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Effects of spatial pattern persistence on the performance of sampling designs for regional trend monitoring analyzed by simulation of space–time fields

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ABSTRACT

The effect of the persistence of spatial patterns on the performance of space–time sampling designs is explored by a simulation study. The performance is evaluated on the basis of the covariance matrix of the two parameters (intercept and slope) of a linear model for the change over time of the spatial means or totals. The evaluated sampling approach is hybrid, i.e. design-based estimation of spatial means from spatial probability samples is combined with time-series modelling of the spatial means. A simulation algorithm is presented for approximating the covariance matrix of the time-series model parameters from a full space–time model. Designs were evaluated on the basis of the determinant of this matrix and the variance of the estimated trend parameter. As a space–time model a sum-metric space–time variogram is used, the parameters of which are chosen such that the persistence of spatial patterns varies from nearly absent to very strong. Based on the extensive simulations, recommendations on the type of space–time design can most easily be made for situations with either very strong or no persistence of spatial patterns. With strong persistence the supplemented panel (SuP) design is recommendable. With no persistence the independent-synchronous (IS) and serially alternating (SA) designs are the best choice. These designs performed well with regard to both quality criteria. With moderate persistence of spatial patterns the choice of design type is more complicated. The IS and static-synchronous (SS) design performed best on one quality criterion, but worst on the other. Therefore, with moderate pattern persistence, the compromise designs, either SuP or SA, can be a good choice, unless one of the two quality criteria has priority. An R script is provided for *ex ante* evaluation of space–time designs in real-world applications.

1. Introduction

This paper deals with the sampling aspects of monitoring natural resources, while focussing on the selection of sampling locations and times for regional trend monitoring. In regional trend monitoring interest is in global parameters describing the status or trend of the sampled universe. Examples of global status parameters are the space–time mean or total. In this paper we are interested in the temporal trend of spatial means or totals.

An important decision in designing sampling schemes for monitoring is the number of sampling times and the number of sampling locations per sampling round. Given the available budget for monitoring, the more sampling times are planned, the fewer locations per sampling time can be afforded. Another important decision is how many locations should be revisited and when. de Gruijter et al. (2006) distinguish several basic types of space–time designs (Fig. 1). In a *static* design the sampling locations are fixed, but the observations are not synchronized (not shown). Reversely, in an *independent synchronous* design (hereafter referred to as IS-design) the observations are synchronized, but the sampling locations shift over time through the area. The spatial sample at a given time is selected independently from the spatial samples at the other times. No sampling locations are revisited. In a *static-synchronous* design (SS-design) the observations show a two-fold alignment: all sampling locations are revisited at the same times. This design is also known as a pure panel. A *supplemented panel* design (SuP-design) is a compromise between an independent synchronous and a static-synchronous design. Only part of the sampling locations are revisited at the subsequent sampling times. The remaining part is replaced by new locations, selected independently from the revisited locations and all locations of other times. Another hybrid design type is the *r*-period synchronous design, referred to as a *serially alternating*

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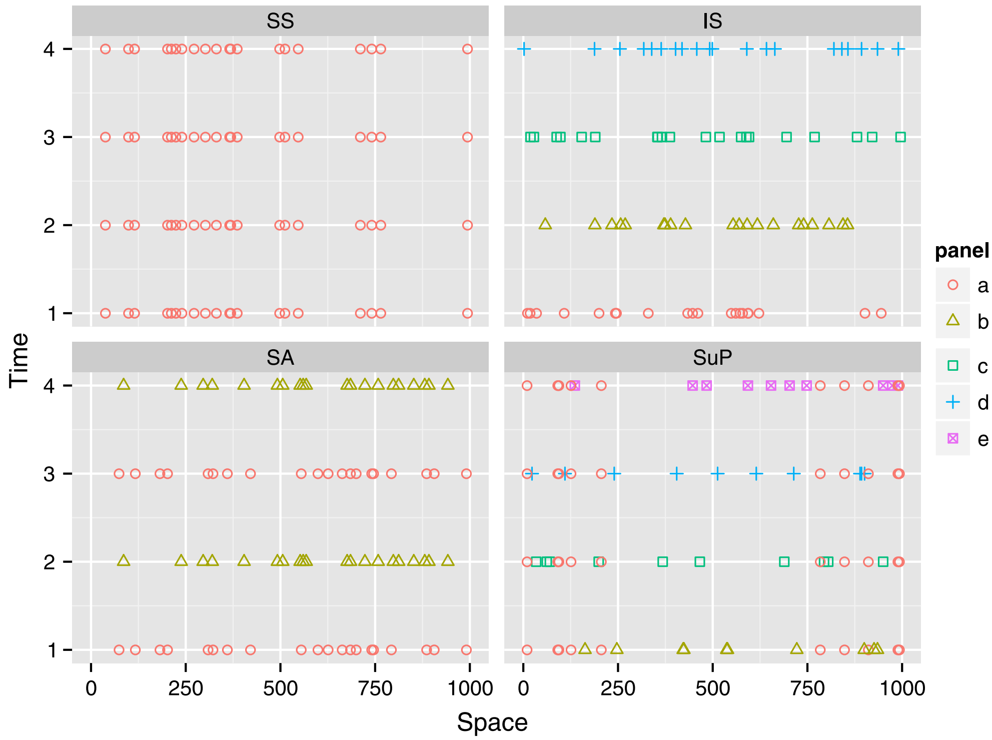

Fig. 1. Four space–time designs, static-synchronous (SS), independent synchronous (IS), serially alternating (SA) and supplemented panel (SuP).

design (SA-design) by Urquhart and Kincaid (1999). After some fixed number of sampling times no new locations are selected anymore, but existing locations are revisited in the same order. In Fig. 1 locations are revisited every second time. Other types of space–time designs exist, such as rotating panels, but these are not considered in this paper.

The aim of this paper is to get insight into the performance of space–time designs for estimating the temporal trend of spatial means or totals. These parameters can be important summary statistics in regional trend monitoring, think for instance of the temporal trend of the total soil organic carbon content in a country, or the trend of the global average air temperature. Needless to say that these statistics are less informative than a map depicting the time trend at point locations. However, for mapping time trends substantial sampling effort is needed, the budget for which might be lacking. One is then forced to accept a less ambitious aim.

The performance of the space–time designs is studied under several super-population models that lead to spatial patterns with different degrees of persistence. With strong persistence we mean that the spatial pattern at time t can be obtained by scaling (adding a constant and/or multiplication by a factor) the spatial pattern at time $t-1$, and adding a small noise term only. In other words, the spatial fields are strongly correlated in time. Examples of persistent patterns can be found, for instance, in soil science. Soil properties that are strongly determined by the parent material, such as cation exchange capacity and acidity, will exhibit persistent spatial patterns, as the redistribution of soil particles is generally small. On the other hand, ecological variables may show very dynamic spatial patterns, due to the migration of living species. Meteorological variables, such as precipitation, may also show dynamic patterns, depending on the level of aggregation in space and time.

Intuitively, with strong persistence, a static-synchronous design will be relatively inefficient for estimating space–time means. Repeated, collocated observations will be more redundant compared to observations from an independent synchronous design. So, with strongly persistent patterns we expect that independent synchronous designs outperform static-synchronous designs for estimating space–time means. However, it is questionable whether this also holds for estimating the temporal trend of the spatial mean. It is well-known that in Generalized Least Squares fitting of a simple linear model, the variance of the estimated trend (slope parameter) decreases with increasing covariance of the observations, while keeping the residual variance constant. The same effect might also occur in estimating a linear trend of spatial means. Besides, we are interested in the effect of the design type on the joint uncertainty about the model parameters, as quantified by the determinant of the covariance matrix of intercept and trend.

The space–time designs will be evaluated under the hybrid, design- and model-based, sampling approach (Brus and de Gruijter, 2012). In this hybrid approach design-based estimation of spatial means from spatial probability samples is combined with time-series modelling of the spatial means. This approach is of special interest for estimating global space–time parameters, such as space–time means (totals) or the trend of spatial means (totals), from a limited number (say several tens) of sampling locations per time. With these sample sizes calibration of a full space–time model may become rather speculative. Important advantages of the hybrid approach are its simplicity and robustness to model assumptions (Brus and de Gruijter, 2012).

This paper is organized as follows. First, we present the hybrid sampling approach. Then we describe a simulation algorithm for predicting the variance of the hybrid estimator from a geostatistical space–time model. This is followed by a simulation study in which we compare four basic types of space–time design under three space–time models with different persistence of spatial patterns. Then we shortly describe an R script for *ex ante* evaluation of space–time designs in real-world case studies. This R script is applied in a case study on radiation monitoring in the northwestern part of Germany, the results of which are shortly described in a separate section. In a final section the results of the simulation and case study are discussed, and some conclusions are drawn.