

## ARTICLE TEMPLATE

# An Application of Spatiotemporal Modeling to Finite Population Abundance Prediction

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## ARTICLE HISTORY

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## ABSTRACT

Insert abstract here.

## KEYWORDS

spatial; temporal; kriging;

## 1. Introduction

### 1.1. Motivation

Moose surveys in Alaska and western Canada are often performed annually in many regions. The primary goal of these surveys is to predict moose abundance, the total number of moose, in the region. Because of time and money constraints, only some areas (sites) in the region of interest are selected to be in the survey. Biologists fly to these selected sites, count the number of moose, and can then use a spatial statistical model to find a prediction for the finite abundance for that year (Ver Hoef 2008).

Though these surveys are annual, each survey is analysed completely independently of surveys from previous years (e.g. Gasaway et al. 1986; Kellie and DeLong 2006; Boertje et al. 2009; Peters et al. 2014). For example, a model for a survey conducted in the year 2019 only uses counts on sites that were sampled in that year. However, using counts from previous years in a model that incorporates both spatial and temporal correlation (spatiotemporal) could result in a prediction for the realized total or mean that is more precise than predictions from a spatial model using only counts from the most recent survey year.

Though the framework of the motivation is given with an example on moose surveys, this type of analysis could be useful for many examples involving prediction in a finite region with spatial sites that are surveyed regularly.

### 1.2. Background

- Add paragraph about background of spatiotemporal models

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Prediction for a total, a subset of the total, or a mean in a finite number of spatial locations should incorporate a finite population correction to the variance of the predictor (Ver Hoef 2008; Higham et al. 2021). In the context of ecological monitoring in spatiotemporal prediction, we are often most interested in predicting the total abundance for the most recent year of the survey. In this case, the finite population correction should adjust based on the number of sites surveyed in the current year of the survey, so that, for example, the prediction variance is zero if all sites in the current year are sampled.

The rest of this paper is organized as follows. In Section 2, we couple spatiotemporal modeling with finite population prediction to develop the Best-Linear-Unbiased-Predictor for any linear function of site abundance, including the total abundance across all sites. In Section 3, we apply the predictor to a moose data set in the TOC region of Alaska. In Section 4, we conduct a brief simulation study to examine the properties of the predictor. Finally, in Section 5, we conclude and give directions for future research.

## 2. Methods

We now give details on the development of the predictor for abundance. We first detail the spatiotemporal model. Because of the heavy use of notation in the spatiotemporal model development, we first introduce a purely spatial model (without temporal variability) and a purely temporal model (without spatial variability). We then build the spatiotemporal model and develop a finite population correction factor to give a Best-Linear-Unbiased-Predictor (BLUP) and its prediction variance for total abundance in a given year.

### 2.1. Spatial Model

First, we consider a spatial linear model for a response variable  $Y_s(\mathbf{s}_i)$ ,  $i = 1, 2, \dots, n_s$ , where the vector  $\mathbf{s}_i$  contains the coordinates for the  $i^{th}$  spatial site location and  $n_s$  is the number of spatial locations. Then, a spatial model for  $\mathbf{y}_s(\mathbf{s}_i)$ , a vector of the  $Y_s(\mathbf{s}_i)$ , is

$$\mathbf{y}_s(\mathbf{s}_i) = \mathbf{X}_s \boldsymbol{\beta}_s + \boldsymbol{\epsilon}_s(\mathbf{s}_i), \quad (1)$$

where  $\mathbf{X}_s$  is a design matrix for the fixed effects and  $\boldsymbol{\beta}_s$  is a parameter vector of fixed effects. The error  $\boldsymbol{\epsilon}_s(\mathbf{s}_i)$  can be decomposed into spatial error and independent error components:

$$\boldsymbol{\epsilon}_s(\mathbf{s}_i) = \mathbf{Z}_s \boldsymbol{\delta} + \mathbf{Z}_s \boldsymbol{\gamma}. \quad (2)$$

In equation 2,  $\mathbf{Z}_s$  is an  $n_s \times n_s$  matrix of 0's and 1's, where the values in a row corresponding to a data point at location  $\mathbf{s}_i$  are a 1 in the  $i^{th}$  column and a 0 in all other columns. Note that, without temporal replication,  $\mathbf{Z}_s$  is the identity matrix so is not necessary to include in equation 2.  $\boldsymbol{\delta}$  is a random vector independent of  $\boldsymbol{\gamma}$  with mean  $\mathbf{0}$  and covariance  $cov(\boldsymbol{\delta}) = \sigma_\delta^2 \mathbf{R}_s$ , where  $\mathbf{R}_s$  is a spatial correlation matrix and  $\sigma_\delta^2$  is sometimes called the spatial partial sill.  $\boldsymbol{\gamma}$  is also a random vector with mean  $\mathbf{0}$  but has covariance  $cov(\boldsymbol{\gamma}) = \sigma_\gamma^2 \mathbf{I}_s$ , where  $\mathbf{I}_s$  is the  $n_s \times n_s$  identity matrix and  $\sigma_\gamma^2$  is sometimes called the spatial nugget.

There are many common parameterizations of  $\mathbf{R}_s$ . One common assumption is to assume the covariance function generating  $\mathbf{R}_s$  is stationary and isotropic, depending only on the spatial distance between the data points. For example, the exponential covariance function is defined as follows. For observations at locations  $i$  and  $i'$  at  $h_{ii'}$  distance apart, row  $i$  and column  $i'$  of  $\mathbf{R}_s$  is equal to

$$\exp(-h_{ii'}/\phi), \quad (3)$$

where  $\phi$  is a spatial range parameter controlling the decay rate of the covariance as distance between two data points increases.

## 2.2. Temporal Model

Next, we consider a temporal linear model for a response variable  $Y_t(t_j)$ ,  $j = 1, 2, \dots, n_t$ , where the vector  $t_j$  contains the time for the  $j^{th}$  time point and  $n_t$  is the number of time points in the data. Then, a temporal model for  $\mathbf{y}_t(t_j)$ , a vector of the  $Y_t(t_j)$ , is

$$\mathbf{y}_t(t_j) = \mathbf{X}_t \boldsymbol{\beta}_t + \boldsymbol{\epsilon}_t(t_j), \quad (4)$$

where  $\mathbf{X}_t$  is a design matrix for the fixed effects and  $\boldsymbol{\beta}_t$  is a parameter vector of fixed effects. The error  $\boldsymbol{\epsilon}_t(t_j)$  can be decomposed into temporal error and independent error components:

$$\boldsymbol{\epsilon}_t(t_j) = \mathbf{Z}_t \boldsymbol{\tau} + \mathbf{Z}_t \boldsymbol{\eta}. \quad (5)$$

In equation 5,  $\mathbf{Z}_t$  is an  $n_t \times n_t$  matrix of 0's and 1's, where the values in a row corresponding to a data point at time point  $t_j$  are a 1 in the  $j^{th}$  column and a 0 in all other columns. Note that, without spatial replication,  $\mathbf{Z}_t$  is the identity matrix so is not necessary to include in equation 5.  $\boldsymbol{\tau}$  is a random vector independent of  $\boldsymbol{\eta}$  with mean  $\mathbf{0}$  and covariance  $cov(\boldsymbol{\tau}) = \sigma_\tau^2 \mathbf{R}_t$ , where  $\mathbf{R}_t$  is a spatial correlation matrix and  $\sigma_\tau^2$  is sometimes called the temporal partial sill.  $\boldsymbol{\eta}$  is also a random vector with mean  $\mathbf{0}$  but has covariance  $cov(\boldsymbol{\eta}) = \sigma_\eta^2 \mathbf{I}_t$ , where  $\mathbf{I}_t$  is the  $n_t \times n_t$  identity matrix and  $\sigma_\eta^2$  is sometimes called the temporal nugget.

There are many common parameterizations of  $\mathbf{R}_t$ . One common assumption is to assume the covariance function generating  $\mathbf{R}_t$  is stationary, depending only on the temporal distance between the data points. For example, the exponential covariance function is defined as follows. For observations at time points  $j$  and  $j'$  at  $m_{jj'}$  units apart, row  $j$  and column  $j'$  of  $\mathbf{R}_t$  is equal to

$$\exp(-m_{jj'}/\rho), \quad (6)$$

where  $\rho$  is a temporal range parameter controlling the decay rate of the covariance as time units between two data points increases. Note that the exponential form of  $\mathbf{R}_t$  is equivalent to an AR(1) (CITE) time series model if the time points are equally spaced and the correlation parameter is greater than zero.

### 2.3. Spatiotemporal Model

We now combine the spatial error components and temporal error components to formulate a model for data collected across both space and time. Let  $Y(\mathbf{s}_i, t_j)$ ,  $i = 1, 2, \dots, n_s$  and  $j = 1, 2, \dots, n_t$ , be a random variable, where  $\mathbf{s}_i$  and  $n_s$  are defined in subsection 2.1 and  $t_j$  and  $n_t$  are defined in subsection 2.2. With each spatial location at each time point, the total number of data points is  $n_s \cdot n_t \equiv N$ . Then, a spatiotemporal model for  $\mathbf{y}(\mathbf{s}_i, t_j)$ , a vector of the  $Y(\mathbf{s}_i, t_j)$ , is

$$\mathbf{y}(\mathbf{s}_i, t_j) = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\epsilon}(\mathbf{s}_i, t_j), \quad (7)$$

where  $\mathbf{X}$  is a design matrix for the fixed effects and  $\boldsymbol{\beta}$  is a parameter vector of fixed effects. The error  $\boldsymbol{\epsilon}(\mathbf{s}_i, t_j)$  can be decomposed into spatial and temporal components, as in Dumelle et al. (2021). Perhaps the simplest model would be to simply model the error  $\boldsymbol{\epsilon}(\mathbf{s}_i, t_j)$  by summing the spatial and temporal errors defined in equation 2 and equation 5:

$$\boldsymbol{\epsilon}(\mathbf{s}_i, t_j) = \mathbf{Z}_s\boldsymbol{\delta} + \mathbf{Z}_s\boldsymbol{\gamma} + \mathbf{Z}_t\boldsymbol{\tau} + \mathbf{Z}_t\boldsymbol{\eta}. \quad (8)$$

With spatial and temporal replication,  $\mathbf{Z}_s$  is an  $N \times n_s$  matrix while  $\mathbf{Z}_t$  is an  $N \times n_t$  matrix. However, even when the spatial covariance function generating  $\mathbf{Z}_s\boldsymbol{\delta} + \mathbf{Z}_s\boldsymbol{\gamma}$  and the temporal covariance function generating  $\mathbf{Z}_t\boldsymbol{\tau} + \mathbf{Z}_t\boldsymbol{\eta}$  are strictly positive definite, the sum of the spatial and temporal components is not necessarily strictly positive definite (Myers and Journel (1990)).

A more flexible, given in Dumelle et al. (2021), is a product-sum linear mixed model

$$\mathbf{y}(\mathbf{s}_i, t_j) = \mathbf{X}\boldsymbol{\beta} + \mathbf{Z}_s\boldsymbol{\delta} + \mathbf{Z}_s\boldsymbol{\gamma} + \mathbf{Z}_t\boldsymbol{\tau} + \mathbf{Z}_t\boldsymbol{\eta} + \boldsymbol{\omega} + \boldsymbol{\nu}, \quad (9)$$

In equation 9,  $\boldsymbol{\omega}$  is a random vector of length  $N$  with mean  $\mathbf{0}$  and covariance  $cov(\boldsymbol{\omega}) = \sigma_\omega^2 \mathbf{R}_{st}$  where  $\mathbf{R}_{st}$  is a spatiotemporal correlation matrix and  $\sigma_\omega^2$  is sometimes called the spatiotemporal partial sill.  $\boldsymbol{\nu}$  is also a random vector of length  $n$  with mean  $\mathbf{0}$  but has covariance  $cov(\boldsymbol{\nu}) = \sigma_\nu^2 \mathbf{I}_{st}$ , where  $\mathbf{I}_{st}$  is the  $N \times N$  identity matrix and  $\sigma_\nu^2$  is sometimes called the spatiotemporal nugget.

A common formulation for  $\mathbf{R}_{st}$  is

$$\mathbf{R}_{st} \equiv \mathbf{Z}_s \mathbf{R}_s \mathbf{Z}'_s \odot \mathbf{Z}_t \mathbf{R}_t \mathbf{Z}'_t,$$

where  $\odot$  is the Hadamard product operator.

If we assume that  $\boldsymbol{\delta}$ ,  $\boldsymbol{\gamma}$ ,  $\boldsymbol{\tau}$ ,  $\boldsymbol{\eta}$ ,  $\boldsymbol{\omega}$ , and  $\boldsymbol{\nu}$  are mutually independent of each other, then

$$var(\mathbf{y}) \equiv \boldsymbol{\Sigma} = \sigma_\delta^2 \mathbf{Z}_s \mathbf{R}_s \mathbf{Z}'_s + \sigma_\gamma^2 \mathbf{Z}_s \mathbf{I}_s \mathbf{Z}'_s + \sigma_\tau^2 \mathbf{Z}_t \mathbf{R}_t \mathbf{Z}'_t + \sigma_\eta^2 \mathbf{Z}_t \mathbf{I}_t \mathbf{Z}'_t + \sigma_\omega^2 \mathbf{R}_{st} + \sigma_\nu^2 \mathbf{I}_{st}. \quad (10)$$

Note that the model in equation 9 does not have any distributional assumptions: we only need to specify the mean and variance of  $\mathbf{y}$ . However, if we also assume that  $\mathbf{y}$  is multivariate normal (with mean  $\mathbf{X}\boldsymbol{\beta} \equiv \boldsymbol{\mu}$  and variance  $\boldsymbol{\Sigma}$  (Equation 10)), then all model parameters can be easily estimated with Maximum Likelihood or Restricted Maximum Likelihood.

## 2.4. Finite Population Kriging

The model in equation 9 is for the  $N$ -length vector  $\mathbf{y}$ . However, often we do not have the resources to sample or observe every spatial site in every year. Throughout this section, let the subscript  $o$  denote observations that were observed (both past and present), the subscript  $u$  denote observations that were unobserved, and the subscript  $a$  denote all observations. Then, we can re-order the response vector so that

$$\mathbf{y}_a = [\mathbf{y}'_u, \mathbf{y}'_o]'. \quad (11)$$

Let  $\tilde{\mathbf{y}}_a = [\tilde{\mathbf{y}}'_u, \tilde{\mathbf{y}}'_o]'$  denote the fixed, realized values of the response variable for one data-generating process. Our primary goal is to use the model developed in equation 9 to predict values for  $\tilde{\mathbf{y}}_u$  from the observed data in  $\tilde{\mathbf{y}}_o$ . That is, we want to find optimal weights  $\mathbf{a}'$  to apply to the observed data  $\mathbf{a}'\tilde{\mathbf{y}}_o$ , such that  $\mathbf{a}'\mathbf{y}_o$  is the Best Linear Unbiased Predictor (BLUP) for  $\mathbf{b}'_a\mathbf{y}_a$ . For example, if we are interested in the total abundance across all years, then  $\mathbf{b}_a$  is a column vector of 1's, so that we are adding up all values of the response for a predictor of total abundance.

Unbiasedness implies that  $E(\mathbf{q}'\mathbf{y}_o) = E(\mathbf{b}'_a\mathbf{y}_a)$  for all  $\beta$ . So, denoting  $\mathbf{X}_o$  as the design matrix for sampled sites,  $\mathbf{q}'\mathbf{X}_o\beta = \mathbf{b}'\mathbf{X}\beta$  for every  $\beta$ , implying that  $\mathbf{q}'\mathbf{X}_o = \mathbf{b}'\mathbf{X}_a$ .

The kriging weights are then found by finding  $\boldsymbol{\lambda}_s$ , an  $n_o \times 1$  vector, such that

$$E\{(\mathbf{q}'\mathbf{y}_o - \mathbf{b}'_a\mathbf{y}_a)(\mathbf{q}'\mathbf{y}_o - \mathbf{b}'_a\mathbf{y}_a)\} - E\{(\boldsymbol{\lambda}'_o\mathbf{y}_o - \mathbf{b}'_a\mathbf{z}_a)(\boldsymbol{\lambda}'_o\mathbf{y}_o - \mathbf{b}'_a\mathbf{y}_a)\} \quad (12)$$

is greater than 0 for all  $\mathbf{q}'$ . The prediction equations are

$$\begin{pmatrix} \Sigma_{o,o} & \mathbf{X}_o \\ \mathbf{X}'_o & 0 \end{pmatrix} \begin{pmatrix} \boldsymbol{\lambda} \\ m \end{pmatrix} = \begin{pmatrix} \Sigma_{o,o} & \Sigma_{o,u} \\ \mathbf{X}'_o & \mathbf{X}'_u \end{pmatrix} \begin{pmatrix} \mathbf{b}_o \\ \mathbf{b}_u \end{pmatrix}, \quad (13)$$

where again the subscripts  $o$  and  $u$  denote observed and unobserved data points. For example, letting  $n_o$  denote the number of observed data points,  $\Sigma_{o,o}$  denotes the  $n_o \times n_o$  submatrix of  $\Sigma$  corresponding only to rows and columns of observed data points and  $\Sigma_{u,o}$  denotes the  $(N - n_o) \times n_o$  submatrix of  $\Sigma$  corresponding to rows of data points that were not observed and columns of observations that were observed. Then, the optimal prediction weights  $\boldsymbol{\lambda}_o$  are an  $n_o \times 1$  vector:

$$\boldsymbol{\lambda}'_o = \mathbf{b}'_o + \mathbf{b}'_u (\Sigma_{u,o} \Sigma_{o,o}^{-1}) - \mathbf{b}'_u (\Sigma_{u,o} \Sigma_{o,o}^{-1}) \mathbf{X}_o (\mathbf{X}'_o \Sigma_{o,o}^{-1} \mathbf{X}_o)^{-1} \mathbf{X}'_o \Sigma_{o,o}^{-1} + \mathbf{b}'_u \mathbf{X}'_u (\mathbf{X}'_o \Sigma_{o,o}^{-1} \mathbf{X}_o)^{-1} \mathbf{X}_o \Sigma_{o,o}^{-1}. \quad (14)$$

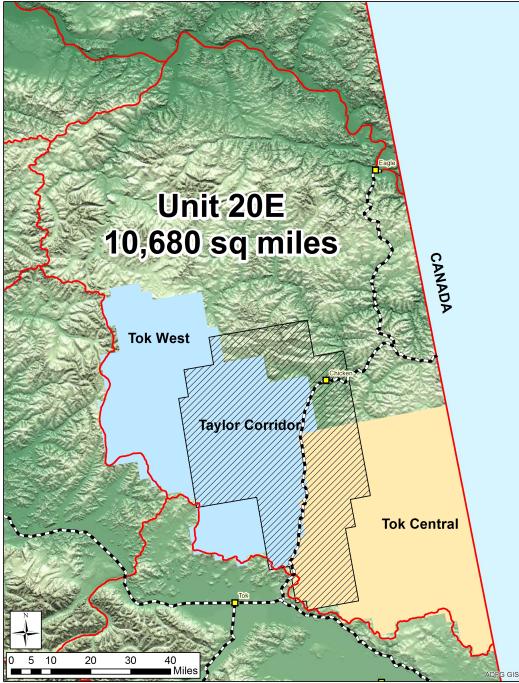
Then, the BLUP for  $\mathbf{b}'_a\mathbf{y}_a$  is

$$\hat{\mathbf{b}'_a\mathbf{y}_a} = \boldsymbol{\lambda}'_o \tilde{\mathbf{y}}_o, \quad (15)$$

with a prediction variance of

$$E((\boldsymbol{\lambda}'_o\mathbf{y}_o - \mathbf{b}'_a\mathbf{y}_a)(\boldsymbol{\lambda}'_o\mathbf{y}_o - \mathbf{b}'_a\mathbf{y}_a)) = \boldsymbol{\lambda}'_o \Sigma_{o,o} \boldsymbol{\lambda}_o - 2\mathbf{b}'_a \Sigma_{a,o} \boldsymbol{\lambda}_o + \mathbf{b}'_a \Sigma_{a,a} \mathbf{b}_a. \quad (16)$$

A common prediction of interest is the total abundance in the most recent time point of the survey. Then,  $\mathbf{b}_a$  is a vector of 1's and 0's, where the  $k^{th}$  element of  $\mathbf{b}_a$  is a 1 if the  $k^{th}$  element of  $\mathbf{y}_a$  is from the most current time point of the survey and



**Figure 1.** A map of the Taylor Corridor in the TOK region of Alaska.

the  $k^{th}$  element of  $\mathbf{b}_a$  is a 0 otherwise. If we order  $\mathbf{y}_a$  with the unobserved, past data points first, the unobserved, current data points second, the observed, past data points third, and the observed, current data points fourth, then

$$\mathbf{b}_a = [\mathbf{b}'_{up}, \mathbf{b}'_{uc}, \mathbf{b}'_{op}, \mathbf{b}'_{oc}]' = [0', \mathbf{1}', 0', \mathbf{1}']', \quad (17)$$

where the subscripts  $up$ ,  $uc$ ,  $op$ , and  $oc$  denote unobserved sites in past years, unobserved sites in current years, observed sites in past years, and observed sites in current years, respectively.

$\boldsymbol{\lambda}_o$  can then be rewritten as

$$\boldsymbol{\lambda}'_o = \mathbf{b}'_o + \mathbf{b}'_{uc}(\boldsymbol{\Sigma}_{uc,o}\boldsymbol{\Sigma}_{o,o}^{-1}) - \mathbf{b}'_{uc}(\boldsymbol{\Sigma}_{uc,o}\boldsymbol{\Sigma}_{o,o}^{-1})\mathbf{X}_o(\mathbf{X}'_o\boldsymbol{\Sigma}_{o,o}^{-1}\mathbf{X}_o)^{-1}\mathbf{X}'_o\boldsymbol{\Sigma}_{o,o}^{-1} + \mathbf{b}'_{uc}\mathbf{X}'_{uc}(\mathbf{X}'_o\boldsymbol{\Sigma}_{o,o}^{-1}\mathbf{X}_o)^{-1}\mathbf{X}_o\boldsymbol{\Sigma}_{o,o}^{-1}. \quad (18)$$

with a prediction variance of

$$\boldsymbol{\lambda}'_o\boldsymbol{\Sigma}_{o,o}\boldsymbol{\lambda}_o - 2\mathbf{b}'_c\boldsymbol{\Sigma}_{c,o}\boldsymbol{\lambda}_o + \mathbf{b}'_c\boldsymbol{\Sigma}_{c,c}\mathbf{b}_c, \quad (19)$$

where  $c$  denotes observations in the most current time point.

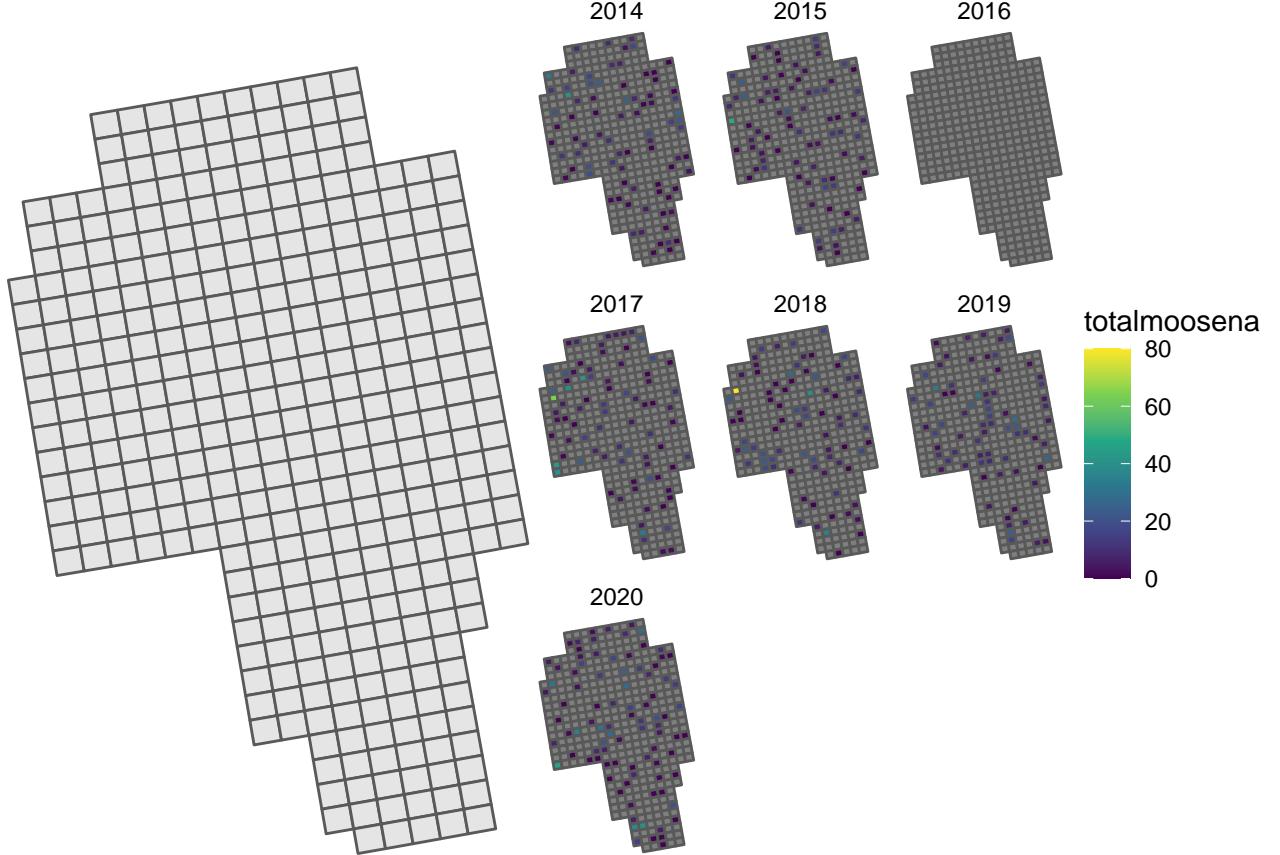
### 3. Application

#### 3.1. Data Description

Abundance surveys are performed in the Taylor Corridor of the TOK region of Alaska annually (Figure 1). In particular, surveys were conducted every year from 2014 through 2020, except for the year 2016, during which there was not sufficient snow

cover to perform a survey. There are a total of 381 unique spatial locations, which we refer to as "sites," and a total of 7 unique time points in the data set, including the missing year of 2016.

In each year of the survey, an aerial team of biologists selects some of the 381 sites to survey. The number of sites in the sampling frame that are selected varies from a low of 76 in the year 2019 to a high of 90 in the year 2020. Throughout the 7 unique time points, some sites are surveyed as many as four or five different times while others are never surveyed.



Before each the survey begins in each year, biologists stratify the sites into a "HIGH" stratum and a "LOW" stratum. There are 230 sites in the "HIGH" stratum while there are 151 sites in the "LOW" stratum. A map of the sites in the TOK region is given in Figure (make figure and put in figure number).

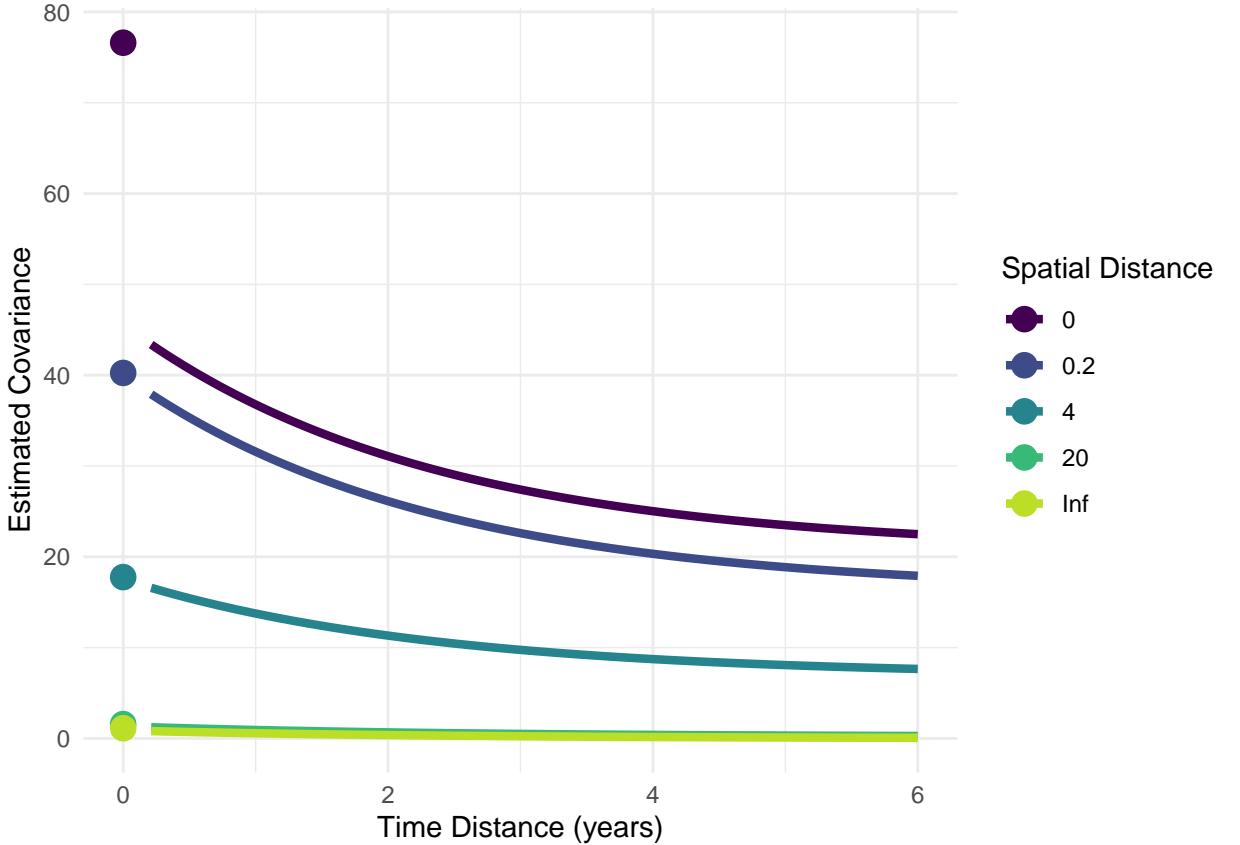
### 3.2. Model Fitting

We fit the product-sum covariance model defined in equation 9 using REML, with stratum as a covariate in the design matrix, an exponential spatial correlation structure defined in 3, and an exponential temporal correlation structure defined in 6. Table 1 gives the estimated parameters from the model fit.

	$\hat{\sigma}_\delta^2$	$\hat{\phi}$	$\hat{\sigma}_\gamma^2$	$\hat{\sigma}_\tau^2$	$\hat{\rho}$	$\hat{\sigma}_\eta^2$	$\hat{\sigma}_\omega^2$	$\hat{\sigma}_\nu^2$
1	16.9	13.3	3.8	0.9	6.9	0.2	30.8	24.0

**Table 1.** Table of estimated covariance parameters in the model.

To help interpret what some of these fitted covariance parameter estimates mean,



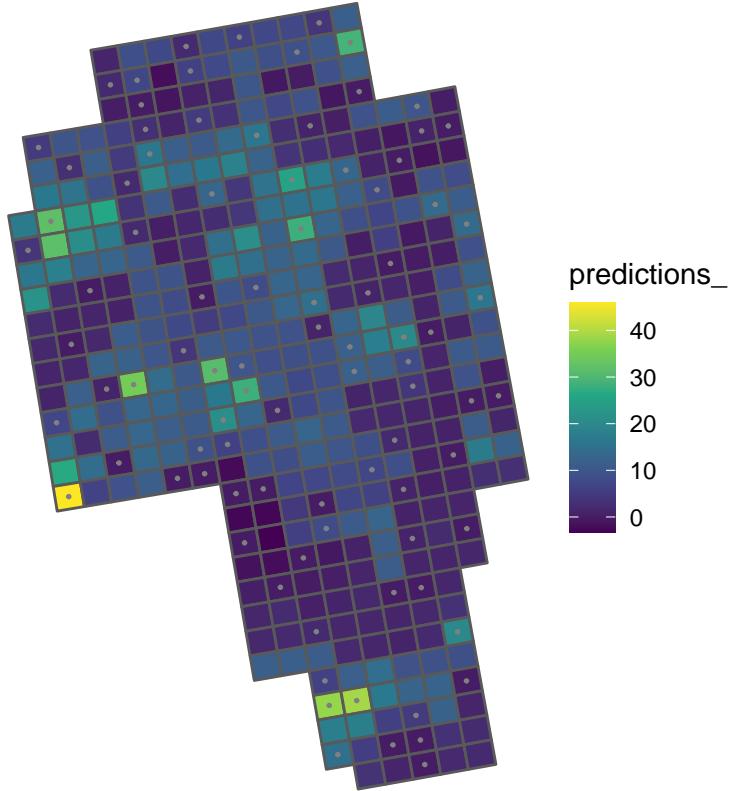
**Figure 2.** Estimated covariance from the fitted parameters in a product-sum model.

we can construct a fitted covariance plot (Figure 2). Note that the centroids of two sites directly adjacent to one another are about 4 units apart. So, we see from Figure @ref(fig:covplot) that the covariance between random response values from sites that are adjacent is estimated to be about 20 units if the response values are in the same year. The covariance between random responses values from adjacent sites is estimated to be about 10 units if the response values are 6 years apart. As the spatial distance between two sites increases, the covariance between the response values decreases to 0. In fact, the model estimates that, no matter what the time distance is, when two response values are 20 or more units apart, the covariance is nearly 0 units.

The estimated vector of fixed effects, using "HIGH" as the reference group, is  $\beta = (11.26, -9.76)$ . Therefore the overall mean for sites in the "HIGH" stratum is estimated to be 11.26 moose while the overall mean for sites in the "LOW" stratum is estimated to be 1.5 moose.

### 3.3. Prediction

We now use the model in subsection 3.2 to predict the total abundance across all sites in the year 2020, the most recent year of the survey. Plugging in estimates of the covariance parameters into equations 18 and 19 and letting elements of  $\mathbf{b}_a$  be 1's for data points in 2020 and 0's otherwise, we obtain a prediction of 2874 moose and a standard error of 234 moose. A 90% normal-based prediction interval for the total abundance in 2020 is (2489, 3259) moose. Sitewise predictions for sites in 2020 are



**Figure 3.** A map of the predictions for the sites in the year 2020.

given in the map in Figure 3.

For comparison, we use the spatial **sptotal** package (CITE) to compute the prediction for the total abundance of moose in the year 2020 (CITE Ver Hoef 2008). We also use the standard simple random sampling estimator  $\bar{y} \cdot \frac{n_s}{n_o}$ , where  $\bar{y}$  is the sample mean for the data points in 2020,  $n_s$  is the total number of sites in 2020, and  $n_o$  is the number of observed data points in 2020. The simple random sampling estimator has a standard error for the total abundance of  $n_s^2 \cdot \frac{\hat{\sigma}^2}{n_o} \cdot (1 - \frac{n_o}{n_s})$ .

For the purely spatial model, the prediction for the total number of moose in 2020 in the region is 2870 moose with a standard error of 319 moose. For the simple random sampling estimator, the estimated total number of moose in 2020 in the region is 3052 with a standard error of **se\_srs**. While the predictions for the total are similarly across the three methods, we see that the spatiotemporal model is most efficient ( $SE = 234$ ). We lose some of that efficiency by ignoring the data in previous years but still assuming that the data are spatially correlated (as in the model fit with **sptotal**). And, we lose even more efficiency by taking advantage of neither the temporal nor the spatial correlation (as in the simple random sample estimator).

Then, use it for every year since (without multiple comparisons)

Mention Bayesian

Moose surveys in the TOC region were historically analyzed without explicitly using any data from surveys in past years. Therefore, we compare the spatiotemporal prediction and prediction interval with a spatial model fit with the **sptotal** package using only the data from the year 2020. The prediction total abundance is 2888 moose with a 95% prediction interval of (2306, 3469) moose. We see that the predictions are somewhat similar, but that, because the strictly spatial analysis ignores information

from past years, the prediction interval for the spatiotemporal analysis is more narrow.

#### 4. Simulation

- possibly include `sptotal` (on current year only) and `SRS` (on current year only) as reference comparisons.

For a preliminary simulation, we use a grid of 100 spatial sites and 5 time points. The spatiotemporal process is simulated as a sum-with-error model with an exponential spatial correlation structure and an exponential temporal correlation structure with the following parameters

The mean is

- $\beta = 10$ .

The spatial parameters are

- $\sigma_\delta^2 = 0.9$ ,
- $\sigma_\gamma^2 = 0.1$ ,
- $\phi = 5$ .

The temporal parameters are

- $\sigma_\tau^2 = 0.7$ ,
- $\sigma_\eta^2 = 0.3$ ,
- $\rho = 0.8$ .

And, the spatiotemporal nugget is

- $\sigma_\nu^2 = 0.4$ .

The sample size  $n$  is 100 (of the 500 total data points). For 100 iterations, the percentage of 90% prediction intervals that covered the true total was 81%.

There are a few plausible reasons for this low coverage:

- there is something incorrect about the method or code used.
- the sample size is only 100 sites, meaning that, on average, only 20 sites get selected per year. This small sample size may mean that the 8 parameters cannot be estimated accurately. I believe that this is the actual cause of the lower than nominal coverage and hope to do a larger simulation study next.
- only 100 simulations were done.

Hampering investigation of this is the fact that the simulations take a long time to run. The `stmodel` package will be very helpful for this, as we can replace the slow code for fitting the spatiotemporal model with faster code from the package.

#### 5. Discussion

- mention substantial reduction of se in the application (and, presumably, the simulations).
- mention normal-based-related limitations

- mention Bayesian approach, and its potential flaws
- mention possible extension to imperfect detection
- mention forecasting potential
- take-home message: monitoring programs that use regularly surveys might consider incorporating time into their analysis to improve precision of predictors (e.g. NARS for lake assessments).

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