GLUE-urbanQuant

Environmental Variable-By-Distance LMMs

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Contents

Load Data

```r
## Load data
urban.quantification.full.data <- read_csv(
  file = "data/analysis_data/urbanQuant-full_data.csv",
  col_types = c("fffnnninnnnnnnininnnnnnn"),
  show_col_types = FALSE
)
```

Linear Mixed-Effects Models

ISC

Fit the Linear Mixed-Effects Model

```
ISC.LMM <- lmer(
  ISC_Mean ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```
## Check model convergence
check_convergence(ISC.LMM)
# Model converged

## Check for boundary singularity
check_singularity(ISC.LMM)
# No singularity

## Visual assessment
check_model(ISC.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(ISC.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(ISC.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P = 0.008)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P < 0.001)
# Non-normality for random effects 'City: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City: Standardized_Distance' detected (P = 0.005)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(ISC.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(ISC.LMM)
# No outliers detected
```

Model Contrasts & Predictions

```
ISC.LMM.emmeans <- emmeans(
  ISC.LMM,
```

```
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 1: Estimated marginal means of sample type in the ISC LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	25.649	1.061	222.215	24.182	0
Random_Points	18.330	1.062	223.301	17.262	0
Systematic_Points	18.615	1.063	224.088	17.514	0
Random_Transect	21.828	1.061	222.512	20.572	0

Table 2: Effect sizes for the pairwise contrasts of sample type in the ISC LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	0.434	0.05	407.822	0.337	0.532
(GLUE - Systematic_Points)	0.417	0.05	410.250	0.320	0.515
(GLUE - Random_Transect)	0.227	0.05	404.638	0.129	0.324
(Random_Points - Systematic_Points)	-0.017	0.05	413.581	-0.115	0.081
(Random_Points - Random_Transect)	-0.207	0.05	408.652	-0.305	-0.110
(Systematic_Points - Random_Transect)	-0.191	0.05	411.098	-0.288	-0.093

```
ISC.LMM.emtrends <- emtrends(
    ISC.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 3: Predicted change in ISC from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the ISC linear mixed-effects model. Note: predictions have not been back-transformed.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	-63.991	1.968	341.707	-67.862	-60.121
Random_Points	-41.068	2.052	403.217	-45.101	-37.034
Systematic_Points	-40.382	2.051	403.202	-44.414	-36.351
Random_Transect	-64.397	1.972	344.403	-68.275	-60.518

Marginal & Conditional R^2

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(ISC.LMM)
# Marginal = 0.400
# Conditional = 0.635
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
ISC.LMM.anova.table <- anova(
  object = ISC.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 4: ANOVA table for the ISC linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	355560.70	355560.70	1	135.179	1251.754	0
Sampling_Design	78937.20	26312.40	3	402.587	92.633	0
Standardized_Distance:Sampling_Design	63586.97	21195.65	3	411.899	74.619	0

Partial η^2 for Fixed Effects

Table 5: Effect sizes for the ISC linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.903	0.95	0.880	1
Sampling_Design	0.408	0.95	0.349	1
Standardized_Distance:Sampling_Design	0.352	0.95	0.292	1

ranova

```r
## Fit a ranova
ISC.LMM.ranova <- ranova(
  ISC.LMM,
  reduce.terms = FALSE
)
```

Table 6: Summary of the ranova for the ISC linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	-91947.01	183924.0	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	-92706.17	185436.3	1518.330	3
(Standardized_Distance | City)	12	-92141.79	184307.6	389.569	3

ICC for Random Effects

Table 7: Table of the effect sizes for the random effects in the ISC linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.269
City	0.593

HII

Fit the Linear Mixed-Effects Model

```r
HII.LMM <- lmer(
  HII ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```r
## Check model convergence
check_convergence(HII.LMM)
# Model converged

## Check for boundary singularity
check_singularity(HII.LMM)
# No singularity

## Visual assessment
check_model(HII.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(HII.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(HII.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P = 0.021)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P = 0.001)
# Non-normality for random effects 'City: (Intercept)' detected (P < 0.001)
# Normality for random effects 'City: Standardized_Distance' detected (P = 0.147)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(HII.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(HII.LMM)
# No outliers detected
```

Model Contrasts & Predictions

```r
HII.LMM.emmeans <- emmeans(
  HII.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 8: Estimated marginal means of sample type in the HII LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	44.238	0.653	208.658	67.696	0
Random_Points	41.989	0.654	208.770	64.247	0
Systematic_Points	41.955	0.654	209.232	64.159	0
Random_Transect	41.886	0.654	208.702	64.093	0

Table 9: Effect sizes for the pairwise contrasts of sample type in the HII LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	0.294	0.063	408.378	0.170	0.418
(GLUE - Systematic_Points)	0.299	0.063	410.142	0.175	0.423
(GLUE - Random_Transect)	0.308	0.063	407.470	0.184	0.432
(Random_Points - Systematic_Points)	0.005	0.063	410.734	-0.120	0.129
(Random_Points - Random_Transect)	0.014	0.063	408.533	-0.110	0.137
(Systematic_Points - Random_Transect)	0.009	0.063	410.304	-0.115	0.133

```
## Set the emtrends
HII.LMM.emtrends <- emtrends(
    HII.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 10: Predicted change in HII from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the HII linear mixed-effects model.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	-21.826	1.045	330.582	-23.882	-19.770
Random_Points	-25.818	1.076	371.664	-27.935	-23.701
Systematic_Points	-24.083	1.077	372.412	-26.200	-21.966
Random_Transect	-26.218	1.046	331.815	-28.277	-24.160

Marginal & Conditional $\mathbf{R^2}$

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(HII.LMM)
# Marginal = 0.307
# Conditional = 0.679
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
HII.LMM.anova.table <- anova(
  object = HII.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 11: ANOVA table for the HII linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	54310.308	54310.308	1	136.148	929.228	0.000
Sampling_Design	362.895	120.965	3	406.618	2.070	0.104
Standardized_Distance:Sampling_Design	1136.802	378.934	3	425.548	6.483	0.000

Partial η^2 for Fixed Effects

Table 12: Effect sizes for the HII linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.872	0.95	0.843	1
Sampling_Design	0.015	0.95	0.000	1
Standardized_Distance:Sampling_Design	0.044	0.95	0.014	1

ranova

```r
## Fit a ranova
HII.LMM.ranova <- ranova(
  HII.LMM,
  reduce.terms = FALSE
)
```

Table 13: Summary of the ranova for the HII linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	-74691.29	149412.6	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	-76078.31	152180.6	2774.044	3
(Standardized_Distance | City)	12	-74988.49	150001.0	594.414	3

ICC for Random Effects

Table 14: Table of the effect sizes for the random effects in the HII linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.052
City	0.267

Mean NDVI

Fit the Linear Mixed-Effects Model

```
mean.NDVI.LMM <- lmer(
  Mean_NDVI ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```
## Check model convergence
check_convergence(mean.NDVI.LMM)
# Model converged

## Check for boundary singularity
check_singularity(mean.NDVI.LMM)
# No singularity

## Visual assessment
check_model(mean.NDVI.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(mean.NDVI.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(mean.NDVI.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P < 0.001)
# Non-normality for random effects 'City: (Intercept)' detected (P = 0.031)
# Normality for random effects 'City: Standardized_Distance' detected (P = 0.473)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(mean.NDVI.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(mean.NDVI.LMM)
# 1 outlier detected
```

Model Contrasts & Predictions

```
mean.NDVI.LMM.emmeans <- emmeans(
  mean.NDVI.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```r
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 15: Estimated marginal means of sample type in the mean.NDVI LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	4531.845	90.205	170.560	50.239	0
Random_Points	4782.821	90.253	170.922	52.994	0
Systematic_Points	4764.808	90.296	171.256	52.769	0
Random_Transect	4704.912	90.222	170.688	52.148	0

Table 16: Effect sizes for the pairwise contrasts of sample type in the mean.NDVI LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	-0.238	0.047	408.466	-0.330	-0.146
(GLUE - Systematic_Points)	-0.221	0.047	411.269	-0.313	-0.128
(GLUE - Random_Transect)	-0.164	0.047	405.327	-0.256	-0.072
(Random_Points - Systematic_Points)	0.017	0.047	414.395	-0.075	0.110
(Random_Points - Random_Transect)	0.074	0.047	409.408	-0.018	0.166
(Systematic_Points - Random_Transect)	0.057	0.047	412.232	-0.036	0.149

```r
## Set the emtrends
mean.NDVI.LMM.emtrends <- emtrends(
    mean.NDVI.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 17: Predicted change in Mean NDVI from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the Mean NDVI linear mixed-effects model.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	2742.777	122.587	307.843	2501.562	2983.992
Random_Points	1714.060	127.777	362.871	1462.783	1965.337
Systematic_Points	1688.671	127.742	363.123	1437.464	1939.878
Random_Transect	2902.935	122.845	310.299	2661.220	3144.651

Marginal & Conditional $\mathbf{R^2}$

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(mean.NDVI.LMM)
# Marginal = 0.194
# Conditional = 0.616
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
mean.NDVI.LMM.anova.table <- anova(
  object = mean.NDVI.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 18: ANOVA table for the Mean NDVI linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	614005485	614005485	1	135.874	551.133	0
Sampling_Design	170738654	56912885	3	396.609	51.085	0
Standardized_Distance:Sampling_Design	165673645	55224548	3	409.676	49.570	0

Partial η^2 for Fixed Effects

Table 19: Effect sizes for the Mean NDVI linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.802	0.95	0.757	1
Sampling_Design	0.279	0.95	0.217	1
Standardized_Distance:Sampling_Design	0.266	0.95	0.206	1

ranova

```r
## Fit a ranova
mean.NDVI.LMM.ranova <- ranova(
  mean.NDVI.LMM,
  reduce.terms = FALSE
)
```

Table 20: Summary of the ranova for the Mean NDVI linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	-181021.9	362073.7	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	-181651.1	363326.2	1258.521	3
(Standardized_Distance | City)	12	-181376.0	362776.1	708.369	3

ICC for Random Effects

Table 21: Table of the effect sizes for the random effects in the Mean NDVI linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.162
City	0.356

Min NDVI

Fit the Linear Mixed-Effects Model

```
min.NDVI.LMM <- lmer(
  Min_NDVI ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```
## Check model convergence
check_convergence(min.NDVI.LMM)
# Model converged

## Check for boundary singularity
check_singularity(min.NDVI.LMM)
# No singularity

## Visual assessment
check_model(min.NDVI.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(min.NDVI.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(min.NDVI.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P < 0.001)
# Non-normality for random effects 'City: (Intercept)' detected (P = 0.021)
# Non-normality for random effects 'City: Standardized_Distance' detected (P < 0.001)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(min.NDVI.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(min.NDVI.LMM)
# 1 outlier detected
```

Model Contrasts & Predictions

```
min.NDVI.LMM.emmeans <- emmeans(
  min.NDVI.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 22: Estimated marginal means of sample type in the min.NDVI LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	1576.291	123.888	147.738	12.724	0
Random_Points	1568.031	123.911	147.847	12.655	0
Systematic_Points	1568.748	123.939	147.981	12.657	0
Random_Transect	1630.352	123.898	147.786	13.159	0

Table 23: Effect sizes for the pairwise contrasts of sample type in the min.NDVI LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	0.009	0.045	409.527	-0.079	0.097
(GLUE - Systematic_Points)	0.008	0.045	412.859	-0.080	0.096
(GLUE - Random_Transect)	-0.057	0.045	406.438	-0.145	0.031
(Random_Points - Systematic_Points)	-0.001	0.045	415.846	-0.089	0.088
(Random_Points - Random_Transect)	-0.066	0.045	410.545	-0.154	0.023
(Systematic_Points - Random_Transect)	-0.065	0.045	413.905	-0.153	0.024

```
## Set the emtrends
min.NDVI.LMM.emtrends <- emtrends(
    min.NDVI.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 24: Predicted change in Min NDVI from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the Min NDVI linear mixed-effects model.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	1416.357	127.292	230.811	1165.555	1667.159
Random_Points	743.290	131.317	261.299	484.716	1001.864
Systematic_Points	740.726	131.325	261.564	482.136	999.315
Random_Transect	1378.633	127.491	232.206	1127.447	1629.819

Marginal & Conditional R^2

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(min.NDVI.LMM)
# Marginal = 0.036
# Conditional = 0.722
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
min.NDVI.LMM.anova.table <- anova(
  object = min.NDVI.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 25: ANOVA table for the Min NDVI linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	85184526	85184526	1	136.097	94.195	0
Sampling_Design	43161348	14387116	3	395.049	15.909	0
Standardized_Distance:Sampling_Design	63577713	21192571	3	413.865	23.434	0

Partial η^2 for Fixed Effects

Table 26: Effect sizes for the Min NDVI linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.409	0.95	0.308	1
Sampling_Design	0.108	0.95	0.060	1
Standardized_Distance:Sampling_Design	0.145	0.95	0.093	1

ranova

```r
## Fit a ranova
min.NDVI.LMM.ranova <- ranova(
  min.NDVI.LMM,
  reduce.terms = FALSE
)
```

Table 27: Summary of the ranova for the Min NDVI linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	-178818.8	357667.5	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	-179342.3	358708.6	1047.053	3
(Standardized_Distance | City)	12	-179403.9	358831.8	1170.255	3

ICC for Random Effects

Table 28: Table of the effect sizes for the random effects in the Min NDVI linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.060
City	0.469

Max NDVI

Fit the Linear Mixed-Effects Model

```
max.NDVI.LMM <- lmer(
  Max_NDVI ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```
## Check model convergence
check_convergence(max.NDVI.LMM)
# Model converged

## Check for boundary singularity
check_singularity(max.NDVI.LMM)
# No singularity

## Visual assessment
check_model(max.NDVI.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(max.NDVI.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(max.NDVI.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P = 0.016)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P = 0.014)
# Non-normality for random effects 'City: (Intercept)' detected (P < 0.001)
# Normality for random effects 'City: Standardized_Distance' detected (P = 0.080)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(max.NDVI.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(max.NDVI.LMM)
# 3 outliers detected
```

Model Contrasts & Predictions

```
max.NDVI.LMM.emmeans <- emmeans(
  max.NDVI.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```r
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 29: Estimated marginal means of sample type in the max.NDVI LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	6742.934	85.213	177.657	79.130	0
Random_Points	7147.082	85.274	178.172	83.813	0
Systematic_Points	7131.948	85.322	178.579	83.588	0
Random_Transect	7002.961	85.232	177.815	82.163	0

Table 30: Effect sizes for the pairwise contrasts of sample type in the max.NDVI LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	-0.369	0.046	408.193	-0.459	-0.278
(GLUE - Systematic_Points)	-0.355	0.046	410.986	-0.446	-0.264
(GLUE - Random_Transect)	-0.237	0.046	404.641	-0.328	-0.147
(Random_Points - Systematic_Points)	0.014	0.046	414.541	-0.077	0.105
(Random_Points - Random_Transect)	0.131	0.046	409.158	0.041	0.222
(Systematic_Points - Random_Transect)	0.118	0.046	411.975	0.027	0.209

```r
## Set the emtrends
max.NDVI.LMM.emtrends <- emtrends(
    max.NDVI.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 31: Predicted change in Max NDVI from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the Max NDVI linear mixed-effects model.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	3384.873	124.040	347.780	3140.909	3628.836
Random_Points	2275.892	129.608	413.719	2021.119	2530.665
Systematic_Points	2252.000	129.554	413.959	1997.335	2506.665
Random_Transect	3711.333	124.315	350.677	3466.835	3955.830

Marginal & Conditional $\mathbf{R^2}$

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(max.NDVI.LMM)
# Marginal = 0.291
# Conditional = 0.630
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
max.NDVI.LMM.anova.table <- anova(
  object = max.NDVI.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 32: ANOVA table for the Max NDVI linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	1179782834	1179782834	1	136.136	982.134	0
Sampling_Design	230050168	76683389	3	401.215	63.837	0
Standardized_Distance:Sampling_Design	204488525	68162842	3	410.789	56.744	0

Partial η^2 for Fixed Effects

Table 33: Effect sizes for the Max NDVI linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.878	0.95	0.850	1
Sampling_Design	0.323	0.95	0.262	1
Standardized_Distance:Sampling_Design	0.293	0.95	0.232	1

ranova

```r
## Fit a ranova
max.NDVI.LMM.ranova <- ranova(
  max.NDVI.LMM,
  reduce.terms = FALSE
)
```

Table 34: Summary of the ranova for the Max NDVI linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	-181817.8	363665.6	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	-182467.9	364959.7	1300.094	3
(Standardized_Distance | City)	12	-182133.3	364290.6	630.953	3

ICC for Random Effects

Table 35: Table of the effect sizes for the random effects in the Max NDVI linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.221
City	0.407

Mean Annual Temperature

Fit the Linear Mixed-Effects Model

```
mean.annual.temperature.LMM <- lmer(
  Mean_Annual_Temperature ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```
## Check model convergence
check_convergence(mean.annual.temperature.LMM)
# Model converged

## Check for boundary singularity
check_singularity(mean.annual.temperature.LMM)
# No singularity

## Visual assessment
check_model(mean.annual.temperature.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(mean.annual.temperature.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(mean.annual.temperature.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P < 0.001)
# Normality for random effects 'City: (Intercept)' detected (P = 0.245)
# Non-normality for random effects 'City: Standardized_Distance' detected (P < 0.001)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(mean.annual.temperature.LMM)
# Heteroscedasticity (non-constant error variance) detected (P = 0.009)

## Check for outliers
check_outliers(mean.annual.temperature.LMM)
# 20 outliers detected
```

Model Contrasts & Predictions

```
mean.annual.temperature.LMM.emmeans <- emmeans(
  mean.annual.temperature.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```r
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 36: Estimated marginal means of sample type in the mean.annual.temperature LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	11.210	0.385	136.601	29.151	0
Random_Points	11.033	0.385	136.600	28.692	0
Systematic_Points	11.035	0.385	136.609	28.697	0
Random_Transect	11.085	0.385	136.603	28.825	0

Table 37: Effect sizes for the pairwise contrasts of sample type in the mean.annual.temperature LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	0.262	0.071	409.045	0.122	0.402
(GLUE - Systematic_Points)	0.259	0.071	410.773	0.118	0.399
(GLUE - Random_Transect)	0.186	0.071	408.920	0.045	0.326
(Random_Points - Systematic_Points)	-0.003	0.071	410.874	-0.143	0.137
(Random_Points - Random_Transect)	-0.076	0.071	409.483	-0.216	0.064
(Systematic_Points - Random_Transect)	-0.073	0.071	411.219	-0.213	0.067

```r
## Set the emtrends
mean.annual.temperature.LMM.emtrends <- emtrends(
    mean.annual.temperature.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 38: Predicted change in Mean Annual Temperature from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the Mean Annual Temperature linear mixed-effects model. Note: predictions have not been back-transformed.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	-0.898	0.105	317.108	-1.105	-0.691
Random_Points	-1.087	0.107	346.652	-1.298	-0.876
Systematic_Points	-1.031	0.108	348.209	-1.243	-0.820
Random_Transect	-1.109	0.105	318.526	-1.315	-0.902

Marginal & Conditional R^2

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(mean.annual.temperature.LMM)
# Marginal = 0.005
# Conditional = 0.978
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
mean.annual.temperature.LMM.anova.table <- anova(
  object = mean.annual.temperature.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 39: ANOVA table for the Mean Annual Temperature linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	71.682	71.682	1	136.543	157.267	0.000
Sampling_Design	5.046	1.682	3	344.774	3.691	0.012
Standardized_Distance:Sampling_Design	2.091	0.697	3	420.871	1.529	0.206

Partial η^2 for Fixed Effects

Table 40: Effect sizes for the Mean Annual Temperature linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.535	0.95	0.445	1
Sampling_Design	0.031	0.95	0.004	1
Standardized_Distance:Sampling_Design	0.011	0.95	0.000	1

ranova

```r
## Fit a ranova
mean.annual.temperature.LMM.ranova <- ranova(
  mean.annual.temperature.LMM,
  reduce.terms = FALSE
)
```

Table 41: Summary of the ranova for the Mean Annual Temperature linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	-23365.21	46760.43	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	-25049.12	50122.24	3367.817	3
(Standardized_Distance | City)	12	-24555.95	49135.91	2381.481	3

ICC for Random Effects

Table 42: Table of the effect sizes for the random effects in the Mean Annual Temperature linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.001
City	1.009

Temperature Seasonality

Fit the Linear Mixed-Effects Model

```r
temperature.seasonality.LMM <- lmer(
  Temperature_Seasonality ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```r
## Check model convergence
check_convergence(temperature.seasonality.LMM)
# Model converged

## Check for boundary singularity
check_singularity(temperature.seasonality.LMM)
# No singularity

## Visual assessment
check_model(temperature.seasonality.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(temperature.seasonality.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(temperature.seasonality.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P < 0.001)
# Normality for random effects 'City: (Intercept)' detected (P = 0.073)
# Non-normality for random effects 'City: Standardized_Distance' detected (P < 0.001)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(temperature.seasonality.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(temperature.seasonality.LMM)
# 13 outliers detected
```

Model Contrasts & Predictions

```r
temperature.seasonality.LMM.emmeans <- emmeans(
  temperature.seasonality.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```r
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 43: Estimated marginal means of sample type in the temperature.seasonality LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	7.290	0.249	135.082	29.305	0
Random_Points	7.271	0.249	135.082	29.230	0
Systematic_Points	7.274	0.249	135.083	29.243	0
Random_Transect	7.290	0.249	135.082	29.306	0

Table 44: Effect sizes for the pairwise contrasts of sample type in the temperature.seasonality LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	0.147	0.056	410.741	0.038	0.256
(GLUE - Systematic_Points)	0.122	0.056	413.437	0.012	0.231
(GLUE - Random_Transect)	-0.002	0.056	409.636	-0.112	0.107
(Random_Points - Systematic_Points)	-0.025	0.056	414.332	-0.135	0.084
(Random_Points - Random_Transect)	-0.149	0.056	411.430	-0.259	-0.040
(Systematic_Points - Random_Transect)	-0.124	0.056	414.140	-0.233	-0.015

```r
## Set the emtrends
temperature.seasonality.LMM.emtrends <- emtrends(
    temperature.seasonality.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 45: Predicted change in Temperature Seasonality from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the Temperature Seasonality linear mixed-effects model.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	-0.089	0.024	185.127	-0.136	-0.042
Random_Points	-0.066	0.024	197.178	-0.114	-0.019
Systematic_Points	-0.069	0.024	197.626	-0.116	-0.021
Random_Transect	-0.071	0.024	185.735	-0.118	-0.024

Marginal & Conditional R^2

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(temperature.seasonality.LMM)
# Marginal < 0.001
# Conditional = 0.998
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
temperature.seasonality.LMM.anova.table <- anova(
  object = temperature.seasonality.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 46: ANOVA table for the Temperature Seasonality linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	0.183	0.183	1	135.121	11.289	0.001
Sampling_Design	0.460	0.153	3	402.621	9.472	0.000
Standardized_Distance:Sampling_Design	0.043	0.014	3	425.223	0.887	0.448

Partial η^2 for Fixed Effects

Table 47: Effect sizes for the Temperature Seasonality linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.077	0.95	0.020	1
Sampling_Design	0.066	0.95	0.028	1
Standardized_Distance:Sampling_Design	0.006	0.95	0.000	1

ranova

```r
## Fit a ranova
temperature.seasonality.LMM.ranova <- ranova(
  temperature.seasonality.LMM,
  reduce.terms = FALSE
)
```

Table 48: Summary of the ranova for the Temperature Seasonality linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	12192.13	-24354.25	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	11206.89	-22389.78	1970.470	3
(Standardized_Distance | City)	12	10356.82	-20689.64	3670.613	3

ICC for Random Effects

Table 49: Table of the effect sizes for the random effects in the Temperature Seasonality linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.000
City	1.026

Range Annual Temperature

Fit the Linear Mixed-Effects Model

```
range.annual.temperature.LMM <- lmer(
  Range_Annual_Temperature ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```
## Check model convergence
check_convergence(range.annual.temperature.LMM)
# Model converged

## Check for boundary singularity
check_singularity(range.annual.temperature.LMM)
# No singularity

## Visual assessment
check_model(range.annual.temperature.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(range.annual.temperature.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(range.annual.temperature.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P < 0.001)
# Non-normality for random effects 'City: (Intercept)' detected (P = 0.031)
# Non-normality for random effects 'City: Standardized_Distance' detected (P < 0.001)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(range.annual.temperature.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(range.annual.temperature.LMM)
# 5 outliers detected
```

Model Contrasts & Predictions

```
range.annual.temperature.LMM.emmeans <- emmeans(
  range.annual.temperature.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 50: Estimated marginal means of sample type in the range.annual.temperature LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	30.119	0.709	135.317	42.489	0
Random_Points	29.983	0.709	135.318	42.297	0
Systematic_Points	29.997	0.709	135.319	42.317	0
Random_Transect	30.119	0.709	135.318	42.488	0

Table 51: Effect sizes for the pairwise contrasts of sample type in the range.annual.temperature LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	0.226	0.066	408.436	0.096	0.356
(GLUE - Systematic_Points)	0.203	0.066	410.189	0.073	0.333
(GLUE - Random_Transect)	0.001	0.066	407.799	-0.129	0.130
(Random_Points - Systematic_Points)	-0.023	0.066	410.769	-0.153	0.107
(Random_Points - Random_Transect)	-0.225	0.066	408.955	-0.355	-0.095
(Systematic_Points - Random_Transect)	-0.202	0.066	410.714	-0.332	-0.072

```
## Set the emtrends
range.annual.temperature.LMM.emtrends <- emtrends(
    range.annual.temperature.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 52: Predicted change in Range Annual Temperature from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the Range Annual Temperature linear mixed-effects model. Note: predictions have not been back-transformed.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	0.024	0.118	193.754	-0.209	0.257
Random_Points	-0.096	0.120	205.178	-0.332	0.141
Systematic_Points	-0.092	0.120	205.455	-0.329	0.144
Random_Transect	0.031	0.118	194.362	-0.202	0.265

Marginal & Conditional R^2

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(range.annual.temperature.LMM)
# Marginal < 0.001
# Conditional = 0.995
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
range.annual.temperature.LMM.anova.table <- anova(
  object = range.annual.temperature.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 53: ANOVA table for the Range Annual Temperature linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	0.034	0.034	1	134.769	0.094	0.759
Sampling_Design	2.086	0.695	3	380.881	1.928	0.125
Standardized_Distance:Sampling_Design	1.542	0.514	3	410.590	1.426	0.235

Partial η^2 for Fixed Effects

Table 54: Effect sizes for the Range Annual Temperature linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.001	0.95	0	1
Sampling_Design	0.015	0.95	0	1
Standardized_Distance:Sampling_Design	0.010	0.95	0	1

ranova

```r
## Fit a ranova
range.annual.temperature.LMM.ranova <- ranova(
  range.annual.temperature.LMM,
  reduce.terms = FALSE
)
```

Table 55: Summary of the ranova for the Range Annual Temperature linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	-21025.43	42080.86	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	-22462.75	44949.50	2874.636	3
(Standardized_Distance | City)	12	-22574.74	45173.48	3098.618	3

ICC for Random Effects

Table 56: Table of the effect sizes for the random effects in the Range Annual Temperature linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.000
City	1.019

Annual Precipitation

Fit the Linear Mixed-Effects Model

```
annual.precipitation.LMM <- lmer(
  Annual_Precipitation ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```
## Check model convergence
check_convergence(annual.precipitation.LMM)
# Model converged

## Check for boundary singularity
check_singularity(annual.precipitation.LMM)
# No singularity

## Visual assessment
check_model(annual.precipitation.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(annual.precipitation.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(annual.precipitation.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P < 0.001)
# Non-normality for random effects 'City: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City: Standardized_Distance' detected (P < 0.001)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(annual.precipitation.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(annual.precipitation.LMM)
# 15 outliers detected
```

Model Contrasts & Predictions

```
annual.precipitation.LMM.emmeans <- emmeans(
  annual.precipitation.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 57: Estimated marginal means of sample type in the annual.precipitation LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	944.764	29.514	137.599	32.010	0
Random_Points	959.033	29.515	137.603	32.494	0
Systematic_Points	958.843	29.515	137.615	32.486	0
Random_Transect	956.033	29.515	137.603	32.392	0

Table 58: Effect sizes for the pairwise contrasts of sample type in the annual.precipitation LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	-0.208	0.068	407.315	-0.342	-0.073
(GLUE - Systematic_Points)	-0.205	0.068	408.777	-0.340	-0.070
(GLUE - Random_Transect)	-0.164	0.068	406.738	-0.299	-0.030
(Random_Points - Systematic_Points)	0.003	0.068	409.429	-0.132	0.137
(Random_Points - Random_Transect)	0.044	0.068	407.811	-0.091	0.178
(Systematic_Points - Random_Transect)	0.041	0.068	409.280	-0.094	0.176

```
## Set the emtrends
annual.precipitation.LMM.emtrends <- emtrends(
    annual.precipitation.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 59: Predicted change in Annual Precipitation from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the Annual Precipitation linear mixed-effects model. Note: predictions have not been back-transformed.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	-4.220	11.390	253.265	-26.651	18.212
Random_Points	43.340	11.624	274.673	20.457	66.224
Systematic_Points	38.330	11.626	274.943	15.444	61.217
Random_Transect	29.736	11.404	254.437	7.279	52.194

Marginal & Conditional $\mathbf{R^2}$

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(annual.precipitation.LMM)
# Marginal = 0.001
# Conditional = 0.962
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
annual.precipitation.LMM.anova.table <- anova(
  object = annual.precipitation.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 60: ANOVA table for the Annual Precipitation linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	36756.73	36756.73	1	136.174	7.799	0.006
Sampling_Design	45444.24	15148.08	3	372.500	3.214	0.023
Standardized_Distance:Sampling_Design	123199.47	41066.49	3	412.128	8.713	0.000

Partial η^2 for Fixed Effects

Table 61: Effect sizes for the Annual Precipitation linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.054	0.95	0.009	1
Sampling_Design	0.025	0.95	0.002	1
Standardized_Distance:Sampling_Design	0.060	0.95	0.024	1

ranova

```r
## Fit a ranova
annual.precipitation.LMM.ranova <- ranova(
  annual.precipitation.LMM,
  reduce.terms = FALSE
)
```

Table 62: Summary of the ranova for the Annual Precipitation linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	-122211.5	244453.0	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	-123725.7	247475.4	3028.389	3
(Standardized_Distance | City)	12	-123233.2	246490.3	2043.287	3

ICC for Random Effects

Table 63: Table of the effect sizes for the random effects in the Annual Precipitation linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.005
City	0.991

Precipitation Seasonality

Fit the Linear Mixed-Effects Model

```
precipitation.seasonality.LMM <- lmer(
  Precipitation_Seasonality ~ Standardized_Distance * Sampling_Design
    + (1 | City:Sampling_Design)
    + (1 | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
# No convergence with random slopes
```

Check Model Assumptions

```
## Check model convergence
check_convergence(precipitation.seasonality.LMM)
# Model converged

## Check for boundary singularity
check_singularity(precipitation.seasonality.LMM)
# No singularity

## Visual assessment
check_model(precipitation.seasonality.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(precipitation.seasonality.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(precipitation.seasonality.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City: (Intercept)' detected (P < 0.001)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(precipitation.seasonality.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(precipitation.seasonality.LMM)
# No outliers detected
```

Model Contrasts & Predictions

```
precipitation.seasonality.LMM.emmeans <- emmeans(
  precipitation.seasonality.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
  adjust = "none",
```

```r
  pbkrtest.limit = 21500
)
```

Table 64: Estimated marginal means of sample type in the precipitation.seasonality LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	33.847	2.24	135.281	15.113	0
Random_Points	33.939	2.24	135.284	15.154	0
Systematic_Points	33.942	2.24	135.288	15.155	0
Random_Transect	33.980	2.24	135.281	15.172	0

Table 65: Effect sizes for the pairwise contrasts of sample type in the precipitation.seasonality LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	-0.039	0.05	423.141	-0.137	0.059
(GLUE - Systematic_Points)	-0.040	0.05	427.153	-0.139	0.058
(GLUE - Random_Transect)	-0.057	0.05	419.538	-0.155	0.041
(Random_Points - Systematic_Points)	-0.001	0.05	431.352	-0.100	0.097
(Random_Points - Random_Transect)	-0.017	0.05	423.794	-0.116	0.081
(Systematic_Points - Random_Transect)	-0.016	0.05	427.816	-0.115	0.082

```r
## Set the emtrends
precipitation.seasonality.LMM.emtrends <- emtrends(
    precipitation.seasonality.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 66: Predicted change in Precipitation Seasonality from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the Precipitation Seasonality linear mixed-effects model.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	-0.478	0.107	21056.18	-0.689	-0.267
Random_Points	-0.348	0.134	20957.06	-0.610	-0.086
Systematic_Points	-0.420	0.135	20859.86	-0.685	-0.155
Random_Transect	-0.264	0.109	21072.92	-0.477	-0.051

Marginal & Conditional R^2

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(precipitation.seasonality.LMM)
# Marginal < 0.001
# Conditional = 0.992
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
precipitation.seasonality.LMM.anova.table <- anova(
  object = precipitation.seasonality.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 67: ANOVA table for the Precipitation Seasonality linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	212.261	212.261	1	20935.072	38.243	0.000
Sampling_Design	0.933	0.311	3	1153.428	0.056	0.983
Standardized_Distance:Sampling_Design	11.785	3.928	3	21002.065	0.708	0.547

Partial η^2 for Fixed Effects

Table 68: Effect sizes for the Precipitation Seasonality linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.002	0.95	0.001	1
Sampling_Design	0.000	0.95	0.000	1
Standardized_Distance:Sampling_Design	0.000	0.95	0.000	1

ranova

```r
## Fit a ranova
precipitation.seasonality.LMM.ranova <- ranova(
  precipitation.seasonality.LMM,
  reduce.terms = FALSE
)
```

Table 69: Summary of the ranova for the Precipitation Seasonality linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df	P-value
<none>	11	-49711.40	99444.8	NA	NA	NA
(1 | City:Sampling_Design)	10	-50390.90	100801.8	1359.004	1	0
(1 | City)	10	-50955.86	101931.7	2488.912	1	0

ICC for Random Effects

Table 70: Table of the effect sizes for the random effects in the Precipitation Seasonality linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.001
City	0.991

Aridity Index

Fit the Linear Mixed-Effects Model

```
aridity.index.LMM <- lmer(
  Aridity_Index ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```
## Check model convergence
check_convergence(aridity.index.LMM)
# Model converged

## Check for boundary singularity
check_singularity(aridity.index.LMM)
# No singularity

## Visual assessment
check_model(aridity.index.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(aridity.index.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(aridity.index.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P < 0.001)
# Non-normality for random effects 'City: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City: Standardized_Distance' detected (P < 0.001)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(aridity.index.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(aridity.index.LMM)
# 16 outliers detected
```

Model Contrasts & Predictions

```
aridity.index.LMM.emmeans <- emmeans(
  aridity.index.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```r
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 71: Estimated marginal means of sample type in the aridity.index LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	8533.509	288.280	138.713	29.601	0
Random_Points	8688.586	288.260	138.674	30.142	0
Systematic_Points	8696.837	288.278	138.708	30.168	0
Random_Transect	8671.909	288.261	138.675	30.084	0

Table 72: Effect sizes for the pairwise contrasts of sample type in the aridity.index LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	-0.143	0.05	409.527	-0.242	-0.044
(GLUE - Systematic_Points)	-0.151	0.05	412.578	-0.250	-0.052
(GLUE - Random_Transect)	-0.128	0.05	408.226	-0.227	-0.029
(Random_Points - Systematic_Points)	-0.008	0.05	413.760	-0.106	0.091
(Random_Points - Random_Transect)	0.015	0.05	410.246	-0.083	0.114
(Systematic_Points - Random_Transect)	0.023	0.05	413.331	-0.076	0.122

```r
## Set the emtrends
aridity.index.LMM.emtrends <- emtrends(
    aridity.index.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 73: Predicted change in Aridity Index from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the Aridity Index linear mixed-effects model. Note: predictions have not been back-transformed.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	555.829	141.845	258.796	276.511	835.147
Random_Points	1039.292	146.117	291.987	751.717	1326.868
Systematic_Points	919.610	146.215	293.010	631.845	1207.375
Random_Transect	963.628	141.792	258.897	684.415	1242.841

Marginal & Conditional $\mathbf{R^2}$

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(aridity.index.LMM)
# Marginal = 0.006
# Conditional = 0.908
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
aridity.index.LMM.anova.table <- anova(
  object = aridity.index.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 74: ANOVA table for the Aridity Index linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	62853733	62853733	1	137.399	53.665	0.000
Sampling_Design	5457565	1819188	3	374.172	1.553	0.200
Standardized_Distance:Sampling_Design	19103842	6367947	3	441.423	5.437	0.001

Partial η^2 for Fixed Effects

Table 75: Effect sizes for the Aridity Index linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.281	0.95	0.181	1
Sampling_Design	0.012	0.95	0.000	1
Standardized_Distance:Sampling_Design	0.036	0.95	0.009	1

ranova

```r
## Fit a ranova
aridity.index.LMM.ranova <- ranova(
  aridity.index.LMM,
  reduce.terms = FALSE
)
```

Table 76: Summary of the ranova for the Aridity Index linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	-181354.9	362739.8	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	-182111.9	364247.7	1513.900	3
(Standardized_Distance | City)	12	-182240.0	364503.9	1770.145	3

ICC for Random Effects

Table 77: Table of the effect sizes for the random effects in the Aridity Index linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.007
City	0.789

GDP 2005

Fit the Linear Mixed-Effects Model

```
GDP.2005.LMM <- lmer(
  log10(GDP_2005 + 1) ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```
## Check model convergence
check_convergence(GDP.2005.LMM)
# Model converged

## Check for boundary singularity
check_singularity(GDP.2005.LMM)
# No singularity

## Visual assessment
check_model(GDP.2005.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(GDP.2005.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(GDP.2005.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P < 0.001)
# Non-normality for random effects 'City: (Intercept)' detected (P < 0.001)
# Normality for random effects 'City: Standardized_Distance' detected (P = 0.132)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(GDP.2005.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(GDP.2005.LMM)
# No outliers detected
```

Model Contrasts & Predictions

```
GDP.2005.LMM.emmeans <- emmeans(
  GDP.2005.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 78: Estimated marginal means of sample type in the GDP.2005 LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	6.624	0.074	198.576	89.975	0
Random_Points	6.143	0.074	198.921	83.397	0
Systematic_Points	6.123	0.074	199.510	83.076	0
Random_Transect	6.239	0.074	198.779	84.720	0

Table 79: Effect sizes for the pairwise contrasts of sample type in the GDP.2005 LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	0.486	0.052	409.492	0.384	0.587
(GLUE - Systematic_Points)	0.505	0.052	412.103	0.403	0.607
(GLUE - Random_Transect)	0.388	0.052	407.804	0.287	0.490
(Random_Points - Systematic_Points)	0.019	0.052	413.851	-0.083	0.121
(Random_Points - Random_Transect)	-0.097	0.052	410.287	-0.199	0.005
(Systematic_Points - Random_Transect)	-0.116	0.052	412.911	-0.218	-0.015

```
## Set the emtrends
GDP.2005.LMM.emtrends <- emtrends(
  GDP.2005.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 80: Predicted change in GDP 2005 from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the GDP 2005 linear mixed-effects model. Note: predictions have not been back-transformed.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	-3.020	0.111	313.397	-3.238	-2.803
Random_Points	-3.114	0.115	373.145	-3.341	-2.887
Systematic_Points	-2.922	0.115	374.341	-3.149	-2.695
Random_Transect	-3.399	0.111	316.023	-3.617	-3.181

Marginal & Conditional R^2

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(GDP.2005.LMM)
# Marginal = 0.356
# Conditional = 0.650
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
GDP.2005.LMM.anova.table <- anova(
  object = GDP.2005.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 81: ANOVA table for the GDP 2005 linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	1278.807	1278.807	1	136.573	1299.449	0
Sampling_Design	79.242	26.414	3	397.954	26.840	0
Standardized_Distance:Sampling_Design	18.163	6.054	3	421.129	6.152	0

Partial η^2 for Fixed Effects

Table 82: Effect sizes for the GDP 2005 linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.905	0.95	0.883	1
Sampling_Design	0.168	0.95	0.113	1
Standardized_Distance:Sampling_Design	0.042	0.95	0.013	1

ranova

```r
## Fit a ranova
GDP.2005.LMM.ranova <- ranova(
  GDP.2005.LMM,
  reduce.terms = FALSE
)
```

Table 83: Summary of the ranova for the GDP 2005 linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	-31324.65	62679.30	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	-32065.10	64154.20	1480.906	3
(Standardized_Distance | City)	12	-31570.56	63165.12	491.825	3

ICC for Random Effects

Table 84: Table of the effect sizes for the random effects in the GDP 2005 linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.090
City	0.168

SSP1 2030

Fit the Linear Mixed-Effects Model

```
SSP1.2030.LMM <- lmer(
  log10(SSP_1_2030 + 1) ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```
## Check model convergence
check_convergence(SSP1.2030.LMM)
# Model converged

## Check for boundary singularity
check_singularity(SSP1.2030.LMM)
# No singularity

## Visual assessment
check_model(SSP1.2030.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(SSP1.2030.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(SSP1.2030.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P < 0.001)
# Non-normality for random effects 'City: (Intercept)' detected (P < 0.001)
# Normality for random effects 'City: Standardized_Distance' detected (P = 0.201)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(SSP1.2030.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(SSP1.2030.LMM)
# No outliers detected
```

Model Contrasts & Predictions

```
SSP1.2030.LMM.emmeans <- emmeans(
  SSP1.2030.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 85: Estimated marginal means of sample type in the SSP1.2030 LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	6.635	0.089	233.883	74.590	0
Random_Points	5.892	0.089	234.276	66.205	0
Systematic_Points	5.858	0.089	235.307	65.756	0
Random_Transect	6.012	0.089	234.207	67.556	0

Table 86: Effect sizes for the pairwise contrasts of sample type in the SSP1.2030 LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	0.530	0.052	410.380	0.428	0.633
(GLUE - Systematic_Points)	0.554	0.052	413.158	0.451	0.657
(GLUE - Random_Transect)	0.445	0.052	409.148	0.342	0.548
(Random_Points - Systematic_Points)	0.024	0.052	414.483	-0.079	0.127
(Random_Points - Random_Transect)	-0.086	0.052	411.154	-0.188	0.017
(Systematic_Points - Random_Transect)	-0.110	0.052	413.948	-0.212	-0.007

```
## Set the emtrends
SSP1.2030.LMM.emtrends <- emtrends(
    SSP1.2030.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 87: Predicted change in SSP1 2030 from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the SSP1 2030 linear mixed-effects model. Note: predictions have not been back-transformed.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	-3.799	0.143	383.876	-4.081	-3.517
Random_Points	-4.028	0.151	470.416	-4.324	-3.731
Systematic_Points	-3.689	0.151	473.597	-3.986	-3.393
Random_Transect	-4.613	0.144	387.458	-4.896	-4.331

Marginal & Conditional R^2

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(SSP1.2030.LMM)
# Marginal = 0.355
# Conditional = 0.600
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
SSP1.2030.LMM.anova.table <- anova(
  object = SSP1.2030.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 88: ANOVA table for the SSP1 2030 linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	3040.767	3040.767	1	137.066	1547.374	0
Sampling_Design	239.328	79.776	3	393.964	40.596	0
Standardized_Distance:Sampling_Design	70.195	23.398	3	431.281	11.907	0

Partial η^2 for Fixed Effects

Table 89: Effect sizes for the SSP1 2030 linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.919	0.95	0.900	1
Sampling_Design	0.236	0.95	0.176	1
Standardized_Distance:Sampling_Design	0.076	0.95	0.037	1

ranova

```r
## Fit a ranova
SSP1.2030.LMM.ranova <- ranova(
  SSP1.2030.LMM,
  reduce.terms = FALSE
)
```

Table 90: Summary of the ranova for the SSP1 2030 linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df	P
<none>	15	-38688.85	77407.7	NA	NA	
(Standardized_Distance | City:Sampling_Design)	12	-39459.75	78943.5	1541.803	3	
(Standardized_Distance | City)	12	-38893.30	77810.6	408.904	3	

ICC for Random Effects

Table 91: Table of the effect sizes for the random effects in the SSP1 2030 linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.061
City	0.184

SSP1 2100

Fit the Linear Mixed-Effects Model

```
SSP1.2100.LMM <- lmer(
  log10(SSP_1_2100 + 1) ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```
## Check model convergence
check_convergence(SSP1.2100.LMM)
# Model converged

## Check for boundary singularity
check_singularity(SSP1.2100.LMM)
# No singularity

## Visual assessment
check_model(SSP1.2100.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(SSP1.2100.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(SSP1.2100.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P < 0.001)
# Non-normality for random effects 'City: (Intercept)' detected (P < 0.001)
# Normality for random effects 'City: Standardized_Distance' detected (P = 0.150)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(SSP1.2100.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(SSP1.2100.LMM)
# No outliers detected
```

Model Contrasts & Predictions

```
SSP1.2100.LMM.emmeans <- emmeans(
  SSP1.2100.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 92: Estimated marginal means of sample type in the SSP1.2100 LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	7.023	0.091	238.224	77.143	0
Random_Points	6.258	0.091	238.614	68.717	0
Systematic_Points	6.224	0.091	239.712	68.267	0
Random_Transect	6.377	0.091	238.564	70.027	0

Table 93: Effect sizes for the pairwise contrasts of sample type in the SSP1.2100 LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	0.525	0.052	410.544	0.422	0.627
(GLUE - Systematic_Points)	0.548	0.052	413.360	0.445	0.651
(GLUE - Random_Transect)	0.443	0.052	409.351	0.340	0.546
(Random_Points - Systematic_Points)	0.023	0.052	414.636	-0.080	0.126
(Random_Points - Random_Transect)	-0.082	0.052	411.318	-0.184	0.021
(Systematic_Points - Random_Transect)	-0.105	0.052	414.148	-0.208	-0.002

```
## Set the emtrends
SSP1.2100.LMM.emtrends <- emtrends(
    SSP1.2100.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 94: Predicted change in SSP1 2100 from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the SSP1 2100 linear mixed-effects model. Note: predictions have not been back-transformed.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	-3.849	0.150	380.461	-4.144	-3.554
Random_Points	-4.152	0.158	464.899	-4.462	-3.842
Systematic_Points	-3.806	0.158	468.115	-4.116	-3.495
Random_Transect	-4.716	0.150	383.951	-5.012	-4.420

Marginal & Conditional R^2

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(SSP1.2100.LMM)
# Marginal = 0.349
# Conditional = 0.593
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
SSP1.2100.LMM.anova.table <- anova(
  object = SSP1.2100.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 95: ANOVA table for the SSP1 2100 linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	3114.135	3114.135	1	137.120	1465.930	0
Sampling_Design	235.776	78.592	3	394.568	36.996	0
Standardized_Distance:Sampling_Design	72.853	24.284	3	433.168	11.431	0

Partial η^2 for Fixed Effects

Table 96: Effect sizes for the SSP1 2100 linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.914	0.95	0.895	1
Sampling_Design	0.220	0.95	0.160	1
Standardized_Distance:Sampling_Design	0.073	0.95	0.035	1

ranova

```r
## Fit a ranova
SSP1.2100.LMM.ranova <- ranova(
  SSP1.2100.LMM,
  reduce.terms = FALSE
)
```

Table 97: Summary of the ranova for the SSP1 2100 linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	-39516.56	79063.11	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	-40289.98	80603.96	1546.852	3
(Standardized_Distance | City)	12	-39715.60	79455.21	398.097	3

ICC for Random Effects

Table 98: Table of the effect sizes for the random effects in the SSP1 2100 linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.057
City	0.169

SSP2 2030

Fit the Linear Mixed-Effects Model

```
SSP2.2030.LMM <- lmer(
  log10(SSP_2_2030 + 1) ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```
## Check model convergence
check_convergence(SSP2.2030.LMM)
# Model converged

## Check for boundary singularity
check_singularity(SSP2.2030.LMM)
# No singularity

## Visual assessment
check_model(SSP2.2030.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(SSP2.2030.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(SSP2.2030.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P < 0.001)
# Non-normality for random effects 'City: (Intercept)' detected (P < 0.001)
# Normality for random effects 'City: Standardized_Distance' detected (P = 0.195)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(SSP2.2030.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(SSP2.2030.LMM)
# No outliers detected
```

Model Contrasts & Predictions

```
SSP2.2030.LMM.emmeans <- emmeans(
  SSP2.2030.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```r
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 99: Estimated marginal means of sample type in the SSP2.2030 LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	6.620	0.089	234.346	74.659	0
Random_Points	5.877	0.089	234.741	66.256	0
Systematic_Points	5.844	0.089	235.777	65.808	0
Random_Transect	5.998	0.089	234.671	67.619	0

Table 100: Effect sizes for the pairwise contrasts of sample type in the SSP2.2030 LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	0.531	0.052	410.374	0.428	0.634
(GLUE - Systematic_Points)	0.555	0.052	413.151	0.452	0.658
(GLUE - Random_Transect)	0.445	0.052	409.142	0.342	0.547
(Random_Points - Systematic_Points)	0.024	0.052	414.476	-0.079	0.127
(Random_Points - Random_Transect)	-0.086	0.052	411.149	-0.189	0.016
(Systematic_Points - Random_Transect)	-0.110	0.052	413.940	-0.213	-0.007

```r
## Set the emtrends
SSP2.2030.LMM.emtrends <- emtrends(
    SSP2.2030.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 101: Predicted change in SSP2 2030 from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the SSP2 2030 linear mixed-effects model. Note: predictions have not been back-transformed.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	-3.795	0.143	383.780	-4.076	-3.514
Random_Points	-4.019	0.151	470.289	-4.315	-3.724
Systematic_Points	-3.681	0.151	473.465	-3.977	-3.385
Random_Transect	-4.606	0.143	387.362	-4.888	-4.324

Marginal & Conditional R^2

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(SSP2.2030.LMM)
# Marginal = 0.355
# Conditional = 0.600
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
SSP2.2030.LMM.anova.table <- anova(
  object = SSP2.2030.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 102: ANOVA table for the SSP2 2030 linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	3029.123	3029.123	1	137.069	1546.692	0
Sampling_Design	239.842	79.947	3	393.974	40.822	0
Standardized_Distance:Sampling_Design	69.991	23.330	3	431.213	11.913	0

Partial η^2 for Fixed Effects

Table 103: Effect sizes for the SSP2 2030 linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.919	0.95	0.900	1
Sampling_Design	0.237	0.95	0.177	1
Standardized_Distance:Sampling_Design	0.077	0.95	0.037	1

ranova

```r
## Fit a ranova
SSP2.2030.LMM.ranova <- ranova(
  SSP2.2030.LMM,
  reduce.terms = FALSE
)
```

Table 104: Summary of the ranova for the SSP2 2030 linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	-38652.28	77334.56	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	-39423.35	78870.70	1542.137	3
(Standardized_Distance | City)	12	-38855.90	77735.80	407.240	3

ICC for Random Effects

Table 105: Table of the effect sizes for the random effects in the SSP2 2030 linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.061
City	0.183

SSP2 2100

Fit the Linear Mixed-Effects Model

```
SSP2.2100.LMM <- lmer(
  log10(SSP_2_2100 + 1) ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```
## Check model convergence
check_convergence(SSP2.2100.LMM)
# Model converged

## Check for boundary singularity
check_singularity(SSP2.2100.LMM)
# No singularity

## Visual assessment
check_model(SSP2.2100.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(SSP2.2100.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(SSP2.2100.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P < 0.001)
# Non-normality for random effects 'City: (Intercept)' detected (P < 0.001)
# Normality for random effects 'City: Standardized_Distance' detected (P = 0.165)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(SSP2.2100.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(SSP2.2100.LMM)
# No outliers detected
```

Model Contrasts & Predictions

```
SSP2.2100.LMM.emmeans <- emmeans(
  SSP2.2100.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```r
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 106: Estimated marginal means of sample type in the SSP2.2100 LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	6.989	0.091	238.169	77.031	0
Random_Points	6.227	0.091	238.561	68.604	0
Systematic_Points	6.193	0.091	239.653	68.160	0
Random_Transect	6.347	0.091	238.508	69.935	0

Table 107: Effect sizes for the pairwise contrasts of sample type in the SSP2.2100 LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	0.526	0.052	410.526	0.423	0.629
(GLUE - Systematic_Points)	0.549	0.052	413.327	0.446	0.652
(GLUE - Random_Transect)	0.443	0.052	409.338	0.340	0.545
(Random_Points - Systematic_Points)	0.023	0.052	414.602	-0.080	0.126
(Random_Points - Random_Transect)	-0.083	0.052	411.297	-0.186	0.020
(Systematic_Points - Random_Transect)	-0.106	0.052	414.113	-0.209	-0.003

```r
## Set the emtrends
SSP2.2100.LMM.emtrends <- emtrends(
    SSP2.2100.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 108: Predicted change in SSP2 2100 from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the SSP2 2100 linear mixed-effects model. Note: predictions have not been back-transformed.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	-3.844	0.149	380.788	-4.137	-3.551
Random_Points	-4.136	0.157	465.360	-4.445	-3.828
Systematic_Points	-3.791	0.157	468.567	-4.099	-3.482
Random_Transect	-4.702	0.150	384.284	-4.996	-4.408

Marginal & Conditional R^2

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(SSP2.2100.LMM)
# Marginal = 0.350
# Conditional = 0.594
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
SSP2.2100.LMM.anova.table <- anova(
  object = SSP2.2100.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 109: ANOVA table for the SSP2 2100 linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	3100.199	3100.199	1	137.098	1475.501	0
Sampling_Design	236.308	78.769	3	394.872	37.489	0
Standardized_Distance:Sampling_Design	72.152	24.051	3	433.098	11.447	0

Partial η^2 for Fixed Effects

Table 110: Effect sizes for the SSP2 2100 linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.915	0.95	0.895	1
Sampling_Design	0.222	0.95	0.162	1
Standardized_Distance:Sampling_Design	0.073	0.95	0.035	1

ranova

```r
## Fit a ranova
SSP2.2100.LMM.ranova <- ranova(
  SSP2.2100.LMM,
  reduce.terms = FALSE
)
```

Table 111: Summary of the ranova for the SSP2 2100 linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	-39398.76	78827.51	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	-40174.87	80373.73	1552.221	3
(Standardized_Distance | City)	12	-39595.17	79214.34	392.827	3

ICC for Random Effects

Table 112: Table of the effect sizes for the random effects in the SSP2 2100 linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.057
City	0.163

SSP5 2030

Fit the Linear Mixed-Effects Model

```
SSP5.2030.LMM <- lmer(
  log10(SSP_5_2030 + 1) ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```
## Check model convergence
check_convergence(SSP5.2030.LMM)
# Model converged

## Check for boundary singularity
check_singularity(SSP5.2030.LMM)
# No singularity

## Visual assessment
check_model(SSP5.2030.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(SSP5.2030.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(SSP5.2030.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P < 0.001)
# Non-normality for random effects 'City: (Intercept)' detected (P < 0.001)
# Normality for random effects 'City: Standardized_Distance' detected (P = 0.182)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(SSP5.2030.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(SSP5.2030.LMM)
# No outliers detected
```

Model Contrasts & Predictions

```
SSP5.2030.LMM.emmeans <- emmeans(
  SSP5.2030.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```r
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 113: Estimated marginal means of sample type in the SSP5.2030 LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	6.676	0.089	234.272	74.908	0
Random_Points	5.929	0.089	234.666	66.505	0
Systematic_Points	5.895	0.089	235.706	66.054	0
Random_Transect	6.050	0.089	234.598	67.857	0

Table 114: Effect sizes for the pairwise contrasts of sample type in the SSP5.2030 LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	0.530	0.052	410.411	0.428	0.633
(GLUE - Systematic_Points)	0.554	0.052	413.200	0.451	0.657
(GLUE - Random_Transect)	0.445	0.052	409.178	0.342	0.547
(Random_Points - Systematic_Points)	0.024	0.052	414.525	-0.079	0.127
(Random_Points - Random_Transect)	-0.085	0.052	411.187	-0.188	0.017
(Systematic_Points - Random_Transect)	-0.109	0.052	413.991	-0.212	-0.007

```r
## Set the emtrends
SSP5.2030.LMM.emtrends <- emtrends(
    SSP5.2030.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 115: Predicted change in SSP5 2030 from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the SSP5 2030 linear mixed-effects model. Note: predictions have not been back-transformed.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	-3.795	0.144	384.055	-4.078	-3.512
Random_Points	-4.030	0.151	470.802	-4.328	-3.733
Systematic_Points	-3.691	0.151	474.012	-3.988	-3.393
Random_Transect	-4.616	0.144	387.643	-4.899	-4.332

Marginal & Conditional R^2

```
## Calculate the marginal and conditional R-squared
r2_nakagawa(SSP5.2030.LMM)
# Marginal = 0.361
# Conditional = 0.562
```

ANOVA

```
## Fit an ANOVA with Type III sums-of-squares
SSP5.2030.LMM.anova.table <- anova(
  object = SSP5.2030.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 116: ANOVA table for the SSP5 2030 linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	3048.941	3048.941	1	137.073	1538.040	0
Sampling_Design	240.072	80.024	3	393.906	40.368	0
Standardized_Distance:Sampling_Design	70.792	23.597	3	431.437	11.904	0

Partial η^2 for Fixed Effects

Table 117: Effect sizes for the SSP5 2030 linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.918	0.95	0.899	1
Sampling_Design	0.235	0.95	0.175	1
Standardized_Distance:Sampling_Design	0.076	0.95	0.037	1

ranova

```r
## Fit a ranova
SSP5.2030.LMM.ranova <- ranova(
  SSP5.2030.LMM,
  reduce.terms = FALSE
)
```

Table 118: Summary of the ranova for the SSP5 2030 linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	-38780.95	77591.90	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	-39549.51	79123.01	1537.115	3
(Standardized_Distance | City)	12	-38984.87	77993.74	407.835	3

ICC for Random Effects

Table 119: Table of the effect sizes for the random effects in the SSP5 2030 linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.060
City	0.183

SSP5 2100

Fit the Linear Mixed-Effects Model

```
SSP5.2100.LMM <- lmer(
  log10(SSP_5_2100 + 1) ~ Standardized_Distance * Sampling_Design
    + (Standardized_Distance | City:Sampling_Design)
    + (Standardized_Distance | City),
  data = urban.quantification.full.data,
  REML = TRUE,
  control = lmerControl(optCtrl = list(maxfun = 100000), optimizer = "bobyqa")
)
```

Check Model Assumptions

```
## Check model convergence
check_convergence(SSP5.2100.LMM)
# Model converged

## Check for boundary singularity
check_singularity(SSP5.2100.LMM)
# No singularity

## Visual assessment
check_model(SSP5.2100.LMM)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(SSP5.2100.LMM, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(SSP5.2100.LMM, effects = "random")
# Non-normality for random effects 'City:Sampling_Design: (Intercept)' detected (P < 0.001)
# Non-normality for random effects 'City:Sampling_Design: Standardized_Distance' detected (P < 0.001)
# Non-normality for random effects 'City: (Intercept)' detected (P < 0.001)
# Normality for random effects 'City: Standardized_Distance' detected (P = 0.058)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(SSP5.2100.LMM)
# Heteroscedasticity (non-constant error variance) detected (P < 0.001)

## Check for outliers
check_outliers(SSP5.2100.LMM)
# No outliers detected
```

Model Contrasts & Predictions

```
SSP5.2100.LMM.emmeans <- emmeans(
  SSP5.2100.LMM,
  specs = pairwise ~ Sampling_Design,
  weights = "cells",
```

```r
  adjust = "none",
  pbkrtest.limit = 21500
)
```

Table 120: Estimated marginal means of sample type in the SSP5.2100 LMM.

Sample Type	Estimate	SE	df	t	P-value
GLUE	7.381	0.093	239.920	79.179	0
Random_Points	6.591	0.093	240.312	70.683	0
Systematic_Points	6.556	0.093	241.465	70.224	0
Random_Transect	6.712	0.093	240.272	71.975	0

Table 121: Effect sizes for the pairwise contrasts of sample type in the SSP5.2100 LMM.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	0.521	0.052	410.810	0.419	0.623
(GLUE - Systematic_Points)	0.544	0.052	413.715	0.442	0.646
(GLUE - Random_Transect)	0.442	0.052	409.606	0.340	0.543
(Random_Points - Systematic_Points)	0.023	0.052	414.993	-0.079	0.125
(Random_Points - Random_Transect)	-0.080	0.052	411.595	-0.181	0.022
(Systematic_Points - Random_Transect)	-0.103	0.052	414.515	-0.205	-0.001

```r
## Set the emtrends
SSP5.2100.LMM.emtrends <- emtrends(
    SSP5.2100.LMM,
    specs = "Sampling_Design",
    var = "Standardized_Distance",
  pbkrtest.limit = 21500
)
```

Table 122: Predicted change in SSP5 2100 from the urban center (standardized distance = 0) and the rural limit (standardized distance = 1) for each Sample Type from the SSP5 2100 linear mixed-effects model. Note: predictions have not been back-transformed.

Sample Type	Predicted Change	SE	df	CI_lower	CI_upper
GLUE	-3.836	0.155	380.682	-4.141	-3.531
Random_Points	-4.200	0.163	466.117	-4.520	-3.879
Systematic_Points	-3.842	0.163	469.535	-4.163	-3.521
Random_Transect	-4.757	0.155	384.187	-5.063	-4.452

Marginal & Conditional R^2

```r
## Calculate the marginal and conditional R-squared
r2_nakagawa(SSP5.2100.LMM)
# Marginal = 0.338
# Conditional = 0.582
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
SSP5.2100.LMM.anova.table <- anova(
  object = SSP5.2100.LMM,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 123: ANOVA table for the SSP5 2100 linear mixed-effects model.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Standardized_Distance	3193.643	3193.643	1	137.219	1391.656	0
Sampling_Design	240.585	80.195	3	394.173	34.946	0
Standardized_Distance:Sampling_Design	79.067	26.356	3	434.638	11.485	0

Partial η^2 for Fixed Effects

Table 124: Effect sizes for the SSP5 2100 linear mixed-effects model.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Standardized_Distance	0.910	0.95	0.889	1
Sampling_Design	0.210	0.95	0.151	1
Standardized_Distance:Sampling_Design	0.073	0.95	0.035	1

ranova

```r
## Fit a ranova
SSP5.2100.LMM.ranova <- ranova(
  SSP5.2100.LMM,
  reduce.terms = FALSE
)
```

Table 125: Summary of the ranova for the SSP5 2100 linear mixed-effects model.

	n_parameters	log_likelihood	AIC	LRT	df
<none>	15	-40333.25	80696.50	NA	NA
(Standardized_Distance | City:Sampling_Design)	12	-41089.26	82202.52	1512.018	3
(Standardized_Distance | City)	12	-40531.47	81086.94	396.442	3

ICC for Random Effects

Table 126: Table of the effect sizes for the random effects in the SSP5 2100 linear mixed-effects model.

Term	ICC
City:Sampling_Design	0.053
City	0.164

Environmental Heterogeneity

Data Management

```
## Remove NAs for the environmental heterogeneity analysis
environmental.variable.data <- urban.quantification.full.data %>%
    select(
        City, Sampling_Design, Distance, ISC_Mean:Mean_NDVI,
        Mean_Annual_Temperature, Annual_Precipitation,
        SSP_2_2030:SSP_2_2100
        ) %>%
    drop_na()

## Normalize the matrix before calculating the Euclidean distance
standardized.environmental.variable.matrix <- decostand(
    environmental.variable.data %>% select(-c(City, Sampling_Design)),
    method = "standardize"
)

## Calculate the Euclidean distances among sampling locations by environmental variables
environmental.variable.euclidean.distance <- vegdist(
    standardized.environmental.variable.matrix,
    method = "euclidean"
)

## Set grouping by city and sample type
environmental.variable.groups <- paste(
    environmental.variable.data$City, environmental.variable.data$Sampling_Design
)

## Calculate environmental heterogeneity
sampling.design.dispersions <- betadisper(
    environmental.variable.euclidean.distance,
    group = environmental.variable.groups,
    type = "centroid"
)$distances

## Compile the environmental heterogeneity data
environmental.heterogeneity.data <- tibble(
    City = environmental.variable.data$City,
    Sampling_Design = environmental.variable.data$Sampling_Design,
    Environmental_Heterogeneity = sampling.design.dispersions
)
```

Fit the Model

```r
environmental.heterogeneity.ANOVA.model <- lmer(
  log(Environmental_Heterogeneity) ~ Sampling_Design + (1 | City),
  data = environmental.heterogeneity.data,
  REML = TRUE
)
```

Check Model Assumptions

```r
## Check model convergence
check_convergence(environmental.heterogeneity.ANOVA.model)
# Model converged

## Check for boundary singularity
check_singularity(environmental.heterogeneity.ANOVA.model)
# No singularity

## Visual assessment
check_model(environmental.heterogeneity.ANOVA.model)
# Visual check = good

## Check normality of fixed effects (Shapiro-Wilk test)
check_normality(environmental.heterogeneity.ANOVA.model, effects = "fixed")
# Non-normality of residuals detected (P < 0.001)

## Check normality of random effects (Shapiro-Wilk test)
check_normality(environmental.heterogeneity.ANOVA.model, effects = "random")
# Random effects 'City: (Intercept)' appear as normally distributed (P = 0.072)

## Check for non-constant variance of residuals (i.e., heteroscedasticity)
check_heteroscedasticity(environmental.heterogeneity.ANOVA.model)
# Error variance appears to be homoscedastic (P = 0.331)

## Check for outliers
check_outliers(environmental.heterogeneity.ANOVA.model)
# No outliers detected
```

ANOVA

```r
## Fit an ANOVA with Type III sums-of-squares
environmental.heterogeneity.ANOVA.model.table <- anova(
  object = environmental.heterogeneity.ANOVA.model,
  type = "III",
  ddf = "Satterthwaite"
)
```

Table 127: Summary table for the environmental heterogeneity ANOVA.

	Sums-of-Squares	Mean-Square	Num_df	Den_df	F	P-value
Sampling_Design	315.353	105.118	3	21065.71	404.244	0

η^2 for Fixed Effects

Table 128: Effect size of sample type for the environmental heterogeneity ANOVA.

Term	eta-squared	Confidence Level	CI Lower	CI Upper
Sampling_Design	0.054	0.95	0.05	1

ICC for Random Effects

Table 129: Effect size of the random intercept for city in the environmental heterogeneity ANOVA.

ICC_adjusted	ICC_unadjusted	optional
0.223	0.214	FALSE

Estimated Marginal Means & Contrasts

Table 130: Estimated marginal means of sample type in the environmental heterogeneity ANOVA.

Sample Type	Estimate	SE	df	t	P-value
GLUE	0.353	0.024	152.923	14.430	0
Random_Points	0.123	0.024	153.262	5.013	0
Systematic_Points	0.124	0.024	153.732	5.060	0
Random_Transect	0.380	0.024	153.123	15.545	0

Table 131: Pairwise contrasts of sample type in the environmental heterogeneity ANOVA.

Term	Contrast	Null Value	Estimate	SE	df	t	P-valu
Sampling_Design	GLUE - Random_Points	0	0.230	0.01	21066.17	23.312	0.00
Sampling_Design	GLUE - Systematic_Points	0	0.229	0.01	21065.99	23.074	0.00
Sampling_Design	GLUE - Random_Transect	0	-0.027	0.01	21065.24	-2.780	0.00
Sampling_Design	Random_Points - Systematic_Points	0	-0.001	0.01	21066.38	-0.124	0.90
Sampling_Design	Random_Points - Random_Transect	0	-0.258	0.01	21066.22	-26.037	0.00
Sampling_Design	Systematic_Points - Random_Transect	0	-0.256	0.01	21065.98	-25.786	0.00

Table 132: Effect sizes for the pairwise contrasts of sample type in the environmental heterogeneity ANOVA.

Contrast	Cohen's d	SE	df	CI Lower	CI Upper
(GLUE - Random_Points)	0.452	0.019	21066.17	0.413	0.490
(GLUE - Systematic_Points)	0.449	0.020	21065.99	0.411	0.488
(GLUE - Random_Transect)	-0.054	0.019	21065.24	-0.092	-0.016
(Random_Points - Systematic_Points)	-0.002	0.020	21066.38	-0.041	0.036
(Random_Points - Random_Transect)	-0.505	0.020	21066.22	-0.544	-0.467
(Systematic_Points - Random_Transect)	-0.503	0.020	21065.98	-0.541	-0.464

Export Data

```
# ISC
write_rds(
  ISC.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/ISC_distance_sampling_design_LMM.rds"
)
# HII
write_rds(
  HII.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/HII_distance_sampling_design_LMM.rds"
)
# Mean NDVI
write_rds(
  mean.NDVI.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/mean_NDVI_distance_sampling_design_LMM.rds"
)
# Min NDVI
write_rds(
  min.NDVI.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/min_NDVI_distance_sampling_design_LMM.rds"
)
# Max NDVI
write_rds(
  max.NDVI.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/max_NDVI_distance_sampling_design_LMM.rds"
)
# Mean annual temperature
write_rds(
  mean.annual.temperature.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/mean_annual_temperature_distance_sampling_design_L
)
# Temperature seasonality
write_rds(
  temperature.seasonality.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/temperature_seasonality_distance_sampling_design_L
)
# Range annual temperature
write_rds(
  range.annual.temperature.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/range_annual_temperature_distance_sampling_design_
)
# Annual precipitation
write_rds(
  annual.precipitation.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/annual_precipitation_distance_sampling_design_LMM.
)
# Precipitation seasonality
write_rds(
  precipitation.seasonality.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/precipitation_seasonality_distance_sampling_design
)
# Aridity index
write_rds(
```

```r
  aridity.index.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/aridity_index_distance_sampling_design_LMM.rds"
)
# GDP 2005
write_rds(
  GDP.2005.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/GDP_2005_distance_sampling_design_LMM.rds"
)
# SSP1 2030
write_rds(
  SSP1.2030.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/SSP1_2030_distance_sampling_design_LMM.rds"
)
# SSP1 2100
write_rds(
  SSP1.2100.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/SSP1_2100_distance_sampling_design_LMM.rds"
)
# SSP2 2030
write_rds(
  SSP2.2030.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/SSP2_2030_distance_sampling_design_LMM.rds"
)
# SSP2 2100
write_rds(
  SSP2.2100.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/SSP2_2100_distance_sampling_design_LMM.rds"
)
# SSP5 2030
write_rds(
  SSP5.2030.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/SSP5_2030_distance_sampling_design_LMM.rds"
)
# SSP5 2100
write_rds(
  SSP5.2100.LMM,
  file = "data/analysis_data/metric_by_distance_LMMs/SSP5_2100_distance_sampling_design_LMM.rds"
)
# Environmental heterogeneity data
write_rds(
  environmental.heterogeneity.data,
  file = "data/analysis_data/environmental_heterogeneity/environmental_heterogeneity_data.rds"
)
# Environmental heterogeneity ANOVA
write_rds(
  environmental.heterogeneity.ANOVA.model,
  file = "data/analysis_data/environmental_heterogeneity/environmental_heterogeneity_sampling_design_mod
)
```

```r
## Remove large distance object
# remove(environmental.variable.euclidean.distance)

## Save the workspace
```

```r
save.image("data_analysis/3-analyses/2-metric_by_distance-workspace.RData")
```

Workspace Information

Table 133: Packages required for data management and analyses.

Package	Loaded Version	Date
bayestestR	0.13.2	2024-02-12
broom	1.0.5	2023-06-09
car	3.1-2	2023-03-30
carData	3.0-5	2022-01-06
correlation	0.8.4	2023-04-06
datawizard	0.9.1	2023-12-21
dplyr	1.1.4	2023-11-17
easystats	0.7.0	2023-11-05
effectsize	0.8.6	2023-09-14
emmeans	1.10.0	2024-01-23
forcats	1.0.0	2023-01-29
ggplot2	3.4.4	2023-10-12
insight	0.19.8	2024-01-31
kableExtra	1.4.0	2024-01-24
knitr	1.45	2023-10-30
lattice	0.22-5	2023-10-24
lme4	1.1-35.1	2023-11-05
lmerTest	3.1-3	2020-10-23
lubridate	1.9.3	2023-09-27
Matrix	1.6-5	2024-01-11
modelbased	0.8.7	2024-02-15
parameters	0.21.5	2024-02-07
performance	0.10.9	2024-02-17
permute	0.9-7	2022-01-27
purrr	1.0.2	2023-08-10
readr	2.1.5	2024-01-10
report	0.5.8	2023-12-07
see	0.8.2	2024-02-14
stringr	1.5.1	2023-11-14
tibble	3.2.1	2023-03-20
tidyr	1.3.1	2024-01-24
tidyverse	2.0.0	2023-02-22
vegan	2.6-4	2022-10-11