Monte Carlo Simulation Tools for REDD+ Uncertainty Estimates

2024-12-19

Contents

Introduction

The ART-TREES Standard V2.01 mandates specific methodologies for calculating and reporting uncertainty estimates associated with emission factors and activity data within jurisdictional and nested REDD+ projects. To strengthen compliance, the ART-TREES project team produced the following report and capacity building resources.

Scope of work

This report focuses on the following technical areas:

- Develop Monte Carlo simulation pathways to quantify uncertainty in emission factors and activity data, ensuring consistency with ART-TREES's emphasis on robust uncertainty analysis and corrective bias assessment.
- Use R or other software to create systems that streamline data workflows and enhance accessibility for MRV purposes. Monte Carlo Simulation for Uncertainty Estimation
- Document methodologies and provide results in formats compliant with ART-TREES reporting standards.
- Prepare technical reports that detail uncertainty estimation methods and database management workflows.
- Develop and deliver training materials to strengthen stakeholder capacity to use ART-TREES-aligned tools and methodologies.

Registry requirements

The TREES 2.0 Standard[1] outlines requirements for reporting uncertainty in emissions and removals, and adjusting estimates where uncertainty levels exceed the defined threshold of a half-width of a 90% confidence interval between the upper and lower bounds (Relative RMSE 10%). Monte Carlo simulations are identified as an appropriate methodology due to their capacity to model variance and provide conservative estimates from large-scale highly-variable datasets. Specifically, "Monte Carlo simulations shall use the 90% confidence interval and a simulation n of 10,000" (p.45).

Aggregation of Uncertainty Across Crediting Periods

The TREES Standard provides a level of flexibility in allowing participants to aggregate uncertainty deductions across multiple crediting periods. At the end of each crediting period, participants may calculate a consolidated uncertainty deduction based on the summed gross emissions reductions and removals achieved over their entire ART participation. If prior uncertainty deductions exceeded the aggregated deduction sum for the total period, the over-deducted credits will be issued into the participant's registry account. This approach aims to incentivise participants to refine data quality and uncertainty estimates.

Inclusion of Biomass Map Uncertainty
Uncertainty must be assessed and reported for emissions factors derived from biomass maps, as these datasets directly impact the accuracy of emission estimates. TREES participants are encouraged to adopt best practices, such as those outlined in the CEOS LPV Biomass Protocol 2021, to enhance calibration, validation, and reliability of spatially explicit datasets. In this guidance document, key recommendations for good practices include appropriate scaling, temporally & spatially consistent reference data and remote sensing, and the use of approved error metrics (90% CI or RMSE). In particular, three likely sources of uncertainty in biomass estimation are highlighted separately for consideration in assessing and calibrating predictions[2].

- Measurement Uncertainty in tree measurements (i.e DBH and height).
- Allometric Model Errors in statistically inferring biomass from from tree measurements
- Sampling & Spatial Uncertainty arising from autocorrelation & over-fitting

Exemption for Allometric Estimates
An exemption from requirements for Monte Carlo simulations is granted to allometric modeled estimates. The TREES Standards V2.0 states that "such errors are considered consistent between emissions in the crediting level and crediting periods" which therefore do not materially influence the net results.=

Calculating Uncertainty Deductions
Cited on page 46 of the TREES Standards V2.0, calculations of uncertainty deductions are derived using the following formulae:

$$UNC_t = (GHGER_t + GHGREMV_t) \times UA_t. \text{ EQ 10}$$

UNC_t	Uncertainty deduction for year t (tCO_2e)
$GHGER_t$	Gross greenhouse gas emissions reductions for year t (tCO_2e)
$GHGREMV_t$	Gross greenhouse gas removals for year t (tCO_2e)
UA_t	The uncertainty adjustment factor for year t

Table 1: Parameters used in Equation 10 The uncertainty adjustment factor ($UAdj_t$) quantifies the proportional adjustment to emissions reductions and removals based on statistical uncertainty. It is defined as:

$$UAdj_t = 0.524417 \times \frac{HW_{90\%t}}{1.645006}$$

90% C I_t	The half-width of 90% confidence interval as percentage of mean
1.645006	t value for a 90% confidence interval
0.524417	A scaling constant to adjust the proportion.

Table 2: Parameters used in Equation 11

Methods review

In Appendix I, annotated results are presented from a rapid literature review of current methodologies and discussions of Monte Carlo simulations of biomass estimations used in REDD+ studies and programs. The search was conducted using keywords including "Monte Carlo simulations," "biomass estimation," "carbon stock uncertainty," and "REDD+ projects". Variants and combinations of these terms, including "forest carbon accounting" and "allometric uncertainty," were also explored. Data sources were visited among Scopus, Web of Science, and Google Scholar,and specialized journals in forestry, remote sensing, and carbon management. The temporal window of the review focused on studies published in the last two decades (2003–2023), reflecting the period during which Monte Carlo methods gained prominence in forest biomass estimation and REDD+ research evolved into a critical global framework. Additional attention was given to high-impact reviews and meta-analyses that provide state-of-the-art evaluations of the field.

Summarize review here...

Current tools

- Details of the design and parameters of the existing excel tool are available here and here.

Current limitations

-

Example script

Environment setup

```
easypackages::packages(
  "animation", "BIOMASS", "caret", "dataMaid", "DescTools", "dplyr",
  "extrafont", "FawR", "ForestToolsRS", "ggplot2", "htmltools",
  "janitor", "jsonlite", "lattice", "kableExtra", "kernlab",
  "knitr", "Mlmetrics", "olsrr", "plotly", "psych", "RColorBrewer",
  "rmarkdown", "readxl", "solarizeddox", "tibble", "tidymodels", "tidyverse",
  "tinytex", "tune", "useful", "webshot", "webshot2",
  prompt = F
  )
```

Monte Carlo of emissions data

Import data This section outlines the tools for importing and preparing forestry and biomass data for analysis, a key step in building ART-TREES-compliant MRV systems. Using the `allodb` package, we load a global allometry database and a dummy dataset from the Smithsonian Institute ForestGEO project.

```
library("allodb") # https://docs.ropensci.org/allodb/
set.seed(333)
data(scbi_stem1)
dataset = scbi_stem1
head(dataset) |> tibble::as_tibble()
```

```
# A tibble: 6 x 6
  treeID stemID   dbh genus species Family
   <int>  <int> <dbl> <chr> <chr>   <chr>
1   2695   2695  1.41 Acer  negundo Sapindaceae
2   1229  38557  1.67 Acer  negundo Sapindaceae
3   1230   1230  1.42 Acer  negundo Sapindaceae
4   1295  32303  1.04 Acer  negundo Sapindaceae
```

```
5   1229  32273  2.47 Acer  negundo Sapindaceae
6     66  31258  2.19 Acer  negundo Sapindaceae
```

```r
psych::describe(dataset)
```

```
         vars    n     mean       sd  median  trimmed     mad min      max
treeID      1 2287  2778.66  1929.26 2525.00  2705.54 2091.95   1  6207.00
stemID      2 2287 16577.12 16197.88 5022.00 15661.27 5749.52   1 40180.00
dbh         3 2287     5.52    10.80    1.67     2.65    0.79   1    92.02
genus*      4 2287    16.37     6.52   18.00    16.71    0.00   1    31.00
species*    5 2287    13.26     9.60    8.00    11.31    0.00   1    40.00
Family*     6 2287    13.07     4.02   13.00    13.33    0.00   1    22.00
            range  skew kurtosis     se
treeID    6206.00  0.27    -1.11  40.34
stemID   40179.00  0.40    -1.75 338.71
dbh         91.02  3.81    16.30   0.23
genus*      30.00 -0.57     0.14   0.14
species*    39.00  1.59     1.30   0.20
Family*     21.00 -0.58     1.44   0.08
```

```r
str(dataset)
```

```
tibble [2,287 x 6] (S3: tbl_df/tbl/data.frame)
 $ treeID : int [1:2287] 2695 1229 1230 1295 1229 66 2600 4936 1229 1005 ...
 $ stemID : int [1:2287] 2695 38557 1230 32303 32273 31258 2600 4936 36996 1005 ...
 $ dbh    : num [1:2287] 1.41 1.67 1.42 1.04 2.47 ...
 $ genus  : chr [1:2287] "Acer" "Acer" "Acer" "Acer" ...
 $ species: chr [1:2287] "negundo" "negundo" "negundo" "negundo" ...
 $ Family : chr [1:2287] "Sapindaceae" "Sapindaceae" "Sapindaceae" "Sapindaceae" ...
```

Table 3: Smithsonian Institute GEOForest dataset from `allodb` package (n = 2287)

Probability density functions Accurate selection of probability density functions (PDFs) is essential for modeling uncertainties in carbon stocks and activity data. This section describes methodologies for fitting PDFs to data, ensuring results are robust and aligned with ART-TREES best practices.

- Use of statistical tests for goodness-of-fit validation.
- Integration of domain expertise to refine parameter selection.

```r
# add allometry database
data(equations)
data("equations_metadata")
show_cols   = c("equation_id", "equation_taxa", "equation_allometry")
eq_tab_acer = new_equations(subset_taxa = "Acer")
head(eq_tab_acer[, show_cols])
```

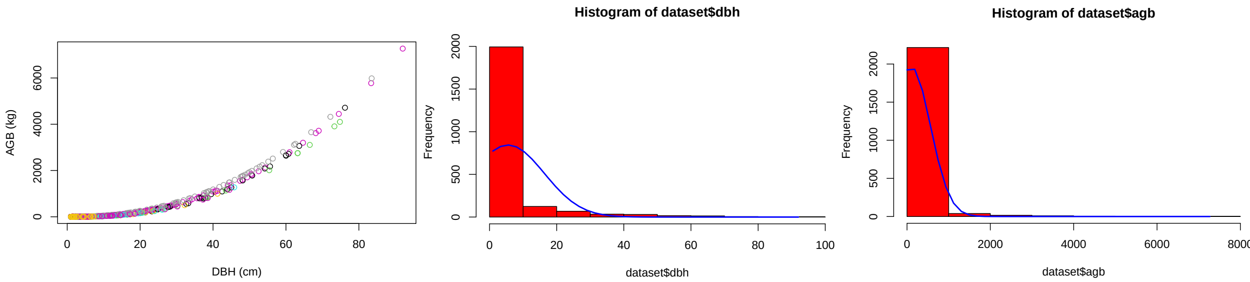
```
# A tibble: 6 x 3
  equation_id equation_taxa        equation_allometry
  <chr>       <chr>                <chr>
1 a4e4d1      Acer saccharum       exp(-2.192-0.011*dbh+2.67*(log(dbh)))
2 dfc2c7      Acer rubrum          2.02338*(dbh^2)^1.27612
3 eac63e      Acer rubrum          5.2879*(dbh^2)^1.07581
4 f49bcb      Acer pseudoplatanus exp(-5.644074+(2.5189*(log(pi*dbh))))
5 14bf3d      Acer mandshuricum    0.0335*(dbh)^1.606+0.0026*(dbh)^3.323+0.1222*~
6 0c7cd6      Acer mono            0.0202*(dbh)^1.810+0.0111*(dbh)^2.740+0.1156*~
```

```r
# Compute above ground biomass
dataset$agb = allodb::get_biomass(
    dbh     = dataset$dbh,
    genus   = dataset$genus,
    species = dataset$species,
    coords  = c(-78.2, 38.9)
  )

# examine dbh ~ agb function
dbh_agb = lm(dbh ~ agb, data = dataset)
#olsrr::ols_test_breusch_pagan(lm(dbh_agb)) #<0.0000
#h = lattice::histogram(dbh ~ agb, data = dataset)
plot(
  x    = dataset$dbh,
  y    = dataset$agb,
  col  = factor(scbi_stem1$genus),
  xlab = "DBH (cm)",
  ylab = "AGB (kg)"
)

# examine univariate distributions
h1 = hist(dataset$dbh, breaks=10, col="red")
xfit<-seq(min(dataset$dbh),max(dataset$dbh),length=40)
yfit<-dnorm(xfit,mean=mean(dataset$dbh),sd=sd(dataset$dbh))
yfit <- yfit*diff(h1$mids[1:2])*length(dataset$dbh)
lines(xfit, yfit, col="blue", lwd=2)

h2 = hist(dataset$agb, breaks=10, col="red")
xfit<-seq(min(dataset$agb),max(dataset$agb),length=40)
yfit<-dnorm(xfit,mean=mean(dataset$agb),sd=sd(dataset$agb))
yfit <- yfit*diff(h2$mids[1:2])*length(dataset$agb)
lines(xfit, yfit, col="blue", lwd=2)
wilcox.test(dataset$dbh) # p<0.00001
```

```

    Wilcoxon signed rank test with continuity correction

data:  dataset$dbh
V = 2616328, p-value < 2.2e-16
alternative hypothesis: true location is not equal to 0
```

```r
wilcox.test(dataset$agb) # p<0.00001
```

```

    Wilcoxon signed rank test with continuity correction

data:  dataset$agb
V = 2616328, p-value < 2.2e-16
alternative hypothesis: true location is not equal to 0
```



Simulation parameters This section introduces the design of the Monte Carlo simulation regime, including:

- Simulation parameters are defined to balance computational efficiency and statistical robustness.
- Cross-validation techniques are employed to evaluate model performance and identify bias or variance.

The `LGOCV` acronym used in the `caret` package functions below stands for “leave one group out cross validation”. We must select the % of test data that is set out from the build upon which the model will be repeatedly trained. Note, the following code applies functions to full dataset without explicit training-test split. **Questions remains on whether we require cross-validation uncertainty estimate to review internal bias, and whether we would like to develop Monte Carlo tools for spatial uncertainty used in Activity Data analysis**. For your consideration, the consultant has previously developed Monte Carlo tools for LULC applications, saved here

```
# Cross-validation split for bias detection
#samples     = caret::createDataPartition(dataset_tidy$volume, p = 0.80, list = FALSE)
#train_data  = dataset_tidy[samples, ]
#test_data   = dataset_tidy[-samples, ]

# Simulation pattern & regime
monte_carlo = trainControl(
  method     = "LGOCV",
  number     = 10,      # number of simulations
  p          = 0.8)      # percentage resampled


# Training model fit with all covariates (".") & the simulation
lm_monte_carlo = train(
  data       = dataset,
  agb ~ .,
  na.action = na.omit,
  trControl = monte_carlo)

lm_monte_carlo
```

```
Random Forest

2287 samples
   6 predictor

No pre-processing
Resampling: Repeated Train/Test Splits Estimated (10 reps, 80%)
Summary of sample sizes: 1832, 1832, 1832, 1832, 1832, 1832, ...
Resampling results across tuning parameters:

  mtry  RMSE       Rsquared   MAE
```

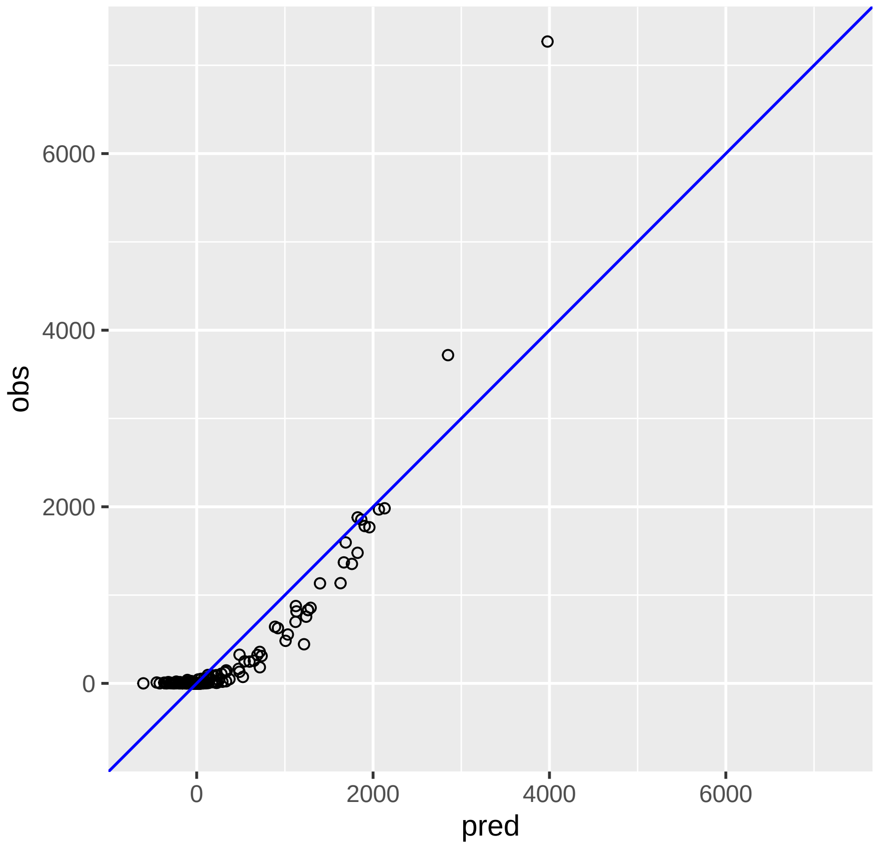
```
  2    334.61483  0.6015149  114.478275
 47     82.00289  0.9713294   13.767440
 93     50.27042  0.9895442    8.611931

RMSE was used to select the optimal model using the smallest value.
The final value used for the model was mtry = 93.
```

Visualize results To enable access to these predictions, we need to instruct `caret` to retain the resampled predictions by setting `savePredictions = "final"` in our `trainControl()` function. It's important to be aware that if you're working with a large dataset or numerous resampling iterations, the resulting `train()` object may grow significantly in size. This happens because `caret` must store a record of every row, including both the observed values and predictions, for each resampling iteration. By visualizing the results, we can offer insights into the performance of our model on the resampled data.

```r
monte_carlo_viz = trainControl(
  method     = "LGOCV",
  p          = 0.8,
  number     = 1,  # just for saving previous results
  savePredictions = "final")

lm_monte_carlo_viz = train(
  agb ~ .,
  data      = dataset,
  method    = "lm",
  na.action = na.omit,
  trControl = monte_carlo_viz)

head(lm_monte_carlo_viz$pred)  # residuals
```

```
  intercept       pred         obs rowIndex  Resample
1      TRUE -368.10404   8.1047583       25 Resample1
2      TRUE 1131.10292 814.9870137       32 Resample1
3      TRUE  137.35669   5.9989558       41 Resample1
4      TRUE  -46.87099   0.7190823       55 Resample1
5      TRUE  -26.59279   0.8106910       65 Resample1
6      TRUE   24.27442   0.8755165       74 Resample1
```

```r
lm_monte_carlo_viz$pred |>
  ggplot(aes(x=pred,y=obs)) +
    geom_point(shape=1) +
    geom_abline(slope=1, colour='blue')  +
    coord_obs_pred()
```



Monte Carlo of activity data This section showcases application of Monte Carlo simulations to uncertainty of LULC classification maps and activity data.

Import data

```
remotes::install_github("ytarazona/ForesToolboxRS")
library(ForesToolboxRS)
dir.create("./data/testdata")
download.file("https://github.com/ytarazona/ft_data/raw/main/data/LC08_232066_20190727_SR.zip", destfile
unzip("testdata/LC08_232066_20190727_SR.zip", exdir = "testdata")
download.file("https://github.com/ytarazona/ft_data/raw/main/data/signatures.zip", destfile = "testdata/
unzip("testdata/signatures.zip", exdir = "testdata")

image <- stack("./data/testdata/LC08_232066_20190727_SR.tif")
sig <- read_sf("./data/testdata/signatures.shp")
```

RandomForest classifier

```
classRF <- mla(img = image, model = "randomForest", endm = sig, training_split = 80)
print(classRF)
```

Classify land cover

```
# Classification
colmap <- c("#0000FF","#228B22","#FF1493", "#00FF00")
plot(classRF$Classification, main = "RandomForest Classification", col = colmap, axes = TRUE)
```

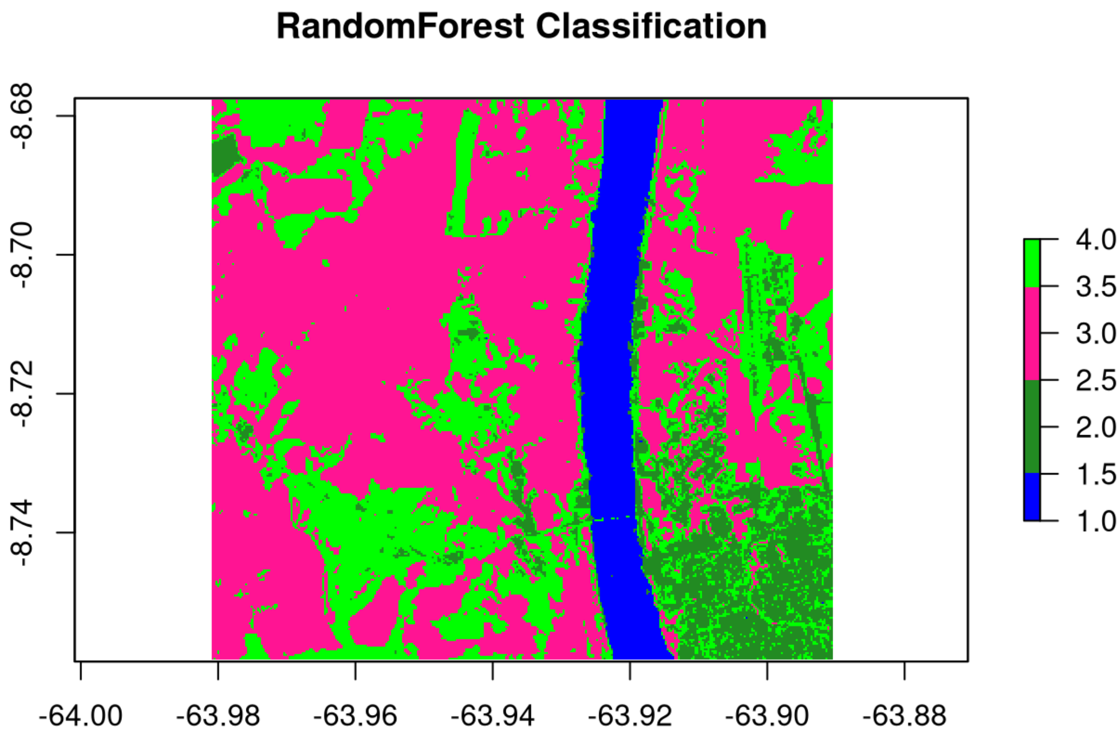


Figure 2: LULC map classified with randomForest classifier kernel

Monte Carlo of classification uncertainty

```
plot(
  cal_ml$svm_mccv,
  main = "Monte Carlo Cross-Validation calibration",
  col = "darkmagenta",
  type = "b",
  ylim = c(0, 0.4),
  ylab = "Error between 0 and 1",
  xlab = "Number of iterations"
)
lines(cal_ml$randomForest_mccv, col = "red", type = "b")
lines(cal_ml$naiveBayes_mccv, col = "green", type = "b")
lines(cal_ml$knn_mccv, col = "blue", type = "b")
legend(
  "topleft",
  c(
    "Support Vector Machine",
    "Random Forest",
    "Naive Bayes",
    "K-nearest Neighbors"
  ),
  col = c("darkmagenta", "red", "green", "blue"),
  lty = 1,
```

```
  cex = 0.7
)
```

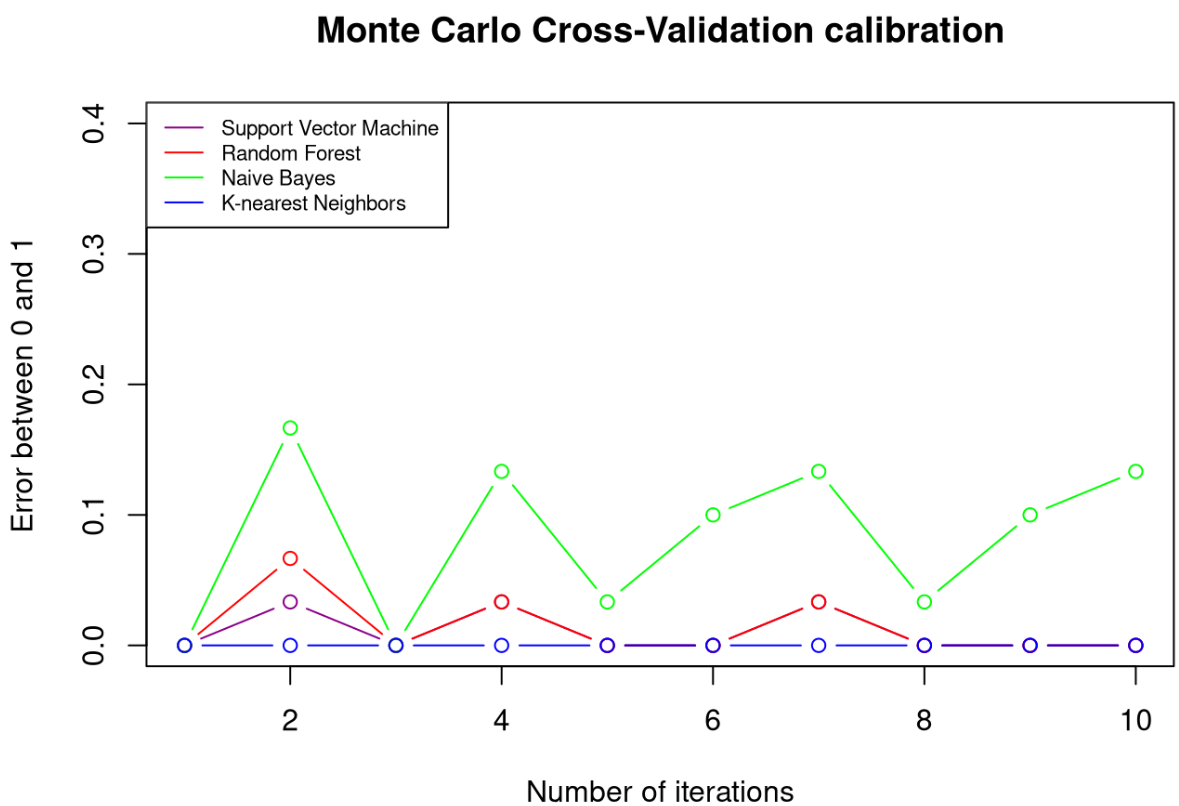


Figure 3: Monte Carlo ensemble of uncertainty estimates of common classifiers.

Appendix I: Review parameters & results Search parameters used in literature review of current Monte Carlo methods in REDD+ and ART-TREES projects

Parameter	Description
Keywords	Monte Carlo simulations Biomass estimation Carbon stock uncertainty REDD+ projects Forest carbon accounting Allometric uncertainty
Data Sources	Scopus Web of Science Google Scholar Grey Literature from REDD+ working groups (i.e. UNFCCC, IPCC)
Temporal Window	2003–2023
Focus Areas	Applications of Monte Carlo simulations in biomass and carbon stock estimations.

Parameter	Description
Inclusion Criteria	Addressing uncertainty in input data (e.g., allometric equations, plot-level measurements). Integration of Monte Carlo methods in REDD+ policy frameworks and carbon accounting. Peer-reviewed articles and high-impact reviews Case studies and empirical research involving REDD+ projects. Discussions of methodological advancements or critiques of Monte Carlo approaches.

Table 4: Search parameters used in a review of Monte Carlo tools in REDD+ reporting.

REDD+ scheme[^1]	Monte Carlo applied	Region	Key Findings	Ref
ADD	Uncertainty of SAAB estimate	Rondônia, Brazil	Estimated ± 20% measurement error in SAAB using Monte Carlo simulations; emphasized large trees' role in biomass.	[3]
ADD	AGB Uncertainty	Kenya, Mozambique	Assessed mixed-effects models in estimating mangrove biomass.	[4]
ADD	Blanket uncertainty propagation	Ghana	AGB prediction error >20%; addressed error propagation from trees to pixels in remote sensing.	[5]
ADD	Plot-based uncertainty	New Zealand	Cross-plot variance greatest magnitude of uncertainty	[6]
JNR	Multi-scale AGB uncertainty modeling	Minnesota, USA	Cross-scale tests showing effects of spatial resolution on AGB uncertainty.	[7]
NA	Allometric uncertainty modeling	Panama	Allometric models identified as largest source of biomass estimation error.	[8]
ADD	Sampling and allometric uncertainty	Tapajos Nat Forest, Brazil	Significance of allometric models on uncertainty of root biomass, 95% CI, 21 plots.	[9]

REDD+ scheme[^1]	Monte Carlo applied	Region	Key Findings	Ref
ADD	Uncertainty of volume estimates	Santa Catarina, Brazil	Negligible effects of residual uncertainty on large-area estimates	[10]
NA	Uncertainty metrics in model selection	Oregon, USA	Uncertainty estimates call for local validation or new local model development	[11]
ADD	AGB model uncertainty	French Guiana	AGB sub-model errors dominate uncertainty; height and wood-specific gravity errors are minor but can cause bias.	[12]
IFM	Emission factor uncertainty	Central Africa	Model selection is the largest error source (40%); weighting models reduces uncertainty in emission factors.	[13]
NA	Uncertainty in ecosystem nutrient estimate	New Hampshire, USA	Identified 8% uncertainty in nitrogen budgets, mainly from plot variability (6%) and allometric errors (5%).	[14]

Table 5: Results of a review of literature on Monte Carlo methodologies in REDD+ projects

Session runtime

```
devtools::session_info()
```

```
- Session info ---------------------------------------------------------------
 setting  value
 version  R version 4.1.0 (2021-05-18)
 os       macOS 15.2
 system   aarch64, darwin20
 ui       X11
 language (EN)
 collate  en_US.UTF-8
 ctype    en_US.UTF-8
 tz       America/Costa_Rica
 date     2025-01-08
 pandoc   3.6.1 @ /usr/local/bin/ (via rmarkdown)
```

```
- Packages -------------------------------------------------------------------
 package      * version    date (UTC) lib source
 allodb       * 0.0.1.9000 2025-01-07 [1] Github (ropensci/allodb@4207f86)
 animation    * 2.7        2021-10-07 [1] CRAN (R 4.1.0)
 assertthat     0.2.1      2019-03-21 [1] CRAN (R 4.1.0)
 backports      1.5.0      2024-05-23 [1] CRAN (R 4.1.0)
 BIOMASS      * 2.1.11     2023-09-29 [1] CRAN (R 4.1.0)
 broom        * 1.0.7      2024-09-26 [1] CRAN (R 4.1.0)
 c2z          * 0.2.0      2023-08-10 [1] CRAN (R 4.1.0)
 cachem         1.1.0      2024-05-16 [1] CRAN (R 4.1.0)
 caret        * 7.0-1      2024-12-10 [1] CRAN (R 4.1.0)
 chromote       0.3.1      2024-08-30 [1] CRAN (R 4.1.0)
 class          7.3-23     2025-01-01 [1] CRAN (R 4.1.0)
 classInt       0.4-10     2023-09-05 [1] CRAN (R 4.1.0)
 cli            3.6.3      2024-06-21 [1] CRAN (R 4.1.0)
 codetools      0.2-20     2024-03-31 [1] CRAN (R 4.1.0)
 colorspace     2.1-1      2024-07-26 [1] CRAN (R 4.1.0)
 data.table     1.16.4     2024-12-06 [1] CRAN (R 4.1.0)
 DBI            1.2.3      2024-06-02 [1] CRAN (R 4.1.0)
 devtools       2.4.5      2022-10-11 [1] CRAN (R 4.1.0)
 dials        * 1.3.0      2024-07-30 [1] CRAN (R 4.1.0)
 DiceDesign     1.10       2023-12-07 [1] CRAN (R 4.1.0)
 digest         0.6.37     2024-08-19 [1] CRAN (R 4.1.0)
 dplyr        * 1.1.4      2023-11-17 [1] CRAN (R 4.1.0)
 e1071          1.7-16     2024-09-16 [1] CRAN (R 4.1.0)
 easypackages   0.1.0      2016-12-05 [1] CRAN (R 4.1.0)
 ellipsis       0.3.2      2021-04-29 [1] CRAN (R 4.1.0)
 evaluate       1.0.1      2024-10-10 [1] CRAN (R 4.1.0)
 extrafont    * 0.19       2023-01-18 [1] CRAN (R 4.1.0)
 extrafontdb    1.0        2012-06-11 [1] CRAN (R 4.1.0)
 farver         2.1.2      2024-05-13 [1] CRAN (R 4.1.0)
 fastmap        1.2.0      2024-05-15 [1] CRAN (R 4.1.0)
 foreach        1.5.2      2022-02-02 [1] CRAN (R 4.1.0)
 fs             1.6.5      2024-10-30 [1] CRAN (R 4.1.0)
 furrr          0.3.1      2022-08-15 [1] CRAN (R 4.1.0)
 future         1.34.0     2024-07-29 [1] CRAN (R 4.1.0)
 future.apply   1.11.3     2024-10-27 [1] CRAN (R 4.1.0)
 generics       0.1.3      2022-07-05 [1] CRAN (R 4.1.0)
 ggplot2      * 3.5.1      2024-04-23 [1] CRAN (R 4.1.0)
 globals        0.16.3     2024-03-08 [1] CRAN (R 4.1.0)
 glue           1.8.0      2024-09-30 [1] CRAN (R 4.1.0)
 gower          1.0.2      2024-12-17 [1] CRAN (R 4.1.0)
 GPfit          1.0-8      2019-02-08 [1] CRAN (R 4.1.0)
 gtable         0.3.6      2024-10-25 [1] CRAN (R 4.1.0)
 hardhat        1.4.0      2024-06-02 [1] CRAN (R 4.1.0)
 htmltools    * 0.5.8.1    2024-04-04 [1] CRAN (R 4.1.0)
 htmlwidgets    1.6.4      2023-12-06 [1] CRAN (R 4.1.0)
 httpuv         1.6.15     2024-03-26 [1] CRAN (R 4.1.0)
 httr           1.4.7      2023-08-15 [1] CRAN (R 4.1.0)
 infer        * 1.0.7      2024-03-25 [1] CRAN (R 4.1.0)
 ipred          0.9-15     2024-07-18 [1] CRAN (R 4.1.0)
 iterators      1.0.14     2022-02-05 [1] CRAN (R 4.1.0)
 janitor      * 2.2.1      2024-12-22 [1] CRAN (R 4.1.0)
 jsonlite     * 1.8.9      2024-09-20 [1] CRAN (R 4.1.0)
```

```
kableExtra   * 1.4.0      2024-01-24 [1] CRAN (R 4.1.0)
kernlab      * 0.9-33     2024-08-13 [1] CRAN (R 4.1.0)
KernSmooth     2.23-26    2025-01-01 [1] CRAN (R 4.1.0)
knitr        * 1.49       2024-11-08 [1] CRAN (R 4.1.0)
labeling       0.4.3      2023-08-29 [1] CRAN (R 4.1.0)
later          1.4.1      2024-11-27 [1] CRAN (R 4.1.0)
lattice      * 0.22-6     2024-03-20 [1] CRAN (R 4.1.0)
lava           1.8.0      2024-03-05 [1] CRAN (R 4.1.0)
lazyeval       0.2.2      2019-03-15 [1] CRAN (R 4.1.0)
lhs            1.2.0      2024-06-30 [1] CRAN (R 4.1.0)
lifecycle      1.0.4      2023-11-07 [1] CRAN (R 4.1.0)
listenv        0.9.1      2024-01-29 [1] CRAN (R 4.1.0)
lubridate      1.9.4      2024-12-08 [1] CRAN (R 4.1.0)
magrittr       2.0.3      2022-03-30 [1] CRAN (R 4.1.0)
MASS           7.3-54     2021-05-03 [1] CRAN (R 4.1.0)
Matrix         1.3-3      2021-05-04 [1] CRAN (R 4.1.0)
memoise        2.0.1      2021-11-26 [1] CRAN (R 4.1.0)
mime           0.12       2021-09-28 [1] CRAN (R 4.1.0)
miniUI         0.1.1.1    2018-05-18 [1] CRAN (R 4.1.0)
minpack.lm     1.2-4      2023-09-11 [1] CRAN (R 4.1.0)
mnormt         2.1.1      2022-09-26 [1] CRAN (R 4.1.0)
modeldata    * 1.4.0      2024-06-19 [1] CRAN (R 4.1.0)
ModelMetrics   1.2.2.2    2020-03-17 [1] CRAN (R 4.1.0)
munsell        0.5.1      2024-04-01 [1] CRAN (R 4.1.0)
nlme           3.1-166    2024-08-14 [1] CRAN (R 4.1.0)
nnet           7.3-20     2025-01-01 [1] CRAN (R 4.1.0)
parallelly     1.41.0     2024-12-18 [1] CRAN (R 4.1.0)
parsnip      * 1.2.1      2024-03-22 [1] CRAN (R 4.1.0)
pillar         1.10.1     2025-01-07 [1] CRAN (R 4.1.0)
pkgbuild       1.4.5      2024-10-28 [1] CRAN (R 4.1.0)
pkgconfig      2.0.3      2019-09-22 [1] CRAN (R 4.1.0)
pkgload        1.4.0      2024-06-28 [1] CRAN (R 4.1.0)
plotly       * 4.10.4     2024-01-13 [1] CRAN (R 4.1.0)
plyr           1.8.9      2023-10-02 [1] CRAN (R 4.1.0)
pROC           1.18.5     2023-11-01 [1] CRAN (R 4.1.0)
processx       3.8.4      2024-03-16 [1] CRAN (R 4.1.0)
prodlim        2024.06.25 2024-06-24 [1] CRAN (R 4.1.0)
profvis        0.4.0      2024-09-20 [1] CRAN (R 4.1.0)
promises       1.3.2      2024-11-28 [1] CRAN (R 4.1.0)
proxy          0.4-27     2022-06-09 [1] CRAN (R 4.1.0)
ps             1.8.1      2024-10-28 [1] CRAN (R 4.1.0)
psych        * 2.4.12     2024-12-23 [1] CRAN (R 4.1.0)
purrr        * 1.0.2      2023-08-10 [1] CRAN (R 4.1.0)
R6             2.5.1      2021-08-19 [1] CRAN (R 4.1.0)
randomForest   4.7-1.2    2024-09-22 [1] CRAN (R 4.1.0)
rappdirs       0.3.3      2021-01-31 [1] CRAN (R 4.1.0)
RColorBrewer * 1.1-3      2022-04-03 [1] CRAN (R 4.1.0)
Rcpp           1.0.13-1   2024-11-02 [1] CRAN (R 4.1.0)
recipes      * 1.1.0      2024-07-04 [1] CRAN (R 4.1.0)
remotes        2.5.0      2024-03-17 [1] CRAN (R 4.1.0)
reshape2       1.4.4      2020-04-09 [1] CRAN (R 4.1.0)
rlang          1.1.4      2024-06-04 [1] CRAN (R 4.1.0)
rmarkdown    * 2.29       2024-11-04 [1] CRAN (R 4.1.0)
rpart          4.1.23     2023-12-05 [1] CRAN (R 4.1.0)
```

```
 rsample      * 1.2.1      2024-03-25 [1] CRAN (R 4.1.0)
 rstudioapi     0.17.1     2024-10-22 [1] CRAN (R 4.1.0)
 Rttf2pt1       1.3.12     2023-01-22 [1] CRAN (R 4.1.0)
 rvest          1.0.4      2024-02-12 [1] CRAN (R 4.1.0)
 scales       * 1.3.0      2023-11-28 [1] CRAN (R 4.1.0)
 sessioninfo    1.2.2      2021-12-06 [1] CRAN (R 4.1.0)
 sf             1.0-19     2024-11-05 [1] CRAN (R 4.1.0)
 shiny          1.10.0     2024-12-14 [1] CRAN (R 4.1.0)
 snakecase      0.11.1     2023-08-27 [1] CRAN (R 4.1.0)
 stringi        1.8.4      2024-05-06 [1] CRAN (R 4.1.0)
 stringr        1.5.1      2023-11-14 [1] CRAN (R 4.1.0)
 survival       3.8-3      2024-12-17 [1] CRAN (R 4.1.0)
 svglite        2.1.3      2023-12-08 [1] CRAN (R 4.1.0)
 systemfonts    1.1.0      2024-05-15 [1] CRAN (R 4.1.0)
 terra          1.8-5      2024-12-12 [1] CRAN (R 4.1.0)
 tibble       * 3.2.1      2023-03-20 [1] CRAN (R 4.1.0)
 tidymodels   * 1.2.0      2024-03-25 [1] CRAN (R 4.1.0)
 tidyr        * 1.3.1      2024-01-24 [1] CRAN (R 4.1.0)
 tidyselect     1.2.1      2024-03-11 [1] CRAN (R 4.1.0)
 timechange     0.3.0      2024-01-18 [1] CRAN (R 4.1.0)
 timeDate       4041.110   2024-09-22 [1] CRAN (R 4.1.0)
 tinytex      * 0.54       2024-11-01 [1] CRAN (R 4.1.0)
 tune         * 1.2.1      2024-04-18 [1] CRAN (R 4.1.0)
 units          0.8-5      2023-11-28 [1] CRAN (R 4.1.0)
 urlchecker     1.0.1      2021-11-30 [1] CRAN (R 4.1.0)
 useful       * 1.2.6.1    2023-10-24 [1] CRAN (R 4.1.0)
 usethis        3.1.0      2024-11-26 [1] CRAN (R 4.1.0)
 utf8           1.2.4      2023-10-22 [1] CRAN (R 4.1.0)
 vctrs          0.6.5      2023-12-01 [1] CRAN (R 4.1.0)
 viridisLite    0.4.2      2023-05-02 [1] CRAN (R 4.1.0)
 webshot      * 0.5.5      2023-06-26 [1] CRAN (R 4.1.0)
 webshot2     * 0.1.1      2023-08-11 [1] CRAN (R 4.1.0)
 websocket      1.4.2      2024-07-22 [1] CRAN (R 4.1.0)
 withr          3.0.2      2024-10-28 [1] CRAN (R 4.1.0)
 workflows    * 1.1.4      2024-02-19 [1] CRAN (R 4.1.0)
 workflowsets * 1.1.0      2024-03-21 [1] CRAN (R 4.1.0)
 xfun           0.49       2024-10-31 [1] CRAN (R 4.1.0)
 xml2           1.3.6      2023-12-04 [1] CRAN (R 4.1.0)
 xtable         1.8-4      2019-04-21 [1] CRAN (R 4.1.0)
 yaml           2.3.10     2024-07-26 [1] CRAN (R 4.1.0)
 yardstick    * 1.3.1      2024-03-21 [1] CRAN (R 4.1.0)

 [1] /Library/Frameworks/R.framework/Versions/4.1-arm64/Resources/library

------------------------------------------------------------------------------
```

```r
Sys.getenv()
```

```
__CF_USER_TEXT_ENCODING
                        0x1F5:0x0:0x52
__CFBundleIdentifier    com.rstudio.desktop
CLICOLOR_FORCE          1
COMMAND_MODE            unix2003
DISPLAY                 /private/tmp/com.apple.launchd.rEbaaZBvq1/org.xquartz:0
DYLD_FALLBACK_LIBRARY_PATH
```

```
                        /Library/Frameworks/R.framework/Resources/lib:/Library/Java/JavaVirtualMachines/
EDITOR                  vi
GIT_ASKPASS             rpostback-askpass
HOME                    /Users/seamus
LANG                    en_US.UTF-8
LC_CTYPE                en_US.UTF-8
LN_S                    ln -s
LOGNAME                 seamus
MAKE                    make
MallocNanoZone          0
MPLENGINE               tkAgg
NOT_CRAN                true
ORIGINAL_XDG_CURRENT_DESKTOP
                        undefined
PAGER                   /usr/bin/less
PATH                    /usr/bin:/usr/bin:/usr/local/bin:/System/Cryptexes/App/usr/bin:/usr/bin:/bin:/us
PKGLOAD_PARENT_TEMPDIR
                        /var/folders/_t/0yt99n3d0s1c1hnx40n3g9gw0000gn/T//Rtmpuy8FJG
PWD                     /Users/seamus/repos/monte-carlo-trees
PYTHONIOENCODING        utf-8
R_ARCH
R_BROWSER               /usr/bin/open
R_BZIPCMD               /usr/bin/bzip2
R_CLI_HAS_HYPERLINK_IDE_HELP
                        true
R_CLI_HAS_HYPERLINK_IDE_RUN
                        true
R_CLI_HAS_HYPERLINK_IDE_VIGNETTE
                        true
R_DOC_DIR               /Library/Frameworks/R.framework/Resources/doc
R_GZIPCMD               /usr/bin/gzip
R_HOME                  /Library/Frameworks/R.framework/Resources
R_INCLUDE_DIR           /Library/Frameworks/R.framework/Resources/include
R_LIBS                  /Library/Frameworks/R.framework/Versions/4.1-arm64/Resources/library
R_LIBS_SITE
R_LIBS_USER             ~/Library/R/arm64/4.1/library
R_MAX_MEM_SIZE          "16Gb"
R_MAX_VSIZE             "8000000"
R_PAPERSIZE             a4
R_PAPERSIZE_USER        a4
R_PDFVIEWER             /usr/bin/open
R_PLATFORM              aarch64-apple-darwin20
R_PRINTCMD              lpr
R_QPDF                  /Library/Frameworks/R.framework/Resources/bin/qpdf
R_RD4PDF                times,inconsolata,hyper
R_RUNTIME
R_SESSION_TMPDIR        /var/folders/_t/0yt99n3d0s1c1hnx40n3g9gw0000gn/T//RtmpFZgIVa
R_SHARE_DIR             /Library/Frameworks/R.framework/Resources/share
R_STRIP_SHARED_LIB      strip -x
R_STRIP_STATIC_LIB      strip -S
R_SYSTEM_ABI            macos,gcc,gxx,gfortran,gfortran
R_TEXI2DVICMD           /opt/R/arm64/bin/texi2dvi
R_UNZIPCMD              /usr/bin/unzip
R_ZIPCMD                /usr/bin/zip
```

```
RETICULATE_PYTHON_FALLBACK
                         /usr/bin/python3
RMARKDOWN_MATHJAX_PATH
                         /Applications/RStudio.app/Contents/Resources/app/resources/mathjax-27
RMARKDOWN_PREVIEW_DIR    /var/folders/_t/0yt99n3d0s1c1hnx40n3g9gw0000gn/T//Rtmpuy8FJG
RS_LOG_LEVEL             WARN
RS_RPOSTBACK_PATH        /Applications/RStudio.app/Contents/Resources/app/bin/rpostback
RS_SHARED_SECRET         92f9d667-3c9a-47fd-8afc-21487813826b
RSTUDIO                  1
RSTUDIO_CHILD_PROCESS_PANE
                         render
RSTUDIO_CLI_HYPERLINKS
                         true
RSTUDIO_CONSOLE_COLOR    256
RSTUDIO_CONSOLE_WIDTH    152
RSTUDIO_FALLBACK_LIBRARY_PATH
                         /var/folders/_t/0yt99n3d0s1c1hnx40n3g9gw0000gn/T/rstudio-fallback-library-path-
RSTUDIO_LONG_VERSION     2023.03.2+454
RSTUDIO_PANDOC           /Applications/RStudio.app/Contents/Resources/app/quarto/bin/tools
RSTUDIO_PROGRAM_MODE     desktop
RSTUDIO_SESSION_PID      1113
RSTUDIO_SESSION_PORT     23243
RSTUDIO_USER_IDENTITY    seamus
RSTUDIO_VERSION          2023.03.2.454
RSTUDIO_WINUTILS         bin/winutils
RSTUDIOAPI_IPC_REQUESTS_FILE
                         /var/folders/_t/0yt99n3d0s1c1hnx40n3g9gw0000gn/T/Rtmpuy8FJG/rstudio-ipc-request
RSTUDIOAPI_IPC_RESPONSE_FILE
                         /var/folders/_t/0yt99n3d0s1c1hnx40n3g9gw0000gn/T/Rtmpuy8FJG/rstudio-ipc-respons
RSTUDIOAPI_IPC_SHARED_SECRET
                         a4c1b573-7a8b-4077-8ea3-8bff1f1a7e85
SED                      /usr/bin/sed
SHELL                    /bin/zsh
SHLVL                    0
SSH_ASKPASS              rpostback-askpass
SSH_AUTH_SOCK            /private/tmp/com.apple.launchd.DC05txFu8Y/Listeners
TAR                      /usr/bin/tar
TERM                     xterm-256color
TMPDIR                   /var/folders/_t/0yt99n3d0s1c1hnx40n3g9gw0000gn/T/
TZDIR                    /var/db/timezone/zoneinfo
USER                     seamus
XPC_FLAGS                0x0
XPC_SERVICE_NAME         application.com.rstudio.desktop.9887254.9887259
```

```r
.libPaths()
```

```
[1] "/Library/Frameworks/R.framework/Versions/4.1-arm64/Resources/library"
```

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