Urban Growth Analysis:

Calculating Metrics to Quantify Urban Sprawl

Jason Parent
jason.parent@uconn.edu
Academic Assistant – GIS Analyst

Daniel Civco
Professor of Geomatics

Center for Land Use Education And Research (CLEAR)
Natural Resources Management and Engineering
University of Connecticut

Shlomo Angel
Adjunct Professor of Urban Planning
Robert F. Wagner School of Public Service, New York University
Woodrow Wilson School of Public and International Affairs,
Princeton University

Image courtesy of the Union of Concerned Scientists: www.ucsusa.org

Project Overview

- Analyze change in urban spatial structure, over a 10 year period, for a global sample of 120 cities.
  - Phase I (Angel *et al.* 2005): Acquire and / or derive necessary data. Develop preliminary set of metrics
  - Phase II (Angel *et al.* 2007): Further develop metrics to quantify and characterize the spatial structure of the cities. Create maps to facilitate qualitative assessment of the urban structure

Phase I Study Objectives

- Select a stratified global sample of 120 cities with population over 100,000
- Classify urban land cover for each city at two time periods: circa 1990 (T_1) and 2000 (T_2)
- Derive preliminary metrics for characterizing urban development at T_1 and T_2

Phase I: Land Cover Derivation

- Land cover derived from Landsat satellite imagery.
- Land cover derived for two dates: T_1 (circa 1990) and T_2 (circa 2000).
- Land cover contained 3 categories: urban, water, and other

Category	Grid cell value
0	No Data
1	Other
2	Water
3	Urban

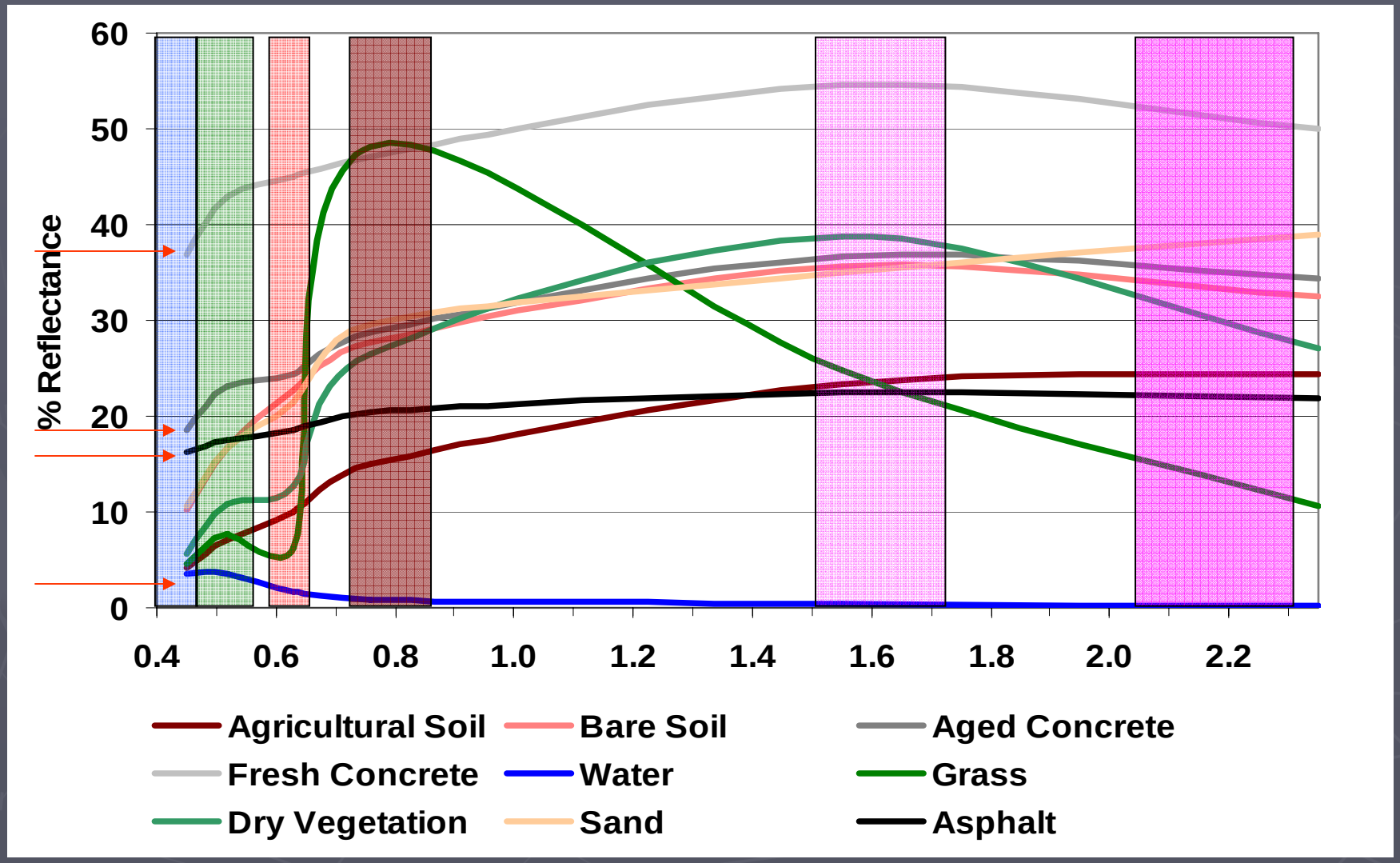
Classification of Built-Up Pixels
LANDSAT

- Satellite series operational since 1972
- Joint project between NASA and USGS
- Two sensors provided data for T_1 and T_2 dates: Thematic Mapper (LANDSAT 4 and 5) and Enhanced Thematic Mapper (LANDSAT 7)

TM and ETM Sensors

	Landsat 4/5 TM		Landsat 7 ETM	
Band	Spectral (υm)	Spatial (m)	Spectral (υm)	Spatial (m)
1 Blue	0.45-0.52	30	0.45-0.52	30
2 Green	0.52-0.60	30	0.52-0.60	30
3 Red	0.63-0.69	30	0.63-0.69	30
4 Near Infrared	0.76-0.90	30	0.76-0.90	30
5 Middle Infrared 1	1.55-1.75	30	1.55-1.75	30
6 Thermal Infrared	10.40-12.50	120	10.40-12.50	60
7 Middle Infrared 2	2.08-2.35	30	2.08-2.35	30
Panchromatic	n/a	n/a	0.50-0.90	15

Spectral Reflectance Curves



Classification of Built-Up Pixels
Image Acquisition and Processing

- Landsat scenes acquired for each study city.
  - As close as possible to 1990 or 2000
  - Minimal cloud cover
- Software: Leica Geosystem's Erdas Imagine 8.7
- Scenes clipped using preliminary set of administrative district boundaries

Classification of Built-Up Pixels

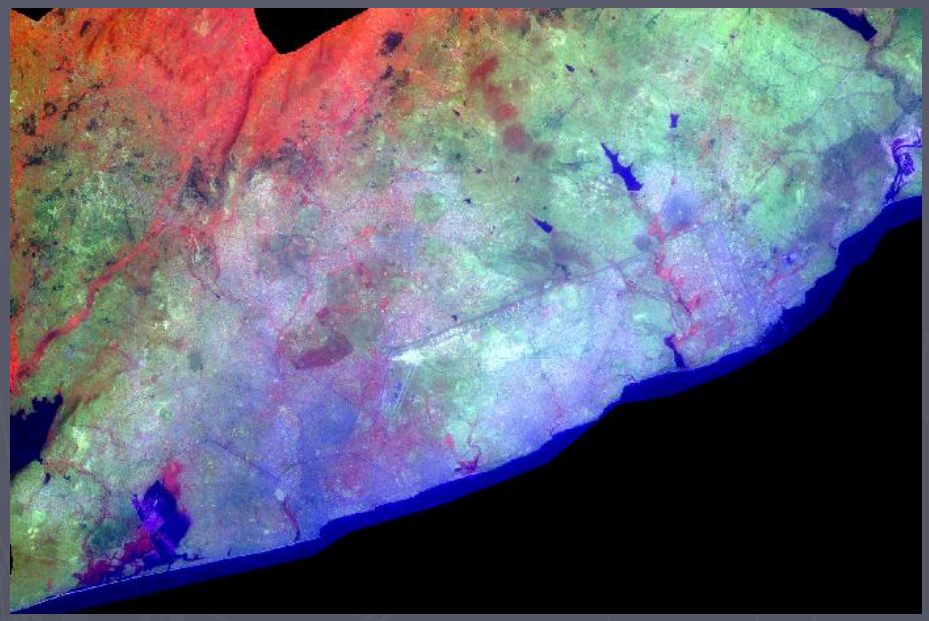
Unsupervised Classification method:

- ISODATA (Iteratively Self-Organized Data Analysis)
- Data assigned to homogenous classes based on spectral properties
  - Ideally classes correspond to a single land cover class
    - Certain types of land cover may have similar spectral properties
    - Shadows and clouds are problems

Classification of Built-Up Pixels

- User identifies land cover type that best corresponds to each ISODATA class
  - Occasionally multiple land cover types correspond to a single class (i.e. urban and barren land)
- Manually edit classification errors using on screen digitizing and recoding
- Recode edited classification image to two classes: urban and non-urban

Classification of Built-Up Pixels



LANDSAT for Accra T_2
(NIR, MIR, and green)

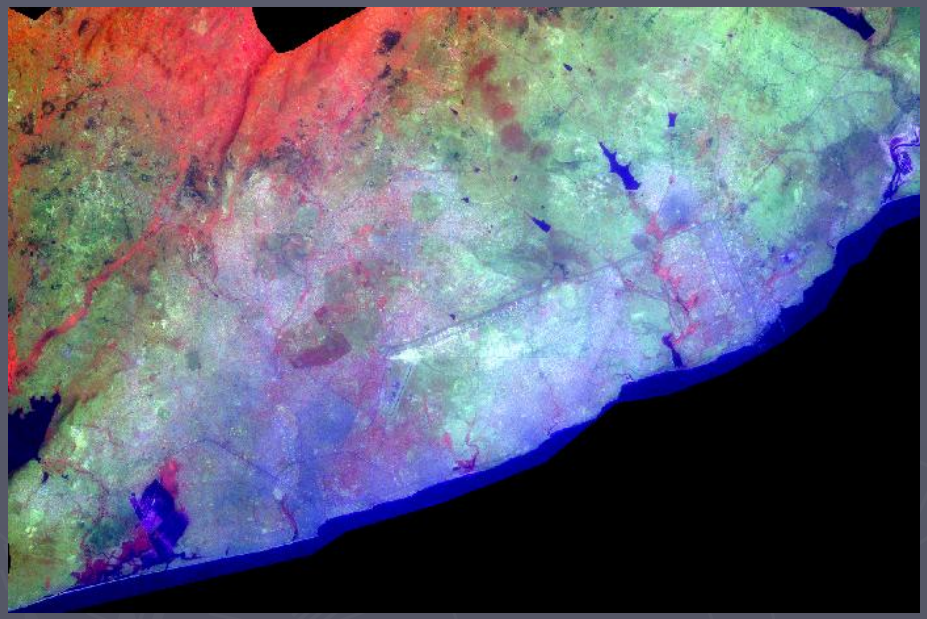
Unsupervised classification
and correction

Urban / Non-urban Image

Classification of Water Pixels:
The Water Index

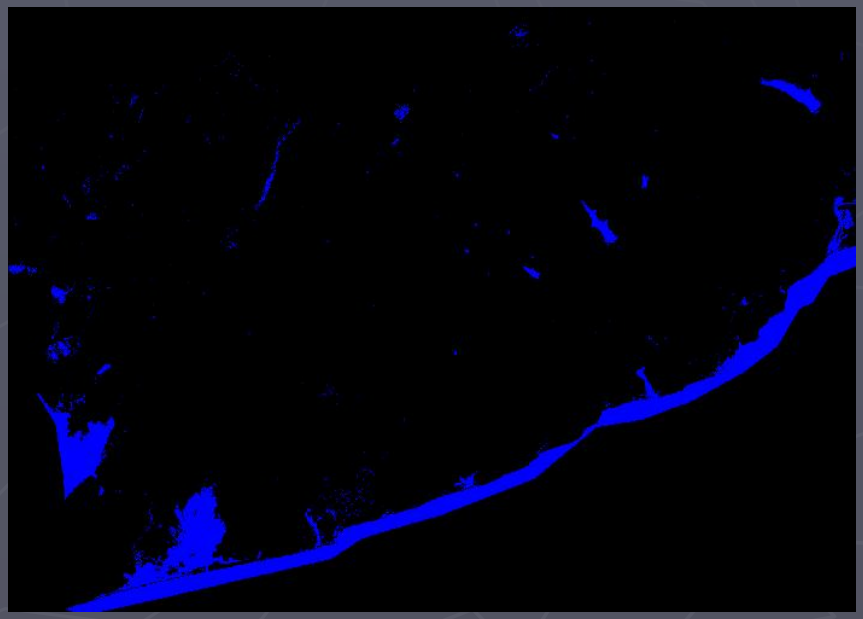
- Water has moderately low reflectance in visible bands (red, green, blue) and very low reflectance in infrared bands.
- Water index is the following ratio (scaled from 0-255):
  - Sum of visible bands / sum of infrared bands
- High water index values = water
  - Analyst identifies a threshold above which indices correspond to water.
- Recode water index image into two classes: water and not water.

Classification of Built-Up Pixels



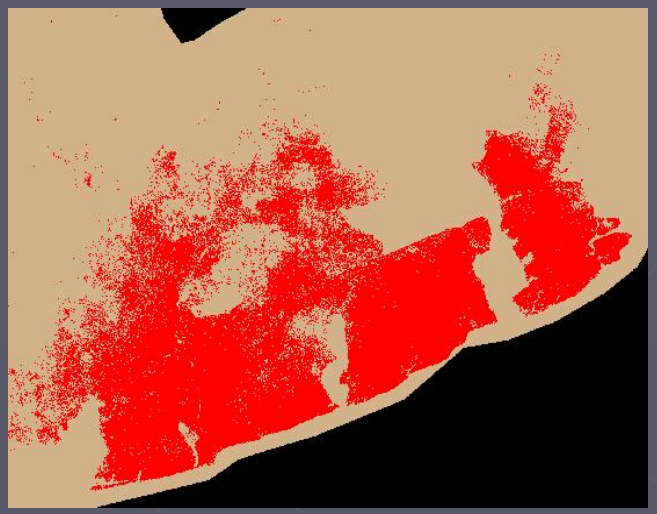
LANDSAT for Accra T_2
(NIR, MIR, and green)

Classification based on water indices

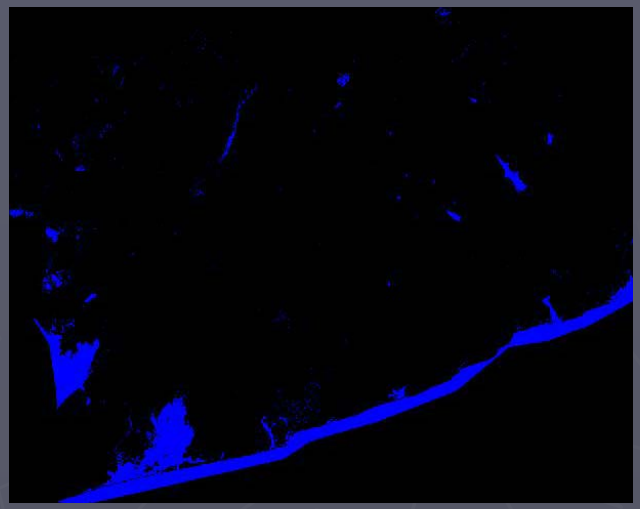


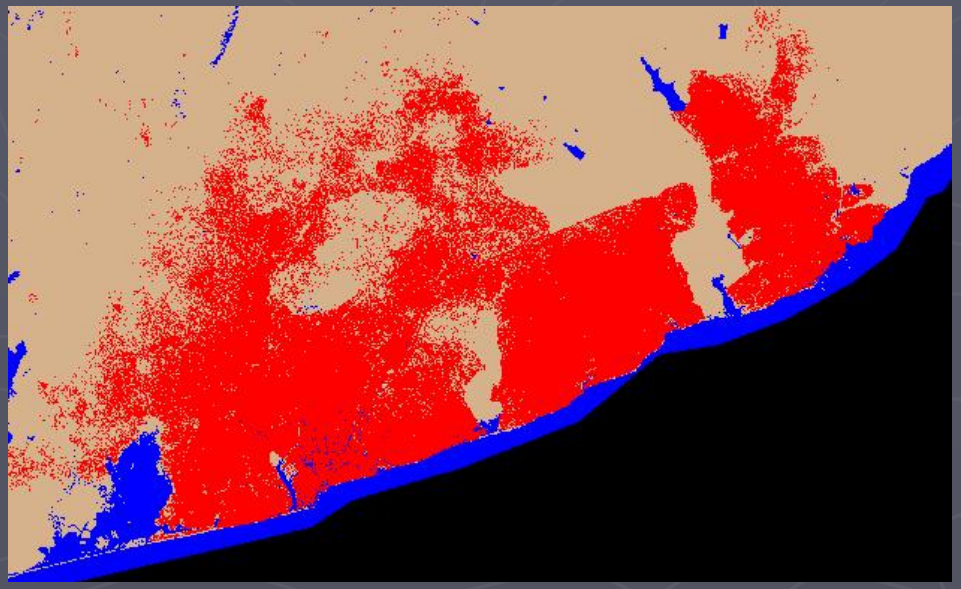
Water for Accra T_2

Combining the Urban and Water Land Cover Maps



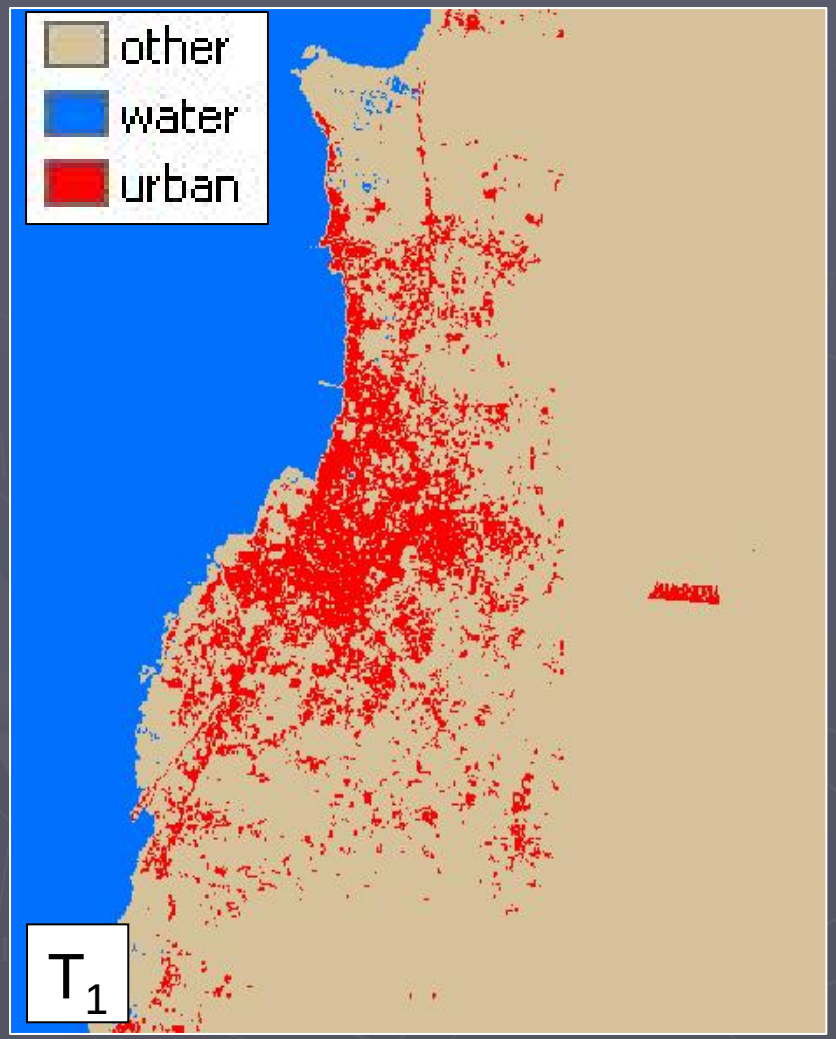
Overlay

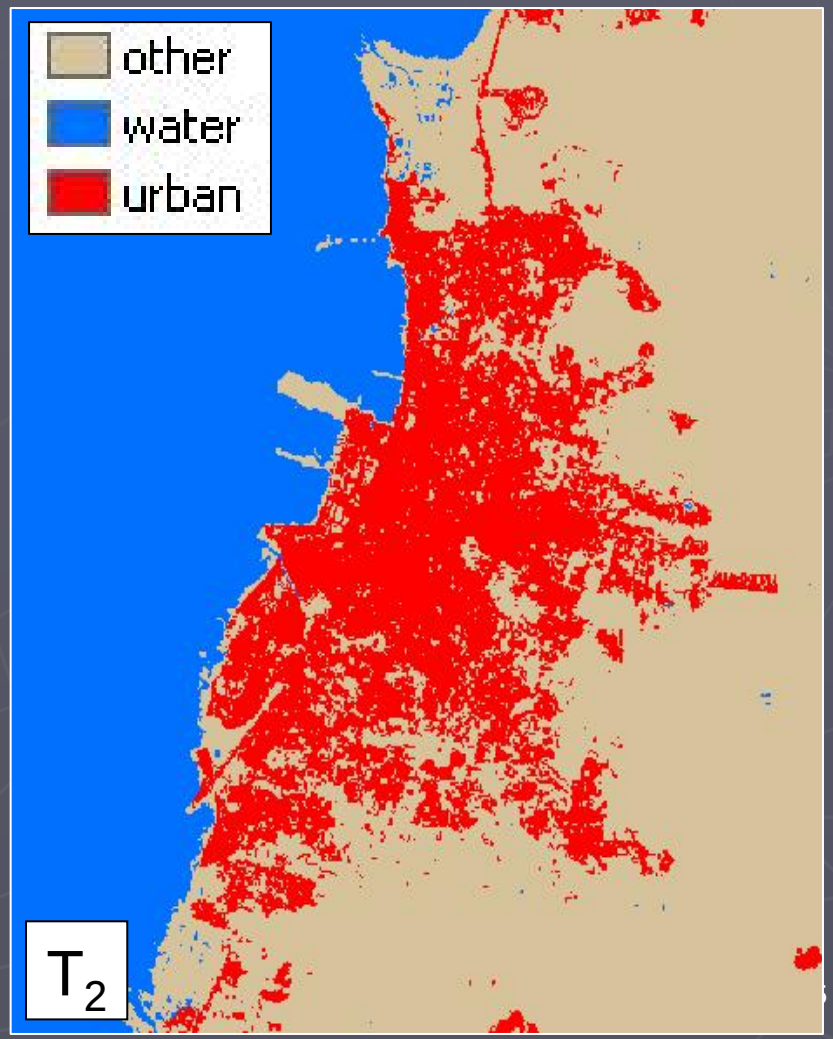




Urban and Water Image for Accra T_2

Bacolod, Philippines:
Land cover





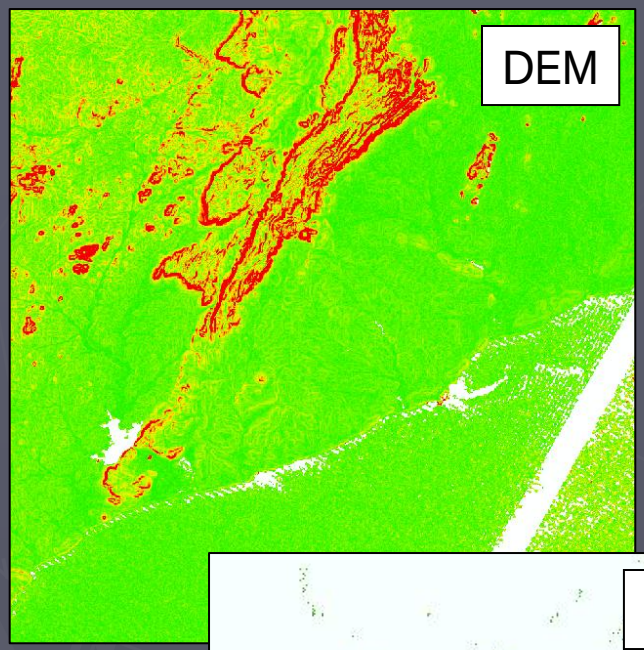
Phase I: Acquisition of City Boundaries

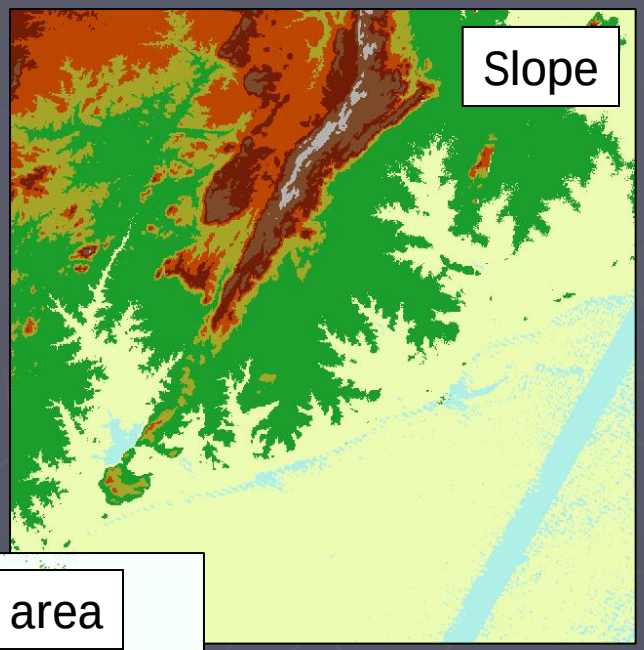
- Administrative districts (*i.e.* Census tracts) acquired for each city.
- Population data were attributed to the administrative districts.
  - Interpolated census data to estimate populations at time of land cover dates.
- Districts define the outer perimeter of the cities and provide population data.

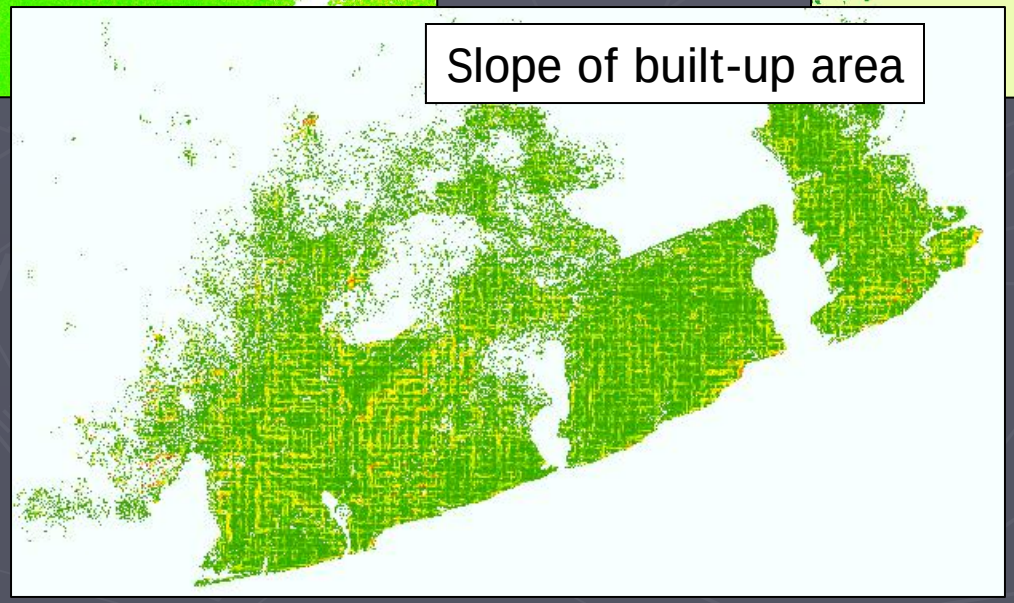
Phase I: Slope

- Slope grid derived from Shuttle Radar Topography Mission (SRTM) data.
- Slope calculated in percent.
- Maximum slope defined as the slope value below which 99% of the urban area exists.

Determining Maximum Slope







Average and Maximum Slope

ObjectID	Value	Count
0	0	106772
1	0.620269119739532	7449
2	0.877192974090576	5391
3	1.24053823947906	7876
4	1.38696384429932	12689
5	1.75438594818115	52398
6	1.86080729961395	4942
7	1.96146309375763	1524
8	2.23641204833984	4674
9	2.48107647895813	5140
10	2.55743503570557	4108

Average and maximum slope

Slope

Pixel count

The maximum slope is the slope value at the 99th percentile

Phase II: The Metrics

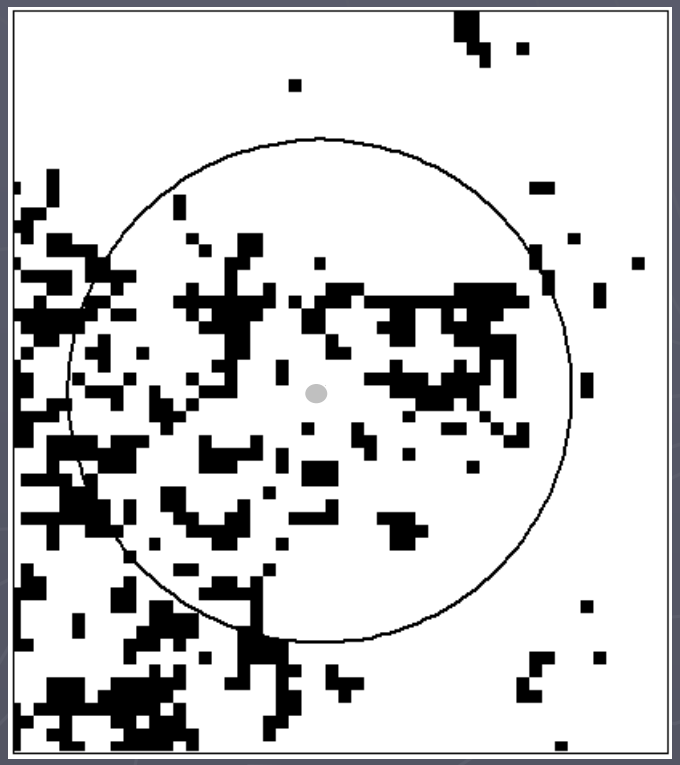
- Several sets of metrics were developed to measure specific aspects of the urban spatial structure
- This presentation presents a sample of metrics from each set
  - Angel et. al. (2007)
  - The complete set of metrics will be presented in future papers at the conclusion of the study
- We present data for Bangkok and Minneapolis for illustrative purposes. Data for the analysis of the 120 cities will be presented in a future paper.

Sprawl Manifestations

- At a given point in time, sprawl is manifested in the built-up area:
  - Multiple urban cores
  - Ribbon or strip developments
  - Scatter developments
  - Fragmented and unusable open space
- Manifestations are quantified with the following metrics:
  - Main core
  - Secondary core(s)
  - Urban fringe
  - Ribbon development
  - Scatter development
- In sprawling cities, low density developments such as ribbon and scatter are expected to increase over time.

Sprawl Manifestation Metrics
Derivation

- Manifestation metrics based on the "urbanness" of a given built-up pixel.
  - Urbanness = percent of neighborhood that is built-up
  - The neighborhood is a 1 km^2 circle.

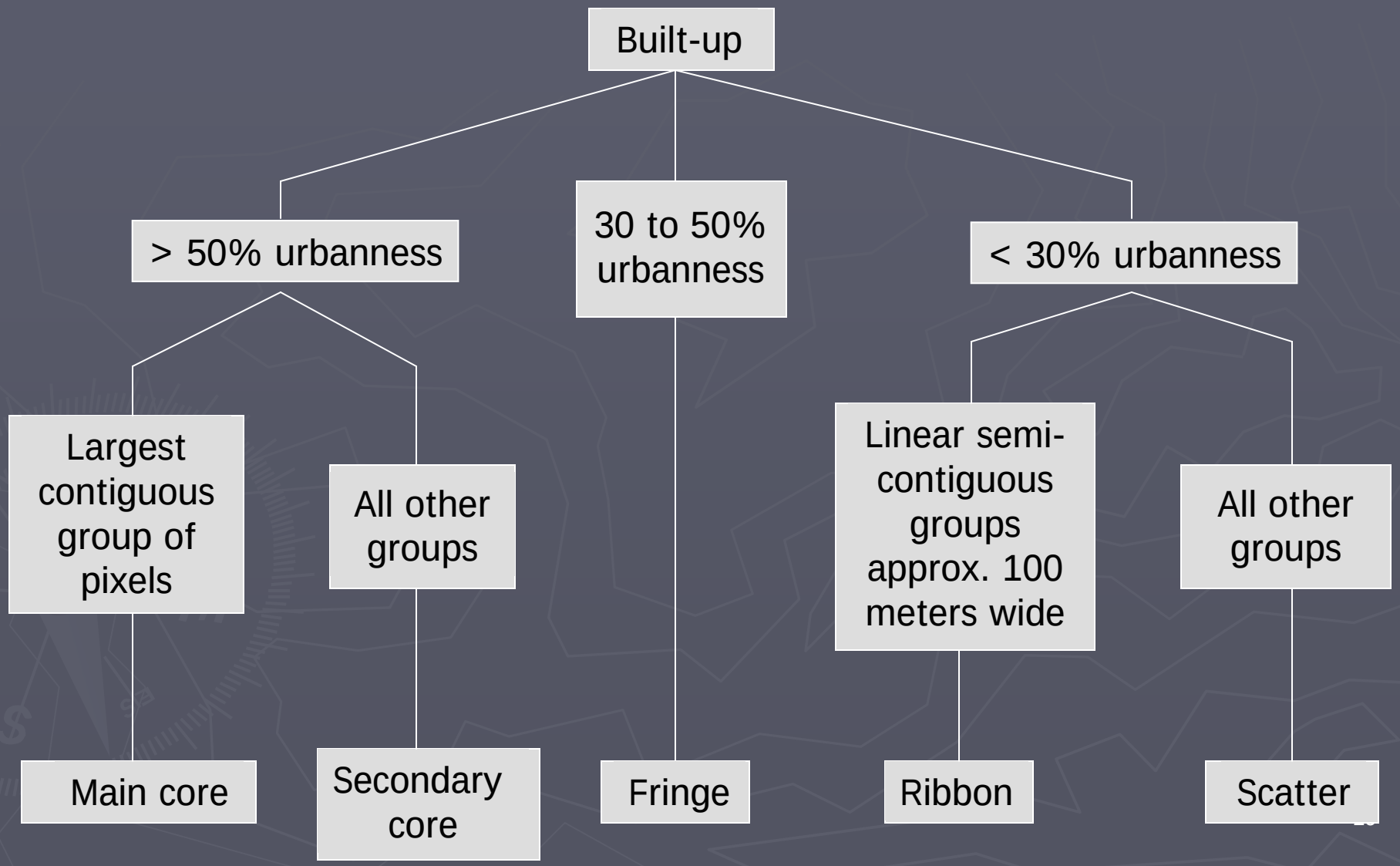


252 built-up pixels = 0.2 km^2

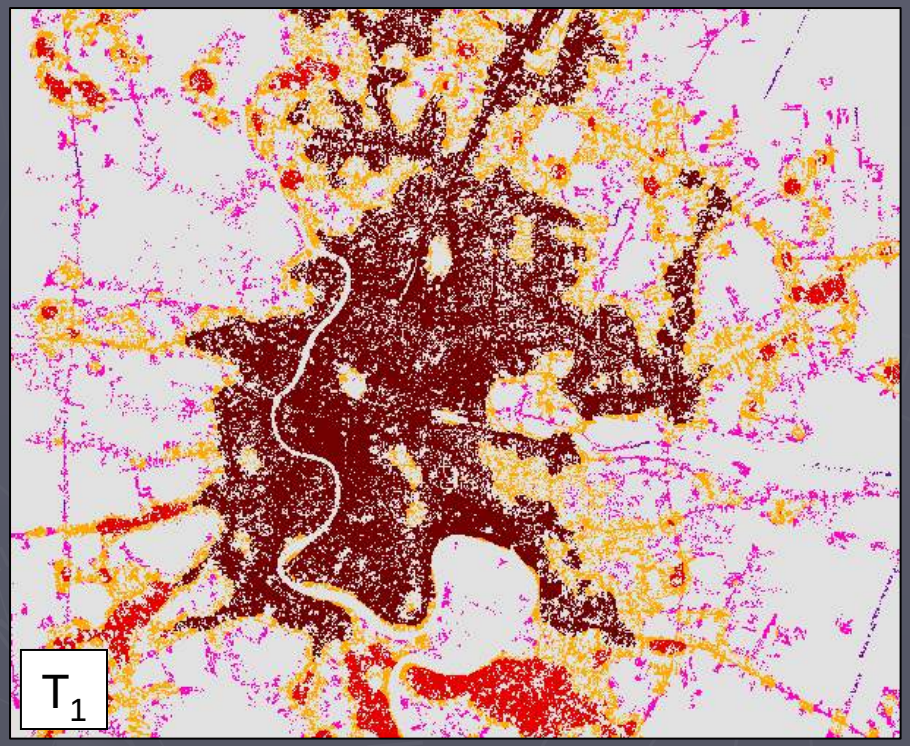
urbanness = 0.2 / 1 = 20%

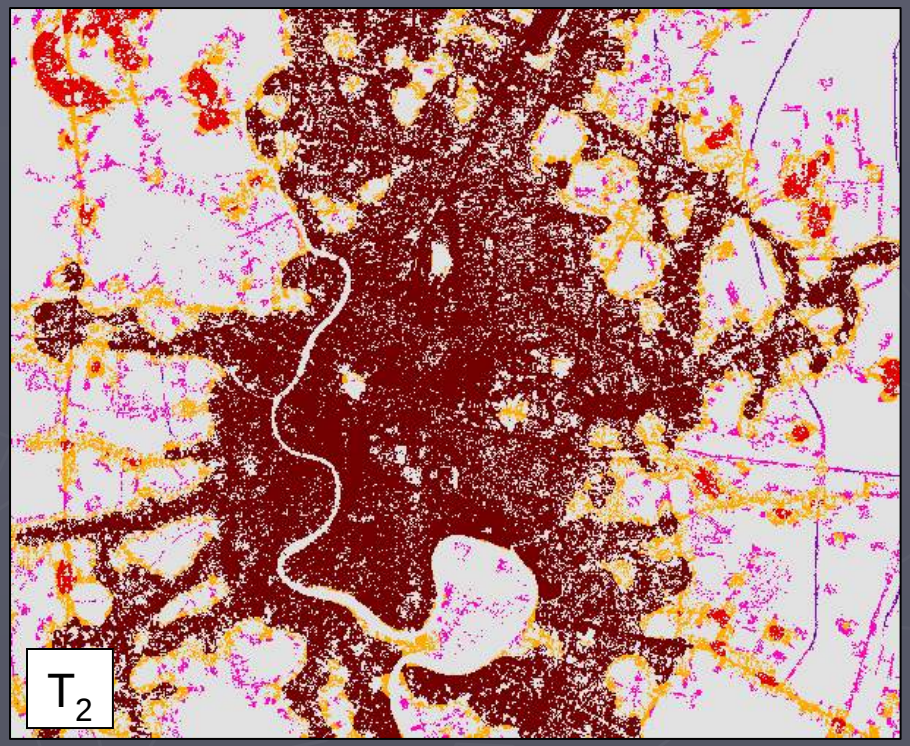
Sprawl Manifestation Metrics

Definitions



Sprawl Manifestations for Bangkok, Thailand





- Main urban core
- Secondary urban cores
- Urban fringe
- Ribbon
- Scatter

Sprawl Manifestation Metrics for Bangkok (1994-2002) and Minneapolis (1992-2001)

Metric		T1		T2		Annual ΔT	
		Bangkok	Minneapolis	Bangkok	Minneapolis	Bangkok	Minneapolis
Built-Up Area	km^2	683.0	885.6	1025.9	1100.0	7.0%	2.8%
	%	100%	100%	100%	100%	0.0%	0.0%
Main Core	km^2	211.8	402.5	461.2	555.7	16.3%	4.3%
	%	31.0%	45.5%	45.0%	50.5%	1.9%	0.6%
Secondary Cores	km^2	80.6	94.7	114.2	172.5	5.8%	9.4%
	%	11.8%	10.7%	11.1%	15.7%	-0.1%	0.6%
Urban Fringe	km^2	201.1	234.6	245.6	232.6	-3.1%	-0.0%
	%	29.5%	26.5%	23.9%	21.2%	-0.8%	-0.6
Urban Ribbon	km^2	11.28	8.2	14.2	9.74	3.5%	2.1%
	%	1.7%	0.9%	1.4%	0.9%	-0.0%	0.0%
Urban Scatter	km^2	178.2	145.6	191.1	129.2	1.0%	-0.1%
	%	26.1%	16.4%	18.6%	11.8%	-1.0%	-0.5%

New Development Classification

- Over a period of time, sprawl is manifested in *new developments* that either extend outward from existing development or 'leapfrog' away from existing development.

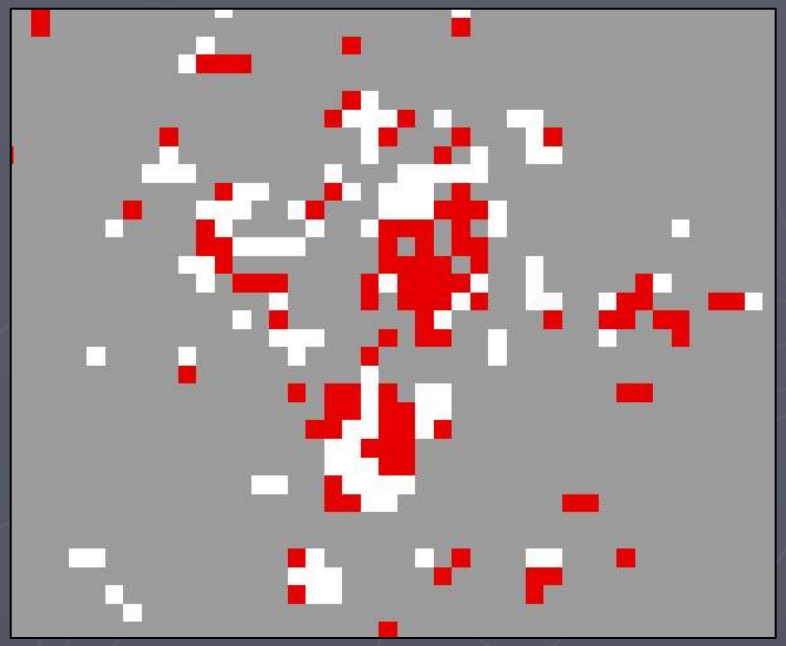
- *New development* is any built-up area added between two time periods - T_1 and T_2.

- Classification of new development is based on location relative to the T_1 urban area.

New Development: Infill

Infill:

- New development occurring within the T_1 urbanized open space
- Increases contiguity of the built-up area by filling in the urbanized open space

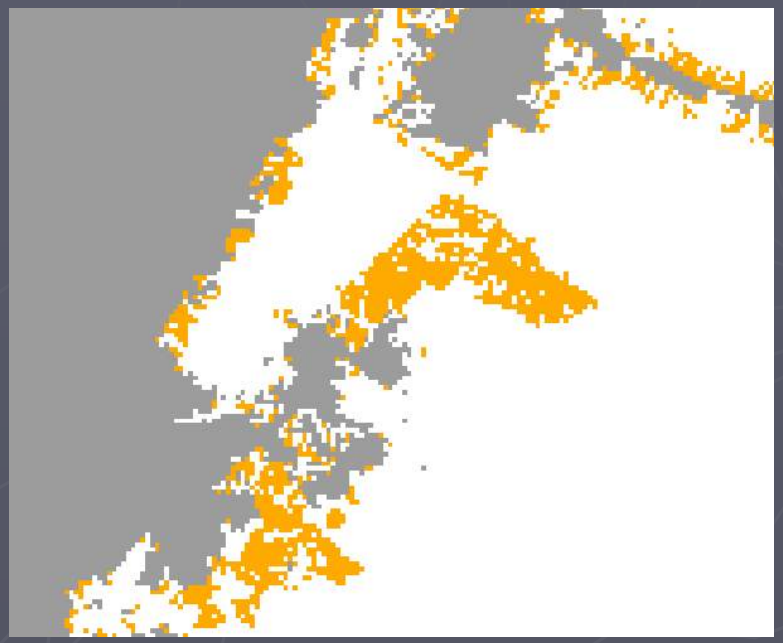


T1 built-up pixels in gray, infill in red

New Development: Extension

<u>Extension:</u>

- New non-infill development intersecting the T_1 urban footprint
- Extends outward from previous development

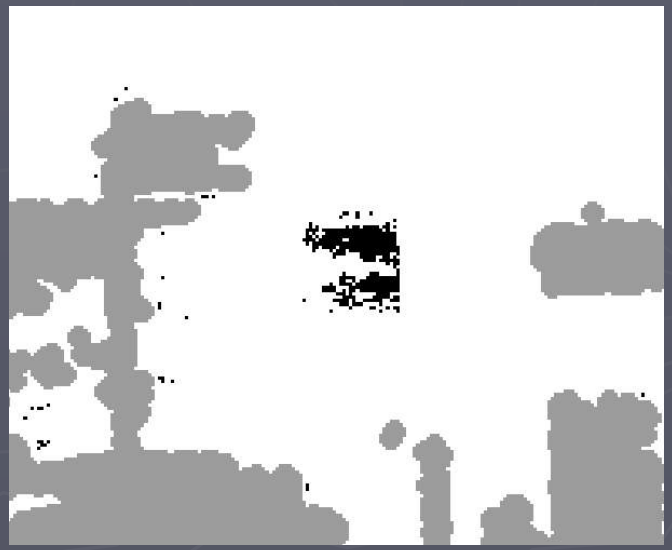


T1 urbanized area in gray, extension in orange

New Development: Leapfrog

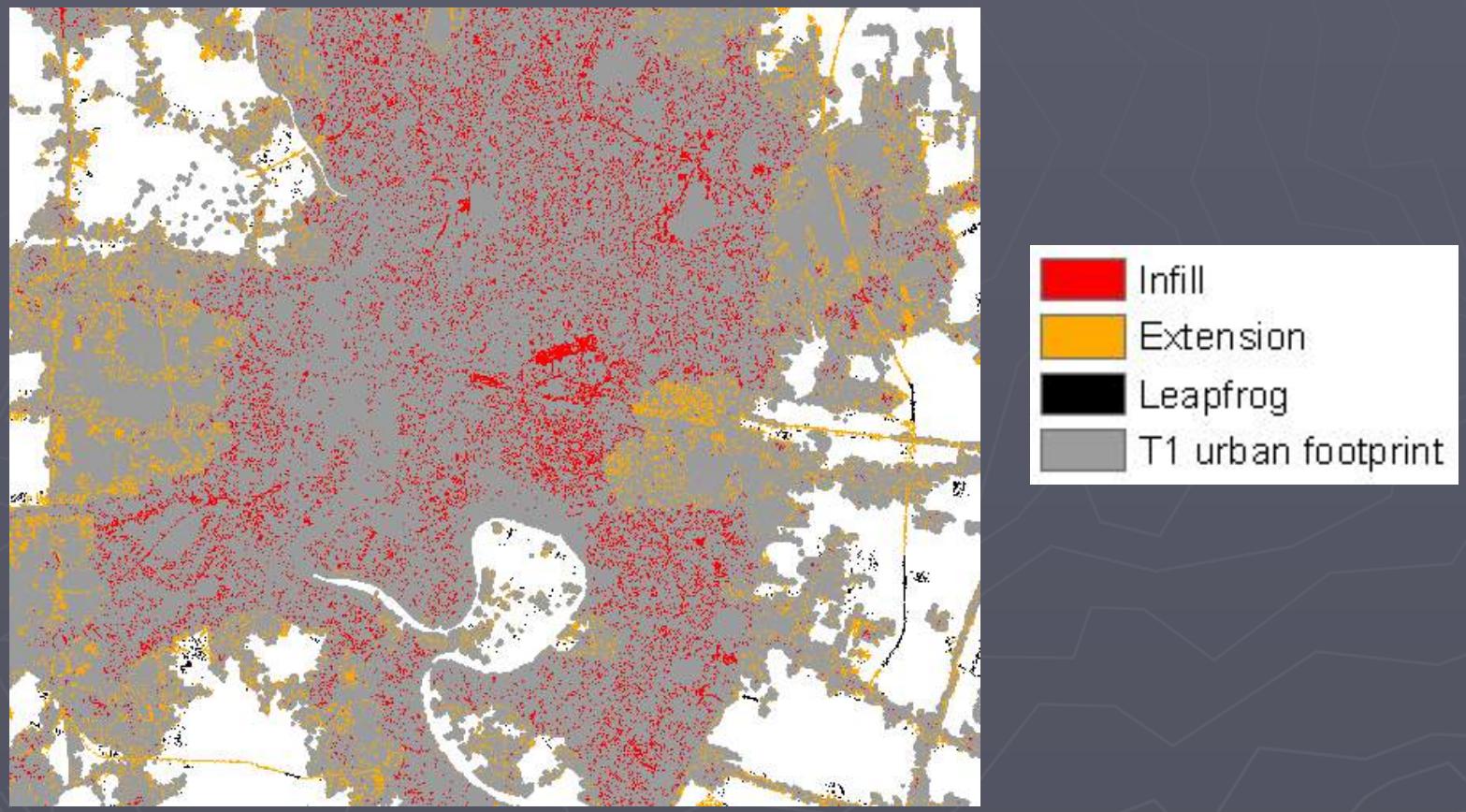
Leapfrog:

- New development not intersecting the T_1 urban footprint
- No contiguity with the previous developed areas
- Has the greatest effect on growth of urban footprint and fragmentation of open lands.



T1 urban footprint in gray, leapfrog in black

New Development (1994-2002) in Bangkok, Thailand



New Development Metrics for Bangkok (1994-2002) and Minneapolis (1992-2001)

Metric		Bangkok	Minneapolis
New development	km^2	342.89	214.00
Infill	km^2	91.81	80.0
	%	27.0%	37.0%
Extension	km^2	215.1	130.4
	%	63.0%	61.0%
Leapfrog	km^2	36.0	3.8
	%	11.0%	2.0%

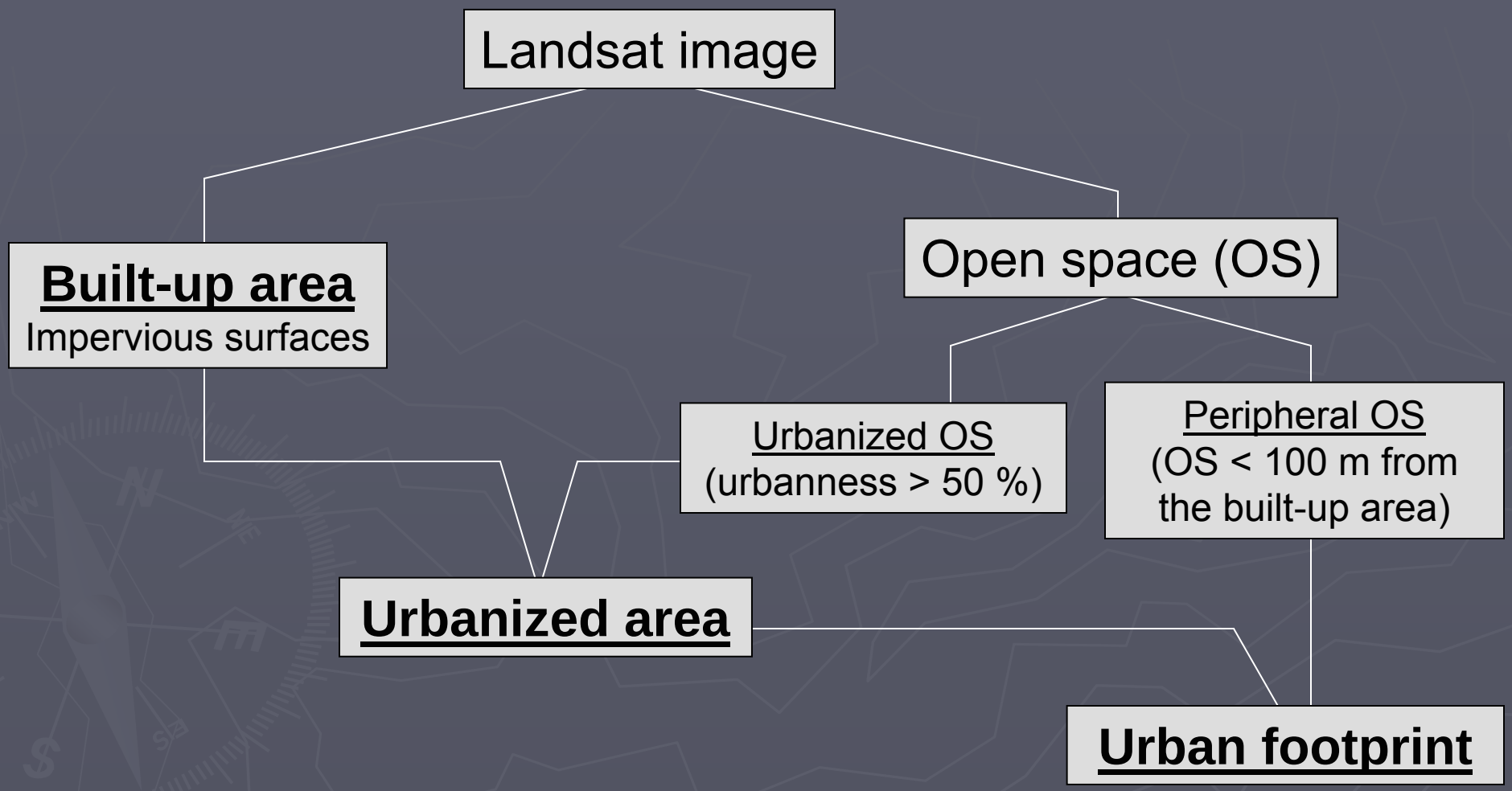
Attributes of Urban Sprawl

- Sprawl attributes are quantifiable for each city
- A set of metrics was developed to describe each attribute
  - Metrics in each set tend to be highly correlated
- We identified four attributes of urban spatial structure that are commonly associated with ‘sprawl’...

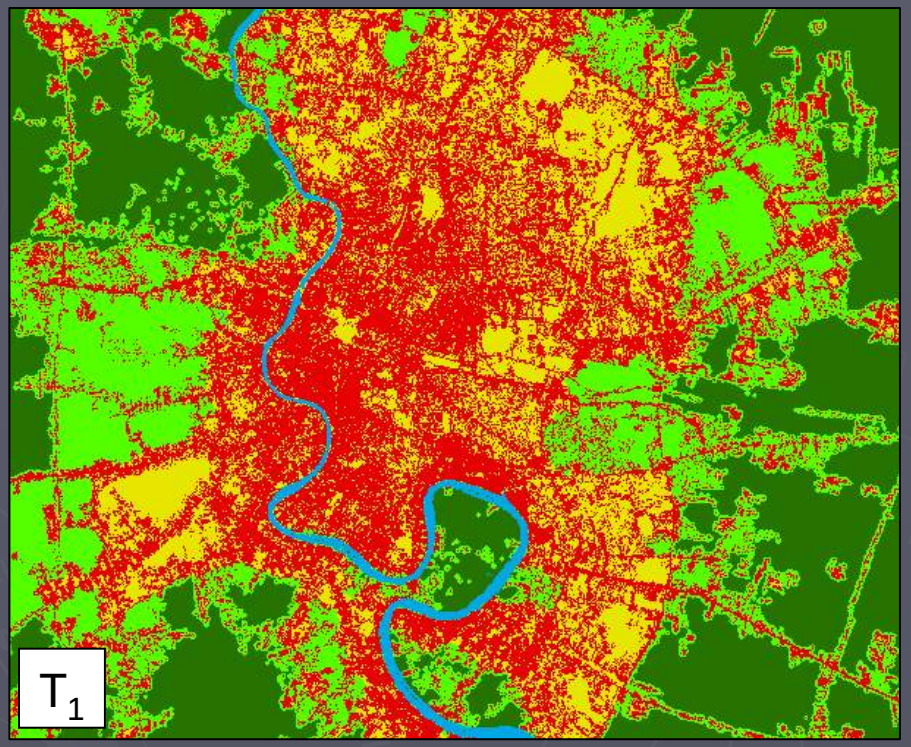
Attribute 1: “Limitless” Urban Extent

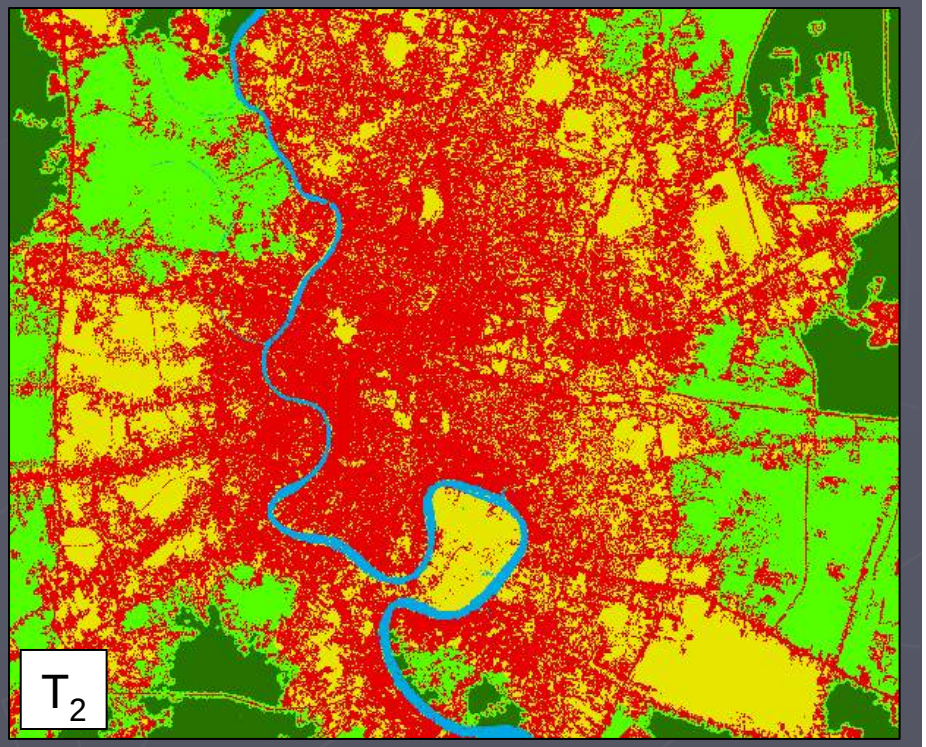
- The land to be considered as urban depends on the issue of interest.
  - Impervious surfaces alone for water quality issues
  - Heavily impacted open land as well as impervious surfaces for ecological issues.
- We present three measures of urban extent, each corresponding to a different perception of what constitutes a city:
  - Built-up area – impervious surfaces
  - Urbanized area – impervious surfaces as well as heavily influenced open space
  - Urban footprint – impervious surfaces and any open space likely to be impacted, to some degree, by the city.

“Limitless” Urban Extent



Urban Extents for Bangkok, Thailand





Urban Extent Metrics for Bangkok (1994-2002) and Minneapolis (1992-2001)

Metric		T1		T2		Annual ΔT	
		Bangkok	Minneapolis	Bangkok	Minneapolis	Bangkok	Minneapolis
Built-up area	km^2	683.1	886.2	1026.1	1100.0	7.0%	2.7
	%	100%	**100%**	100%	**100%**	0.0%	0.0%
Urbanized area	km^2	949.1	1331.5	1456.5	1715.7	5.3%	3.3%
	%	139.0%	150.3%	142.0%	156.0%	0.4%	0.6%
Urbanized OS	km^2	266.0	445.8	430.5	616.0	8.6%	4.4%
	%	39.0%	50.3%	42.0%	56.0%	0.4%	0.6%
Urban Footprint	km^2	1817.9	2314.2	2526.1	2494.7	5.4%	0.9%
	%	266.2%	261.3%	246.2%	226.9%	-2.8%	-3.9%
Peripheral OS	km^2	868.8	982.7	1069.6	779.0	3.2%	-2.4%
	%	127.2%	111.0%	104.3%	70.8%	-3.2%	-4.6%
Affected OS	km^2	1134.9	1428.5	1500.1	1395.0	4.4%	-0.3%
	%	166.2%	161.2%	146.2%	126.8%	-2.8%	-3.9%

Attribute 2: Declining Population Density

- Population densities are expected to decline over time in sprawling cities.
- Population densities measured for the three types of urban extent.

Population Density Metrics for Bangkok (1994-2002) and Minneapolis (1992-2001)

Metric	T1		T2		Annual ΔT	
(Densities in persons / ha)	Bangkok	Minneapolis	Bangkok	Minneapolis	Bangkok	Minneapolis
Population	8,245,332	2,166,839	9,768,215	2,483,342	2.4%	1.6%
Built-up area density	121	24	95	23	-3.2%	-0.9%
Urbanized area density	87	16	67	14	-3.5%	-1.3%
Urban footprint density	45	9	39	10	-2.2%	0.7%

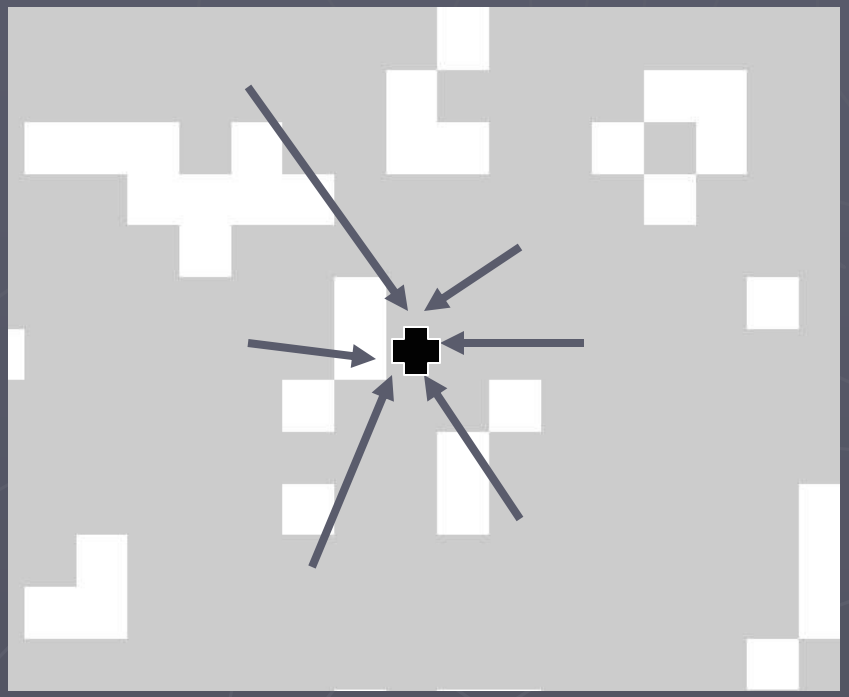
Attribute 3: Non-Compactness of the Urban Area

- The compactness of a sprawling city is expected to decline over time due to leapfrogging and low density development.
- We measure compactness of the *urbanized area.*
- Metrics based on assumption that the circle is the most compact shape possible for a given area.
- Compactness metrics are normalized and range from 0 to 1 with higher values indicating more compact shapes.

Measuring Compactness: The Proximity Index

The Proximity Index:

- Based on average distance, of all points in the urbanized area, to the center of gravity (centroid) of the urbanized area.
- Normalized by the average distance (d) to centroid of the *equal area circle* with radius (r) – a circle with an area equal to that of the urbanized area.
  - d = (2 / 3) * r

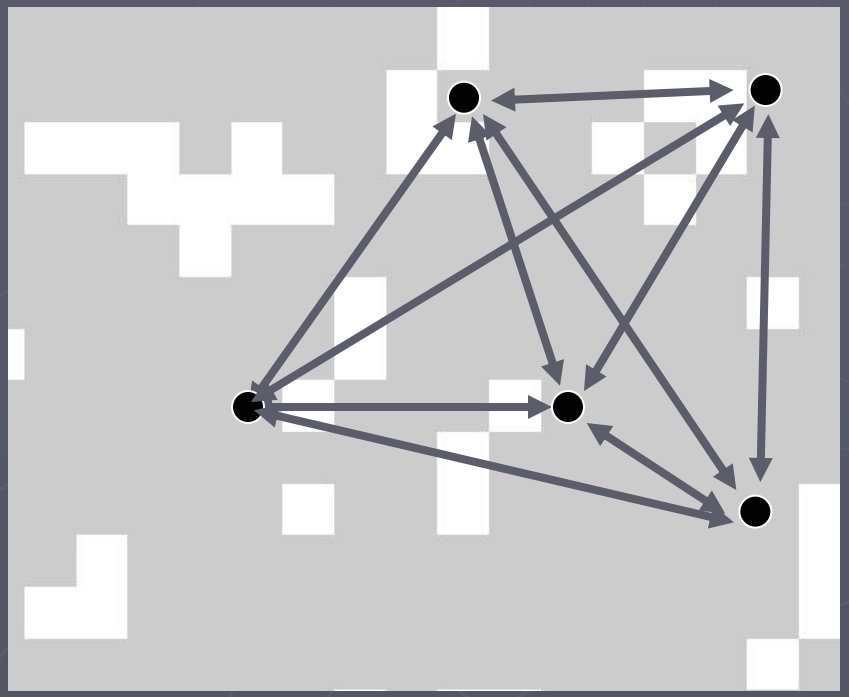


Urbanized area in gray, centroid in black

Measuring Compactness: The Cohesion Index

<u>The Cohesion Index:</u>

- Based on the average distance between all possible pairs of points in the urbanized area
- Normalized by average distance (d) between all pairs of points within the *equal area circle* with radius (r).
  - d = 0.9054 * r



Urbanized area pixels in gray, sample points in black

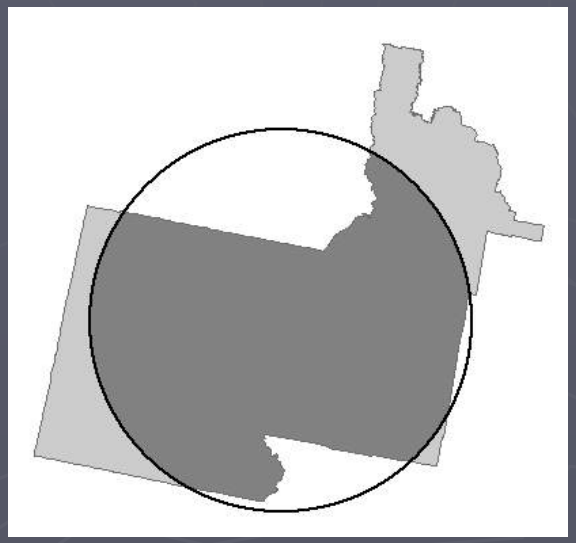
Measuring Compactness: The Compactness and Constrained Compactness Indices

The Compactness Index

- The fraction of the shape area that is within an *equal area circle* centered at the shape centroid.

The Constrained Compactness Index

- The fraction of the shape area that is within the *net equal area circle* centered at the shape centroid.
- The *net equal area circle* has a buildable area (excluding water and excessive slope) equal to the urbanized area



Compactness = 0.75

Compactness Metrics for Bangkok (1994-2002) and Minneapolis (1992-2001)

Metric	T1		T2		Annual ΔT	
	Bangkok	Minneapolis	Bangkok	Minneapolis	Bangkok	Minneapolis
Proximity	0.67	0.87	0.75	0.91	1.11%	0.46%
Cohesion	0.65	0.85	0.72	0.89	0.97%	0.46%
Compactness	0.62	0.75	0.66	0.80	0.56%	0.57%
Constrained compactness	0.62	0.77	0.67	0.82	0.62%	0.57%

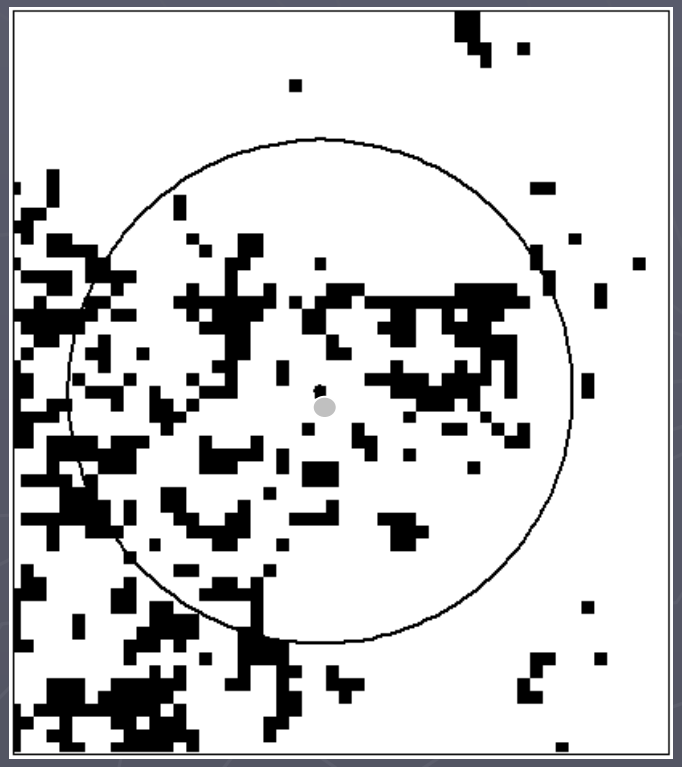
Attribute 4: Non-contiguity of the Built-up Area and the Fragmentation of Open Land

- Sprawling cities are typically expected to become less contiguous over time while adjacent open land becomes increasingly fragmented.
- Contiguity metrics are based on the built-up area.
- Higher values for all metrics indicate lower contiguity of the built-up area and greater fragmentation of open space.

Openness

The Openness Index:

- The average *openness* of all built-up pixels.
- *Openness* is the fraction of open land within a 1 km^2 neighborhood around a given built-up pixel – the complement of *urbanness*.
- Values range from 0 to 1



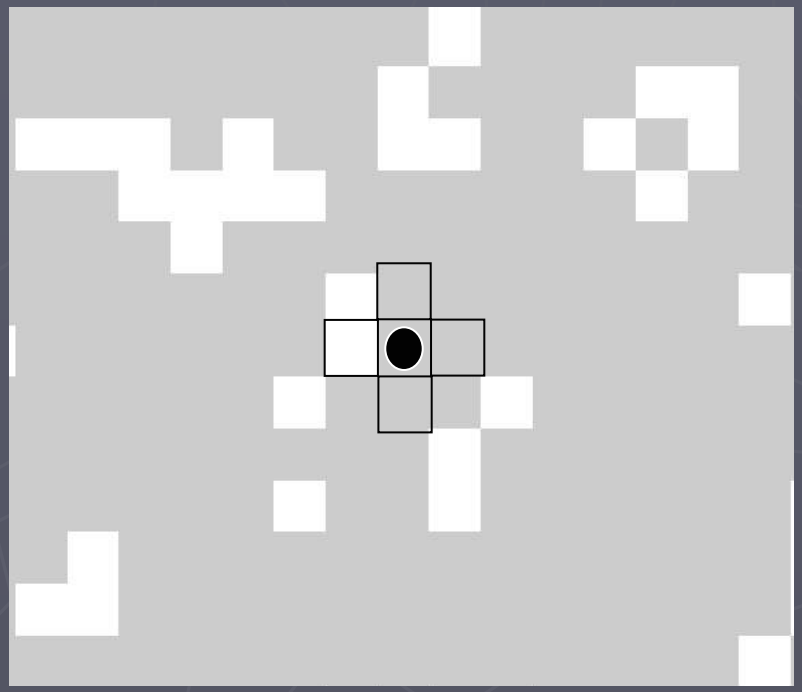
252 built-up pixels = 0.2 km^2

$$\text{openness} = \frac{1\ km^2 - 0.2\ km^2}{1\ km^2} = 0.8$$

Open Space Contiguity

<u>The Open Space Contiguity Index:</u>

- The fraction of built-up pixels that are cardinally adjacent to at least one open space pixel.
- Calculated using a neighborhood operation
- Values range from 0 to 1



Built-up pixels in gray
Open space pixels in white

Open Space Fragmentation

<u>The Open Space Fragmentation Index:</u>

- The ratio of the *affected open land* to the built-up area.
- *Affected open lands* include the urbanized open space and the peripheral open space
- Values are greater than zero

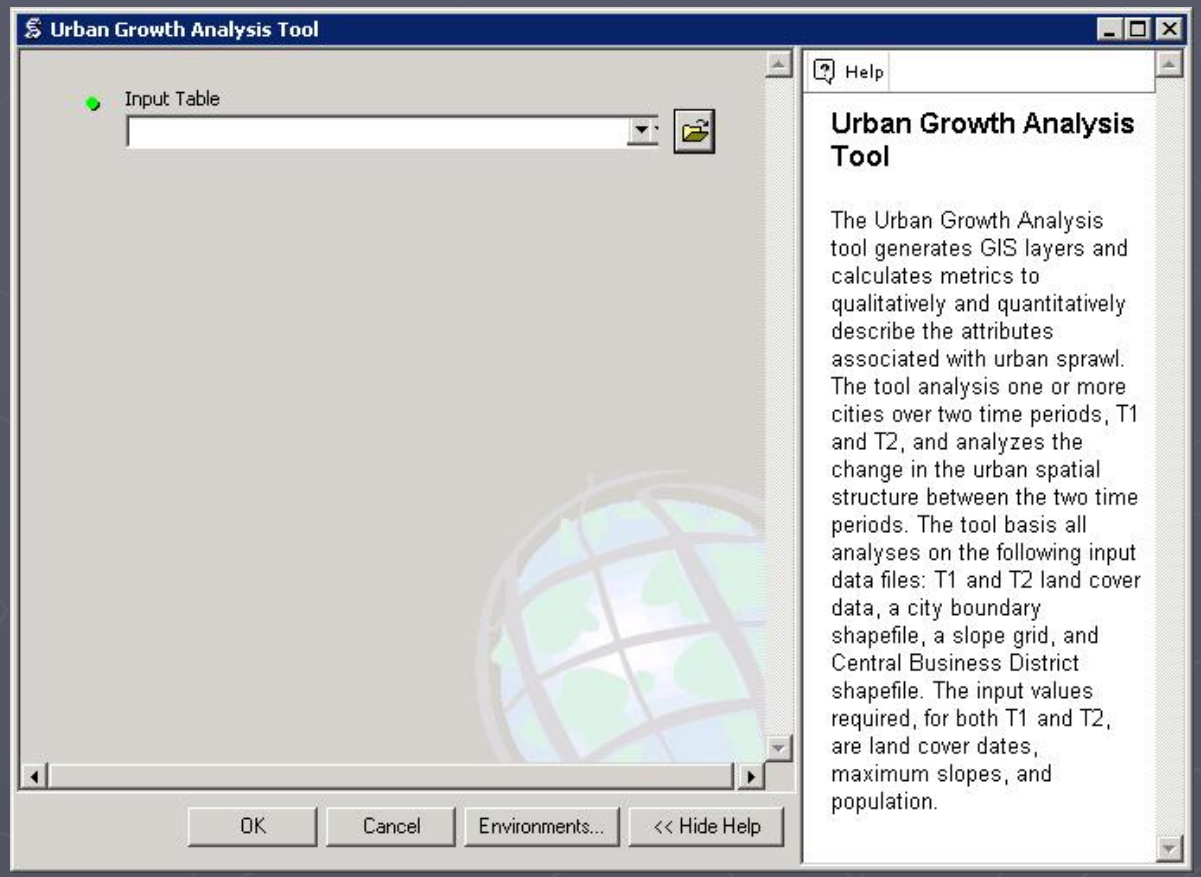
Contiguity and Openness metrics for Bangkok (1994-2002) and Minneapolis (1992-2001)

Metric	T1		T2		Annual ΔT	
	Bangkok	Minneapolis	Bangkok	Minneapolis	Bangkok	Minneapolis
Openness Index	0.54	0.46	0.46	0.41	-1.10%	-0.55%
Open Space Contiguity	0.56	0.55	0.47	0.50	-1.00%	-0.60%
Open Space Fragmentation Index	1.66	1.61	1.46	1.27	-2.80%	-3.90%

The Urban Growth Analysis Tool (UGAT)

- Python script that works with ArcGIS 9.2
  - Executable through python or ArcGIS toolbox
- UGAT performs all analyses needed to derive the metrics and create GIS layers
- Data is input into the tool via a table
  - Table may contain data for any number of cities
  - UGAT will run the analysis for each city listed in the table

The Urban Growth Analysis Tool ArcToolbox Interface



The Urban Growth Analysis Tool Python Interface

```
# Name: Jason Parent
# Date: March 2008
# Purpose: 1) Create raster layers depicing manifestations of urban sprawl for two time
#          2) Calculate metrics to quantify compactness and change in compactness of urb


# Import system modules...
import Helper_UGA,time,sys,os,math

# Create the geoprocessor object...
gp = Helper_UGA.gpCreate()

##inputDataTable = sys.argv[1]
inputDataTable = r"C:\Worldbank\Pathnames.mdb\InputDataTable"

##DataWS = sys.argv[2]
DataWS = r"C:\Worldbank\Input_Data"
#DataWS = r"C:\Projects\CT_UGA\Input_data"

##OutputWS = sys.argv[3]
#OutputWS = r"C:\Worldbank\Output_Data"
OutputWS = r"C:\UGA_test"

errorFile = "%s\\UGA_errFile.txt" % OutputWS

# name of project temp folder...
TempFolder = "C:\\UGA_Temp"

# temporary workspace for ESRI files...
TempWS = "%s\\UGA_temp.gdb" % TempFolder


# get workspaces for all input data files...
wkspDct = Helper_UGA.GetWksps (DataWS)

#-----------------------------------------------------------------------
# URBAN LANDSCAPE CATEGORY VALUES...

core, fring, ribbon, scatter = 1, 2, 3, 4
urbOS, i_urbOS, watUOS, slpUOS = 5, 6, 7, 8
periOS, i_periOS, watPOS, slpPOS = 9, 10, 11, 12
```

Conclusions

- Phase II is currently ongoing as is development of the Urban Growth Analysis Tool. Future papers will provide in-depth and comprehensive discussions of the metrics developed in this project
- The metrics, developed so far in this project, allow rigorous quantitative assessment of the change in urban spatial structure over time
- Metrics in a set tend to be highly correlated
  - provides alternative ways to measure each attribute.
- The Urban Growth Analysis Tool makes it practical to perform the analysis for a large number of cities. The tool will be made available to researchers interested in applying the analysis to their own study areas.

References

- Angel, S, J. R. Parent, and D. L. Civco. May 2007. Urban Sprawl Metrics: An Analysis of Global Urban Expansion Using GIS. ASPRS May 2007 Annual Conference. Tampa, FL

- Angel, S, S. C. Sheppard, D. L. Civco, R. Buckley, A. Chabaeva, L. Gitlin, A. Kraley, J. Parent, M. Perlin. 2005. The Dynamics of Global Urban Expansion. Transport and Urban Development Department. The World Bank. Washington D.C., September.

QUESTIONS?

Urban Growth Analysis:

Calculating Metrics to Quantify Urban Sprawl

Jason Parent
jason.parent@uconn.edu
Academic Assistant – GIS Analyst

Daniel Civco
Professor of Geomatics

Center for Land Use Education And Research (CLEAR)
Natural Resources Management and Engineering
University of Connecticut

Shlomo Angel
Adjunct Professor of Urban Planning
Robert F. Wagner School of Public Service, New York University
Woodrow Wilson School of Public and International Affairs,
Princeton University

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