

# A comparison of design-based and model-based approaches for spatial data.

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## Abstract

This is the abstract.

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## 1. Introduction

There are two general approaches for using data to make statistical inferences about a population: design-based approaches and model-based approaches. When data cannot be obtained for all units in a population (population units), data on a subset of the population units is collected in a sample. In the design-based approach, inferences about the underlying population are informed from a probabilistic process in which population units are selected to be in the sample. Alternatively, in the model-based approach, inferences are made from specific assumptions about the underlying process that generated the data. Each paradigm has a deep historical context (Sterba, 2009) and its own set of general advantages (Hansen et al., 1983).

Though the design-based and model-based approaches apply to statistical inference in a broad sense, we focus on comparing these approaches for spatial data. We define spatial data as variables measured at specific geographic locations. De Gruijter and Ter Braak (1990) give an early comparison of design-based and model-based approaches for spatial data, quashing the belief that design-based

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approaches could not be used for spatially correlated data. Thereafter, several comparisons between design-based and model-based for spatial data have been considered, but they tend to compare design-based approaches that ignore spatial locations to model-based approaches (Brus and De Gruijter, 1997; Ver Hoef, 2002, 2008). Cooper (2006) review the two approaches in an ecological context before introducing a “model-assisted” variance estimator that combines aspects from each approach. In addition to Cooper (2006), there has been substantial research and development into estimators that use both design and model-based principles (see e.g. Cicchitelli and Montanari (2012), Chan-Golston et al. (2020) for a Bayesian approach, and Sterba (2009)). More recent overviews include Brus (2020) and Wang et al. (2012), but no numerical comparison has been made between design-based approaches that incorporate spatial locations and model-based approaches.

The rest of this paper is organized as follows. In Section 2, we compare sampling and estimation procedures between the design-based approach and the model-based approach. In Section 3, we use simulated and real data to study the the behavior of both approaches. And in Section 5, we end with a discussion and provide directions for future research.

## 2. Background

The design-based and model-based approaches incorporate randomness in fundamentally different ways. In this section, we describe the role of randomness and its effects on subsequent inferences. We then discuss specific inference methods for the design-based and model-based approaches for spatial data.

### 2.1. Comparing Design-Based vs. Model-Based

The design-based approach assumes the data are fixed. Randomness is incorporated in the selection of population units according to a sampling design. A sampling design assigns a positive probability of inclusion in the sample (inclusion probability) to each population unit. Some examples of commonly used sampling designs include independent random sampling (IRS), stratified random sampling, and cluster sampling. The goal is to use the sampling design and the sampled data to estimate population parameters like means and totals. These population parameters are typically assumed to be fixed but unknown.

Treating the data as fixed and incorporating randomness through the sampling design yields estimators having very few other assumptions. Confidence intervals for these types of estimators are typically derived using limiting arguments. Means and totals, for example, are asymptotically normally distributed by the Central Limit Theorem. Särndal et al. (2003) and Lohr (2009) provide thorough reviews of the design-based approach.

The model-based approach assumes the data are a random realization of a data-generating process. Randomness is often incorporated through distributional assumptions on this process. Instead of estimating fixed but unknown parameters (as in the design-based approach), the goal of model-based inference

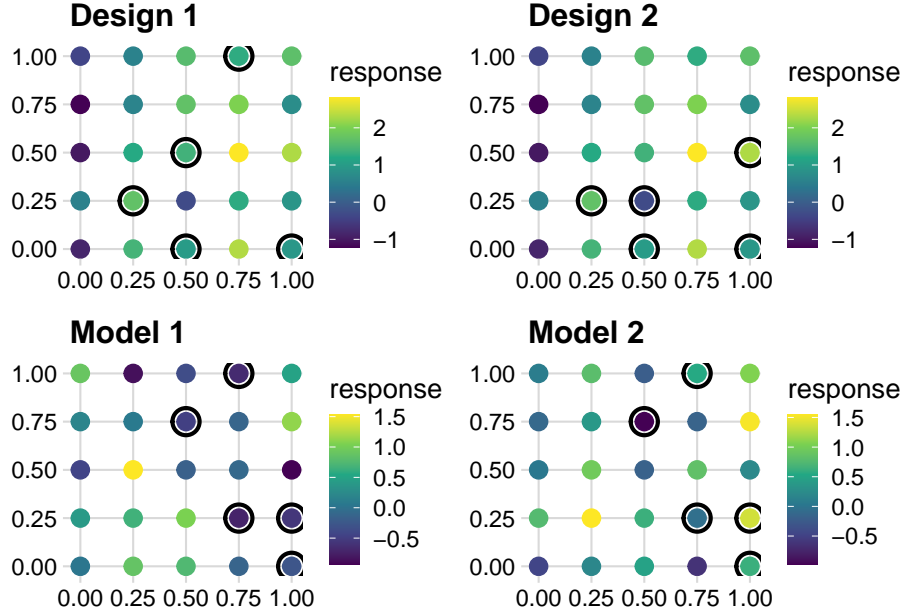


Figure 1: A comparison of sampling under the design-based and model-based frameworks. In the top row, we have one fixed population, and two random samples. In the bottom row, we have two realizations of the same spatial process sampled at the same locations.

in the spatial context is often *prediction* of an unknown quantity. For example, suppose the realized mean of all population units is the quantity of interest. Instead of *estimating* a fixed unknown mean, we are *predicting* the value of the mean, a random variable. We know that if we sampled all population units, we would have an exact prediction for the mean of our one realized process, without any uncertainty. But we are typically not interested in the true, unknown mean of the underlying process.

Assuming the data is a realization of a specific data-generating process yields predictors that are linked to distributional assumptions. These distributional assumptions are used to derive prediction intervals. The distributional assumptions allow the prediction intervals to be more precise. Cressie (1993) and Schabenberger and Gotway (2017) provide reviews of model-based approaches for spatial data.

Description of Figure 1 goes here.

## 2.2. Spatially Balanced Design and Analysis

The design-based approach can use spatial locations to obtain spatially balanced samples. First we discuss spatial balance with respect to the population (Stevens Jr and Olsen, 2004). A sample is spatially balanced with respect to the population if the sampled population units are a miniature of the population units. A sample is a miniature of the population if the distribution of the sampled

99 population units mirrors the density of all population units. Spatial balance  
100 with respect to the population is different than spatial balance with respect to  
101 geography. A sample that is spatially balanced with respect to geography is  
102 spread out in some type of equidistant manner over geographical space and is  
103 not meant to be miniatures of the population. When we refer to spatial balance  
104 henceforth, we mean spatial balance with respect to the population.

105 Spatially balanced samples are useful because they tend to yield estimates that  
106 have lower variance than estimates constructed from sampling designs lacking  
107 spatial balance (Barabesi and Franceschi, 2011; Benedetti et al., 2017; Grafström  
108 and Lundström, 2013; Robertson et al., 2013; Stevens Jr and Olsen, 2004; Wang  
109 et al., 2013). To quantify spatial balance, Stevens Jr and Olsen (2004) proposed  
110 loss functions based on Voroni polygons. The first spatially balanced sampling  
111 algorithm that saw widespread use was the Generalized Random Tessellation  
112 Stratified (Stevens Jr and Olsen, 2004). Since GRTS was developed, several  
113 other spatially balanced sampling algorithms have emerged, including the Local  
114 Pivotal Method (Grafström et al., 2012; Grafström and Matei, 2018), Spatially  
115 Correlated Poisson Sampling (Grafström, 2012), Balanced Acceptance Sampling  
116 (Robertson et al., 2013), Within-Sample-Distance (Benedetti and Piersimoni,  
117 2017), and Halton Iterative Partitioning (Robertson et al., 2018). We focus  
118 on the Generalized Random Tessellation Stratified (GRTS) algorithm to select  
119 spatially balanced sampling because it has several attractive properties detailed  
120 by Stevens Jr and Olsen (2004) and Dumelle et al. (2021).

121 The GRTS algorithm is used to sample from finite and infinite populations  
122 and works by utilizing a mapping between two-dimensional and one-dimensional  
123 space. The population units in two-dimensional space are divided into cells using  
124 a hierarchical index. Population units are then mapped to a one-dimensional  
125 line via the hierarchical indexing. The line length of each population unit equals  
126 its inclusion probability. A systematic sample is conducted on the line and these  
127 samples are linked to a population unit in two-dimensional space, which results  
128 in the desired sample. Stevens Jr and Olsen (2004) provide and Dumelle et al.  
129 (2021) provide further details.

After collecting a sample using the GRTS algorithm, the data are used to  
estimate population parameters. The Horvitz-Thompson estimator (Horvitz and  
Thompson, 1952) yields unbiased estimates of population means and totals. For  
example, if  $\tau$  is a population total, then the Horvitz-Thompson estimator of  $\tau$   
(denoted by  $\hat{\tau}_{ht}$ ), is given by

$$\hat{\tau}_{ht} = \sum_{i=1}^n Z_i \pi_i^{-1}, \quad (1)$$

130 where  $Z_i$  and  $\pi_i$  are the observed value and inclusion probability of the  $i$ th  
131 population unit selected in the sample. A similar formula exists for estimating  
132 the mean,  $\mu$ . Horvitz and Thompson (1952) and Sen (1953) provide variance  
133 estimators for  $\hat{\tau}_{ht}$ , but they have two drawbacks. First, they rely on calculating  
134  $\pi_{ij}$ , the probability that population unit  $i$  and population unit  $j$  are included in  
135 the sample, and this can be very difficult to calculate. Second, they ignore the

spatial locations of the population units. To address these drawbacks, Stevens Jr and Olsen (2003) proposed a local neighborhood variance estimator. The local neighborhood variance estimator does not rely on  $\pi_{ij}$ , and it incorporates spatial locations by assigning higher weights to nearby observations. Stevens Jr and Olsen (2003) show this variance estimator tends to reduce the estimated standard error of  $\hat{\tau}$ , yielding narrower confidence intervals for  $\tau$ .

### 2.3. Finite Population Block Kriging

Finite Population Block Kriging (FPBK) is a model-based approach that expands the geostatistical Kriging framework to the finite population setting (Ver Hoef, 2008). Instead of basing inference off of a specific sampling design, we assume the data are generated by a spatial process. Ver Hoef (2008) gives details on the theory of FPBK, but some of the basic principles are summarized below. Let  $\mathbf{z} \equiv \{z(s_1), z(s_2), \dots, z(s_N)\}$  be a response variable that can be measured at the  $N$  population units and is represented as an  $N \times 1$  vector. Suppose we want to predict some linear function of the response variable,  $f(\mathbf{z}) = \mathbf{b}'\mathbf{z}$ , where  $\mathbf{b}$  is a  $1 \times N$  vector of weights. For example, if we want to predict the population total across all population units, then we would use a vector of 1's for the weights.

Typically, however, we only have a sample of the  $N$  population units. Denoting quantities that are part of the sampled population units with a subscript  $s$  and quantities that are part of the unsampled population units with a subscript  $u$ ,

$$\begin{pmatrix} \mathbf{z}_s \\ \mathbf{z}_u \end{pmatrix} = \begin{pmatrix} \mathbf{X}_s \\ \mathbf{X}_u \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} \boldsymbol{\delta}_s \\ \boldsymbol{\delta}_u \end{pmatrix}, \quad (2)$$

where  $\mathbf{X}_s$  and  $\mathbf{X}_u$  are the design matrices for the sampled and unsampled population units, respectively;  $\boldsymbol{\beta}$  is the parameter vector of fixed effects; and  $\boldsymbol{\delta}_s$  and  $\boldsymbol{\delta}_u$  are random errors for the sampled and unsampled population units, respectively. Denoting  $\boldsymbol{\delta} \equiv [\boldsymbol{\delta}_s \ \boldsymbol{\delta}_u]'$ , we assume the expectation of  $\boldsymbol{\delta}$  equals  $\mathbf{0}$ .

We also typically assume that there is spatial correlation in  $\boldsymbol{\delta}$ , which can be modeled using a covariance function. It is common to assume the covariance function is second-order stationary and isotropic (Cressie, 1993), and that the spatial covariance decreases as the separation between population units increases. Many spatial covariance functions exist, but the primary function we use throughout the simulations and applications in this manuscript is the exponential covariance function: the  $i, j^{th}$  entry for  $\text{cov}(\boldsymbol{\delta})$  is

$$\text{cov}(\delta_i, \delta_j) = \theta_1 \exp(-3h_{i,j}/\theta_2) + \theta_3 \mathbb{1}\{\mathbf{h}_{i,j} = 0\}, \quad (3)$$

where  $h_{i,j}$  is the distance between population units  $i$  and  $j$ , and  $\boldsymbol{\theta}$  is a vector of spatial covariance parameters of the partial sill  $\theta_1$ , the range  $\theta_2$ , and the nugget  $\theta_3$ , and  $\mathbb{1}$  is an indicator function. However, any spatial covariance function could be used in the place of the exponential, including functions that allow for non-stationarity or anisotropy (Chiles and Delfiner, 1999, pp. 80–93).

With the above model formulation, the Best Linear Unbiased Predictor (BLUP) for  $f(\mathbf{b}'\mathbf{z})$  and its prediction variance can be computed. While details

of the derivation are in (Ver Hoef, 2008), we note here that the predictor and its variance are both moment-based.

We note that we only use FPBK in this paper in order to focus more on comparing the design-based and model-based approaches. However, k-nearest-neighbors (Fix and Hodges, 1951; Ver Hoef and Temesgen, 2013), random forest (Breiman, 2001), Bayesian models (Chan-Golston et al., 2020), among others, can also be used to obtain predictions for a mean or total from spatially correlated responses in a finite population setting.

### 3. Numerical Study

There were several variables to alter in the simulations, and the names of the scenarios in future plots mirror these variables

- correlation type: dependent errors or independent errors
- error type:
  - normal: mean 0, variance 2
  - lognormal: log scale mean 0, log scale variance 2 (total variance 47)
  - lognormalbig: log scale mean 0, log scale variance 4 (total variance 2,926)
- sample sizes:  $n = 10, 50, 150$ ;  $N = 900$
- layout: gridded vs random population locations

So for example, the `inderror.normal.n50.randloc` is the simulation having independent random errors that are normal, a sample size of 50, and random population locations.

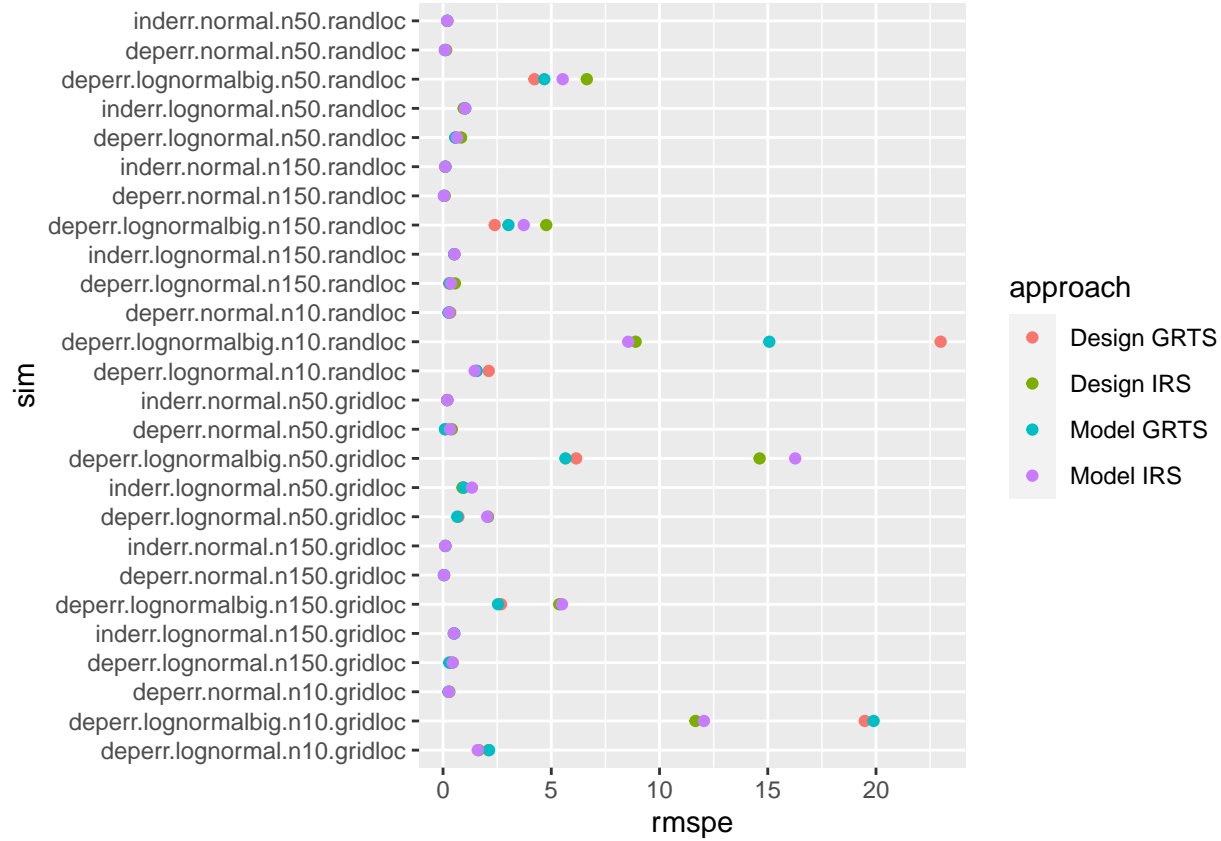
There were 2000 trials for each simulation. The original response (before exponentiating if applicable) for the dependent error cases was normally distributed with an exponential covariance function with partial sill of 0.9, effective range of  $\sqrt{2}$ , and a nugget of 0.1. For the independent error cases, the partial sill was 0 and the nugget was 1.

In each simulation, a GRTS sample and an IRS sample were selected. Then for the GRTS sample, the design-based approach using the local neighborhood variance (Design GRTS) and a model-based approach were applied (Model GRTS). Then for the IRS sample, the design-based approach using the simple random sample variance (Design IRS) and a model-based approach were applied (Model IRS).

The GRTS algorithm and the local neighborhood variance estimator are available in the **R** package `spsurvey` (Dumelle et al., 2021). FPBK can be readily performed in **R** with the `sptotal` package (Higham et al., 2020). We use `sptotal` for both the simulation analysis and the application, estimating parameters with Restricted Maximum Likelihood (REML).

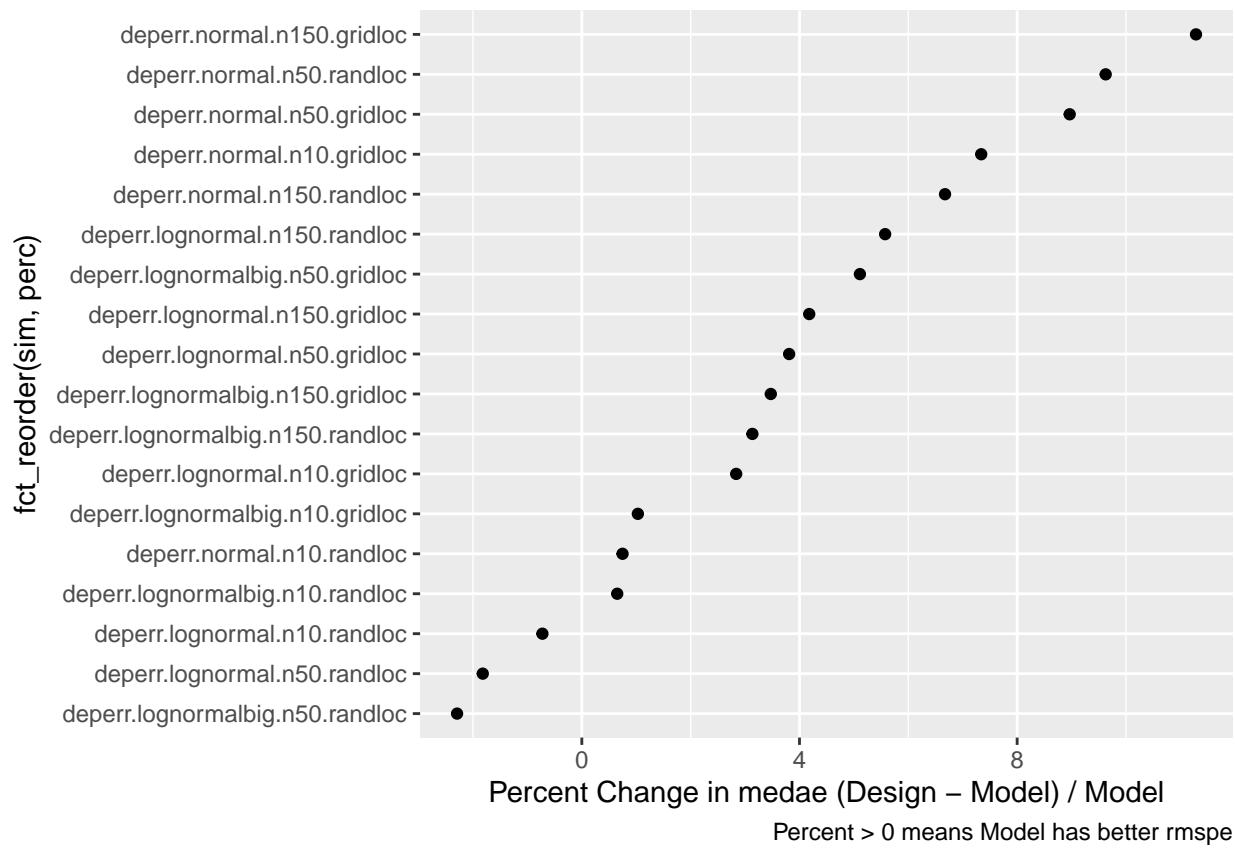
Major Points from August 3 Simulations:

207 1. In most of the dependent error simulation settings, either all four ap-  
 208 proahces (IRS-Design, IRS-Model, GRTS-Design, and GRTS-Model) per-  
 209 form equally or GRTS-Design and GRTS-Model outperform IRS-Design  
 210 and IRS-Model. Exceptions to this are a couple of the settings with very  
 211 small sample sizes ( $n = 10$ ), in which the IRS does better than GRTS.  
 212 In the independent error settings, it usually doesn't matter much which  
 213 approach is used, which makes sense.

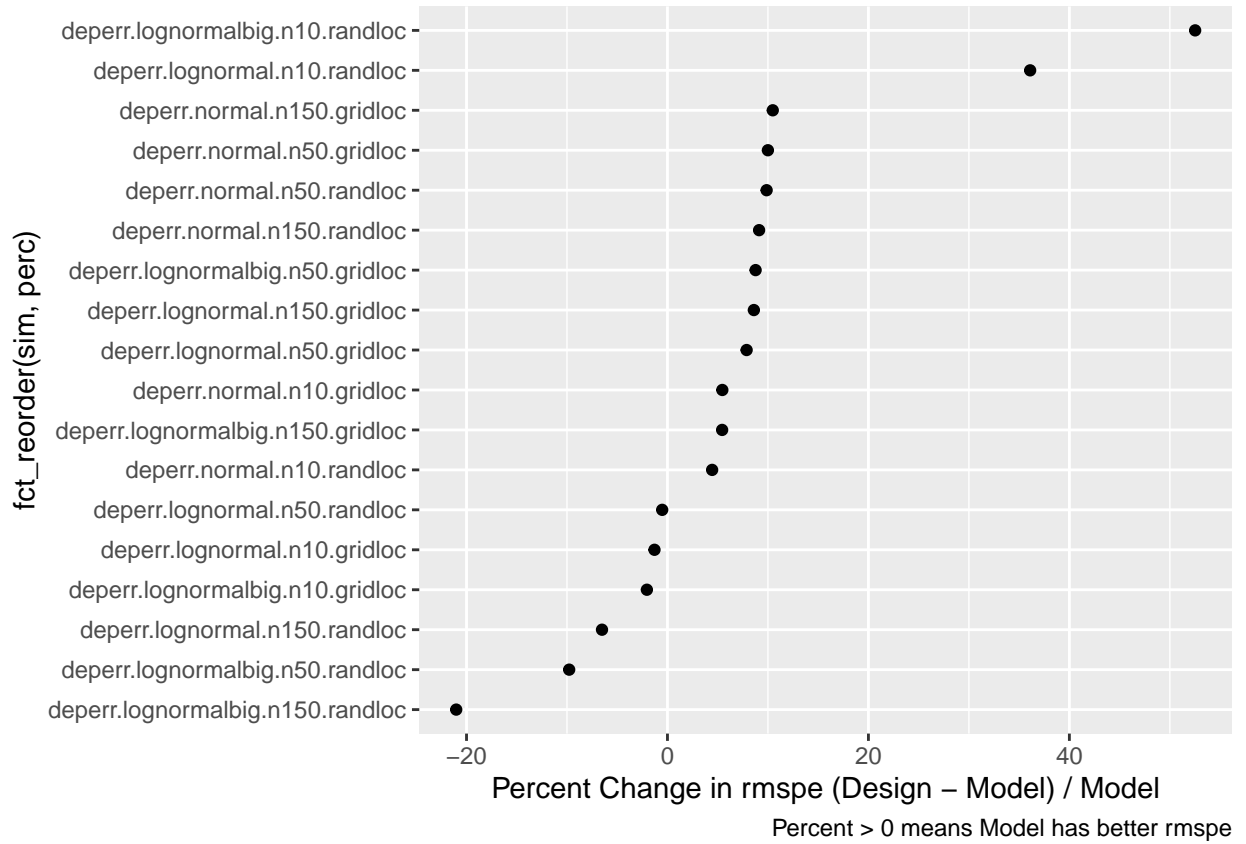


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215 2. We will now focus in a bit more on comparing Design-GRTS to Model-  
 216 GRTS, the two best approaches for any reasonable sample size. In the  
 217 independent error settings, the two approaches perform very similarly,  
 218 so those results are omitted in the following graph. In the dependent  
 219 error settings, using rmspe as the performance criterion, Model-GRTS  
 220 outperforms Design-GRTS in 12 of the 18 settings, the two approaches  
 221 perform very similarly in 3 settings, and Design-GRTS outperforms Model-  
 222 GRTS in 3 settings.

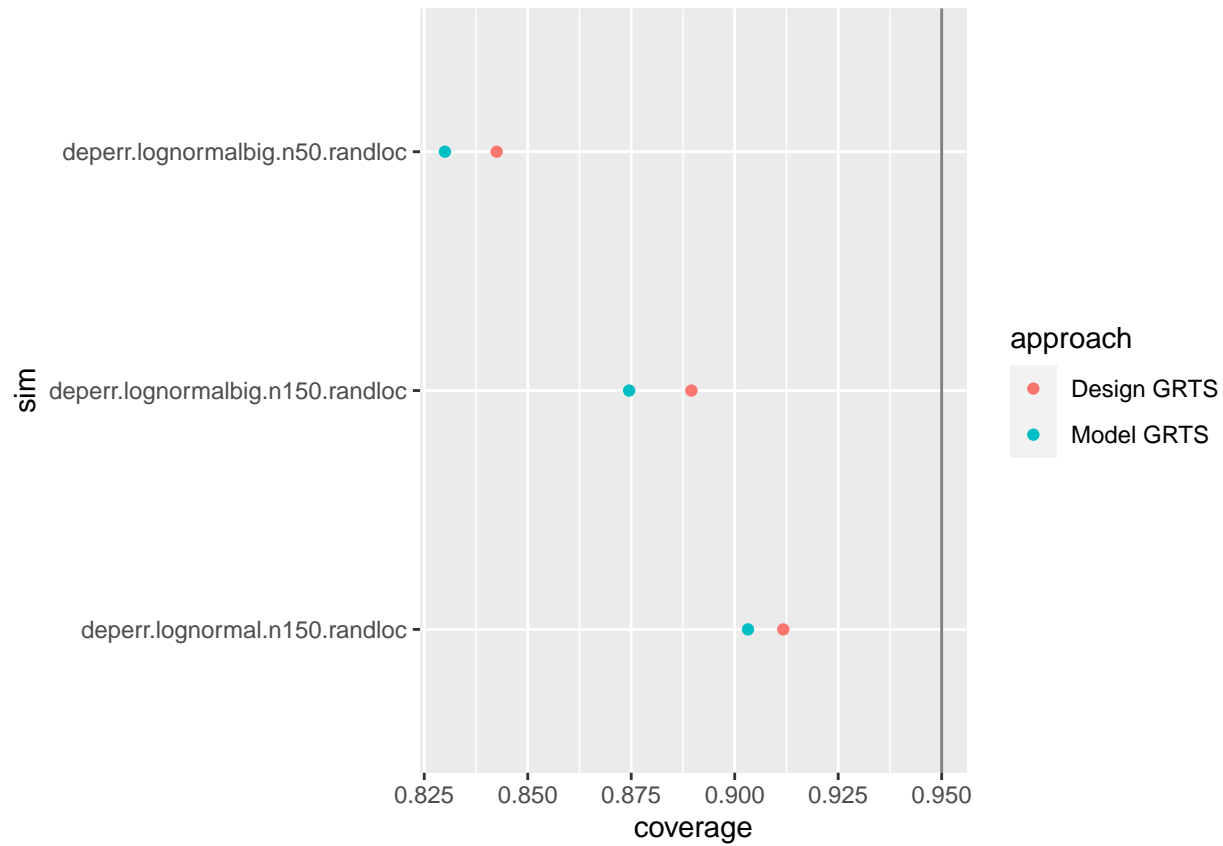






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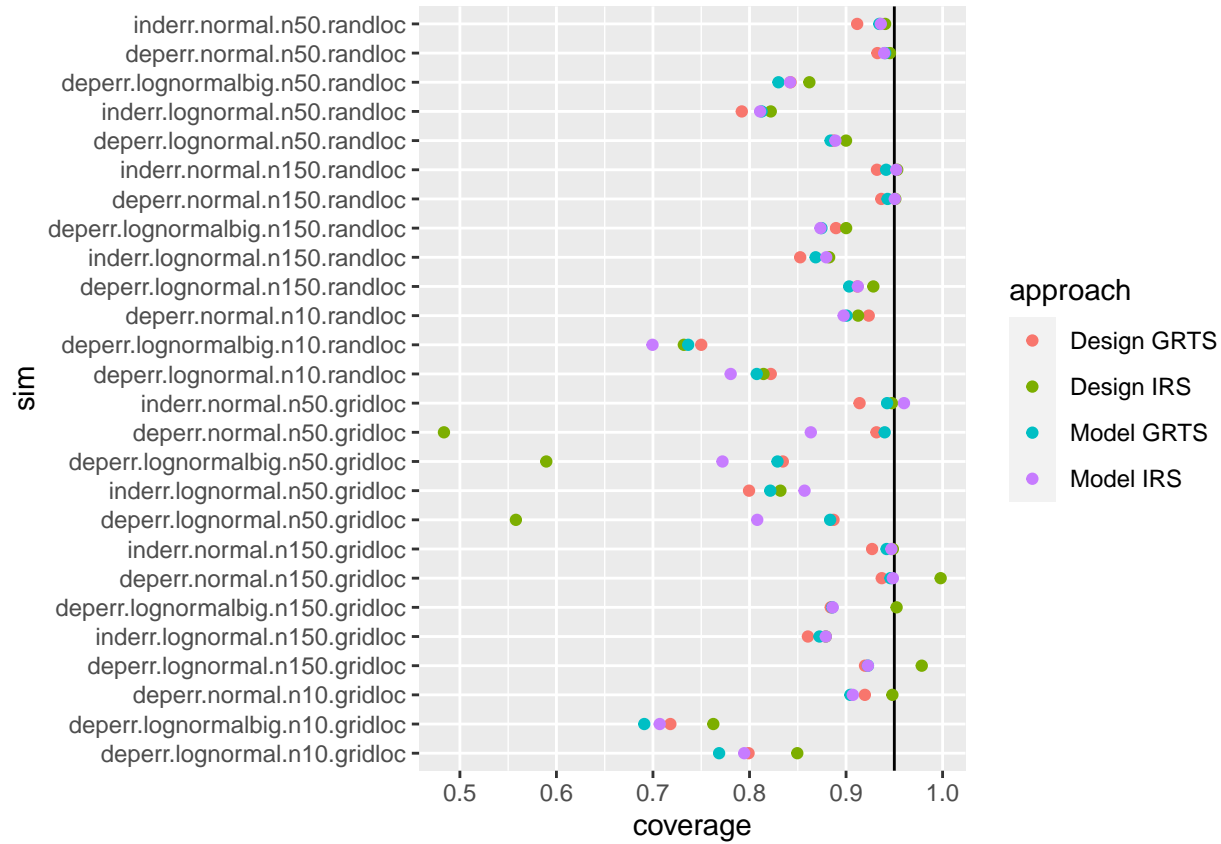
- 225 3. Focusing in on the three settings where Design-GRTS outperforms Model-  
 226 GRTS, we see that, in two of the settings, the log-normal response has a  
 227 large variance, corresponding to a large right-skew after exponentiation.  
 228 All three settings have sites in random locations. However, in only one  
 229 of these settings would we recommend actually using Design-GRTS. In  
 230 the other two settings, the data are sufficiently skewed that a practitioner  
 231 should not use either approach, though it is “safer” to use Design-GRTS.



232

#### 233 4. Coverage

234 For Gaussian errors, coverage for all approaches tended to be near 0.95. There  
 235 was less between-approach deviation in coverages for random locations compared  
 236 to grid locations. Generally, the larger the skew, the worse the coverage, and the  
 237 larger the sample size, the better the coverage. Design GRTS (local neighborhood  
 238 variance) tended to slightly undercover, a result Tony was familiar with.



239

## 240 5. Take-home messages

- 241 • In terms of rmspe, a model-based analysis on a GRTS design yields an  
242 rmspe similar to or lower than a design-based analysis on a GRTS design,  
243 as long as the response variable is not “too skewed.”
- 244 • If the response variable is very skewed, then neither analysis is appropriate,  
245 but, the design-based analysis is better.
- 246 • a spatially balanced GRTS sample outperforms IRS in nearly all dependent  
247 error settings, as expected.
- 248 • methods that use spatial correlation generally perform better on random  
249 location points than they do on gridded points. This makes some intuitive  
250 sense because (1) on average, the minimum distance between an unobserved  
251 point and its nearest observed neighbor should be lower for random points  
252 and (2) the span of the study area is maximized for a grid based on the  
253 way that we set up the simulations (with the random points being drawn  
254 as uniform random variables within the boundary of the grid).
- 255 • comparison of Design-GRTS and Model-GRTS between two settings with  
256 different locations of points, but otherwise the same simulation parameters,

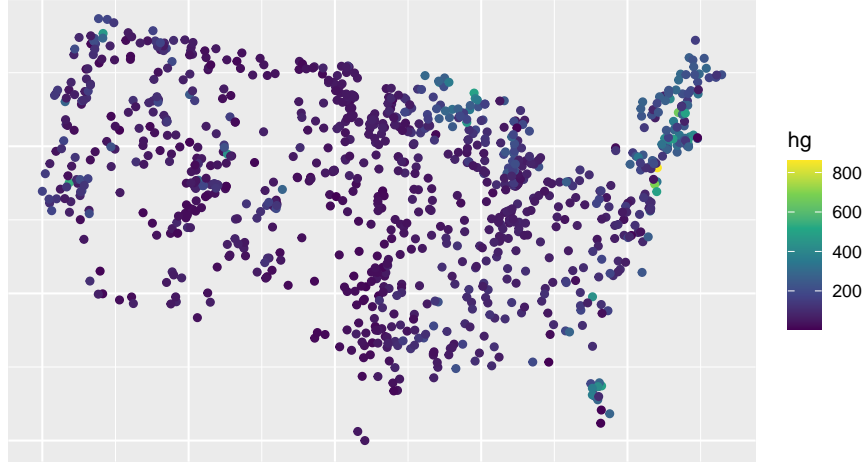


Figure 2: Population distribution of mercury concentration for 986 lakes in the contiguous United States. Thirty-five lakes were dropped from the analysis because they were missing mercury concentration.

should really be done on the same surface realization. One very strange realized response vector could drastically alter the results, especially on the exponentiated log data. In the same way that we compare the four approaches on the same realized data, we should also try to do the same with the locations, if they are of interest. (The realized mean won't be exactly the same but should be close).

#### 4. Application

The Environmental Protection Agency (EPA), states, and tribes periodically conduct National Aquatic Research Surveys (NARS) in the United States to assess the water quality of various bodies of water. We will use the 2012 National Lakes Assessment (NLA), which measures various aspects of lake health and quality in lakes in the contiguous United States, to obtain an interval for mean mercury concentration. Although all lakes in the survey were measured in 2012, there may not always be enough time or money to do so. Therefore, we will explore whether or not we can still obtain a relatively precise estimate for the realized mean mercury concentration if we only take a sample of 100 of the 986 lakes.

Figure 2 shows that mercury concentration is right-skewed, with most lakes having a low value of mercury concentration but a few having a much higher

concentration. Mercury concentration exhibits some spatial correlation, with high mercury concentrations in lakes in the northeast and north central United States. Because we are considering these lakes to be our entire population, we know that the realized mean mercury concentration is 103.03 ng / g.

Table 1: Table XXX. Application of design-based and model-based approaches to the NLA data set on mercury concentration.

| Approach    | Realized Mean | Estimate | SE  | 95% LB | 95% UB |
|-------------|---------------|----------|-----|--------|--------|
| Design IRS  | 103.2         | 112.7    | 8.8 | 95.4   | 129.9  |
| Model IRS   | 103.2         | 110.5    | 7.9 | 95.0   | 125.9  |
| Design GRTS | 103.2         | 101.8    | 6.1 | 89.8   | 113.7  |
| Model GRTS  | 103.2         | 102.3    | 5.9 | 90.8   | 113.9  |

Table 1 shows the application of a design-based analysis on an IRS, a model-based analysis on an IRS, a design-based analysis on a GRTS sample, and a model-based analysis on a GRTS sample. We see that, for all four analyses, the true realized mean mercury concentration is within the bounds of the 95% intervals. However, we should not generalize the results of this particular realization to any other data set or even to other potential samples of this data set.

But, we do note a couple of patterns. The design-based IRS analysis shows the largest standard error: a likely reason is that this is the only approach that does not use the spatial correlation in mercury concentration across the contiguous United States. We also see that, for the samples drawn, the both analyses with the GRTS sampling design have a lower standard error than the analyses with the IRS sampling design. We would expect this to be the case for most samples because mercury concentration exhibits spatial correlation so a spatially balanced sample should usually yield a lower standard error. If it is acceptable to have an interval for mean mercury concentration of about 25 ng / g and if we ignore the other variables that the EPA collects information on in these NLA surveys, then the EPA could consider sampling just 50 lakes to save time and money.

## 5. Discussion

- Pros of Design-Based (items we are not exploring): computationally efficient, few assumptions, more naturally handles binary data,
- Pros of Model-Based (items we are not exploring): covariate inference, more efficient small-area estimation, model selection?, estimated spatial parameters to better understand spatial structure, site-by-site predictions/prediction map

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