Explicit formulas for non-random sample designs in camera trap density estimation

This document derives multiple camera trap density estimators that allow for non-random sample designs in heterogeneous landscapes. The role of a camera trap density estimator is to estimate the density, λ, which can then be used to calculate total abundance as a function of density, sampling frame (A), camera viewshed area (V), and sampling period (T),

$$N = \frac{\lambda A}{VT}.$$

We use theory from the equilibrium solution of the ecological diffusion equation (EDE) to connect movement data and count data for density and abundance estimation. The equilibrium solution of the EDE assumes that animal densities are proportional to animal staying time across locations of a landscape,

$$\frac{d_q}{\sum d_q} = \frac{\phi_q}{\sum \phi_q},$$

where d_q is a density at location q and ϕ_q is the staying time at location q. Generally, q is a small subunit within the entire landscape that is defined with landscape covariates.

Rather than using small-scale units to define the landscape, we aggregate the grid cells into habitat types, h, with common characteristics. Then, we collect habitat-type specific staying times, T_h, across the landscape with telemetry data or camera trap data. For example, with a GPS data set, we find that animals on average spend 50% of time in forested area, 35% on grassland, and 15% on road. With this information, we now know, for example, that road densities should be about 15% of total densities. We use this to calculate total abundances with camera traps as follows.

TDST Model The total density and staying time (TDST) model calculates total density by estimating location-specific densities (d_q) and staying time (ϕ_q),

$$D = \frac{\sum \phi_q}{\phi_q} d_q,$$

where D is the total landscape density. Total abundances can then be calculated with the formula above, $N = \frac{A \sum d_q}{VT}$.

Note that the TDST requires proportional rather than absolute staying time. Proportional staying time can be estimated either with camera trap or telemetry data. For camera traps, motion-sensored cameras are required to capture the time it takes for an animal to cross the camera viewshed. With telemetry data, individuals are tracked for how long they stay in each habitat type. In both cases, it is important to only use data when the animal is moving; otherwise, the model estimates may be biased. Note that because the camera viewshed has a different area from the grid cell area, there is no easy way to translate grid cell staying time to viewshed area staying time. Therefore, these methods cannot be mixed when calculating proportional staying time. Additionally, information must be obtained from each habitat type in order to calculate proportional staying time.

PR model The Poisson regression (PR) model estimates densities, λ, using only count data. Total abundances are then calculated using the formula above. The PR model may be used with and without covariate information, although random sample designs are required for non-biased estimates when covariates are not used.

Habitat PR Model We combine the theory behind the TDST model with density estimates obtained with the non-covariate PR model to explicitly calculate camera-scaled habitat abundances using relative staying time estimates obtained from telemetry data. To derive this, we begin with the total abundance equation,

$$N = \frac{AD}{VT},$$

and substitute total density with the TDST formula,

$$D = \frac{d_h T}{T_h}$$

. Canceling like-terms provides an estimate for total abundance given densities and staying time calculated for each habitat type,

$$N = \frac{d_h A}{T_h V}.$$

The issue with calculating a total abundance for each habitat type is that the model precision relies on the number of cameras used in each habitat, so total abundances can vary dramatically between each habitat estimate. Therefore, we calculate the camera-scaled abundances for each habitat by normalizing the total abundance calculation above by the proportion of the total area encompassed by the habitat and the proportion of cameras placed in the habitat,

$$N_h = \frac{d_h A}{T_h V} \frac{A_h}{A} \frac{C_h}{C} = \frac{d_h A_h C_h}{T_h V C}.$$

The sum over all habitat-specific abundances results in total abundance, $N = \sum N_h$.

The habitat PR model can also be explicitly defined for single-habitat sample designs (i.e., cameras placed exclusively on one habitat type). Specifically, the proportion of cameras placed in the habitat of choice is now 1 while all other habits have 0 cameras, setting all habitat-specific abundances without cameras to zero. Then, total abundance given cameras placed only in habitat h is

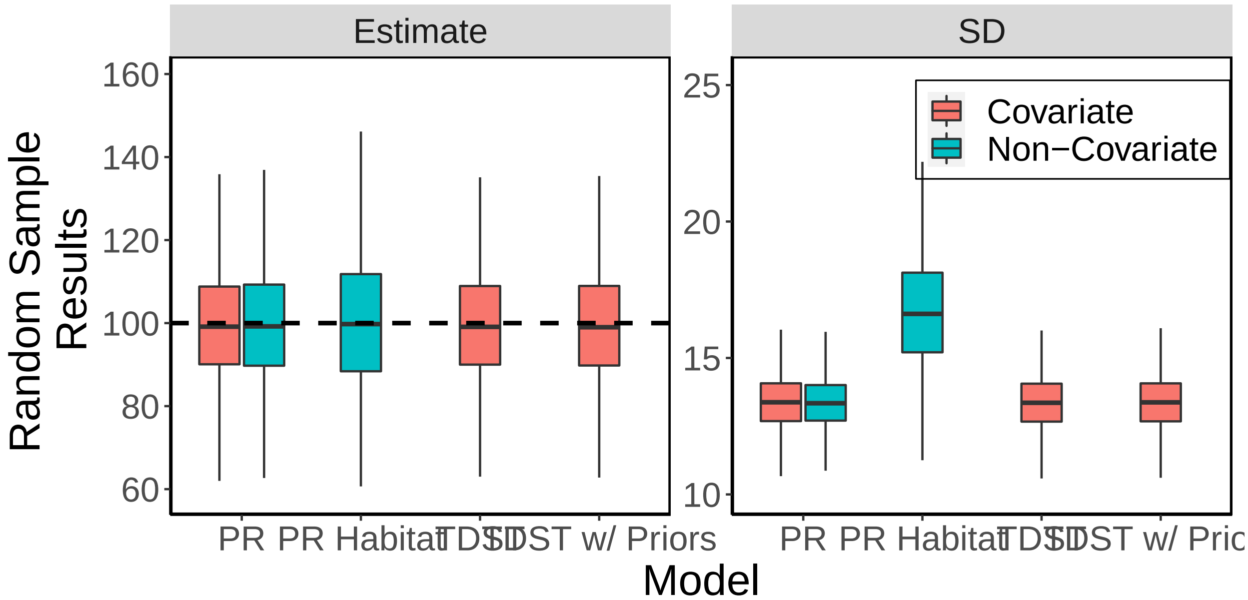
$$N = \frac{d_h A_h}{T_h V},$$

where habitat-specific density, λ_h, is calculated as above.

Results To test these models, we ran simulations where animals move with three different speeds depending on habitat type (slow, medium, fast), and place cameras under three sample designs; randomly, non-randomly (80% in slow habitat, 10% each in medium and fast habitats), and single-habitat (cameras placed in only one habitat type). We then estimated total abundances with the TDST model without priors, TDST model with stay-time priors defined by telemetry data but omitting camera stay time data (TDST no-data), PR model with and without covariates, and the habitat PR model.

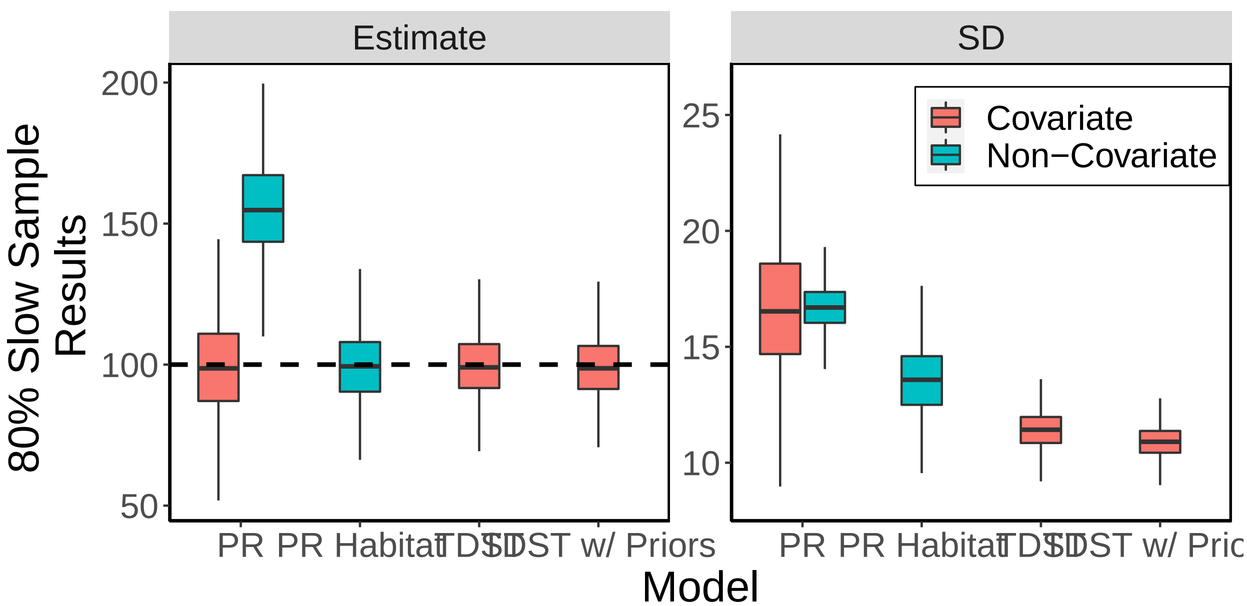
The following boxplots represent summaries of model runs over 1000 iterations. The random sample design is a good indicator of how well each model is working, and the median results show that all models are within 1% of the true abundance (N = 100). In general, the habitat PR model has slightly higher SD than its counterpart, the TDST No Data model while maintaining accuracy across the different sample designs. Note that accuracy for the TDST No Data model and the PR Habitat model rely on the accuracy of the telemetry data (which is near-perfect for our simulations). In future simulations, we should create a survey design for telemetry data to create variance surrounding the habitat-specific movement speeds.

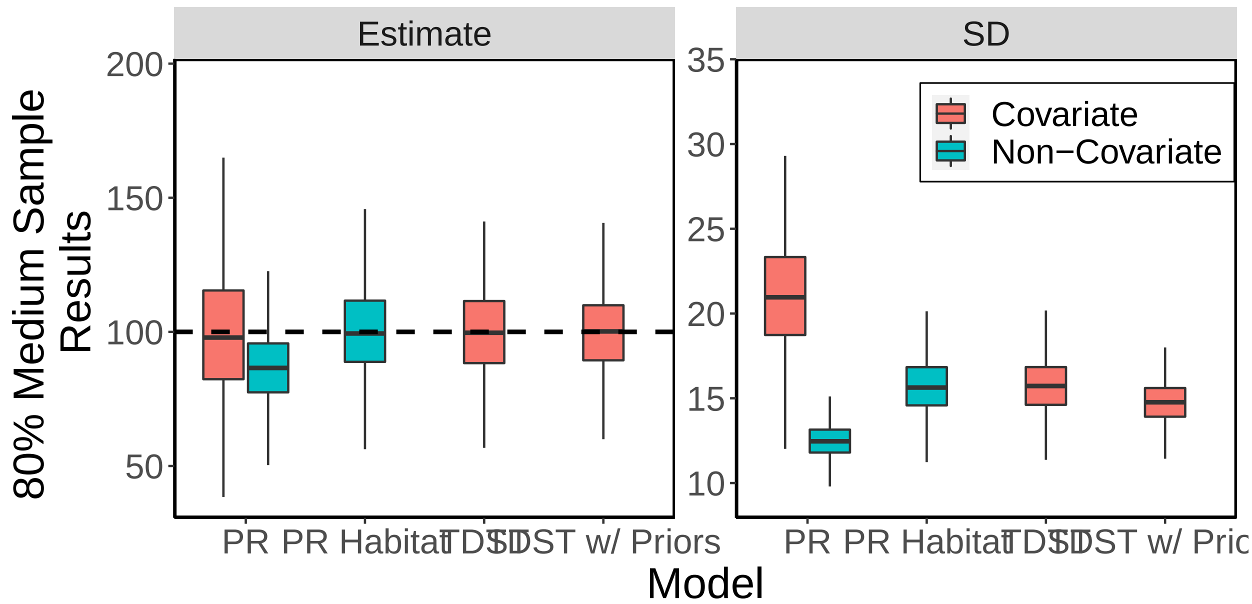
Random Sample Design

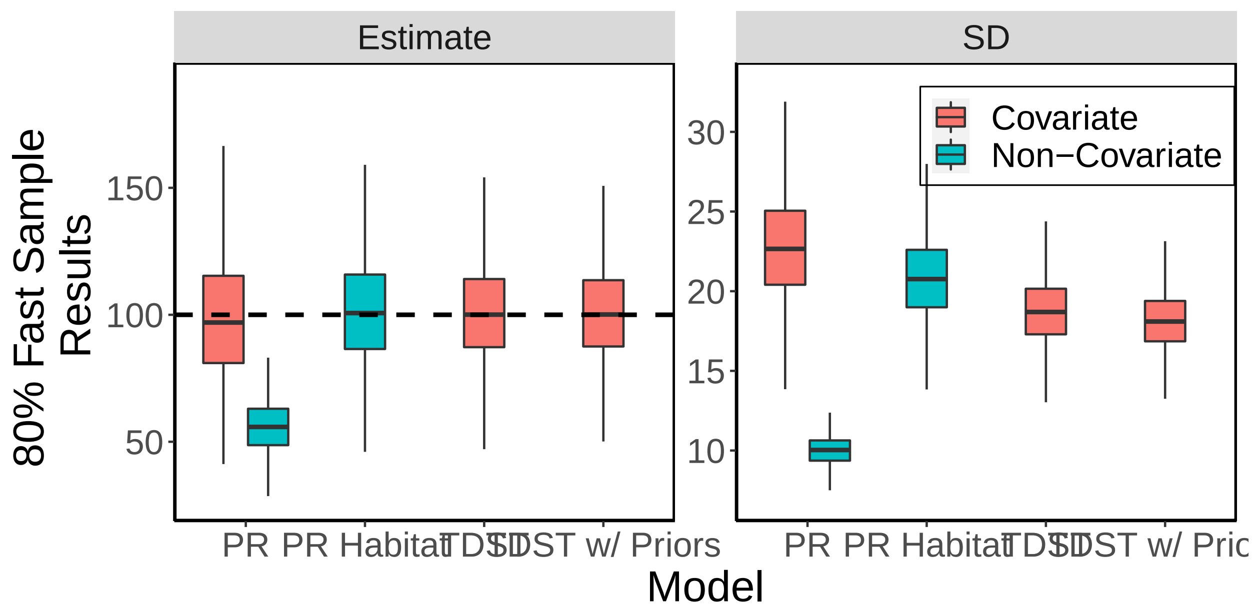


80% Sample Bias

In these simulations, we places 80% of the cameras in one habitat type and 10% of the cameras in each of the other two habitat types.

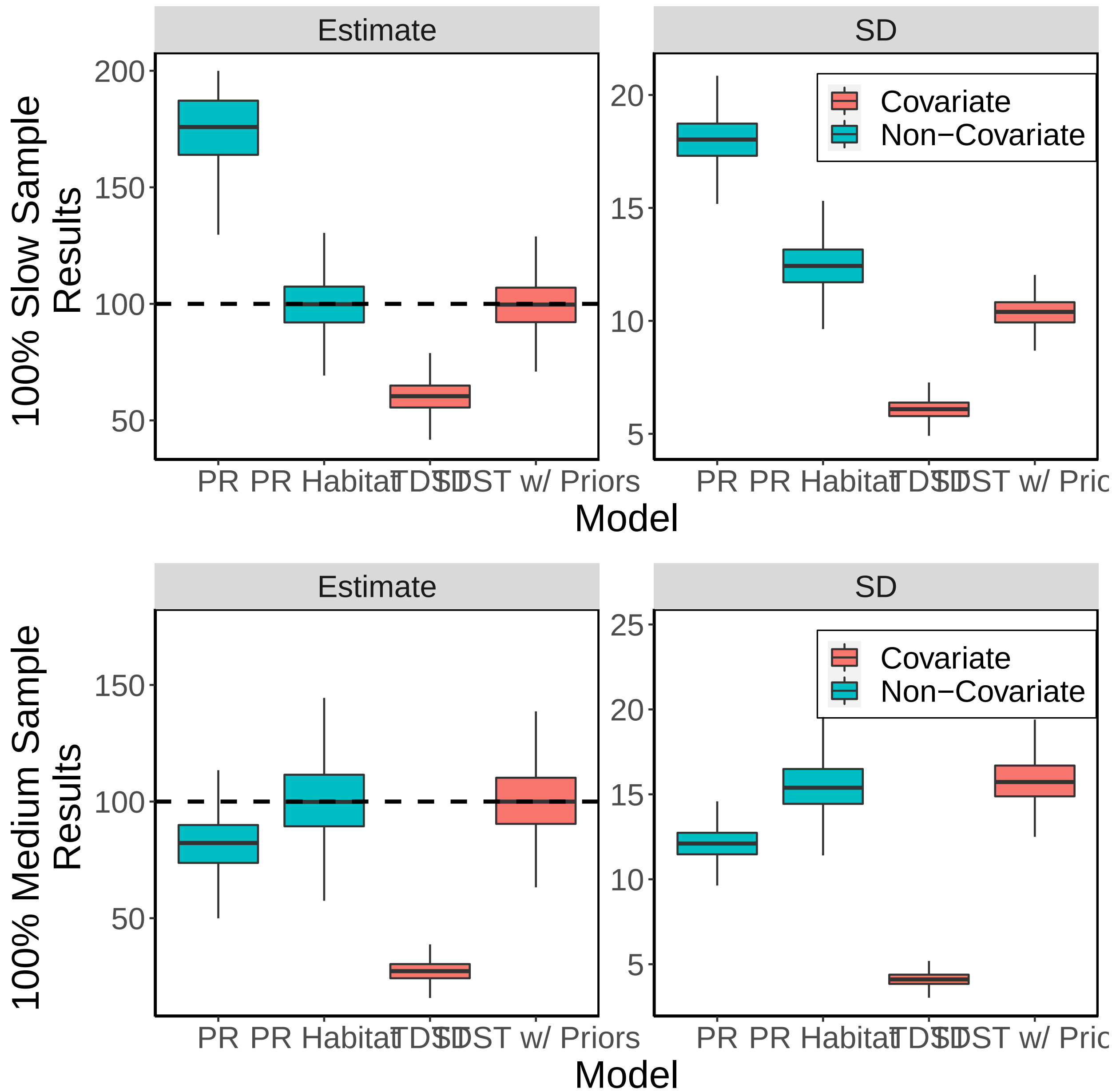


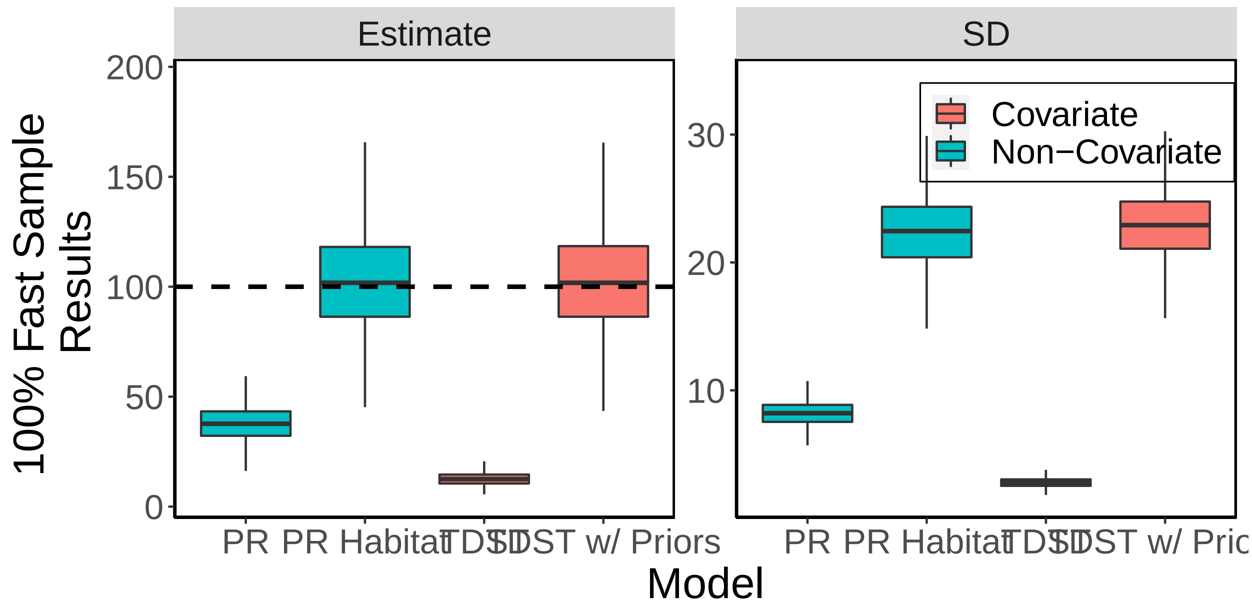




All One Habitat Type

In the following figures, all cameras are placed in one habitat type. Note that because camera data are not available for all habitat types, all staying time information must be collected with telemetry data.


Estimate
SD
100% Slow Sample Results
200
150
100
50
20
15
10
5
Covariate
Non−Covariate
PR
PR Habitat
TDSD
TDST w/ Priors
Model
Estimate
SD
100% Medium Sample Results
150
100
50
25
20
15
10
5
Covariate
Non−Covariate
PR
PR Habitat
TDSD
TDST w/ Priors
Model



Model Summaries

TDST Model

- Uses count and staying time data
- Requires habitat-specific covariate information
- Supports single-habitat camera sample design when auxiliary staying time information is present

PR Model

- Uses count data
- May run with or without covariates
- Requires random sample design when covariates are not used
- Does not support single-habitat camera sample design

Habitat PR Model

- Uses count data and telemetry data
- Supports single-habitat camera sample design