

**Introduction to ciTools**

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## Introduction to ciTools

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#### About This Publication

ciTools is an R package for working with model uncertainty. It gives users access to confidence and prediction intervals for the fitted values of (log-) linear models, generalized linear models, and (log-) linear mixed models. Additionally, ciTools provides functions to determine probabilities and quantiles of the conditional response distribution given each of these models. This briefing introduces the package and provides simple illustrations for using ciTools to perform inference and plot results.

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## **Introduction to ciTools**

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# Executive Summary

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## A. Quantifying Uncertainty

Analysts at IDA developed a new R package, ciTools, to quantify uncertainty easily and quickly, addressing a gap in the software.

Quantifying uncertainty is a critical part of good quantitative data analysis. IDA analysts frequently use statistical models to estimate system performance and use these estimates in reports. Estimates without uncertainty boundaries can be misleading, yet many software packages do not provide straightforward ways to compute intervals around estimated values. Confidence intervals quantify the uncertainty of an estimate of an average, such as the average target location error (TLE) for a sensor. Prediction intervals provide a range within which we would expect a new individual observation to fall, using estimated population variance. Rather than bound the average TLE for a sensor, a prediction interval bounds the TLE of an individual target location provided by the sensor. Prediction intervals are often more intuitive and informative to operators who want to know what to expect when they use a

system in the field. Similarly, probability estimates answer the question, “What is the probability that the sensor will provide me with a target location that is at least  $Q$  meters away from the target?”, while quantile estimates provide a bound for a given percentage of all individual observations. For example a Circular Error Probable of 90 is equivalent to the 0.9 quantile of a system’s TLE. Confidence intervals, prediction intervals, probabilities, and quantiles all answer important questions that come up frequently in data analysis done at IDA.

R is a popular, free, open-source statistical software program used by many IDA analysts; unfortunately, most statistical modeling packages in R do not make it convenient to get uncertainty estimates. Some modeling packages in R make confidence intervals available, but focus is typically on model parameters rather than estimates of the response variable such as a measure of system performance. Prediction intervals, quantiles, and probability estimates are rarely available, if at all, and require analysts to write additional code. The syntax for generating these estimates can vary substantially depending on the type of statistical model used. The package ciTools addresses

these problems by presenting a convenient, consistent set of functions for estimating response variable uncertainty across a wide range of common statistical models used by IDA analysts.

## B. Attributes of ciTools

The R package ciTools provides a uniform, model-invariant, data-first approach for working with model uncertainty in R. Table 1 shows the different types of data for which ciTools provides functionality. For each kind of data, a different family of statistical model is used, and an associated different process is required to accurately estimate uncertainty. In many cases, these processes are difficult and require careful thought to do correctly. By automating the process and making syntax consistent for different types of data, ciTools makes it easier for data analysts to quickly provide accurate results.

The four main functions in ciTools have uniform syntax, making it easy for analysts to easily switch from one type of uncertainty estimate to another. The functions look the same, users provide inputs in the same order for each function, and defaults are consistent across each function. Figure 1 shows the four main functions and their uniform syntax.

Functions in ciTools are also model-invariant, meaning that analysts only have to learn how to do things once. Regardless of the type of data and statistical model the analyst is working with, the same code is used to generate a confidence

interval or quantile estimate. This makes it easy for analysts who have used ciTools for one type of data analysis to use it again for another type of analysis.

**Table 1. Scope of ciTools**

	Confidence Intervals	Prediction Intervals	Probabilities	Quantiles
<b>Linear Data</b>	✓	✓	✓	✓
<b>Count/ Binary Data</b>	✓	✓	✓	✓
<b>Skewed Data</b>	✓	✓	✓	✓
<b>Random Group Data</b>	✓	✓	✓	✓
<b>Reliability Data</b>	Future Work	Future Work	Future Work	Future Work
<b>Skewed, Random Group Data</b>	In Progress	✓	✓	✓

Confidence Intervals	Prediction Intervals
<code>add_ci(data, model, ...)</code>	<code>add_pi(data, model, ...)</code>
Probabilities	Quantiles
<code>add_probs(data, model, quantile, ...)</code>	<code>add_quantile(data, model, probability, ...)</code>

**Figure 1. The four main functions in ciTools have consistent look and syntax.**

Finally, ciTools uses a data-first approach, which makes it fit seamlessly into the “tidyverse”, a popular set of R packages used for cleaning, processing, and plotting data. A data table is the first argument of each function, and each function returns that same data table augmented with the requested interval, probability, or quantile estimate. This approach makes it easy for analysts to write legible code and is consistent with reproducible research best practices. It also makes plotting these uncertainty estimates straightforward because the factors used to generate the model predictions and uncertainty estimates remain in the data table.

## C. Summary

At present, ciTools is available to IDA analysts and the public a large on both the Comprehensive R Archive Network and GitHub. A full set of help files and multiple tutorials are accessible through R.





**ciTools**

A New R Package to Ease Model Inference

John Haman

Matthew Avery



Interval estimates are difficult but vital in OED research.

ciTools makes working with them **easy**.

# Outline

1. Motivating Examples
2. Design of ciTools
  1. Uniformity
  2. Model Invariance
  3. “Data First” Approach
3. Example: ciTools and Graphics
4. Scope of ciTools and Learning More

# Unmanned Reconnaissance Aircraft with Imagery Payload



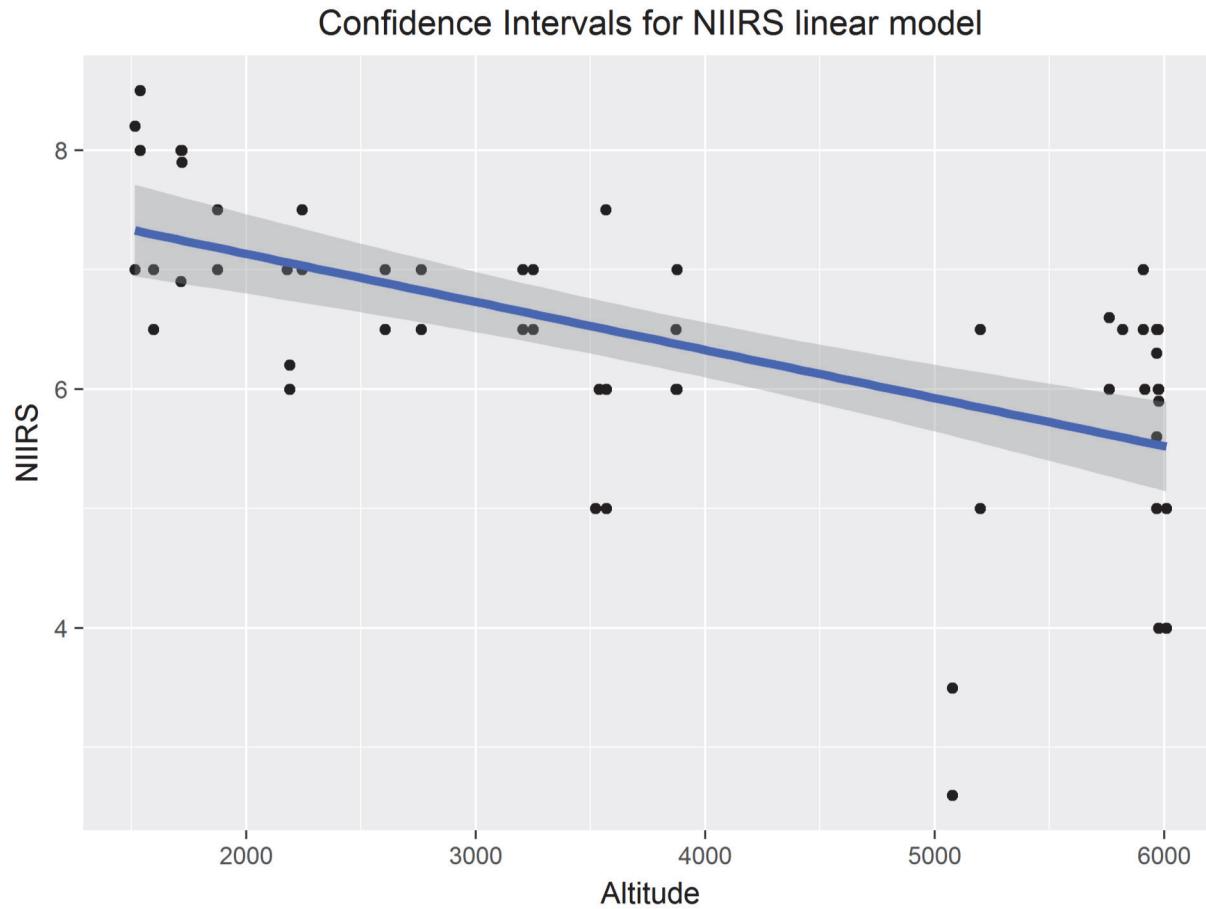
NIIRS = 6



NIIRS = 8

Image Source: fas.org

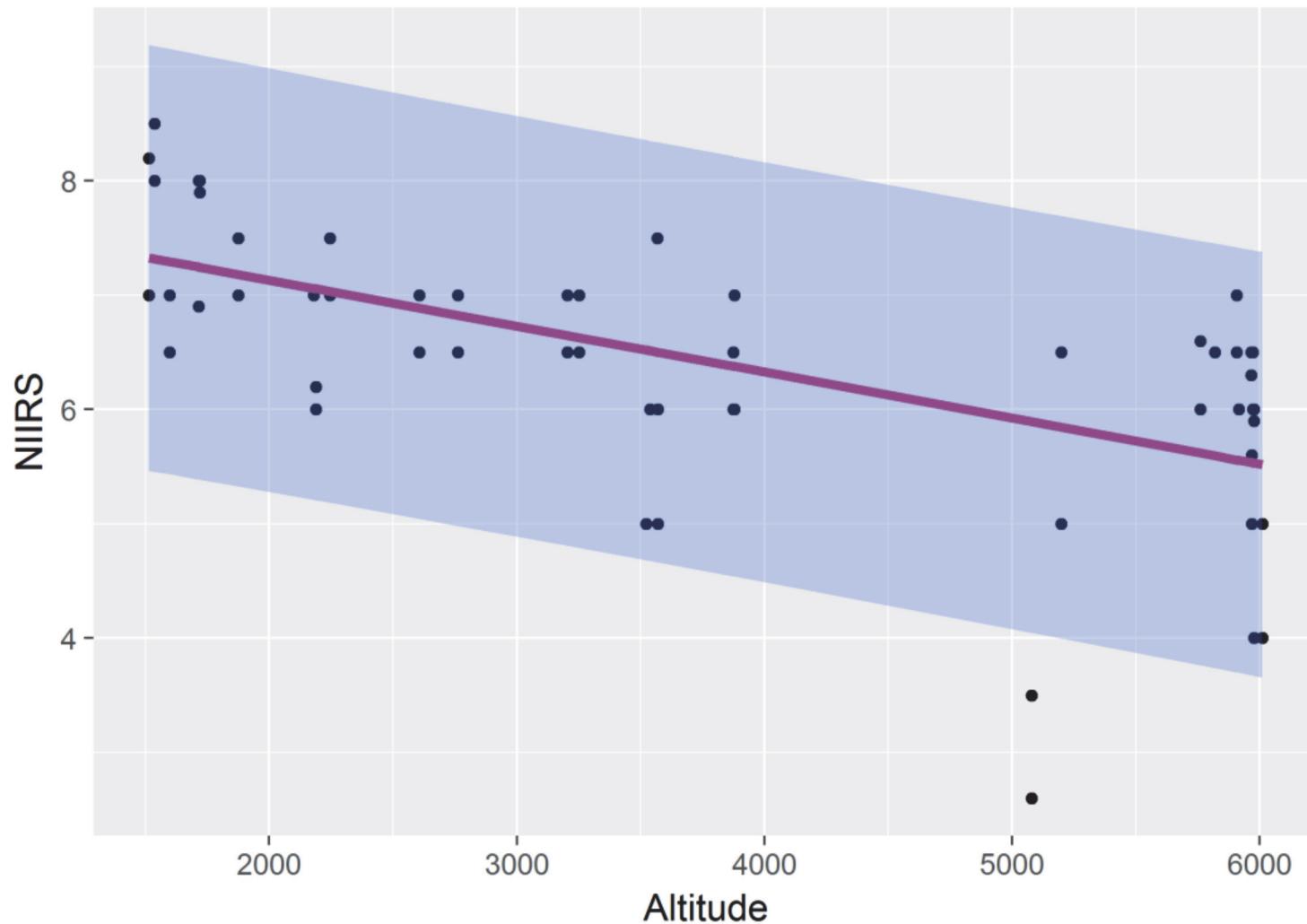
# Confidence intervals for simple linear models are easy and convenient.



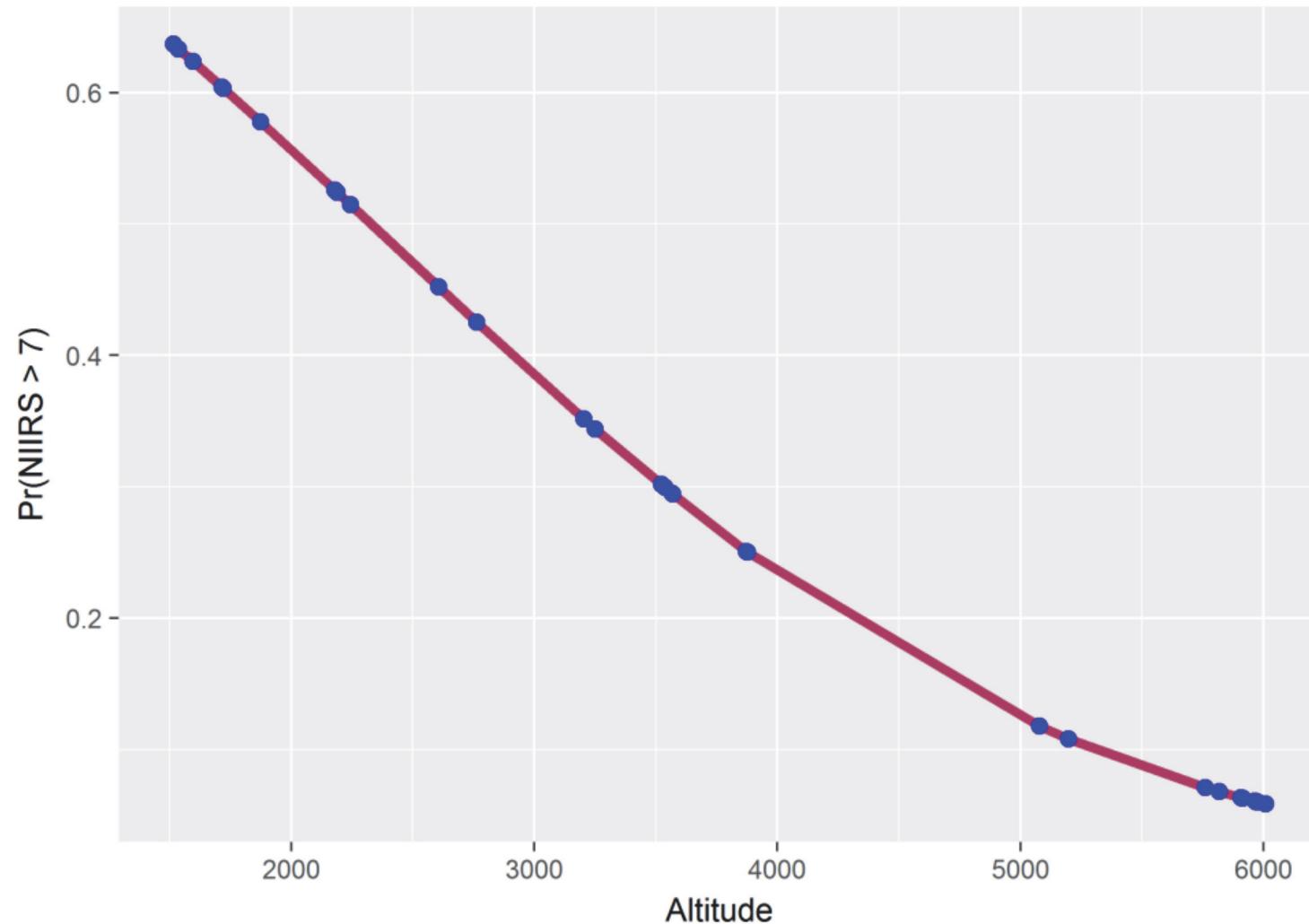
Possible to get confidence intervals *while* plotting in R

# Doing other things can be more difficult ...

NIIRS vs Altitude: 95% Prediction Interval



### Probability that NIIRS > 7 Given Model



ciTools presents a uniform, model-invariant, “data first” approach to working with model uncertainty in R.

# Scope

## Functionality

Data types

	Confidence Intervals	Prediction Intervals	Probabilities	Quantiles
Linear Data				
Count/Binary Data				
Skewed Data				
Random Group Data				
Reliability Data				
Skewed, Random Group Data				

# Minimal, Uniform Design



# Uniformity in `ciTools`

`ciTools` has many capabilities, and they all use the same syntax:

<b>Confidence Intervals</b>	<b>Prediction Intervals</b>
<code>add_ci(data, model, ...)</code>	<code>add_pi(data, model, ...)</code>
<b>Probabilities</b>	<b>Quantiles</b>
<code>add_probs(data, model, quantile, ...)</code>	<code>add_quantile(data, model, probability, ...)</code>

# NIIRS Data: Generating confidence intervals

```
> add_ci(dat, fit)
# A tibble: 65 × 5
  NIIRS Altitude      pred LCB0.025 UCB0.975
  <dbl>    <int>     <dbl>     <dbl>     <dbl>
1 8.0      1537 7.318570 6.938266 7.698875
2 7.0      1874 7.182952 6.837865 7.528039
3 7.0      3251 6.628808 6.389208 6.868409
4 6.5      2606 6.888375 6.609529 7.167220
5 7.5      3568 6.501239 6.271181 6.731296
6 6.5      5818 5.595775 5.241334 5.950216
7 7.0      5908 5.559557 5.195761 5.923352
8 6.3      5966 5.536216 5.166307 5.906125
9 6.5      1597 7.294425 6.920550 7.668299
10 8.0     1716 7.246536 6.885218 7.607853
# ... with 55 more rows
```

# NIIRS Data: Generating probability estimates

```
> add_probs(dat, fit, q = 7)
# A tibble: 65 x 4
  NIIRS Altitude      pred prob_less_than7
  <dbl>    <int>     <dbl>          <dbl>
1     8.0     1537 7.318570        0.3667974
2     7.0     1874 7.182952        0.4222097
3     7.0     3251 6.628808        0.6560007
4     6.5     2606 6.888375        0.5479452
5     7.5     3568 6.501239        0.7052830
6     6.5     5818 5.595775        0.9320821
7     7.0     5908 5.559557        0.9367160
8     6.3     5966 5.536216        0.9395578
9     6.5     1597 7.294425        0.3764595
10    8.0     1716 7.246536        0.3958999
# ... with 55 more rows
```



# Model Invariance



# Model-Invariant Design

The same functions with the same syntax can be applied to each type of model supported.

# Generating a prediction interval for a simple linear model without ciTools

```
## Linear Model Prediction Interval  
predict(model, SE = TRUE, interval = "prediction")
```

# Generating a prediction interval for a poisson GLM without ciTools

```
## Poisson Model Prediction Interval
## Design your own simulation :(
sims <- 1000
obs <- NROW(tb)
modmat <- model.matrix(fit)
response_distr <- fit$family$family
inverselink <- fit$family$linkinv
out <- inverselink(predict(fit, tb))
sims <- arm::sim(fit, n.sims = nSims)
sim_response <- matrix(0, ncol = nSims, nrow = nPreds)

for (i in 1:nPreds){
  if(response_distr == "poisson"){
    sim_response[i,] <- rpois(n = nSims,
      lambda = inverselink(rnorm(nPreds,sims@coef[i,]
        %*% modmat[i,], sd = sims@sigma[i]))))
  }
}

lwr <- apply(sim_response, 1,
             FUN = quantile, probs = alpha / 2, type = 1)
upr <- apply(sim_response, 1,
             FUN = quantile, probs = 1 - alpha / 2, type = 1)

data[["pred"]] <- out
data[[names[1]]] <- lwr
data[[names[2]]] <- upr
```

**ciTools** allows you to use the same code for the inference you want even when you fit models of different types.

```
## Same one-line command
add_pi(dat, my_model)
add_pi(dat, my_other_model)
add_pi(dat, yet_another_model)
```

# “Data First” Syntax



The first input to all functions is a data table, and the only output is the same data table augmented by what you asked for.

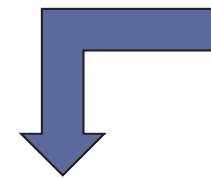
# Why “Data First”?

1. Facilitates function “chains” and plotting through use of the “pipe” operator.
2. Improves code legibility.
3. Consistency with the tidyverse .

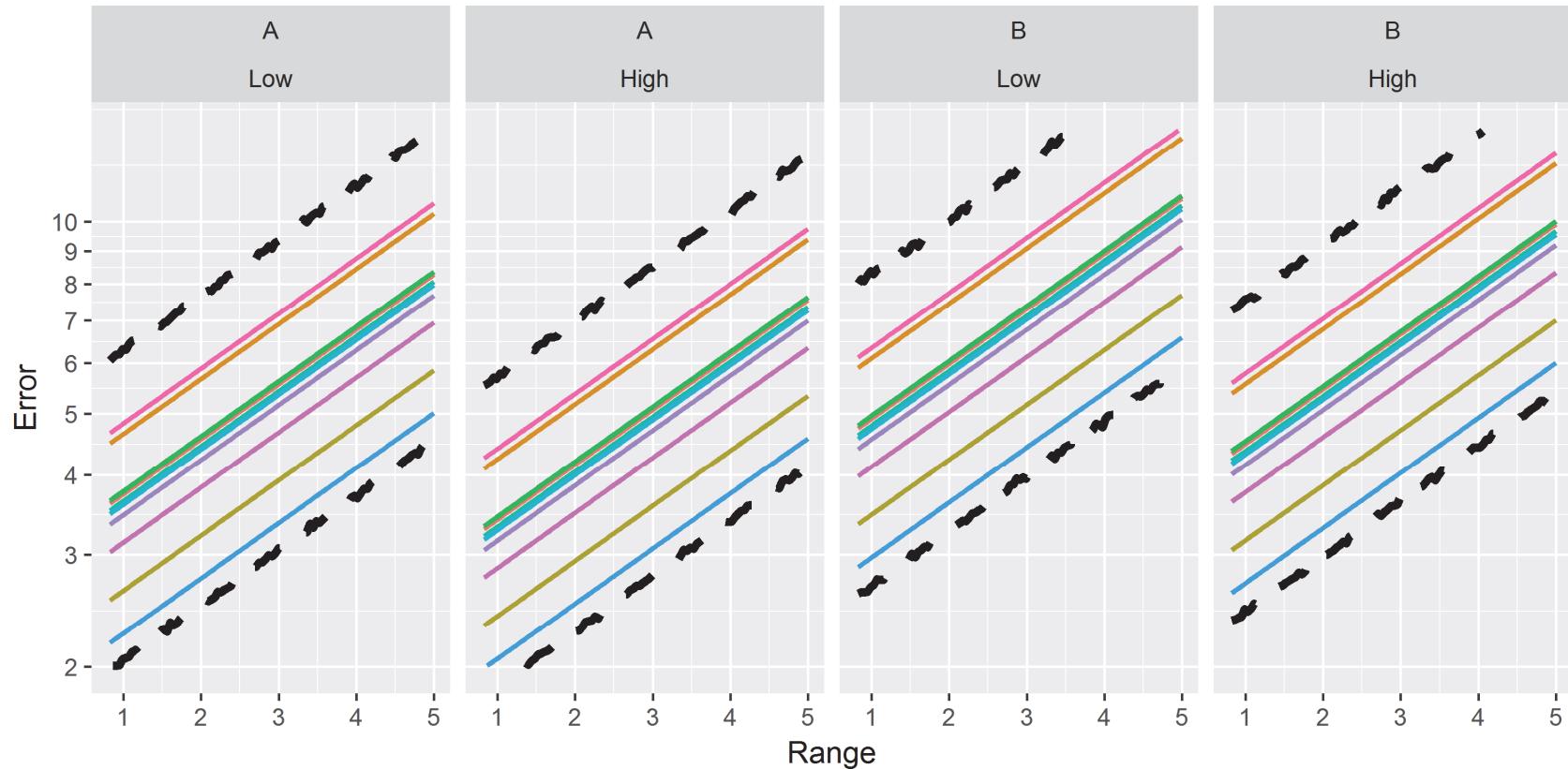
# Plotting with ciTools



# Mixed model data analysis\*



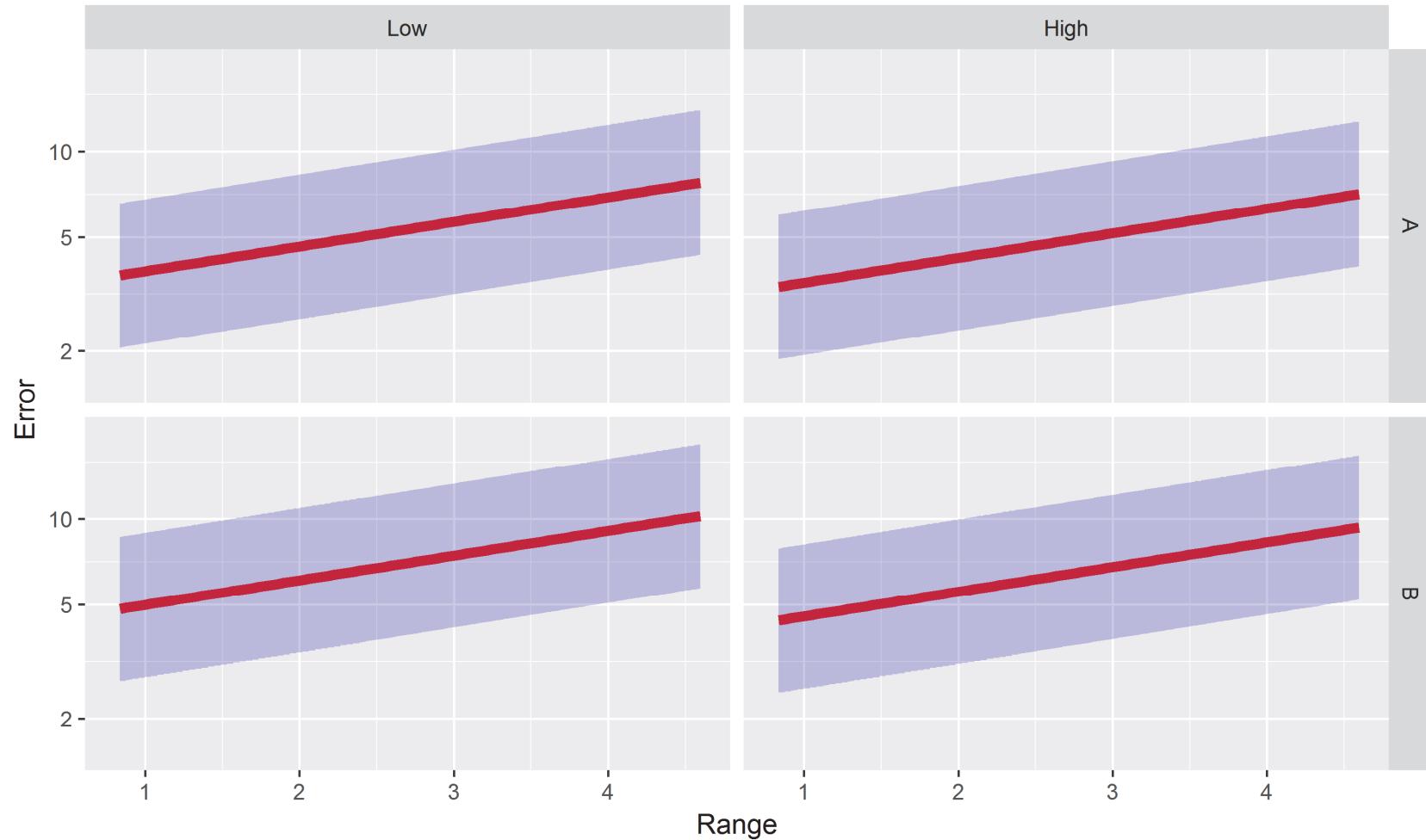
~100 lines of code, requires simulation



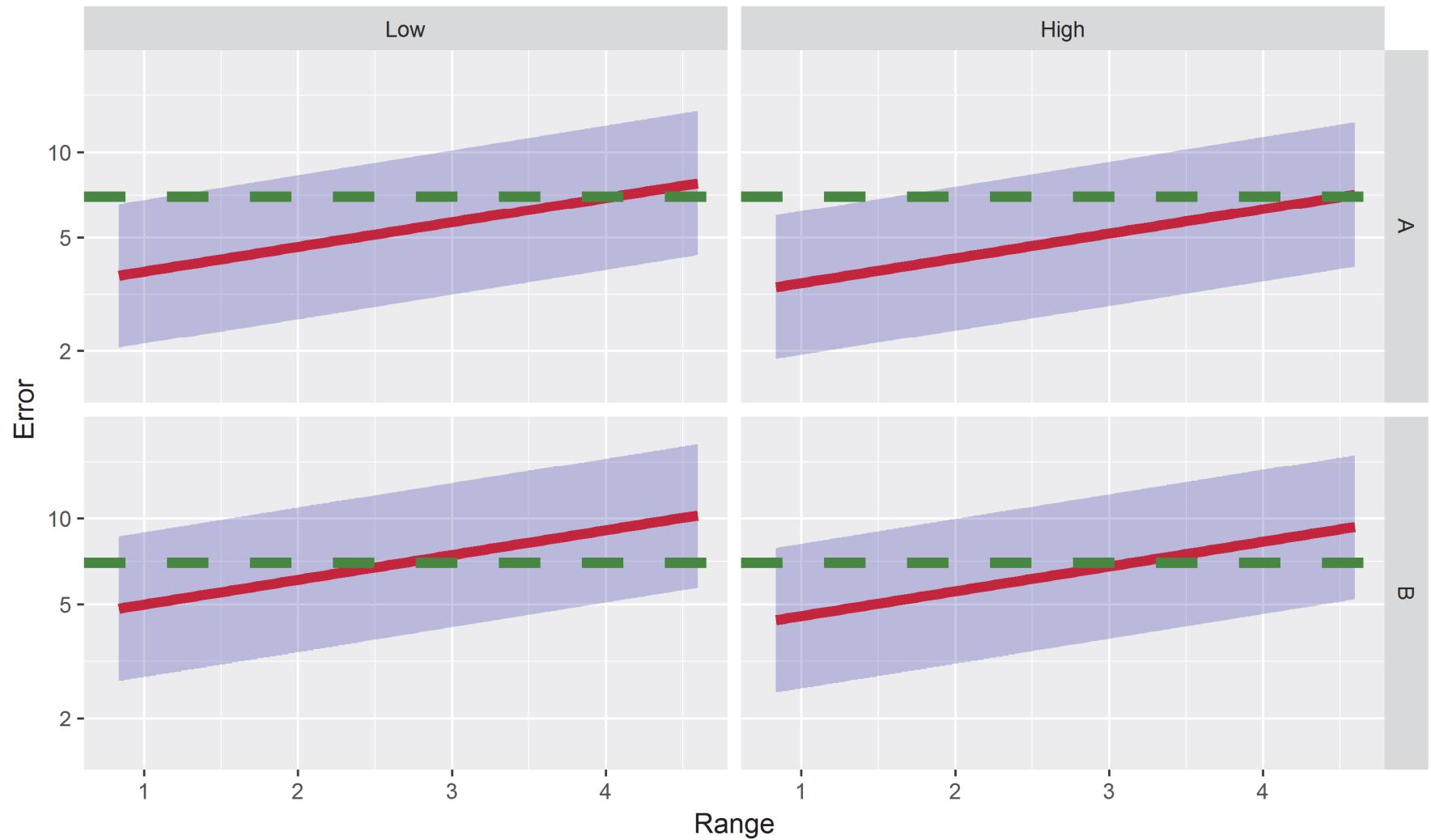
\*True values and factor names obscured for data security.

~10 lines of code,  
no simulation

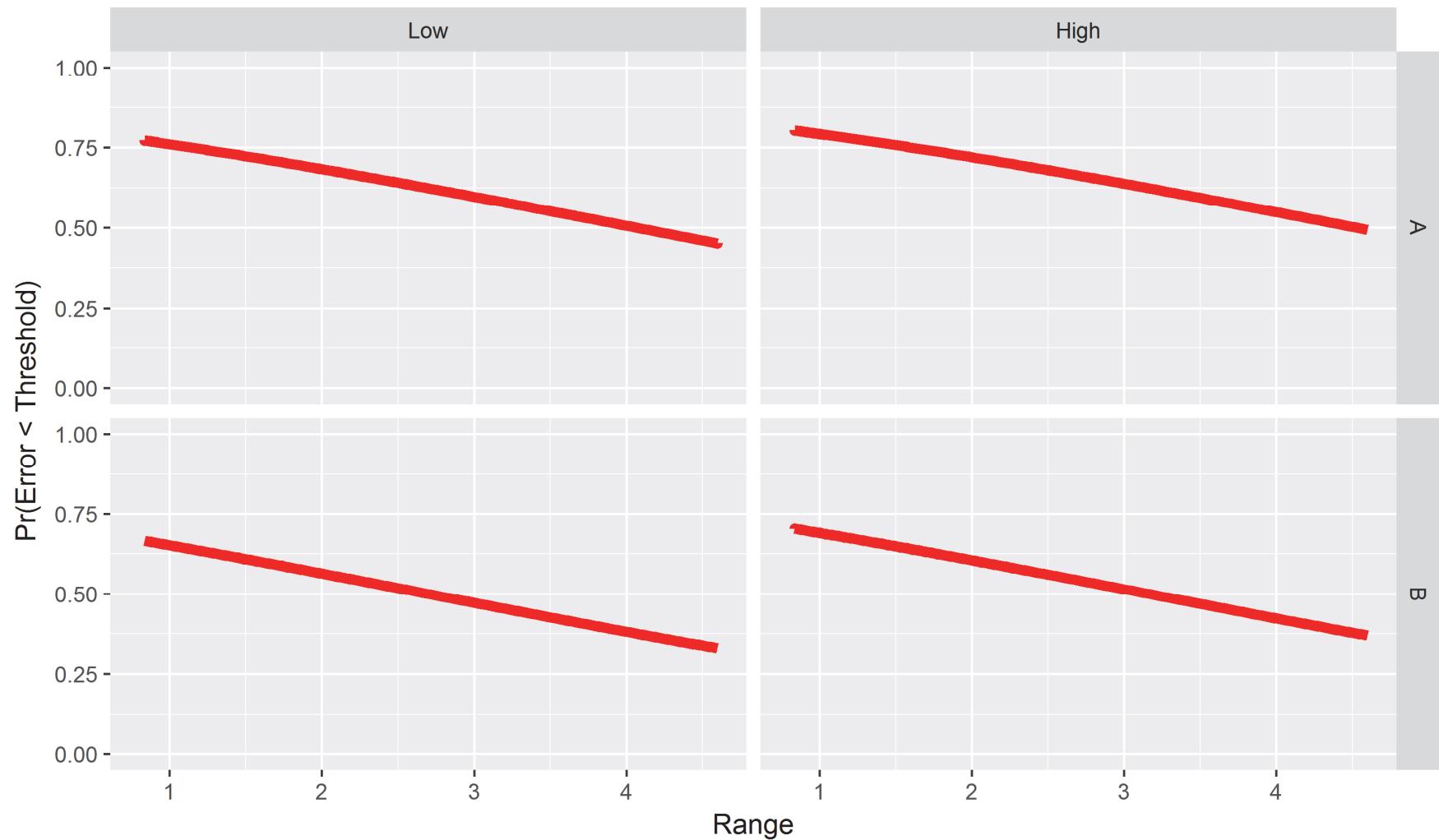
Overall fit + 50% PI



## Overall fit + 50% PI and Threshold



## Probability that Error < Threshold



# The Scope of ciTools



# Current Status of ciTools

	Confidence Intervals	Prediction Intervals	Probabilities	Quantiles
Linear Data	✓	✓	✓	✓
Count/ Binary Data	✓	✓	✓	✓
Skewed Data	✓	✓	✓	✓
Random Group Data	✓	✓	✓	✓
Reliability Data	Future Work	Future Work	Future Work	Future Work
Skewed, Random Group Data	In Progress	✓	✓	✓
...	...	...	...	...

# Getting Help in ciTools

?add\_ci

add\_ci {ciTools}

R Documentation

## Add Confidence Intervals for Predictions to Data Frames.

### Description

This is a generic function to append confidence intervals for predictions of a model fit to a data frame. A confidence interval is generated for the fitted value of each observation in `tb`. These confidence intervals are then appended to `tb` and returned to the user as a tibble.

### Usage

```
add_ci(tb, fit, alpha = 0.05, names = NULL, ...)
```

### Arguments

- `tb` A tibble or data frame on which to make predictions.
- `fit` An object of class `lm`, `glm`, or `lmerMod`. Predictions are made with this object.
- `alpha` A real number between 0 and 1. Controls the confidence level of the interval estimates.
- `names` `NULL` or character vector of length two. If `NULL`, confidence bounds will automatically be named by `add_ci`, otherwise, the lower confidence bound will be named `ciNames[1]` and the upper confidence bound will be named `ciNames[2]`.
- `...` Additional arguments.

### Details

For more specific information about the arguments that are useful in each method, consult

# Explore the math behind the scenes.

Uncertainty Intervals for Common Statistical Models

## Literature Review

John Haman, Matt Avery

July 13, 2017

### **Abstract**

The purpose of this document is to give an overview of all of the methods that are available in the package `ciTools`. In `ciTools`, one can supply our functions with a data set and a statistical model, and then `ciTools` will use either a default method or another method of similar quality to return the type of interval estimate they requested. We are not aware of another document that describes in detail the set of methods that one can use to produce interval estimates for each statistical model.

# **ciTools** in the larger R community

Open source, designed for collaboration and extension

1. Fits into the `tidyverse`.
2. Addresses existing gap in R capability with easy-to-learn syntax.
3. Use of generic functions makes growth easy.