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Sequential spatial analysis of large datasets with applications to modern earthwork compaction roller measurement values

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ABSTRACT

In the context of road construction, modern earthwork compaction rollers equipped with sensors collect a virtually continuous flow of soil property measurements. This sequential, spatial data can be utilized to improve the quality control of the compaction process through the introduction of intelligent compaction. These roller measurement values are observed indirectly through non-linear measurement operators, non-stationary, inherently multivariate with complex correlation structures, and collected in huge quantities. The problem of modeling and estimation in a spatially correlated setting with large amounts of data is well known and many approaches can be found in the literature. Very few studies have been completed investigating sequential, spatially correlated data outside of a point process framework. We propose a sequential, spatial mixed-effects model and develop a sequential, spatial backfitting algorithm to estimate fixed effects and several independent, spatially correlated processes. This new algorithm is demonstrated in a simulation study and applied to earthwork compaction data.

1. Introduction

Sequential, spatial processes are random process in space and time that occur in a consecutive manner. Such processes are often complex and care is needed in modeling to ensure the identifiability of model parameters and maintain computational feasibility. To maintain the computational feasibility of a model, researchers must limit the generality of the statistical model to handle the complex nature of such data. Complexities in the modeling stem from data observed indirectly

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through non-linear measurement operators, non-stationary data, and/or inherently multivariate data with sequential, complex correlation structures. To add to the complexity, the data is usually collected in huge quantities.

An example of such data is modern earthwork compaction as employed for road construction. Modern earthwork compaction rollers are equipped with a sensor measuring soil density and providing data in a virtually continuous flow. These data, coupled with on-board GPS measurements, together termed the roller measurement value (RMV), are large, dense, and spatially correlated. The data are also considered as a sequential spatial process because the construction process requires several layers of material to be compacted, one on top of another, consecutively.

Many researchers have proposed dynamical spatial models and estimation procedures. Waller et al. (1997) develop spatio-temporal models for lung cancer mortality. Wikle et al. (1998) examine climatological data in a spatio-temporal framework. Bailey and Krzanowski (2012) give an overview of several approaches to multivariate geostatistical data and Christensen and Sain (2012) apply latent variable modeling to climate models. Cressie and Wikle (2011) propose a very general hierarchical, dynamical spatio-temporal model (DSTM) setup. For more, see the bibliographic notes of Section 7.8 of their book.

Earthwork compaction and RMVs are a novel and challenging application of spatio-temporal modeling. The data collected at each sequential time step is an aggregation of the current and several previous time steps. Any model chosen must be sufficiently flexible to extract information from the current time step from this aggregated data. There is also a desire to model multiple ranges of spatial variation in RMVs as each layer could potentially have a different range of variation. Due to the unique, sequential nature of modern earthwork compaction, previous spatio-temporal models developed in the literature do not adequately represent the process under consideration. Data and process models mentioned in Section 7.8 of Cressie and Wikle (2011) are too distinct from the current application and a new model must be developed.

A general, sequential, spatial mixed-effects model is proposed. Strategies for fitting such a model and estimating model parameters for large amounts of data are discussed. There are two aspects to this estimation. First, sparse matrices and finite-range covariances can be utilized to deal with large covariance structures as in Furrer and Sain (2009). Second, many of the covariance matrices in this model can be written in quasi-Kronecker structure as in Heersink and Furrer (2012), greatly decreasing the computation requirements of inverse calculations.

The complex, sequential, spatial data collected from earthwork compaction is presented in Section 2. Section 3 introduces a sequential, spatial mixed-effects model and Section 4 develops two backfitting algorithms for such models. Calculation and computation of covariance structures and alternative estimation procedures are also addressed. A simulation study of the backfitting algorithm is presented in Section 5. The algorithm is then applied to earthwork compaction data in Section 6. Finally, in Section 7, current and future research outlook is discussed.

2. Modern earthwork compaction roller measurement values

Modern earthwork compaction rollers are employed to compact material during road construction. A vibrating drum with a diameter of approximately 1 m and length of approximately 2 m traverses the compaction site in several adjacent driving lanes. These rollers collect compaction and location data as they operate. This data, termed the roller measurement value (RMV), can be modeled as a spatial process. The goal of such a model is to improve the quality of the compaction process. This is achieved by improving the identification of weak or soft spots and by ensuring a homogeneous compaction.

The first modern earthwork compaction rollers designed for continuous compaction control (CCC) were used for construction starting in the 1970s in the European community. CCC is a method of documenting compaction and is used to achieve homogeneous compaction in a minimum time (Thurner and Sandström, 2000). Rudimentary intelligent compaction (IC) technology was first available in the late 1990s. IC is an automated system that adjusts roller operation parameters for optimal compaction based on CCC data (Scherocman et al., 2007).

Roller manufacturer Ammann developed their measurement value in the late 1990s. Ammann uses the drum/soil assembly model depicted in Fig. 1, where m_f and m_d are the masses of the frame