# KU ScholarWorks

## GeoComputational Intelligence and High-Performance Geospatial Computing

| | |
|---|---|
| Item Type | Video;Presentation |
| Authors | Guan, Qingfeng |
| Citation | http://www.gis.ku.edu/gisday/2011/ |
| Publisher | GIS Day @ KU Planning Committee |
| Download date | 2024-07-31 21:13:11 |
| Link to Item | http://hdl.handle.net/1808/8463 |

CALMIT
University of Nebraska · Lincoln
Center for Advanced Land Management Information Technologies

GIS Day @ University of Kansas
Nov. 16th, 2011

# GeoComputational Intelligence and High-performance Geospatial Computing

Qingfeng (Gene) Guan, Ph.D
Center for Advanced Land Management Information Technologies
School of Natural Resources
University of Nebraska - Lincoln

# Contents

1. Computational Science and GeoComputation

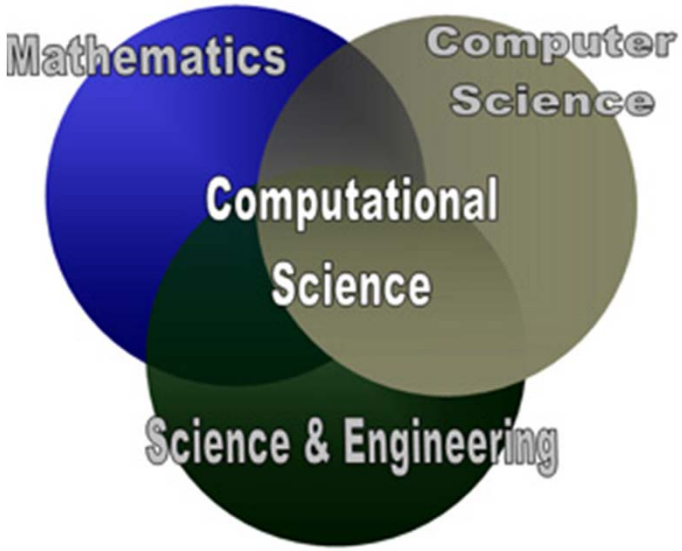
2. GeoComputational Intelligence
   - ANN-based Urban-CA model

3. High-performance Geospatial Computing
   - Parallel Geostatistical Areal Interpolation
   - pRPL and pSLEUTH

4. Conclusion

# Introduction – Computational Science

- **Definition**
  - "*the field of study concerned with constructing mathematical models and numerical solution techniques and using computers to analyze and solve scientific, social scientific and engineering problems.*" (wikipedia)
- **Domains include:**
  - Numerical simulations
  - Model fitting and data analysis
- **Massive computational intensity**



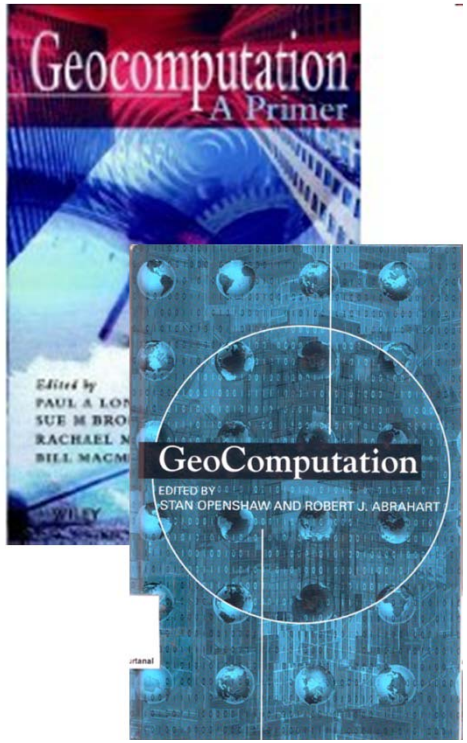

http://www.it.uu.se/edu/masters/CompSc/

# Introduction - GeoComputation

## Definition

- Couclelis (1998) identified the “core GeoComputation” as the innovative (or derived from other disciplines) computer-based geospatial modeling and analysis
  - Contrasted against the traditional computer-supported spatial data analysis and geospatial modeling
- Openshaw (2000) also emphasized Computational Science as the origin of GeoComputation (the Computation part) and the essential concerns about geographical and earth systems (the Geo part)

## The capital G and C



# Introduction – GeoComputation (cont.)

## Methodology

- A wide array of computer-based models and techniques, many of them derived from the field of Artificial Intelligence (AI) and the more recently defined area of Computational Intelligence (CI) (Couclelis, 1998)
  - Expert Systems, Cellular Automata, Neural Networks, Fuzzy Sets, Genetic Algorithms, Fractal Modelling, Visualization and Multimedia, Exploratory Data Analysis and Data Mining, etc.

## High-performance geospatial computing

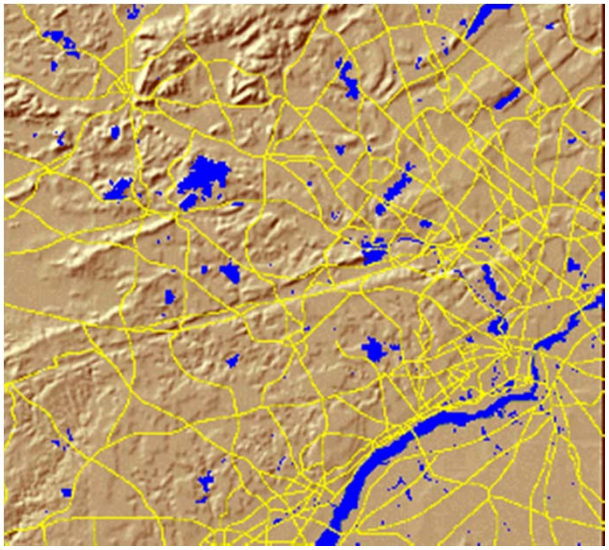
# ANN-Urban-CA: an urban growth model

## Overview

- Combination of a Cellular Automata (CA) model, an Artificial Neural Network (ANN), and a macro-scale socio-economic model
- Integration of Geography, Natural Resource Science, Social Science, and Economics in a GeoComputation framework

# Geospatial Cellular Automata

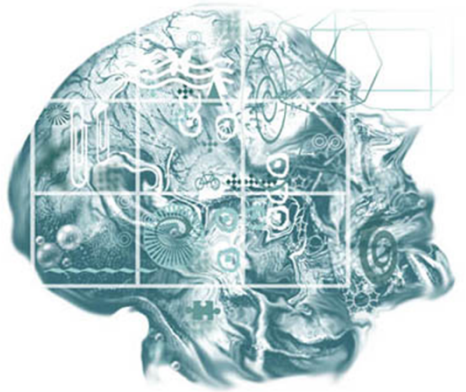
- **Bottom-Up structure**
  - Simple local rules to simulate complex global spatio-temporal dynamics
- **Widely used in geospatial modeling**
  - Land-use/Land-cover Change
  - Wildfire Propagation
  - Flood Spreading
  - Freeway Traffic Flow
  - More and More Coming up…



Prediction of urban development to the year 2050 over southeastern Pennsylvania and part of Delaware using the SLEUTH model http://www.essc.psu.edu/~dajr/chester/animation/movie_small.htm

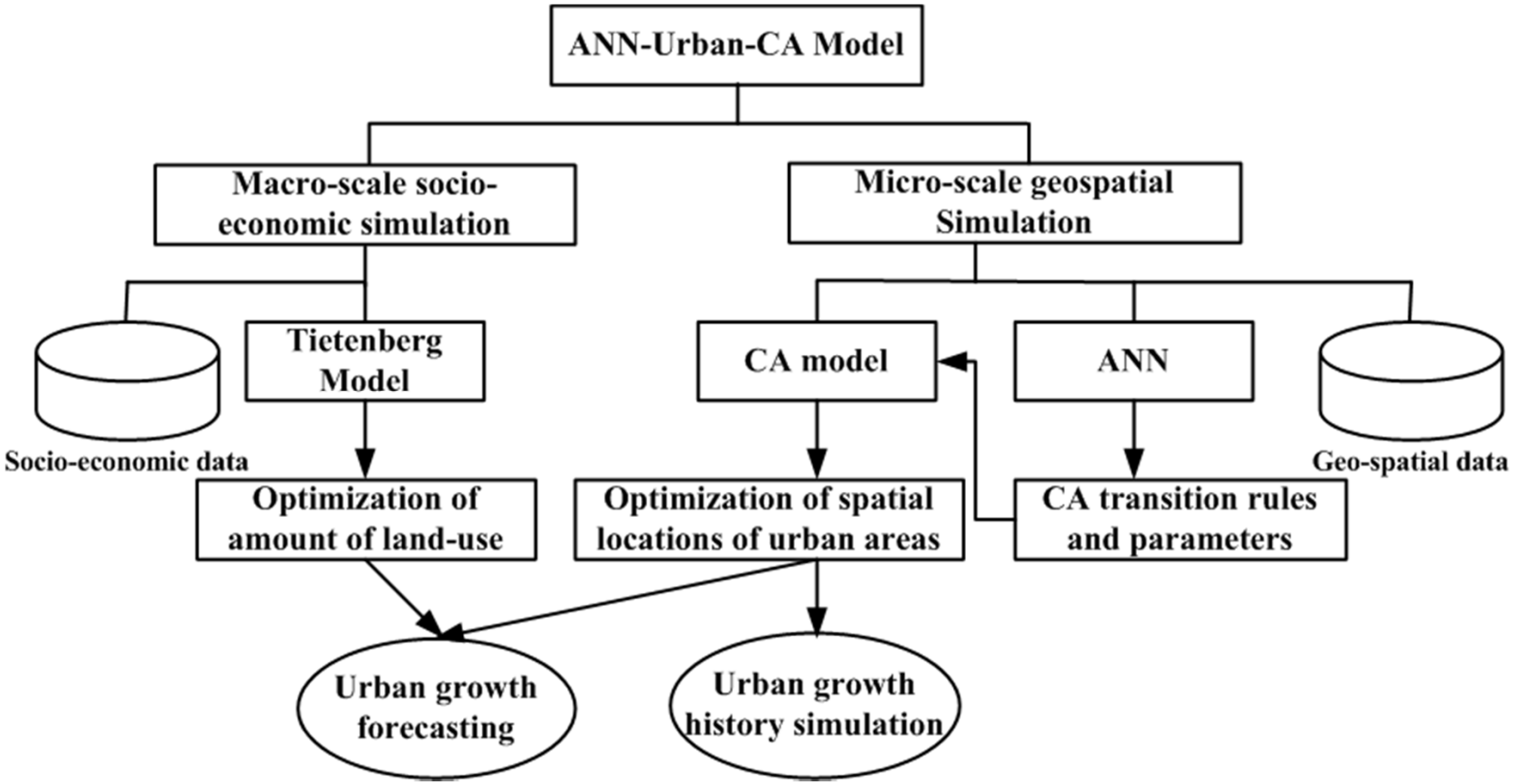
# Issues of Geospatial CA

- **Hard to set proper transition rules and parameters**
  - How to produce realistic simulations?
  - Brute-force calibration
    - Generate results using all possible parameter values
    - Find the “best-match” combination
    - Highly computationally intensive
- **Lack of global control**
  - Bottom-up structure
  - Evolve without constraints



# ANN-Urban-CA: Structure

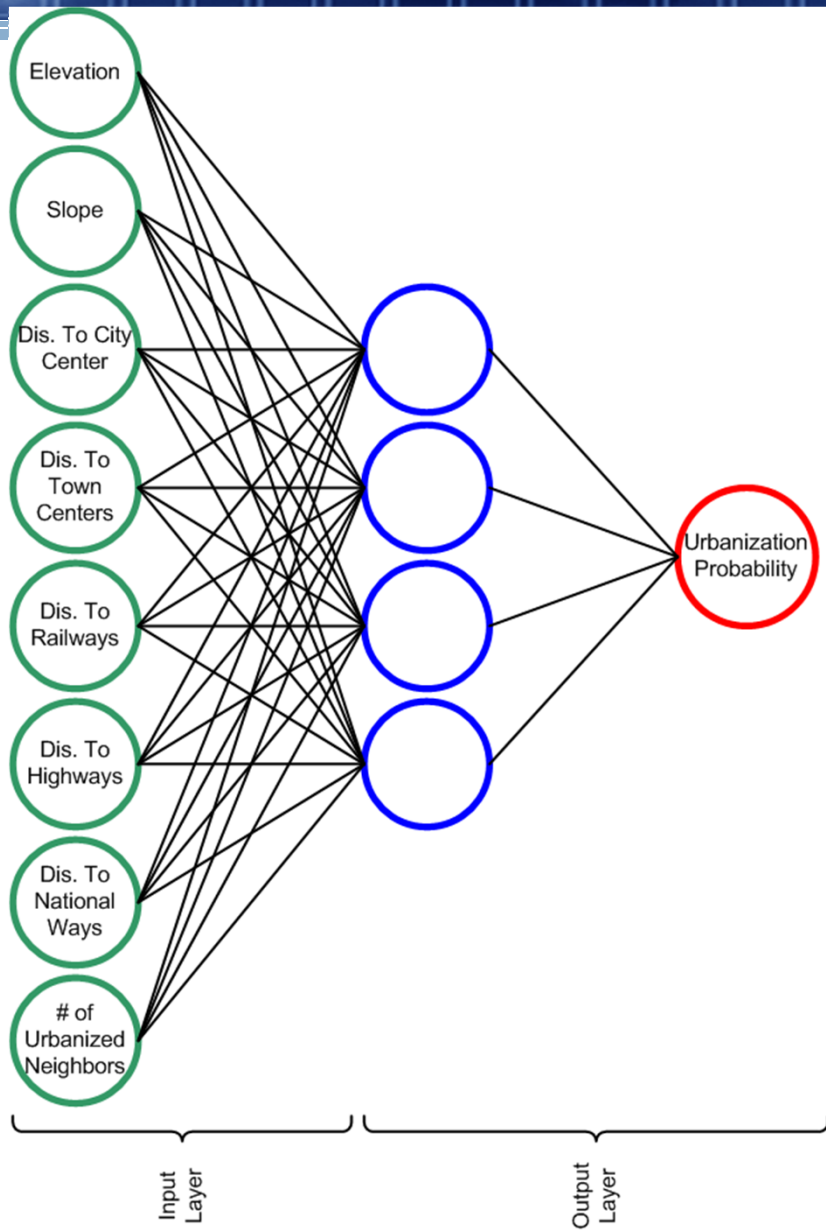
- **An Artificial-Neural-Network-Based, constrained, Cellular Automata model for urban growth simulation**



# ANN-Urban-CA: ANN

## Artificial Neural Network

- ANN is suited for dealing with complex nonlinear relationships, e.g., the impacts of driving factors to urban growth
- ANN can learn from available data, and deal with redundancy, inaccuracy, and noise
- Knowledge and experience can be easily learned and stored for further simulation



# ANN-Urban-CA: Macro Constrain

## Macro-scale Socio-economic model

- The Tietenberg model is used to generate the proper demand for urban space in each period (e. g. year) in the future.
  - A Resource Economic model, which usually is used to solve the problem of "*how to consume resources in the future according to the principle of sustainable development*"
  - Lands are treated as non-regenerative resources, and the urbanization process is treated as land source consumption
  - Population increase as the driving force of land consumption

$$\frac{a - bq_t / P_{ta} - c}{(1+r)^{t-1}} - \lambda = 0$$

$$t = (1, 2, \cdots, n)$$

$$Q - \sum_{t=1}^{n} q_t = 0$$

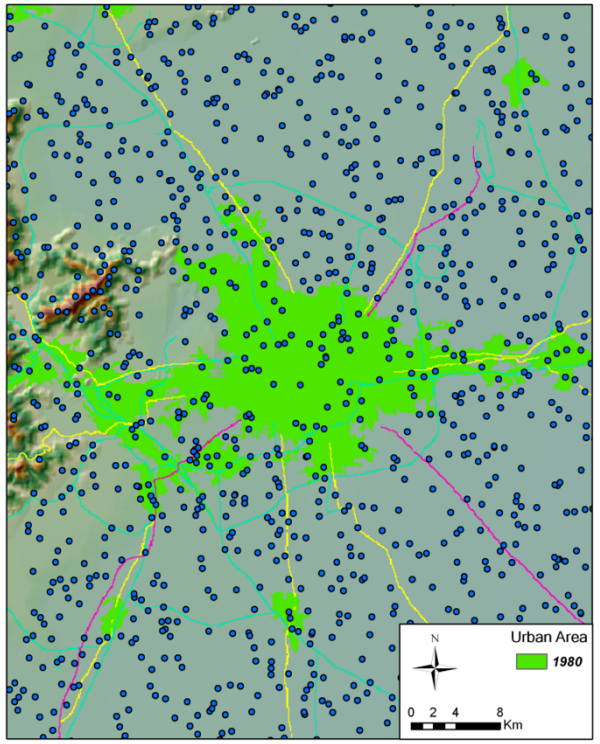
# ANN-Urban-CA: Training

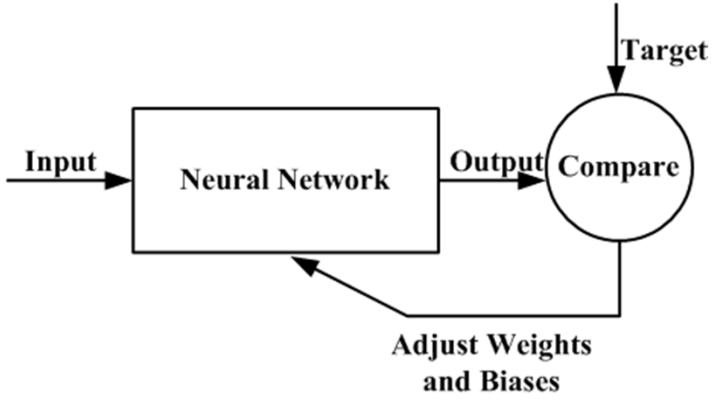
## Purpose

- ANN adjusts the weight values
- Determine the best-fit transition rules and parameters of the CA

## Method

- Back-Propagation (BP) training algorithm
- Input: Driving factors
- Output: Urbanization probability
- Target: Historical urban data



# ANN-Urban-CA: Results

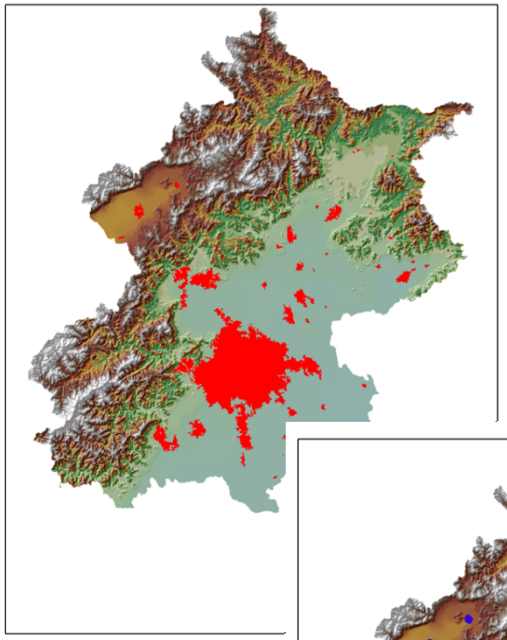
## History Simulation

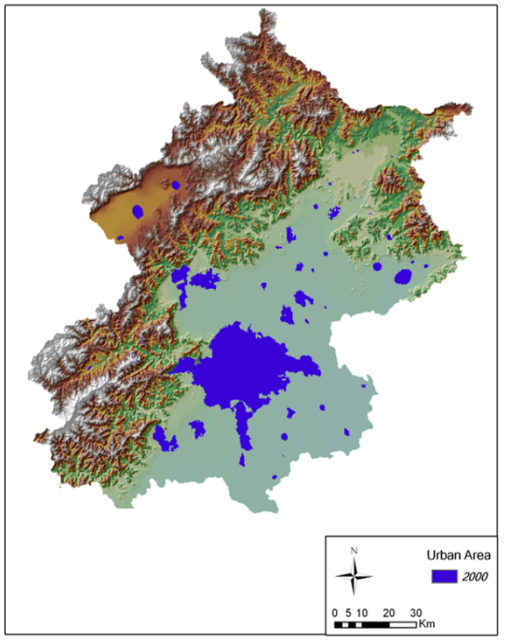
- Trained using samples of Beijing urban maps of 1980, 1995, and 2000
- Simulate urban growth in Beijing 1995 - 2000

$$Lee - Sallee = \frac{A_{real} \cap A_{sim}}{A_{real} \cup A_{sim}} = 0.8318$$

$$correlatio\ n = \frac{\sum_{k}^{n} c_{ij}}{\sqrt{\sum_{k}^{n} (z_i - \overline{z}_i)^2} \times \sqrt{\sum_{k}^{n} (z_j - \overline{z}_j)^2}} = 0.9018$$

Real Beijing urban, 2000



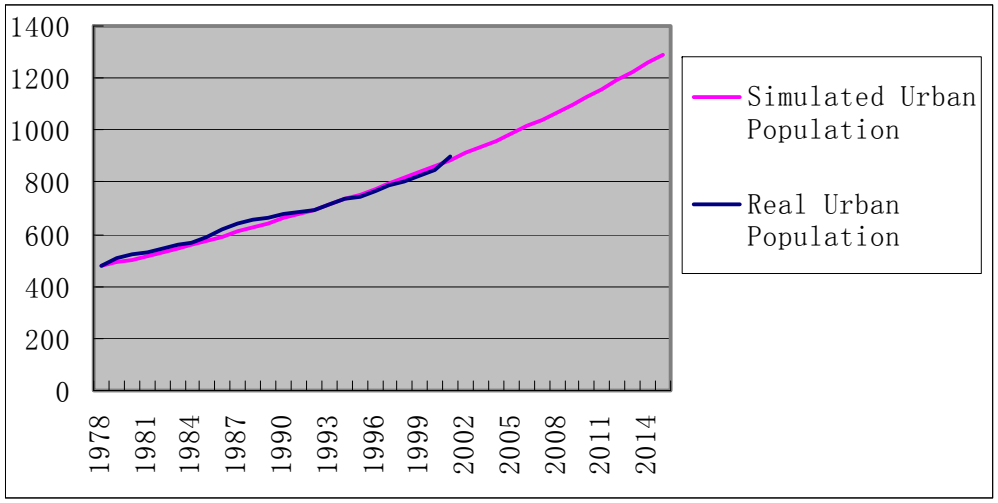



Simulated Beijing urban, 2000

# ANN-Urban-CA: Results

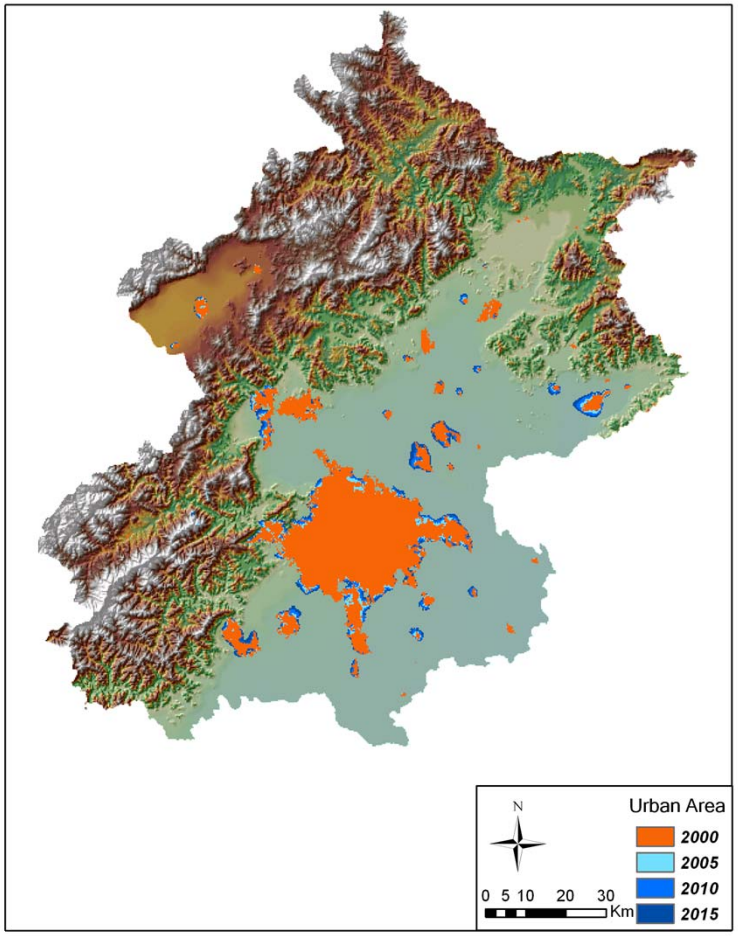
## Future Forecast

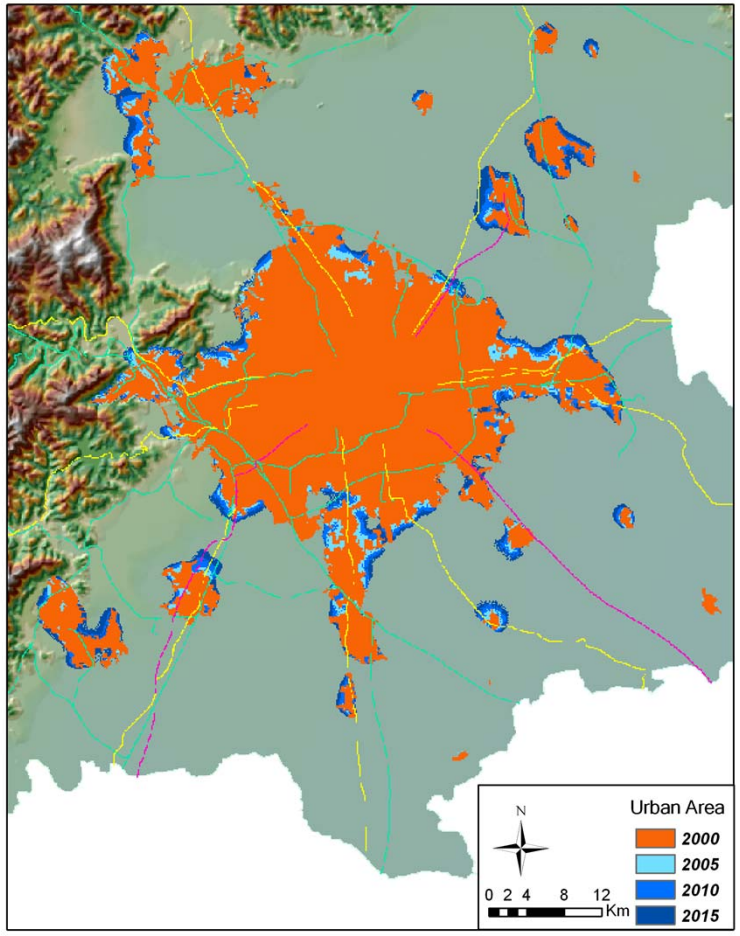
- Increased populations of Beijing 2001- 2015
- By using the Tietenberg Model, 6 scenarios of urbanization were derived




| Years | Increased Pop (10,000) | Total Scenario 1 ($hm^2$) | | Total Scenario 2 ($hm^2$) | | Total Scenario 3 ($hm^2$) | |
|---|---|---|---|---|---|---|---|
| | | r=0 | r=0.01 | r=0 | r=0.01 | r=0 | r=0.01 |
| 2001～2005 | 123.956 | 7522.9 | 8201.1 | 15186.8 | 15781.6 | 17741.5 | 18308.5 |
| 2006～2010 | 141.766 | 8687.9 | 8758.7 | 17538.6 | 17600.8 | 20488.8 | 20548.1 |
| 2011～2015 | 162.134 | 10033.2 | 9284.2 | 20254.6 | 19597.6 | 23661.7 | 23035.4 |

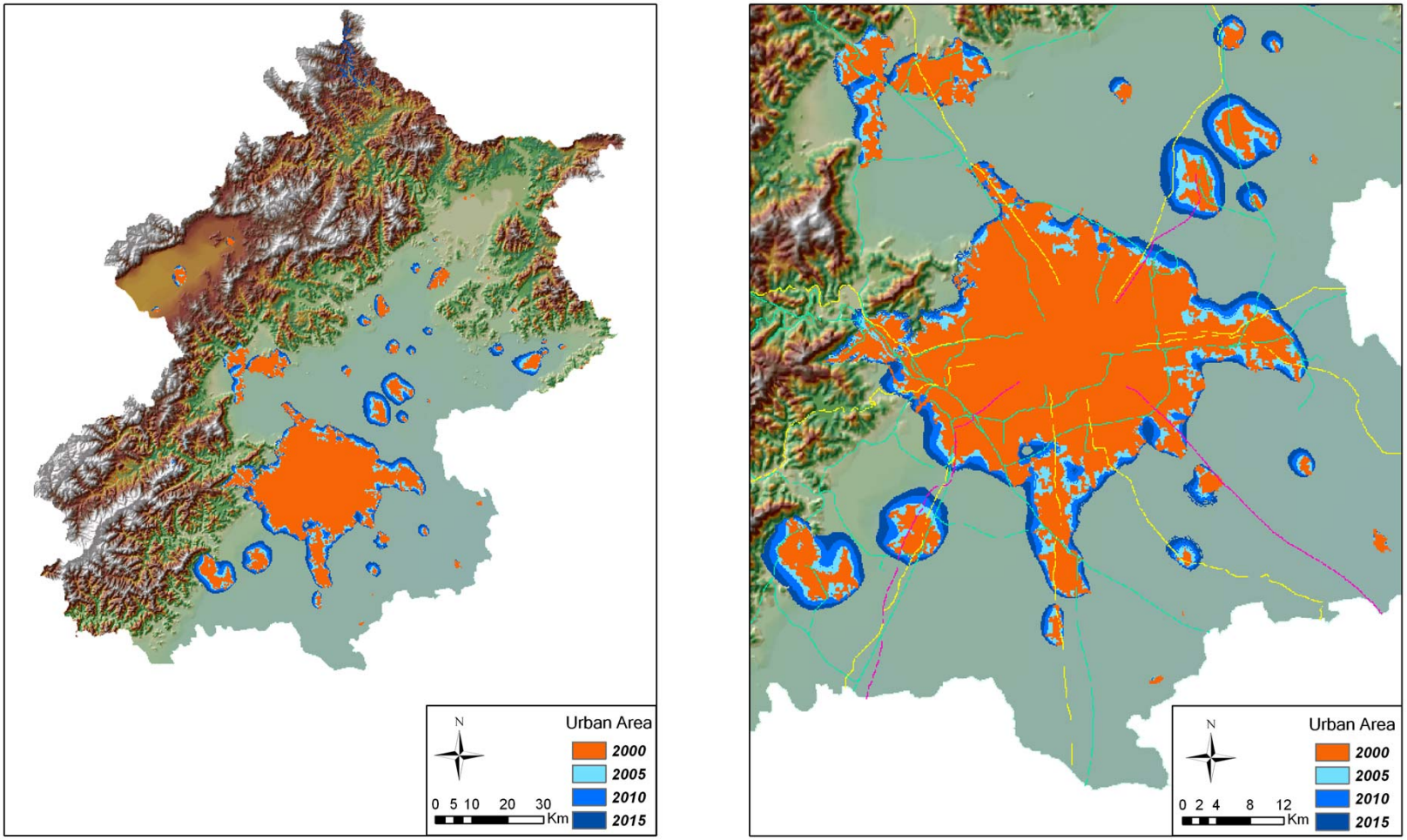
# ANN-Urban-CA: Results




Urban Growth in Beijing 2000 – 2015 (Scenarios 1)

# ANN-Urban-CA: Results




Urban Growth in Beijing 2000 – 2015 (Scenario 4)

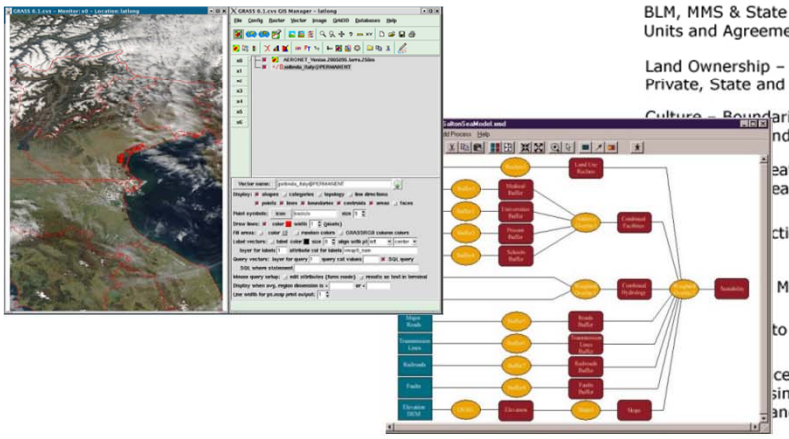
# Sub-Conclusion on ANN-Urban-CA

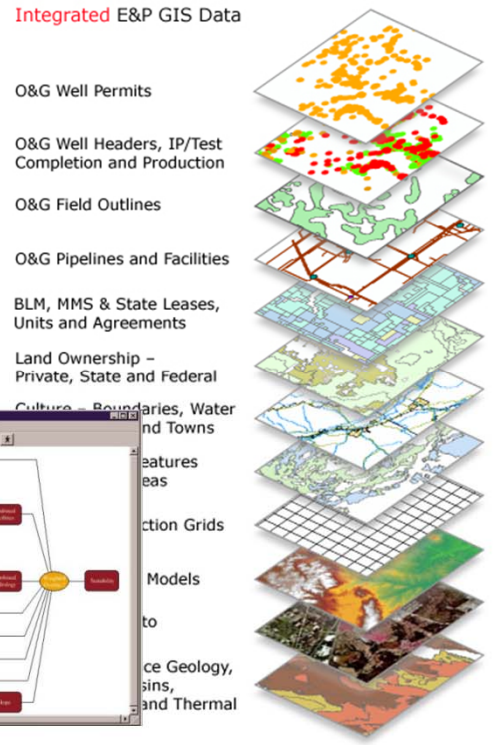
- **ANN's capability of dealing with nonlinear complex systems**
  - Calibrated without heavy computing overhead and subjective human interference
- **Optimal quantity allocation + optimal spatial allocation**
  - Providing an ideal pattern of sustainable urban development, useful in urban planning
- **Highly flexible structure and modeling approach**
  - Easily generalized to model other kinds of spatio-temporal dynamics for various purposes, e.g., spread of invasive species and vegetative epidemics, movement of toxic pollutants in water systems, and land-cover change caused by climate change
  - Open to any possible/available datasets, e.g., numerous remotely sensed data and other natural resource and environmental data

# High-performance Geospatial Computing

## ❖ Why high-performance computing?

- GeoComputation implies HPC
- Increasing demand for computational power in geospatial research and applications
  - Sophisticated and complicated analytical algorithms and simulation models
  - High-resolution and large-volume datasets
  - Rapid processing and real-time response





# High-performance Computing

## Definition

- Usually refers to parallel computing
  - The use of multiple computing units (e.g., computers, processors/CPU cores, or processes) working together on a common task in a concurrent manner in order to achieve higher performance
  - In contrast to sequential computing that usually has only one computing unit
- Performance is usually measured with computing time

## Emerging Cyberinfrastructure

- Grid Computing
- Cloud Computing

A massive parallel computing system (http://ctbp.ucsd.edu/pc/html/intro4.html )

# Areal Interpolation – Introduction

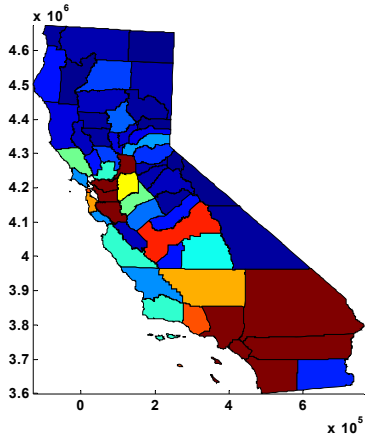
## Definition

- Predicts the unknown (target) attribute values at the required partition (target zones or supports) from a set of known (source) attribute data available on a different partition (source zones or supports)

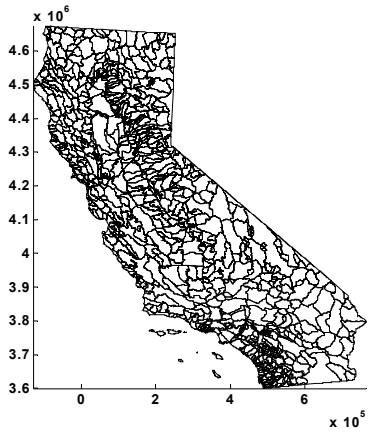
## Two main approaches

- Cartographical methods
  - Use cartographical properties of supports, e.g., area, as the basis
  - Simple and widely used
- Geostatistical methods
  - Use variants of Kriging
  - Accounts for spatial autocorrelation
  - Measure the reliability of prediction
  - Mass-preserving target prediction

Population of counties




Population of watersheds = ?

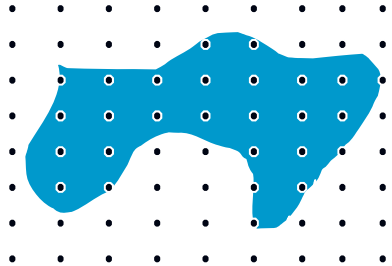


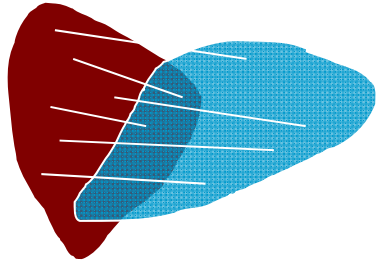

An areal interpolation problem

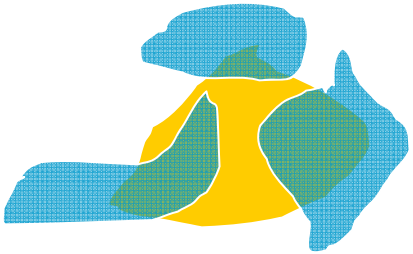
# Geostatistical Areal Interpolation

## Steps

- Discretization of source and target supports with a regular raster (point values not known, just location)
- Computation of support-to-support covariances as integrals from a given point covariance model
  - Between all source supports
  - Between all source and target supports
- Use of Kriging system with computed covariances to derive weights for interpolation
- Interpolated values computed as linear combinations of the Kriging weights and the source data







# FFT-based Areal Interpolation

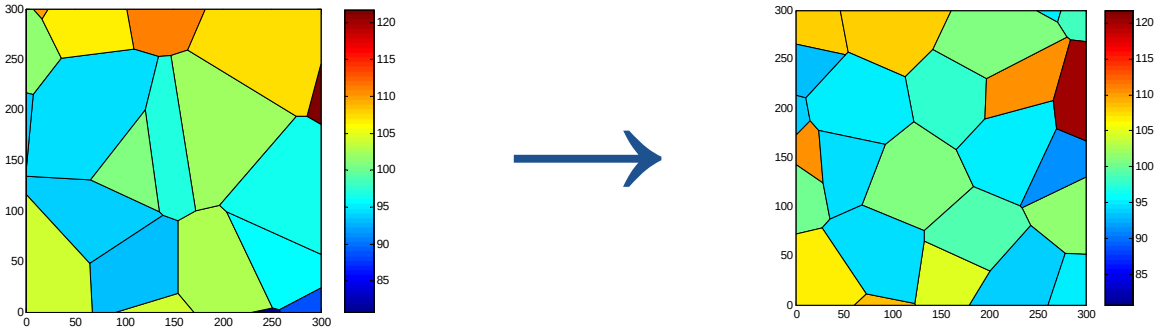
## Traditional geostatistical interpolation

- Highly computationally intensive
  - Massive memory space
  - Long computing time

## FFT-based spectral method

- Use Fast Fourier Transform (FFT) to compute support-to-support covariances

$$\sigma_z(s_k, s_{k'}) = Cov\{Z(s_k), Z(s_{k'})\} = FFT\ (\overline{g_k}) \otimes FFT\ (\overline{C}(1,:)) \otimes FFT\ (\overline{g_{k'}})$$



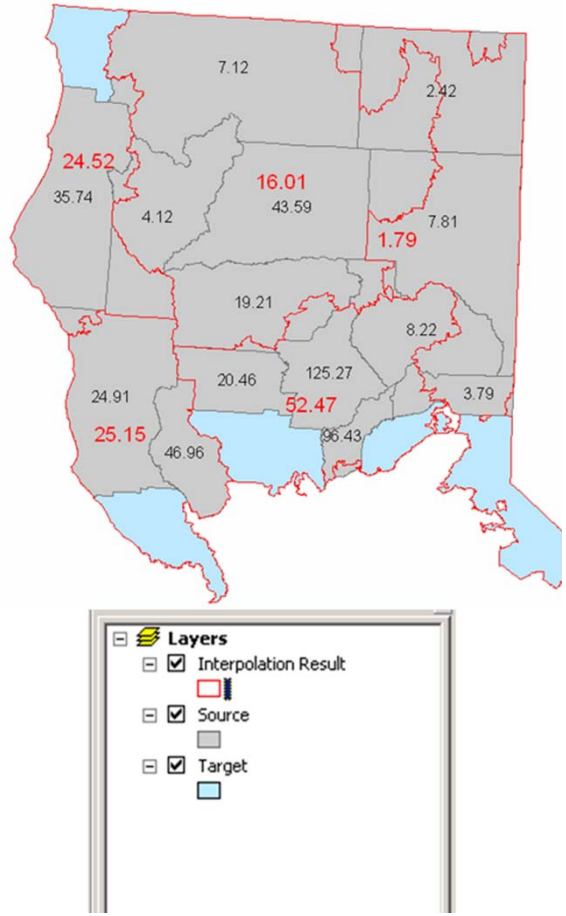

Execution times (for a 360x360 discretization grid)

Traditional method: ~4,000 sec

FFT-based Spectral method: ~50 sec

# FFT-based Areal Interpolation

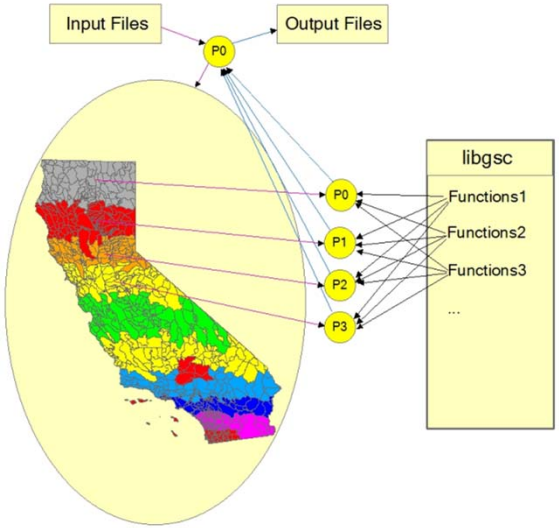
- **FFT-based method is STILL computationally intensive**
  - When it comes to real-world applications
    - Population density from counties to 3-digit zipcode regions in Northern California
    - 500X500 discretization grid
    - Matlab program
    - Penium4 3.2GHz PC with 2GB RAM
    - 900 seconds
- **Solution**
  - Parallel computing
    - The computation of covariance between a pair of supports is independent from that of other pairs
    - The computation of prediction for a target support is independent from that for other target supports

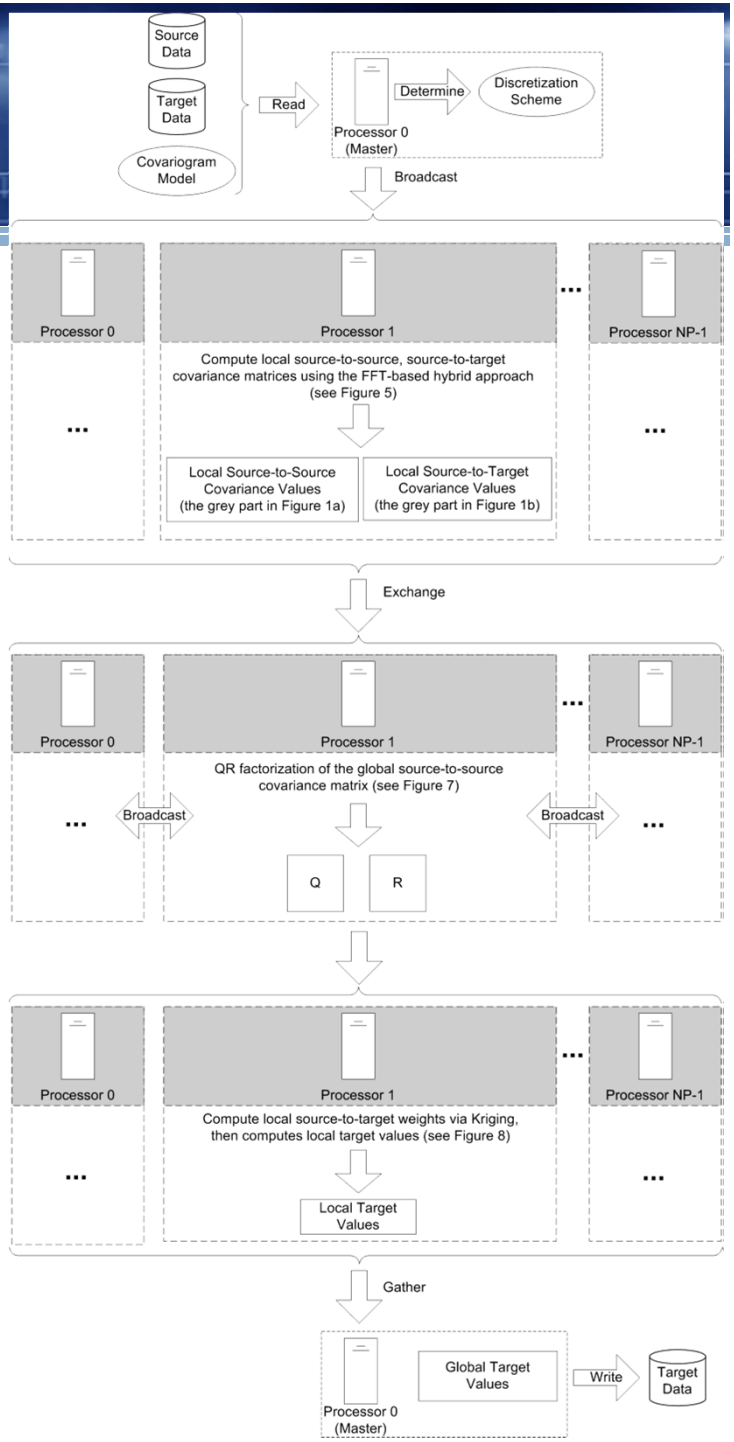


# pAI: Algorithm Overview

## Three parallel processes

- Source-to-source, and source-to-target covariance matrices by means of FFT
- QR factorization of the source-to-source covariance matrix
- Source-to-target weights via Kriging, and predicted attribute values for target supports

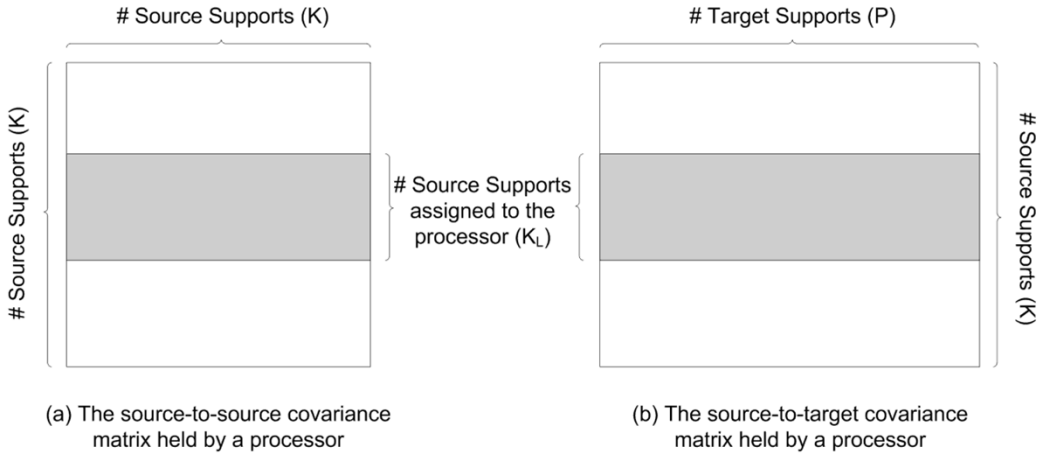


# pAI: 1st Parallel Process

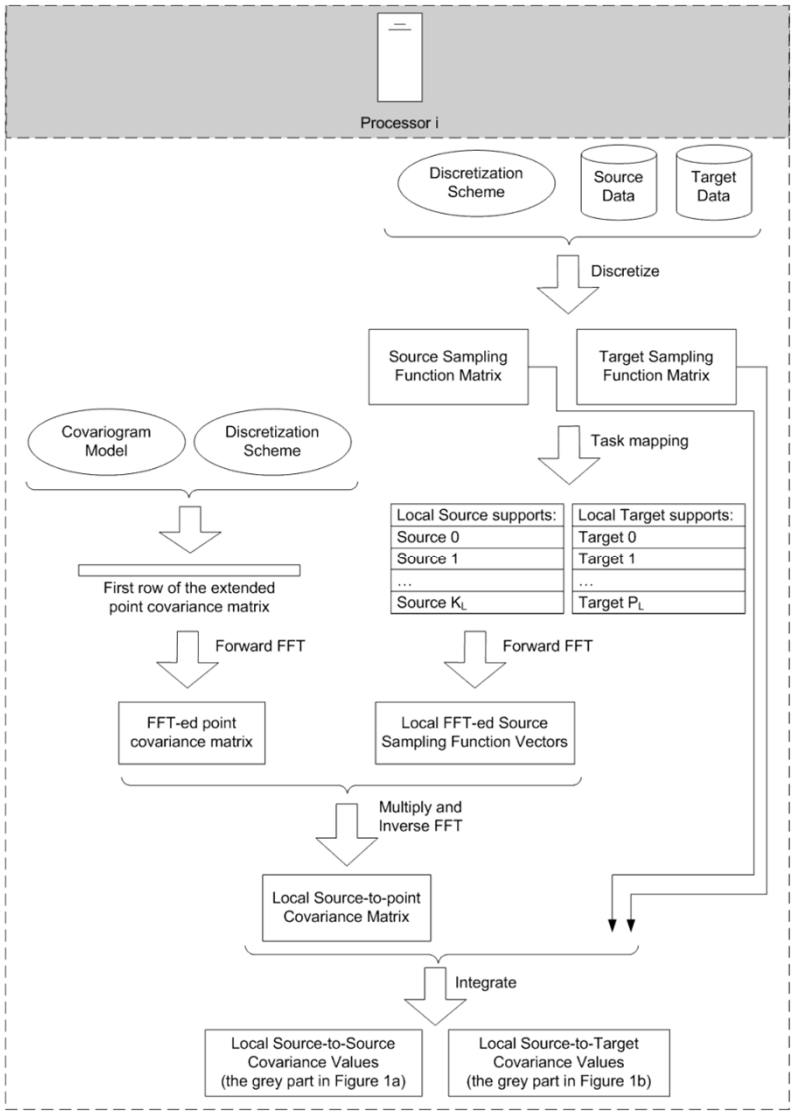
## Support-to-support covariance

- Parallel over source supports
  - Each processor handles a subset of source supports




(a) The source-to-source covariance matrix held by a processor

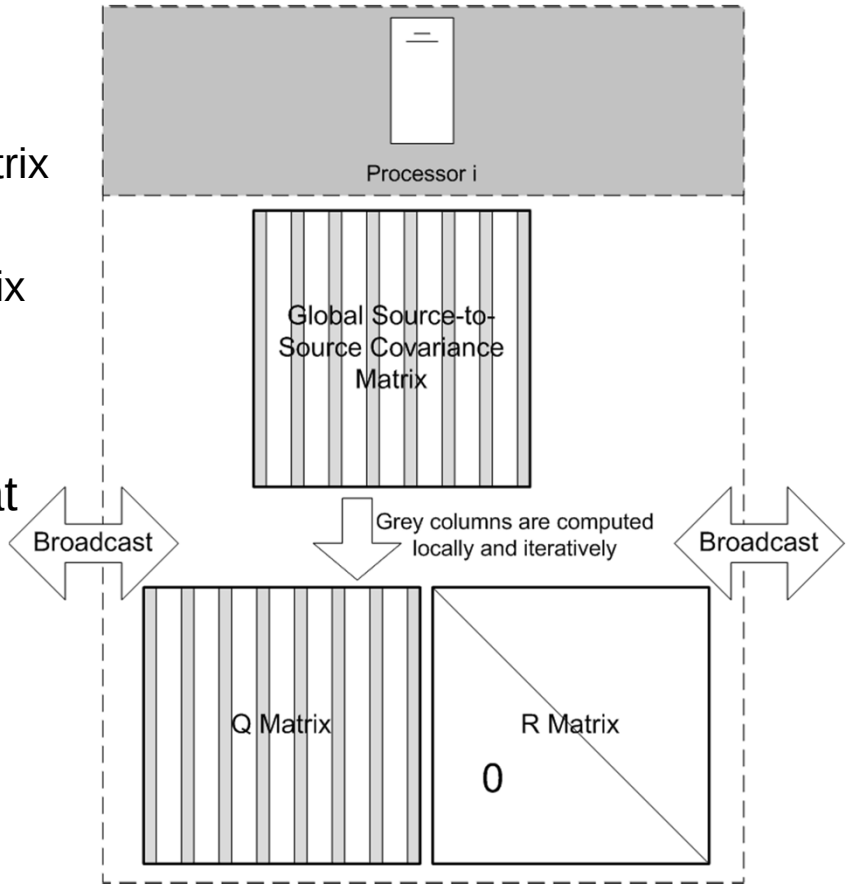
(b) The source-to-target covariance matrix held by a processor



# pAI: 2nd Parallel Process

## QR factorization

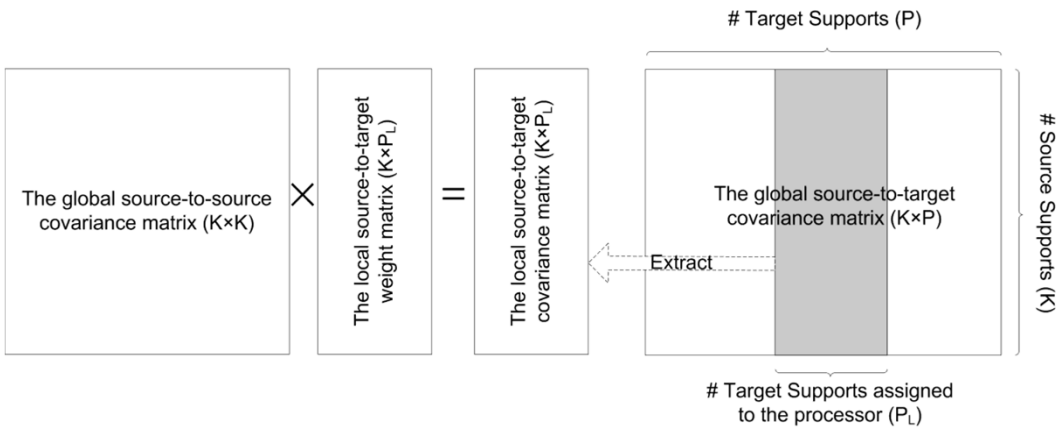
- Needed to solve a Ax=b problem
  - In a Kriging system
    - A: source-to-source covariance matrix
    - x: source-to-target weight matrix
    - b: source-to-target covariance matrix
- Each processor handles a subset of columns in the Q matrix
  - Data exchange among processors at each iteration
  - Non-blocking communication technique
    - Overlap computation and data exchange

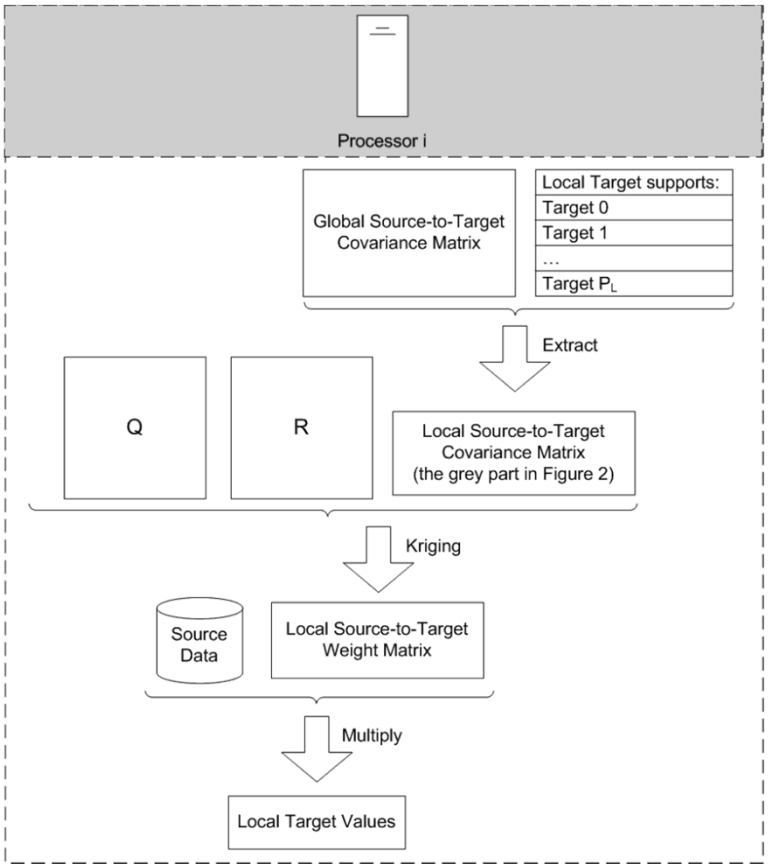


# pAI: 3rd Parallel Process

## Source-to-target weights and target predictions

- Parallel over target supports
  - Each processor handles a subset of target supports



# pAI: Implementation

## Stand-along program

- Written in C++
- Based on Message Passing Interface (MPI)
- Utilizes public-domain libraries
  - FFTW (www.fftw.org)
  - GsTL(http://pangea.stanford.edu/~nremy/GTL/)
  - Shapefile C Library (http://shapelib.maptools.org/) for data I/O
  - Template Numerical Toolkit (TNT, http://math.nist.gov/tnt/index.html)

## User-specified options

- Shapefiles of source and target supports
- Discretization density (point spacing distance)
- Covariogram model
- Task mapping scheme
- Simple Kriging or Ordinary Kriging

# pAI: Experiment Settings

## Two datasets

- Eastern Time Zone dataset
  - Source: population densities of counties in 2000 (2248 polygons)
  - Target: population densities of watersheds (1633 polygons)
- Continental U.S. dataset
  - Source: population densities of counties in 2000 (4703 polygons)
  - Target: population densities of watersheds (2848 polygons)

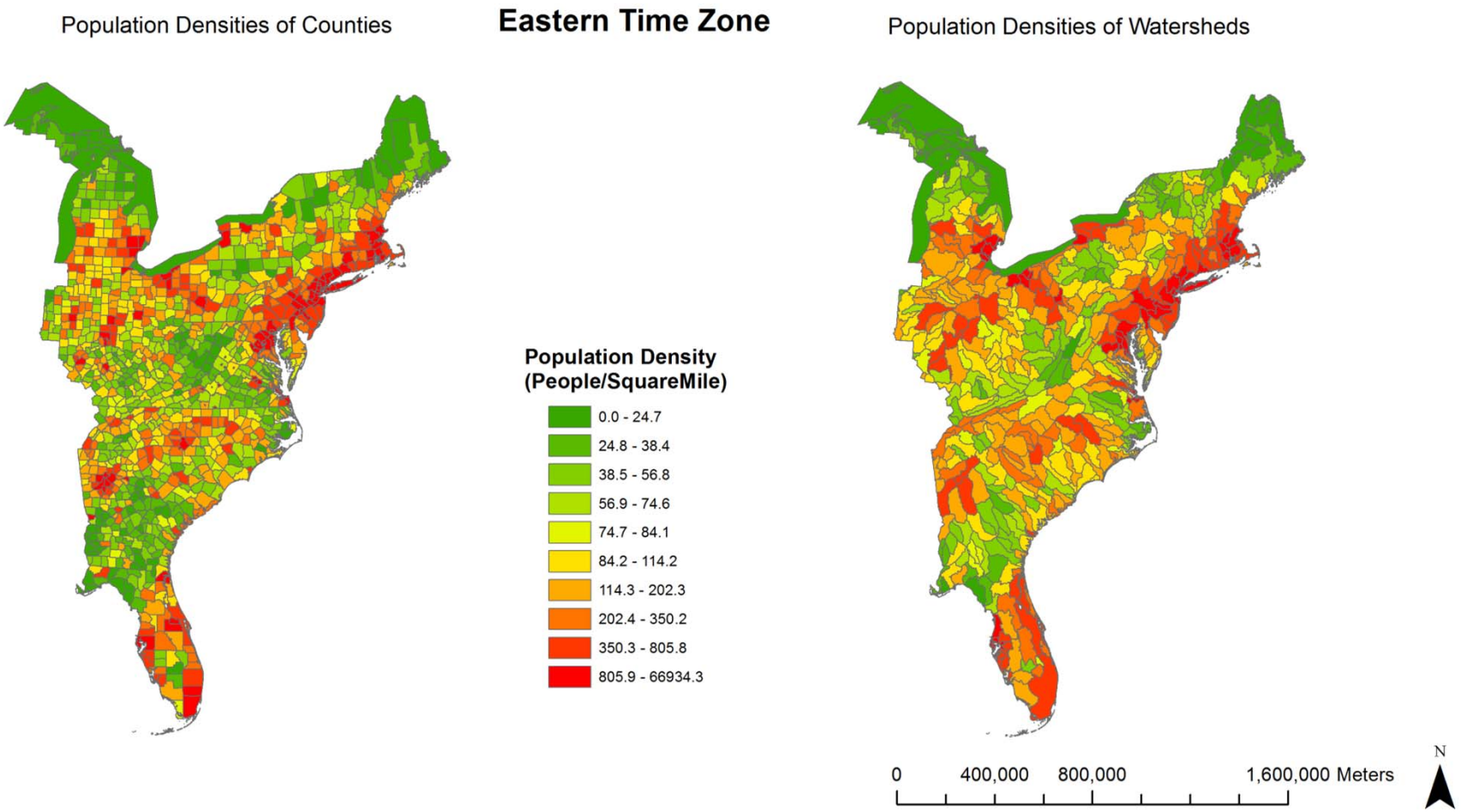
## Discretization scheme

- 2000-meter point spacing
- Eastern Time Zone – 1333X917 grid (1.2 million points)
- Continental U.S. - 1452X2348 grid (3.4 million points)

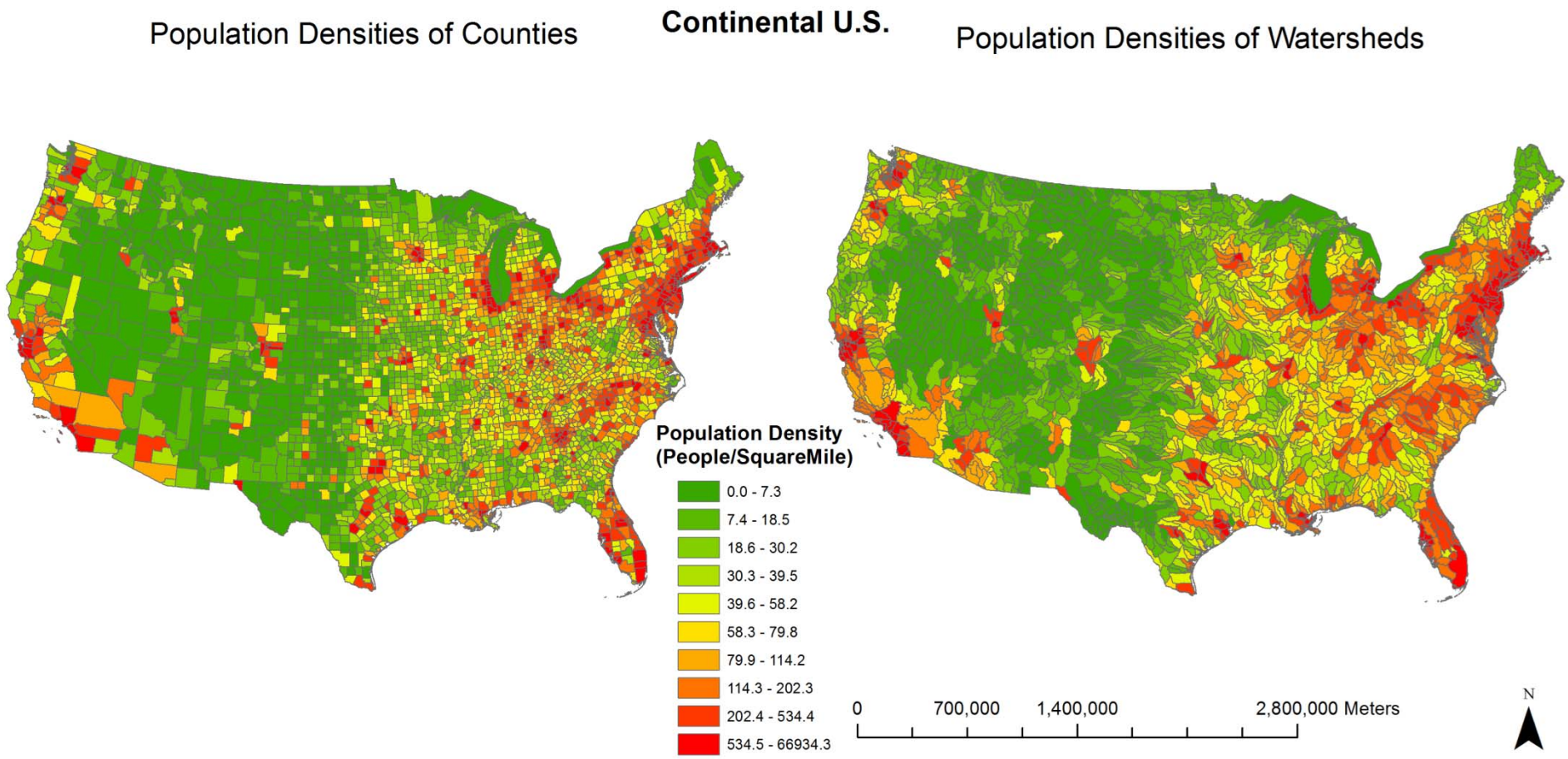
## Computer cluster

- 280 AMD quad core nodes (2.2 GHz, 8 GB RAM per node)
- 871 Opteron two-dual-core nodes (2.8 GHz, 8GB RAM per node)
- 800 MB/second InfiniBand

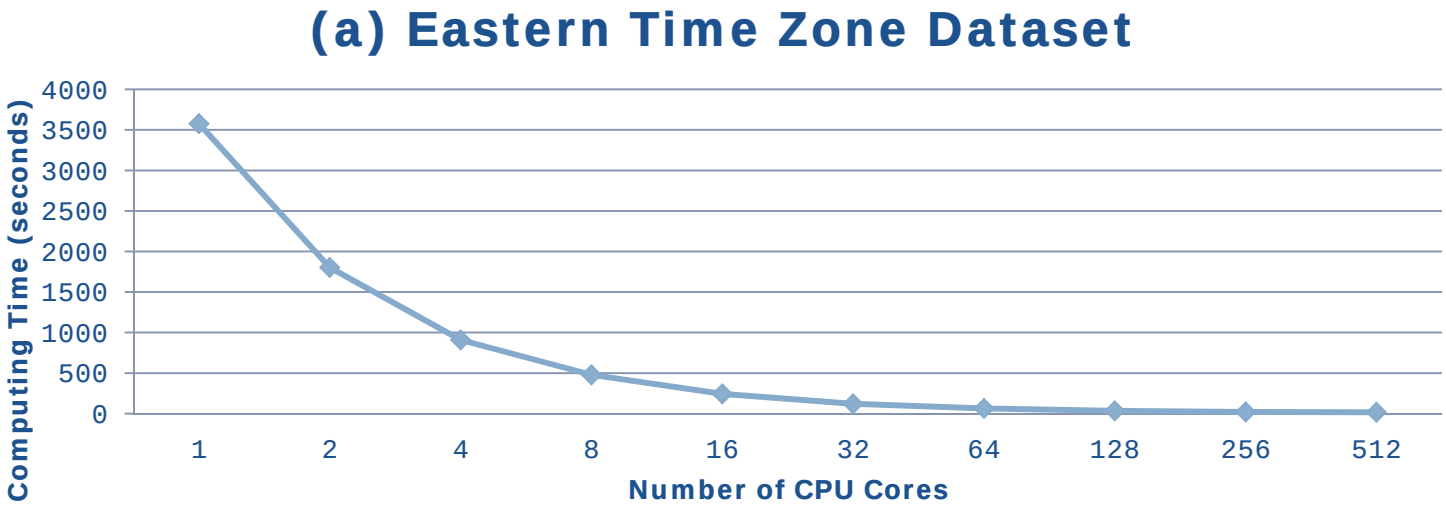
# pAI: Results

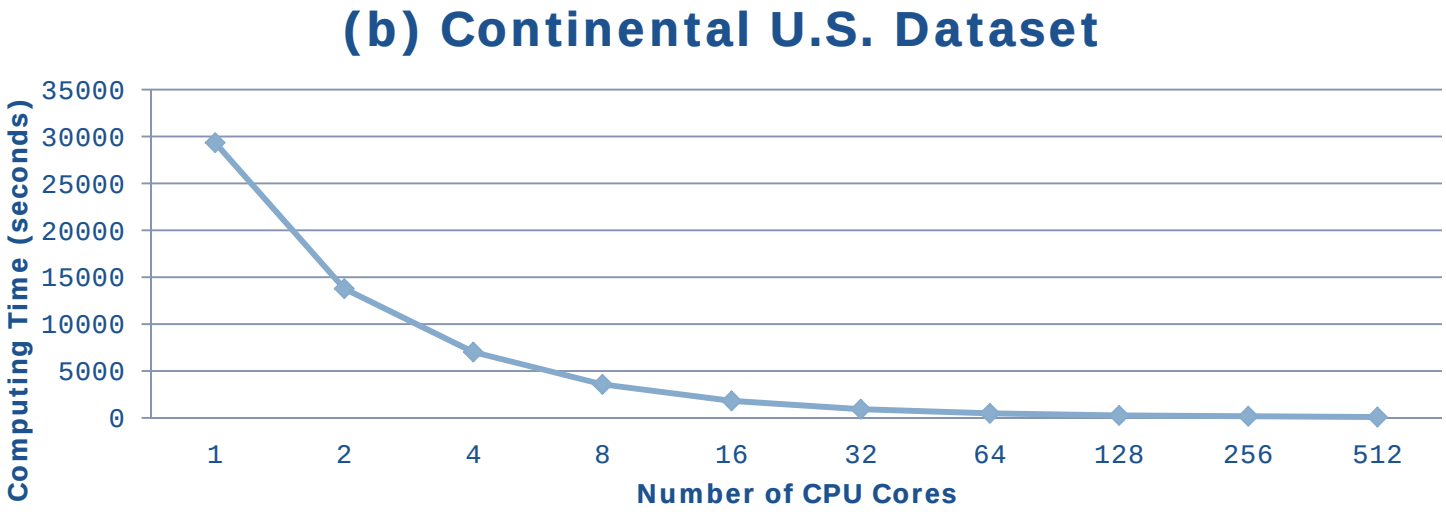

Population Densities of Counties
Eastern Time Zone
Population Densities of Watersheds
Population Density
(People/SquareMile)
0.0 - 24.7
24.8 - 38.4
38.5 - 56.8
56.9 - 74.6
74.7 - 84.1
84.2 - 114.2
114.3 - 202.3
202.4 - 350.2
350.3 - 805.8
805.9 - 66934.3
0
400,000
800,000
1,600,000 Meters
N

# pAI: Results


Population Densities of Counties
Continental U.S.
Population Densities of Watersheds
Population Density
(People/SquareMile)
0.0 - 7.3
7.4 - 18.5
18.6 - 30.2
30.3 - 39.5
39.6 - 58.2
58.3 - 79.8
79.9 - 114.2
114.3 - 202.3
202.4 - 534.4
534.5 - 66934.3
0
700,000
1,400,000
2,800,000 Meters
N

# pAI: Computing time



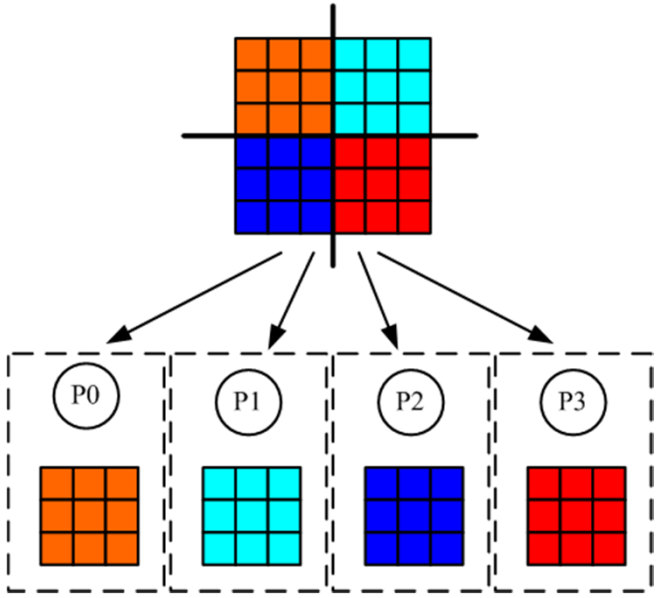
# Sub-Conclusion on pAI

- **This parallel algorithm**
  - Drastically reduced the computing time
  - Achieved fairly high speed-ups and efficiencies
  - Scaled reasonably well as the number of processors increased and as the problem size increased
- **Based on global Kriging**
  - All source supports are used for the prediction for each target
  - Can be used for local Kriging
    - Neighbor search
- **Regular discretization grids**
  - FFT-based technology requires regular grids
  - If irregular discretization is to be used, computational complexity for support-to-support covariance is not uniform anymore
    - Adaptive task mapping methods will help

# pRPL: parallel Raster Processing Library

## ❖ Raster is born to be parallelized

- A raster dataset essentially is a matrix of values, each of which represents the attribute of the corresponding cell of the field
- A matrix can be easily partitioned into sub-matrices and assigned onto multiple processors so that the sub-matrices can be processed simultaneously

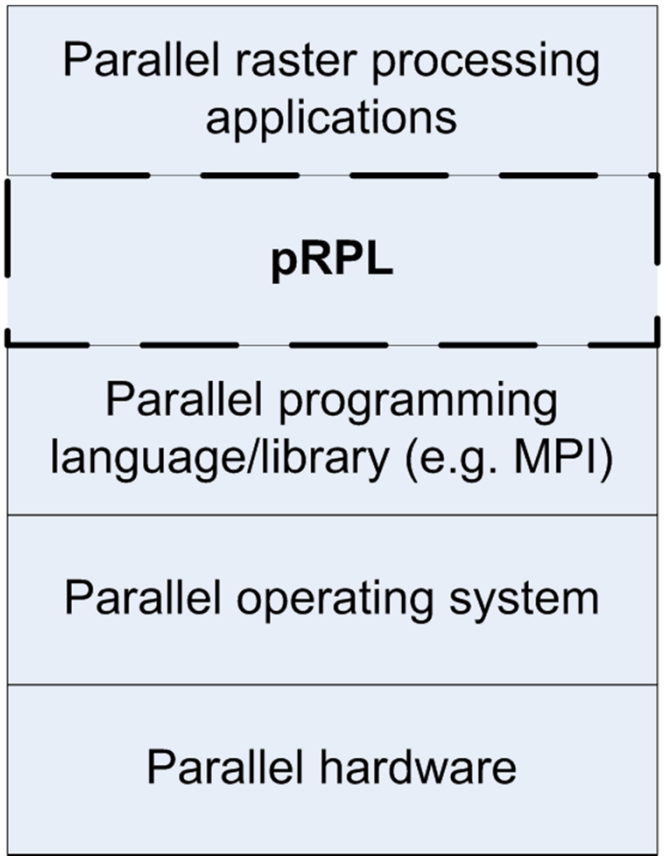


# pRPL: Introduction

- **An open-source general-purpose parallel Raster Processing programming Library**
- **Encapsulates complex parallel computing utilities and routines specifically for raster processing**
  - Enables the implementation of parallel raster-processing algorithms with minimal knowledge of parallel computing and programming
  - Greatly reduces the development complexity
- **Possible usage**
  - Massive-volume geographic raster processing
  - Image (including remote sensing imagery) processing
  - Large-scale Cellular Automata (CA) and Agent-based Modeling
- **Free downloadable and open source**
  - http://sourceforge.net/projects/prpl/

# pRPL: Features

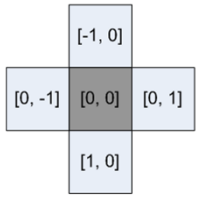
- **Object-Oriented programming style**
  - Written in C++
  - Built upon the Message Passing Interface (MPI)
- **Class templates support arbitrary data types**
  - e.g. integer, char, double precision floating point number, even user-defined types
- **Transparent Parallelism**



# pRPL: Features (cont.)

## Spatially Flexible

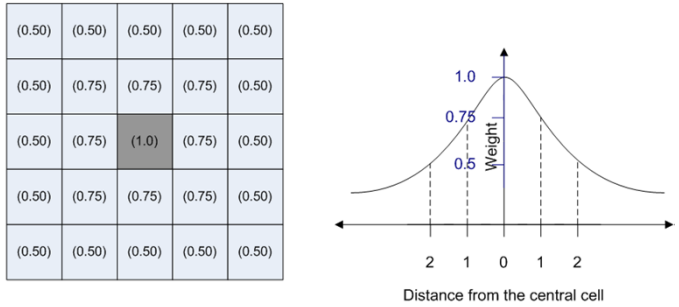
- Supports any arbitrary neighborhood configuration
- Supports centralized and non-centralized algorithms



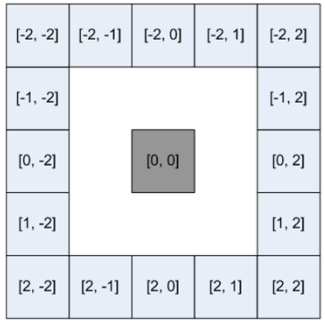

(a) Von Neumann Neighborhood


(b) Moore Neighborhood

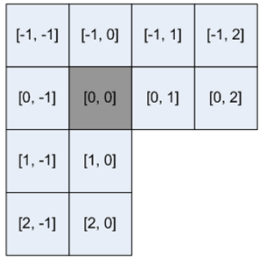

(c) Extended Moore Neighborhood



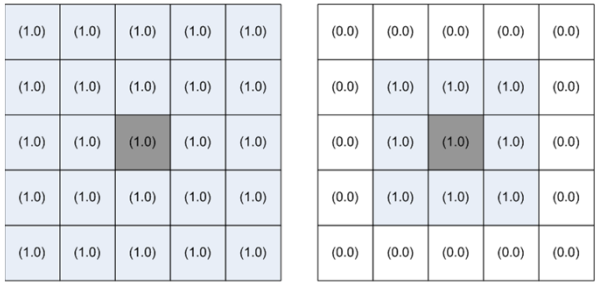

(a) A weighting scheme for kernel algorithms




(d) A discontinuous Neighborhood



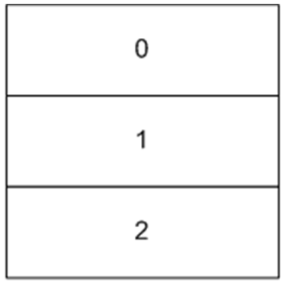

(e) An Asymmetric Neighborhood



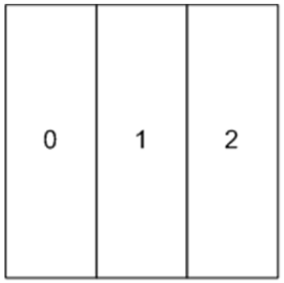

(b) Different weighting schemes for virtually different spatial configurations

# pRPL: Features (cont.)

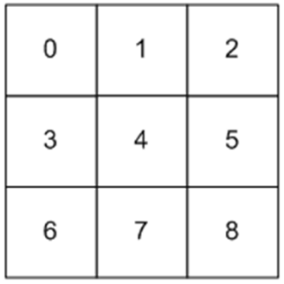
## ❖ Regular and irregular decomposition



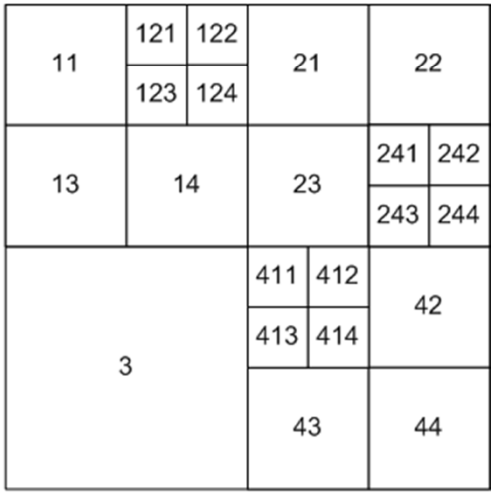

(a) Row-wise decomposition




(b) Column-wise decomposition



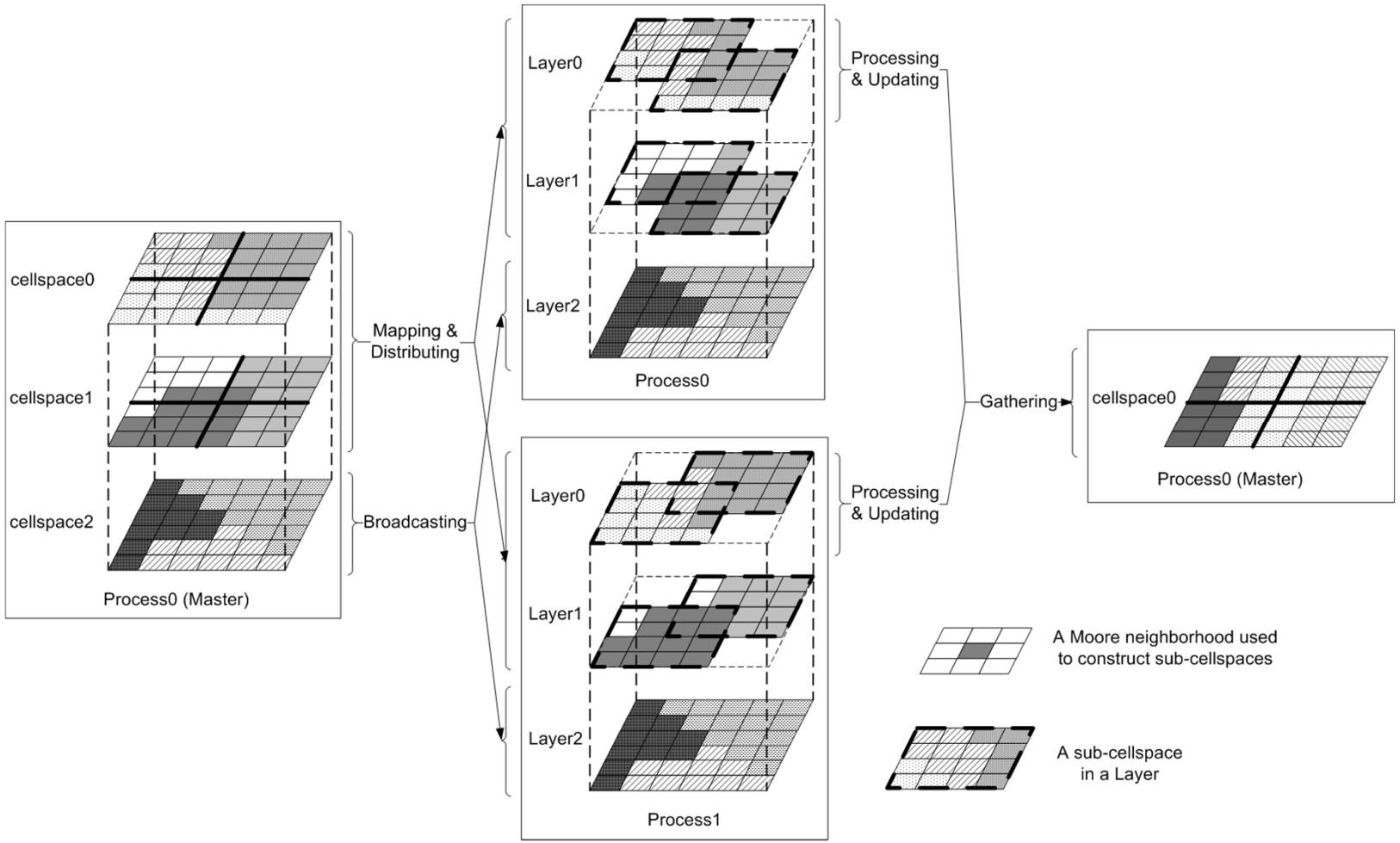

(c) Block-wise decomposition




(d) Quad-tree decomposition

# pRPL: Features (cont.)

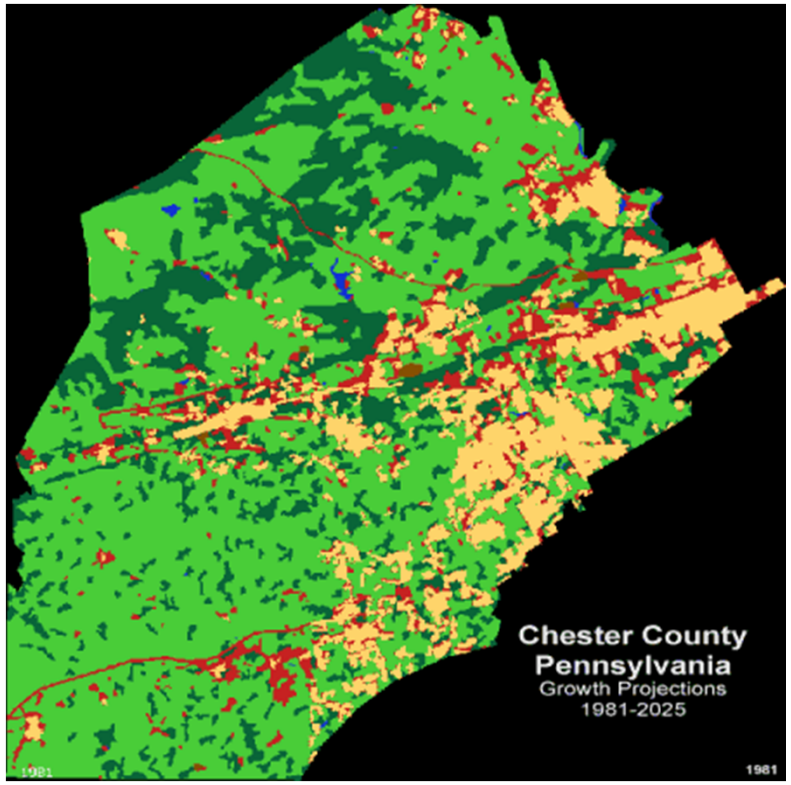
## ❖ Multi-layer processing



# pRPL: Programming

```
int main(int argc, char *argv[]) {

  PRProcess myPrc(MPI_COMM_WORLD); /* Raster processor */
  myPrc.init(argc, argv);


  Layer<int> lyr2update(myPrc, “Int_Layer”);

  … /* load the data on the master processor */


  lyr2update.smplDcmpDstrbt(SMPL_ROW, 2*myPrc.nPrcs()); /* Decompose
distribute */

  MyTransition myTrans; /* Customized Transition object */

  lyr2update.update(myTrans) ; /* Apply the Transition on the Layer */

  lyr2update.gatherCellSpace(); /* Gather the whole cellspace and store it
on the master processor */


  myPrc.finalize();

  return 0;

}
```

# pSLEUTH: Introduction

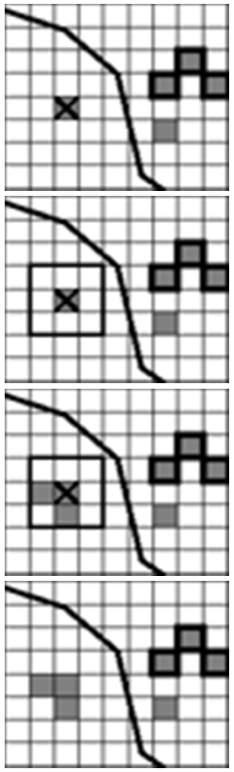



Urban growth in Chester County, Pennsylvania, 1981 – 2025
http://mcmcweb.er.usgs.gov/de_river_basin/phil/modeling.html

## ❖ SLEUTH model

- Uses a modified CA to model the spread of urbanization across a landscape (Clarke et al., 1996, 1997)
- Its name comes from the GIS data layers that are incorporated into the model: **S**lope, **L**anduse, **E**xclusion layer, **U**rban, **T**ransportation, and **H**illshade

# pSLEUTH: Introduction (cont.)



## Coefficients

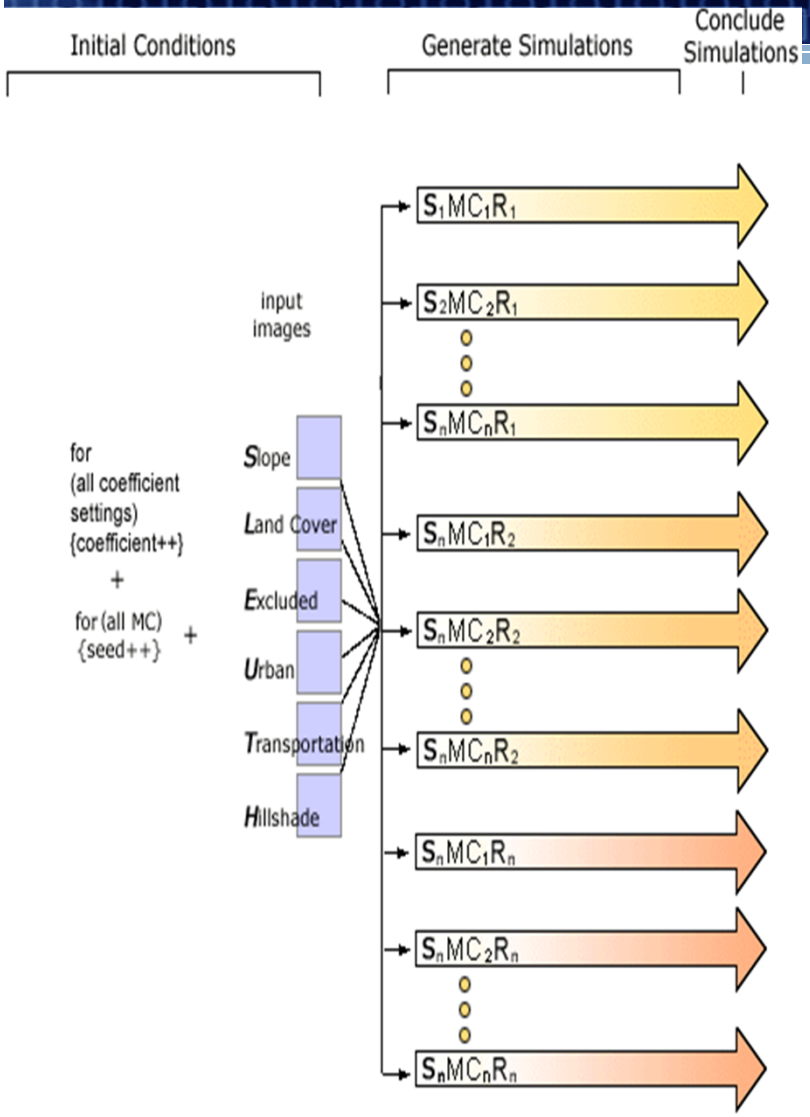
- Dispersion
- Breed
- Spread
- Slope
- Road Gravity

## Rules

- Spontaneous Growth Rule (centralized)
- New Spreading Centers Rule (non-centralized)
- Edge Growth Rule (non-centralized)
- Road-Influenced Growth Rule (non-centralized)

→ For more info. about SLEUTH: http://www.ncgia.ucsb.edu/projects/gig/

# pSLEUTH: Introduction (cont.)



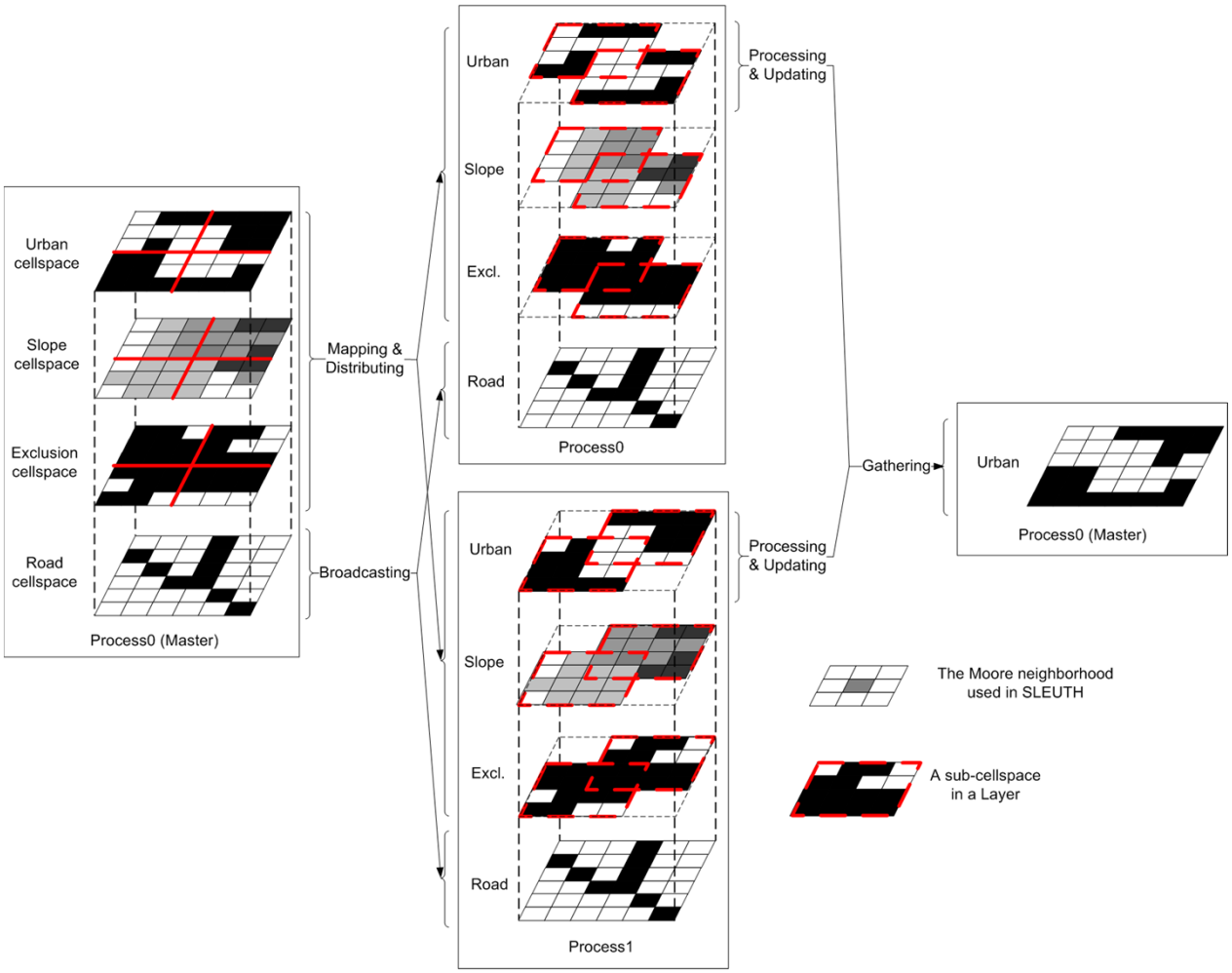

Calibration of SLUETH
http://www.ncgia.ucsb.edu/projects/gig/

## Calibration

- Determine best parameter values to produce realistic results
- Brute-force calibration
  - Produce results using all possible combinations of parameter values
  - Compare with historical data to determine the best-match combination
  - A large number of combinations of parameters ($101^5$ coefficient sets)→ Extremely intensive computing overhead

# pSLEUTH: Parallelization

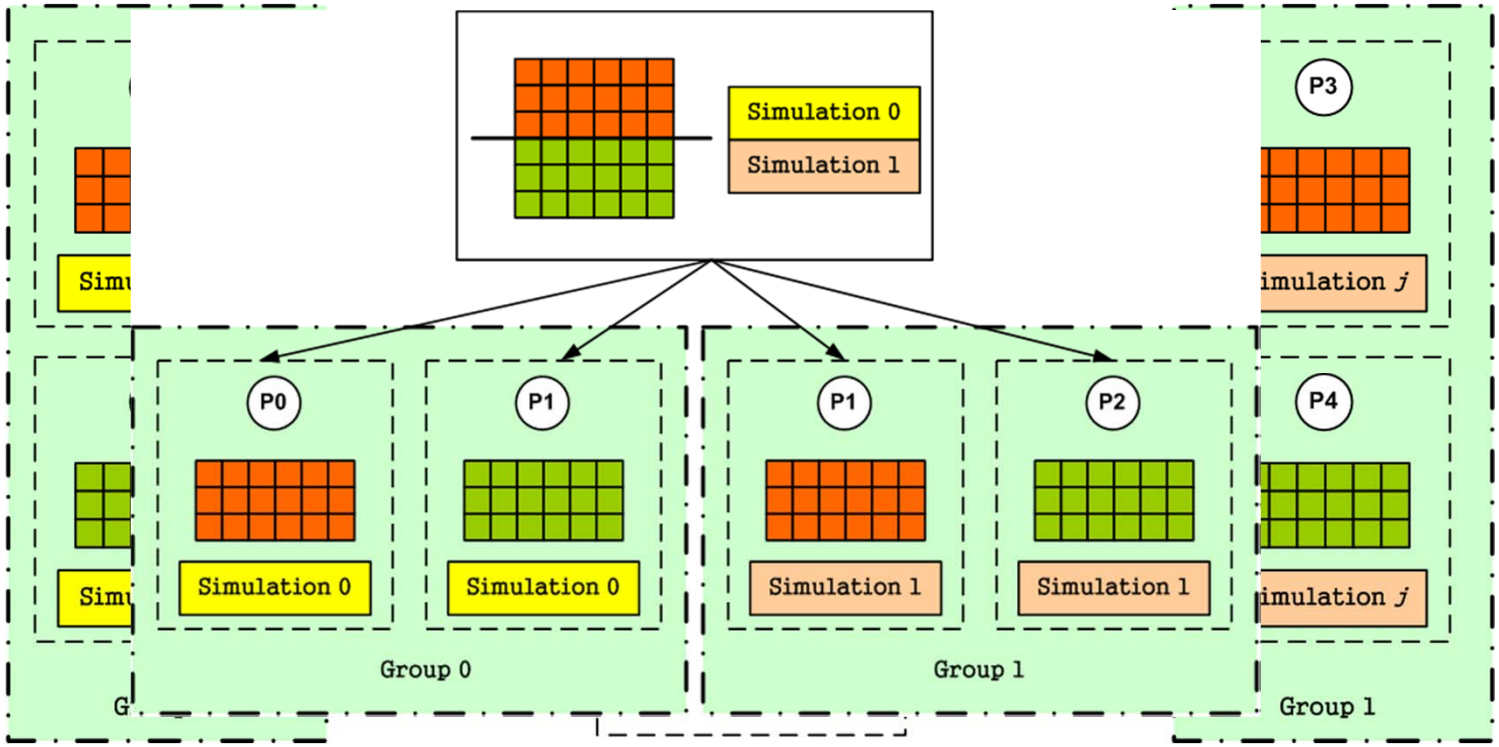
- The four growth rules in the SLEUTH model, were implemented using pRPL



# pSLEUTH: Parallelization (cont.)

## Processer Grouping

- With pRPL, pSLEUTH is able to organize the processors in groups. Data parallelism within a group, task parallelism among groups.
- Static tasking and dynamic tasking



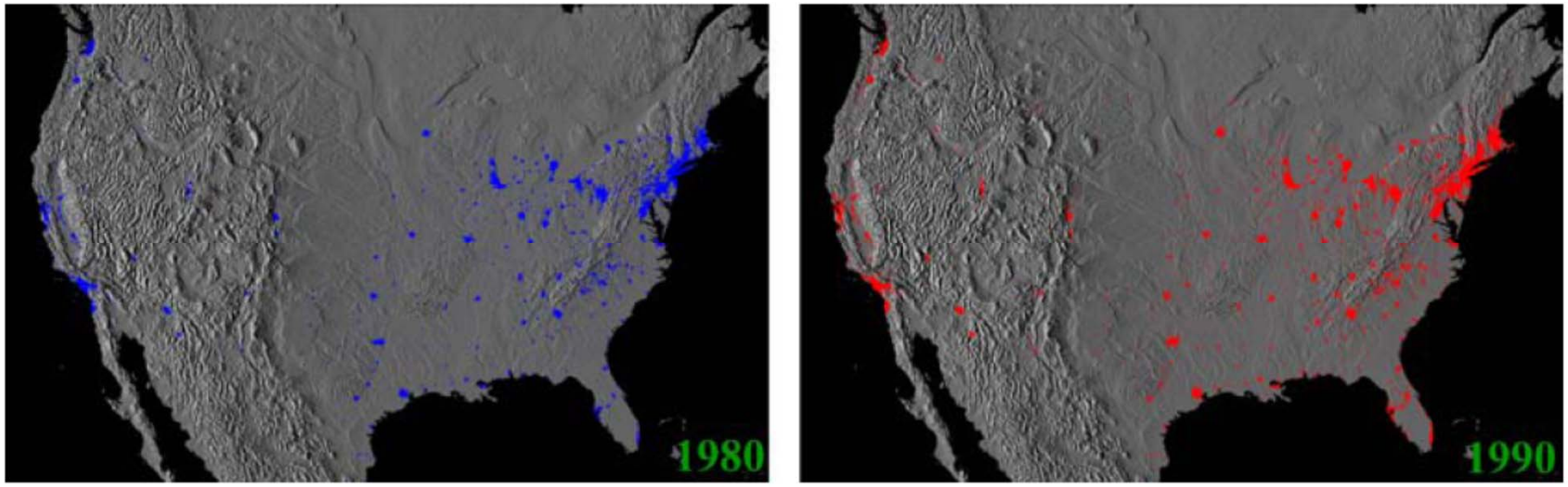
# pSLEUTH: Experiments Settings

## Data

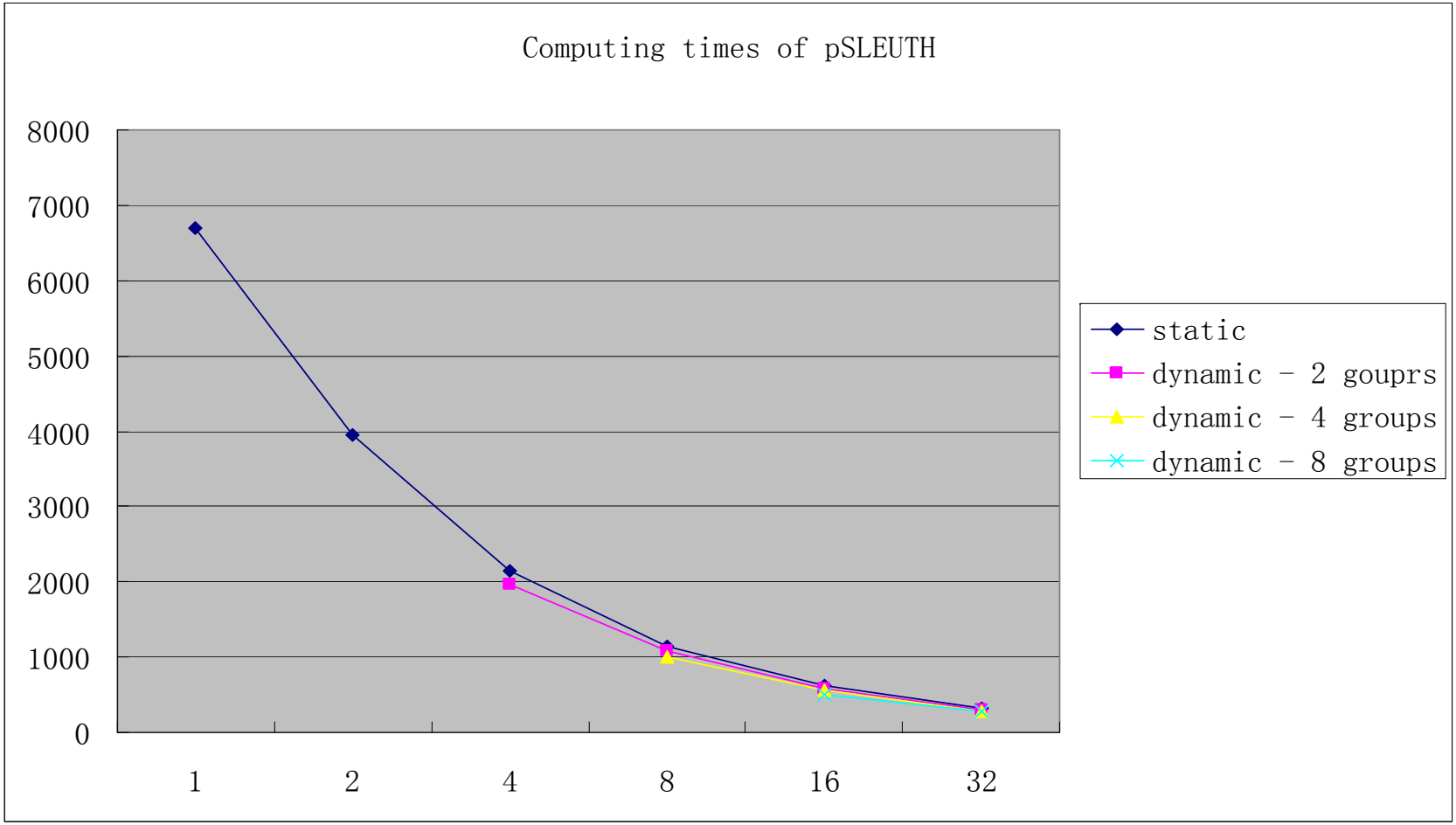
- Urban areas of the continental US (1980 and 1990, 4948×3108)

## Calibration Settings

- Only three values (0, 50, 100) will be evaluated for each coefficient
- The total number of simulations is 243 (= $3^5$)
- Each simulation includes 11 ( = 1990-1980+1) years



# pSLEUTH – Performance

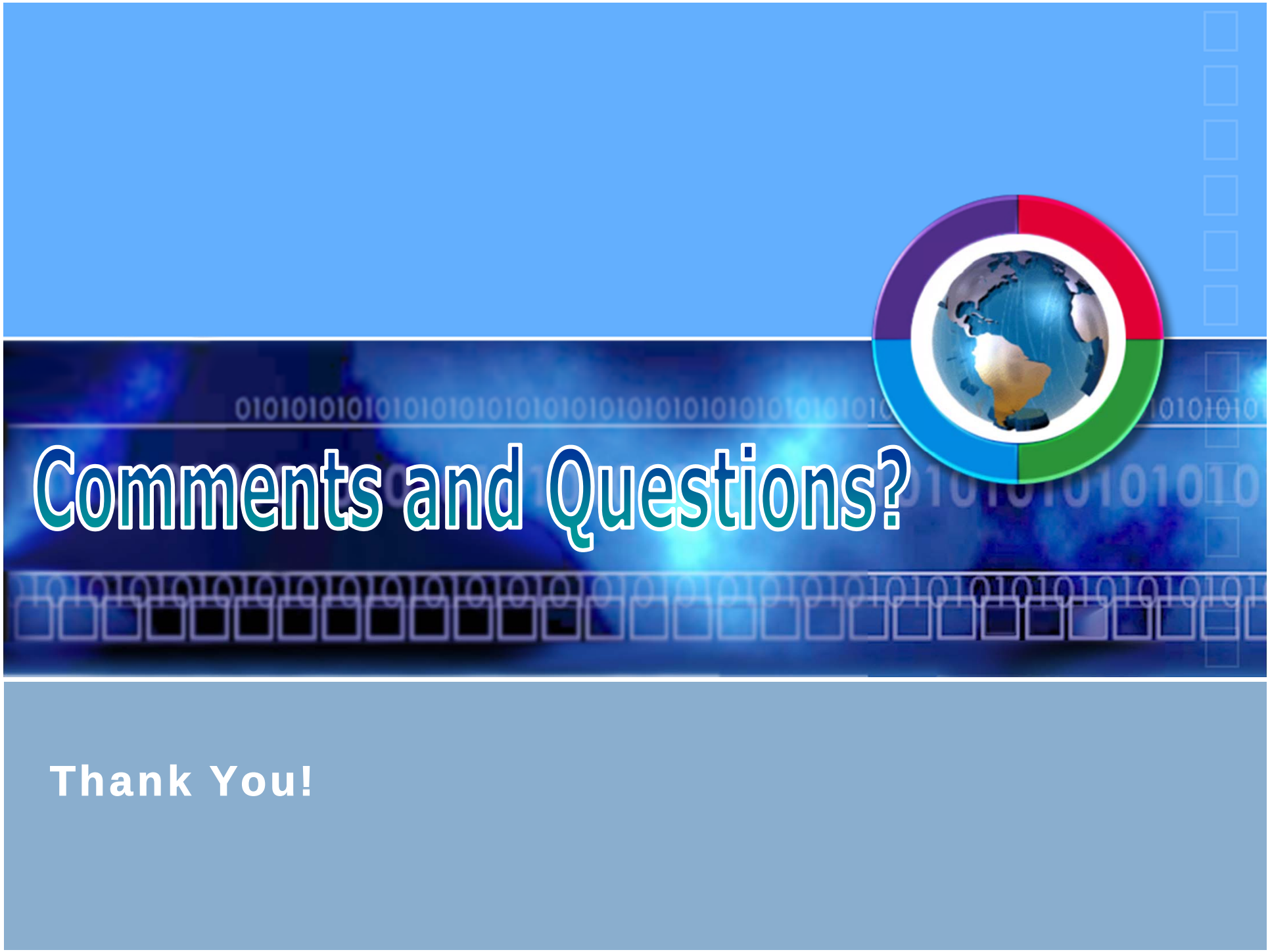


# Sub-Conclusions on pRPL and pSLEUTH

- pRPL greatly reduces the development complexity of implementing a parallel raster processing algorithm
- pRPL can be used for many types of raster-based processing, including Cellular Automata (CA) and Agent-based Modeling
- pRPL largely reduces the computing time, and enables extremely complex geospatial analysis and modeling

# Conclusions

- **GeoComputation is the application of Computational Science in geospatial studies**
  - A large variety of computer-based statistical and mathematical methods for the analysis and modeling of complex geospatial phenomena
  - A natural next step of GIS
  - High-performance computing enables extremely complex geospatial analysis and modeling using massive-volume data
- **GeoComputation can be used as an exploratory-analysis tool, a simulation method, a problem-solving environment, a decision-making-support and planning tool, a theory test-bed, and a theory-discovery approach**


Comments and Questions?
Thank You!