands: Forest or shrubland, >20% vegetation
95	Emergent Herbaceous Wetlands: perennial, >80% Veg

Table 4.5. NLCD Non-Vegetation Classifications

NLCD Class	Land Cover Type
11	Open Water: Water with < 25% vegetation or soil
12	Perennial Ice/Snow: >25% Cover
22	Developed Low Intensity: 20 to 49% Impervious surfaces. Mixed veg and constructed material. Commonly single family housing units.
23	Developed Medium Intensity: 50 to 79% Impervious surfaces. Mixed veg and constructed material. Commonly single family housing units.
24	Developed High Intensity: 80 to 100% Impervious surfaces. Highly developed areas. Commonly apartment complexes, row houses, commercial and industrial buildings.

Los Angeles was unlike any other major city studied in that the majority of the one hundred square mile area surrounding the city center was occupied by low-density development. As a result, large quantities of “developed low intensity” green spaces were not classified as vegetation due to weakened NIR reflectance values and low density canopy cover. A more visual yet less quantifiable error assessment of vegetation classification accuracy is through comparison of high resolution imagery (Figure 4.2). If vegetative cover were to be examined at a higher resolution of 3 meters, then findings would likely show much more fragmented and dense vegetative cover within the urban areas of Los Angeles.

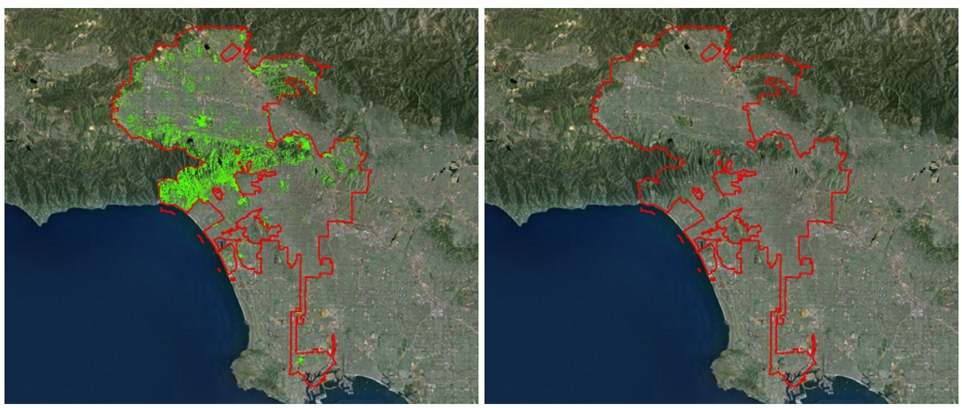

Figure 4.2 Los Angeles Vegetation Classified from NDVI Analysis Compared to Imagery.
Source: ESRI, 2008

NIR reflectance values decrease as the percentages of photosynthetic canopy decreases (Jensen A. , 1979; Weng, 2003). At the resolution of 30 meters per cell, roof tops, driveways, and streets in “developed Low Intensity” (Table 4.4) significantly decrease the amount of photosynthetic canopy cover per cell. As a result, few residential areas, though having partial tree cover, were not classified as vegetation in this study. Further complicating the error assessments, classifications of portions of the NLCD do not always match up with the given land-cover definitions (Multi-Resolution Land Characteristics Consortium, 2007). Based on comparative analysis between the NLCD and imagery from ESRI, 30 meter cells in Central Park in New York City had only 14.9% impervious surfaces in the imagery yet portions were still classified as developed, low intensity in the NLCD (>20% impervious surfaces). According to the definition, these sections should have been classified as ‘developed open space’ (Multi-Resolution Land Characteristics Consortium, 2007, Figure 4.2). As a result, less area was classified as vegetation than in the NDVI leading to false errors (NLCD 2001; Figure 4.2, Table 4.5).

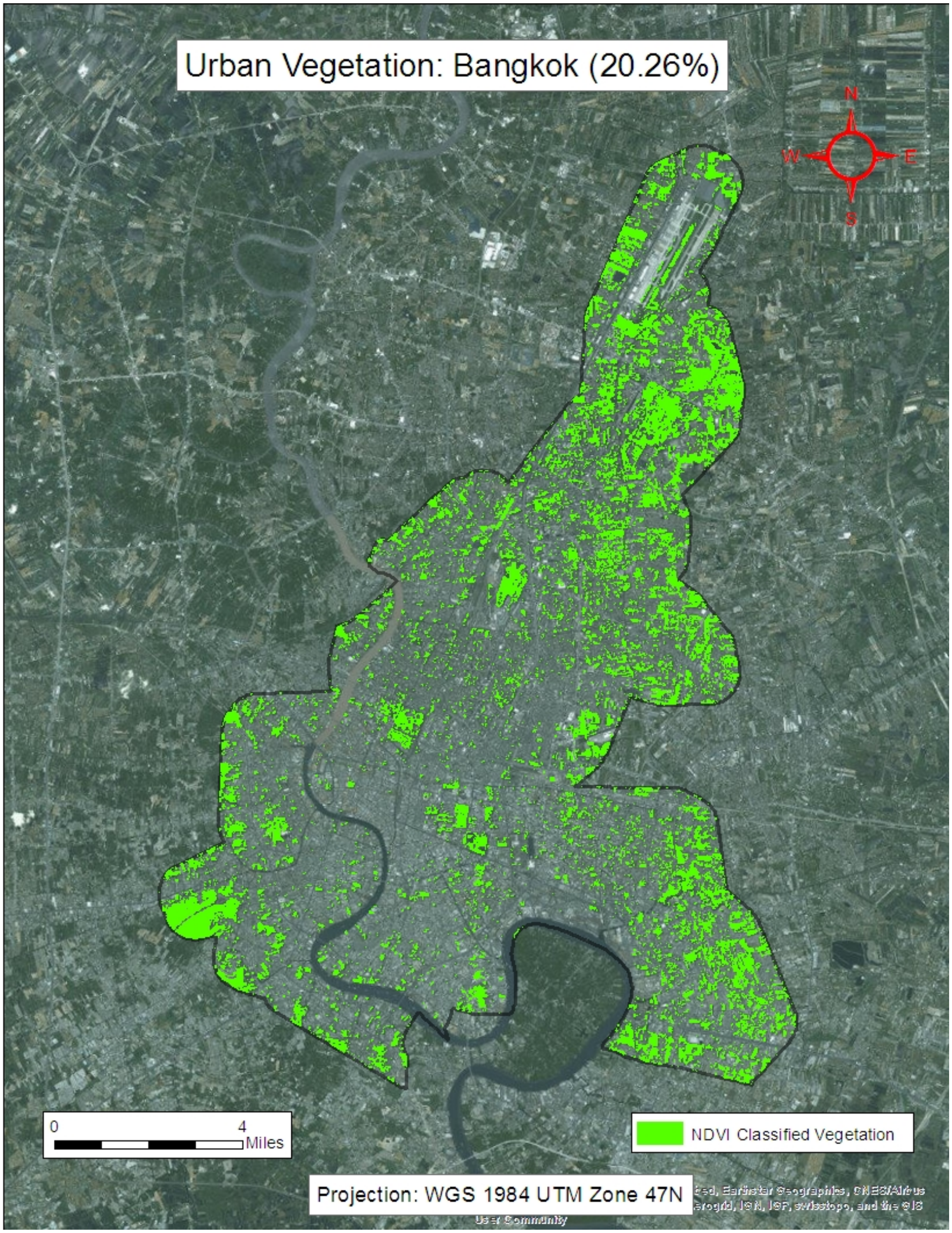

Figure 4.3. Vegetation Index Bangkok

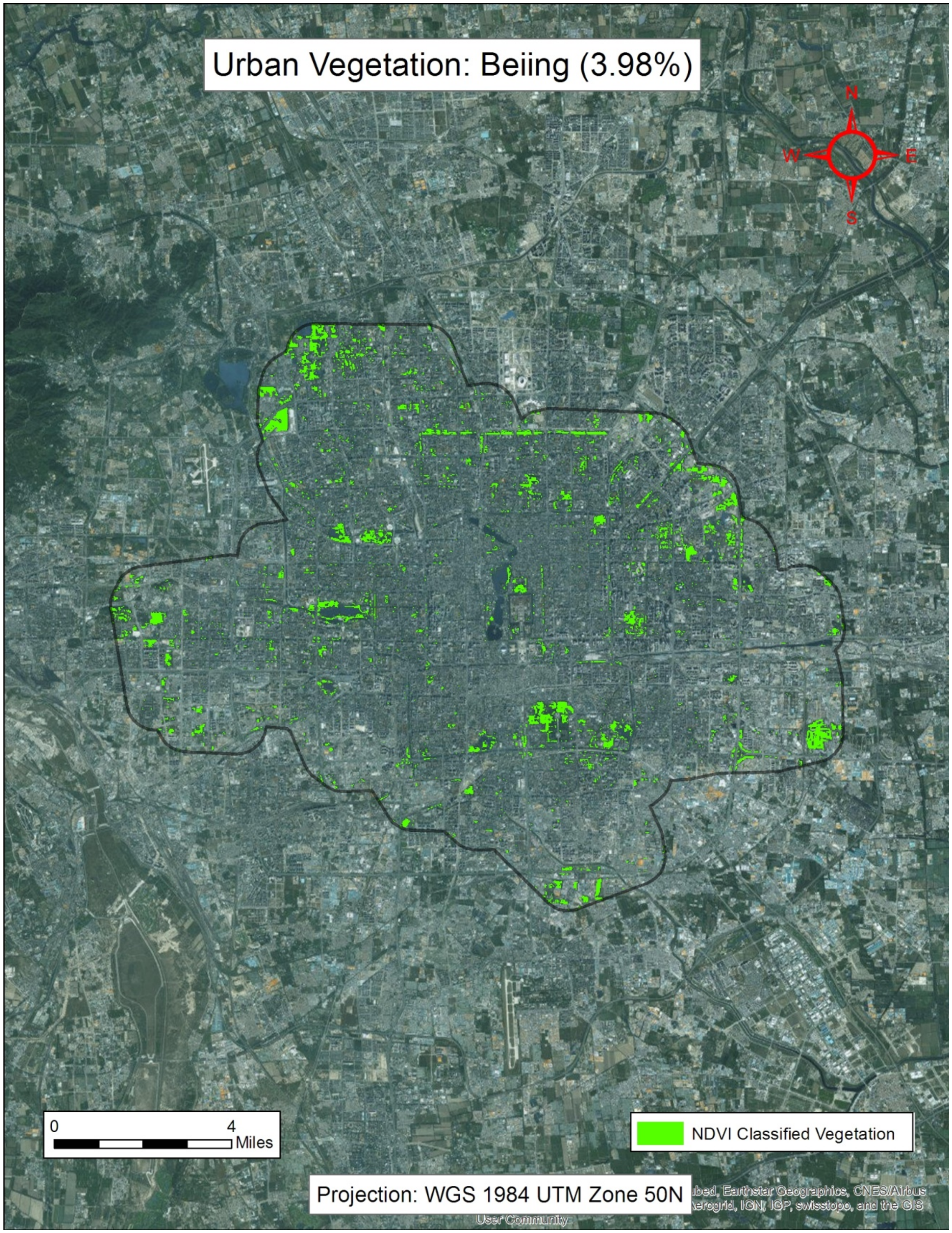

Figure 4.4. Vegetation Index Beijing

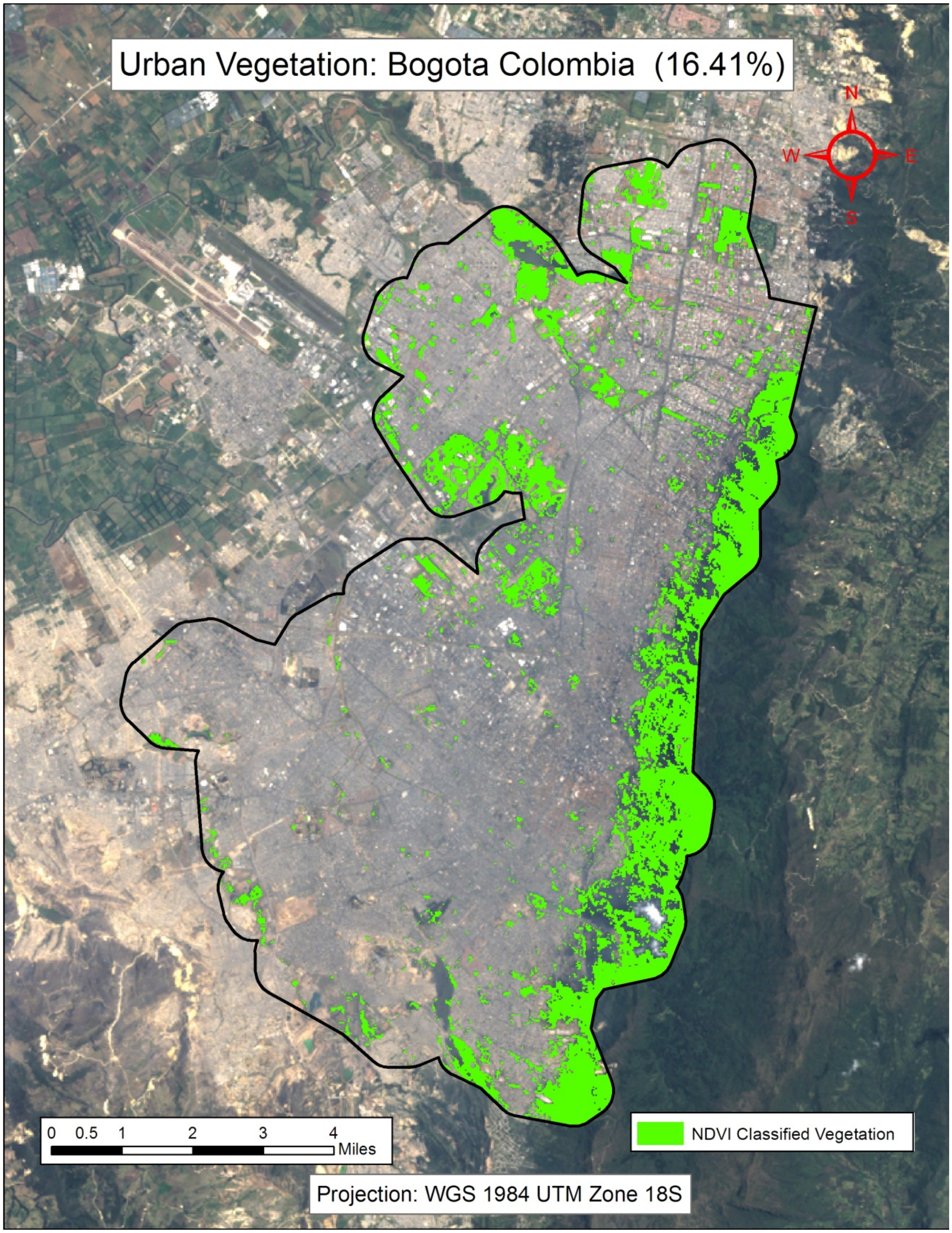

Figure 4.5. Vegetation Index Bogota

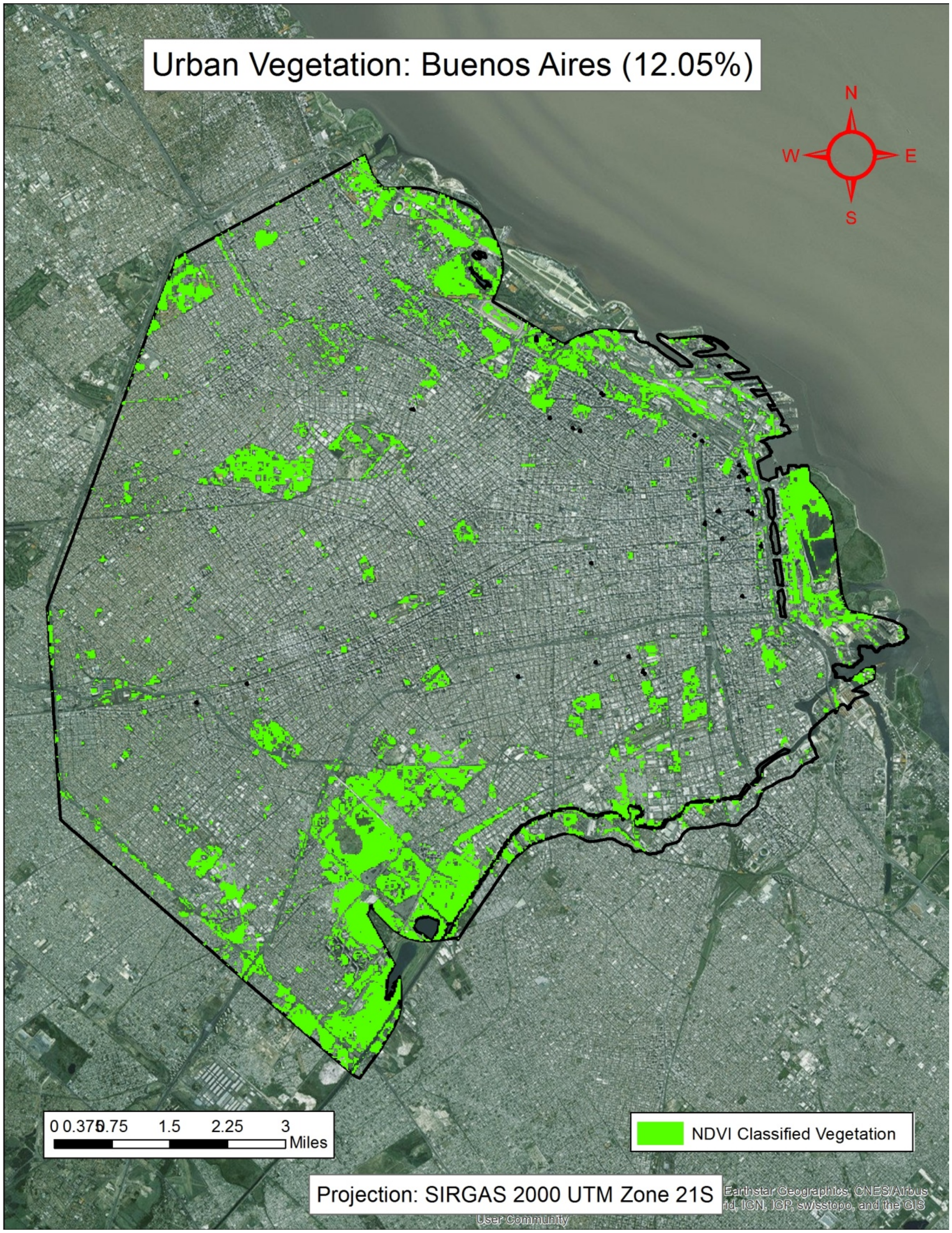

Figure 4.6. Vegetation Index Buenos Aires

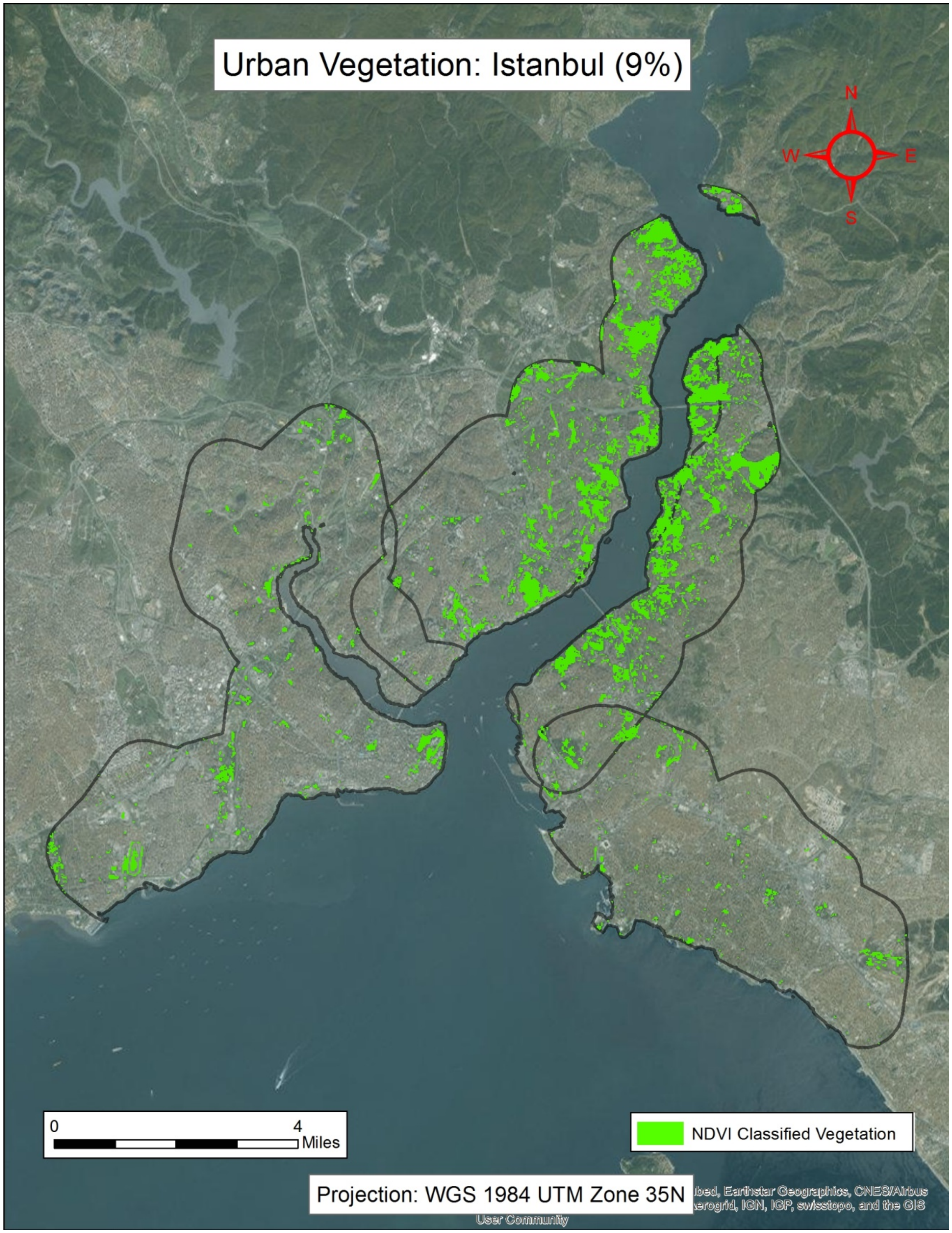

Figure 4.7. Vegetation Index Istanbul

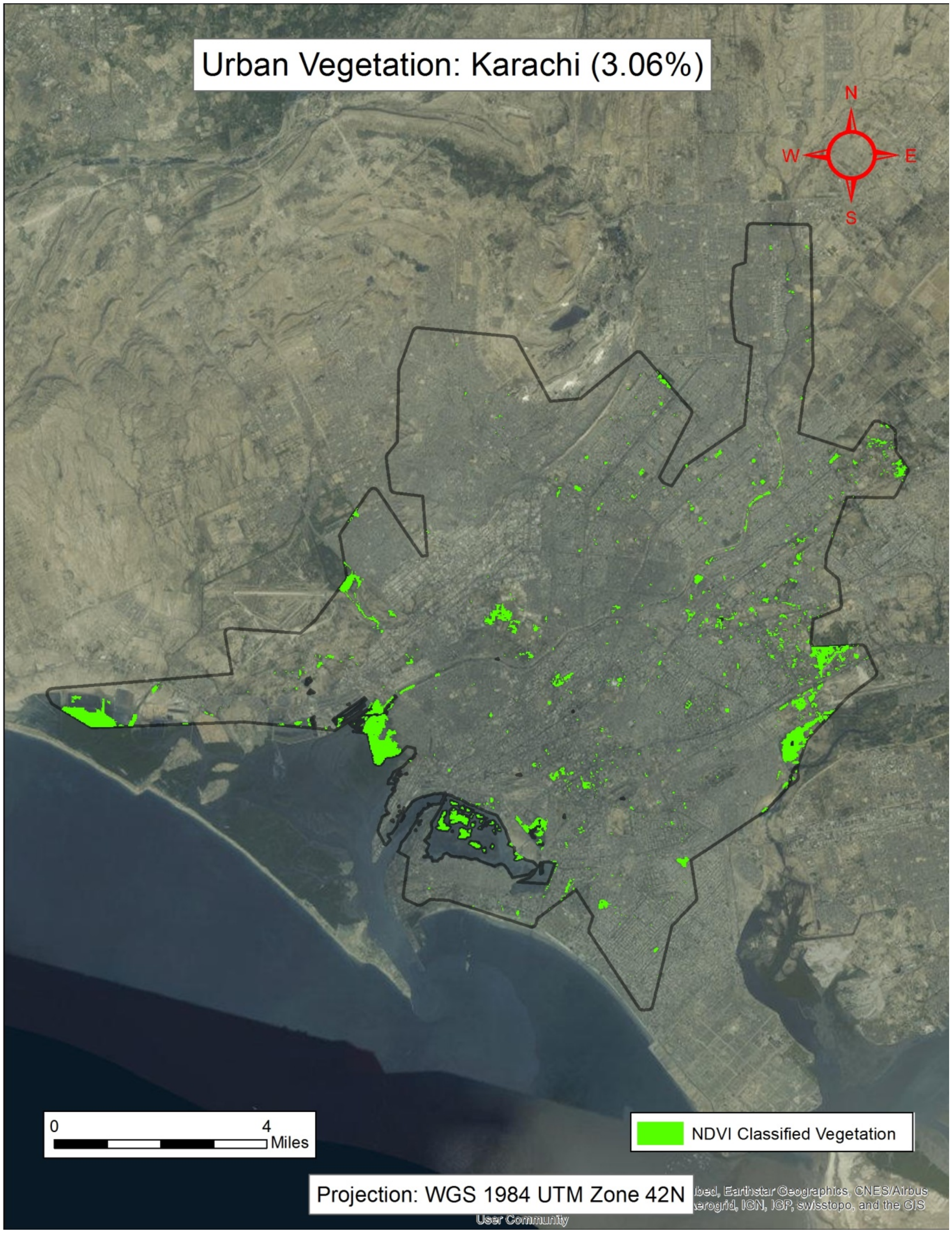

Figure 4.8. Vegetation Index Karachi

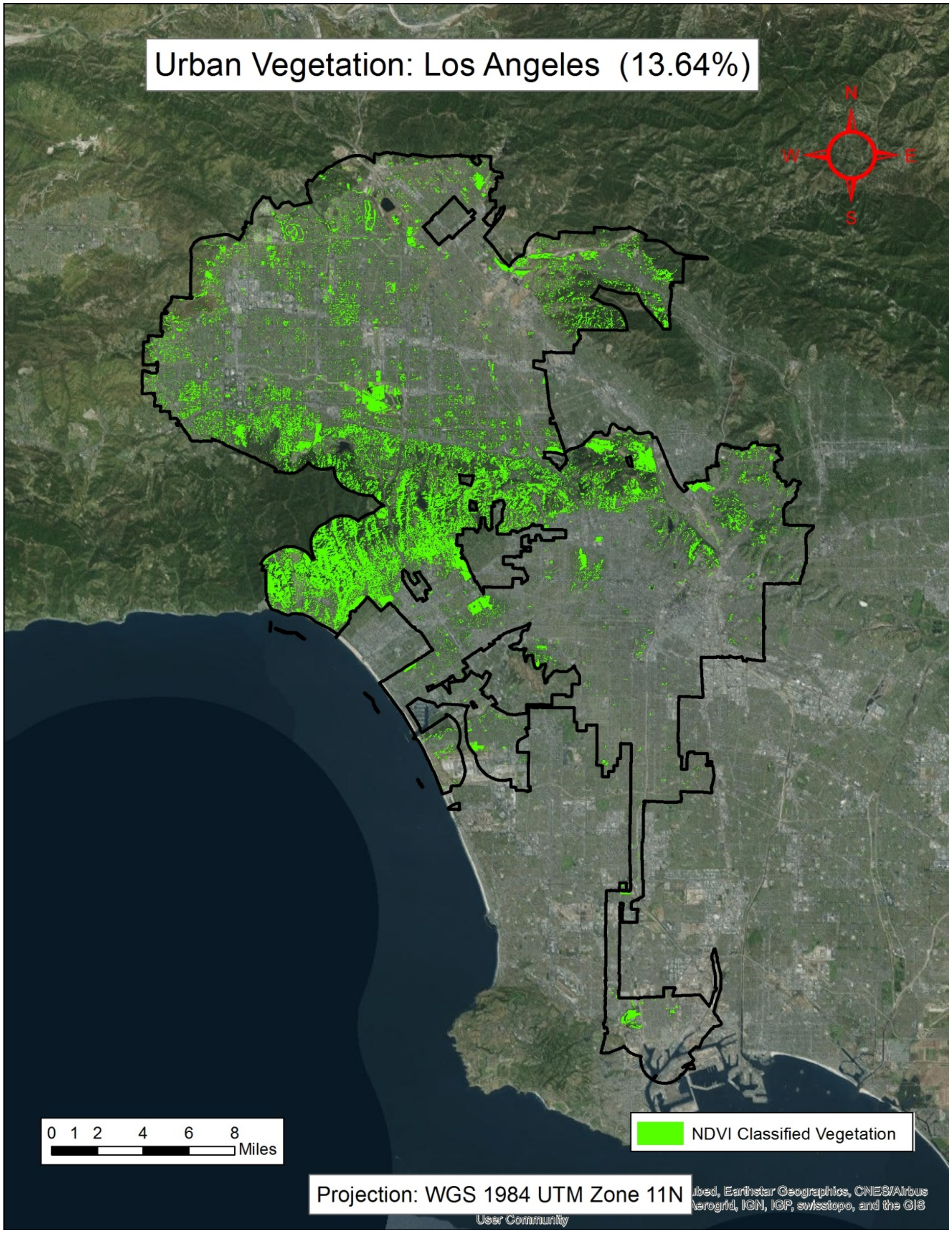

Figure 4.9. Vegetation Index Los Angeles

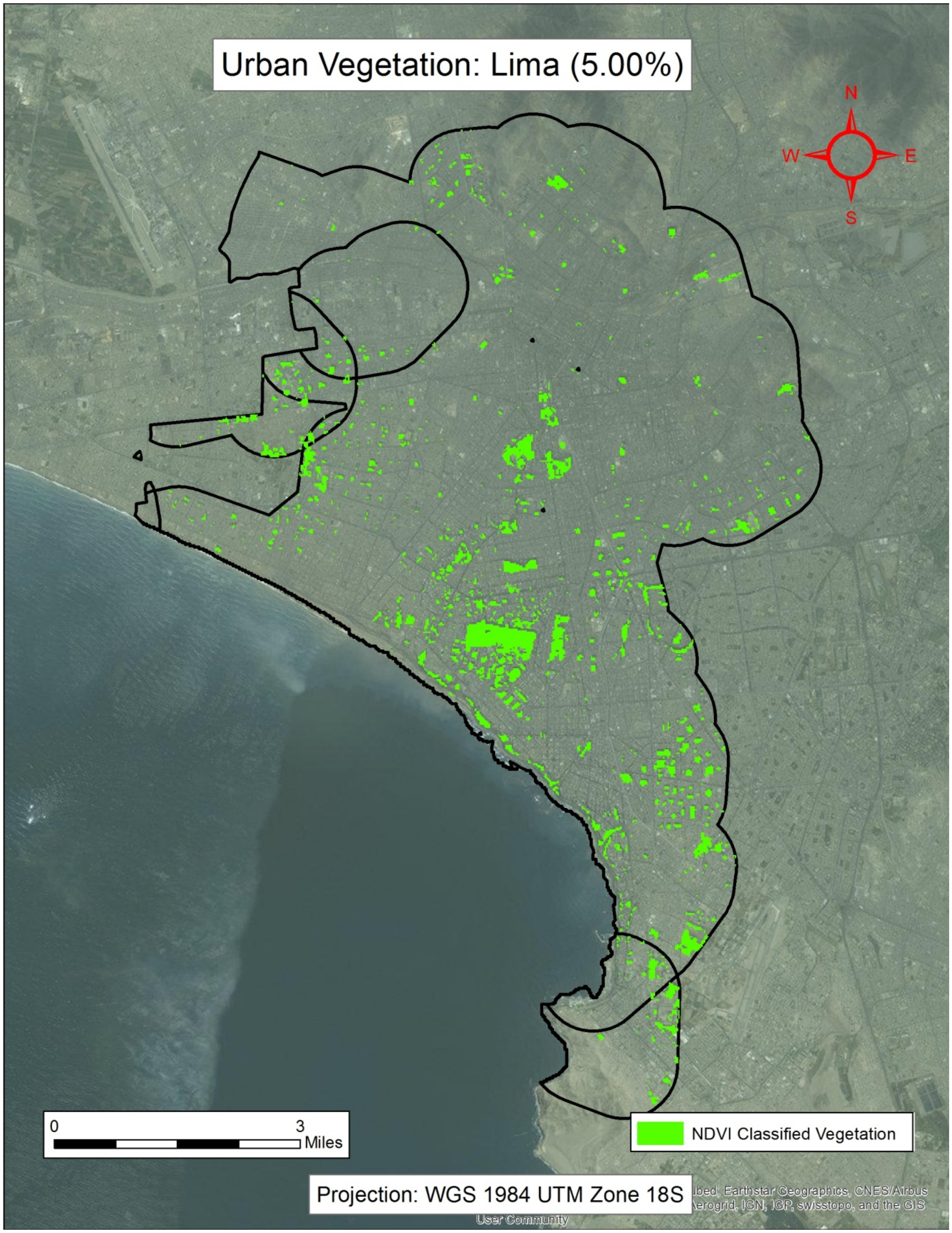

Figure 4.10. Vegetation Index Lima

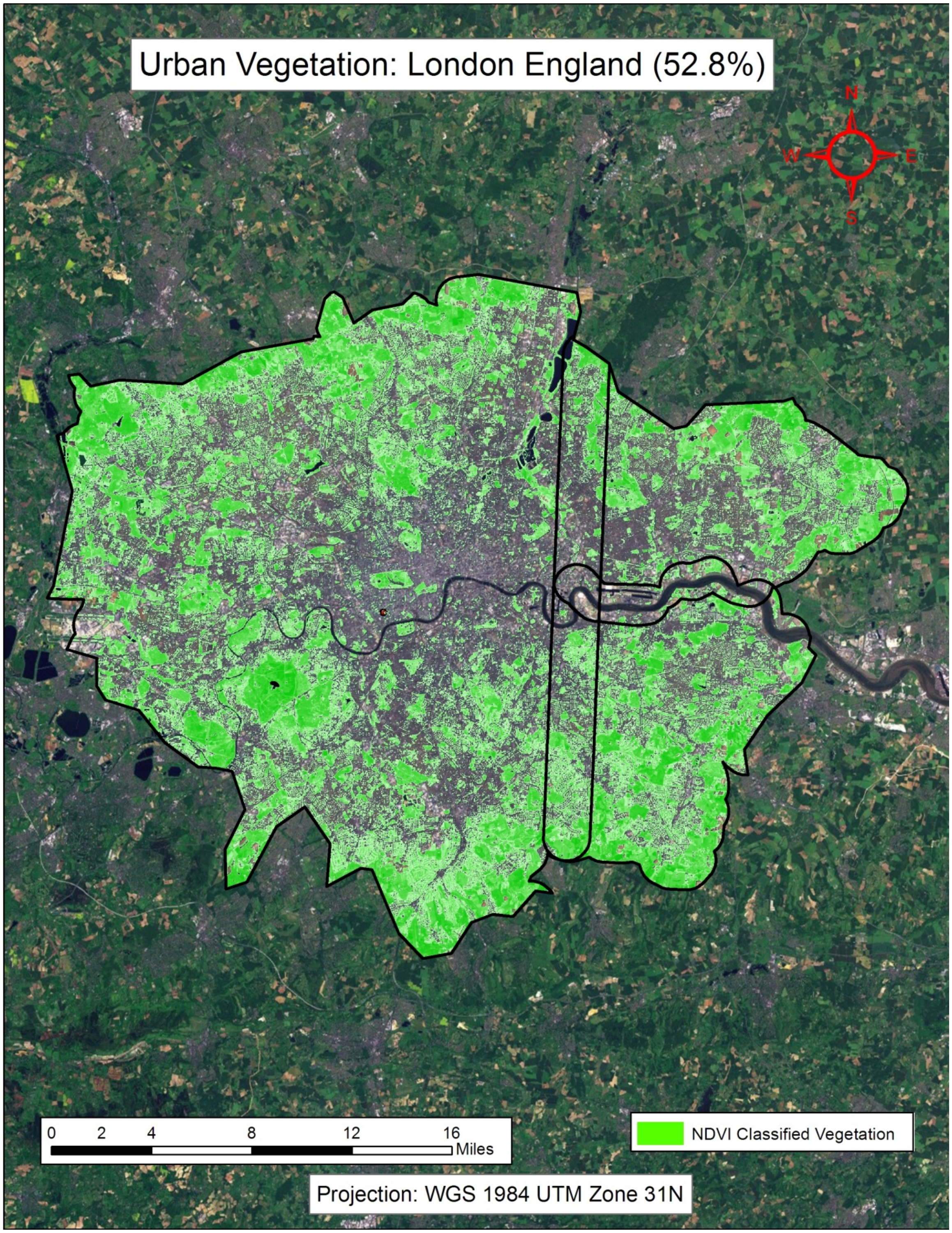

Figure 4.11. Vegetation Index London

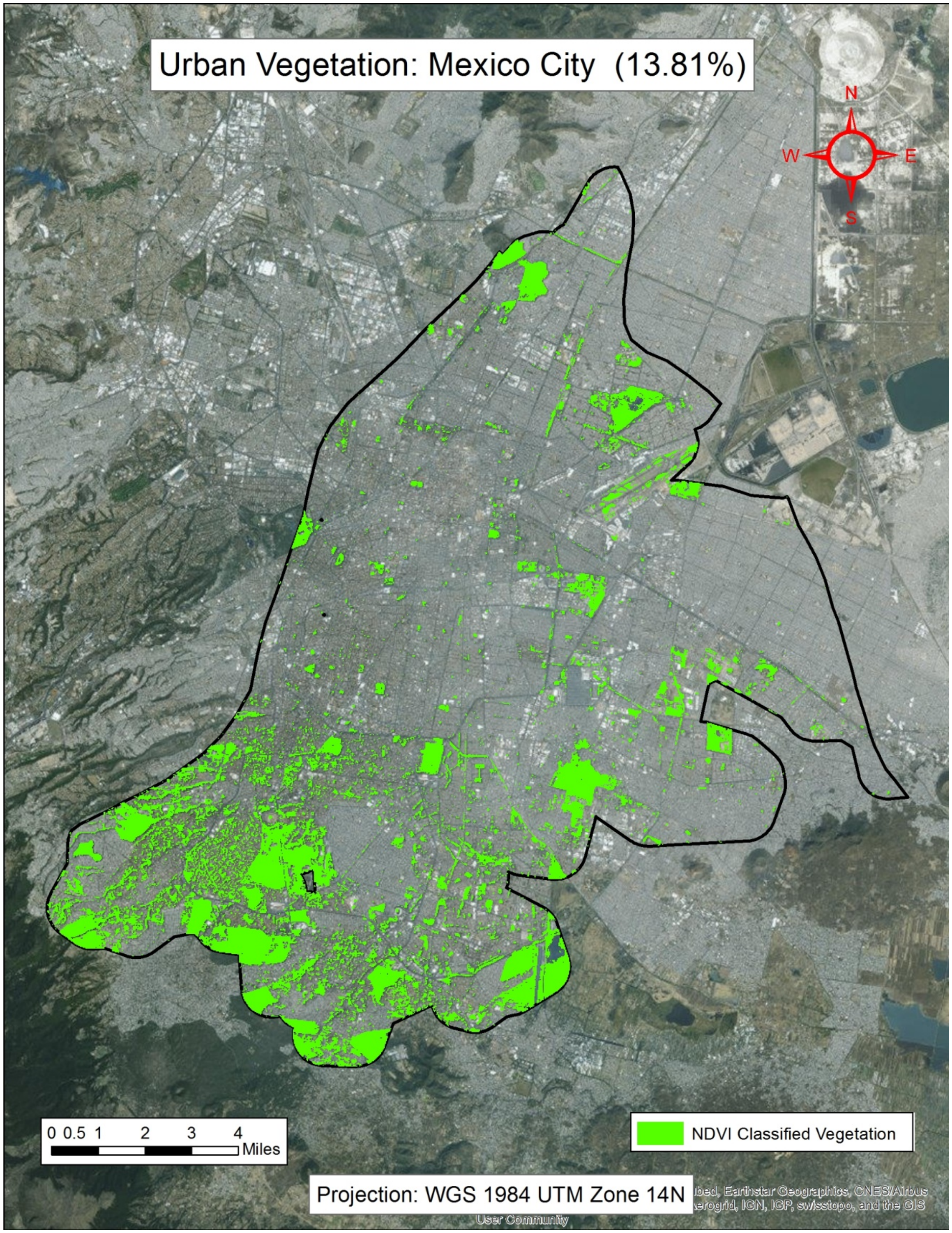

Figure 4.12. Vegetation Index Mexico City

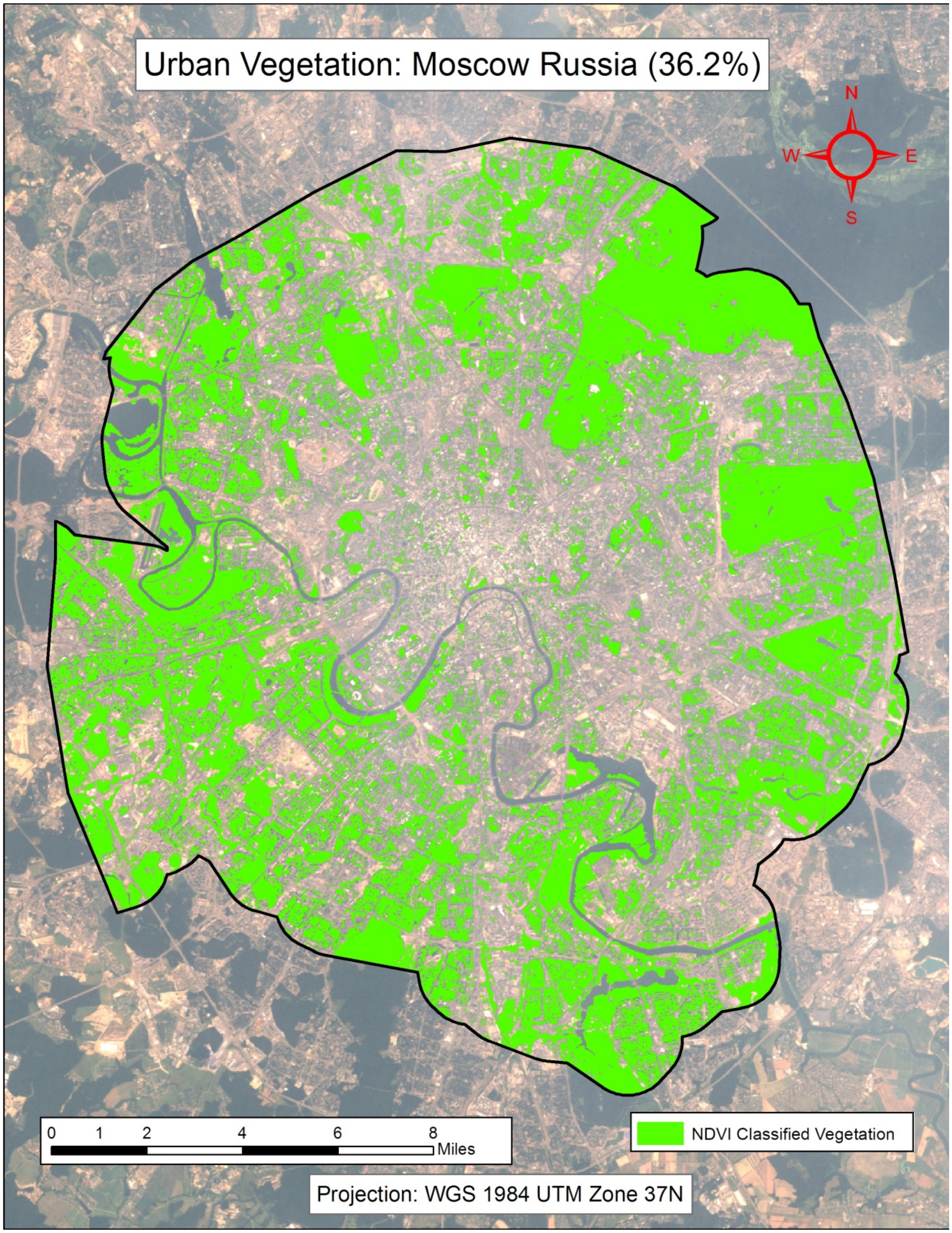

Figure 4.13. Vegetation Index Moscow

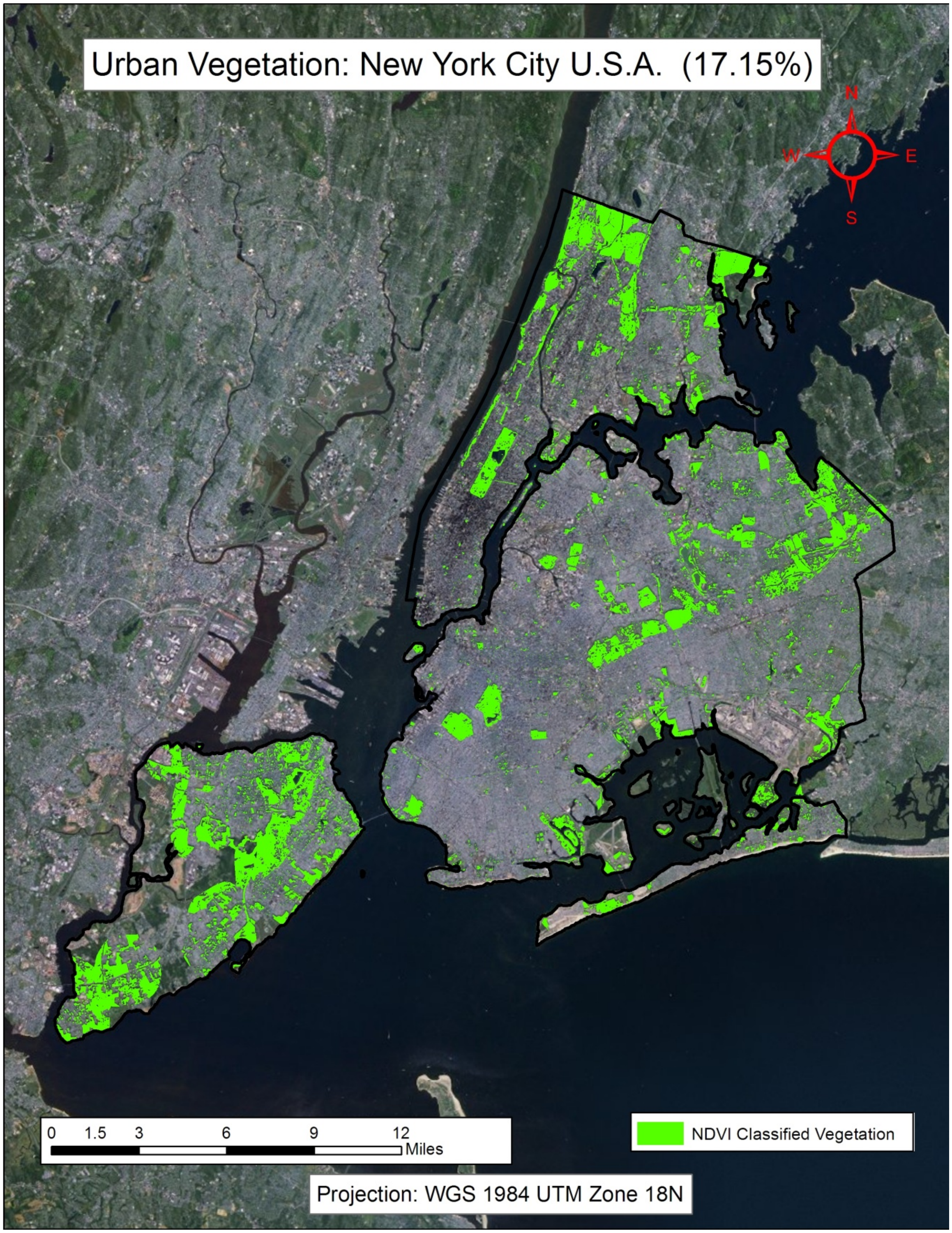

Figure 4.14. Vegetation Index New York City

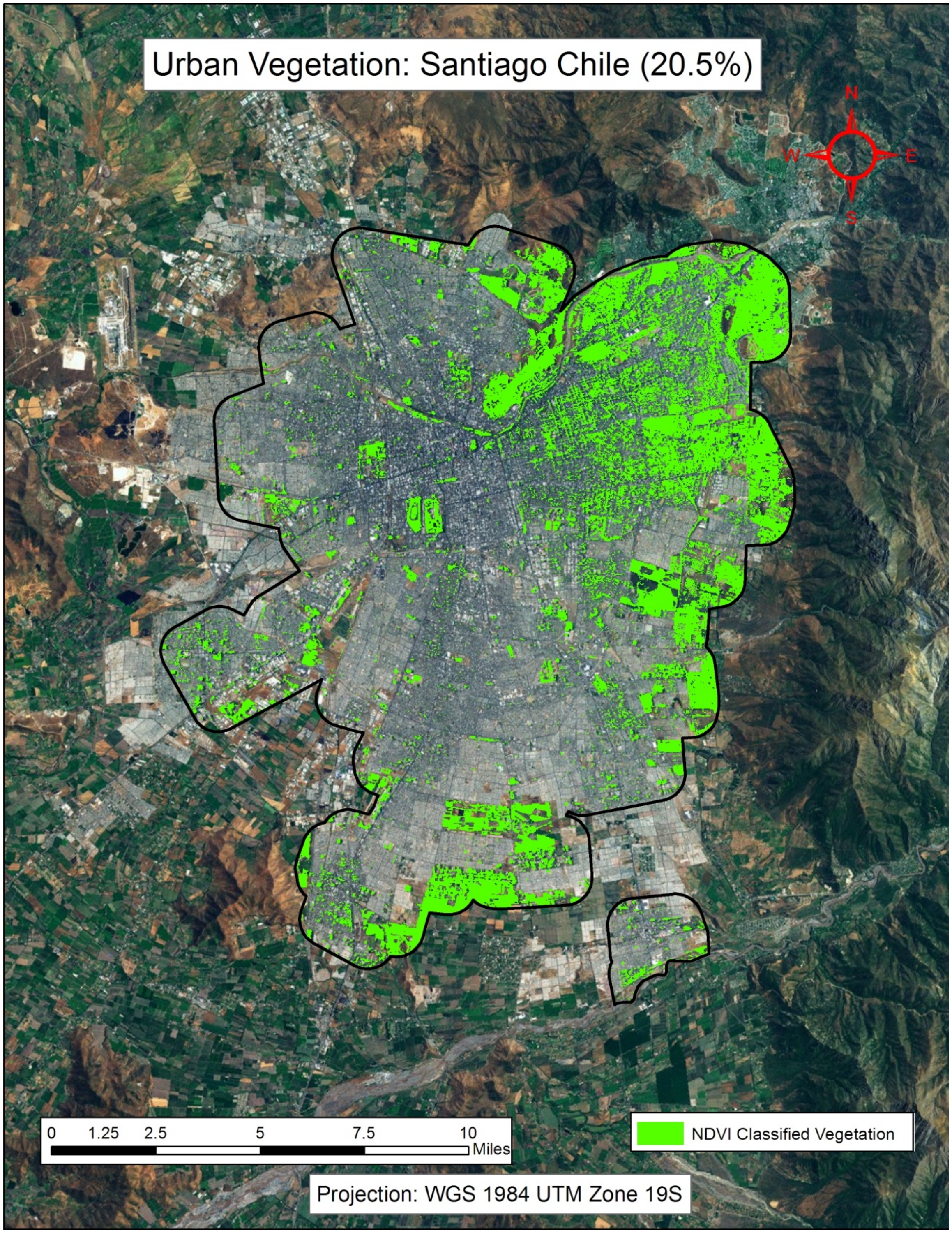

Figure 4.15. Vegetation Index Santiago

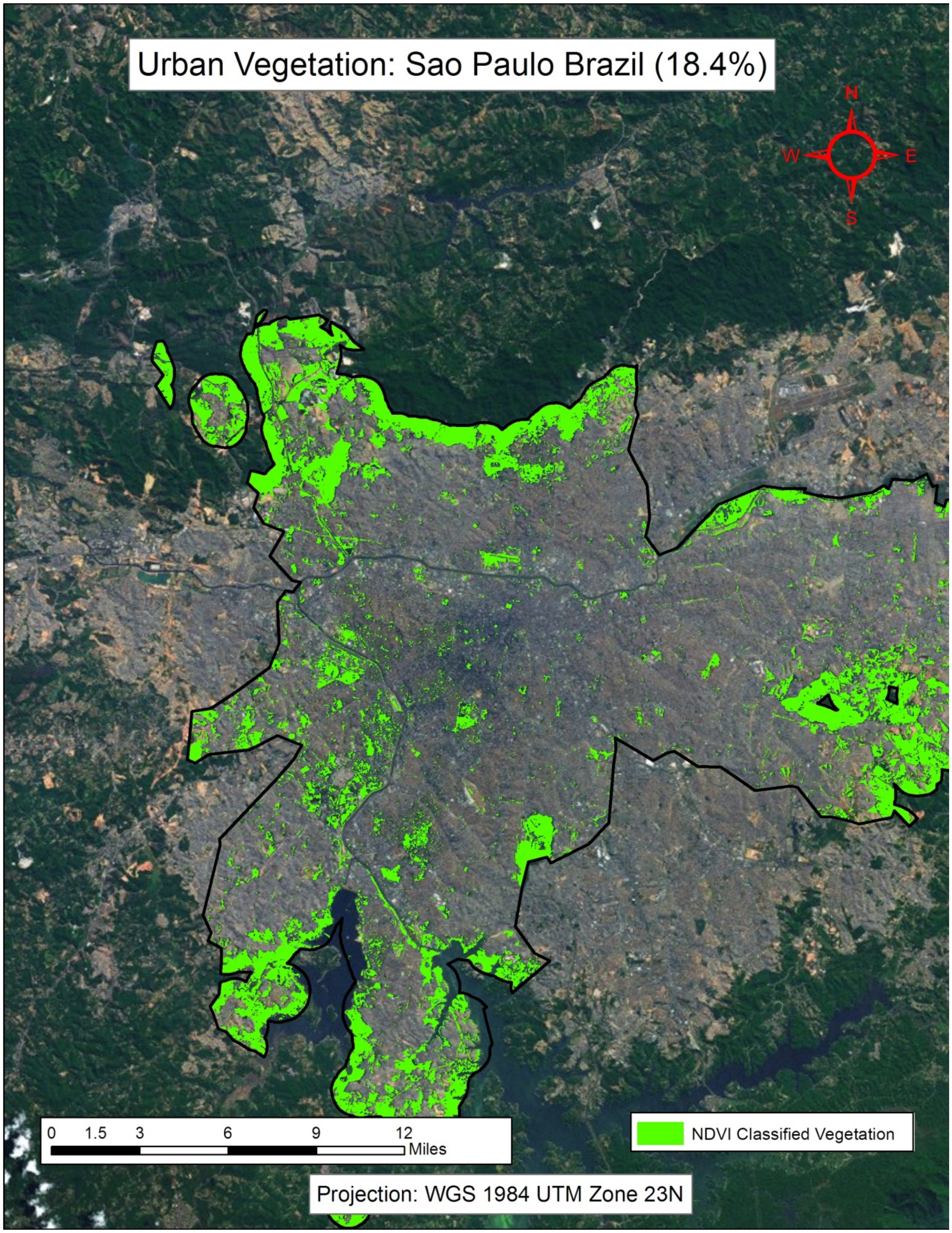

Figure 4.16. Vegetation Index Sao Paulo

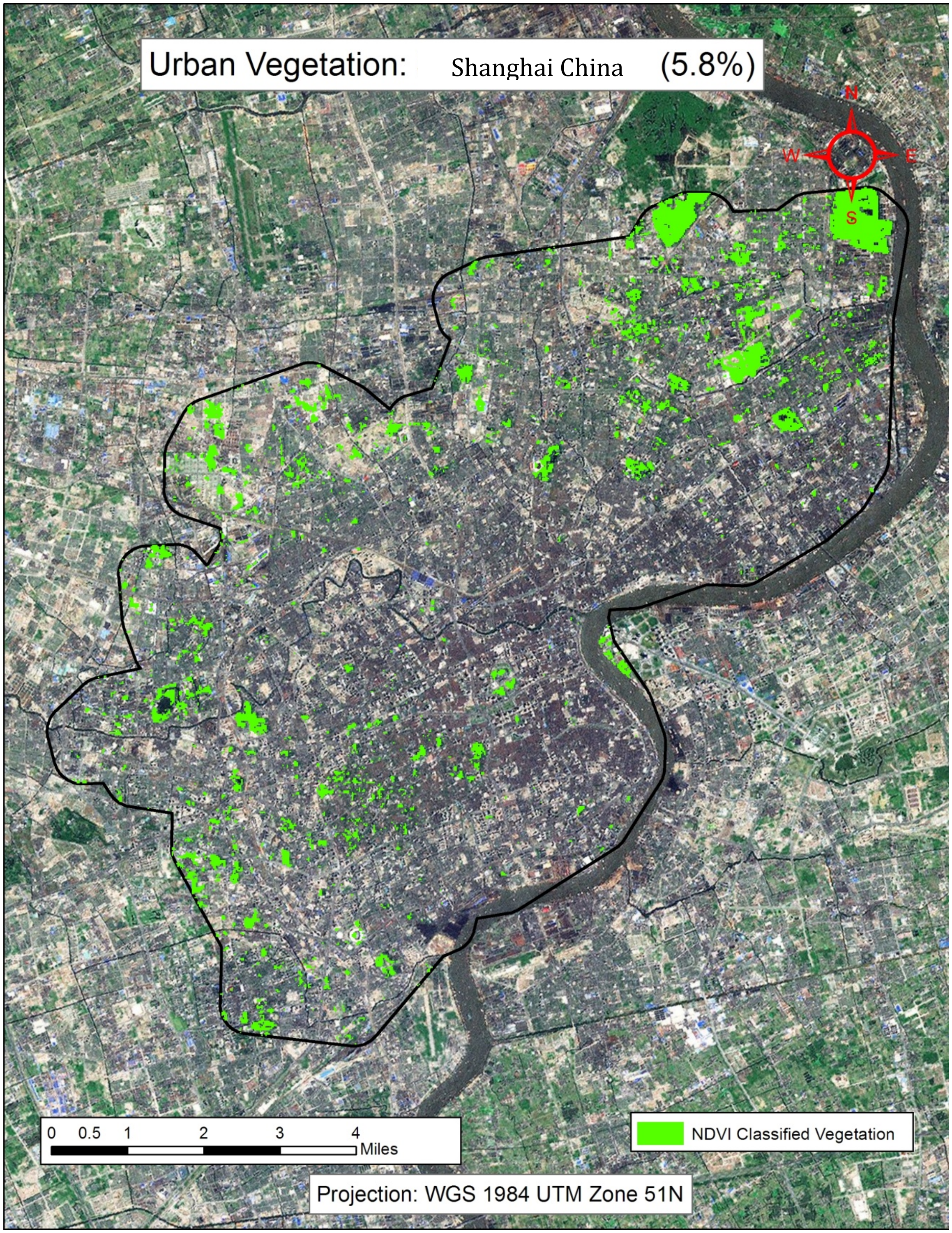

Figure 4.17. Vegetation Index Shanghai

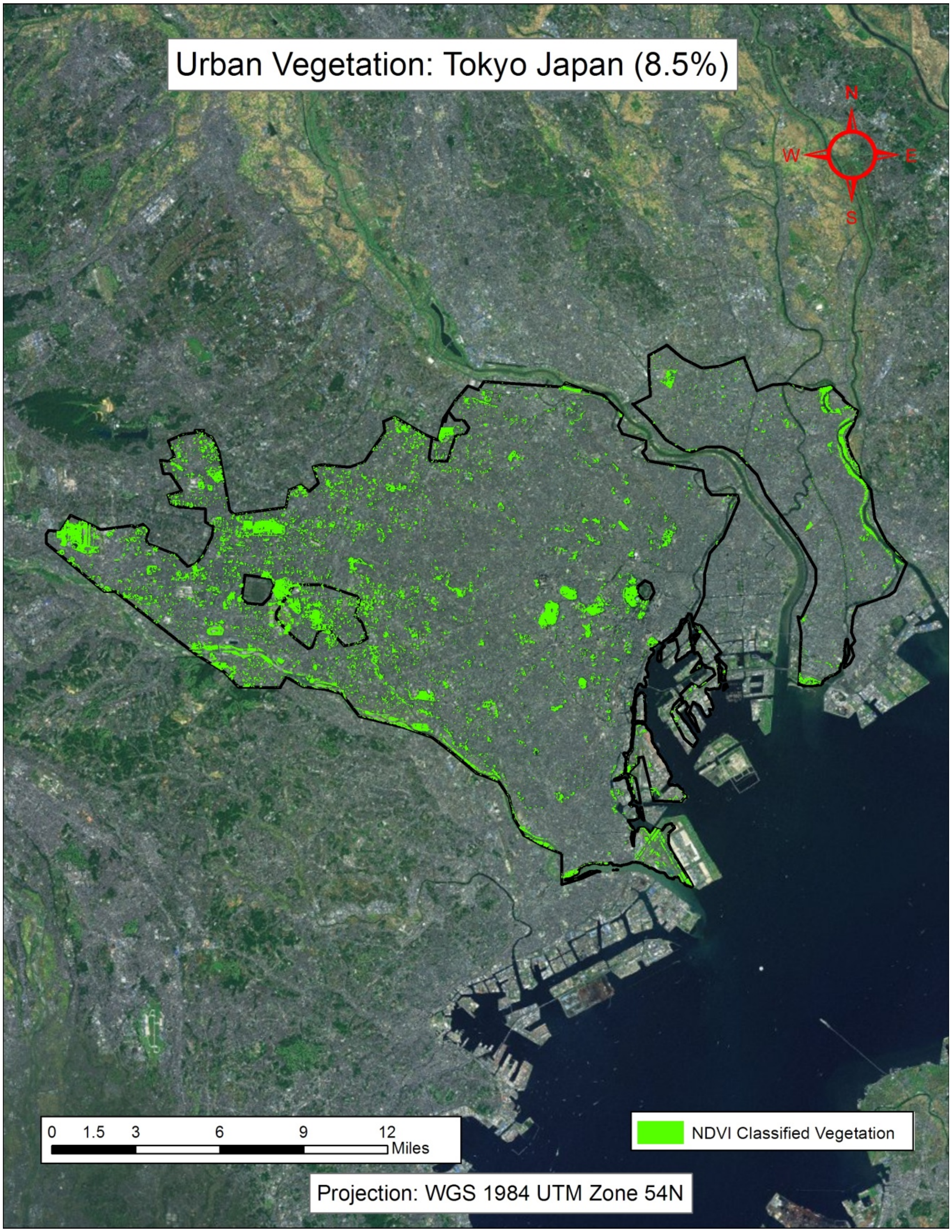

Figure 4.18. Vegetation Index Tokyo

CHAPTER V

DISCUSSION

Sampling

The recorded percentages of total vegetation per total area land mass for each city represent vegetation canopy, leaf area index, vegetation condition, and biomass (Jiang et al., 2006). Seasonality, shadowing, and the angle of the sun all contributed to variation in the minimum threshold for classifying NDVI values as vegetation (Jensen A. , 1979; Jiang, et al., 2006). The average vegetative cover for all sixteen cities in this study was 15%.Comparatively; urban areas are estimated to occupy 3.5% of the lower 48 states with an average canopy of 27% (Nowak et al., 2005).The average for the United States as a whole may be larger due to a variety of factors, including population size, population density, climate, and weather. Given variable conditions and different dates of imagery, minimum NDVI thresholds could have changed for any given sample area. For example, the imagery used for analysis of Karachi, Pakistan was recorded on March 31 of 2011. March marks the end of a dry winter and beginning of a hot and dry spring for this region (Rasul et al., 2005). If imagery had been collected for the time period between June and September during Karachi's monsoon season, then a higher minimum NDVI BV threshold may have been observed. Despite changes in NDVI, the presence of leaf-on vegetation is enough to delineate the boundaries of vegetative cover that would remain consistent from season to season unless the vegetation was removed by deforestation, fire, or some other natural or manmade occurrence.

Physical Variables

Though the amount of vegetative cover in each city is correlated with physical variables including latitude, average annual rainfall, and distance to the ocean, the role of human involvement in the urban landscape plays a critical role. Where zoning and planning occur, vegetation quantity can be regulated and manipulated (Wilson et al., 2003). Residentially zoned areas will typically consist of impervious surfaces including rooftops, driveways, and the interconnected web of streets that comprise neighborhoods. The total coverage and type of coverage is dynamic as development evolves differently amongst global cities. There is a large variety of vegetative cover as it pertains to cities and amongst cities throughout different countries. For example, residential neighborhoods in Mexico City have much less vegetation per square mile than in Los Angeles California. Planned cities result in higher percentages of urban vegetation than unplanned cities typical of developing third world countries. Regardless of city size or planning factors, the results of the vegetative index in this study do not necessarily show the total composition of vegetation in each city. Trees, shrubs, and lawns that exist within urban environments and are surrounded by impervious surfaces will often times not be classified as vegetation due to the low resolution used in the classification of the NDVI.

The highest correlating physical variables with urban vegetation were year of origin (r = -.776), population density (r=.722) and latitude (r=-.464). Temperature also had a strong correlation with vegetation at (r=.401). Further analysis on these results are included in the discussion. The relationship between the year of origin and the amount of vegetation in each city is blurred by the great amount of change that occurs over time. For example, Moscow and London, have both been heavily bombed in the World Wars and have had to rebuild their cities. Population density and vegetation are positively correlated. However it is intuitive to believe that the higher the population density in the city, the less room there is for vegetation. This may be due to the levels of residency in highly developed areas and the resulting openness of remaining spaces within the urban limits.

Vegetation Type

Vegetation extracted from Landsat imagery at a resolution of 30 meters by 30 meters does not differentiate between types of vegetation, meaning it doesn't matter whether the urban vegetation is grass, trees, bushes, golf greens, or any other type of vegetative matter. Any cells with NDVI values above the minimum threshold were included in this study. Different vegetation types result in different environmental impacts. Parks and golf courses were observed in all of the sample areas and large plots of agriculture were observed around most major city centers (ESRI, 2010). While many similarities were observed between all of the studied areas, many occurrences of unique vegetation types were observed as well. In the majority of sample areas, agriculture was the dominant land use type outside of the city limits (ESRI, 2010). There were, however, two cases in Bangkok and Karachi, where crops were found near the city center. In Bangkok, the majority of vegetation within the urban extent appeared to be cropland (ESRI, 2010). In Moscow, Russia, large blocks of preserved indigenous forest occurred within the outer perimeter of the urban extent (ESRI, 2010). In Bogota, the majority of vegetation was highly concentrated along the eastern edge of the city and within a strip of the Andes Mountains (ESRI, 2010). In Buenos Aires, a highway along the outside perimeter of the city was lined with vegetation, and in Tokyo, rivers were protected by generous riparian zones (ESRI, 2010, Figure 5.1).

Figure 5.1 Riparian Zone Along the Arakawa River in Tokyo Japan

Native forests, manmade forests, golf courses, agriculture, riparian zones, and cemeteries were the primary types of vegetation observed in this study. Cemeteries are prevalent in all of the observed cities. Unlike native vegetation or manmade parks, there is typically no canopy associated with cemeteries. The environmental impacts of cemeteries vary from location to location. Specific environmental roles of this type of urban vegetation include reduction of flood risks and reduction of urban heat islands. Due to limited tree canopy cover in graveyards, the level of impact on flood reduction is not as great as it would be in a native forest. This is due to the lack of root systems that soak up large portions of rainfall during any given precipitate weather event. Cemeteries do, however, benefit over built up spaces and impervious surfaces as the water is able to infiltrate the surface and work its way into the groundwater table. The amount of atmospheric pollutant retention is based upon leaf area index and species type. Grass does not have a high leaf area index, nor does it comprise the volume of vegetation found in native or man-made forests. Therefore, cemeteries are not as productive in atmospheric pollutant reduction as other types of urban vegetation.

Golf courses were observed universally throughout all of the sixteen cities included in this study. Pesticides, fertilizers, and sediments are all concerns amongst the environmental impacts of golf courses. While golf courses return a high NDVI value, they do not reap the environmental benefits of other types of urban vegetation such as native forests or parks. Fairways and greens are treated heavily with pesticides and fertilizers resulting in polluted groundwater, creeks, and streams. The surface of greens and fairways does play a beneficial role in the hydrological cycle as it allows water to infiltrate into the ground water table, as opposed to impervious surfaces that divert rainfall to sewers, channels, and streams. The surface area of the vegetation within golf courses is minimal compared to forests and parks. Fairways and greens have such minimal vegetative surface areas, that their ability to retain atmospheric pollutants is negligible. Trees, and bushes within the golf park, however, will retain significant levels of atmospheric pollutants (Hunhammar & Bolund, 1999) .

Native vegetation is rarely found in urban environments. Central Park in New York City, Golden Gate Park in San Francisco, and many other parks within urban environments have been cleared and replanted by landscape architects. One exception found in this study is Trianon Park in Sao Paulo Brazil (Figure 5.2). Trianon Park is a 12 acre protected patch of native vegetation, part of the Mata Atlantica biosphere. This park was established in 1892 by French landscape architect, Paul Villon. (Alvarado, 2012).

Figure 5.2 Trianon Park Native Vegetation, Sao Paulo Brazil

Native vegetation represents the natural ecosystems that have taken generations to develop through natural ecological succession. Within sites where native vegetation is present, competition between flora and fauna is typically stable. In contrast man made forests carry the risk of the introduction of invasive species. When introduced into an urban ecosystem, invasive species may outcompete native species and either take over completely or reduce competition. The selection of species to plant when working with man-made forests is important for the emulation of a native forest environment. Olmsted worked strategically with both native and non-native species. He did not limit himself to working with only native species; rather he sought out species that he expected to thrive (Beveridge, 2000) . Olmsted’s expertise led to the development of many productive and healthy mixed forests within urban environments, most notably Central Park in New York City.

London, England and Moscow, Russia emerged from this study as the two cities with the highest percentage of urban vegetation (Table 4.1).. This is due to the historical origins of Moscow and London and the value placed on vegetation within their urban environments during their early developmental stages. The Royal parks of London include eight separate parks all of which are composed of trees, grasslands, and gardens. The total area of these parks is 5,000 acres, accounting for a major portion of London's 52.78% vegetative cover. The history of the Royal Parks date back to the 15^{th} century when these public areas were preserved for royal hunting chases. More recently public parks, including Regent's Park, have been open since 1845 (Parks, 2012).

In Moscow, vegetation is distributed throughout the city as wedges coming in from outside of the limits. The wedges do not represent entry points into contiguous forests, rather the wedges are part of preserved forests set apart as patches of vegetation within a larger agricultural landscape. The Khimki forest in Moscow, Russia is a 2500 acre tract of preserved land .A planned highway initially was going to split through the center of the Khimki forest. However, after protests and massive public gatherings, the proposed highway was rejected and the Khimki forest remains contiguous and intact. On the other side of Moscow, Sokolniki Park is one of the largest contiguous stretches of urban vegetation within Moscow's city limits. The 1200 acre park is composed of a mixture of native and non-native species. Once used as a hunting ground in the 1600's, it is now preserved for the protection of its natural habitat and a source for public recreation. Both Moscow and London are rich in their acreage of forested parks and this is largely in part due to their historical preservation of green spaces (Kuzminki, 1995).

Beijing, Karachi, Shanghai, and Lima were amongst the cities with the lowest percentages of urban vegetation in this study (Table 4.1). Karachi, Pakistan was ranked lowest in this study, with only 3.06% of its total urban area being covered by vegetation. This is largely due to climatic factors. Karachi is located in a desert environment where the average rainfall is only 9 inches per year and the average annual temperature is 79 degrees (F) of rain per year on average. While vegetation is minimal, there are a few vegetated areas in Karachi that provide refuge from urban development. Most notably, the largest park in Karachi is Gutter Baghicha, established in the early 1900's and comprised of 1017 acres of preserved land. Due to increased development, and lack of planning, the Gutter Baghicha Park is now down to only 480 acres of forest.

Ranked 2nd lowest in urban vegetation of this study was Shanghai, China. Despite having a favorable climate with a moderate level of annual precipitation (45.10 inches/year) Shanghai only contains 5.78% vegetation within its boundaries. Rapid development over the past several decades has led to the urban expansion and increase of impervious surfaces within the city. As a result land surface temperatures have increased significantly within developed areas of Shanghai. While the urban heat island effect is typically associated with city centers and downtown districts, the urban heat island in Shanghai is more prominent in residential areas (Li et al., 2011). This is due to the high level of impervious surfaces and increased density associated with developing countries. Gongging forest park is one of many small parks distributed throughout the city of Shanghai; more vegetated parks evenly distributed throughout Shanghai would reduce the urban heat island effect. Despite the presence of small green spaces within the city limits, Shanghai remains one of the major cities lacking in the density of urban vegetation.Ranked 3rd lowest in urban vegetation, Lima Peru has only 5% vegetative cover. Lima is located in a desert environment that receives only .4 inches of rain per year on average. As a result, vegetation in this city is non-native and requires regular irrigation in order to be sustained. Rapid urbanization and unplanned growth have led to a myriad of environmental problems within the city of Lima Peru. Deforestation of watersheds and recurrent drought has left the city in a state of environmental deterioration (Cathalac, 2008). Despite rapid urbanization and growth, there are still patches of native and non-native vegetation within the city limits. The parque de las leyendas is one of the the only and largest parks in Lima. It includes native vegetation, a zoo and traditional sites. Lima is split by the river of Rimac, the primary water source for the city and all of its inhabitants. Riparian zones can be found alongside the river’s edge; however the entirety of the river’s edge is not protected by riparian zones.

CHAPTER VI

CONCLUSION

This study highlighted the importance of the incorporation of vegetation within the urban environment and painted a picture of the current level of vegetative cover within sixteen of the world's largest cities. The presence of urban vegetation is critical for the environmental health of modern cities. Vegetation within the urban environment supports ecological vitality through the sequestration of atmospheric pollutants, reduction of runoff, and mitigation of the urban heat island effect. The methods in this study built off of the work of Huang, et al. (2007) and suggest that developed countries have both greater quantities of vegetation as well as less dense and compact urban form. A comparative analysis of the cities in this study show differences in vegetative cover and the correlating variables attributed to the discrepancies. Results showed London, England had the greatest percentage of urban vegetation with 53% while Karachi Pakistan had the least at 3.06%. The highest correlating physical variables with urban vegetation were year of origin ($r = -.776$), population density ($r =.722$) and latitude ($r =.464$). Multiple step regression revealed variables effective for the prediction of vegetation quantity in any given city. The best R Square Stepwise Procedure was a three variable model deduced from multiple step regression. It was the only combination of variables with a P value > .05. The percentage of vegetation can be best predicted by the following variables; distance to ocean ($r =.367$), origin year ($r = -.776$), and population density ($r = .722$).

The methodology in this study is unique and may be repeated in further analyses of vegetation within urban environments. The combination of urban boundaries and municipal boundaries provides a reasonable extent of study. Limiting the extent to municipal boundaries prevents the problem encountered with continuous stretches of development as seen in areas such as New York City and Los Angeles. Further, limiting the extent of study to urban boundaries normalizes the methodology so that percentages only include vegetated areas within developed land. Further analysis of urban form may help to determine appropriate buffer distances required to cover patches of vegetation within urban and municipal boundaries Huang, et al. (2007).

Landsat data is also continuously available and may be used to evaluate urban vegetation in other major cities. Improvements in the results of the NDVI should include the attainment of higher resolution imagery. The cities evaluated in this study were examined at the extent of thirty by thirty meter grid cells. Analysis done at the resolution of three meters or greater would incorporate smaller patches of vegetation representative of residential areas. Further, in the coming years satellite imagery may be collected and used in a comparative analysis with cities evaluated in this study for a comparison of vegetative cover change over time. While physical variables represent the climatic features critical to the presence or absence of vegetation in any given location, it is up to the prioritization of planners, developers, and non-profit organizations to preserve vegetative cover as cities continue to expand. One of the critical issues that should be emphasized by planners is the relationship between vegetative cover and the urban heat island effect. Properly placed trees around buildings can reduce energy consumption by up to thirty percent and reduced energy consumption saves cities money in air conditioning costs. Additionally urban vegetation reduces atmospheric pollutants associated with the burning of fossil fuels. Future studies may include correlating NDVI measurements with land surface temperatures as derived by satellite imagery from the Landsat 8 launched in Feb 2013.

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