Spatial analysis with the R Project for Statistical Computing

D G Rossiter
University of Twente
Faculty of Geo-information Science & Earth Observation (ITC)
Enschede (NL)

August 10, 2010

Topics

1. Spatial analysis in R
2. The `sp` package: spatial classes
3. Interfaces with other spatial analysis tools
4. The `gstat` package: geostatistical modelling, prediction and simulation

Spatial analysis in R

1. Spatial data

2. R approaches to spatial data

3. Analysis sequence: R in combination with other programs

Spatial data

- . . . are data with **coördinates**, i.e. known locations
- These are **absolute locations** in one, two or three dimensions
  * in some defined **coördinate system**
  * possibly with some defined **projection** and **datum**
- Points are implicitly related by **distance** and **direction** of **separation**
- Polygons are implicitly related by adjacency, containment
- Such data requires **different analysis** than non-spatial data
  * e.g. can't assume independence of observations
- And they need special **data structures** which recognize the special status of coördinates

R approaches

- No native S classes for these
- S is **extensible** with new classes (S3 or S4 systems), methods and packages
- So, several **add-in packages** have been developed
- Add-in packages which define **spatial classes and methods**:
  * `sp` (Bivand, Pebesma): generic S4 spatial classes
- Add-in packages for **spatial analysis**; statisticians can implement their own ideas; including:
  * `spatial` (Ripley, based on 1981 book)
  * `geoR`, `geoRglm` (Ribeiro & Diggle, basis for 2007 book)
  * `gstat` (Pebesma)
  * `spatstat` (Baddeley & Turner): point patterns
  * `circular`: directional statistics
  * `RandomFields` (Schlather)

Interface to GIS

- Add-in packages:
  - `rgdal`: interface to Geospatial Data Abstraction Library (GDAL)
  - `maptools`: interface to external spatial data structures e.g. shapefiles

(See later topic)

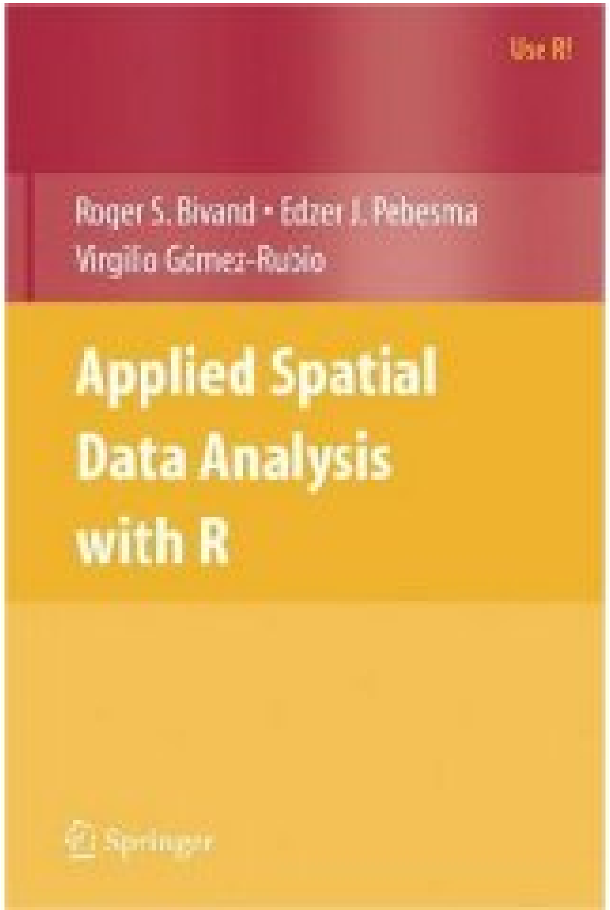
CRAN Task View: Analysis of Spatial Data

`http://cran.r-project.org/web/views/Spatial.html` explains what packages are available for:

- Classes for spatial data
- Handling spatial data
- Reading and writing spatial data
- Point pattern analysis
- Geostatistics
- Disease mapping and areal data analysis
- Spatial regression
- Ecological analysis

Advanced textbook

Bivand, R. S., Pebesma, E. J., & Gómez-Rubio, V. (2008). *Applied Spatial Data Analysis with R*: Springer. `http://www.asdar-book.org/`; ISBN 978-0-387-78170-9



Analysis sequence

Use the most **suitable** tool for each phase of the analysis:

1. Prepare spatial data in GIS or image processing program
   - Can prepare matrices, dataframes (e.g. coördinates and data values), even topology directly in R but usually it's easier to use a specialized program.
2. Import to R
3. Perform analysis in R
4. Display spatial results in R using R graphics
5. Export results to GIS or mapping program
6. Use for further GIS analysis or include in map layout

The sp package

- Motivation: "The advantage of having multiple R packages for spatial statistics seemed to be hindered by a lack of a **uniform interface** for handling spatial data."

- This package provides **classes** and **methods** for dealing with **spatial data** in S

- By itself it does not provide geostatistical analysis

- Various analytical packages can all use these classes

- Data does not have to be restructured for different sorts of analysis

sp Spatial data structures

- Spatial **data structures** (S4 classes):
  - **points**
  - **lines**
  - **polygons**
  - **grids** (rasters)

- These may all have **attributes** (dataframes)

- S4 class names like `SpatialPointsDataFrame`

- Generic methods with appropriate behaviour for each class

sp Methods for handling spatial data

Some standard methods:

- `bbox`: bounding box
- `dimensions`: number of spatial dimensions
- `coordinates`: set or extract coordinates
- `overlay`: combine two spatial layers of different type
  - e.g. retrieve the polygon or grid values on a set of points
  - e.g. retrieve the points or their attributes within (sets of) polygons
- `spsample`: point sampling schemes within a geographic context (grids or polygons)
- `spplot`: visualize spatial data

Converting data to sp classes

Simple rule: data is spatial if it has **coordinates**.

The most common way to assign coordinates is to use the `coordinates` method as the LHS of an expression.

First we see how spatial data looks when it is not treated as spatial data:

```
> library(gstat)   # meuse is an example dataset in this package
> data(meuse); str(meuse); spsample(meuse, 5, "random")
```

```
'data.frame':       155 obs. of  14 variables:
 $ x      : num  181072 181025 181165 181298 181307 ...
 $ y      : num  333611 333558 333537 333484 333330 ...
 $ cadmium: num  11.7 8.6 6.5 2.6 2.8 3 3.2 2.8 2.4 1.6 ...
 $ copper : num  85 81 68 81 48 61 31 29 37 24 ...

Error in function (classes, fdef, mtable)  :
        unable to find an inherited method for function "spsample", for signature "data.frame"
```

Fields `x` and `y` are coordinates but they have no special status in the dataframe. The method `spsample` expects a spatial object but does not find it.

Converting to spatial data

We explicitly identify the fields that are coordinates:

```
> coordinates(meuse) <- ~ x + y; str(meuse)
```

```
Formal class 'SpatialPointsDataFrame' [package "sp"] with 5 slots
  ..@ data       :'data.frame':        155 obs. of  12 variables:
  .. ..$ cadmium: num [1:155] 11.7 8.6 6.5 2.6 2.8 3 3.2 2.8 2.4 1.6 ...
  .. ..$ copper : num [1:155] 85 81 68 81 48 61 31 29 37 24 ...
  ..@ coords.nrs : int [1:2] 1 2
  ..@ coords     : num [1:155, 1:2] 181072 181025 181165 181298 181307 ...
  .. ..- attr(*, "dimnames")=List of 2
  .. .. ..$ : NULL
  .. .. ..$ : chr [1:2] "x" "y"
  ..@ bbox       : num [1:2, 1:2] 178605 329714 181390 333611
  .. ..- attr(*, "dimnames")=List of 2
  .. .. ..$ : chr [1:2] "x" "y"
  .. .. ..$ : chr [1:2] "min" "max"
  ..@ proj4string:Formal class 'CRS' [package "sp"] with 1 slots
  .. .. ..@ projargs: chr NA
```

The S4 class has **slots** (@) for different kinds of information (coordinates, dimensions, data, bounding box, projection)

- Now the `spsample` method works

- It returns an object of class `SpatialPoints` (i.e. just the locations, no attributes)

```
> spsample(meuse, 5, "random")
```

```
SpatialPoints:
          x      y
[1,] 179246 330766
[2,] 180329 330055
[3,] 181280 329798
[4,] 180391 330627
[5,] 178725 330202
```

Interfaces with other spatial analysis

Most spatial data is prepared outside of R; results of R analyses are often presented outside of R. How is information exchanged?

- `maptools`
- `rgdal`
- Projections

The maptools package

These are tools for reading and handling spatial objects, developed as part of the `sp` initiative. For the most part superseded by `rgdal`.

- `read.shape`, `readShapePoints`, `readShapeLines`, `readShapePoly`: read ESRI **shapefiles**

- `writeShapePoints`, `writeShapeLines`, `writeShapePoly`: write ESRI shapefiles

- `read.AsciiGrid`, `write.AsciiGrid`: **ESRI Ascii GRID** interchange format

These are restricted to just the named formats; a more generic solution was needed, which is provided by . . .

The rgdal package

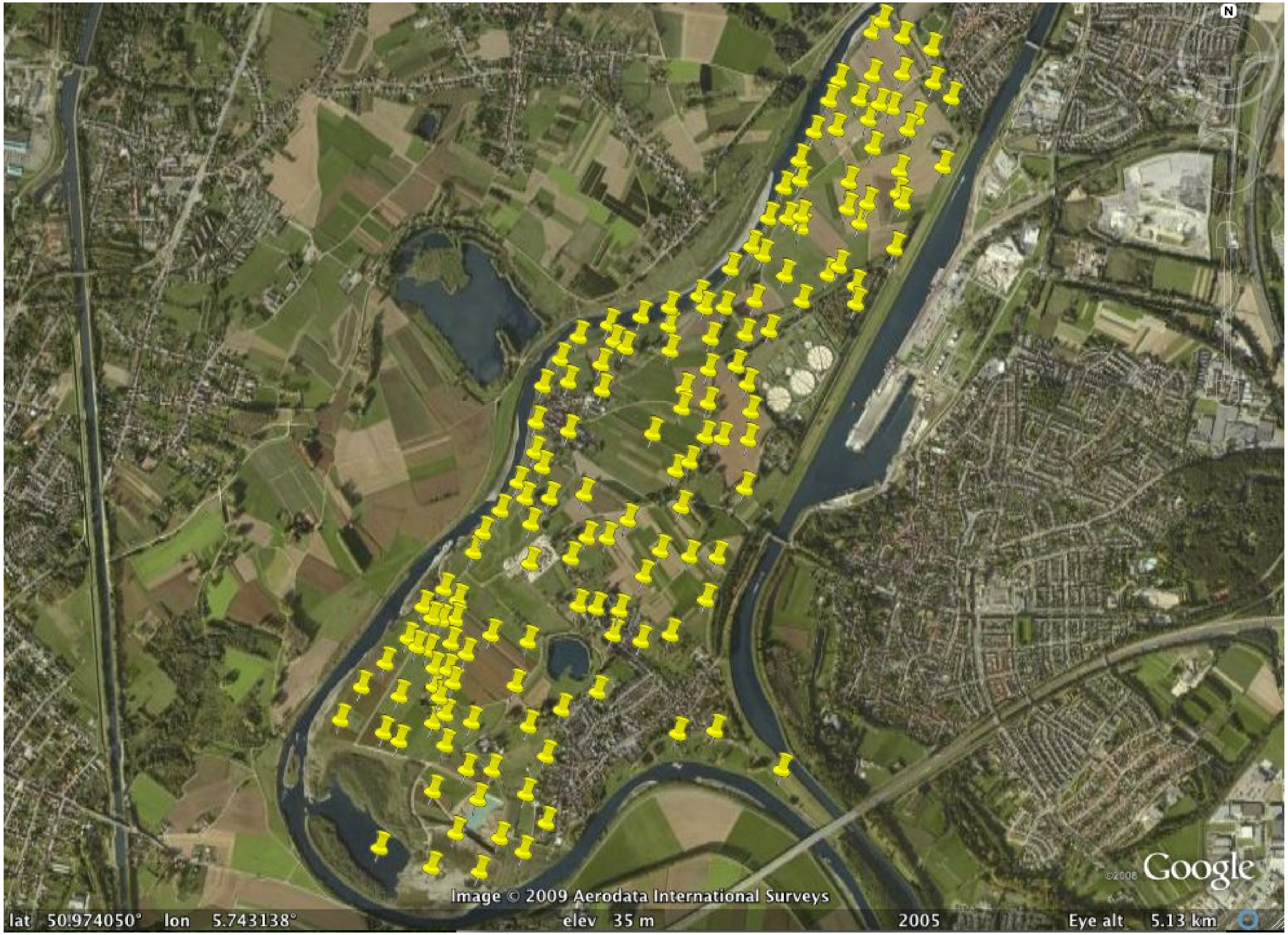
This package provides **bindings** for the **Geospatial Data Abstraction Library** (GDAL)[1], which is an open-source **translator** library for geospatial data formats.

`rgdal` uses the `sp` classes.

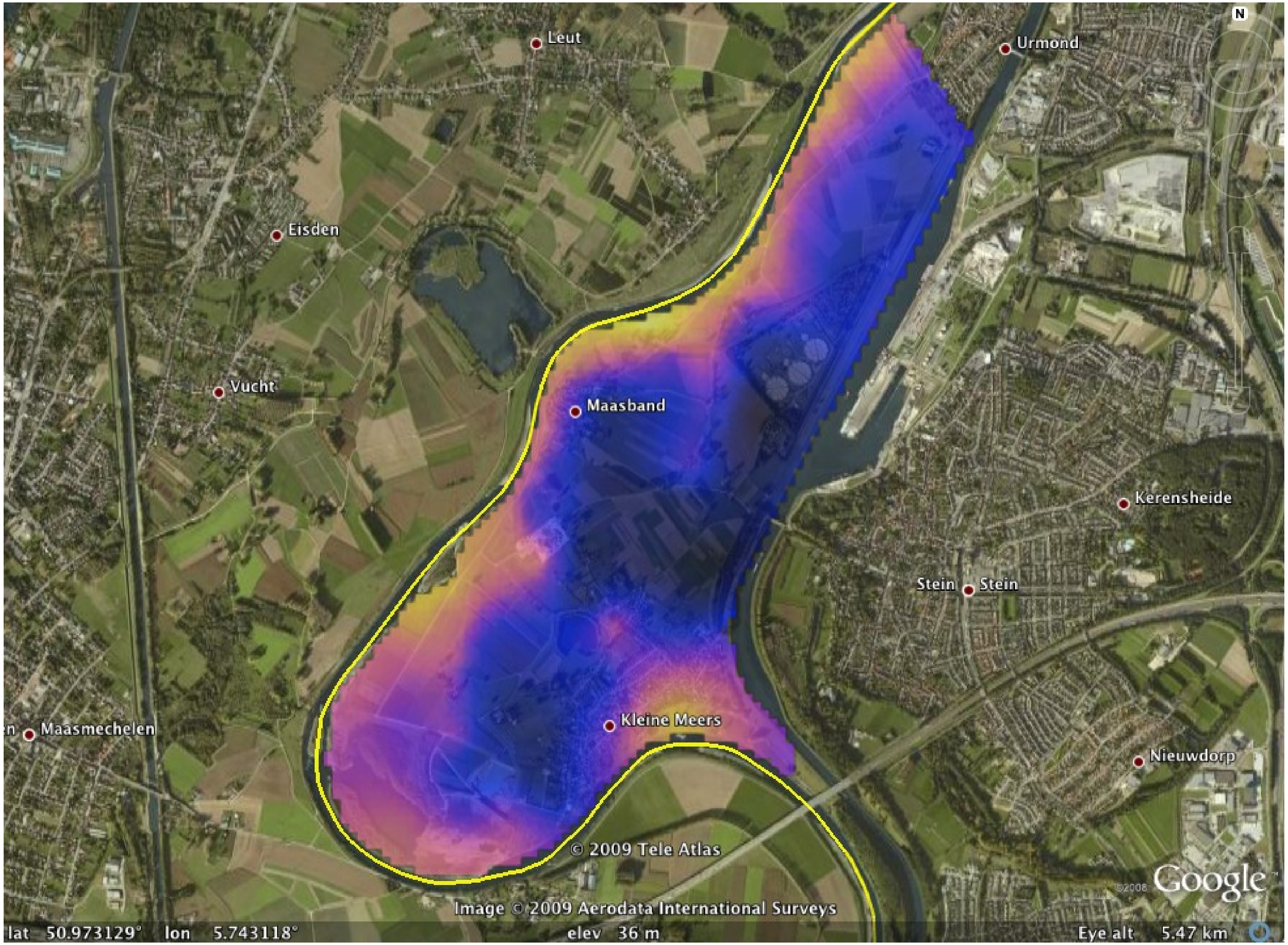
- `readGDAL`; `writeGDAL`: Read/write between GDAL grid maps and Spatial objects
- `readOGR`, `writeOGR`: Read/write spatial vector data using OGR (including **KML** for Google Earth)
  - OGR: C++ open source library providing read (and sometimes write) access to a variety of **vector file formats** including ESRI Shapefiles, S-57, SDTS, PostGIS, Oracle Spatial, and Mapinfo mid/mif and TAB formats

[1] `http://www.gdal.org/`

Example Google Earth layers created with `writeOGR`




zinc: 1672
Directions: To here - From here
Google
Image © 2009 Aerodata International Surveys
lat 50.963207° lon 5.745043°
elev 40 m
2005
Eye alt 459 m


Leut
Urmond
Eisden
Vucht
Maasband
Kerensheide
Stein
Stein
Kleine Meers
Maasmechelen
Nieuwdorp
© 2009 Tele Atlas
Image © 2009 Aerodata International Surveys
Google
lat 50.973129° lon 5.743118°
elev 36 m
Eye alt 5.47 km

Projections

Until a projection is defined, the coördinates are just numbers; they are not related to the Earth's surface. This can be useful for "spatial" analysis of non-Earth objects, e.g. an image from a microscope.

For true geographic analysis, the object must be related to the Earth's figure.

Then true **distances** and **azimuths** can be computed.

The CRS method

sp uses the CRS (Coördinate Reference System) method of the rgdal package to interface with the **proj.4** cartographic projection library from the USGS[2].

For example, to specify the datum, elipsoid, projection, and coördinate system of the Dutch Rijksdriehoek (RDH) system:

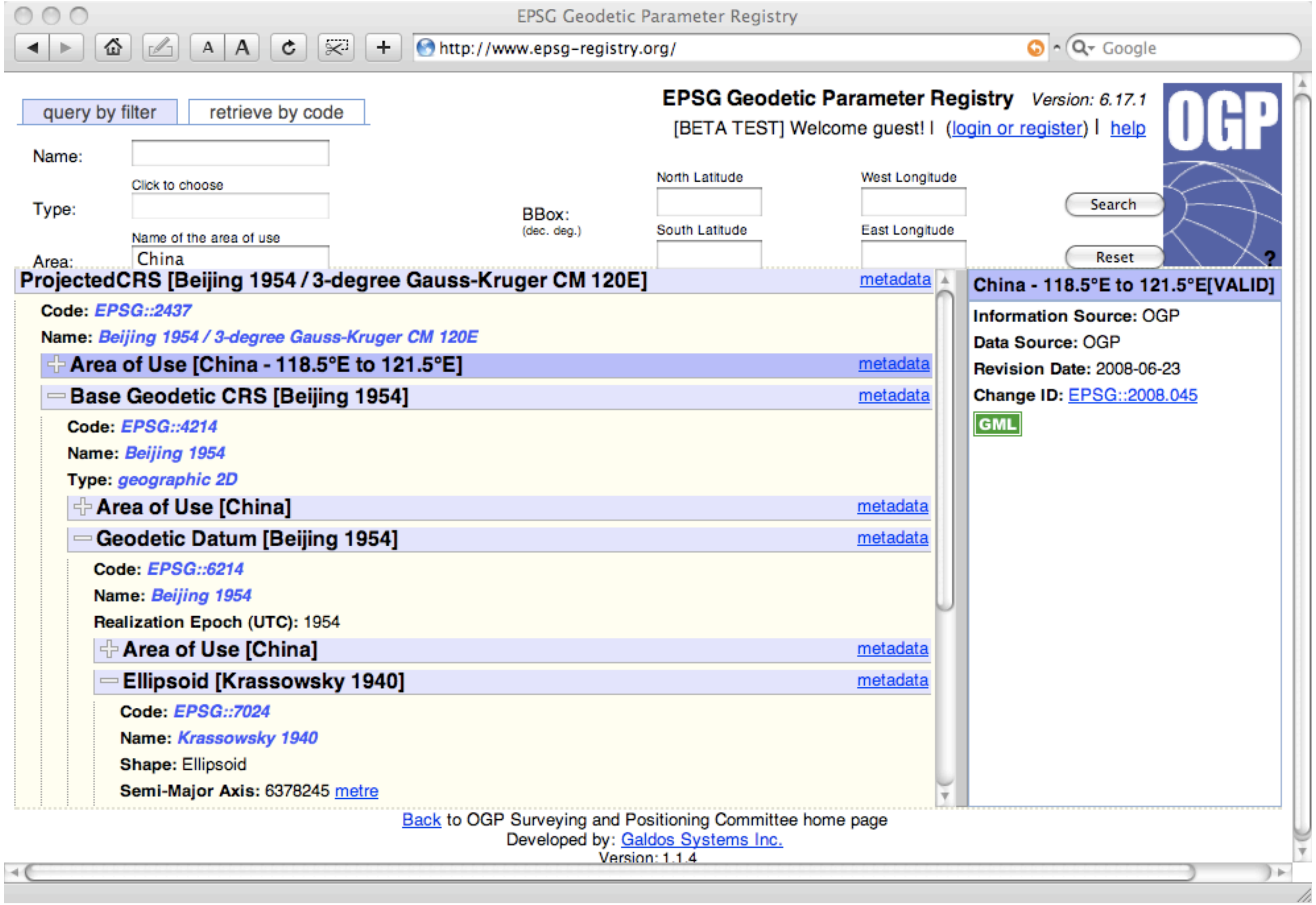
```
> proj4string(meuse) <- CRS("+proj=stere
+     +lat_0=52.15616055555555 +lon_0=5.38763888888889
+     +k=0.999908 +x_0=155000 +y_0=463000
+     +ellps=bessel +units=m +no_defs
+     +towgs84=565.2369,50.0087,465.658,
+       -0.406857330322398,0.350732676542563,-1.8703473836068,
+       4.0812")
```

Most systems are included in the European Petroleum Survey Group (**EPSG**) database[3], in which case just the system's numbrer in that database is enough to specify it:

```
> proj4string(meuse) <- CRS("+init=epsg:28992")
```

[2] http://trac.osgeo.org/proj/
[3] http://www.epsg.org/

On-line EPSG database



(also available as MS-Access 97 off-line database)

The gstat package

- R implementation of the stand-alone **gstat** package for geostatistics
- Author and maintainer Edzer Pebesma
  - mostly developed at Physical Geography, University of Utrecht (NL)
  - since Oct 2007 at Institute for Geoinformatics, University of Münster (D)
- 1992 – 2010 and still going strong
- Purpose: "**modelling**, **prediction** and **simulation** of geostatistical data in one, two or three dimensions"
- Highly-developed suite of tools with rich analytical possibilities; uses the `sp` spatial data structures

There are other R packages with largely overlapping aims but with different philosophies and interfaces (notably, `geoR` and `spatial`).

Modelling

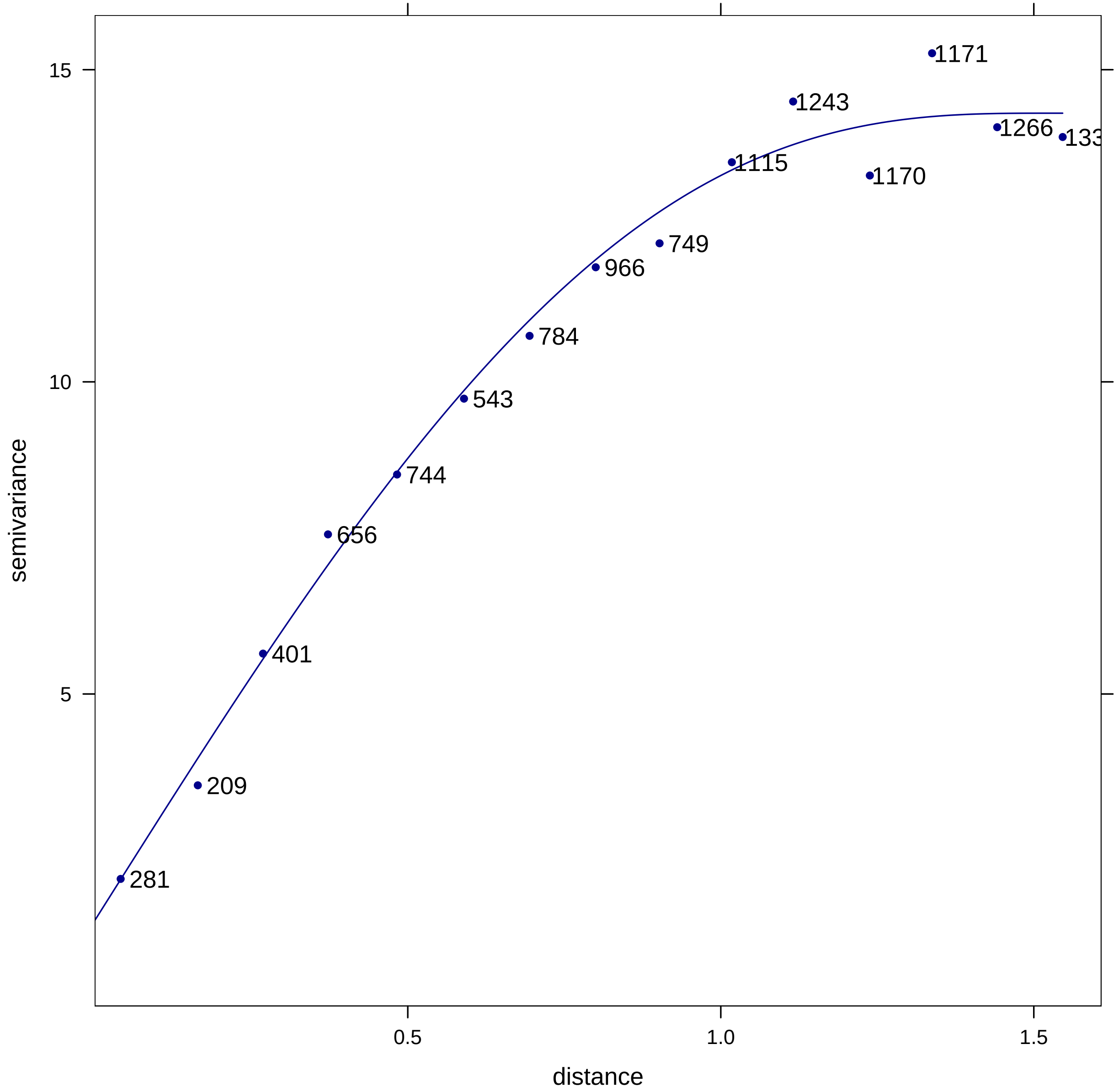
- `variogram`: Compute **experimental variograms** (also directional, residual)
  * User-specifiable cutoff, bins, anisotropy angles and tolerances
  * Can use Matheron or robust estimators
  * Optional argument to produce a **variogram cloud** (all point-pairs)
  * Optional argument to produce a **directional variogram surface** ("map")
- `vgm`: specify a **theoretical variogram model** for an empirical variogram
  * Many authorized models
  * Can specify models with **multiple structures**
- `fit.variogram`: least-squares adjustment of a variogram model to the empirical model
  * User-selectable fitting criteria
  * Can also use restricted maximum likelihood `fit.variogram.reml`
- `fit.lmc`: fit a linear model of **coregionaliztion** (for cokriging)

The gstat method

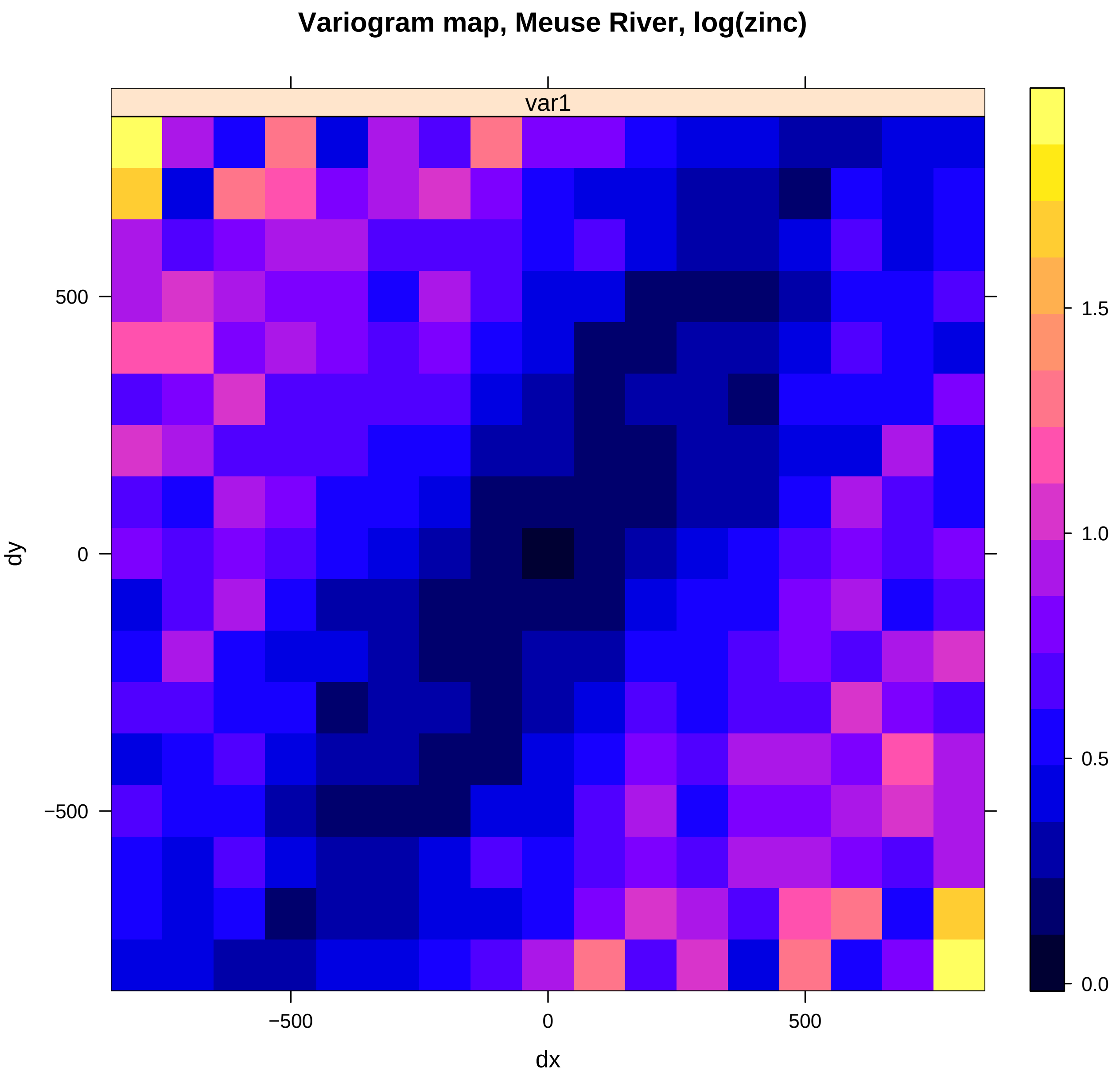
More complicated procedures must be specified with the general `gstat` method.

Example: **cokriging**

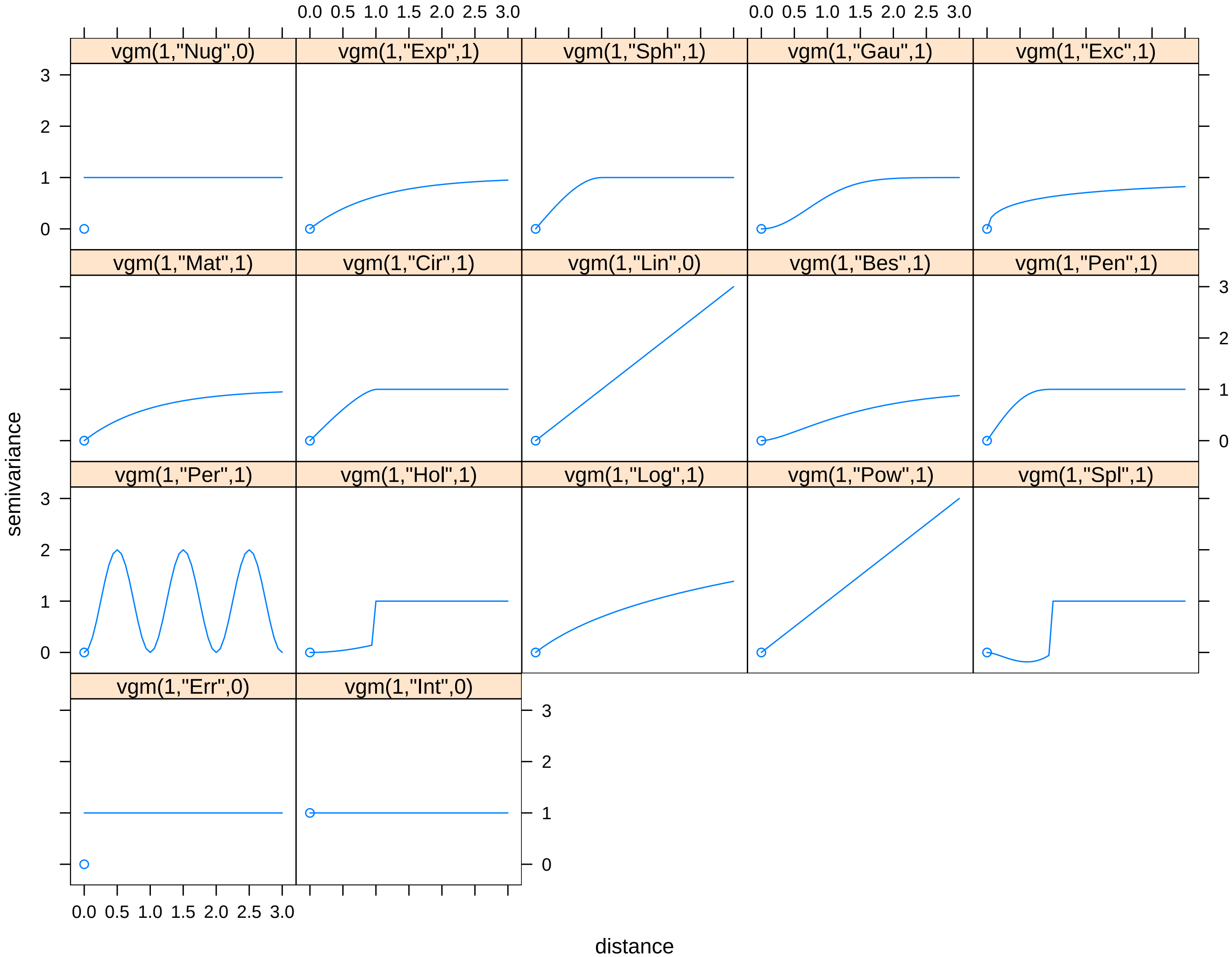
Experimental variogram and fitted model



Variogram map



Authorized models



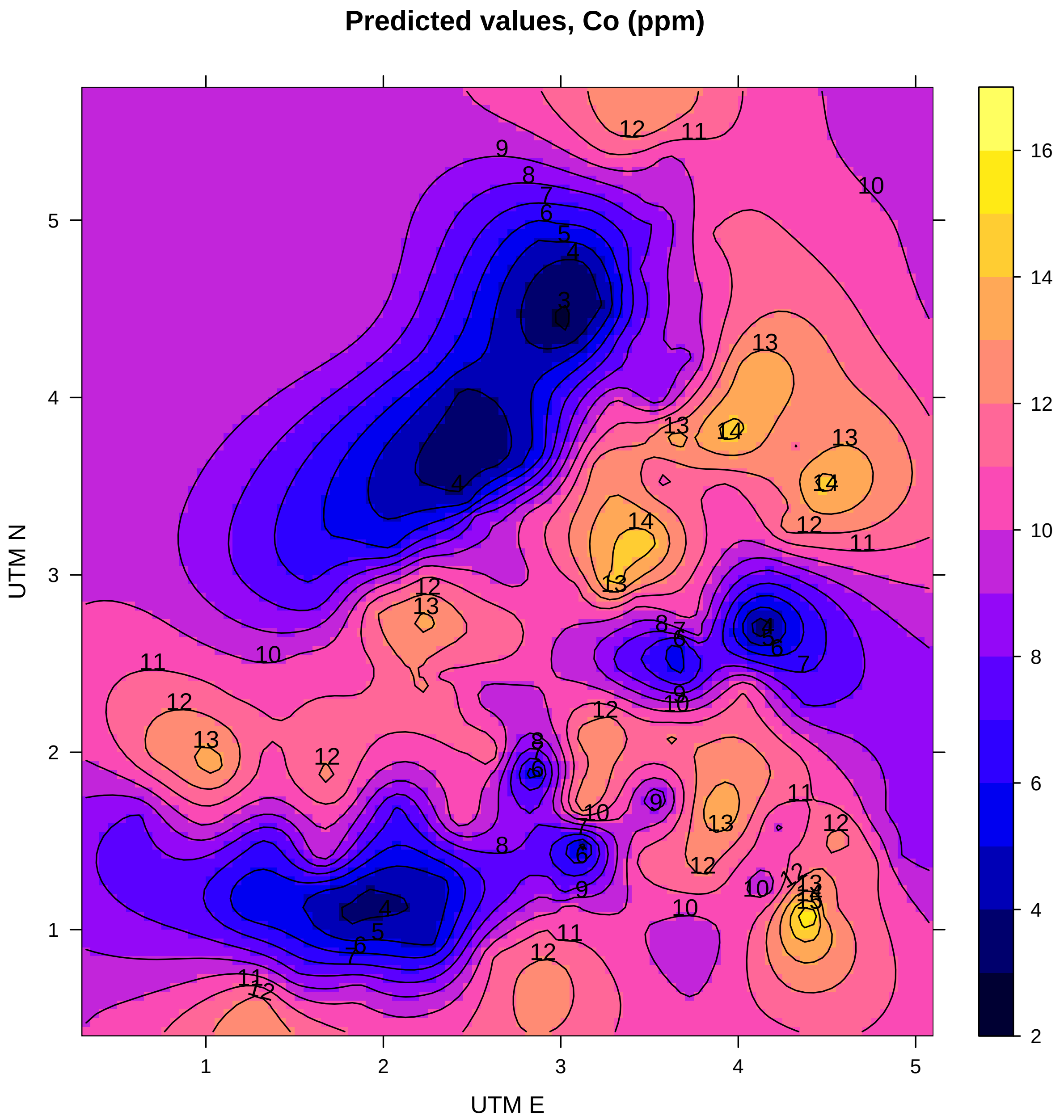
Prediction

- `krige`: Kriging prediction
  - Simple (known spatial mean)
  - Ordinary (spatial mean must be estimated also)
  - Universal, KED (geographic trend or feature-space model)
  - global or in local neighbourhood
  - at points or integrated over blocks

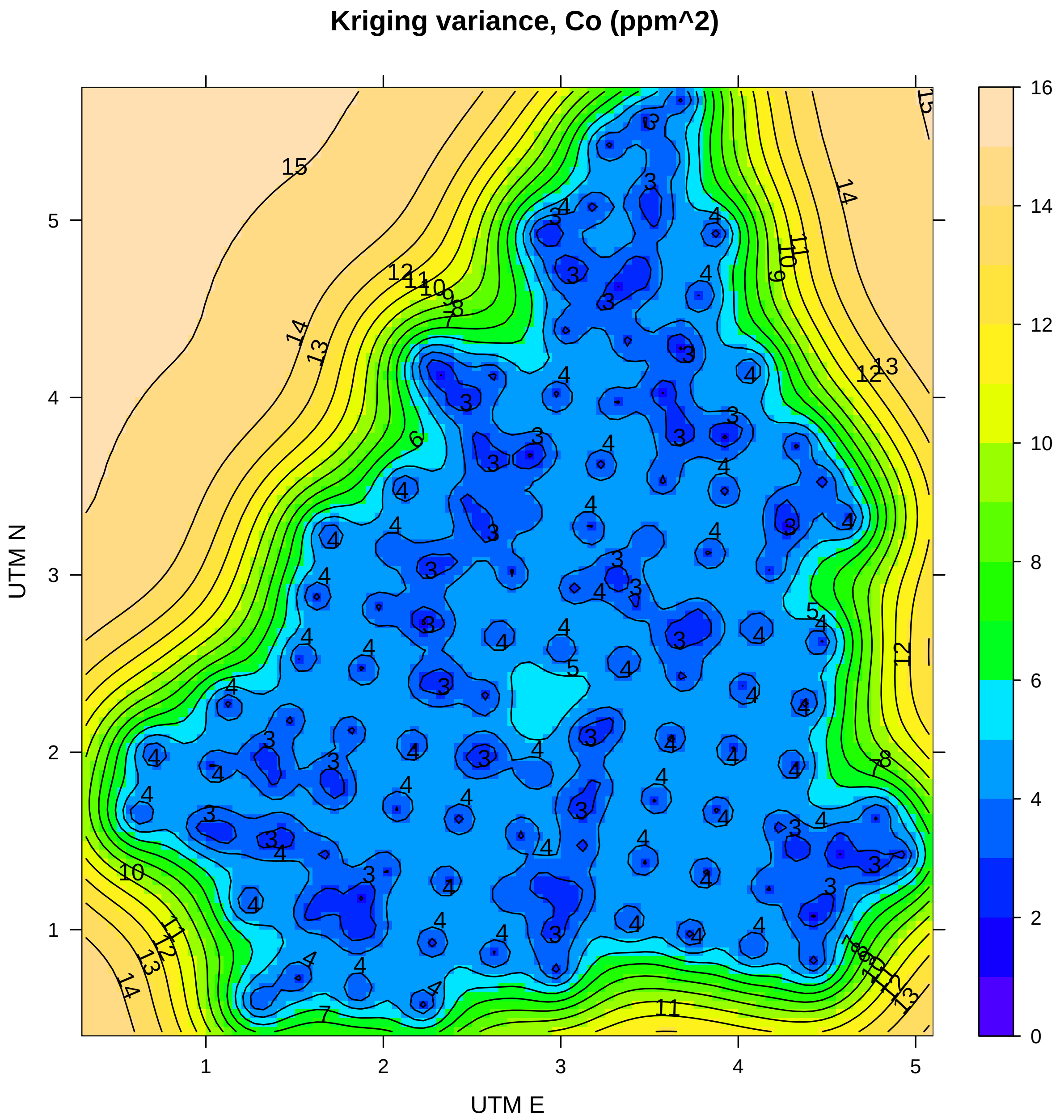
- `idw`: Inverse distance prediction (user-specified power)

- `predict.gstat`: trend surfaces, cokriging

Kriging prediction

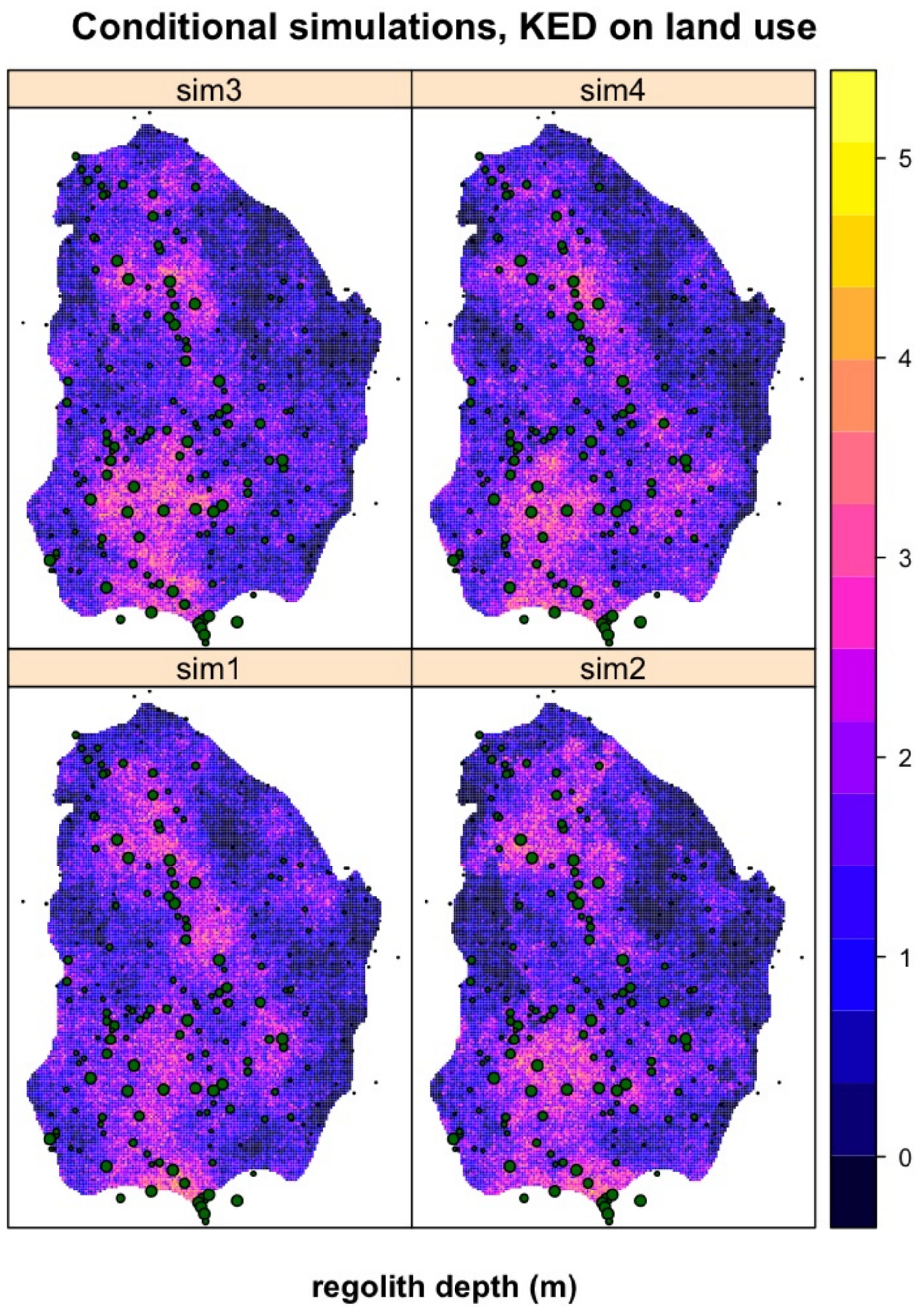


Kriging prediction variance



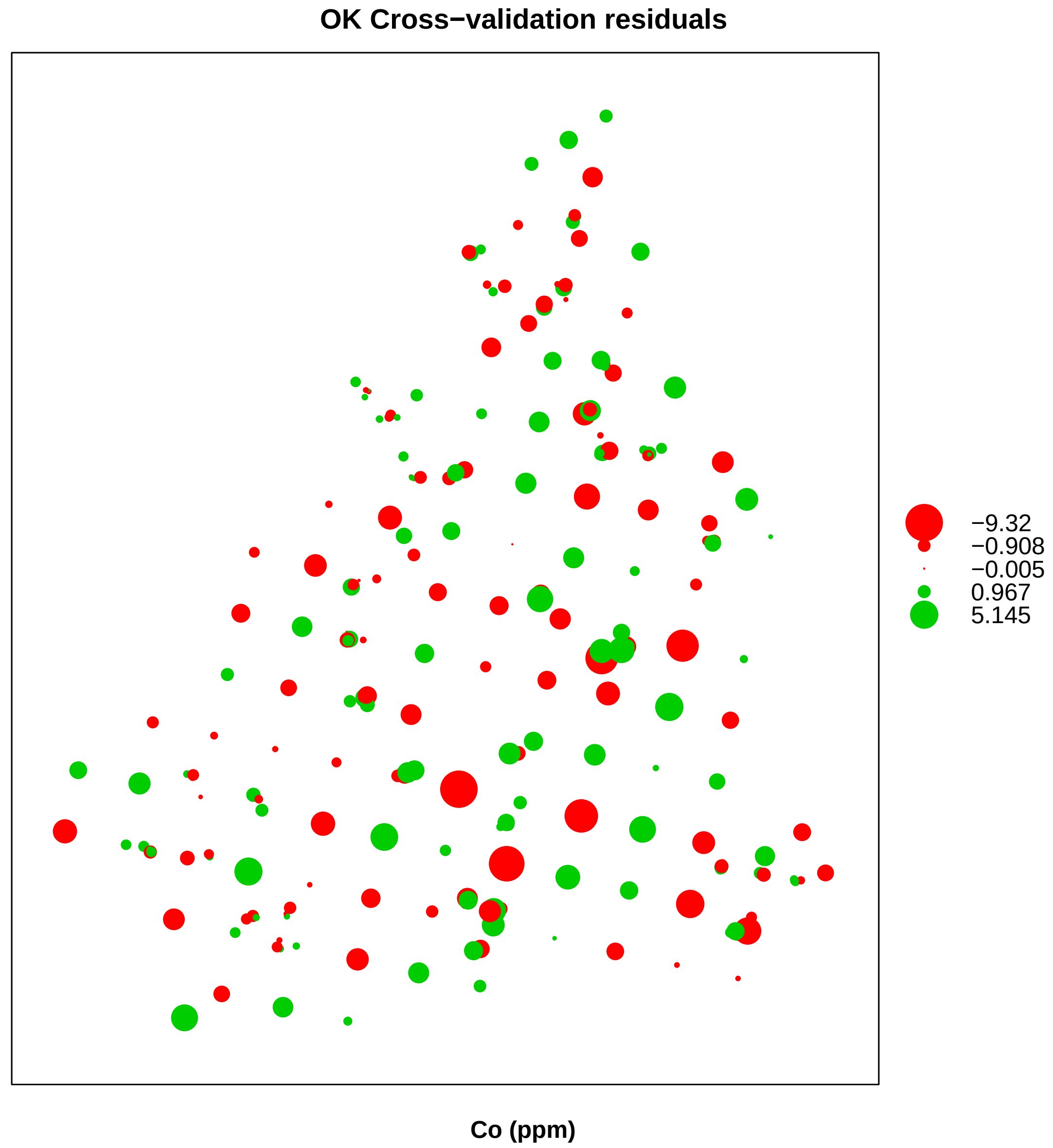
Simulation

- `krige`: optional arguments to specify **conditional** or **unconditional** simulation with a known variogram model
- Shows possible states of nature, given the known data and the fitted model
- More realistic spatial picture than the (smooth) kriged result
- Often used in distributed models


Conditional simulations, KED on land use
sim3
sim4
sim1
sim2
5
4
3
2
1
0
regolith depth (m)

Validation

- `krige.cv`, `gstat.cv`: n-fold **cross-validation**, including leave-one-one cross-validation (LOOCV).

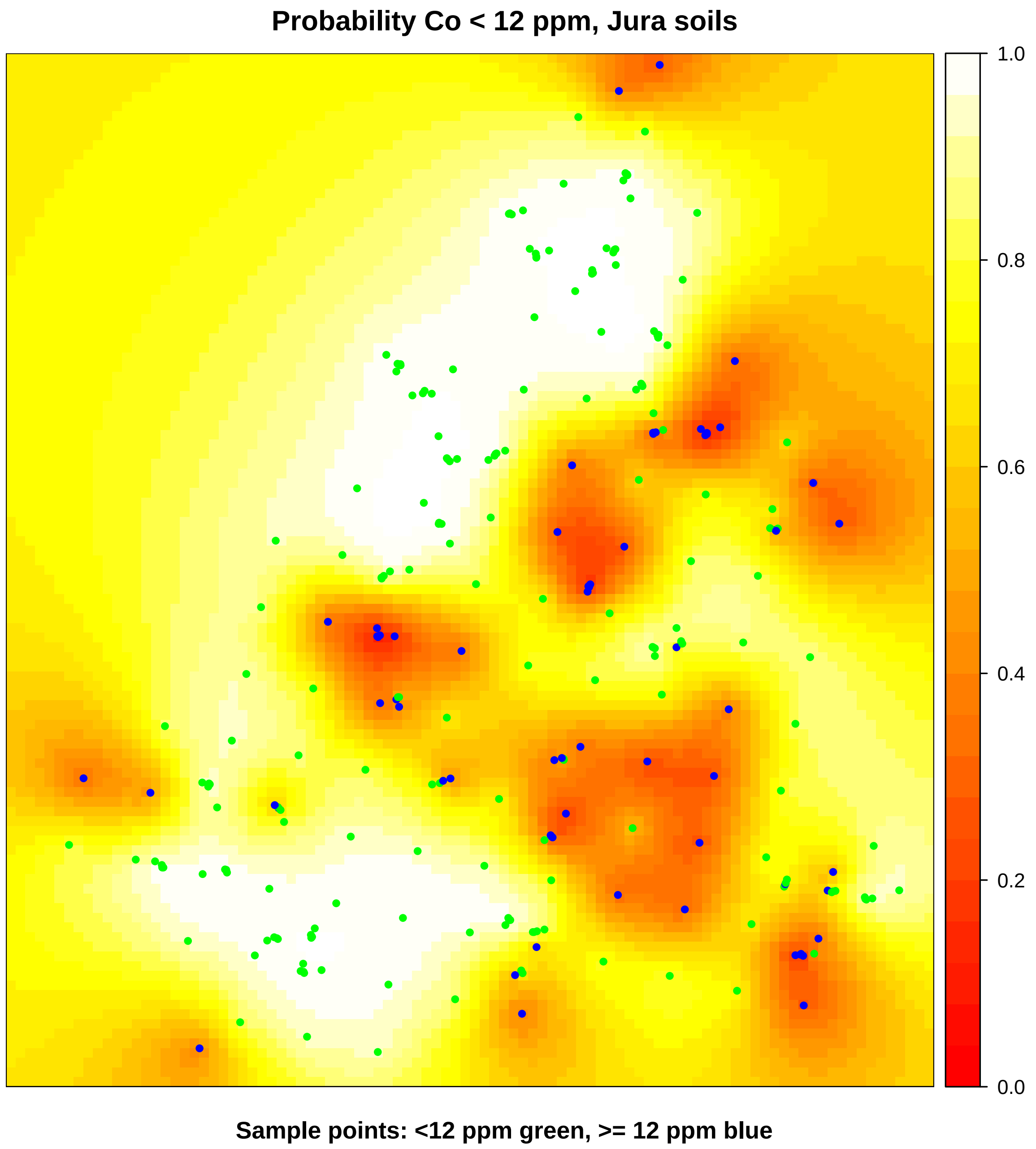


Leave-one-out cross-validation (LOOCV) residuals

Non-parametric methods

- All methods can be applied to **indicators** (0/1, T/F, Y/N)
- It is possible to treat the indicators are **coregionalized** variables

Indicator Kriging prediction



A typical analysis

```
> # load an example dataset into the workspace
> data(meuse)
> # convert it to a spatial object
> coordinates(meuse) <- ~ x + y
> # compute the default experimental variogram
> v <- variogram(log(lead) ~ 1, meuse)
> # plot the variogram and estimate the model by eye
> plot(v)
> vm <- vgm(0.5, "Sph", 1000, 0.1)
> plot(v, model=vm)
> # fit the model with the default automatic fit
> (vmf <- fit.variogram(v, vm))
> # load a prediction grid
> data(meuse.grid)
> #  convert it to a spatial object
> coordinates(meuse.grid) <- ~ 1
> # predict on the grid by Ordinary Kriging
> ko <- krige(log(lead) ~ 1, meuse, newdata=meuse.grid, model=vmf)
> summary(ko)
> # plot the map
> spplot(ko, zcol="var1.pred")
> # leave-one-out cross-validation
> kcv <- krige.cv(log(lead) ~ 1, meuse, model=vmf)
> summary(kcv)
```

Output from modelling and prediction

```
  model    psill  range
1   Nug 0.051563   0.00
2   Sph 0.515307 965.15

[using ordinary kriging]

Object of class SpatialPointsDataFrame
Coordinates:
     min    max
x 178460 181540
y 329620 333740
Number of points: 3103
  var1.pred       var1.var
 Min.   :3.67   Min.   :0.083
 1st Qu.:4.23   1st Qu.:0.125
 Median :4.56   Median :0.145
 Mean   :4.65   Mean   :0.164
 3rd Qu.:5.08   3rd Qu.:0.185
 Max.   :6.30   Max.   :0.422
```

Output from cross-validation

```
Object of class SpatialPointsDataFrame
Coordinates:
     min    max
x 178605 181390
y 329714 333611
Number of points: 155
   var1.pred       var1.var         observed        residual                zscore
 Min.   :3.73   Min.   :0.107   Min.   :3.61   Min.   :-1.036486   Min.   :-2.555439
 1st Qu.:4.37   1st Qu.:0.140   1st Qu.:4.28   1st Qu.:-0.213458   1st Qu.:-0.527381
 Median :4.82   Median :0.157   Median :4.81   Median :-0.011006   Median :-0.027213
 Mean   :4.81   Mean   :0.166   Mean   :4.81   Mean   :-0.000381   Mean   :-0.000285
 3rd Qu.:5.20   3rd Qu.:0.178   3rd Qu.:5.33   3rd Qu.: 0.186346   3rd Qu.: 0.468856
 Max.   :6.10   Max.   :0.467   Max.   :6.48   Max.   : 1.619113   Max.   : 4.028651
```

Conclusion

- A **disadvantage** of working in R is the lack of interactive graphical analysis (e.g. in ArcGIS Geostatistical Analyst)

- The main **advantage** of doing spatial analysis in R is that the full power of the R environment (data manipulation, non-spatial modelling, user-defined functions, graphics . . .) can be brought to bear on spatial analyses

- The advantages of R (**open-source**, **open environment**, packages contributed and vetted by statisticians) apply also to spatial analysis