19th World Congress of Soil Science
Soil solutions for a changing world

4.2.1 Quantitative monitoring of soil changes

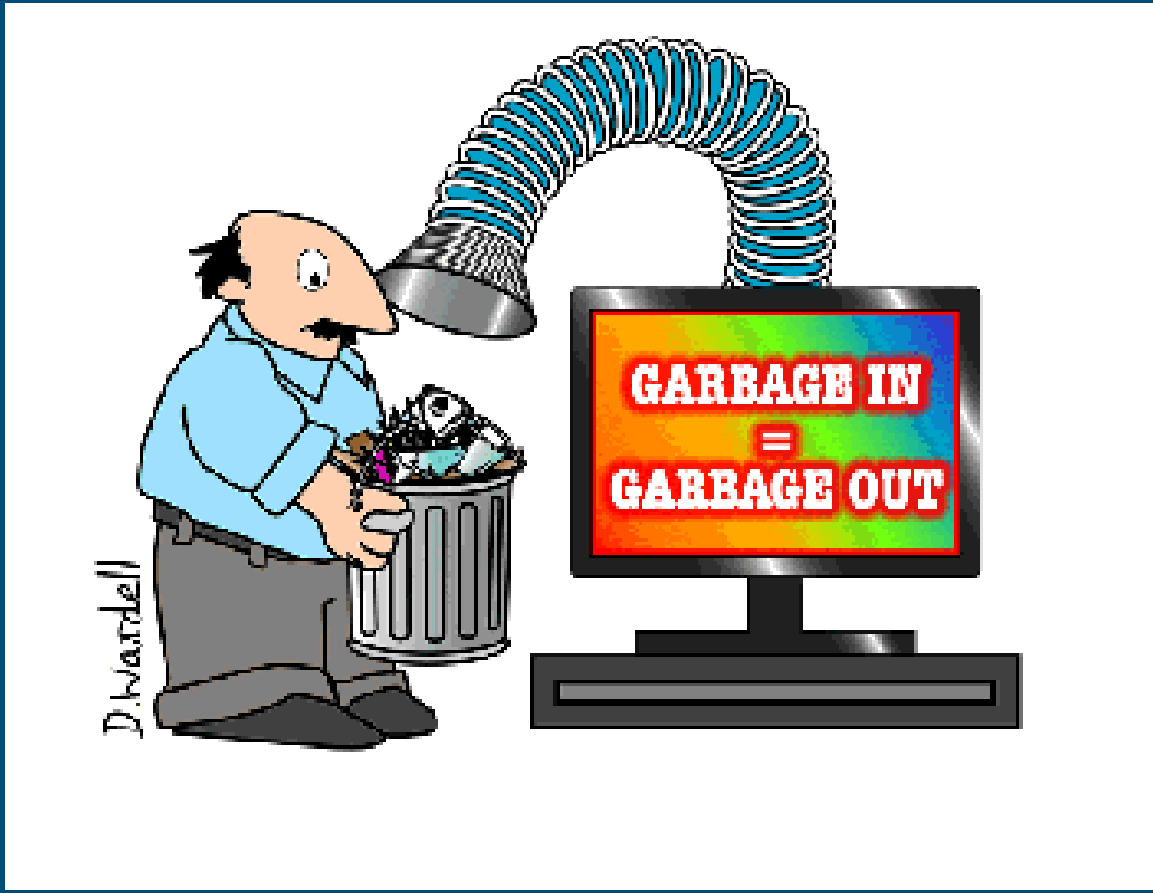
Dick Brus - 0-0003

Design-based and model-based sampling strategies for soil monitoring

Natural resource monitoring as a research topic

- Strong emphasis on modeling
- Few papers on the statistical design of sample

Why should we bother about sampling design?



Two major design decisions

- Design-based or model-based approach?
- Basic type of space-time design

Sampling and statistical inference

	Selection of sampling units	Statistical inference
Design-based	Probability sampling	Uses inclusion probabilities

Sampling and statistical inference

	Selection of sampling units	Statistical inference
Design-bas		
Model-base		

ELSEVIER

Geoderma 80 (1997) 1–44

GEODERMA

Discussion Paper

Random sampling or geostatistical modelling? Choosing between design-based and model-based sampling strategies for soil (with Discussion) [1]

D.J. Brus *, J.J. de Gruijter

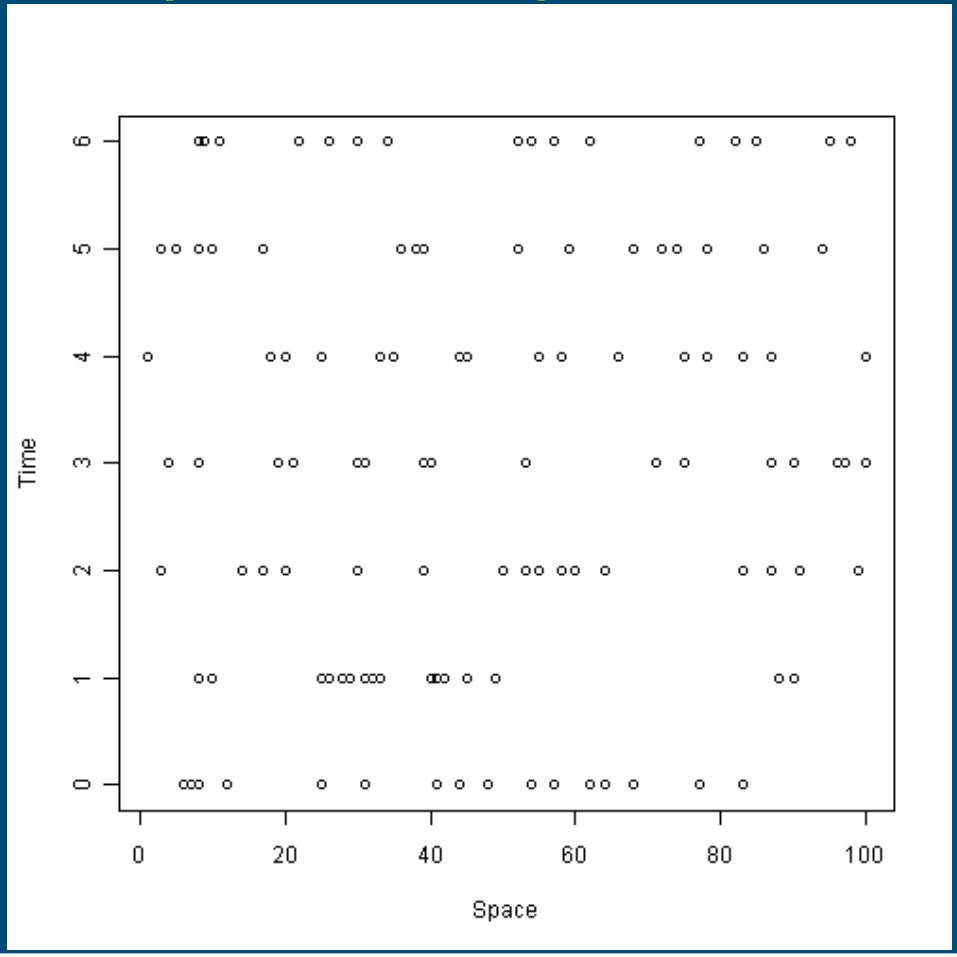
Four approaches for space-time sampling

SPACE

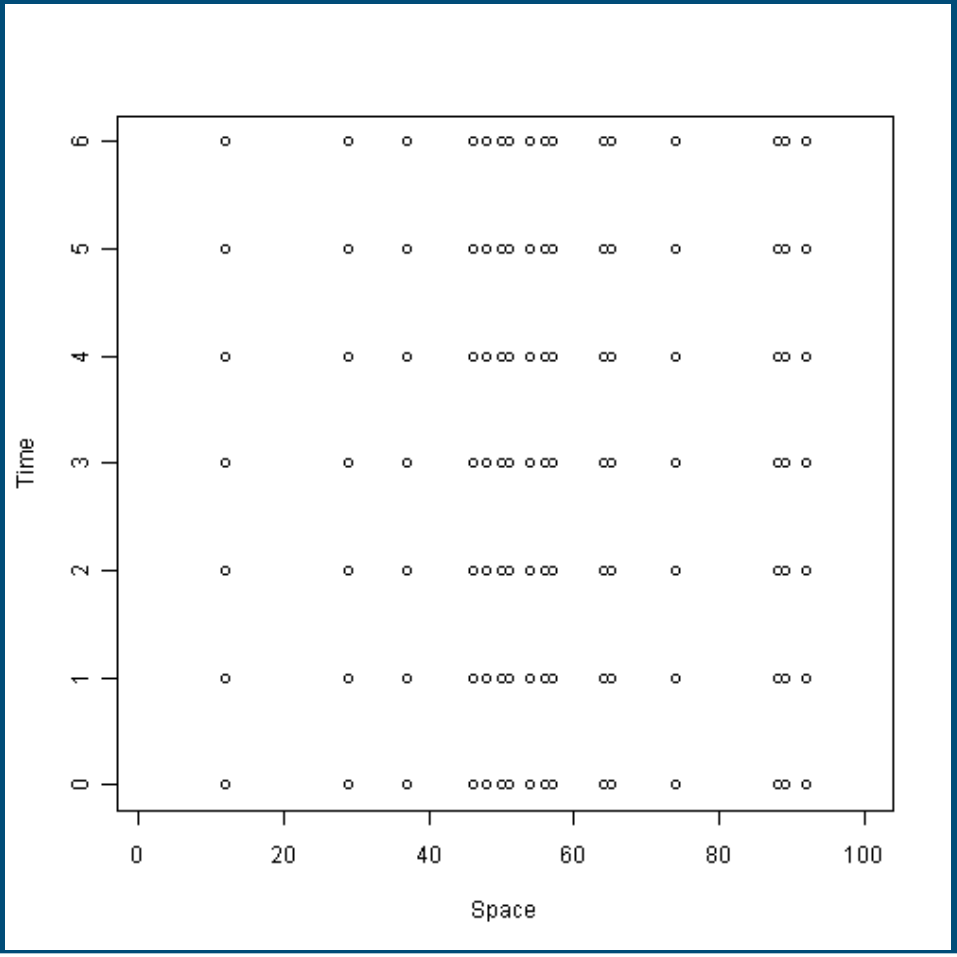
TIME	Design-based	Model-based
Design-based	$D_S D_T$	$(M_S D_T)$
Model-based	$D_S M_T$	$M_S M_T$

Basic space-time sampling designs

Independent synchronous

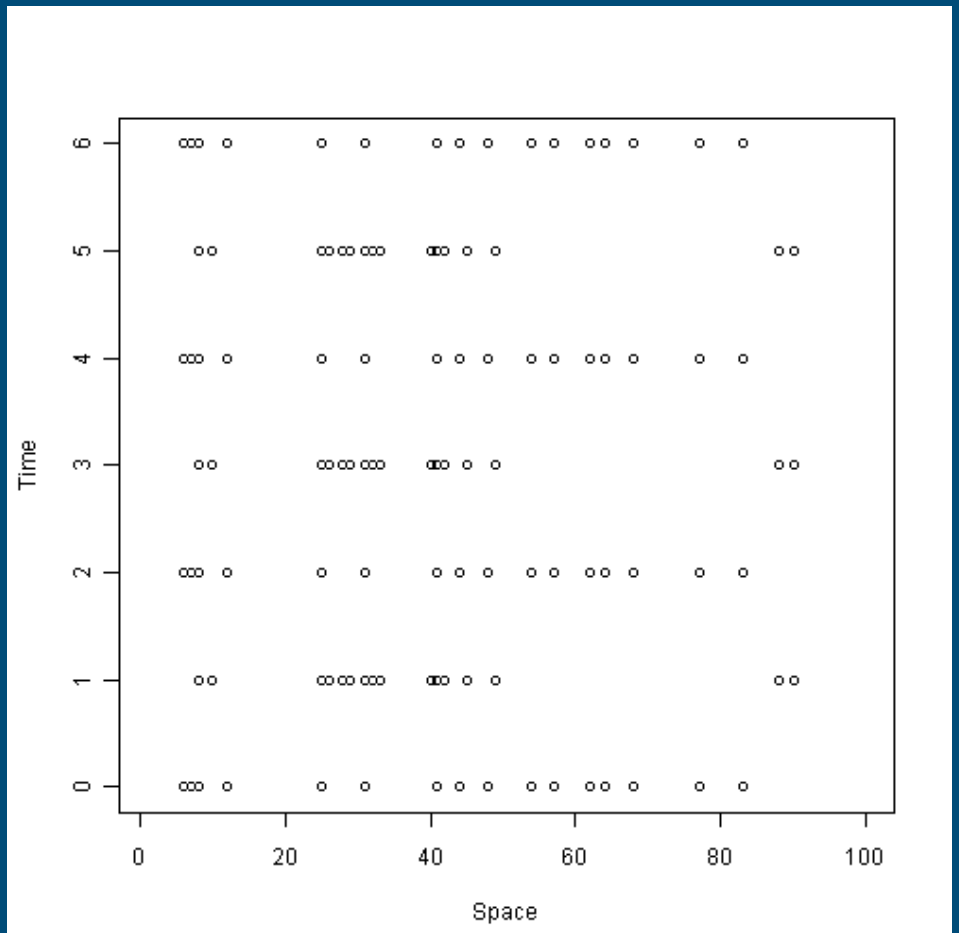


Static-synchronous

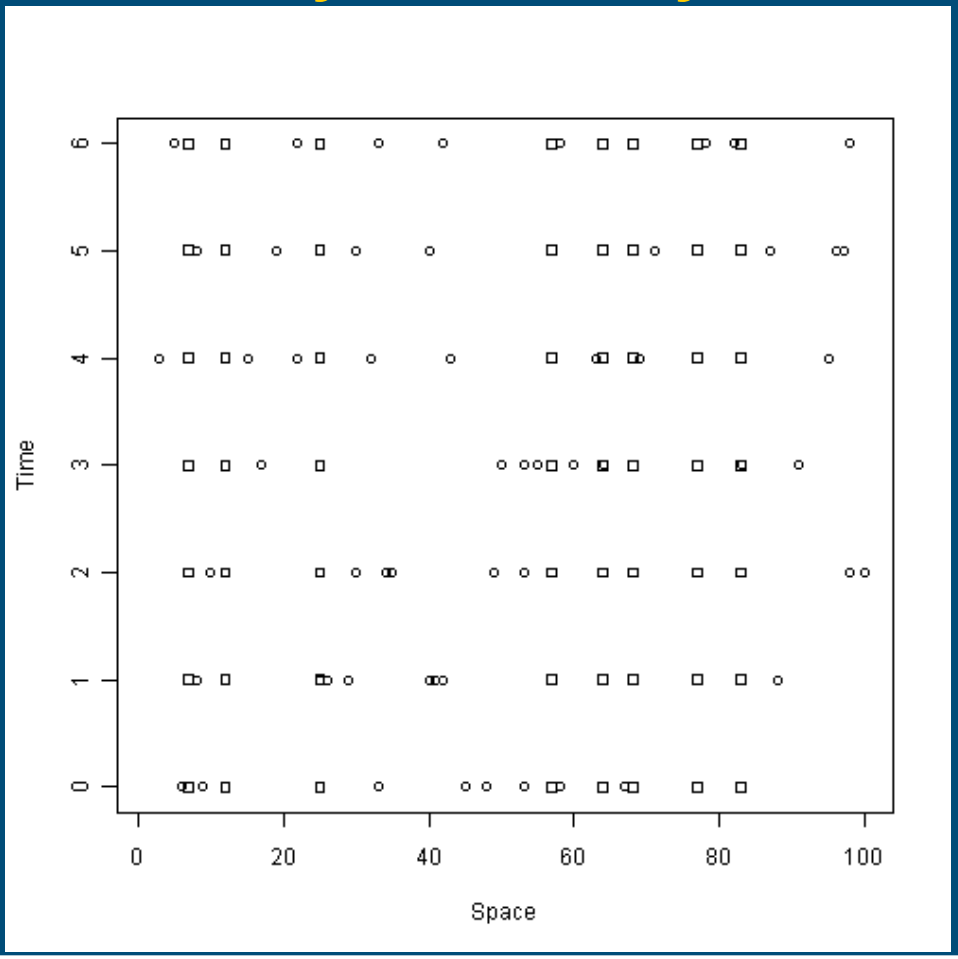


Basic space-time designs (2)

Serially alternating

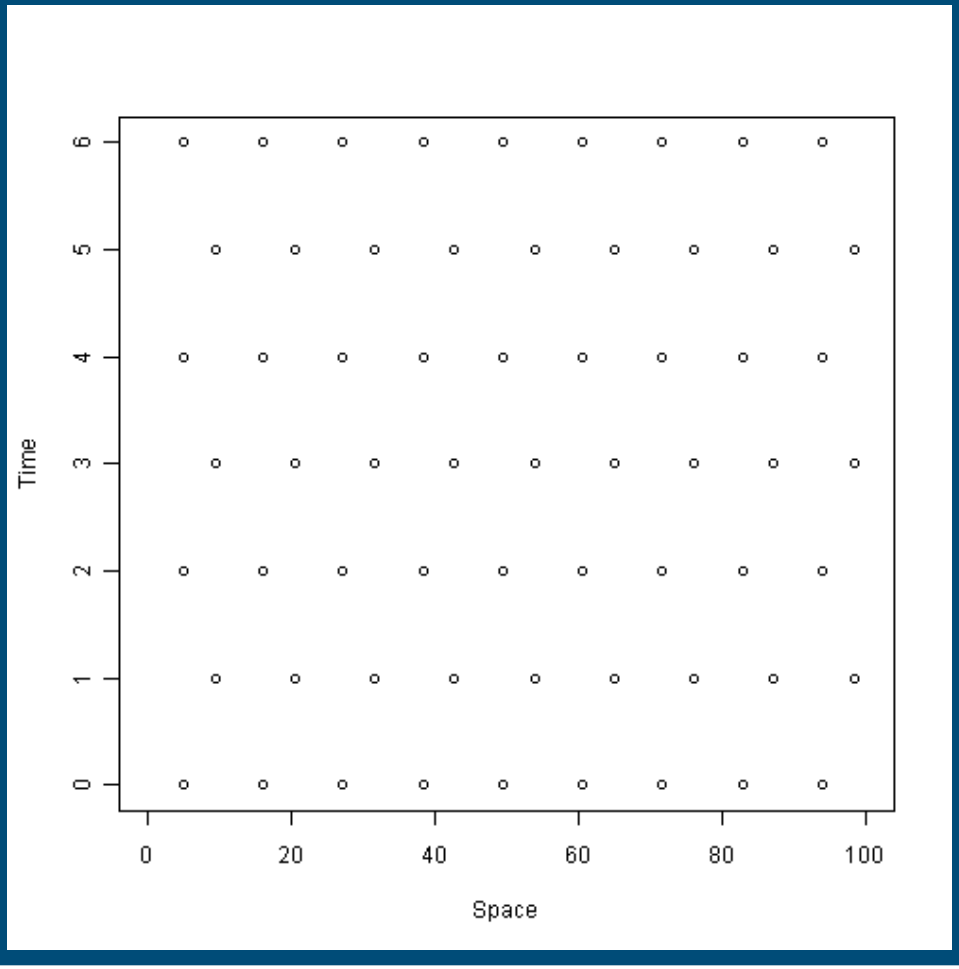


Static-synchr + Synchr.



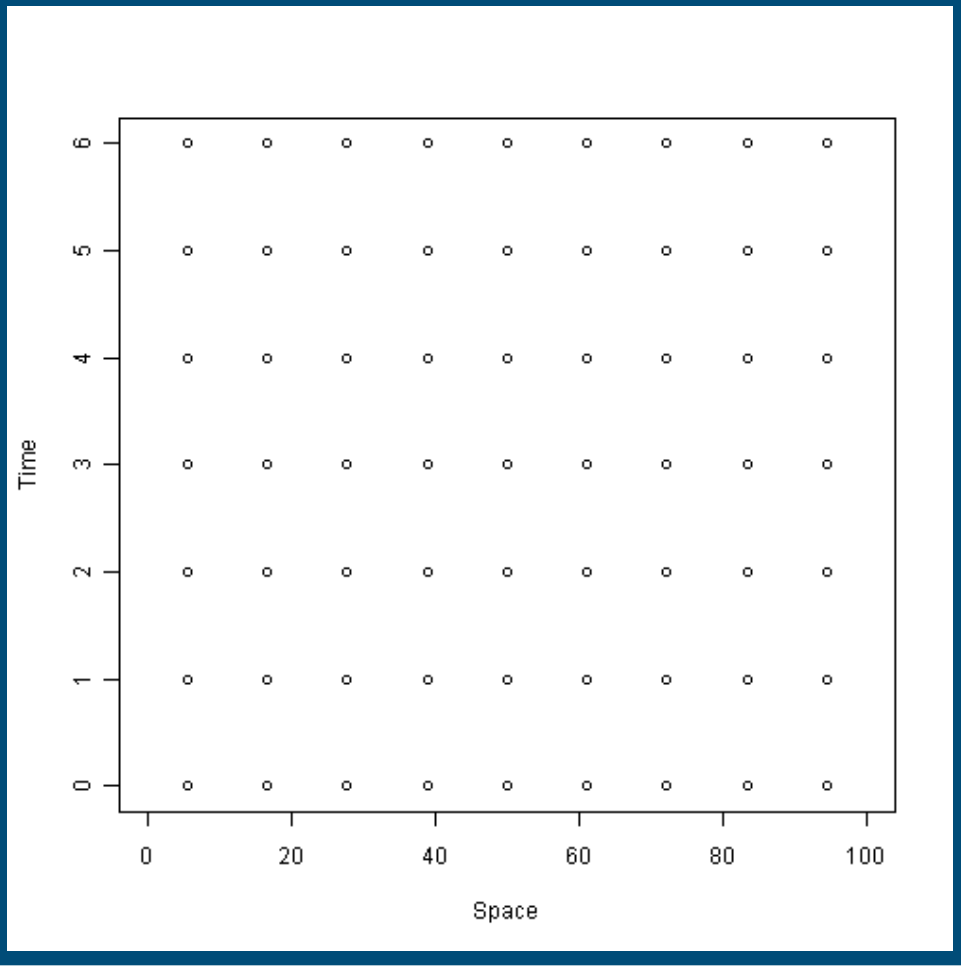
Serially alternating

random grid in space



Static-synchronous

spatial grid *centered*



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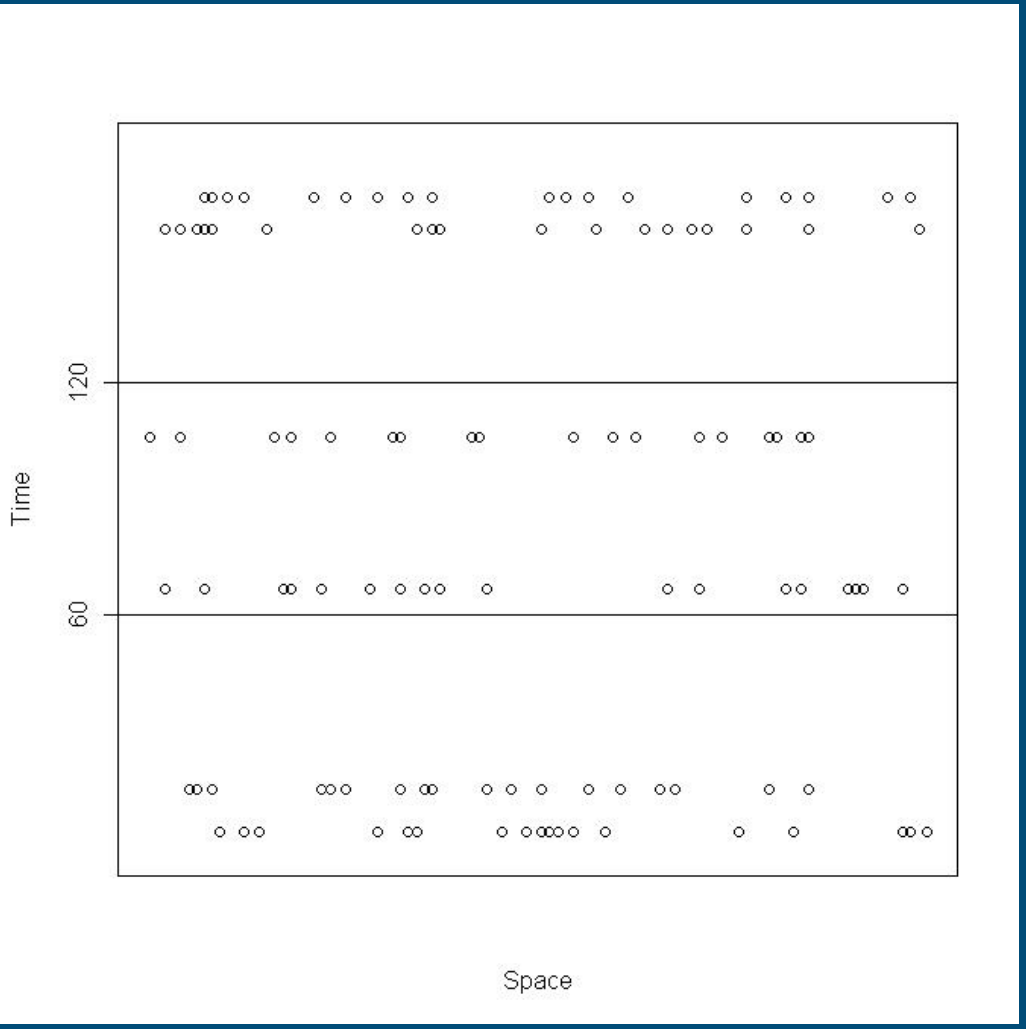
Choice of statistical approach and space-time design

- Global quantities: statistical parameters defined for the sampling universe in its entirety
  - Space-time mean
  - Temporal trend of spatial mean

Space-time mean (total)

- Space-time mean concentration of nutrients in soil, groundwater or surface water
- Space-time total of greenhouse gas emissions in an area
- Fully design-based approach (probability sampling of spatial and of temporal units) can be attractive option
- Basic space-time design: independent synchronous; unbiased estimation of sampling variance

Compliance monitoring of surface water quality



- Space-time: Independent-synchronous
- Time: Stratified simple random (L=3,n_h =2, n=6)
- Space: Simple random (m=18)
- D.J. Brus & M. Knotters, 2008. Sampling design for compliance monitoring of surface water quality: A case study in a polder area. Water Res. Res. 44, W11410

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Temporal trend of spatial mean

- Hybrid sampling approach:

1. Systematic sampling in time, constant interval, first time at start, last time at end
2. Probability sampling in space at all selected times
3. Model-free, design-based estimation of spatial means
4. Stochastic time-series model for spatial means
5. GLS estimation of temporal trend of spatial means

Time-series model for spatial means

$$\bar{Y}(t) = \sum_{j=1}^{q} \beta_j \cdot x_j(t) + \eta(t)$$

$\eta(t)$: model error, mean 0, covariance matrix $\mathbf{C}_\xi$

Time-series model for *estimated* spatial means

$$\hat{\bar{Y}}_{\pi}(t) = \sum_{j=1}^{q} \beta_j \cdot x_j(t) + \eta(t) + \varepsilon(t)$$

$\eta(t)$: model error, mean 0, covariance matrix $\mathbf{C}_{\xi}$

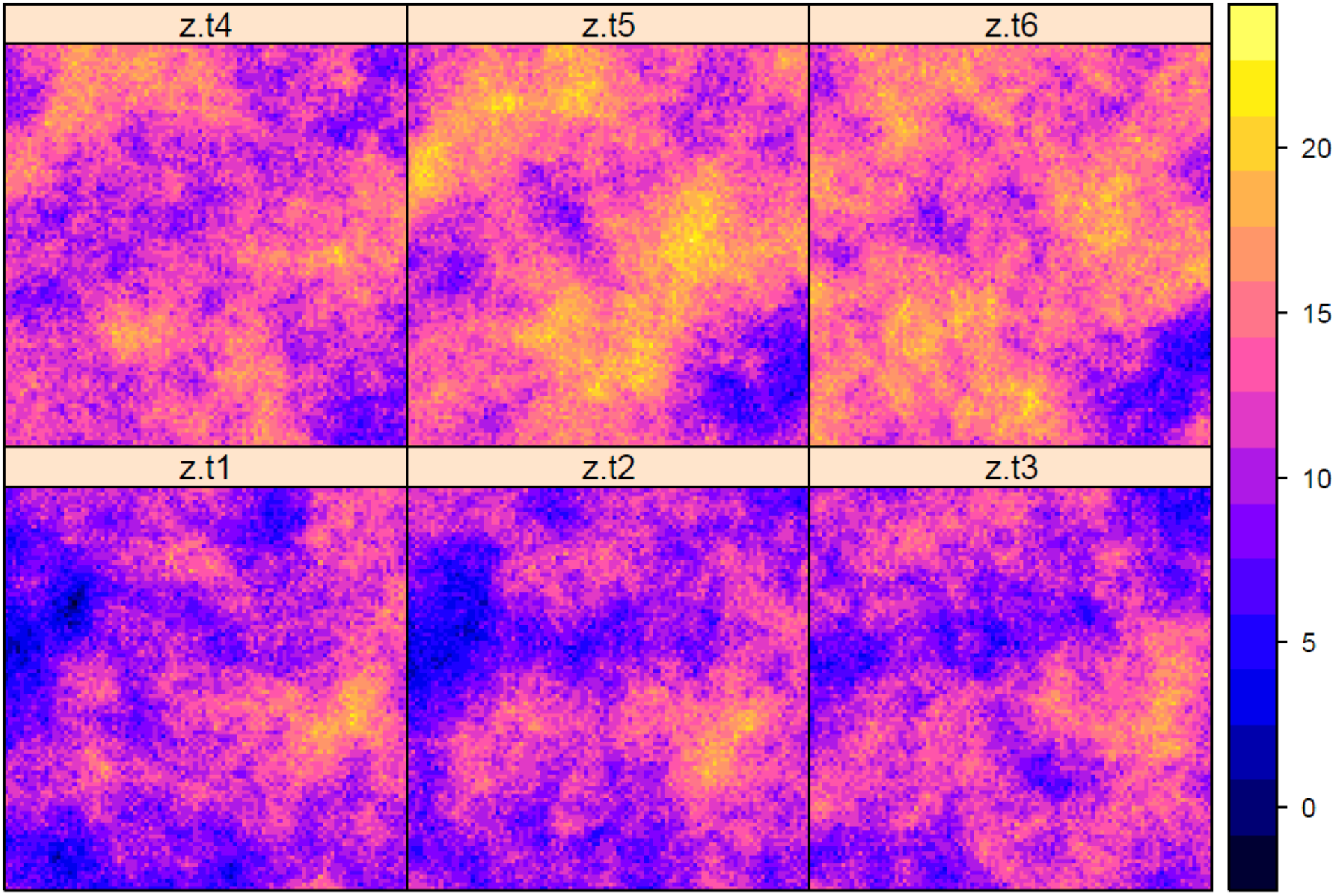
$\varepsilon(t)$: sampling error, mean 0, covariance matrix $\mathbf{C}_{\mathrm{p}}$

$\mathrm{cov}(\eta(t), \varepsilon(t')) = 0$

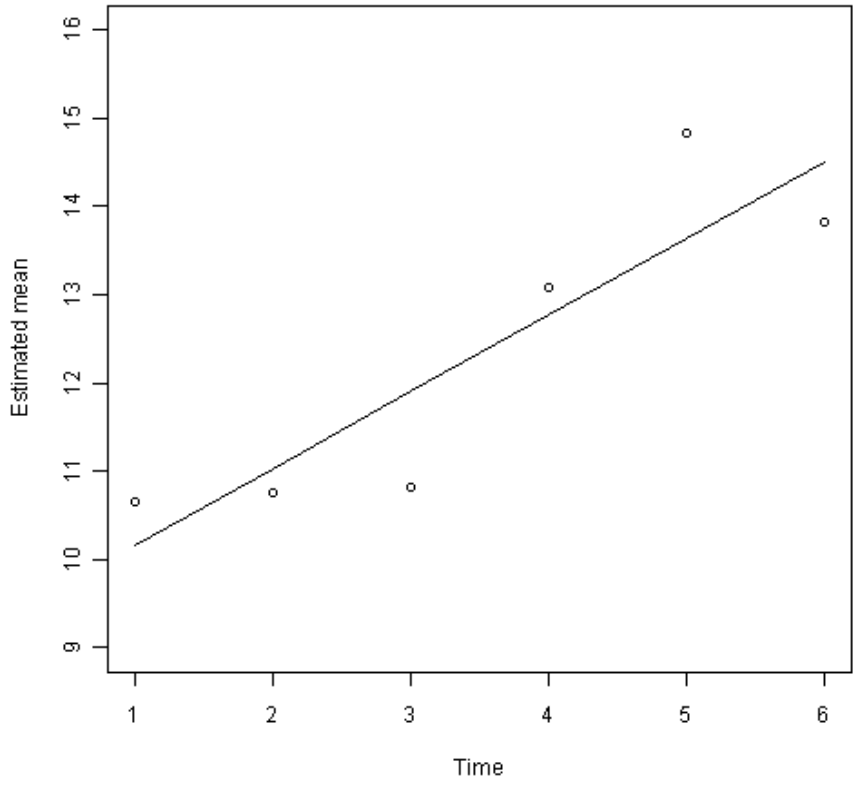
Linear trend model for *estimated* spatial means

$$x_1(t) = 1,\ x_2(t) = t$$

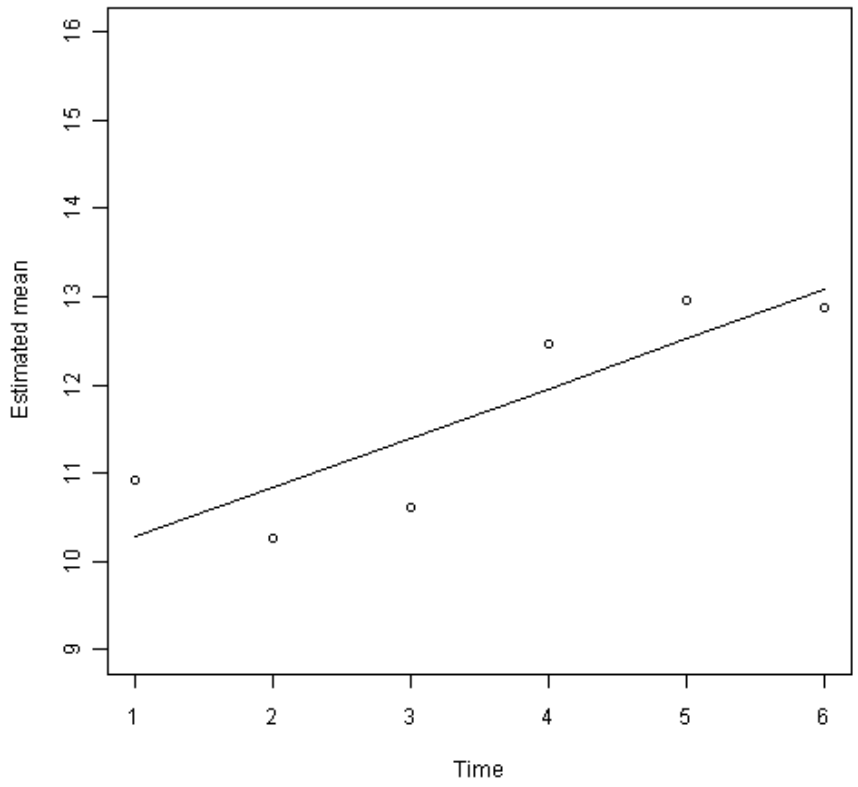
$$\hat{\bar{Y}}_{\pi}(t) = \beta_1 + \beta_2 \cdot t + \eta(t) + \varepsilon(t)$$


z.t4
z.t5
z.t6
z.t1
z.t2
z.t3
20
15
10
5
0

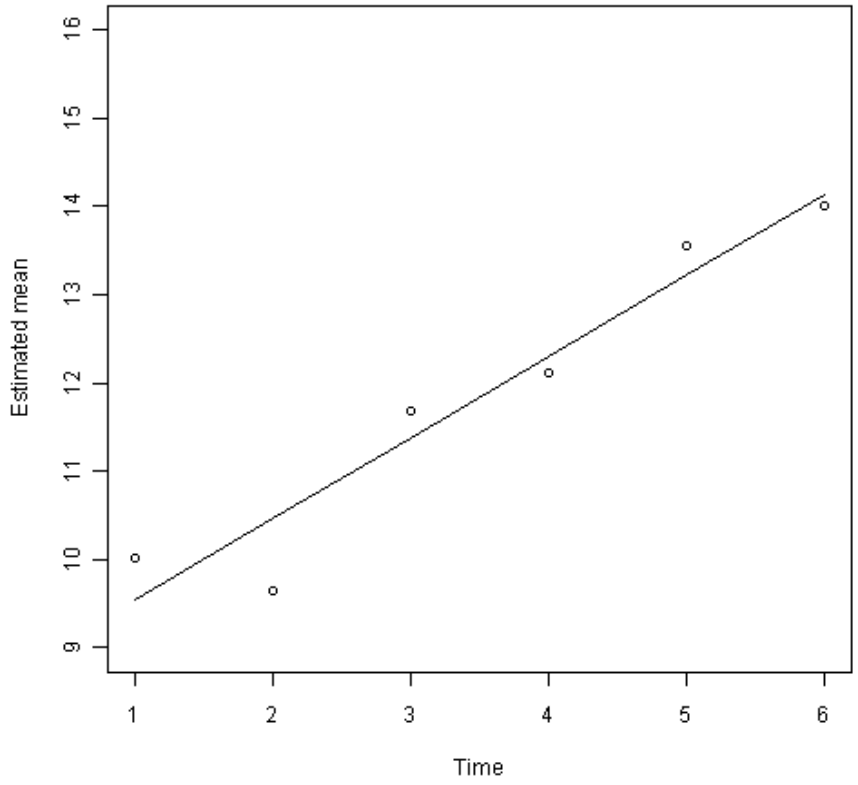
Space-time sample 1 (static-synchronous, SI in space)



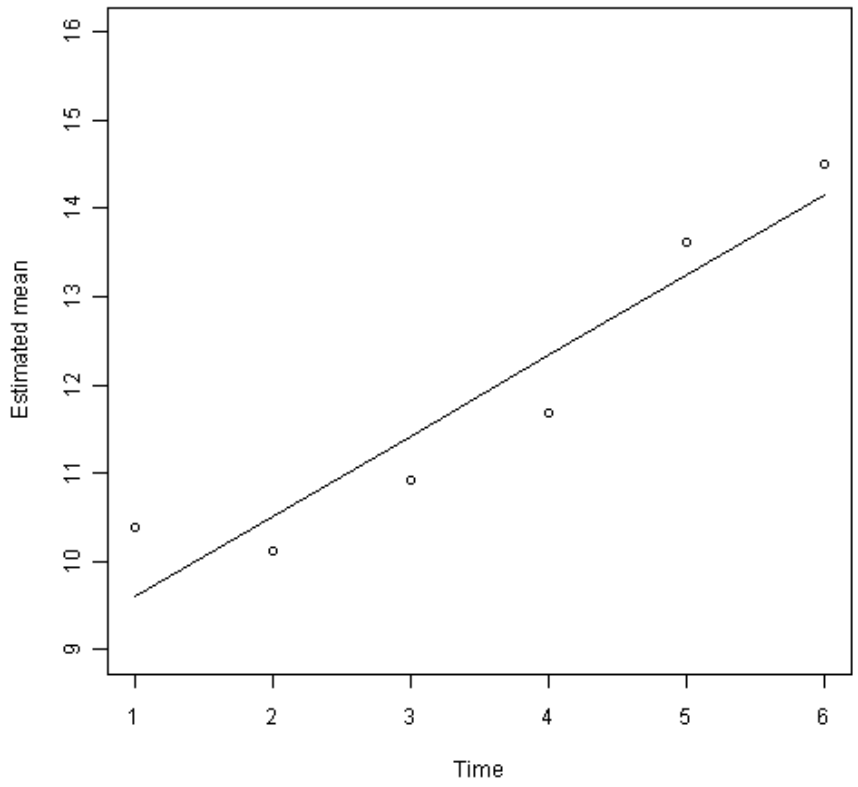
Space-time sample 2



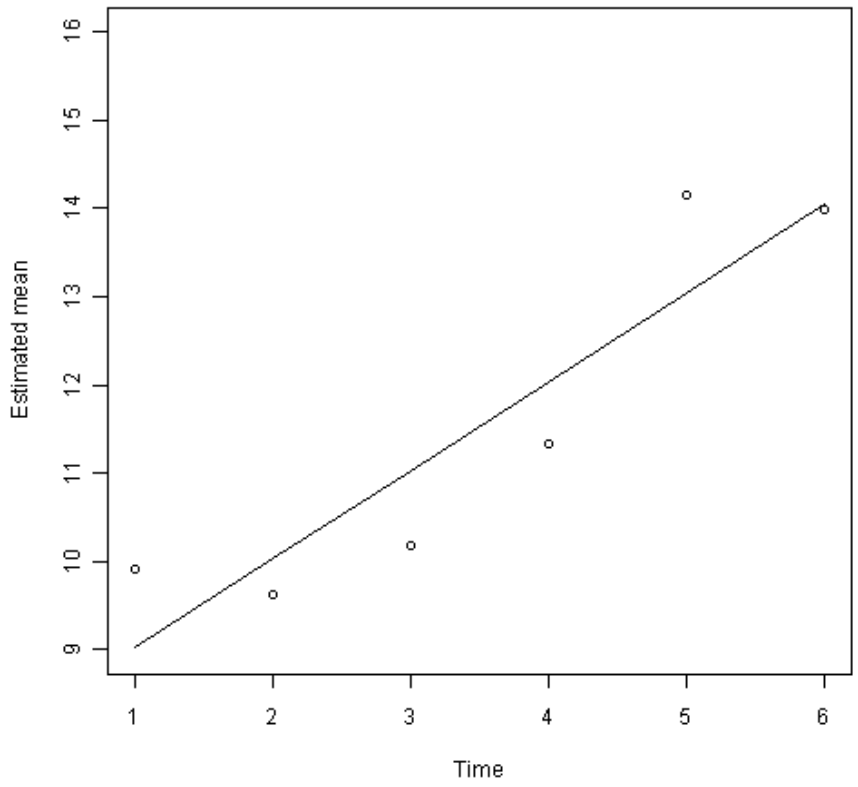
Space-time sample 3



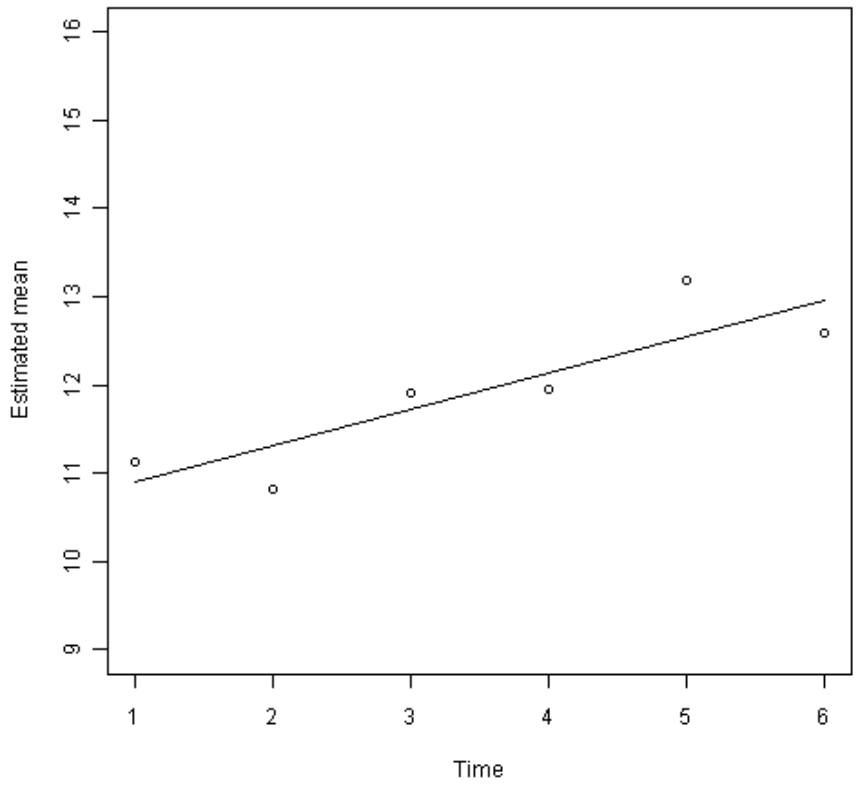
Space-time sample 4



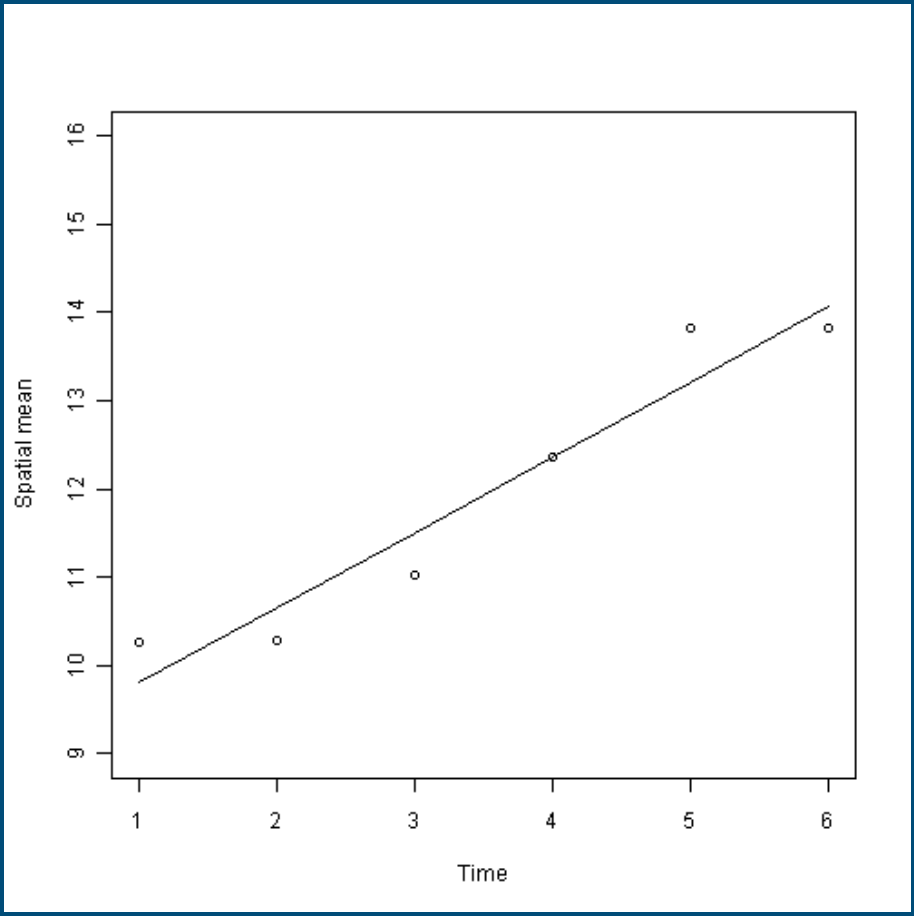
Space-time sample 5



Space-time sample 1000



Exhaustive space-time sample



GLS estimation of trend

- $$\hat{\boldsymbol{\beta}} = (\mathbf{X}'\mathbf{C}_{\xi p}^{-1}\mathbf{X})^{-1}(\mathbf{X}'\mathbf{C}_{\xi p}^{-1}\hat{\mathbf{y}})$$

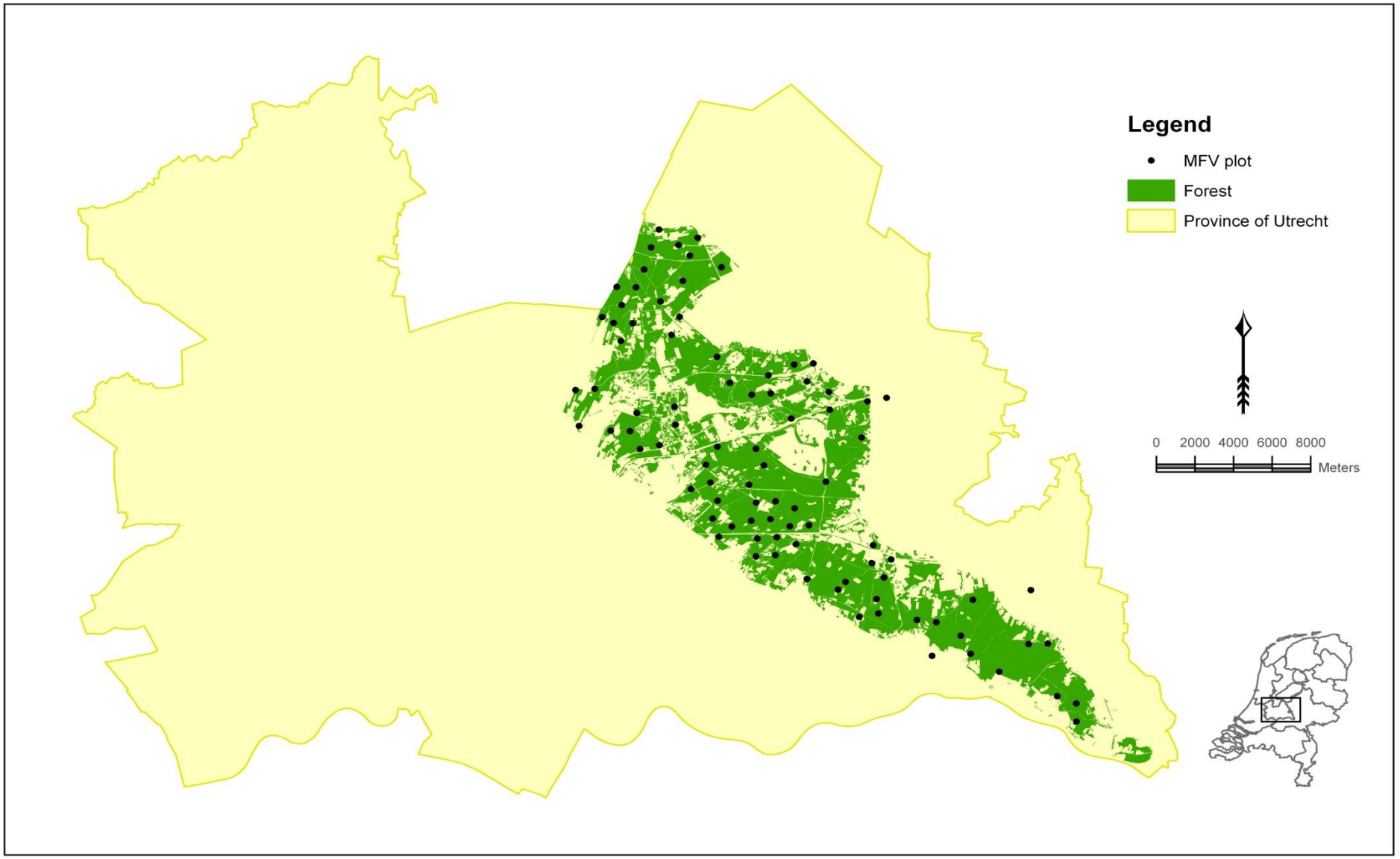
with

$$\mathbf{C}_{\xi p} = \mathbf{C}_{\xi} + \mathbf{C}_{p},$$

- $$\mathrm{Var}(\hat{\boldsymbol{\beta}}) = (\mathbf{X}'\mathbf{C}_{\xi p}^{-1}\mathbf{X})^{-1}$$

- $$\mathrm{Var}(\hat{\boldsymbol{\beta}}) = \mathrm{Var}_{\xi}\left\{\mathrm{E}_{p}(\hat{\boldsymbol{\beta}})|\xi_0\right\} + \mathrm{E}_{\xi}\left\{\mathrm{Var}_{p}(\hat{\boldsymbol{\beta}})|\xi_0\right\}$$

- $$\mathrm{Var}_{\xi}\left\{\mathrm{E}_{p}(\hat{\boldsymbol{\beta}})|\xi_0\right\} = (\mathbf{X}'\mathbf{C}_{\xi}^{-1}\mathbf{X})^{-1}\ ,$$



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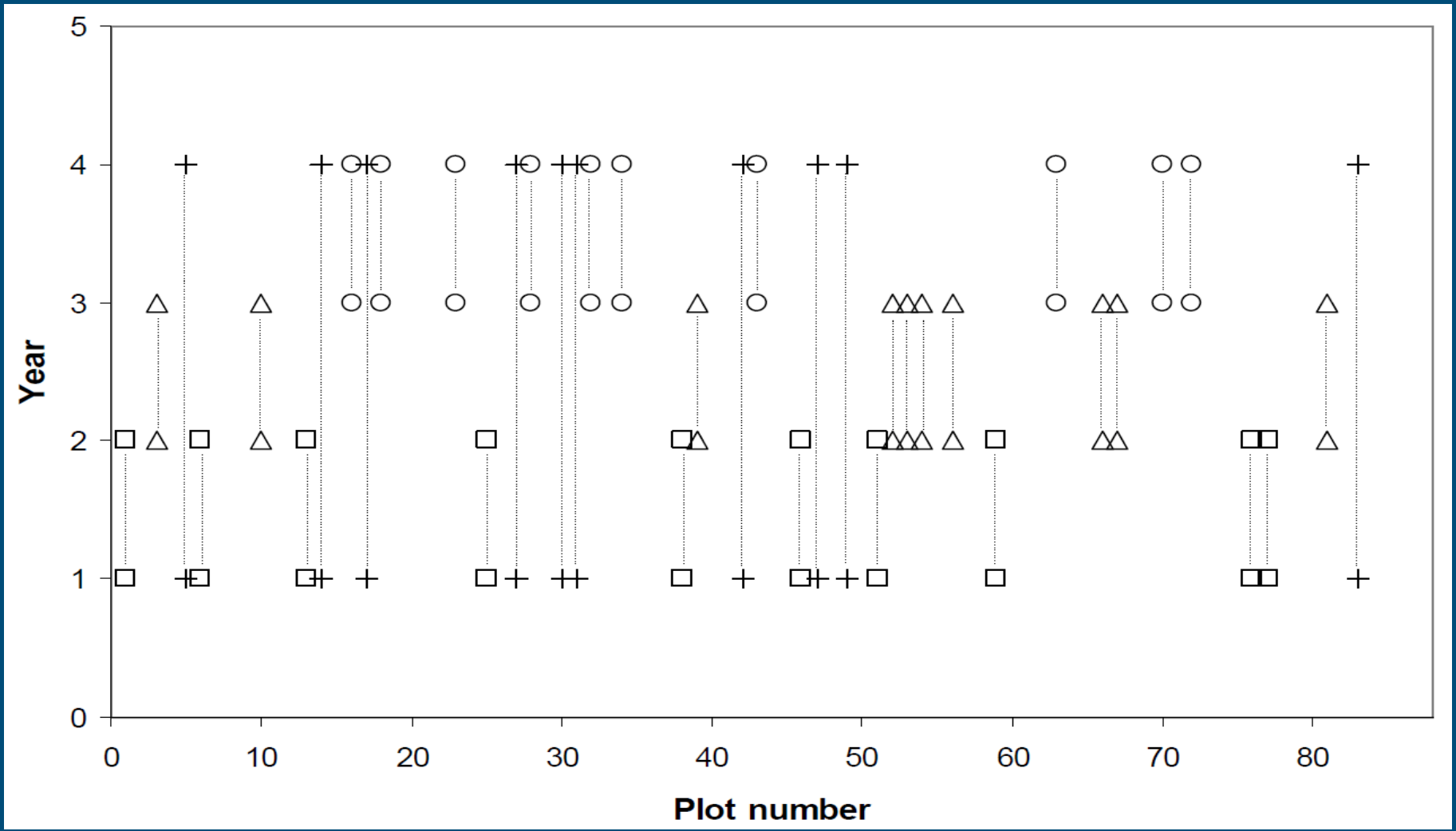
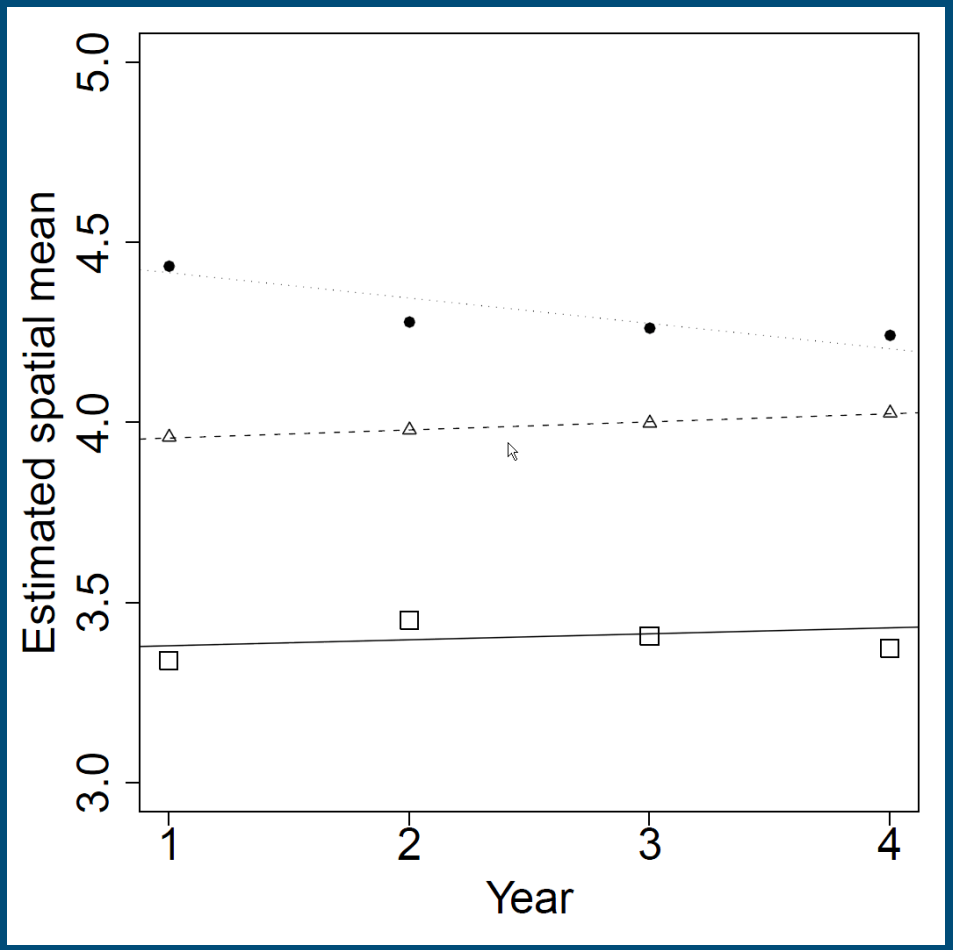
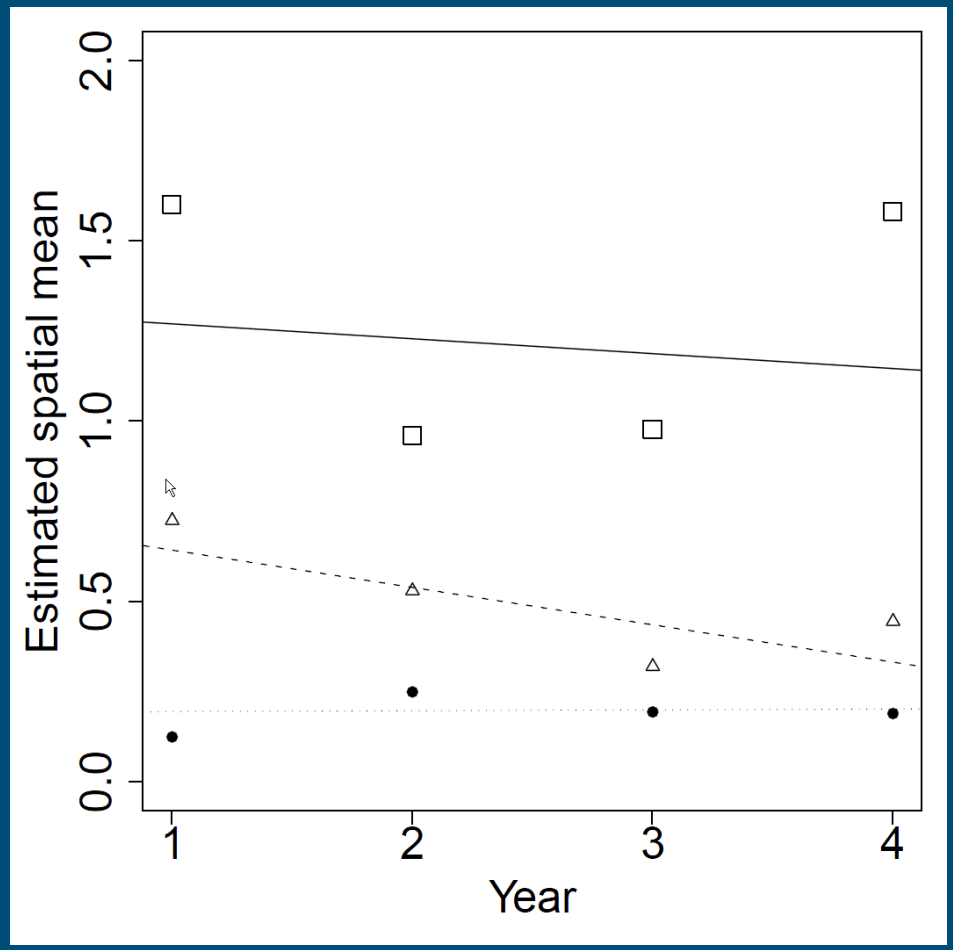
Rotational subsample



pH



NH_4



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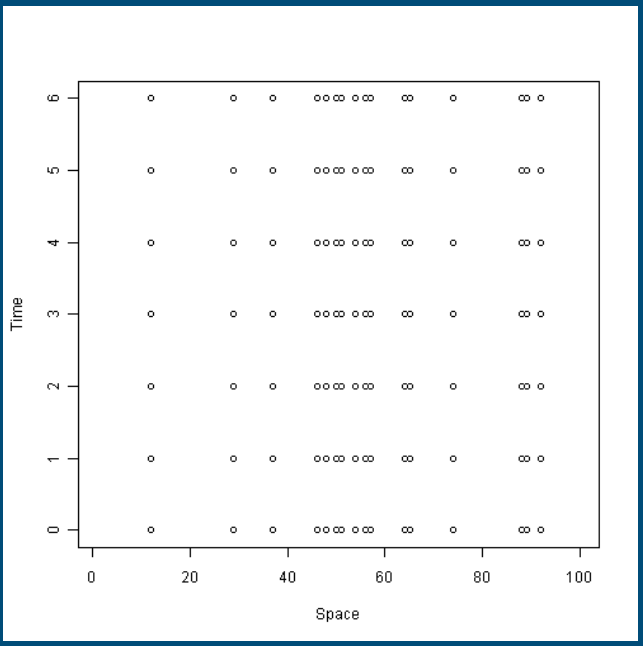
Estimated trend and standard errors. Numbers multiplied by 10^4

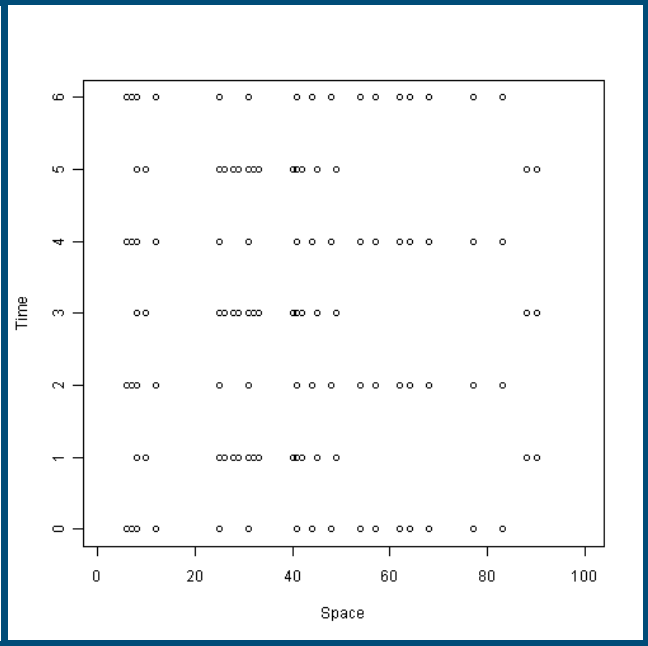
Comp	Depth	trend	se	se_p	se_ξ
pH	top	170	280	280	0
pH	mid	230	240	240	0
pH	sub	-700	210	150	130
NO_3	top	-24	1900	700	1800
NO_3	mid	88	740	470	550
NO_3	sub	240	460	300	310
NH_4	top	-410	2300	880	1700
NH_4	mid	*-1000*	630	360	470
NH_4	sub	23	280	160	200
NO_3 ss	top	480	12000	380	11000
NO_3 ss	mid	-1300	8200	4500	6800
NO_3 ss	sub	-980	6400	4200	4600

Optimization of basic space-time design

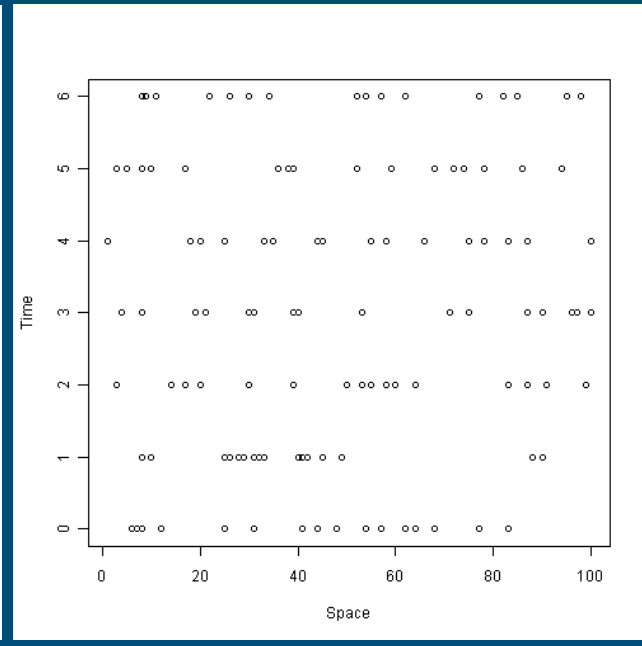
SS



SA



IS



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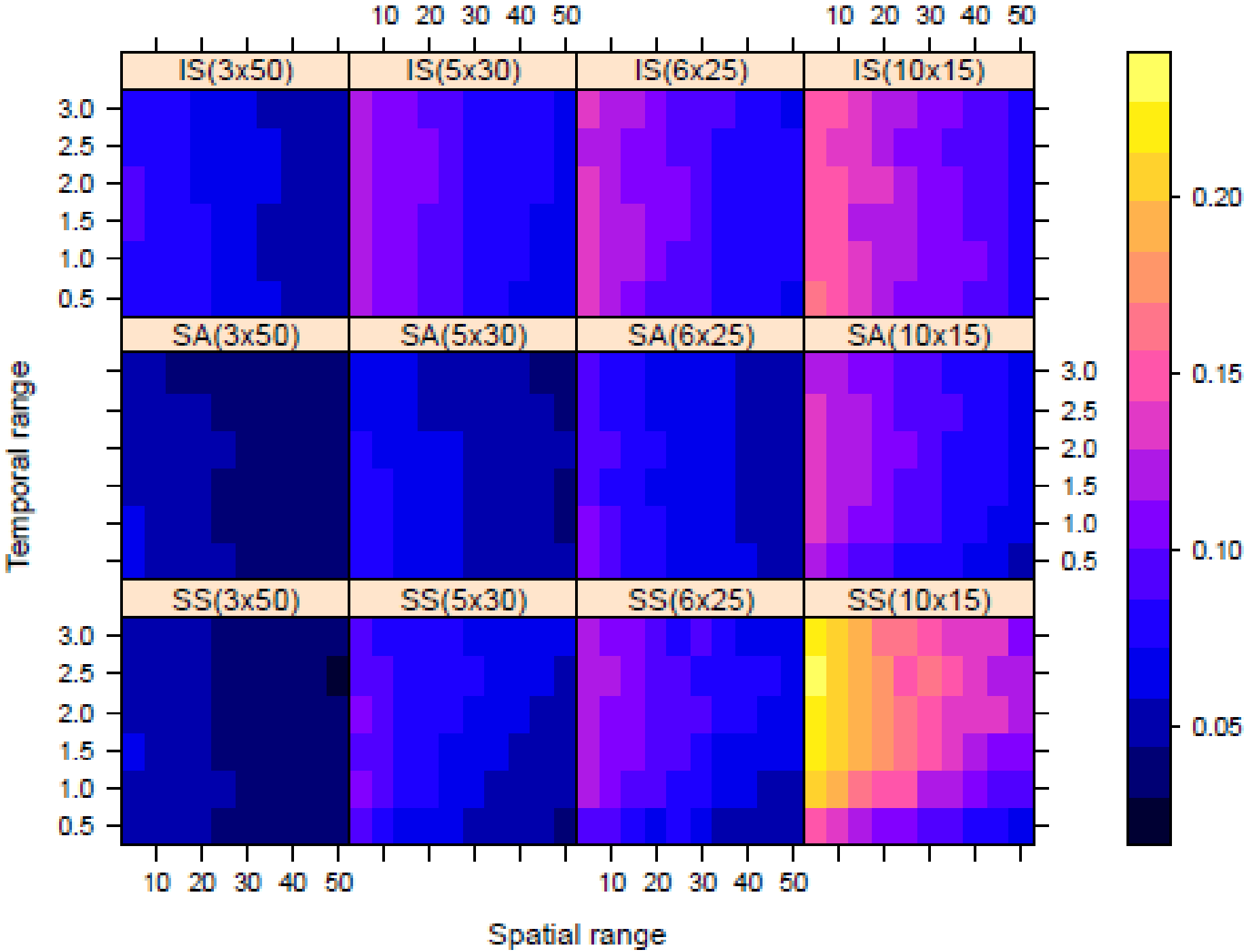

IS(3x50)
IS(5x30)
IS(6x25)
IS(10x15)
SA(3x50)
SA(5x30)
SA(6x25)
SA(10x15)
SS(3x50)
SS(5x30)
SS(6x25)
SS(10x15)
10 20 30 40 50
0.5 1.0 1.5 2.0 2.5 3.0
Temporal range
Spatial range
0.05 0.10 0.15 0.20

Hybrid approach and space-time mean

- Implementation of probability sampling of times can be cumbersome
- *Space-time mean*: *linear trend model* or *any other model* (e.g. constant mean model) can be used to predict the temporal mean of the spatial means (i.e. the space-time mean)
- One-dimensional (universal) block-kriging, accounting for uncertainty in estimated spatial means
- Predicted space-time mean not model free!

Conclusions (1)

- For multi-purpose (national) monitoring, I recommend probability sampling of spatial sampling units
  - It enables model-free, unbiased estimation of spatial means (totals)
- Probability sampling of temporal sampling units undesirable for estimating temporal trends of spatial means (totals)
- Combination of probability sampling of spatial units and non-probability sampling of temporal units leads to hybrid sampling approach

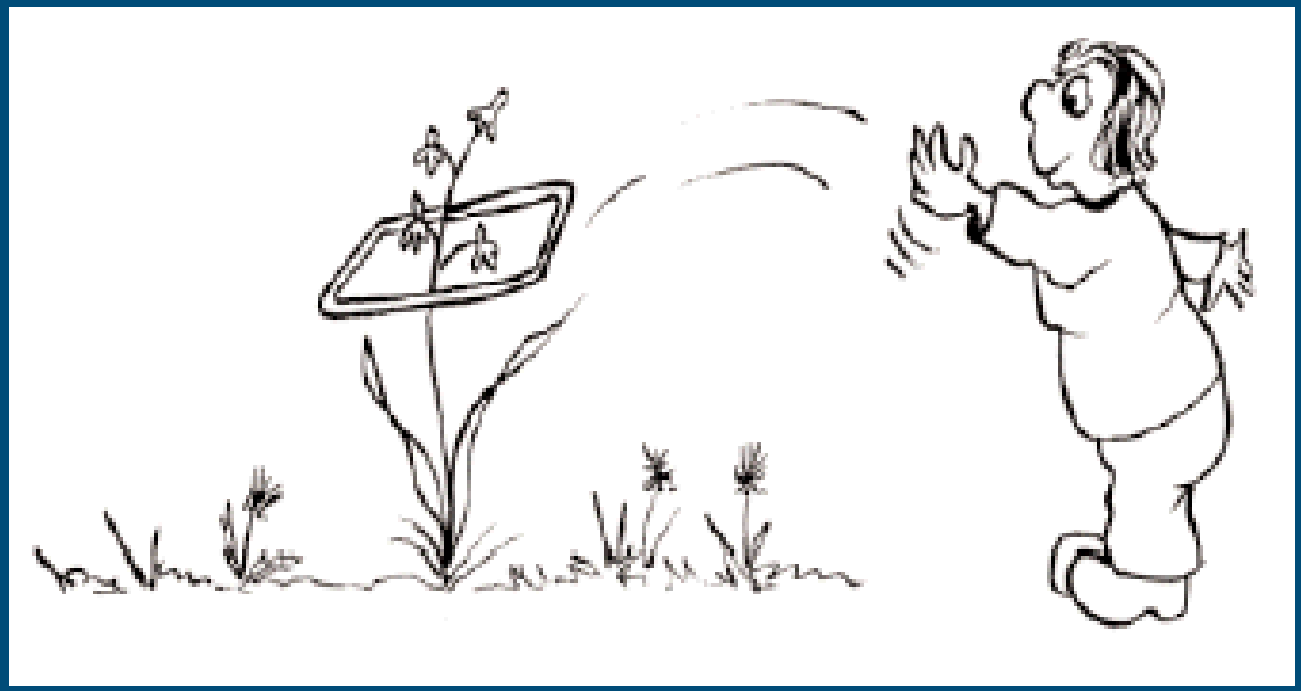
Conclusions (2)

- Hybrid sampling approach can also be used for estimating other statistical parameters such as space-time mean (total)
  - Estimate of space-time mean (total) not model free
- For the temporal trend of the spatial means a serially alternating design seems promising, but more research needed

References

- J.J. de Gruijter, D.J. Brus, M.F.P. Bierkens & M. Knotters, 2006. Sampling for Natural Resource Monitoring. Springer
- D.J. Brus & M. Knotters, 2008. Sampling design for compliance monitoring of surface water quality: A case study in a polder area. Water Res. Res. 44, W11410
- C.J.F. ter Braak, D.J Brus & E. Pebesma (2008) Comparing Sampling Patterns for Kriging the Spatial Mean Temporal Trend, JABES 13.
- D.J. Brus & J.J. de Gruijter. A hybrid design-based and model-based sampling approach to estimate temporal trends of spatial means, JABES (tentatively accepted)

Random sampling is not always probability sampling



- All units must have probability of beng selected > 0
- Selection probabilities must be known