

Spatio-temporal statistics (MATH4341)

Michaelmas term

‘Spatial statistics’

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Concepts

An introduction to spatial statistics:

- Regionalised statistical concepts
- Point pattern data analysis
- Point referenced data analysis
- Implementation in R
- Aerial unit data analysis



Lecture notes

1. Lecture notes part 1: Types of spatial data and modelling
2. Lecture notes part 2: Point referenced data modeling / Geostatistics
3. Lecture notes part 3: Aerial unit data / spatial data on lattices
4. Lecture notes part 4: Spatial point pattern modeling

Reading list

These lecture Handouts have been derived based on the above reading list.

Main textbooks (methods, implementation, and theory):

- Cressie, N. (2015). Statistics for spatial data. John Wiley & Sons.
- Kent, J. T., & Mardia, K. V. (2022). Spatial analysis (Vol. 72). John Wiley & Sons.
- Gaetan, C., & Guyon, X. (2010). Spatial statistics and modeling (Vol. 90). New York: Springer.
- Moller, J., & Waagepetersen, R. P. (2003). Statistical inference and simulation for spatial point processes. CRC press.

Main textbooks (software):

- Bivand, R. S., Pebesma, E. J., Gómez-Rubio, V., & Pebesma, E. J. (2008). Applied spatial data analysis with R (Vol. 747248717, pp. 237-268). New York: Springer.
- Moraga, P. (2023). Spatial statistics for data science: theory and practice with R. CRC Press.

Supplementary textbooks (methods, implementation, and theory):

- Banerjee, S., Carlin, B. P., & Gelfand, A. E. (2014). Hierarchical modeling and analysis for spatial data. CRC press.
- Ripley, B. D. (2005). Spatial statistics. John Wiley & Sons.
- Schabenberger, O., & Gotway, C. A. (2005). Statistical methods for spatial data analysis. CRC press
- Wackernagel, H. (2003). Multivariate geostatistics: an introduction with applications. Springer Science & Business Media.
- Diggle, P. J. (2013). Statistical analysis of spatial and spatio-temporal point patterns. CRC press.
- van Lieshout, M. N. M. (2019). Theory of spatial statistics: a concise introduction. CRC Press.

Lecture notes part 1: Types of spatial data

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Aim. To introduce the types of spatial statistical data. To get a general idea about spatial statistics modeling.

Reading list & references:

- Cressie, N. (2015). Statistics for spatial data. John Wiley & Sons.
– Chapter 1: pp 1- 28

1. MOTIVATIONS

Note 1. Researchers in diverse areas such as geology, soil science, image processing, epidemiology, crop science, ecology, forestry, astronomy, atmospheric science, climatology, ecology, environmental health, and real estate marketing are increasingly faced with the task of analyzing data that are geographically referenced, and often presented as maps.

Note 2. In several problems, the data have a space (and time) label associated with them; this gives the motivation for the development and analysis of (not necessarily statistical) models that indicate whether there is dependence between measurements at different locations.

Note 3. In an epidemiological investigation, for instance, one might wish to analyze lung, breast, colorectal, and cervical cancer rates by county and year in a particular state, with smoking, mammography, and other important screening and staging information also available at some level. Public health professionals who collect such data are charged not only with surveillance, but also statistical inference tasks, such as modeling of trends and correlation structures, estimation of underlying model parameters, hypothesis testing (or comparison of competing models), and prediction of observations at unobserved locations (and times).

Note 4. Spatial statistics is the branch of statistics that focuses on the analysis and modeling of data with inherent spatial relationships, by accounting for spatial dependencies and patterns to derive meaningful insights and make informed decisions.

Shall I ignore spatial dependence? –No!

Note 5. Galton's problem (1888) arises in spatial statistics and cross-cultural research when observations are not statistically independent due to external dependencies like borrowing or common descent. For example, if two neighboring cultures share similar traits, it might

be due to cultural borrowing rather than independent development. This autocorrelation can lead to misleading conclusions if not properly accounted.

Note 6. From your experimental design lectures, recall R. A. Fisher's principles of randomization, blocking and replication to neutralize (not remove) spatial dependence. In his agricultural studies, he noticed that "After choosing the area we usually have no guidance beyond the widely verified fact that patches in close proximity are commonly more alike, as judged by the yield of crops, than those which are further apart." To avoid the "confounding" of treatment effect Fisher properly introduced randomization, namely the controlled introduction of uncertainty.

Note 7. The First Law of Geography, according to Waldo Tobler, is "*everything is related to everything else, but near things are more related than distant things.*" Perhaps, we can paraphrase it by using stats terms to "nearby attribute values are more statistically dependent than distant attribute values".

Example 8. ¹Consider a random sample $\{Z_i \in \mathbb{R}; i = 1, \dots, n\}$ jointly following a Normal distribution with unknown $E(Z_i) = \mu$ and known $\text{Var}(Z_i) = \sigma^2$.

Iid assumption: Assumption that the observables $\{Z_i\}$ are independent. This is equivalent to iid model $Z_i = \mu + \epsilon_i$ with $\epsilon_i \stackrel{\text{iid}}{\sim} N(0, \sigma^2)$.

AR assumption: Assumption that the observables $\{Z_i\}$ are positively autocorrelated as $\text{Cov}(Z_i, Z_j) = \sigma^2 \rho^{|i-j|}$ with known $\rho \in (0, 1)$. This is equivalent to AR model $Z_i = \rho Z_{i-1} + \epsilon_i$ with $\epsilon_i \stackrel{\text{iid}}{\sim} N(0, \sigma^2(1 - \rho^2))$.

Consider the case that the observables $\{Z_i\}$ are positively autocorrelated. Assume You fail to realize the presence of positive correlation in the data and You use the i.i.d model instead.

(1) Effect on parametric estimation of μ

The BLUE of μ is

$$(1.1) \quad \hat{Z} = \bar{Z} = \frac{1}{n} \sum_{i=1}^n Z_i$$

¹No need to worry how the equations are produced.

If the observables were iid then $\text{Var}(\hat{Z}|\text{iid obs}) = \frac{\sigma^2}{n}$ Since the observables are positively autocorrelated

$$(1.2) \quad \begin{aligned} \text{Var}(\hat{Z}|\text{AR obs}) &= \frac{1}{n} \sum_{i=1}^n \sum_{j=1}^n \text{Cov}(Z_i, Z_j) \\ &= \frac{\sigma^2}{n} \overbrace{\left(1 + 2 \frac{\rho}{1-\rho} \left(1 - \frac{1}{n} \right) - \frac{2}{n} \left(\frac{\rho}{1-\rho} \right)^2 \frac{1-\rho^{n-1}}{2} \right)}^{\tau_{n,\rho}=} \end{aligned}$$

If $n = 10$, and $\rho = 0.26$, the $1 - \alpha = 95\%$ confidence interval for μ is

$$\left\{ \bar{Z} \pm q_{\frac{\alpha}{2}} \sqrt{\text{Var}(\hat{Z}|\text{assump.})} \right\} \Rightarrow \begin{cases} \bar{Z} \pm \overbrace{1.96}^{q_{0.95} = \frac{1.96}{2}} \frac{\sigma}{\sqrt{10}} & \text{in i.i.d assum.} \\ \bar{Z} \pm \underbrace{2.485}_{= q_{0.95} \sqrt{\tau_{10,0.26}}} \frac{\sigma}{\sqrt{10}} & \text{in AR assum.} \end{cases}$$

as $\sqrt{\tau_{10,0.26}} = 1.608$. Hence, if we fail to realize the presence of positive autocorrelation in the observables and wrongly the i.i.d model, the resulted confidence interval would be too narrow since the actual coverage probability is $\Phi(2.485) - \Phi(-2.485) = 87.5\%$ instead of 95%.

By re-writing the variance (1.2) as $\text{Var}(\hat{Z}) = \frac{\sigma^2}{n'}$ with

$$n' = 1 + 2 \frac{\rho}{1-\rho} \left(1 - \frac{1}{n} \right) - \frac{2}{n} \left(\frac{\rho}{1-\rho} \right)^2 \frac{1-\rho^{n-1}}{2},$$

we intuitively understand that the effect of the positive spatial correlation is that the equivalent independent observations in the above dataset with size n is n' (i.e. $n' \approx n \frac{1-\rho}{1+\rho}$, for large n). If $n = 10$, and $\rho = 0.26$, then $n' = 6.2$.

(2) Effect on predictive estimation of Z_{n+1}

Under the i.i.d. model, the predictor minimizing the MSPE for the next outcome Z_{n+1} is $\hat{Z}_{n+1}^{\text{iid}} = \bar{Z}$ and has

$$\text{MSPE}(\hat{Z}_{n+1}^{\text{iid}}|\text{ind obs}) = \sigma^2 \left(1 + 2 \frac{\rho}{1-\rho} \left(\rho^n - \frac{1}{n} \right) - 2 \left(\frac{\rho}{1-\rho} \right)^2 \frac{1-\rho^{n-1}}{2} \right)$$

Under the AR model the predictor minimizing the mse of the next outcome Z_{n+1} is

$$\hat{Z}_{n+1}^{\text{AR}} = \rho Z_n + (1-\rho) \frac{Z_1 + (1-\rho) \sum_{i=2}^{n-1} Z_i + Z_n}{n - (n-2)\rho}$$

with MSPE

$$\text{MSPE} \left(\hat{Z}_{n+1}^{\text{AR}} | \text{dep obs} \right) = \sigma^2 \left(1 - \rho^2 \frac{(1 + \rho)(1 - \rho)^2}{n - (n - 2)\rho} \right)$$

Note that the relative efficiency of this mistake is not too bad, e.g. for $n = 10$ and $\rho = 0.26$

$$\text{RE} = \frac{\text{MSPE} \left(\hat{Z}_{10+1}^{\text{AR}} | \text{dep obs} \right)}{\text{MSPE} \left(\hat{Z}_{10+1}^{\text{iid}} | \text{ind obs} \right)} = \frac{1.01952}{1.1} \approx 1.$$

However, if I consider large datasize $n \rightarrow \infty$ the asymptotic relative efficiency is

$$\text{ARE} = \lim_{n \rightarrow \infty} \frac{\text{MSPE} \left(\hat{Z}_{n+1}^{\text{AR}} | \text{dep obs} \right)}{\text{MSPE} \left(\hat{Z}_{n+1}^{\text{iid}} | \text{ind obs} \right)} = \dots = 1 - \rho^2 \approx \begin{cases} 93\% & , \rho = 0.26 \\ 75\% & , \rho = 0.5 \end{cases}$$

Spatial data and spatial process.

Note 9. In spatial statistics, the basic components are data $\{Z_1, \dots, Z_n\}$ observed at spatial locations $\{s_1, \dots, s_n\}$ correspondingly. Classically, the locations are 2D, $s \in S \subset \mathbb{R}^2$, however it can be $S \subset \mathbb{R}^1$ (such as in chromatography applications), or $S \subset \mathbb{R}^3$ (such as in earth science, 3D imaging, etc) depending on the application.

Note 10. Even more exotically, the spatial domain S does not necessarily need to be a Euclidean space (which our course will focus) such as $S \subset \mathbb{R}^d$, $d = 1, 2, 3, \dots$ but any topological space, eg sphere (recall Earth is round...).

Note 11. The locations $s_i \in S$ can be considered either (i.) fixed and hence used for training or (ii.) uncertain/random and hence a quantity for inference. Yet, $\{s_i\}$ can be arranged irregularly in the space or regularly in a grid. Data $Z_i = Z(s_i)$ are random vectors.

Note 12. Let $s \in \mathbb{R}^d$ be a generic data location, and suppose the datum $Z(s)$ at spatial location s is an uncertain and hence random vector. Considering s to vary over index set $S \subset \mathbb{R}^d$ imposes a spatial random process (or multivariate random field)

$$\{Z(s); s \in S\}$$

which can be modeled as a random function / stochastic process (to be defined later.).

Note 13. In spatial problems, spatial data $\{Z_{s_i}\}_{i=1}^n$ at locations $\{s_i\}_{i=1}^n$ are assumed to be realizations of a spatial process (or a multivariate random field)

$$(1.3) \quad \{Z(s); s \in S\},$$

indexed by a spatial set $S \subset \mathbb{R}^d$.

2. PRINCIPAL SPATIAL STATISTICS AREAS

Note 14. We can characterize the spatial statistical problems according to the type of measurement, their specified (assumed) stochastic generating mechanism, and the choice of the spatial locations. In principle, each of them is associated to different motivations, statistical/scientific problems, statistical tools, however, modern applications/problems may involve characteristics from any combination of them.

Note 15. Here, we will study three of spatial statistical areas corresponding to point referenced data, aerial unit data, and point patterns.

2.1. Point referenced data / Geostatistics.

Note 16. Climate or environmental data are often presented in the form of a map, for example the maximum temperatures on a given day in a country, the concentrations of some pollutant in a city or the mineral content in soil. In mathematical terms, such maps can be described as realizations of a random function (random field/stochastic process); that is, an ensemble of random quantities indexed by points in a region of interest. The aim is usually interpolation, and the associated statistical inference.

Note 17. Such data were first analyzed in geological sciences. Hence, for historical reasons, this area of spatial statistics is often called Geostatistics and the point referenced data are also called geocoded or geostatistical data.

Note 18. Mathematically speaking, the spatial domain S is a continuous fixed subset of \mathbb{R}^d that contains a d -dimensional rectangle of positive volume. The datum $Z(s)$ is a random vector (outcome) at specific location $s \in S$ which can vary continuously over domain S . In practice, the actual data are observations $\{Z_i\}_{i=1}^n$ at n (finite number) fixed locations $\{s_i\}_{i=1}^n \subset S$ such as $Z_i = Z(s_i)$. The locations $\{s_i\}$ are fixed and can be arranged irregularly in the space or regularly as a grid.

Note 19. Geostatistics aims to answer questions about modeling, identification and separation of small and large scale variations, prediction at unobserved locations and reconstruction of the spatial process $Z(\cdot)$ across the whole space S .

Example 20. (Meuse river data set) Due to pollution of the Meuse river over many years, considerable amounts of heavy metals have accumulated in the overbank sediments of the embanked floodplains of their lower river reaches. The spatial variability of metal pollution of floodplain soils, which is controlled primarily by deposition of contaminated overbank sediments during flood events is under consideration. The process governing heavy metal distribution seems that polluted sediment is carried by the river, and mostly deposited close to the river bank, and areas with low elevation.

The Meuse river R dataset `meuse{sp}` contains locations and topsoil heavy metal concentrations (such as zinc, lead, copper, and cadmium), along with a number of soil and landscape variables at the observation locations, collected in a flood plain of the river Meuse, near the village of Stein (NL). Figure 2.1 show 155 measurements of topsoil concentrations of the above heavy metals cadmium, copper, lead, and zinc collected in a flood plain of the river Meuse. Here, the locations $\{s_i\}$ are fixed and arranged irregularly as chosen by experimental design. The quantities of interest $\{(Z_i^{\text{zinc}}, Z_i^{\text{lead}}, Z_i^{\text{copper}}, Z_i^{\text{cadmium}})\}$ are the concentrations of zinc, lead, copper, and cadmium, at these locations; whose joint distribution along the flood plain of the river Meuse is of interest.

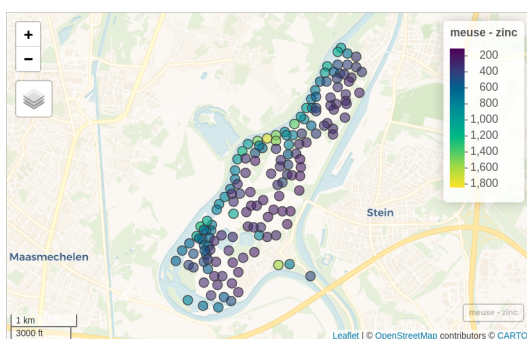
Example 21. (Coal ash dataset in Pennsylvania) Figure 2.2 shows 208 coal ash core measurements/samples collected on a regular grid of points in the Robena Mine in Greene County, Pennsylvania. The percentage of coal ash at the sampled locations is denoted by the colorbar. The sampled locations $\{s_i\}$ are fixed, and regularly spaced in a grid. As s are coordinates, they vary continuously over the spatial domain which is Robena Mine. The quantity of interest is the percentage of ash coal at these locations $\{Z(s_i)\}$. A mining engineer could be interested in predicting the ash distributions and the washability characteristics of coal along a seam in advance of mining. A spatial statistician would be able to produce a statistical model to predict ash concentrations between sampled points as well as quantify related uncertainties. Once a reasonable model that accounts for both the global trends and the local dependencies in the data is found and validated, the mining engineer could proceed to try and fill in the gaps, in other words, to estimate the percentage of coal ash at missing grid points based on the sampled percentages.

2.2. Aerial unit data / spatial data on lattices.

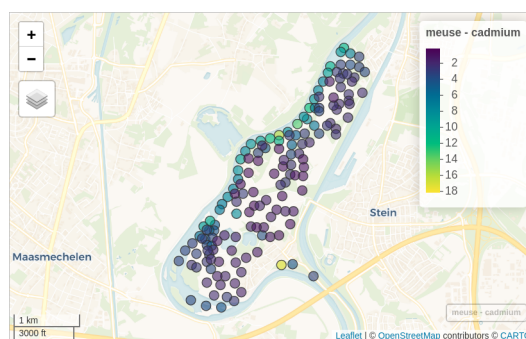
Note 22. Sometimes observations are collected over areal units such as pixels, census districts, or tomographic bins. In such cases, the random field models $\{Z(s); s \in S\}$ have a discrete index set S . The aims are usually, noise removal from an image and smoothing rather than interpolation.

Note 23. Mathematically speaking, the index set S of the data $\{Z(s)\}$ is a fixed (not random) and finite collection of points (locations) $s \in S$. The locations $s \in S$ can be irregular or arranged in a regular grid. Often, there is a natural adjacency relation or neighborhood structure. Often, datum $Z(s)$ is a random vector at location $s \in S$ and it represents an integral or average of the quantity of interest over some region represented by $s \in S$.

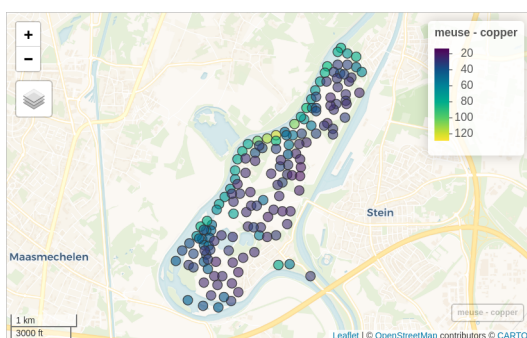
Example 24. In a UK epidemiological study, S may be the centroids of the UK counties, and $Z(s)$ may represent the average value of a characteristic in county s . In image processing,



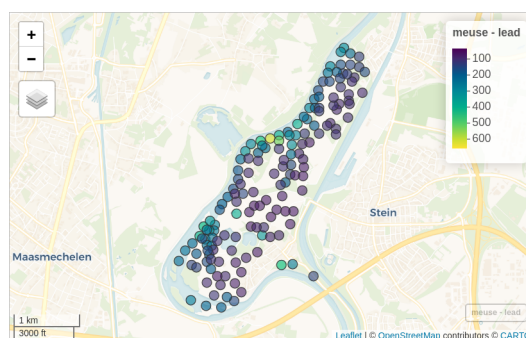
(A) zinc concentration



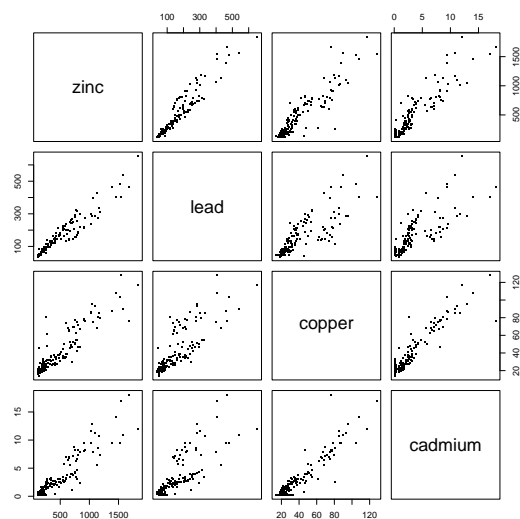
(B) cadmium concentration



(C) copper concentration



(D) lead concentration



(E) scatter plot

FIGURE 2.1. Map of the meuse dataset

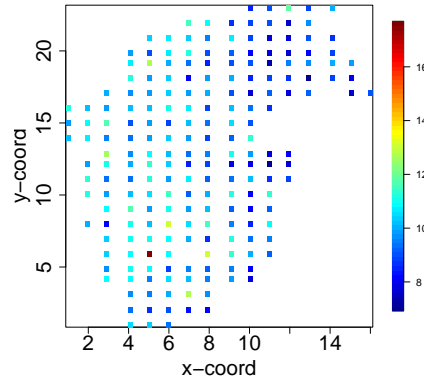


FIGURE 2.2. (Coal ash data set) Percentage of coal ash at 208 locations.

S may be a grid of pixels (locations are fixed and regular). In statistical physics, S may be a collection of atoms and genuinely finite (locations are fixed and regular).

Example 25. (Image restoration data) Figure 2.3a shows an (observed) image from a gray-scale photo-micrograph of the micro-structure of the Ferrite-Pearlite steel obtained by PNNL's project supported by DoE. The lighter part is ferrite while the darker part is pearlite. We focus our analysis on the first quarter fragment of size 240×320 pixels (red frame). This image is contaminated by noise due to the instrument errors. Interest lies in removing the noise (denoising) and recovering the real image. Figure 2.3b shows the restored image after appropriate statistical processing. Here the locations are pixels arranged in a fixed regular grid (hence discrete and not continuous). The each observation $Z(s)$ is the color of a pixel s ; here it is scalar as the observed pixels are in tones of grey, however it could be a 3D if the pixels were colored.

Example 26. (North Carolina SIDS data set) Figure 2.4a shows the total number of deaths from Sudden Infant Death Syndrome (SIDS) in 1974 for each of the 100 counties in North Carolina. Figure 2.4b shows the corresponding live births in each county and same period. This is the R data set `nc{spdep}`. The centroids of the counties do not lie on a regular grid. The sizes and shapes of the counties vary and can be quite irregular. The recorded counts are not tied to a precise location but tallied up county-wise. This kind of accumulation over administrative units is usual for privacy-sensitive data in, for instance, the crime or public health domains. A public health official could be interested in spatial patterns; e.g., whether or not there are clusters of counties with a high incidence of SIDS, or areas where the SIDS counts are higher than what would be expected based on the number of live births in the area. Perhaps, we can eyeball the figures and see that there is a higher SIDS rate in the

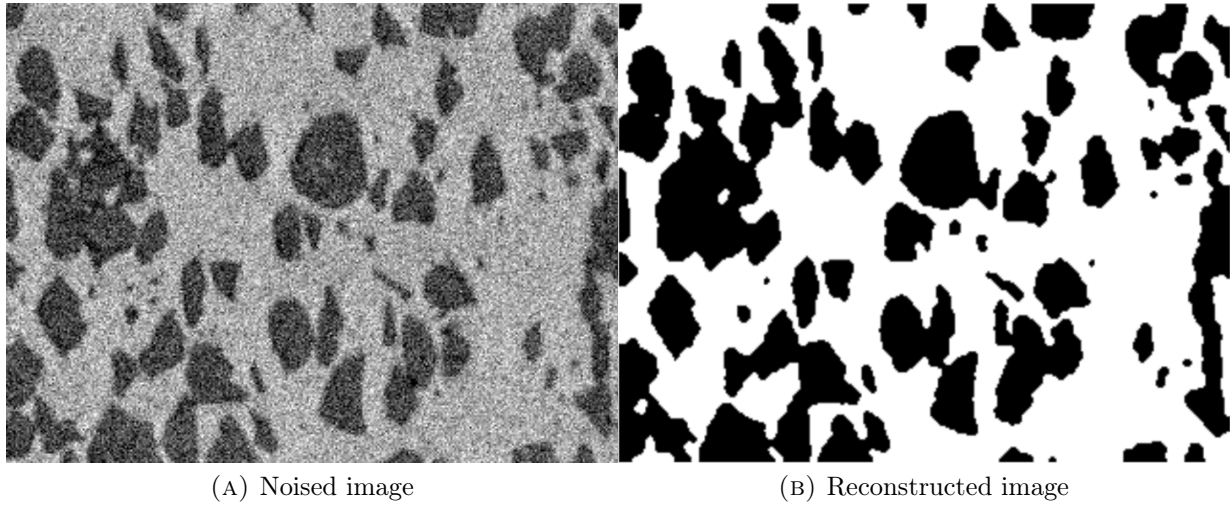


FIGURE 2.3. Ferrite-Pearlite steel image (Image restoration)

north-east areas compared to the north-west with similar birth numbers. A statistician can develop a statistical model providing inference about such questions.

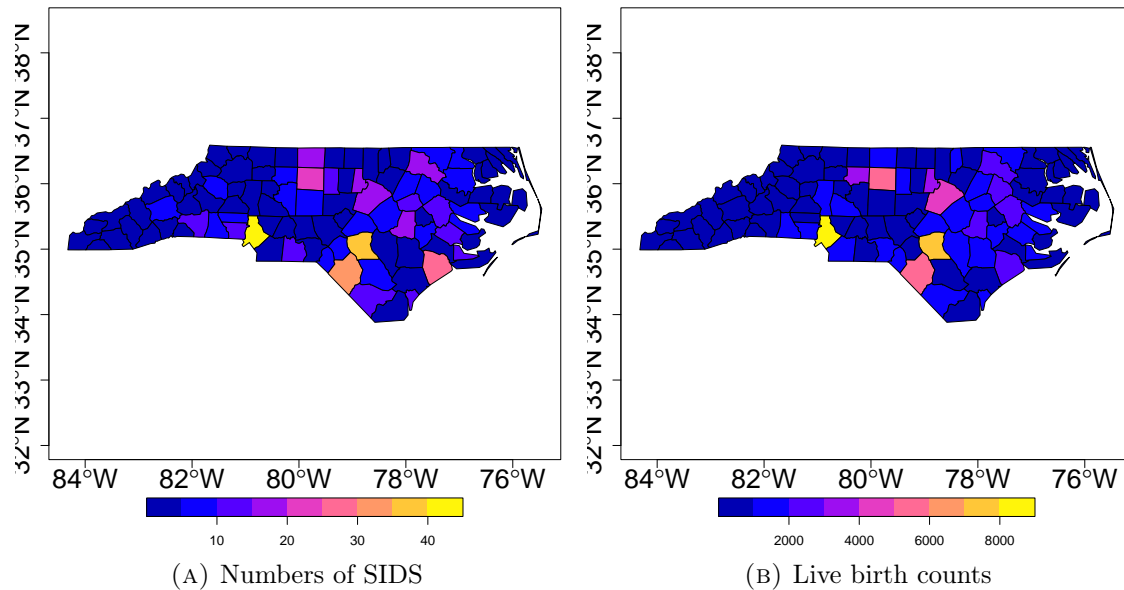


FIGURE 2.4. North Carolina SIDS data (Aerial unit data)

Example 27. (Columbus Columbus OH data set) Figures 2.5a, 2.5b, and 2.5c show the Property crime (number per thousand households) in 49 districts in Columbus in 1980, as well as the average value of the house (in 1,000 USD), and the average household income (in 1,000 USD). This is the R dataset `columbus{spdep}`. The recorded counts are not tied to a

precise household but tallied up county-wise (aerial unit) for privacy reasons. The locations $\{s_i\}$ are these areal unites; we observe they are not in a grid, and they do not have the same size or shape. Interest may lie to find whether high rates of crime are clustered in a particular areas, and if yes, perhaps what is the association of it with the value of the houses in the area.

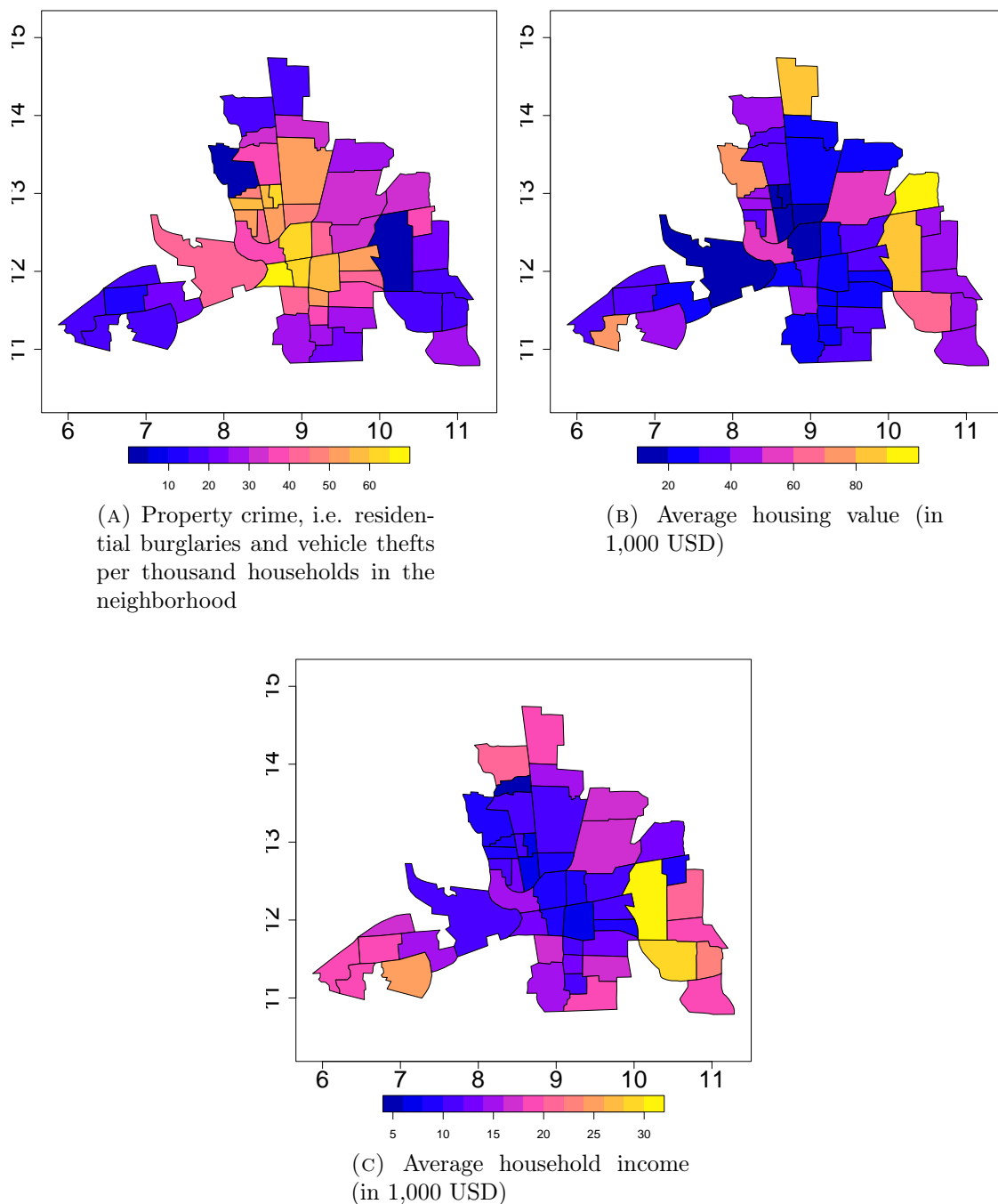


FIGURE 2.5. Columbus Columbus OH spatial analysis dataset

2.3. Spatial point patterns.

Note 28. Sometimes the locations at which events occur are random. Typical examples include locations of trees in forests, outbreaks of forest fires, or epicentres of earthquakes. Such random patterns of locations are said to form a point pattern.

Note 29. Rigorously, the spatial domain S is a random set of points; specifically a point process, in \mathbb{R}^d at which some events happened.

Note 30. In the most general case, $Z(s)$ is a random vector at location $s \in S$ (eg other covariates are associated to the location s); these covariates are called marked variables. We will refer to it as a Marked spatial point process.

Note 31. In the simplest case, no covariate for Z is specified, and hence $Z(s)$ represents only the occurrences of an even at location s , one could think of the data taking scalar values $Z(s) = 1$ or $Z(s) = 0$ when the event has occurred or not for all $s \in S$. We will refer to it as a spatial point process

Note 32. Questions in the spatial point pattern problems are mainly whether the pattern of locations is exhibiting complete spatial randomness, clustering (aggregation), or regularity (repulsiveness). In the marked spatial point process where additional covariates are measured, we could possibly investigate the factors/variables associated to this behavior as well. A statistical approach to address such questions is needed as different observers may disagree on the amount of clustering or randomness. Usually patterns from a completely random process may appear to be wrongly clustered when just eyeballed by an individual.

Example 33. (Tropical rain forest trees in Barro/Colorado) Figure 2.6 shows the positions (dots) of 3605 *Beilschmiedia* trees in a 1000×5000 meter rectangular stand in a tropical rain forest at Barro Colorado Island, Panama. All spatial coordinates are in the Cartesian coordinate system and in meters. Dataset is available from the R package `bei{spatstat}`. The scientific question may be if the trees are distributed over the area in a uniform way, they form clusters, or they are arranged in a specific pattern. Here, the locations of the dots/trees are not fixed but random/uncertain and of course they are matter of inference. This is a point process as each location is associated to an occurrence only and not any other covariate. The statistician's task is to design models able to test and quantify heterogeneity/homogeneity.

Example 34. The domain scientist is interested in knowing whether the spatial locations are completely spatially random, clustered, or regularly distributed.

- (1) (Japanese pine trees) The Japanese pine trees dataset in R `japanesepines{spatstat}` represents locations of 65 saplings of Japanese black pine (*Pinus thunbergii*) in a 5.7×5.7 square meter sampling region in a natural forest.

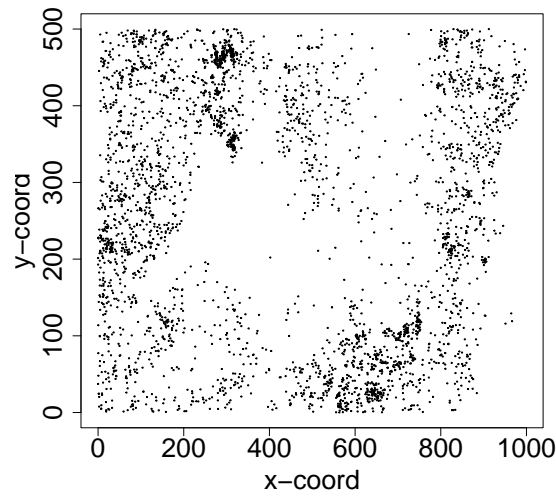
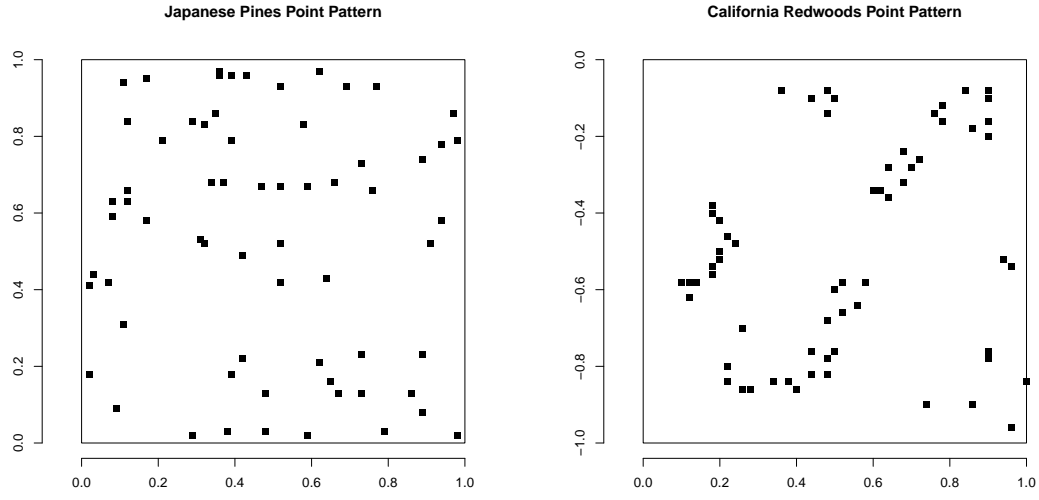


FIGURE 2.6. Locations of tropical rain forest trees in Barro/Colorado (Spatial point pattern data)

- (2) (California Redwoods) The data represent the locations of 62 seedlings and saplings of California Giant Redwood (*Sequoiadendron giganteum*) recorded in a square sampling region.
- (3) (Biological Cells) The data record the locations of the centres of 42 biological cells observed under optical microscopy in a histological section. The microscope field-of-view has been rescaled to the unit square.

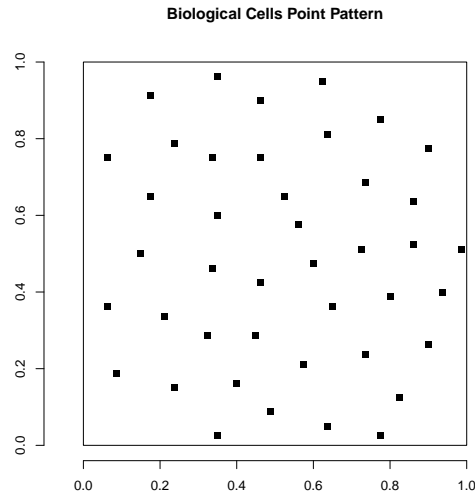
Figure 2.7 presents the aforesaid spatial point patterns. It is difficult to eyeball, perhaps Figure 2.7a of the Japanese pine trees seems neither clustered nor regularly distributed but rather completely randomly distributed; Figure 2.7b of the California redwoods shows a clustered pattern; and Figure 2.7c shows a regular pattern.

Example 35. (Longleaf Pines Point Pattern) Figure 2.8 shows locations (as Cartesian coordinates) and relative diameters at breast height in dbh (as the size of the dot) of all longleaf pine trees in the 24ha region of the Wade Tract, an old-growth forest in Thomas County, Georgia in 1979. Dataset is available from R package `spatstat`. Longleaf pine is a fire-adapted species of trees. The domain scientist is interested in knowing whether the spatial locations are spatially random, or clustered, if large (small) trees cluster and how do large and small trees interact. A statistician can design models able to quantify such notions and provide inference. Here, the locations are random (not fixed) and in fact an object of inference. The diameter at breast height recorded along with the tree's location is the marked variable, and hence, the whole process is a marked process.



(A) Japanese Pines

(B) California Redwoods



(C) Biological Cells

FIGURE 2.7. Spatial Point Patterns

3. UNCERTAINTY QUANTIFICATION AND MODELING

Note 36. In spatial problems, uncertainty is expressed probabilistically through a spatial stochastic process (or a multivariate random field), which can be written most generally as

$$(3.1) \quad \{Y(s); s \in \mathcal{S}\},$$

To be
defined
rigorously
later

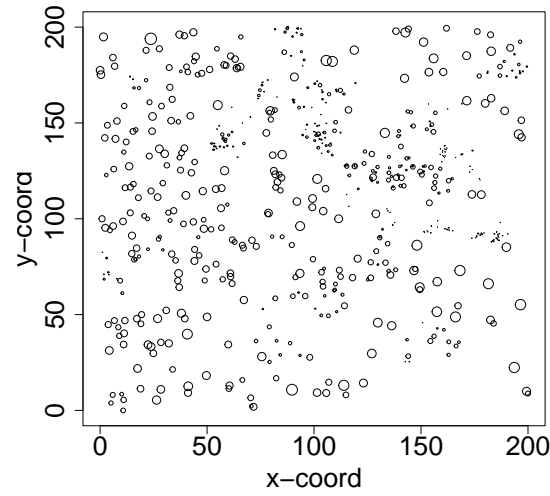


FIGURE 2.8. Longleaf Pines Point Pattern (Spatial point data)

Here $Y(s)$ is the random attribute value at location s , $\mathcal{S} \subset \mathbb{R}^d$ is a subset of \mathbb{R}^d ($d = 1, 2, 3$), contained in \mathcal{S} is a possibly random fixed or random set S that indexes those parts of \mathcal{S} relevant to the scientific study.

Spatial process model.

Note 37. The scientific uncertainty (i.e. the (known) uncertainty about the scientific problem) is expressed via the spatial process model. E.g., uncertainty about the real picture in Fig. 2.3a.

Note 38. This spatial stochastic process can be a: geostatistical process, lattice process, or point process depending on the principal spatial statistical area (Section 2) the application is associated with.

Note 39. The joint probability model defined by the random $\{Y(s); s \in S\}$ is

$$(3.2) \quad \text{pr}(Y, S) = \text{pr}(Y|S) \text{pr}(S)$$

Note 40. The specification of $\text{pr}(S)$ represents the three principal spatial statistical areas. E.g., for spatial data on lattices or point referenced data problems where the locations are fixed and not uncertain, we can consider $\text{pr}(Y, S) = \text{pr}(Y|S)$ with $\text{pr}(S) = 1_{\{S\}}(S)$ and hence ignore S and $\text{pr}(S)$ from the notation.

Data model.

Note 41. The measurement uncertainty is quantified via the data model. E.g. the “noisy image” in Fig. 2.3a.

Note 42. The data model is specified to be the conditional distribution of the data Z given the spatial stochastic process Y and the S , namely

$$(3.3) \quad \text{pr}(Z|Y, S)$$

Note 43. If the data are assumed to be conditionally independent, such as $Z(s) \perp Z(s') | Y, S$ then

$$(3.4) \quad \text{pr}(Z|Y, S) = \prod_{i=1}^n \text{pr}(Z(s_i) | Y, S)$$

Note 44. The spatial statistical dependence of in Z , articulated by the First Law of Geography, follows by

$$\text{pr}(Z|S) = \int \text{pr}(Z|Y, S) \text{pr}(Y|S) dY$$

The hierarchical statistical model.

Note 45. To sum up the (known) uncertainty in spatial the statistics problem is expressed via the so called Hierarchical spatial model

$$(3.5) \quad \begin{cases} Z|Y, S & \text{data model} \\ Y, S & \text{spatial process model} \end{cases}$$

with

$$\text{pr}(Z, Y, S) = \text{pr}(Z|Y, S) \text{pr}(Y|S) \text{pr}(S)$$

The Empirical (Bayes) hierarchical model.

Note 46. Often the decomposition (3.5) is parametrized with respect to unknown parameters $\theta \in \Theta$ we wish to learn given the observables; this is often called the Empirical hierarchical model i.e.

$$(3.6) \quad \begin{cases} Z|Y, S, \theta & \text{data model} \\ Y, S|\theta & \text{spatial process model} \end{cases}$$

with

$$\text{pr}(Z, Y, S|\theta) = \text{pr}(Z|Y, S, \theta) \text{pr}(Y|S, \theta) \text{pr}(S|\theta)$$

...more details in the next lecture.

The Bayesian hierarchical model.

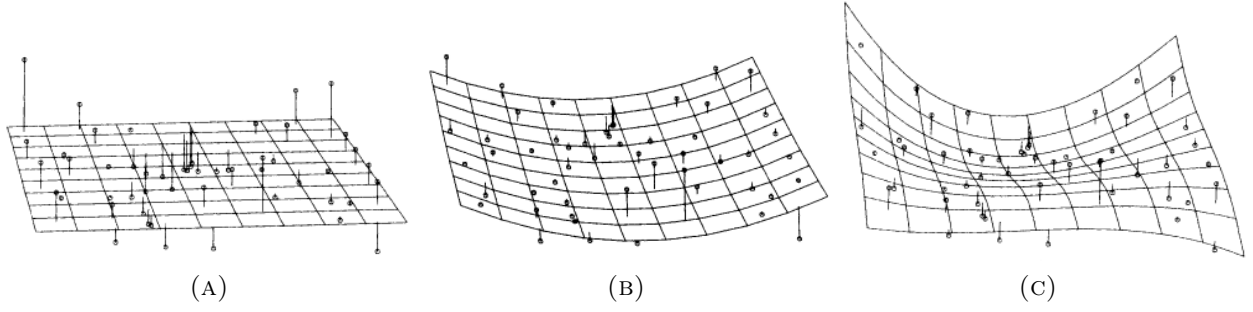


FIGURE 3.1. Examples representing the hierarchical spatial model (3.8) for different values of $\theta = (\sigma^2, \beta, \phi)$

Note 47. In Bayesian statistics, the hierarchical model in (3.5) is completed by the $\theta \sim \text{pr}(\cdot)$ adding a third layer leading to the Bayesian hierarchical model

$$(3.7) \quad \begin{cases} Z|Y, S, \theta & \text{data model} \\ Y, S|\theta & \text{spatial process model} \\ \theta & \text{hyper-parameter prior model} \end{cases}$$

with

$$\text{pr}(Z, Y, S, \theta) = \text{pr}(Z|Y, S, \theta) \text{pr}(Y|S, \theta) \text{pr}(S|\theta) \text{pr}(\theta)$$

Example 48. (A naive example) Consider Example ??, and observations $\{(Z_i, s_i)\}_{i=1}^n$ where Z_i is the Cr measurement in ppb at the i -th location $s_i \in \mathbb{R}^2$. Perhaps one may consider that the real Cr, lets denoted as Y , may follow a Normal distribution with a mean $\mu = S\beta$ parametrized as $[\mu]_i = \beta_0 + s_{(1),i}\beta_1 + s_{(2),i}\beta_2 + s_{(1),i}s_{(2),i}\beta_{12} + \dots$ at a location s (to consider spatial dependence) with some unknown parameter β , and covariance matrix parametrized as $[C]_{i,j} = c(s_i, s_j)$ with $c(s, s') = \sigma^2 \exp(-\phi \|s - s'\|)$; here β , ϕ , and σ^2 are unknown parameters. One may consider that the measurements Z at each location are the result of observing Y_i (the real Cr) but contaminated by additive random noise, as $Z_i = Y_i + \epsilon_i$, $\epsilon_i \sim N(0, \sigma^2)$. To sum up, we have build the hierarchical model

$$(3.8) \quad \begin{cases} Z|Y, \sigma^2 \sim N(Y, I\sigma^2) \\ Y|\sigma^2, \beta, \phi \sim N(S\beta, C) \end{cases}$$

Figure 3.1 shows the hierarchical spatial model (3.8) for different values of $\theta = (\sigma^2, \beta, \phi)$; the surface corresponds to the spatial process $\{Y(s); s \in \mathbb{R}^2\}$ and is presented at three different instances each of them with different values for (β, ϕ) , while the dots correspond to the observations $\{(Z(s_i), s_i)\}_{i=1}^n$ and their deviation from the spatial process is controlled by σ^2 . If we work on the fully Bayesian framework (!!!), we can complete the model with priors on $\theta = (\sigma^2, \beta, \phi)$ as $\sigma^2 \sim \text{IG}(\kappa_\sigma, \lambda_\sigma)$, $\phi \sim \text{IG}(\kappa_\phi, \lambda_\phi)$, and $\beta \sim N(b, Iv)$, with some

That's a snapshot for what follows.

known hyper-parameters $\kappa_\sigma, \lambda_\sigma, \kappa_\phi, \lambda_\phi, b, v$. To sum up, we have build the Bayesian model

$$\begin{cases} Z|Y, \sigma^2 \sim & \text{N}(Y, I\sigma^2) \\ Y|\sigma^2, \beta, \phi \sim & \text{N}(S\beta, C) \\ \beta \sim & \text{N}(b, Iv) \\ \sigma^2 \sim & \text{IG}(\kappa_\sigma, \lambda_\sigma) \\ \phi \sim & \text{IG}(\kappa_\phi, \lambda_\phi) \end{cases}$$