Supplementary material for ‘Early high rates and disparity in the evolution of ichthyosaurs’

Benjamin C. Moon Thomas L. Stubbs

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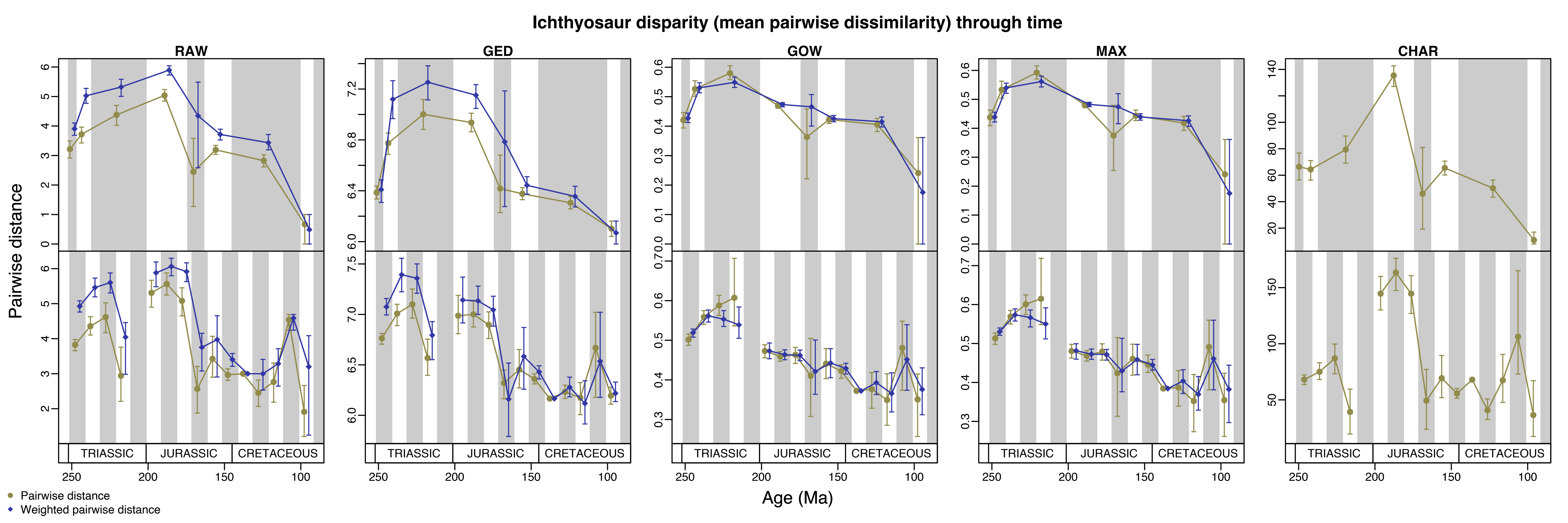
Contents

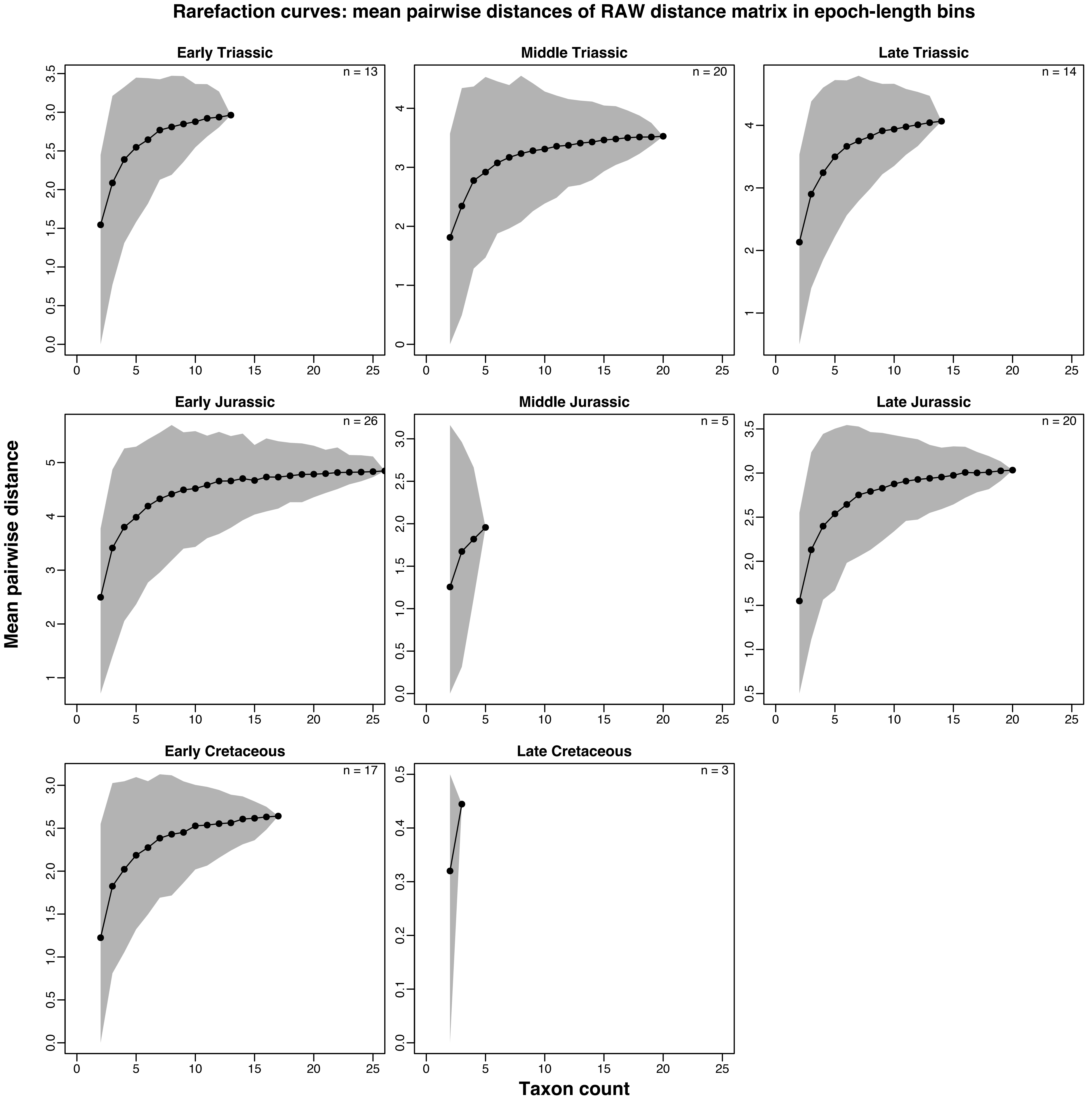
Supplementary figures

Supplementary figure 1. (following page) **Per-bin discrete skeletal disparity of Ichthyosauriformes though the Mesozoic.** Pairwise and weighted pairwise dissimilarity measured from raw Euclidean (RAW), generalised Euclidean (GED), Gower (GOW), and maximum observed rescaled (MAX) distances between taxa in the cladistic dataset of Moon [1] binned into epochs and equal 10-million-year bins. Also, pairwise number of comparable characters between taxa (CHAR) indicating the variation in completeness and comparability in each bin. Mean values and 95% confidence intervals are shown from 500 bootstrap replicates.

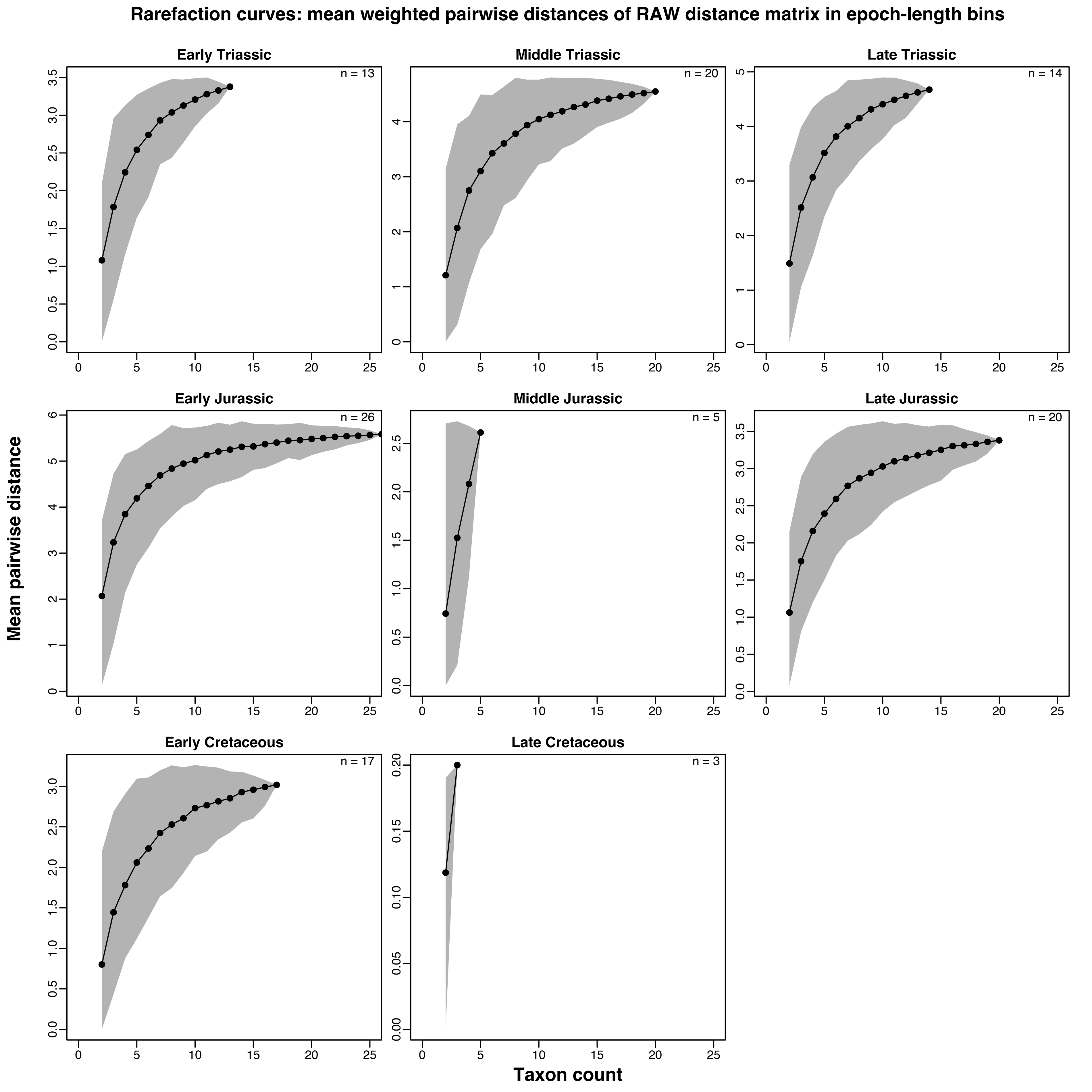


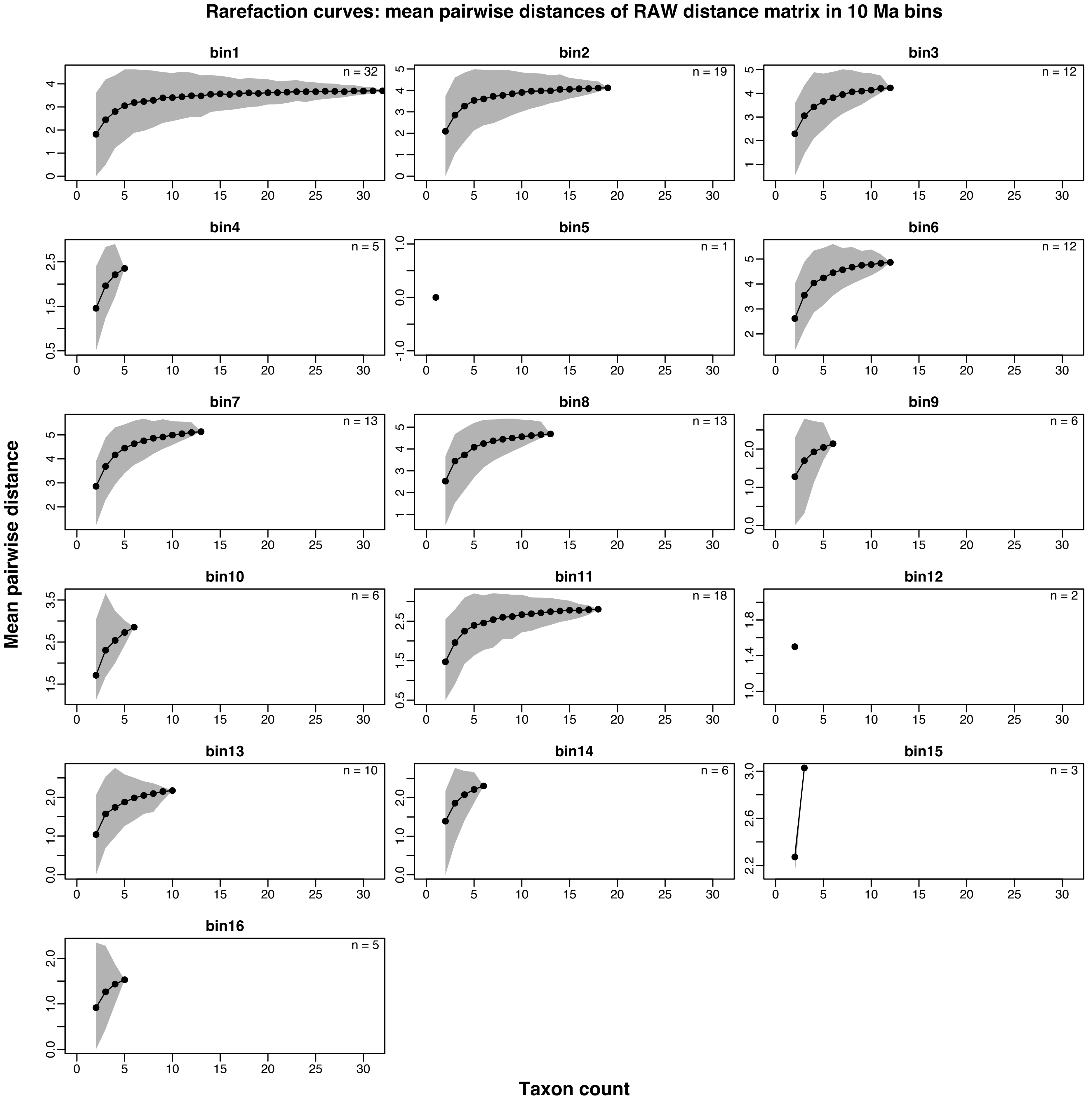
Ichthyosaur disparity (mean pairwise dissimilarity) through time
RAW
GED
GOW
MAX
CHAR
Pairwise distance
TRIASSIC
JURASSIC
CRETACEOUS
Age (Ma)
Pairwise distance
Weighted pairwise distance

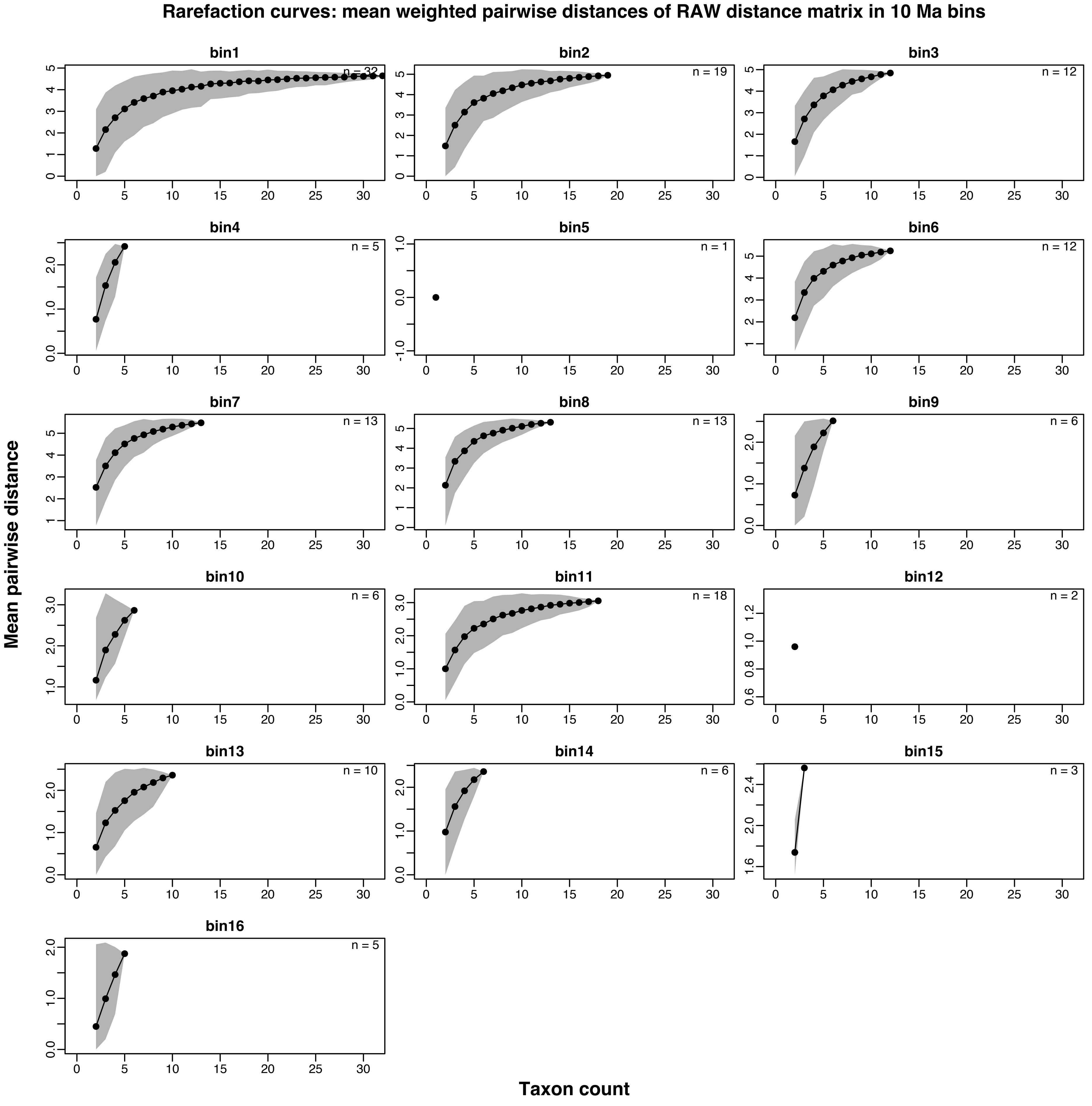
Supplementary figure 2. (following pages) **Per-bin rarefaction curves for each disparity-time curve shown in Supplementary Figure 1.** Disparity for each pin is sequentiall rarefied on taxon occurrnece. Error polygon gives 95% confidence interval from 500 replicates.

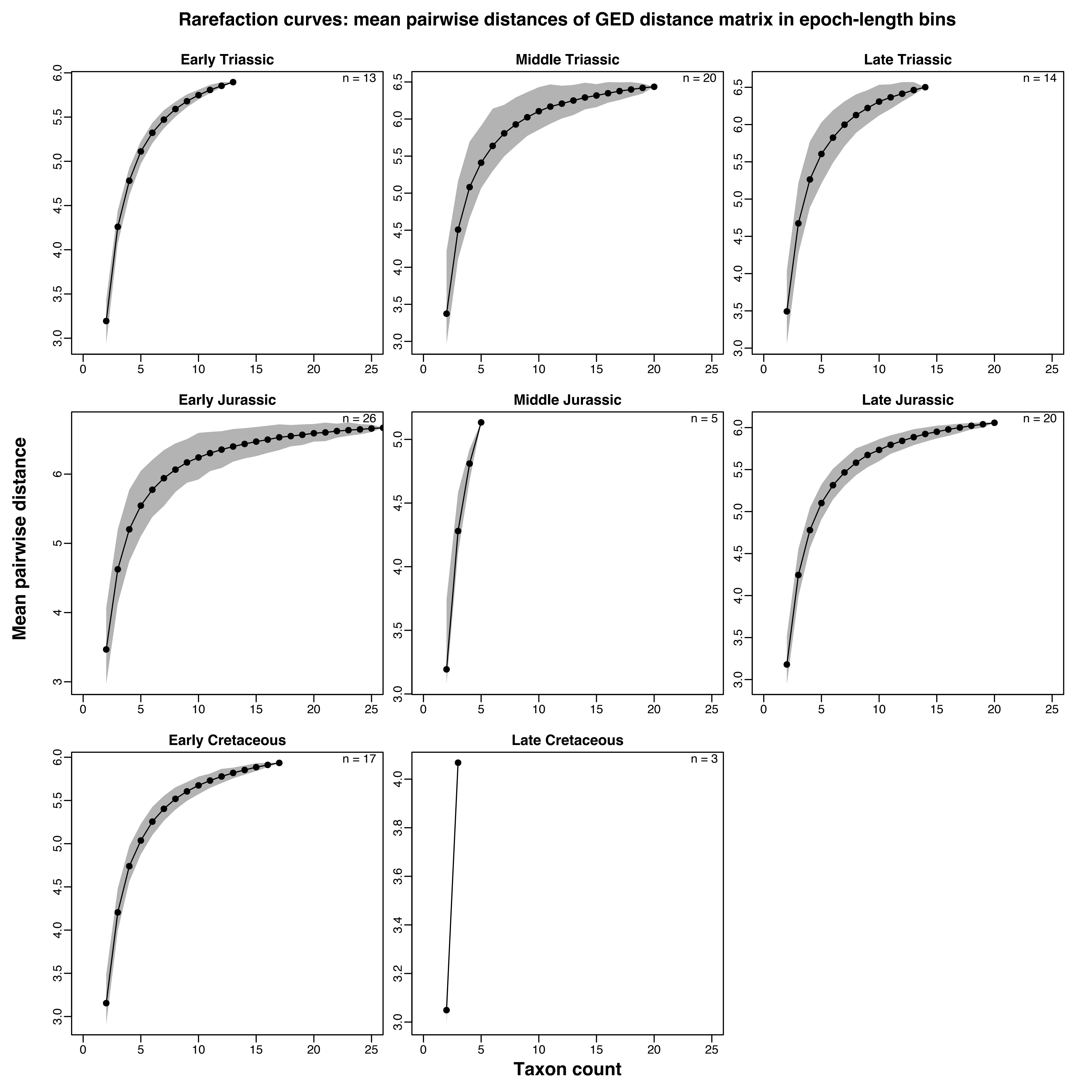


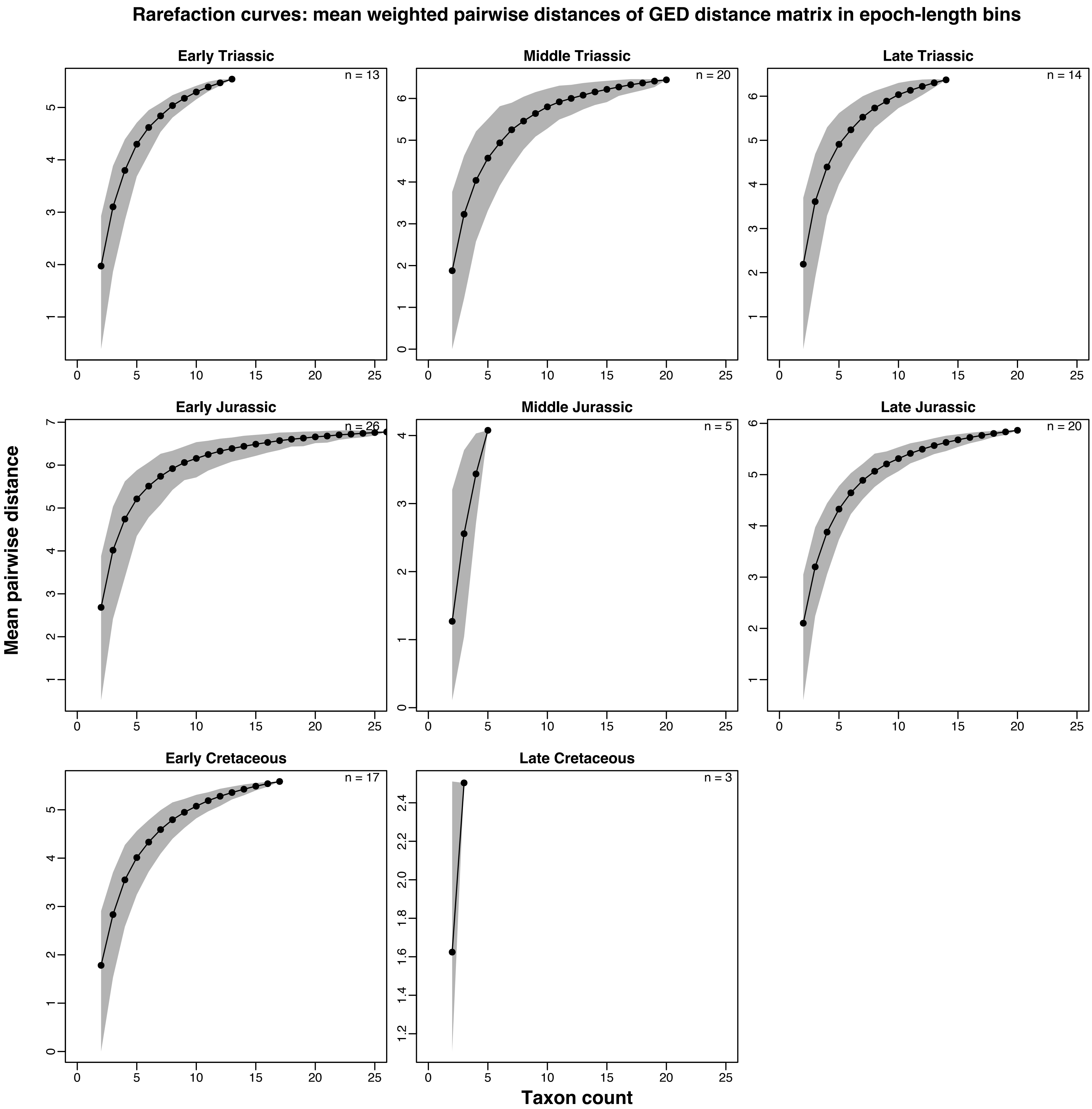
Rarefaction curves: mean pairwise distances of RAW distance matrix in epoch-length bins
Early Triassic
n = 13
Middle Triassic
n = 20
Late Triassic
n = 14
Early Jurassic
n = 26
Middle Jurassic
n = 5
Late Jurassic
n = 20
Early Cretaceous
n = 17
Late Cretaceous
n = 3
Mean pairwise distance
Taxon count

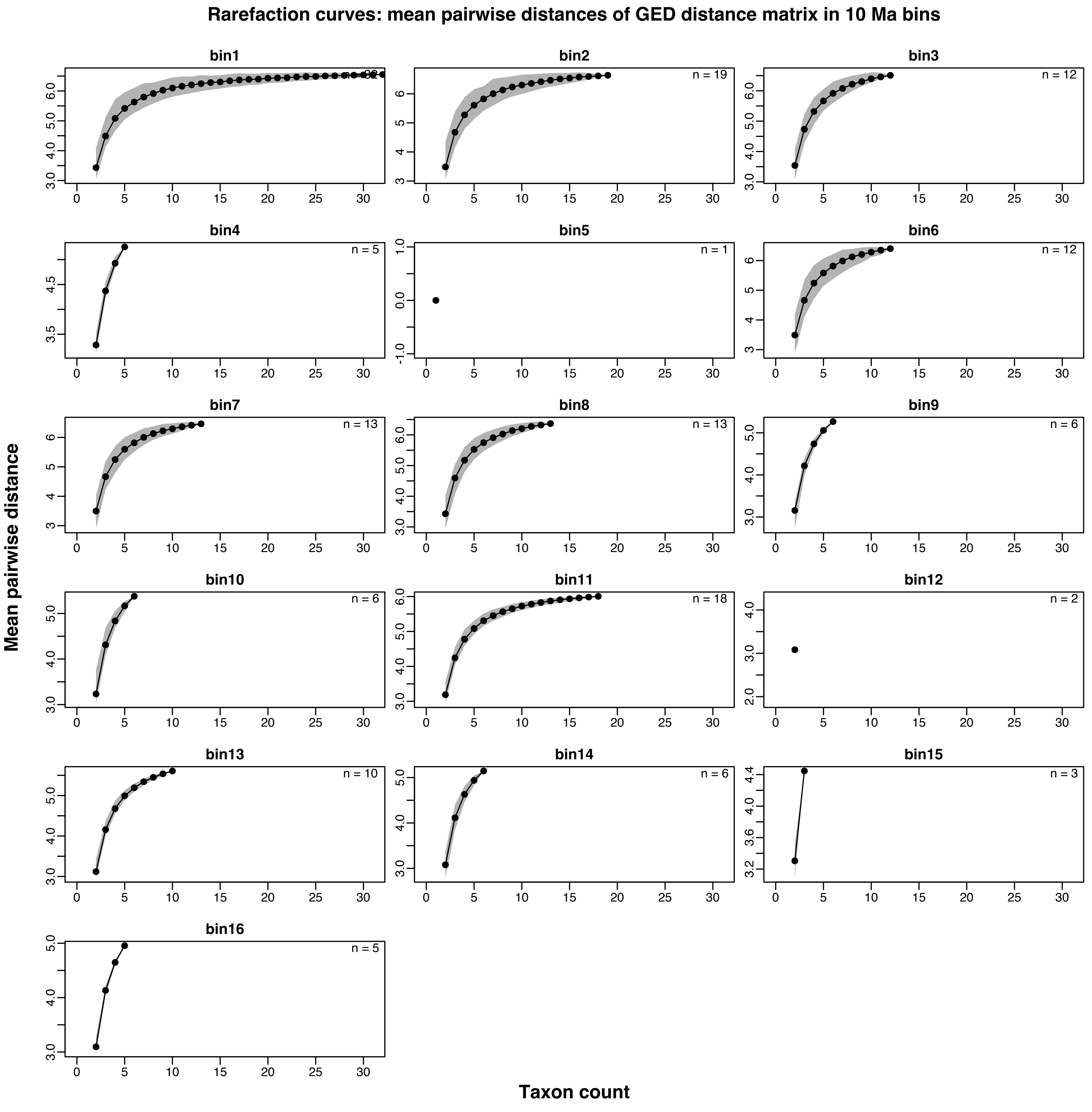

Rarefaction curves: mean weighted pairwise distances of RAW distance matrix in epoch-length bins
Early Triassic
n = 13
Middle Triassic
n = 20
Late Triassic
n = 14
Early Jurassic
n = 26
Middle Jurassic
n = 5
Late Jurassic
n = 20
Early Cretaceous
n = 17
Late Cretaceous
n = 3
Mean pairwise distance
Taxon count

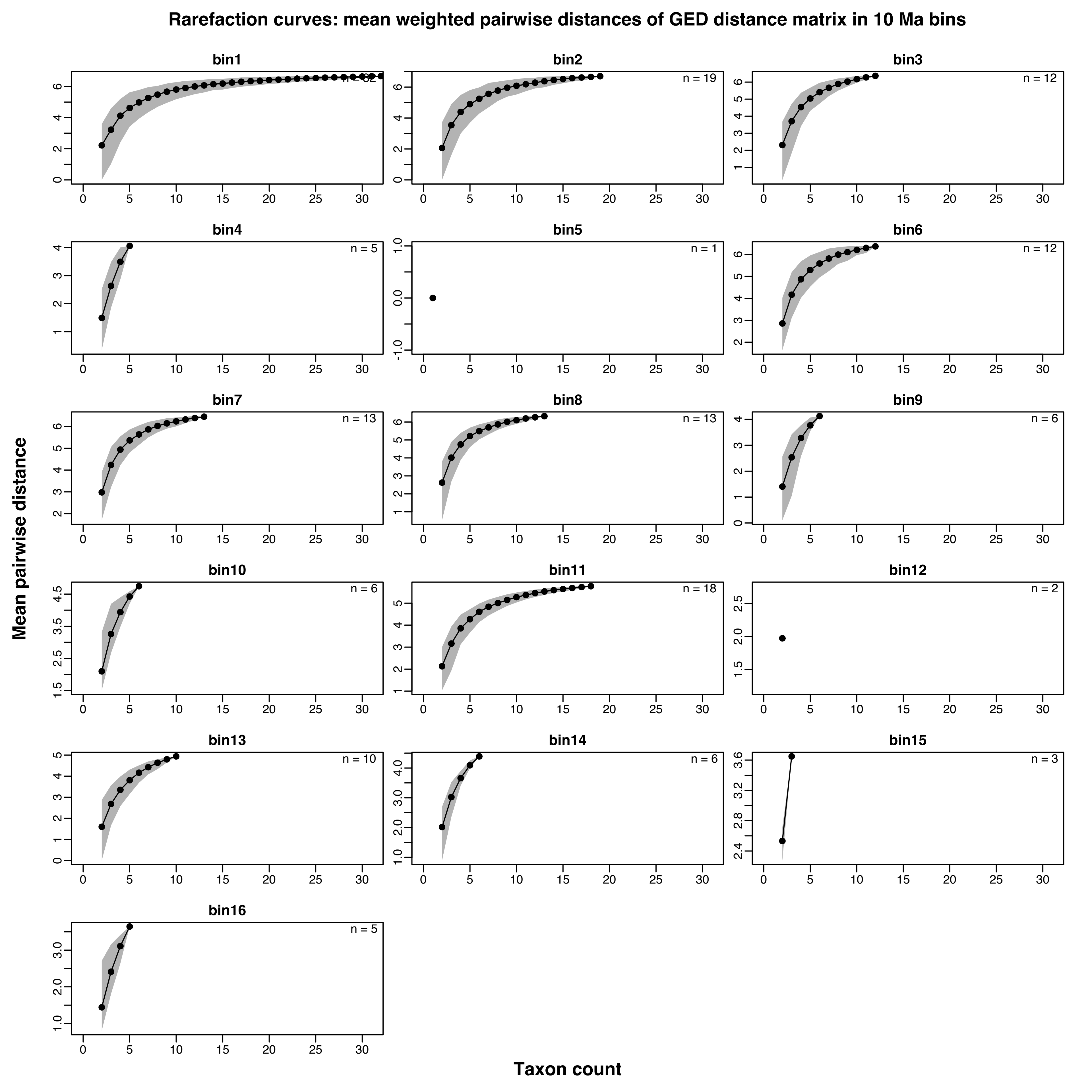

Rarefaction curves: mean pairwise distances of RAW distance matrix in 10 Ma bins
bin1
n = 32
bin2
n = 19
bin3
n = 12
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 13
bin9
n = 6
bin10
n = 6
bin11
n = 18
bin12
n = 2
bin13
n = 10
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean pairwise distance
Taxon count

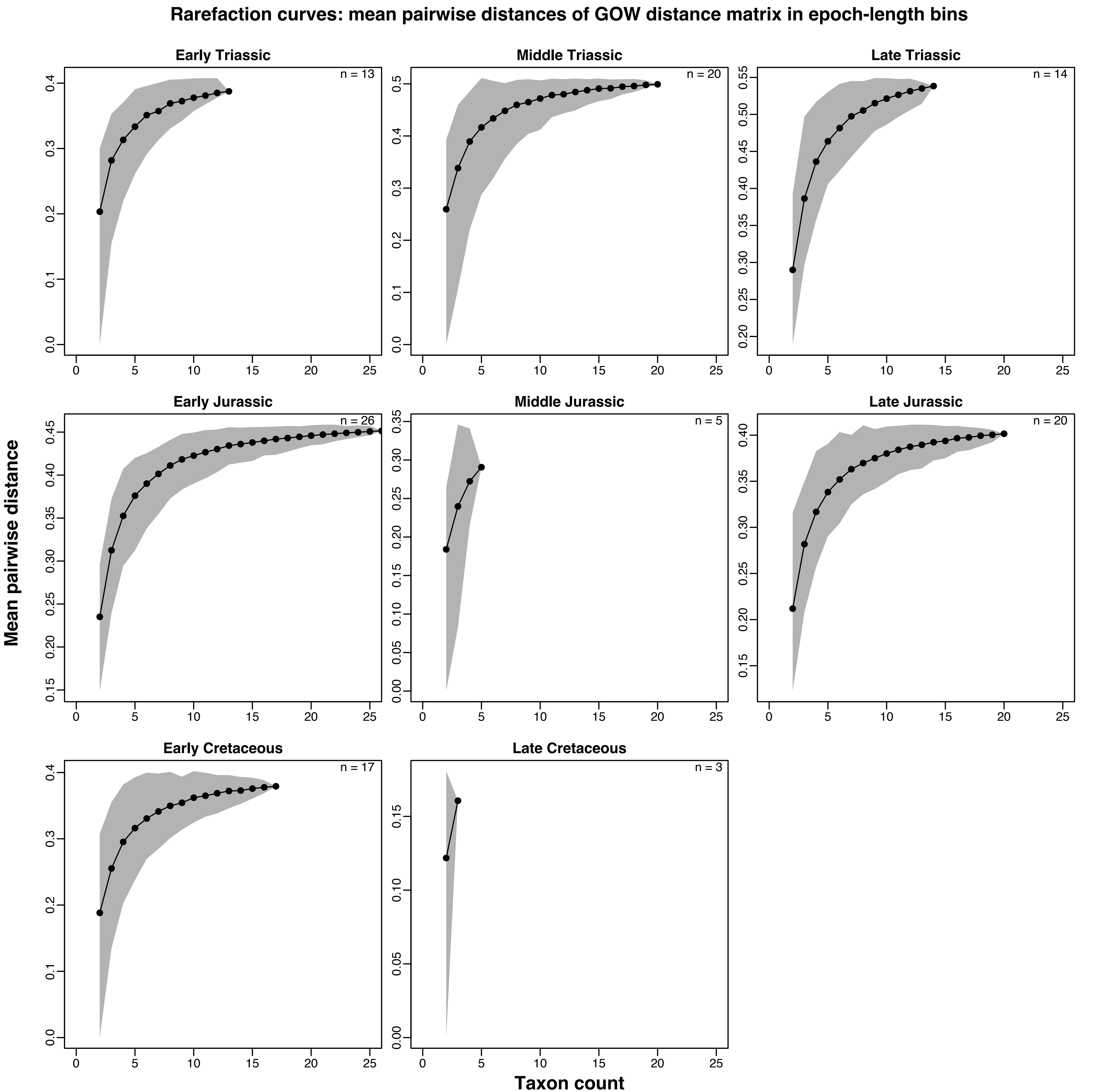

Rarefaction curves: mean weighted pairwise distances of RAW distance matrix in 10 Ma bins
bin1
n = 32
bin2
n = 19
bin3
n = 12
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 13
bin9
n = 6
bin10
n = 6
bin11
n = 18
bin12
n = 2
bin13
n = 10
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean pairwise distance
Taxon count

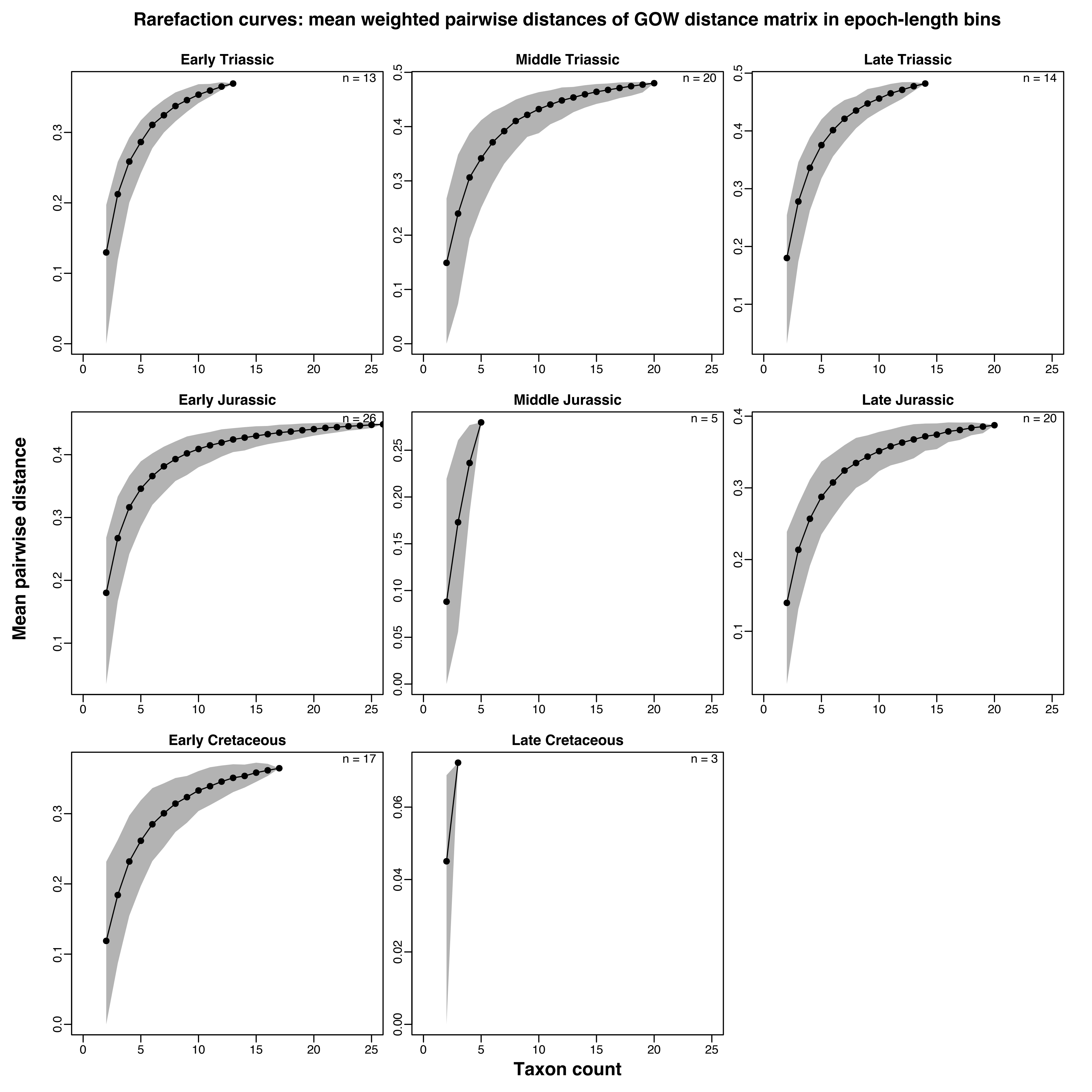

Rarefaction curves: mean pairwise distances of GED distance matrix in epoch-length bins
Early Triassic
n = 13
Middle Triassic
n = 20
Late Triassic
n = 14
Early Jurassic
n = 26
Middle Jurassic
n = 5
Late Jurassic
n = 20
Early Cretaceous
n = 17
Late Cretaceous
n = 3
Mean pairwise distance
Taxon count


Rarefaction curves: mean weighted pairwise distances of GED distance matrix in epoch-length bins
Early Triassic
n = 13
Middle Triassic
n = 20
Late Triassic
n = 14
Early Jurassic
n = 26
Middle Jurassic
n = 5
Late Jurassic
n = 20
Early Cretaceous
n = 17
Late Cretaceous
n = 3
Mean pairwise distance
Taxon count

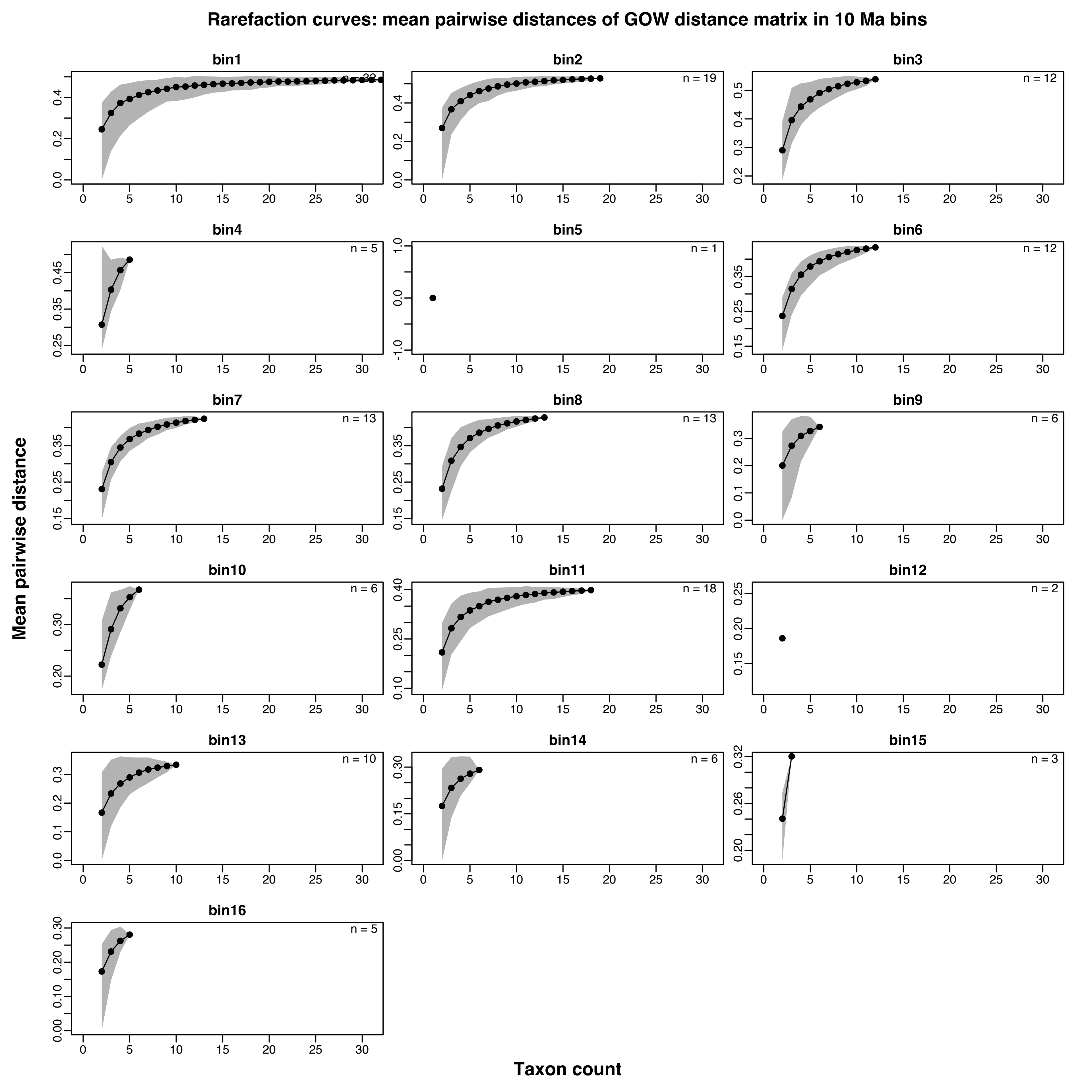

Rarefaction curves: mean pairwise distances of GED distance matrix in 10 Ma bins
bin1
n = 32
bin2
n = 19
bin3
n = 12
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 13
bin9
n = 6
bin10
n = 6
bin11
n = 18
bin12
n = 2
bin13
n = 10
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean pairwise distance
Taxon count


Rarefaction curves: mean weighted pairwise distances of GED distance matrix in 10 Ma bins
bin1
bin2
n = 19
bin3
n = 12
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 13
bin9
n = 6
bin10
n = 6
bin11
n = 18
bin12
n = 2
bin13
n = 10
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean pairwise distance
Taxon count

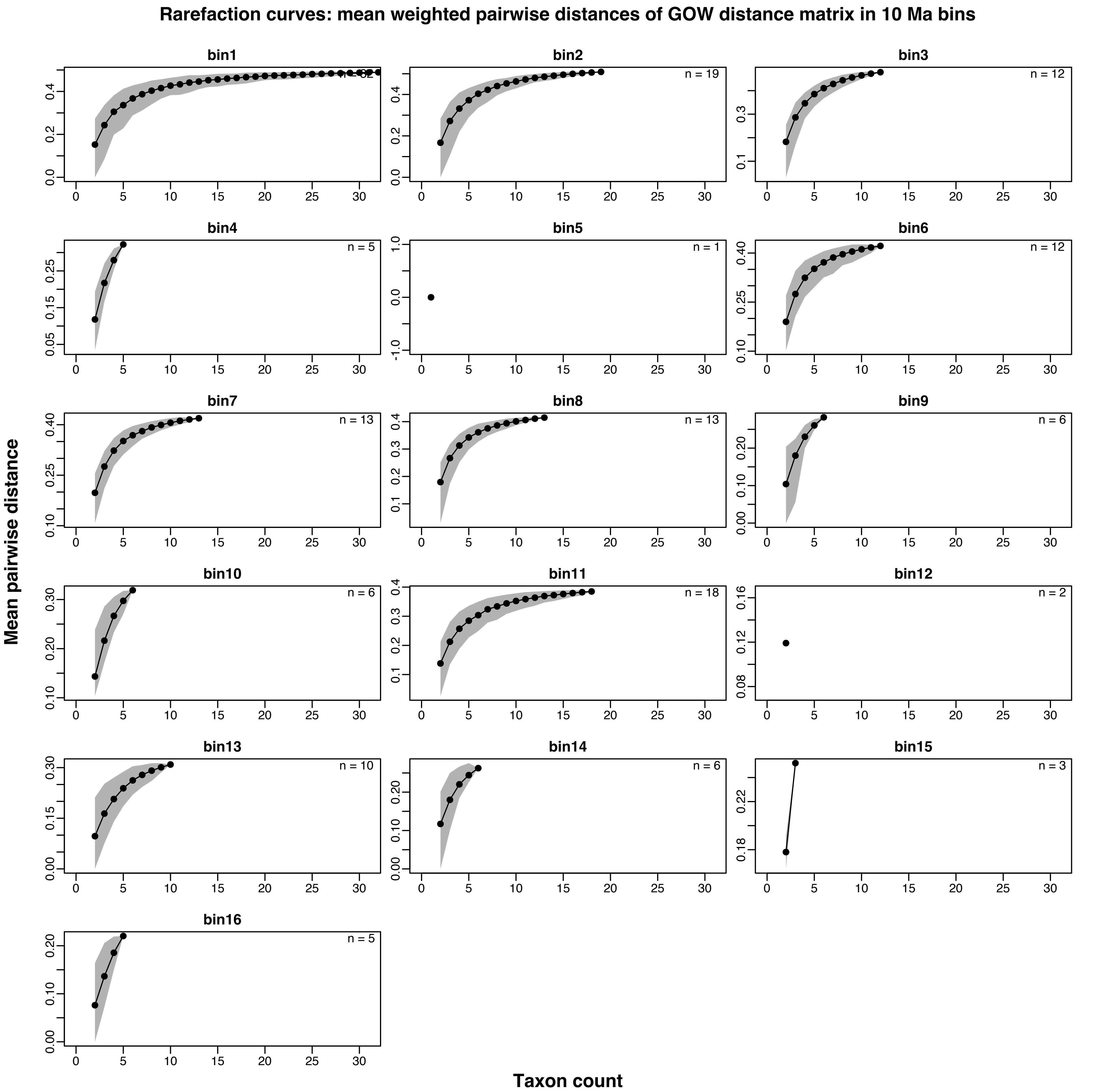

Rarefaction curves: mean pairwise distances of GOW distance matrix in epoch-length bins
Early Triassic
n = 13
Middle Triassic
n = 20
Late Triassic
n = 14
Early Jurassic
n = 26
Middle Jurassic
n = 5
Late Jurassic
n = 20
Early Cretaceous
n = 17
Late Cretaceous
n = 3
Mean pairwise distance
Taxon count

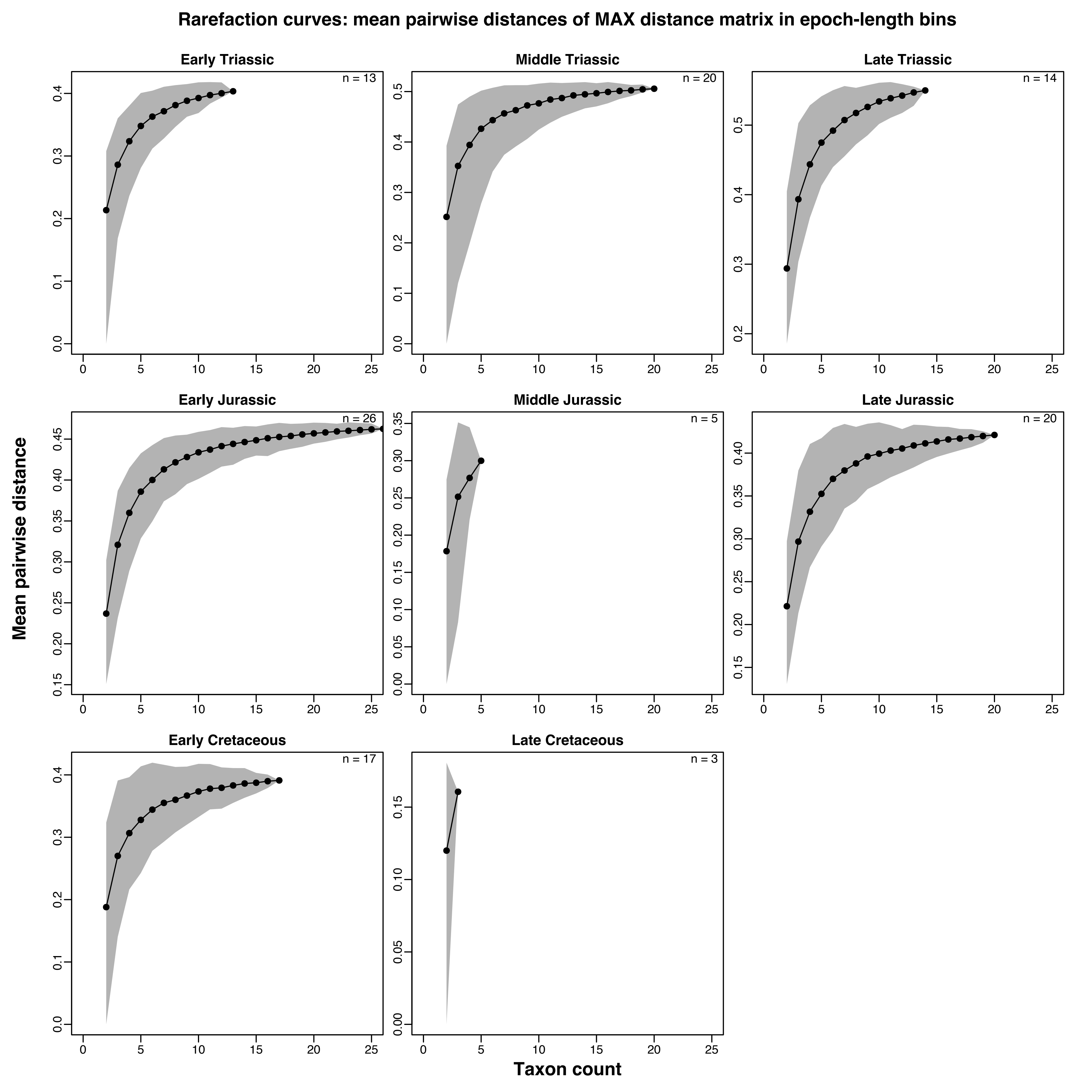


Rarefaction curves: mean weighted pairwise distances of GOW distance matrix in epoch-length bins
Early Triassic
n = 13
Middle Triassic
n = 20
Late Triassic
n = 14
Early Jurassic
n = 26
Middle Jurassic
n = 5
Late Jurassic
n = 20
Early Cretaceous
n = 17
Late Cretaceous
n = 3
Mean pairwise distance
Taxon count

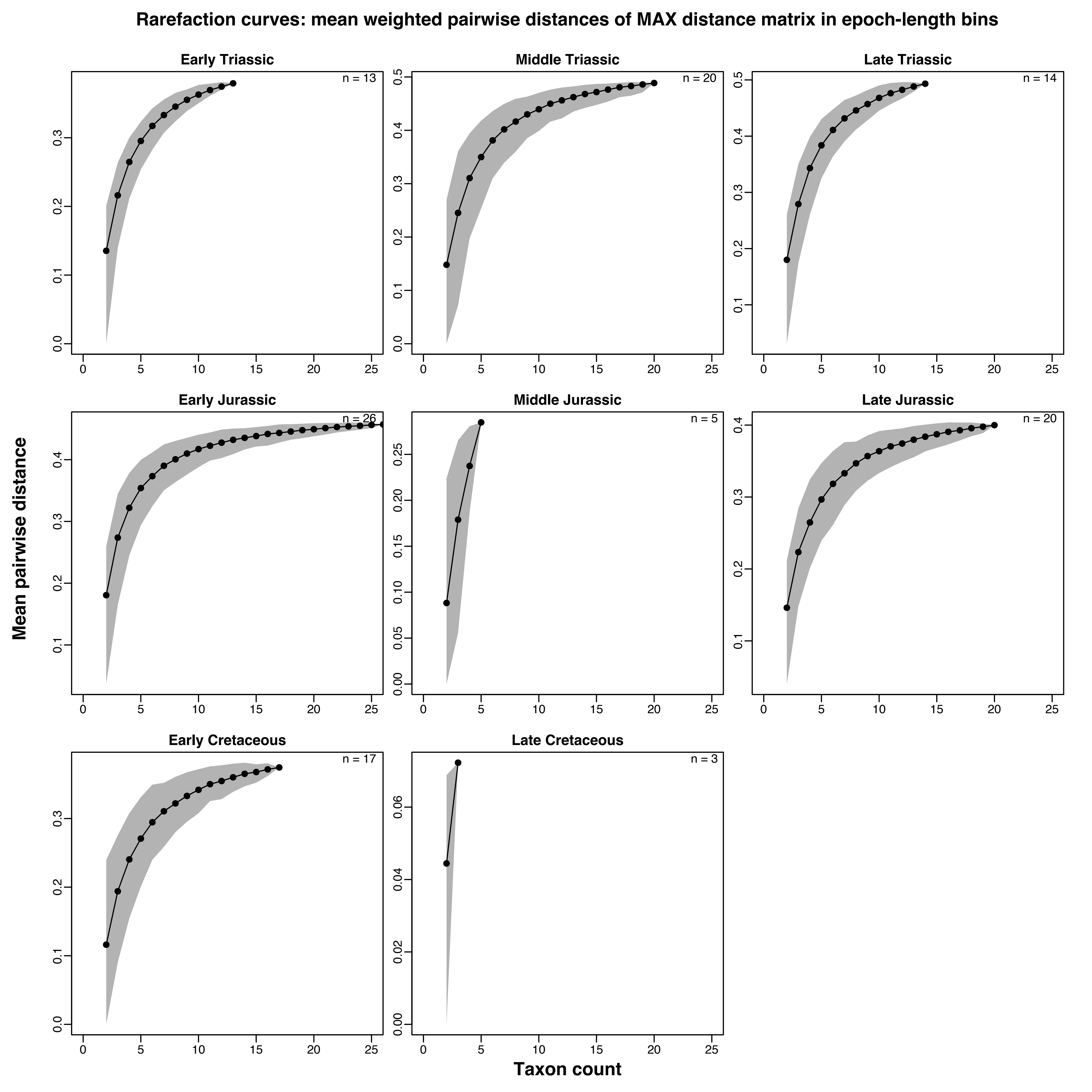


Rarefaction curves: mean pairwise distances of GOW distance matrix in 10 Ma bins
bin1
n = 32
bin2
n = 19
bin3
n = 12
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 13
bin9
n = 6
bin10
n = 6
bin11
n = 18
bin12
n = 2
bin13
n = 10
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean pairwise distance
Taxon count

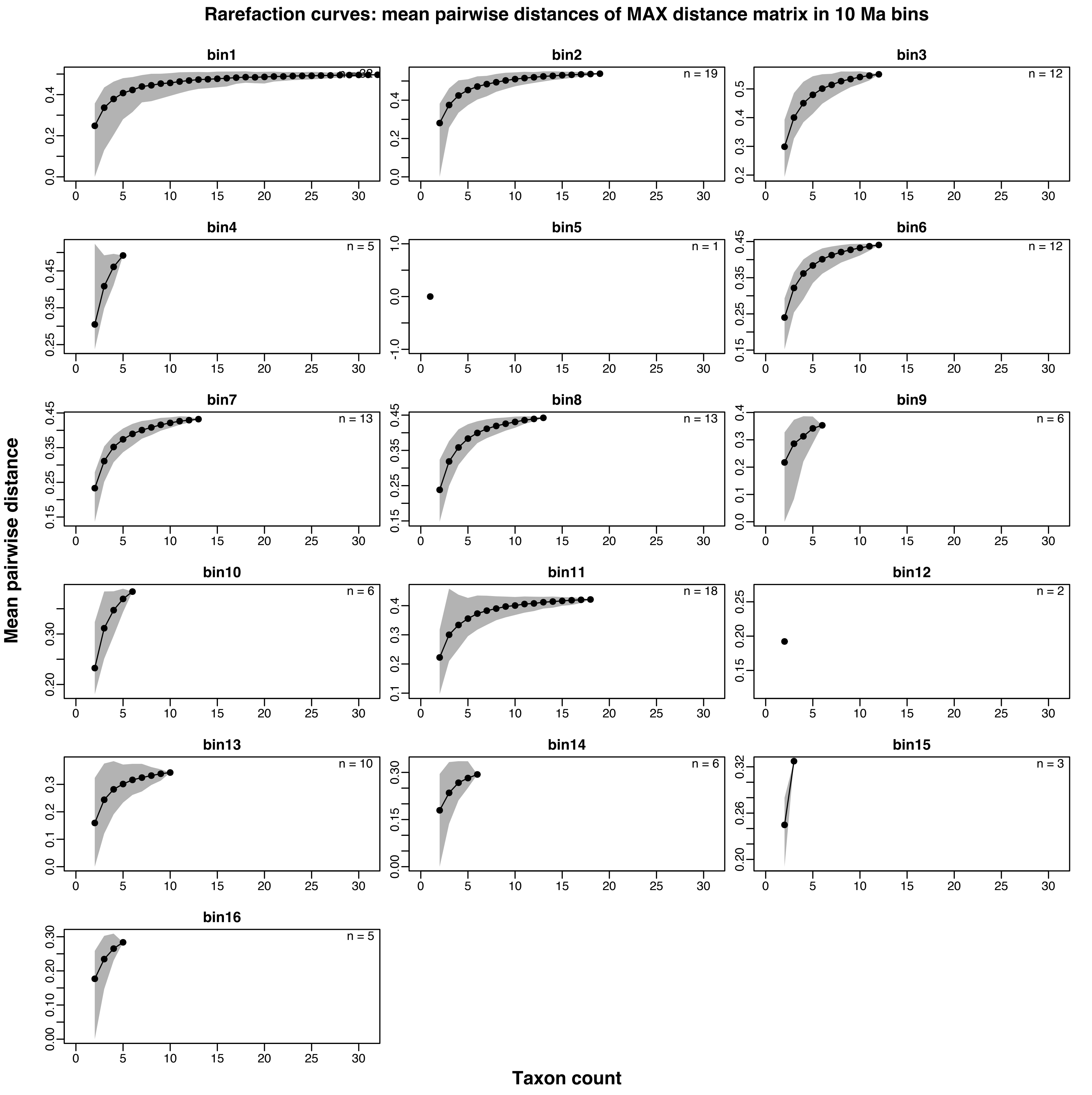

Rarefaction curves: mean weighted pairwise distances of GOW distance matrix in 10 Ma bins
bin1
n = 32
bin2
n = 19
bin3
n = 12
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 13
bin9
n = 6
bin10
n = 6
bin11
n = 18
bin12
n = 2
bin13
n = 10
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean pairwise distance
Taxon count

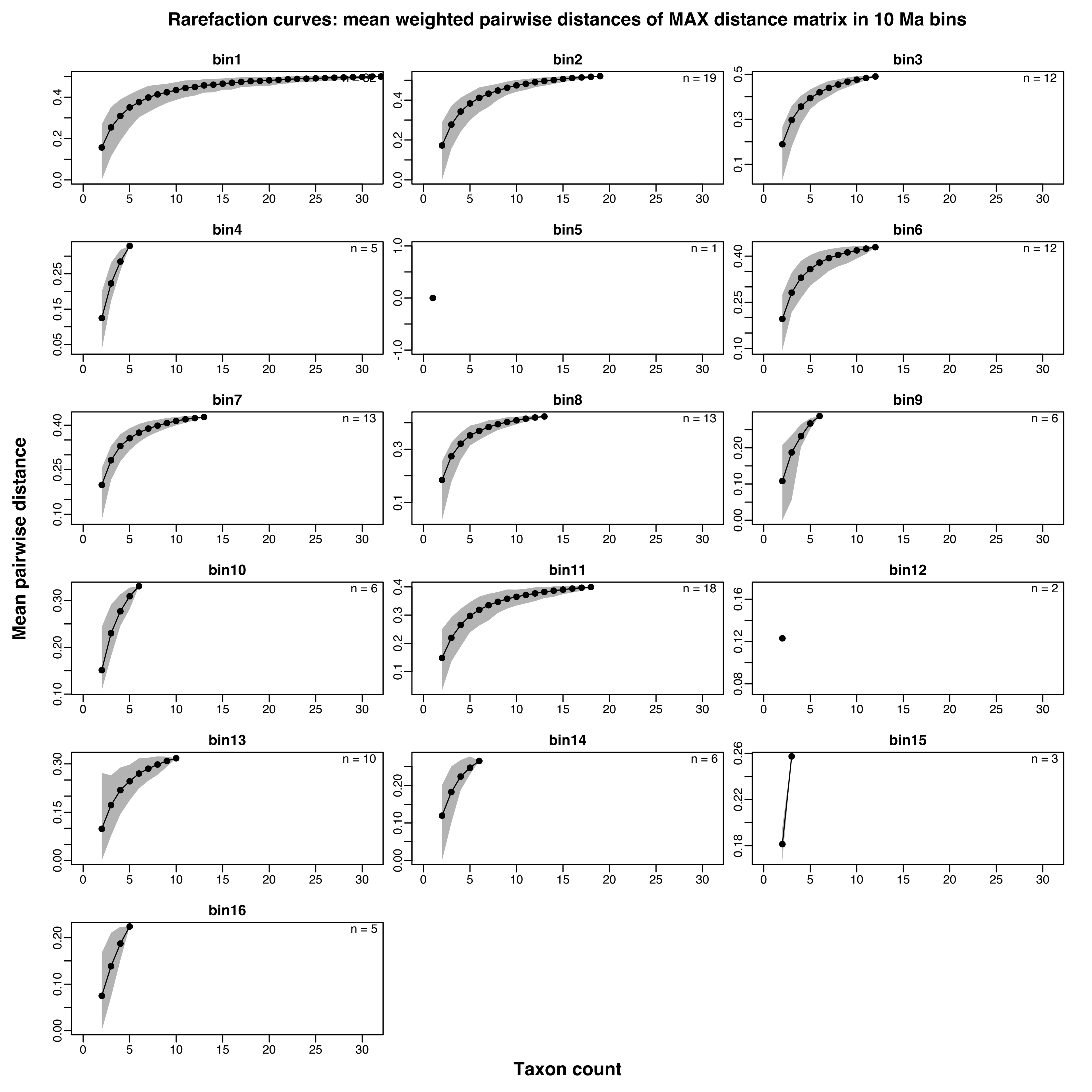


Rarefaction curves: mean pairwise distances of MAX distance matrix in epoch-length bins
Early Triassic
n = 13
Middle Triassic
n = 20
Late Triassic
n = 14
Early Jurassic
n = 26
Middle Jurassic
n = 5
Late Jurassic
n = 20
Early Cretaceous
n = 17
Late Cretaceous
n = 3
Mean pairwise distance
Taxon count



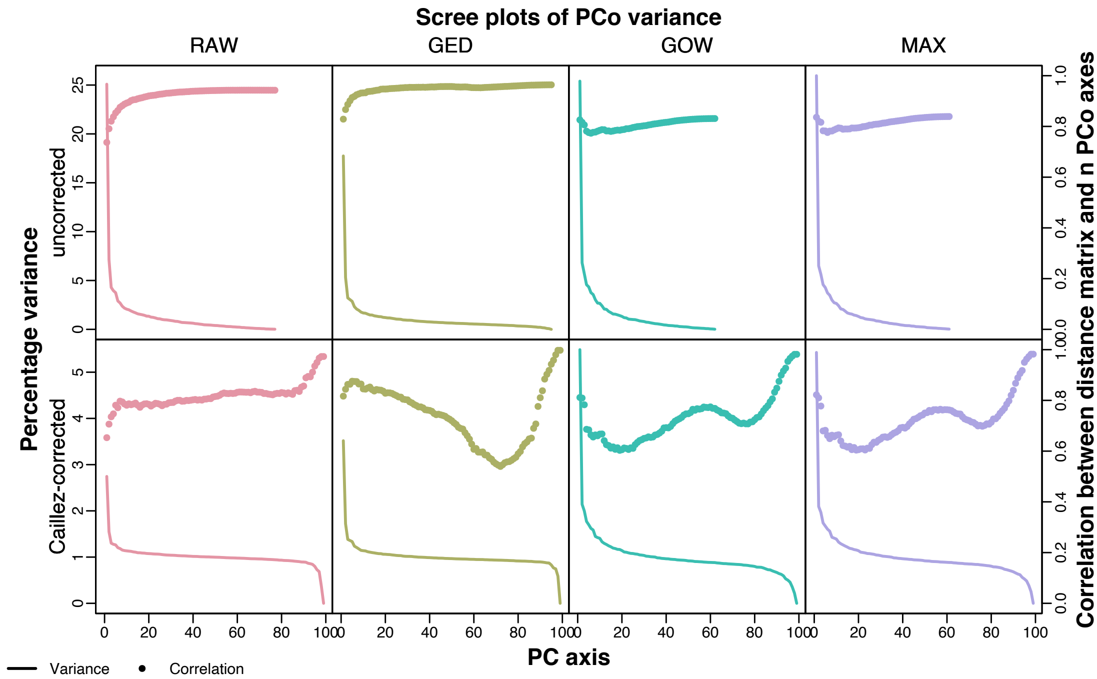
Rarefaction curves: mean weighted pairwise distances of MAX distance matrix in epoch-length bins
Early Triassic
n = 13
Middle Triassic
n = 20
Late Triassic
n = 14
Early Jurassic
n = 26
Middle Jurassic
n = 5
Late Jurassic
n = 20
Early Cretaceous
n = 17
Late Cretaceous
n = 3
Mean pairwise distance
Taxon count


Rarefaction curves: mean pairwise distances of MAX distance matrix in 10 Ma bins
bin1
n = 32
bin2
n = 19
bin3
n = 12
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 13
bin9
n = 6
bin10
n = 6
bin11
n = 18
bin12
n = 2
bin13
n = 10
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean pairwise distance
Taxon count

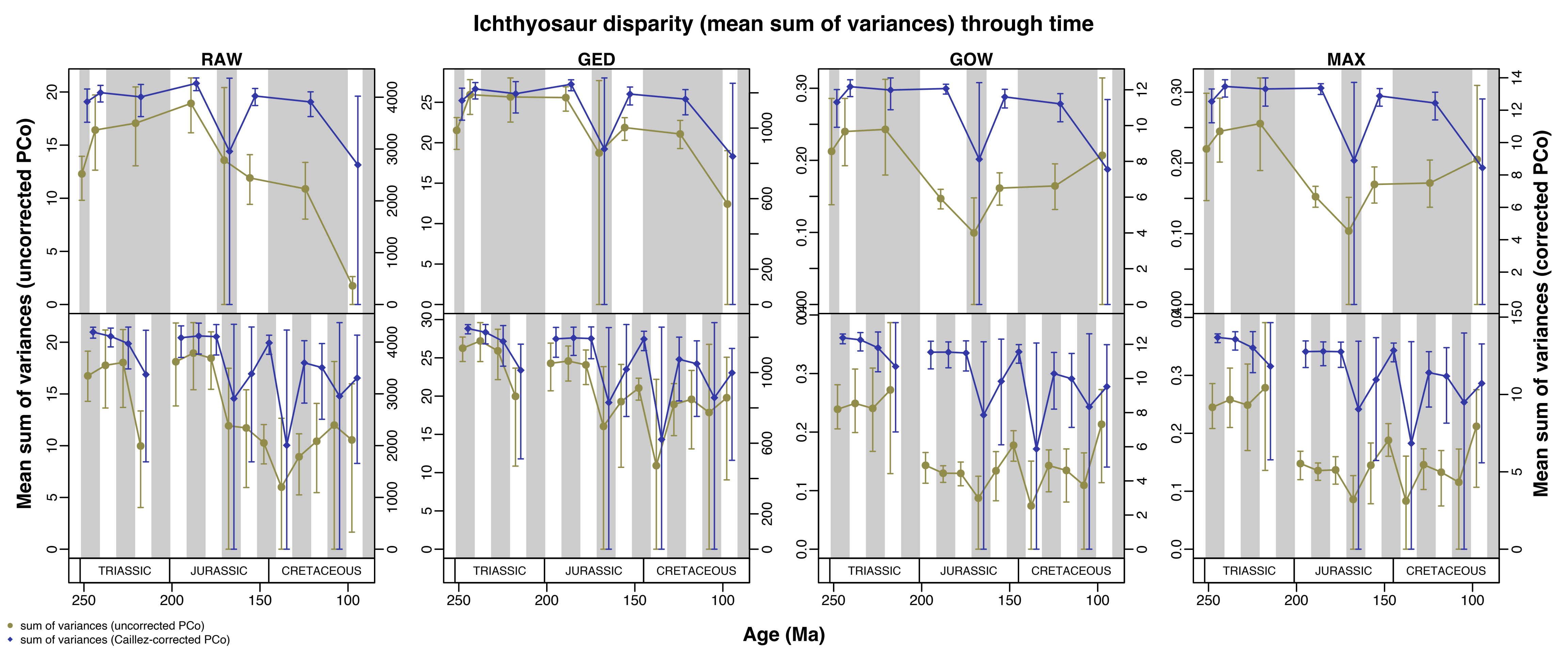


Rarefaction curves: mean weighted pairwise distances of MAX distance matrix in 10 Ma bins
bin1
n = 32
bin2
n = 19
bin3
n = 12
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 13
bin9
n = 6
bin10
n = 6
bin11
n = 18
bin12
n = 2
bin13
n = 10
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean pairwise distance
Taxon count

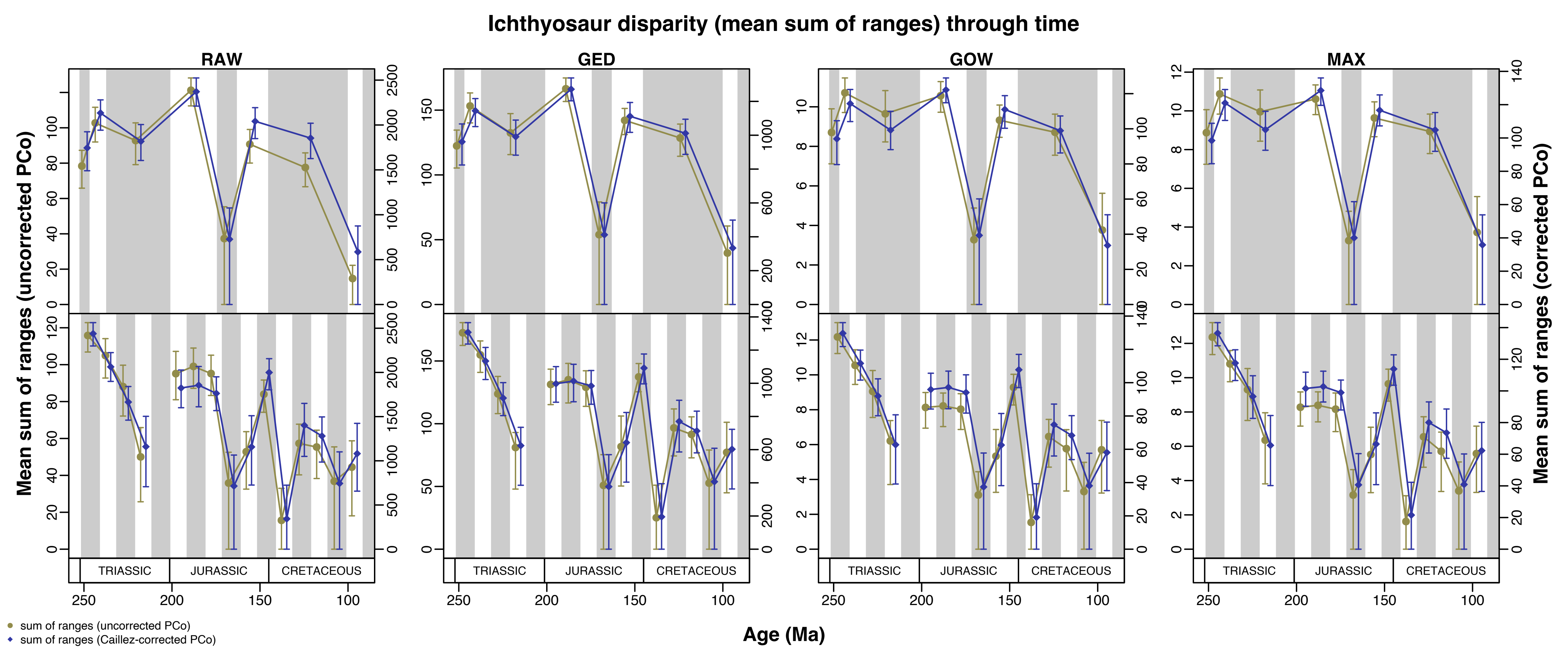
Supplementary figure 3. **Cumulative variance described by axes of the ordinated data and the correlation of these axes with the original data.** Axes from principal coordinates analysis of the four distance matrices used here derived from the cladistic data set of Moon [1].



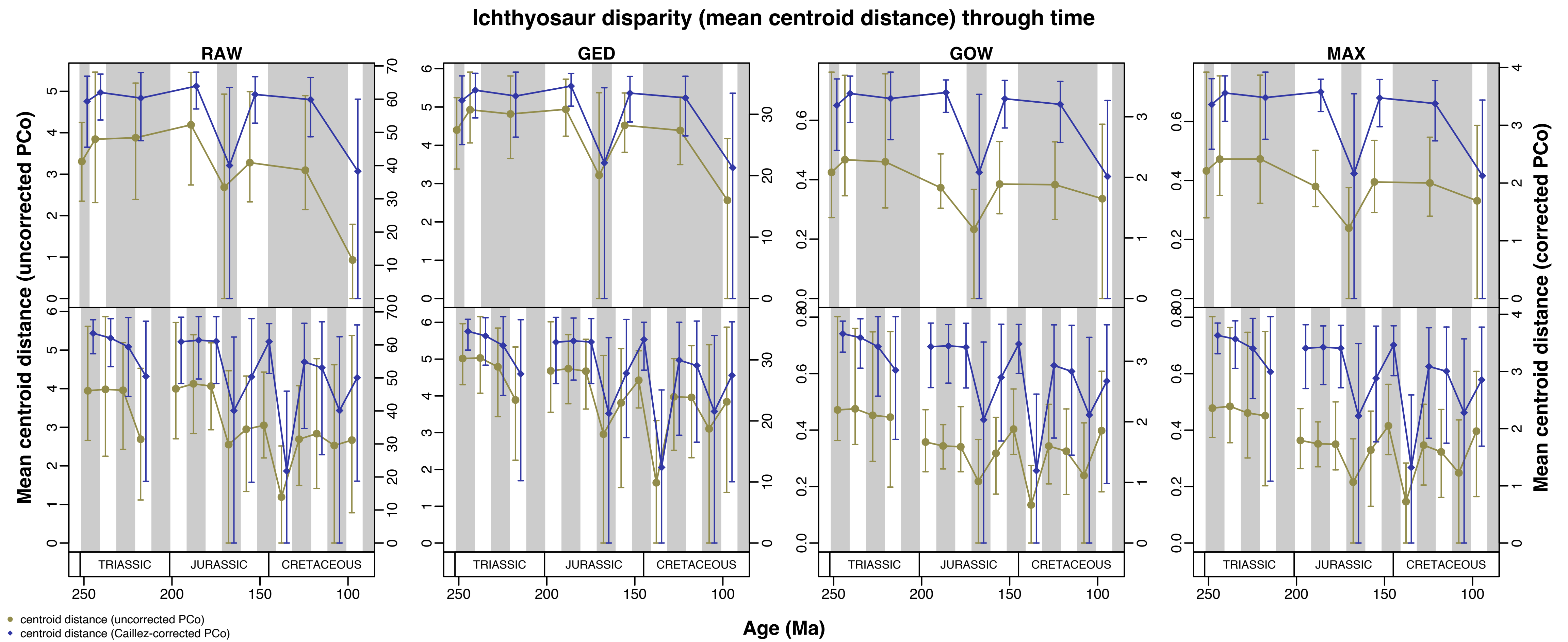
Supplementary figure 4. (following pages) **Per-bin discrete skeletal disparity of Ichthyosauriformes through the Mesozoic from ordinated data.** Ichthyosaur disparity represented by mean sum of variances, mean sum of ranges, and mean centroid distance from each of eight PCA (four distance matrices: RAW, GED, GOW, MAX; with and without negative eigenvalue correction) on the cladistic matrix of Moon [1]. Error bars show 95% confidence intervals from 500 bootstrap replicates.



Ichthyosaur disparity (mean sum of variances) through time
RAW
GED
GOW
MAX
Mean sum of variances (uncorrected PCo)
Mean sum of variances (corrected PCo)
TRIASSIC
JURASSIC
CRETACEOUS
Age (Ma)
sum of variances (uncorrected PCo)
sum of variances (Caillez-corrected PCo)

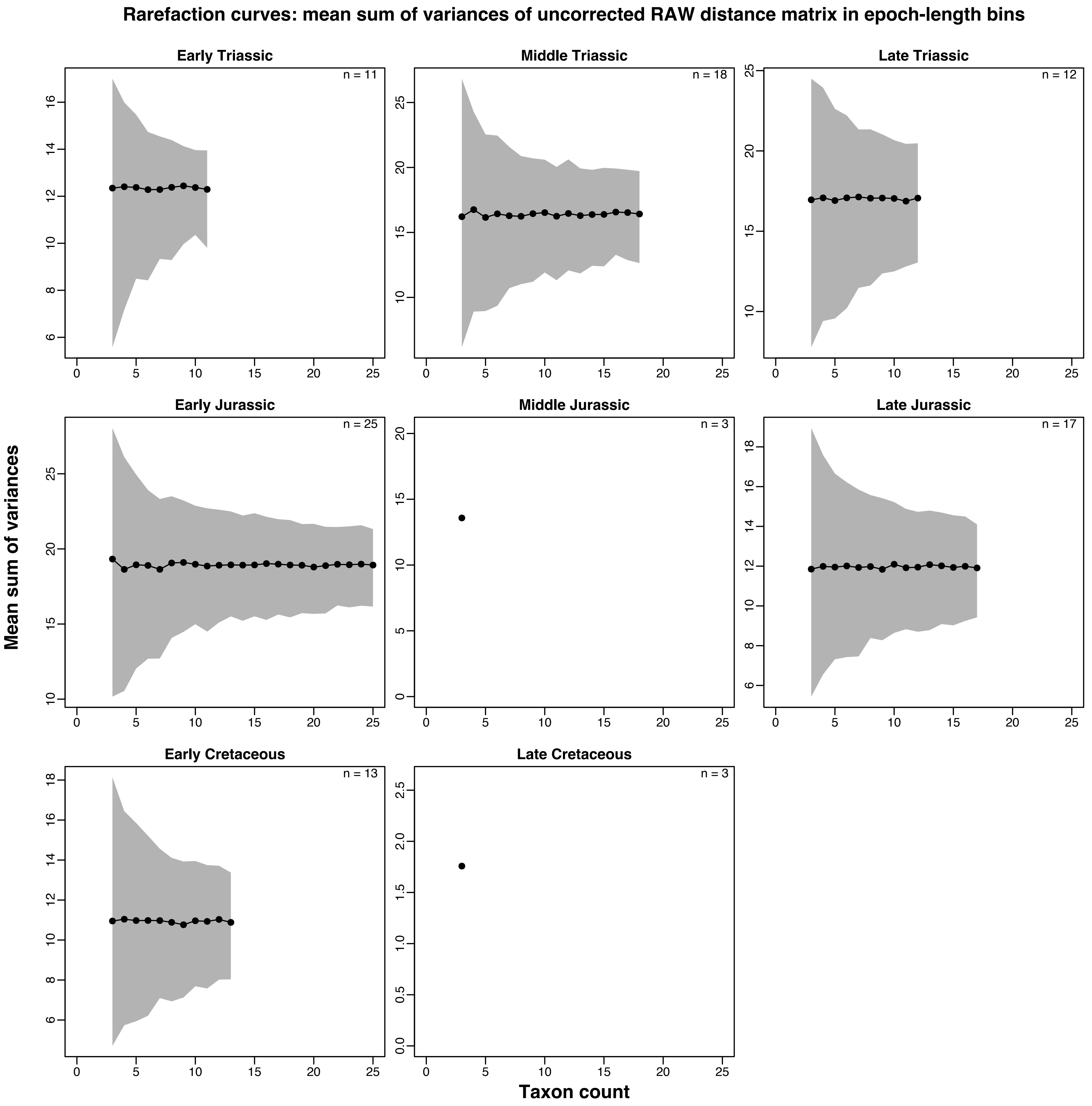


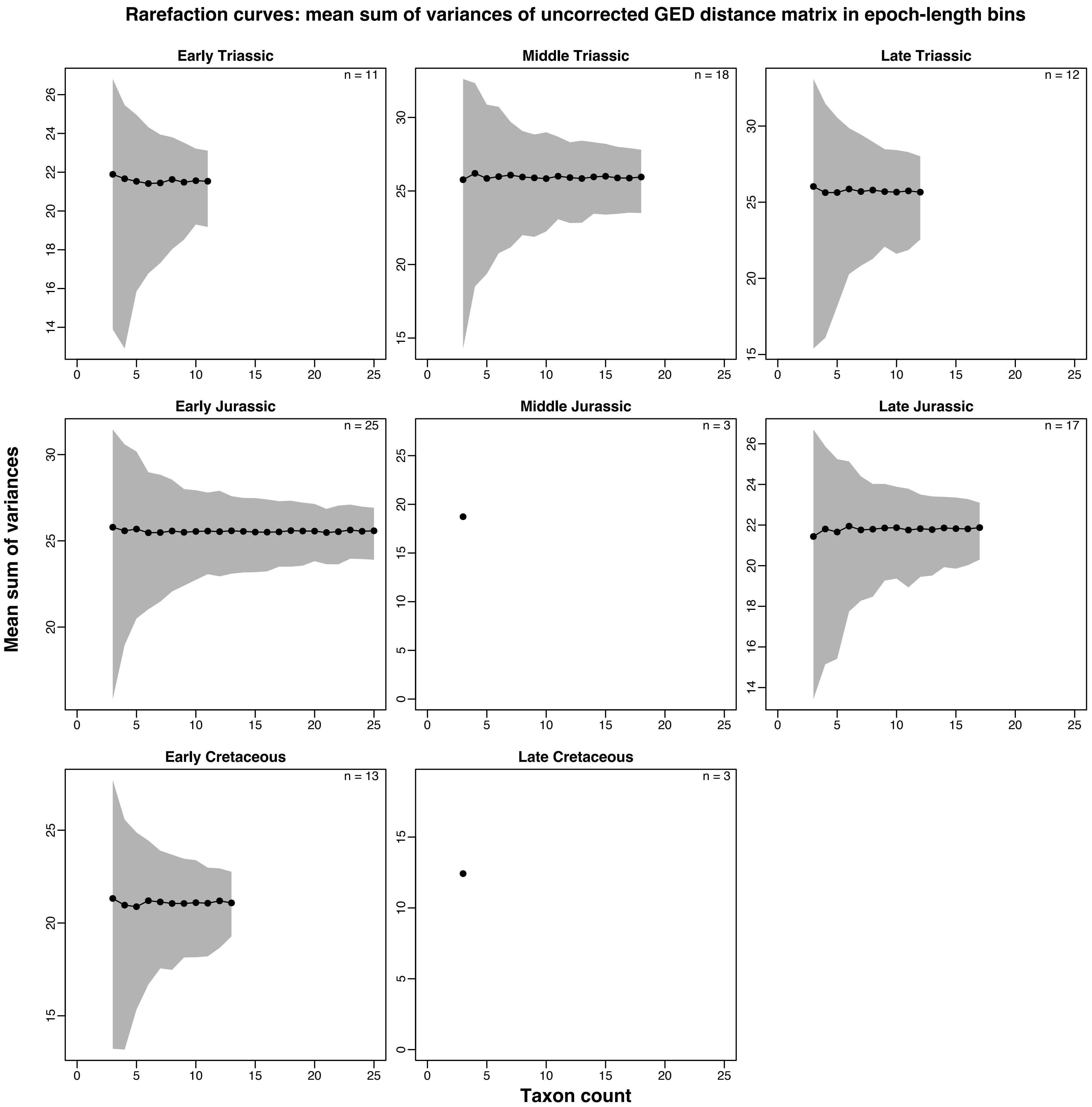
Ichthyosaur disparity (mean sum of ranges) through time
RAW
GED
GOW
MAX
Mean sum of ranges (uncorrected PCo)
Mean sum of ranges (corrected PCo)
TRIASSIC
JURASSIC
CRETACEOUS
Age (Ma)
sum of ranges (uncorrected PCo)
sum of ranges (Cailliez-corrected PCo)



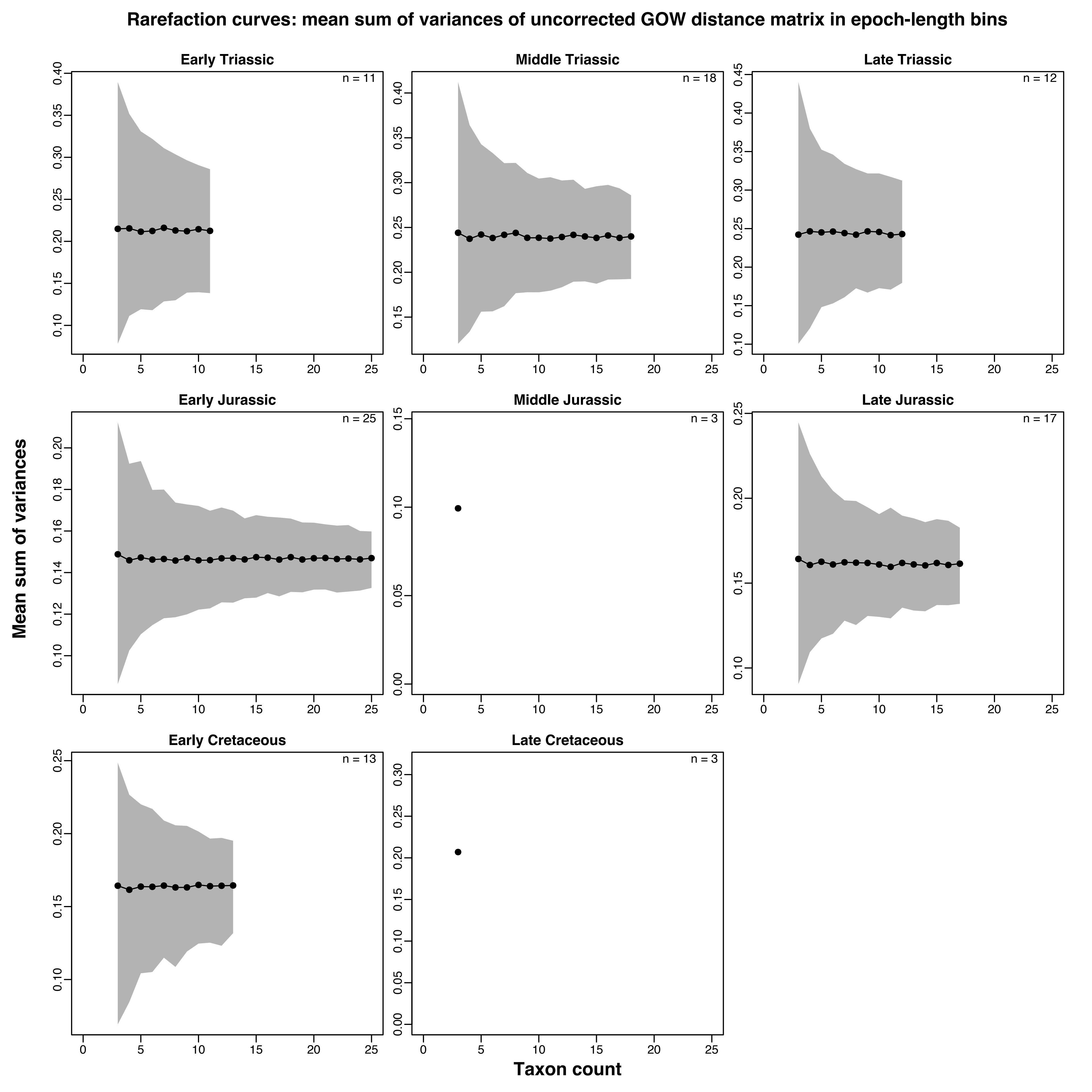
Ichthyosaur disparity (mean centroid distance) through time
RAW
GED
GOW
MAX
Mean centroid distance (uncorrected PCo)
Mean centroid distance (corrected PCo)
TRIASSIC
JURASSIC
CRETACEOUS
Age (Ma)
centroid distance (uncorrected PCo)
centroid distance (Caillez-corrected PCo)

Supplementary figure 5. (following pages) **Per-bin rarefaction curves for each disparity-time curve shown in Supplementary Figure 4** Disparity for each bin is sequentially rarefied on taxon occurrences. Error polygon gives 95% confidence interval from 500 replicates.

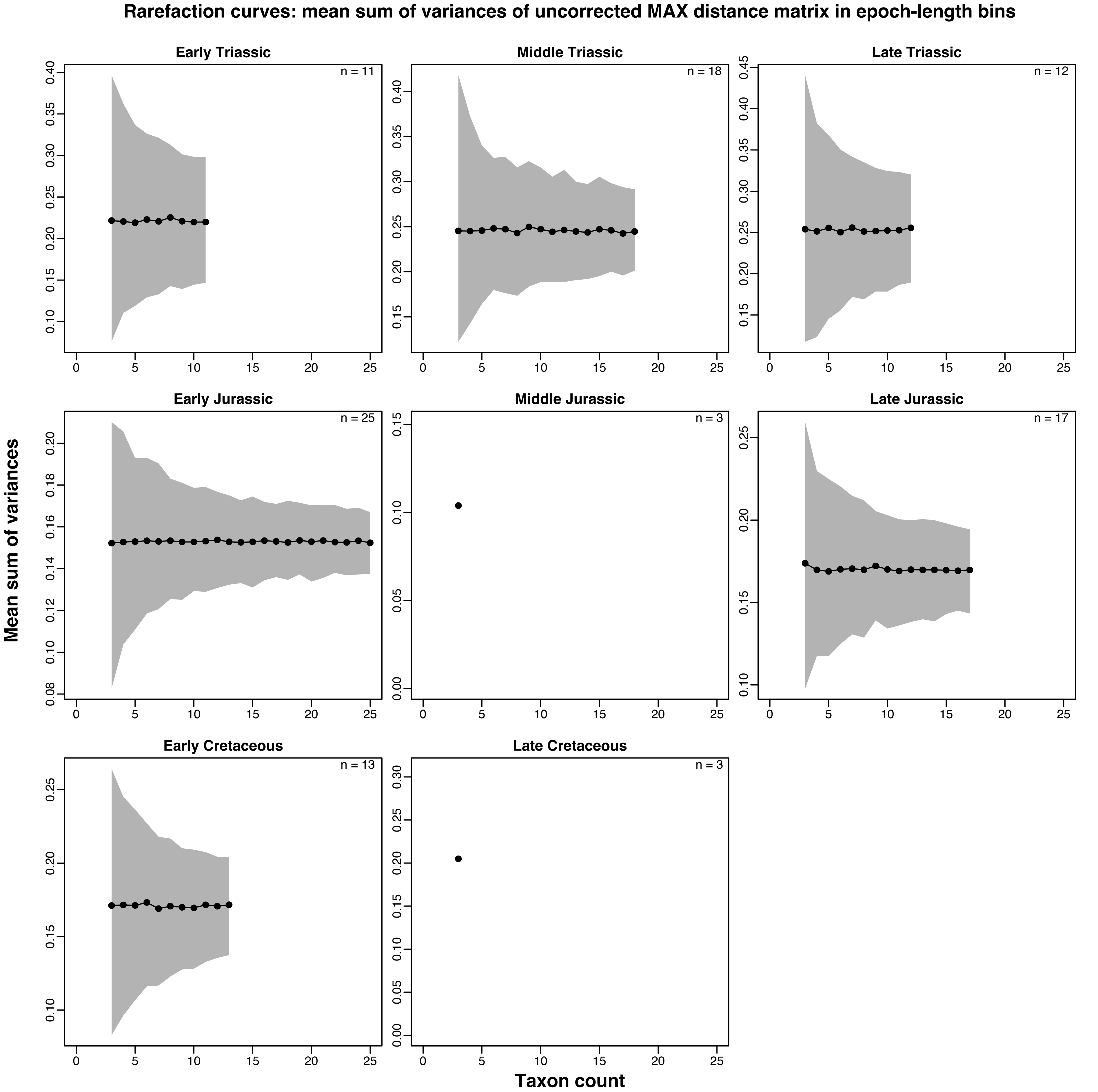

Rarefaction curves: mean sum of variances of uncorrected RAW distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of variances
Taxon count



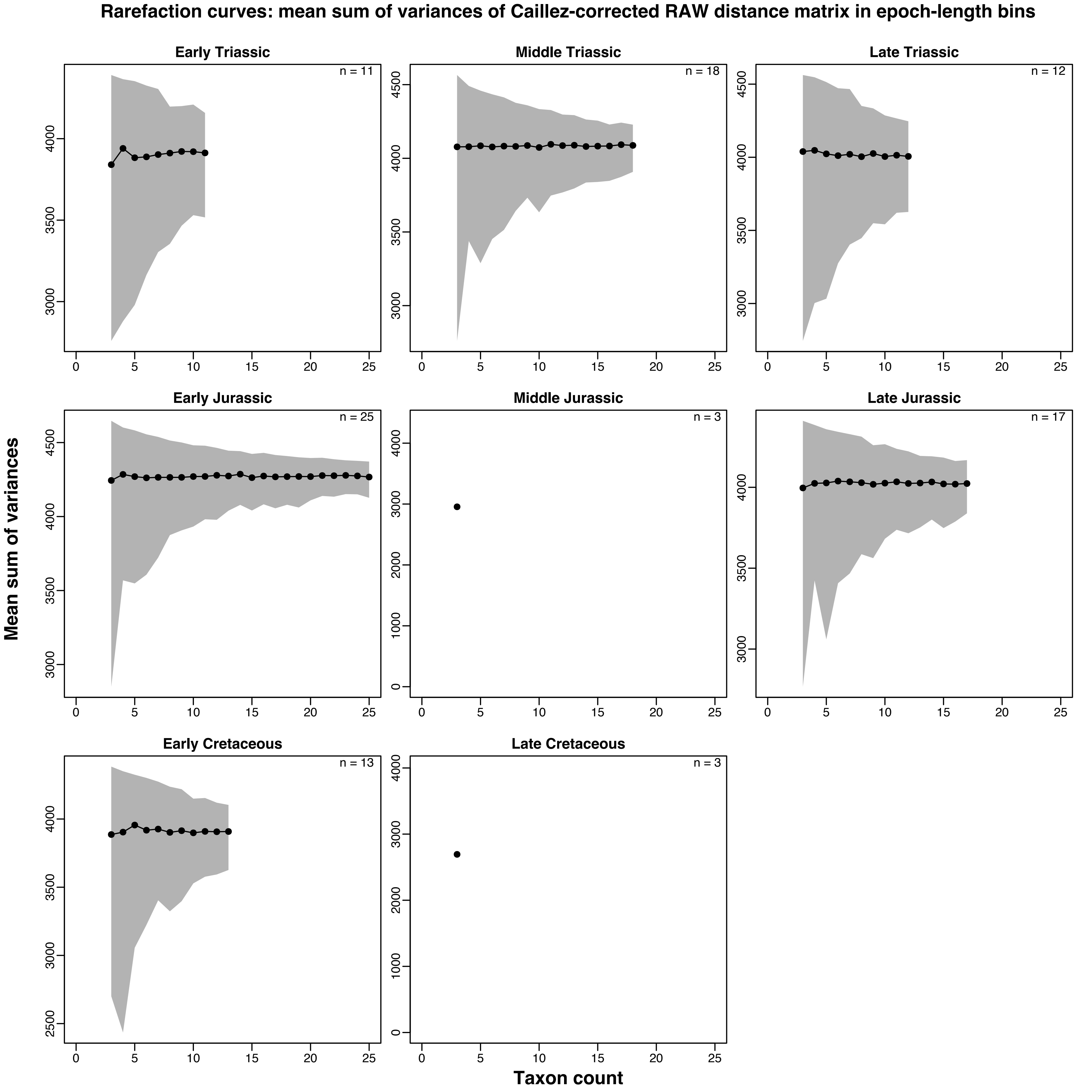
Rarefaction curves: mean sum of variances of uncorrected GED distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of variances
Taxon count

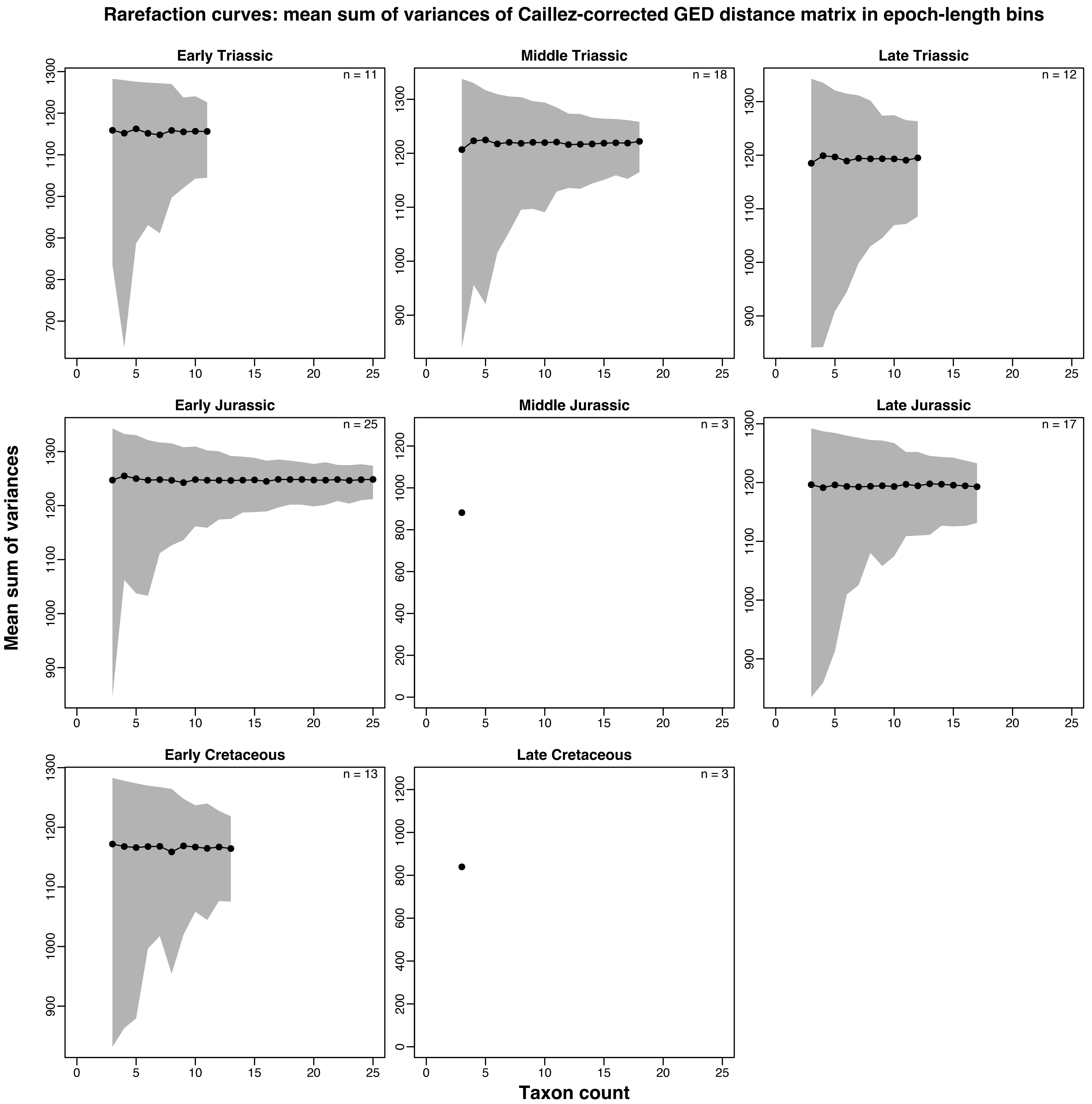


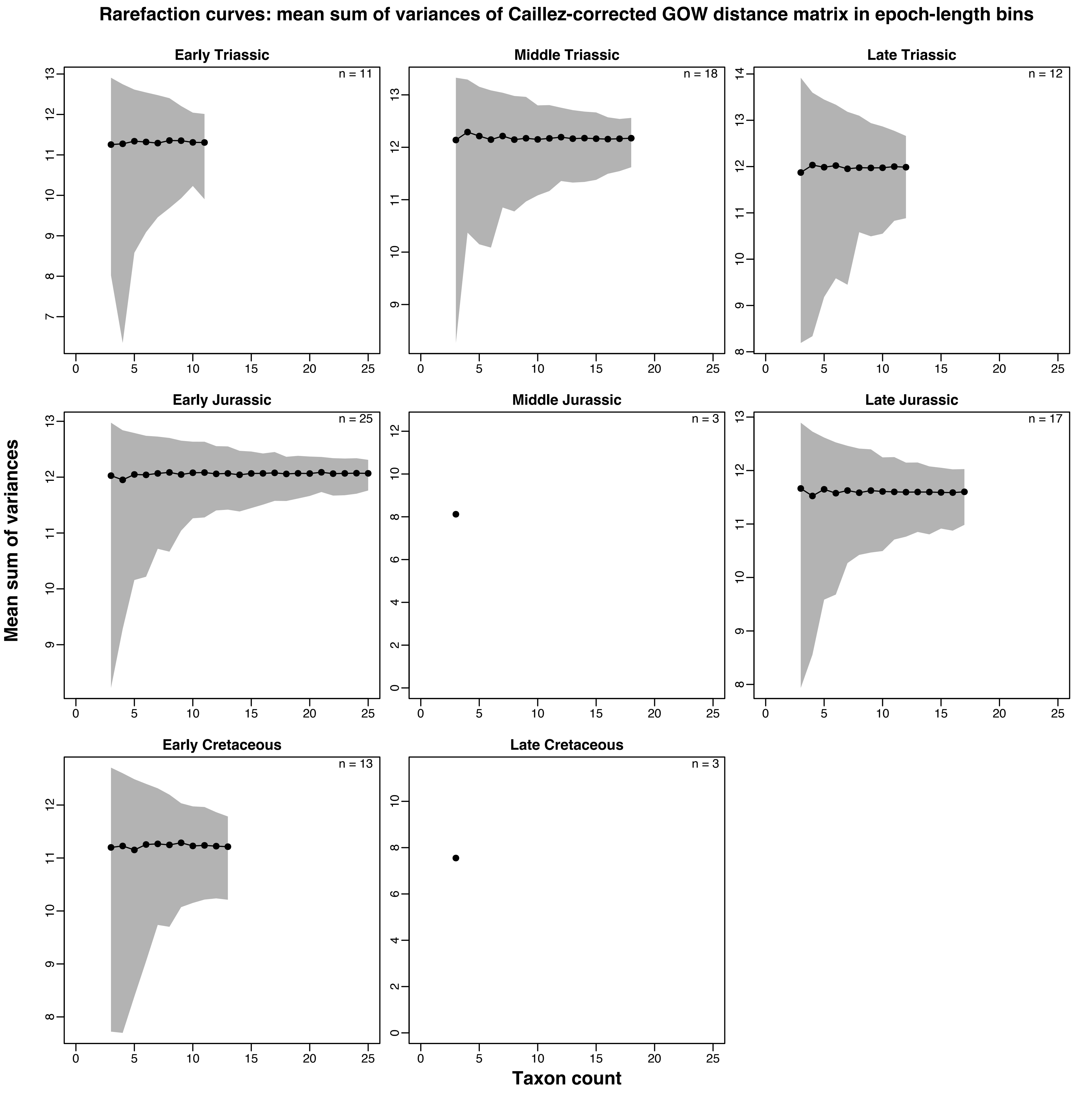
Rarefaction curves: mean sum of variances of uncorrected GOW distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of variances
Taxon count



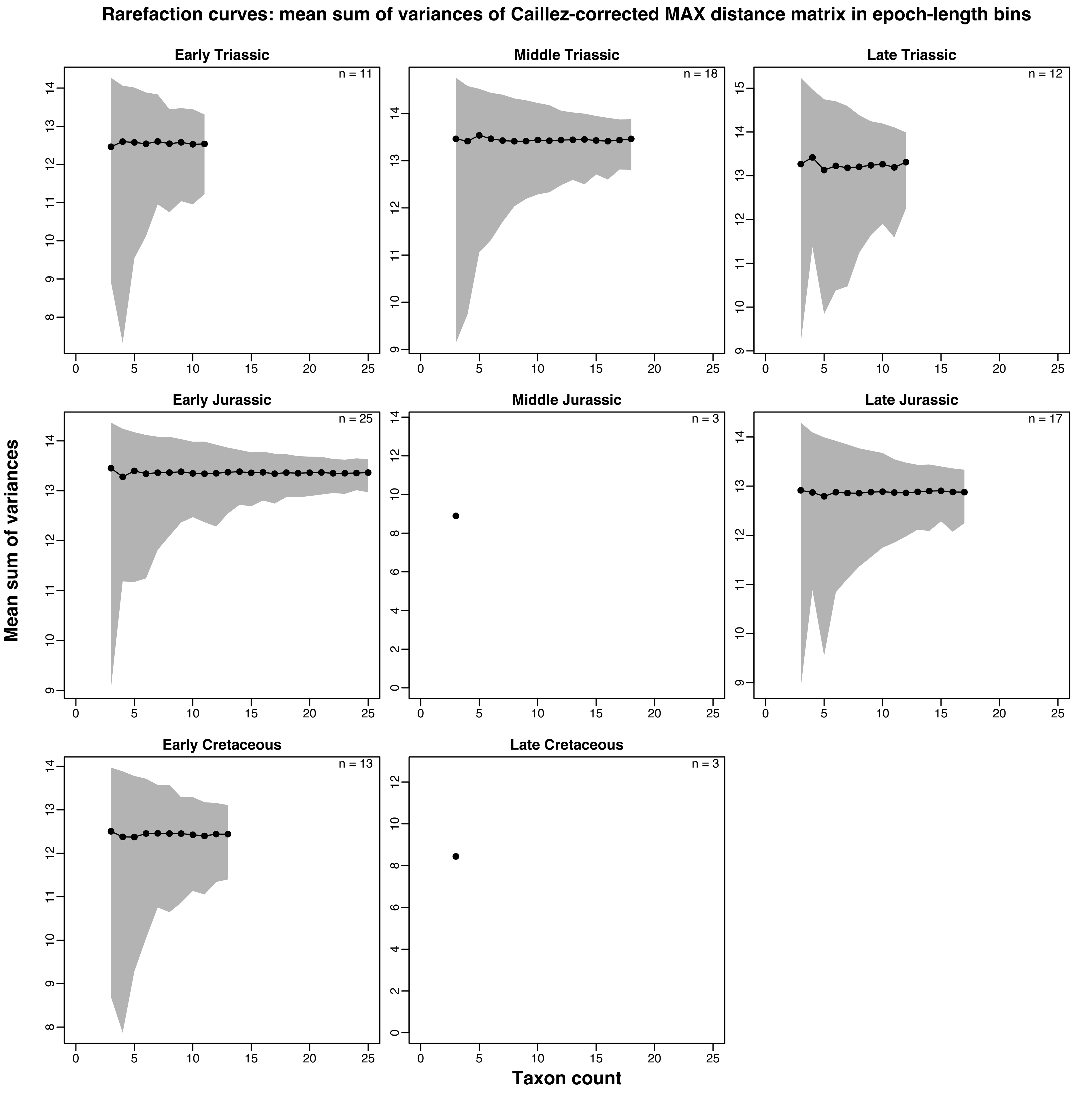
Rarefaction curves: mean sum of variances of uncorrected MAX distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of variances
Taxon count

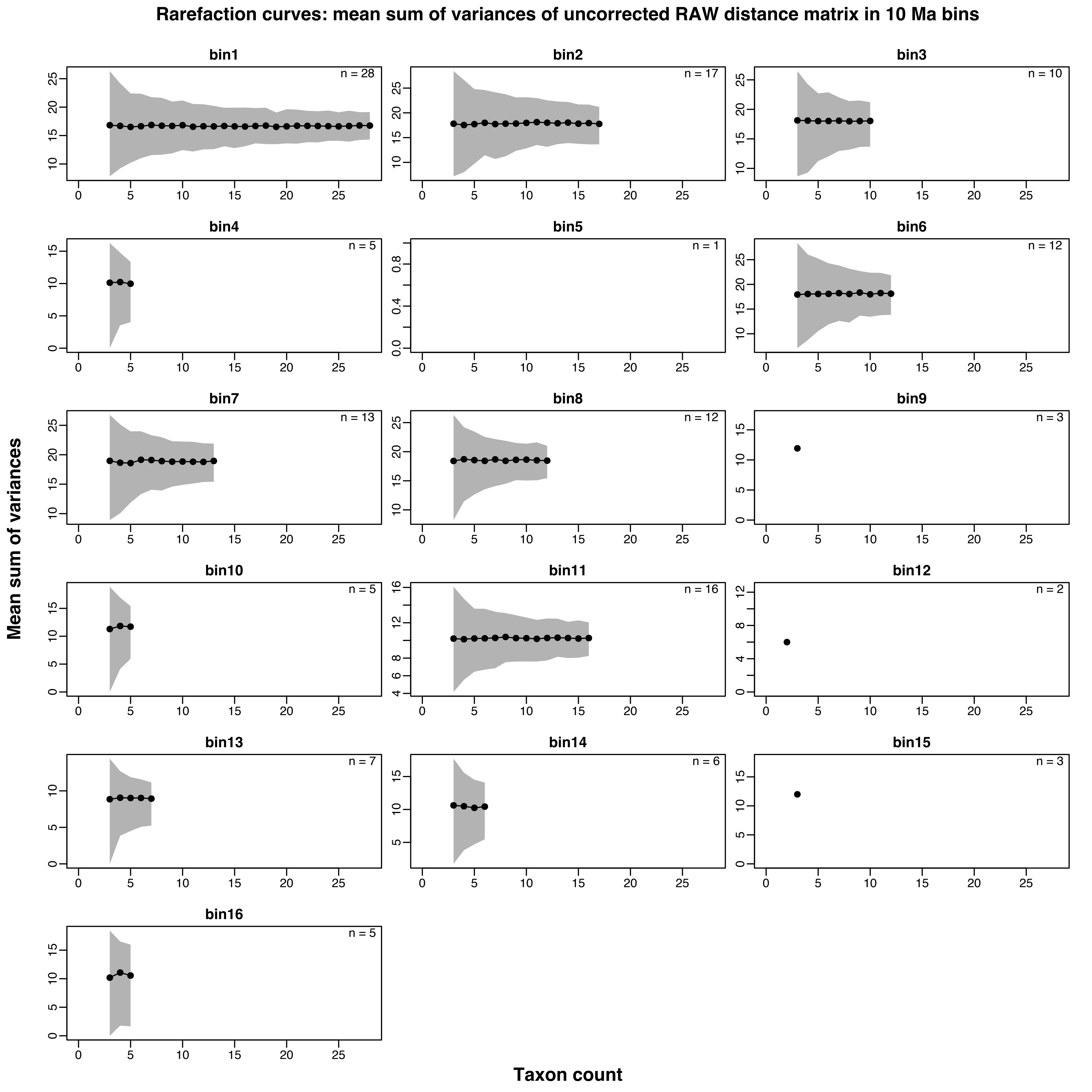

Rarefaction curves: mean sum of variances of Caillez-corrected RAW distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of variances
Taxon count

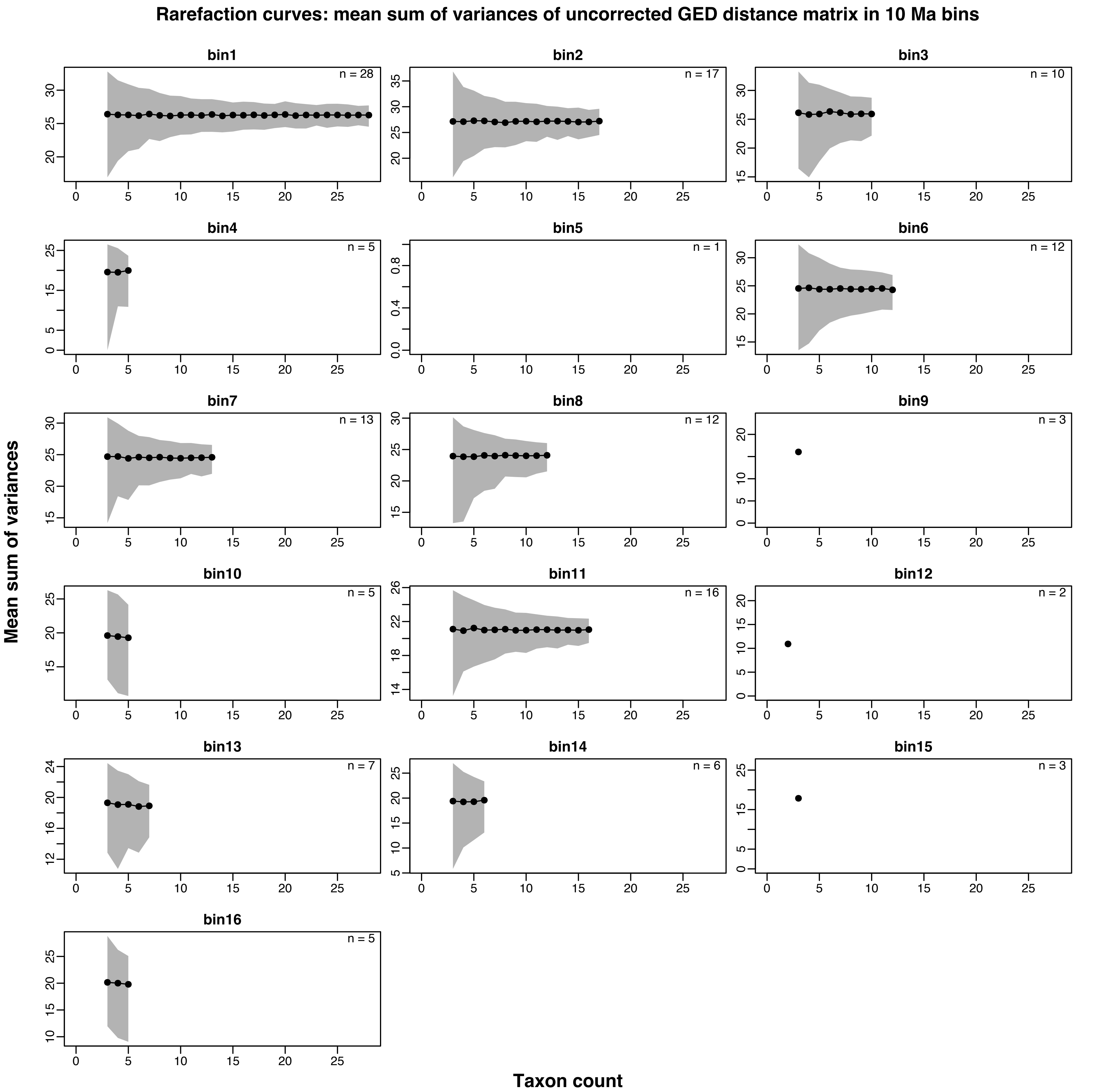

Rarefaction curves: mean sum of variances of Caillez-corrected GED distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of variances
Taxon count



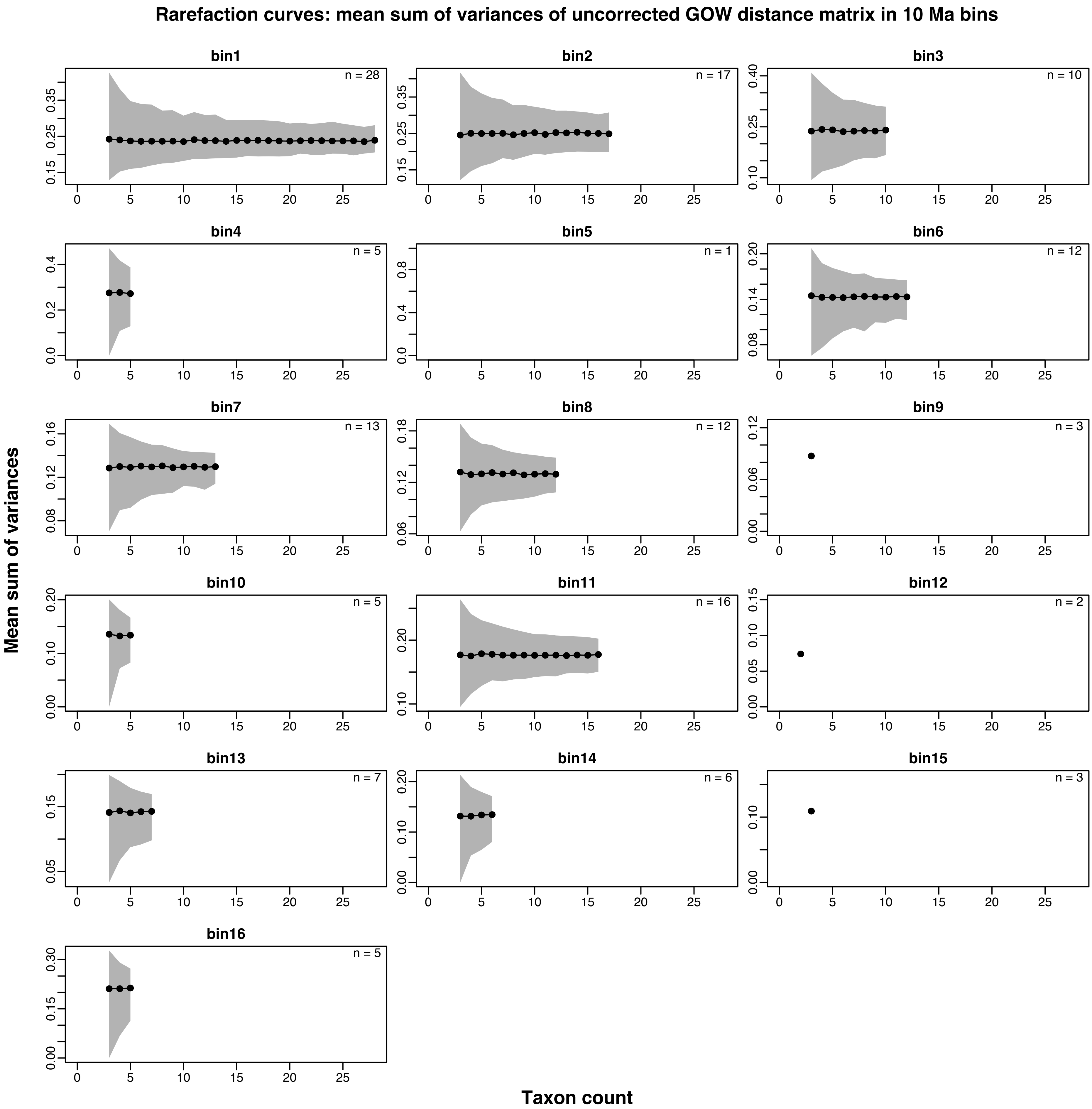
Rarefaction curves: mean sum of variances of Caillez-corrected GOW distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of variances
Taxon count


Rarefaction curves: mean sum of variances of Caillez-corrected MAX distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of variances
Taxon count

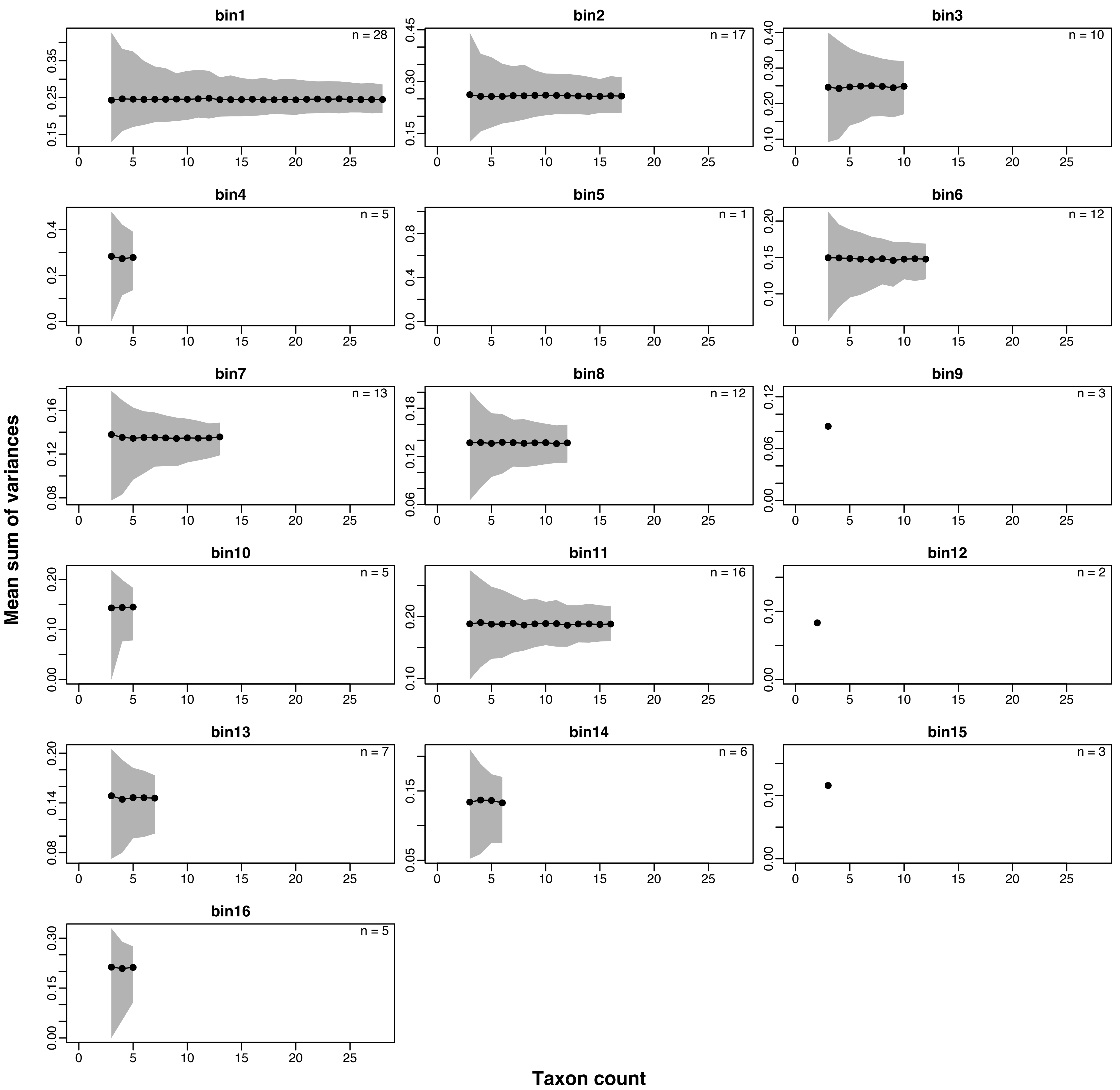

Rarefaction curves: mean sum of variances of uncorrected RAW distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean sum of variances
Taxon count



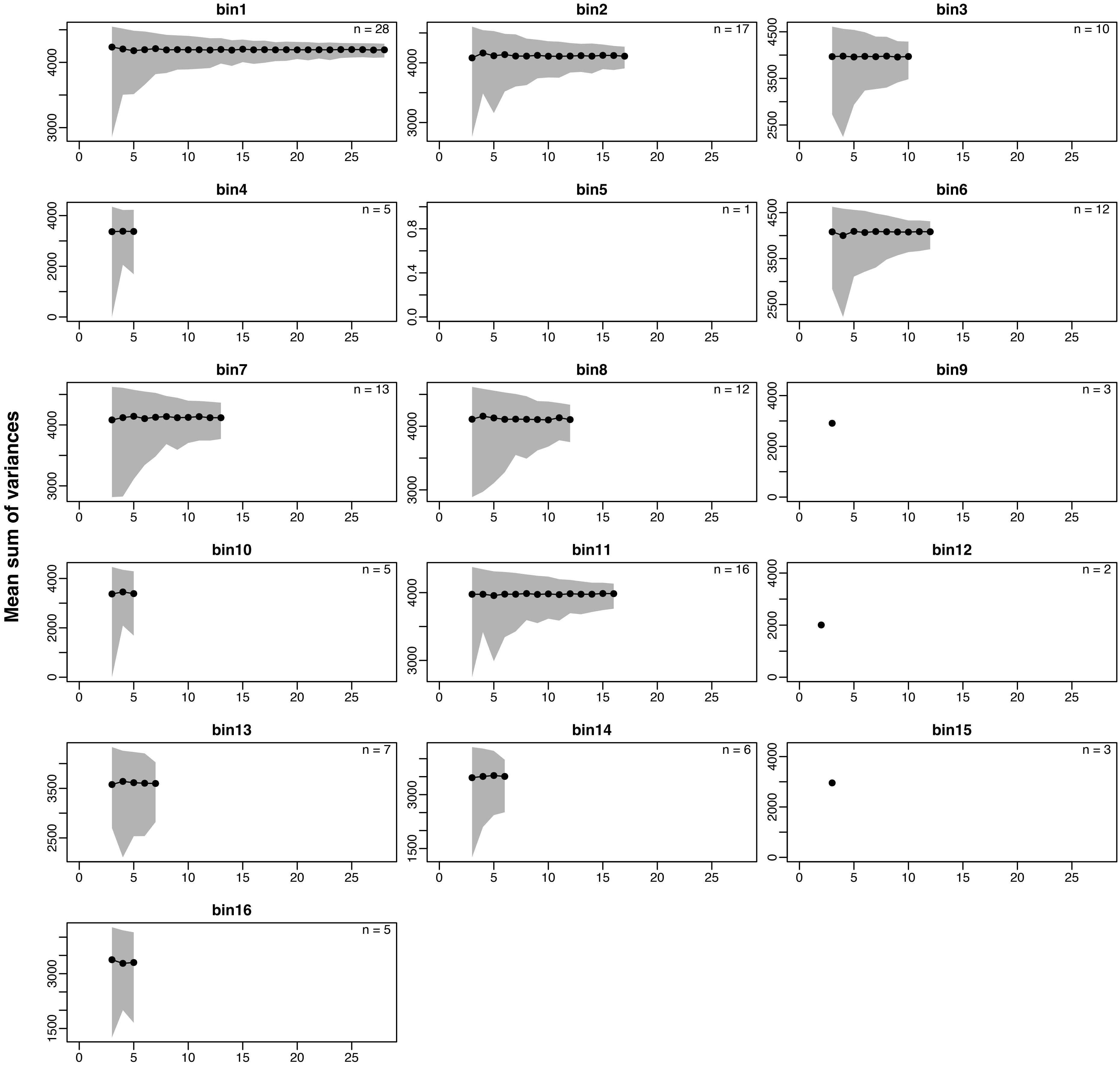
Rarefaction curves: mean sum of variances of uncorrected GED distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean sum of variances
Taxon count

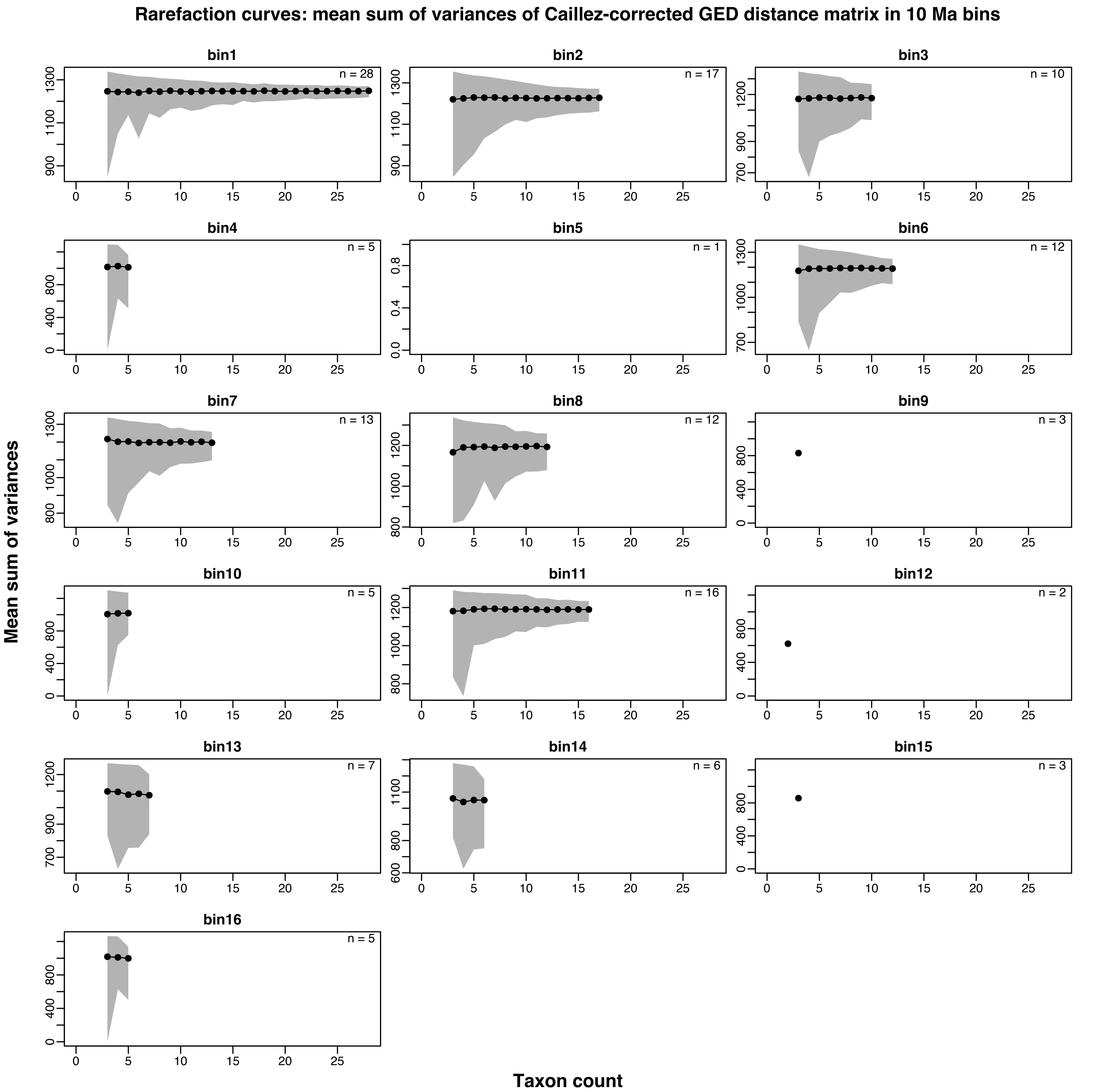

Rarefaction curves: mean sum of variances of uncorrected GOW distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean sum of variances
Taxon count

Rarefaction curves: mean sum of variances of uncorrected MAX distance matrix in 10 Ma bins

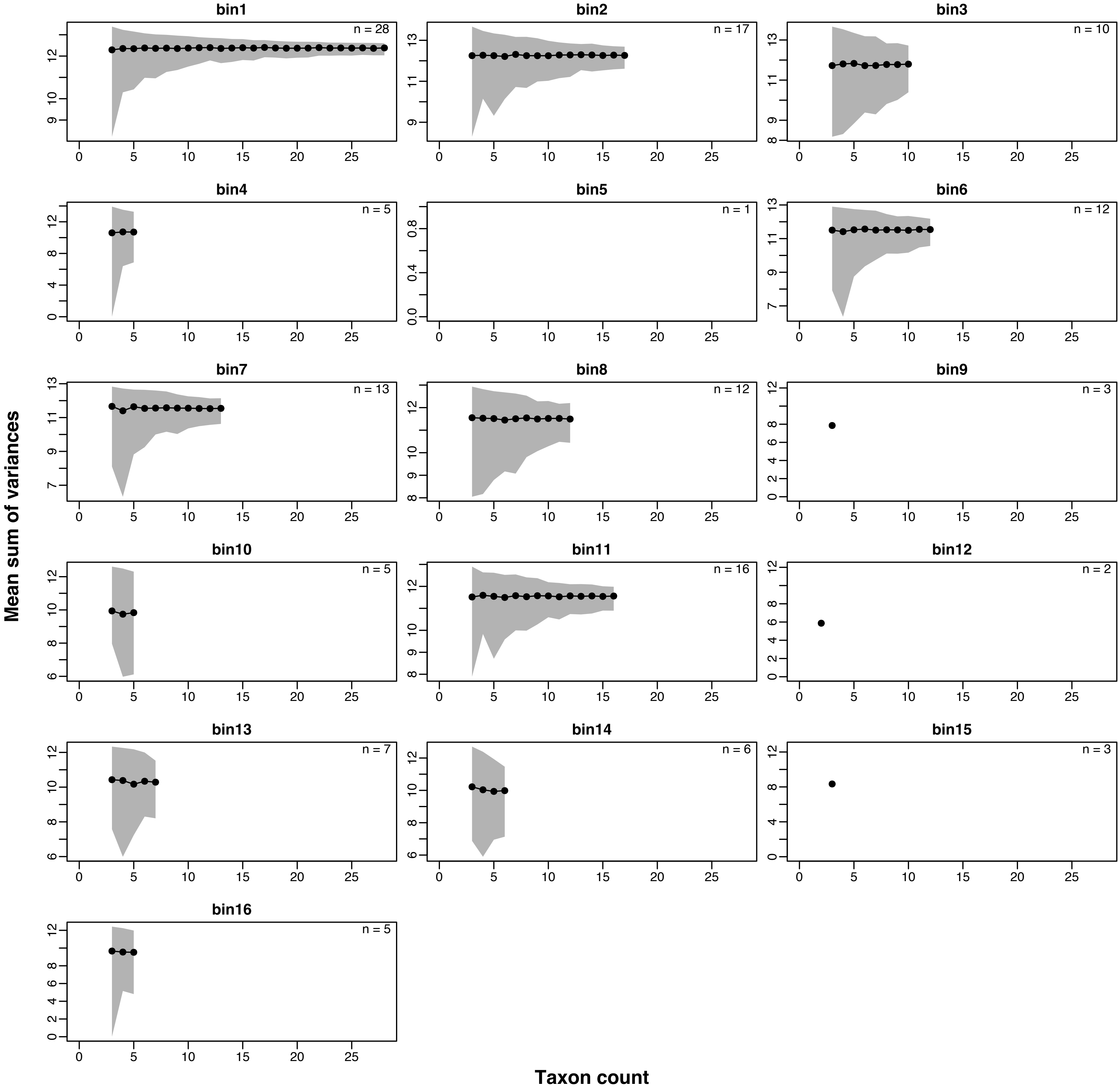


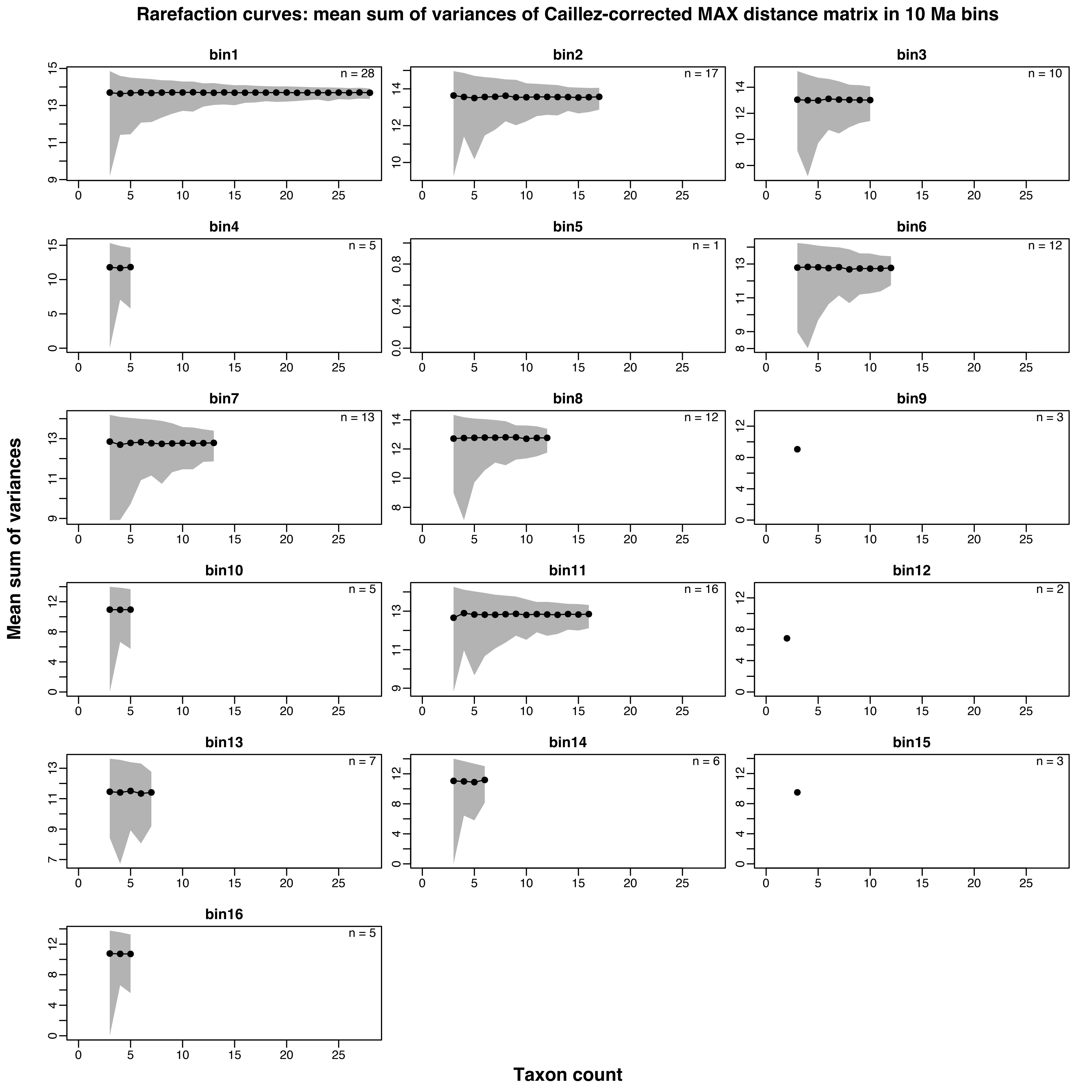
Rarefaction curves: mean sum of variances of Caillez-corrected RAW distance matrix in 10 Ma bins

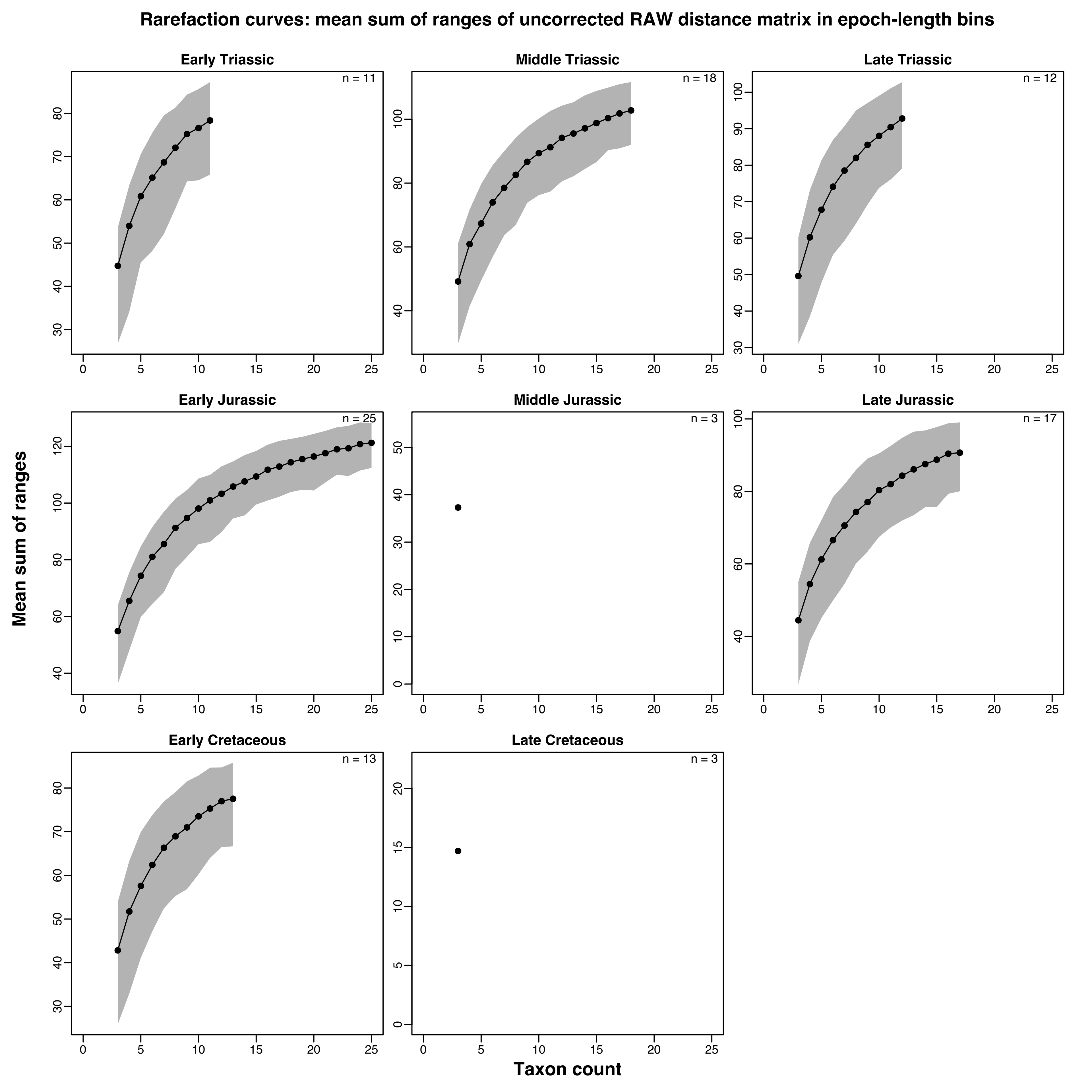



Rarefaction curves: mean sum of variances of Caillez-corrected GED distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean sum of variances
Taxon count

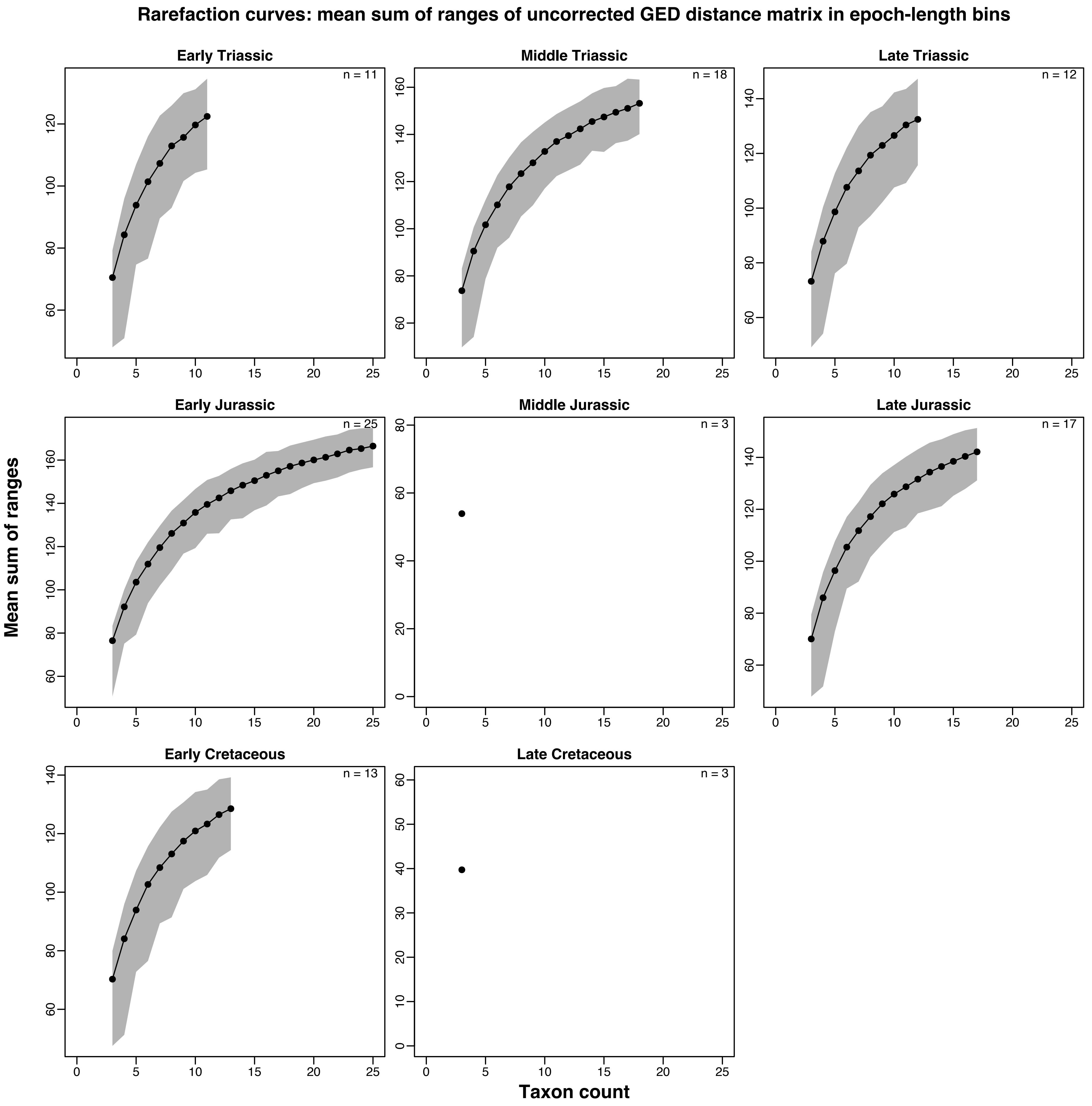
Rarefaction curves: mean sum of variances of Caillez-corrected GOW distance matrix in 10 Ma bins



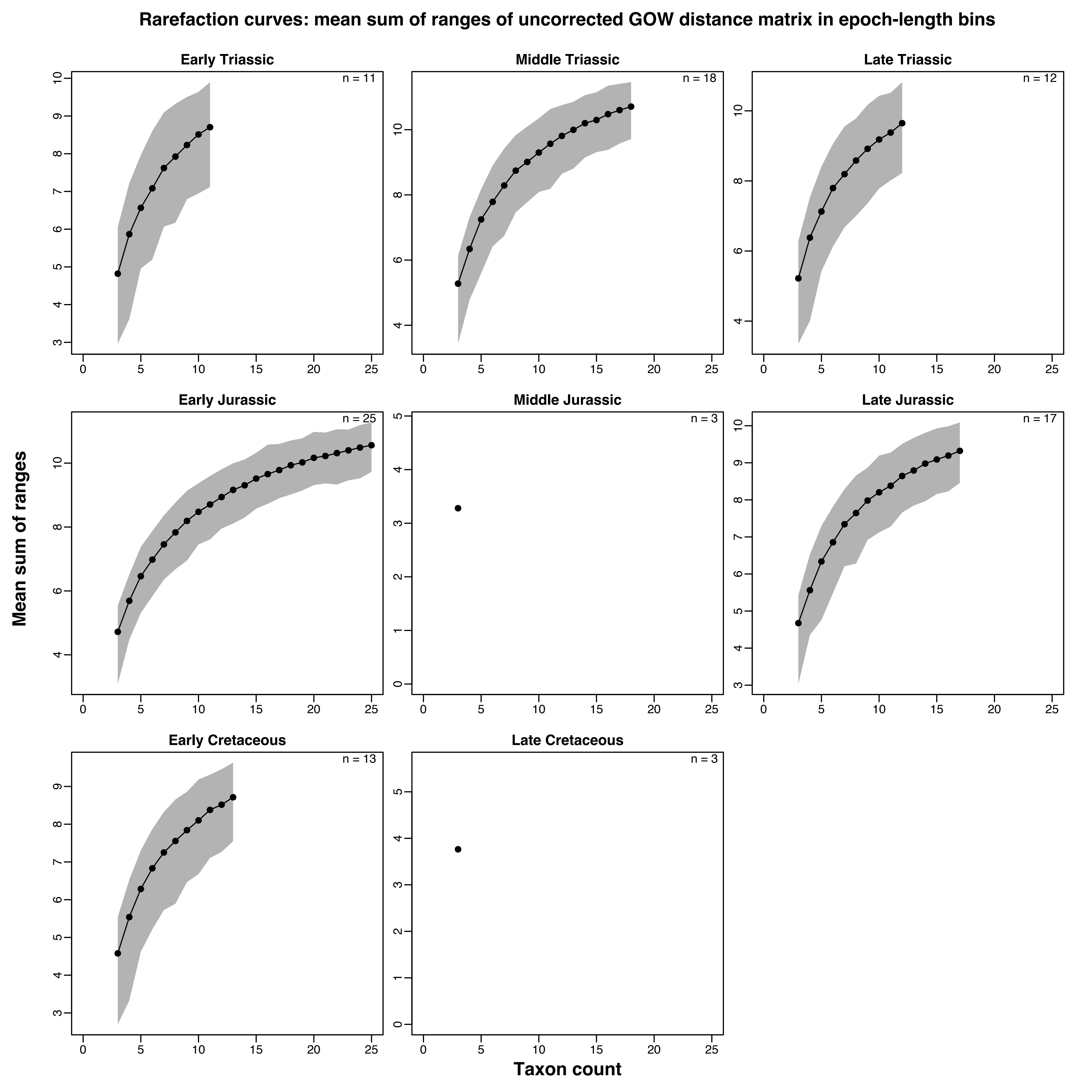

Rarefaction curves: mean sum of variances of Caillez-corrected MAX distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean sum of variances
Taxon count

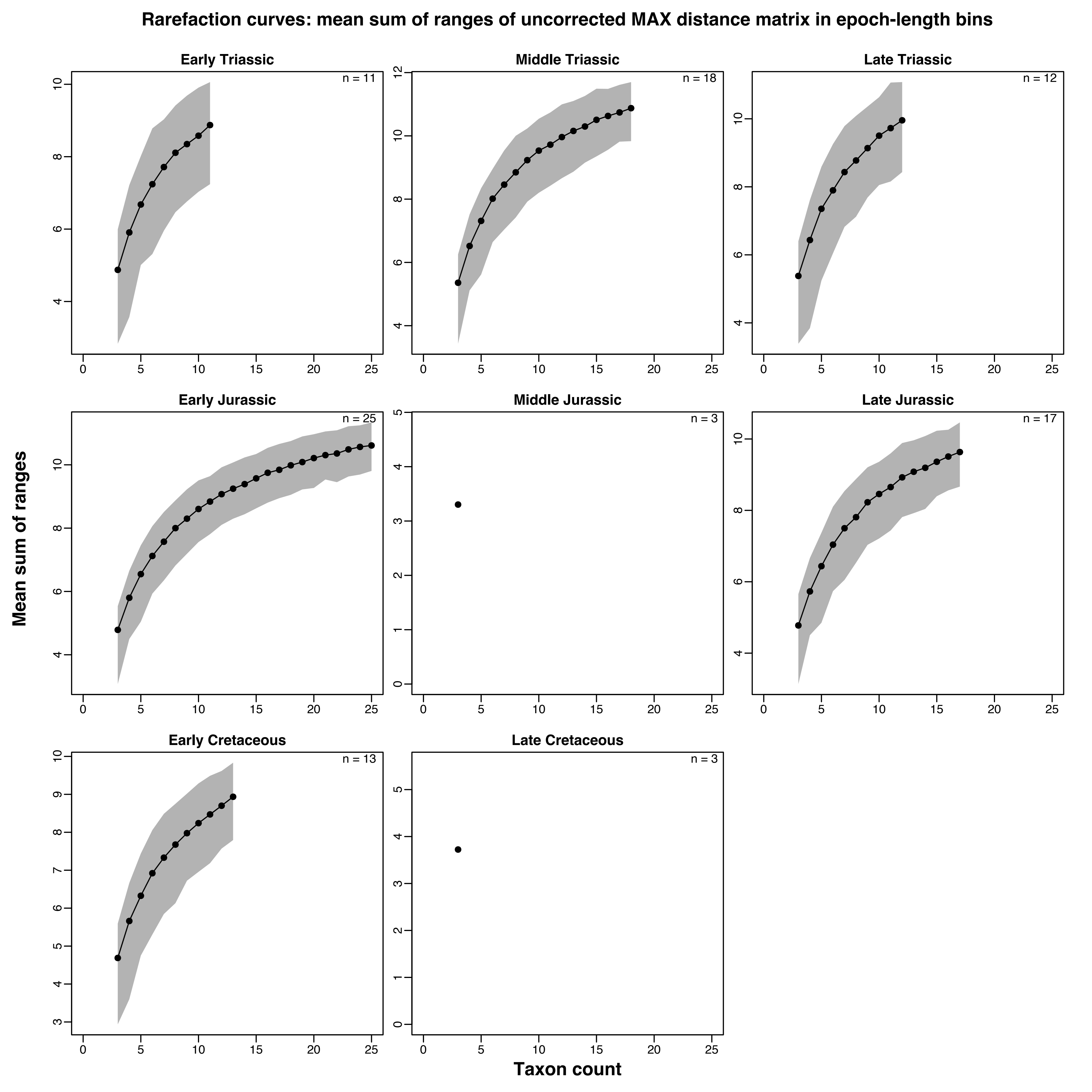


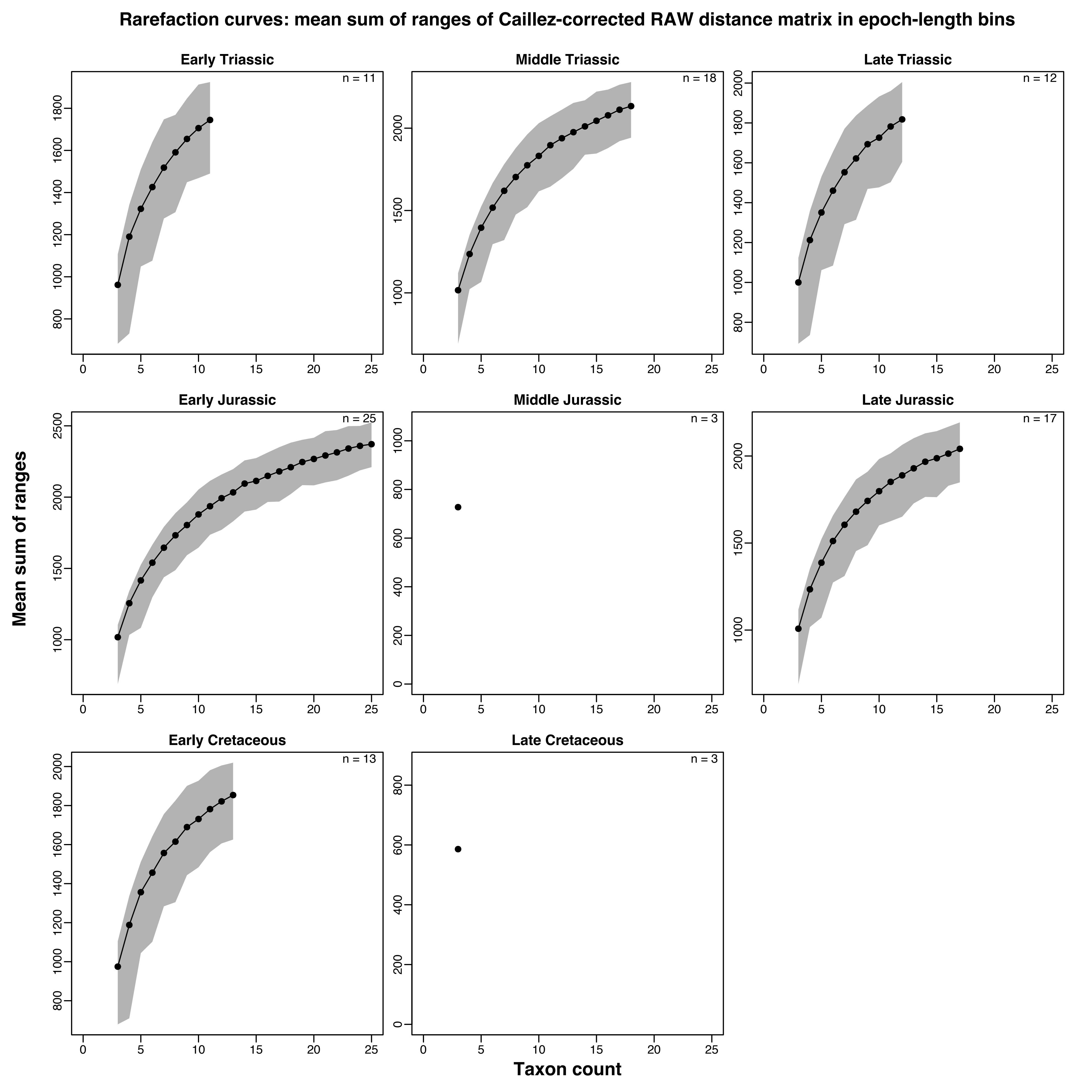
Rarefaction curves: mean sum of ranges of uncorrected RAW distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of ranges
Taxon count

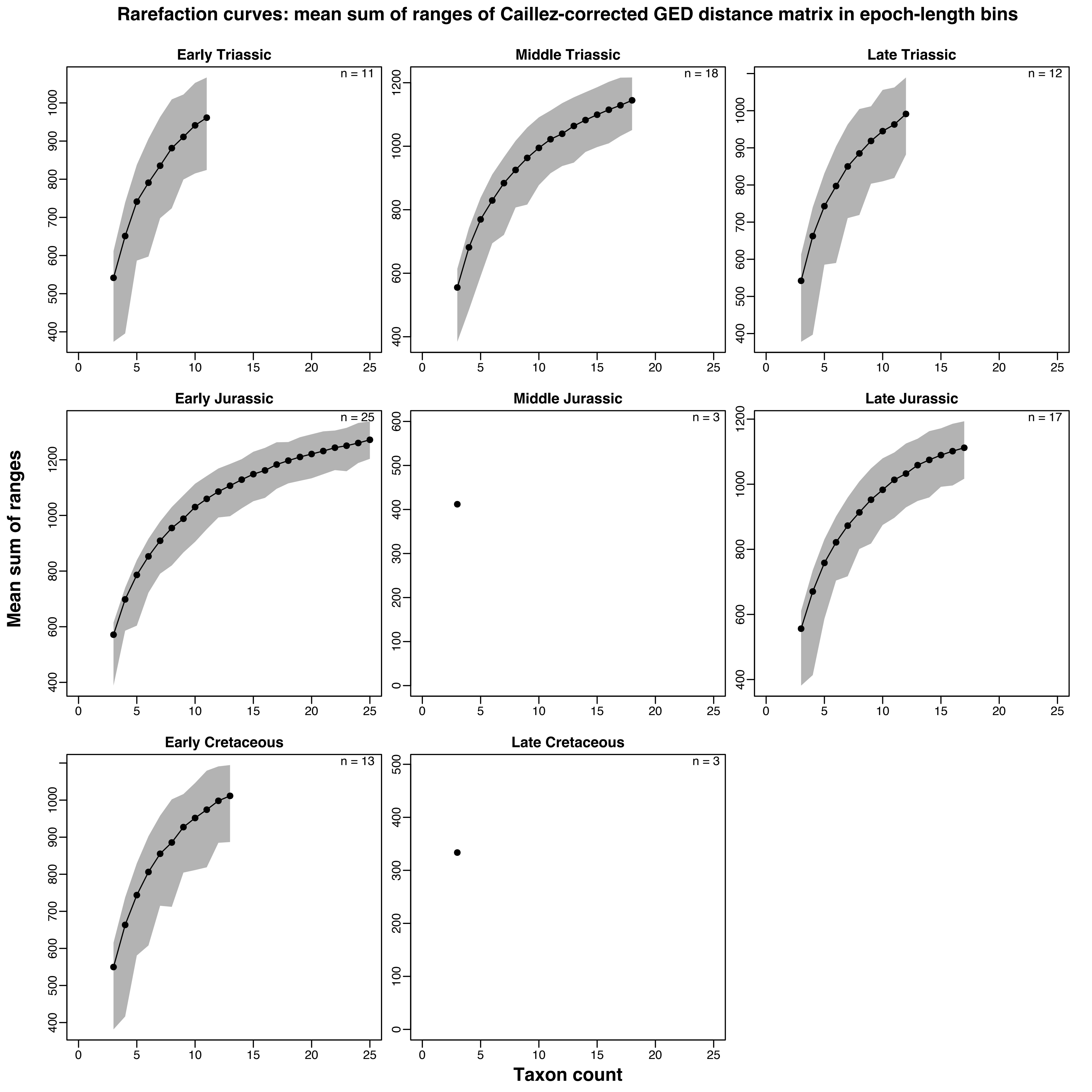


Rarefaction curves: mean sum of ranges of uncorrected GED distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of ranges
Taxon count

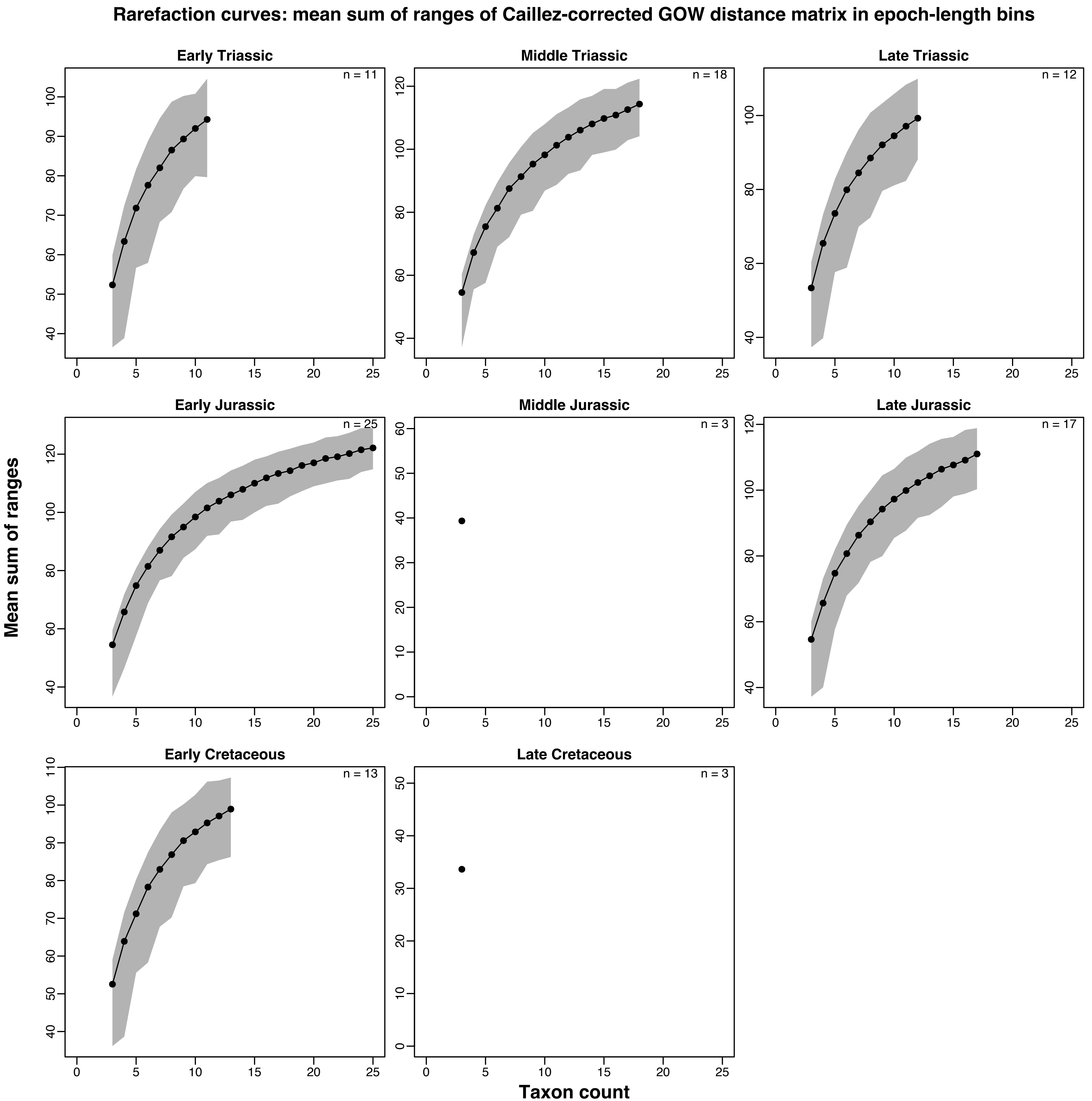

Rarefaction curves: mean sum of ranges of uncorrected GOW distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of ranges
Taxon count


Rarefaction curves: mean sum of ranges of uncorrected MAX distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of ranges
Taxon count

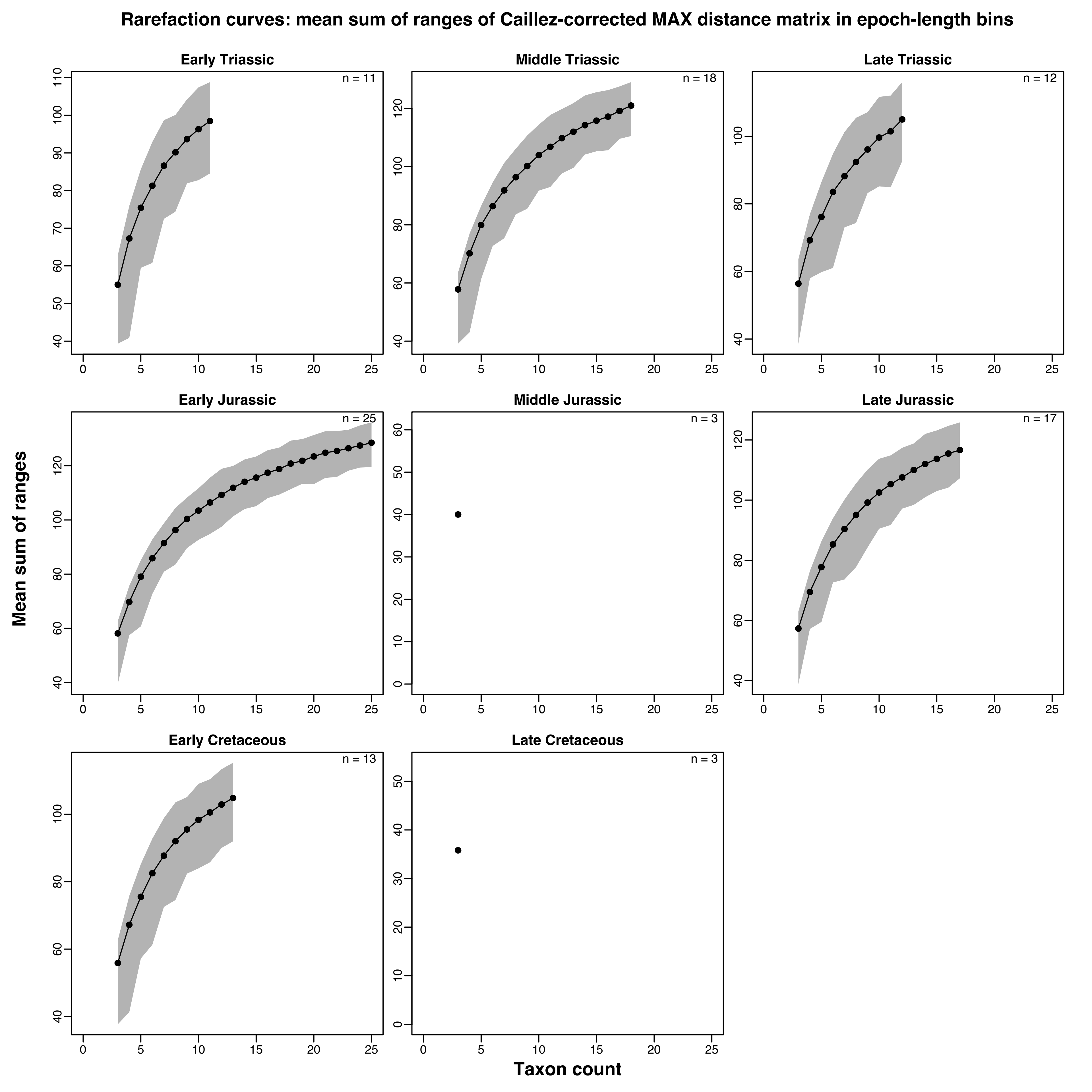

Rarefaction curves: mean sum of ranges of Caillez-corrected RAW distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of ranges
Taxon count

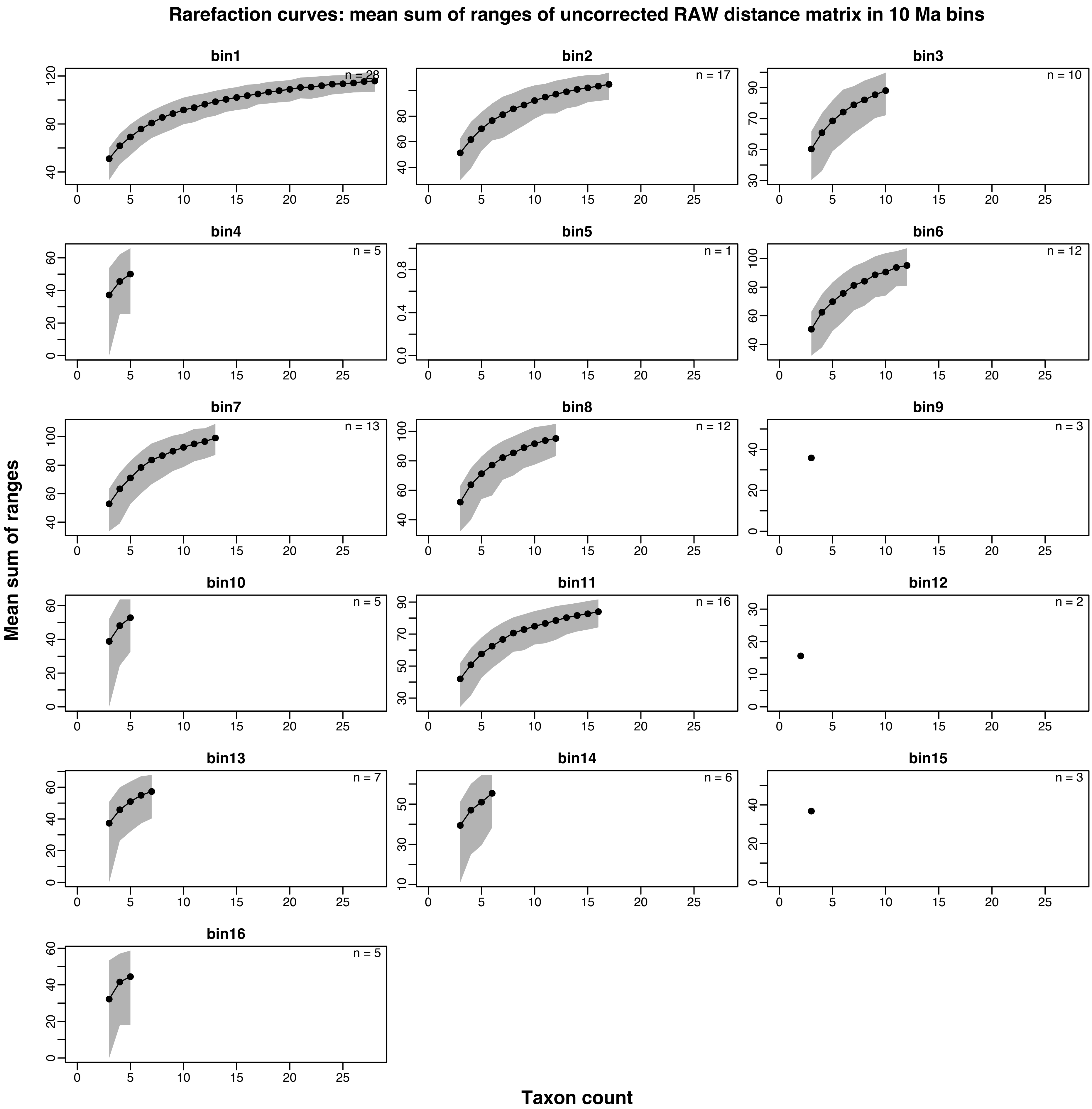


Rarefaction curves: mean sum of ranges of Caillez-corrected GED distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of ranges
Taxon count

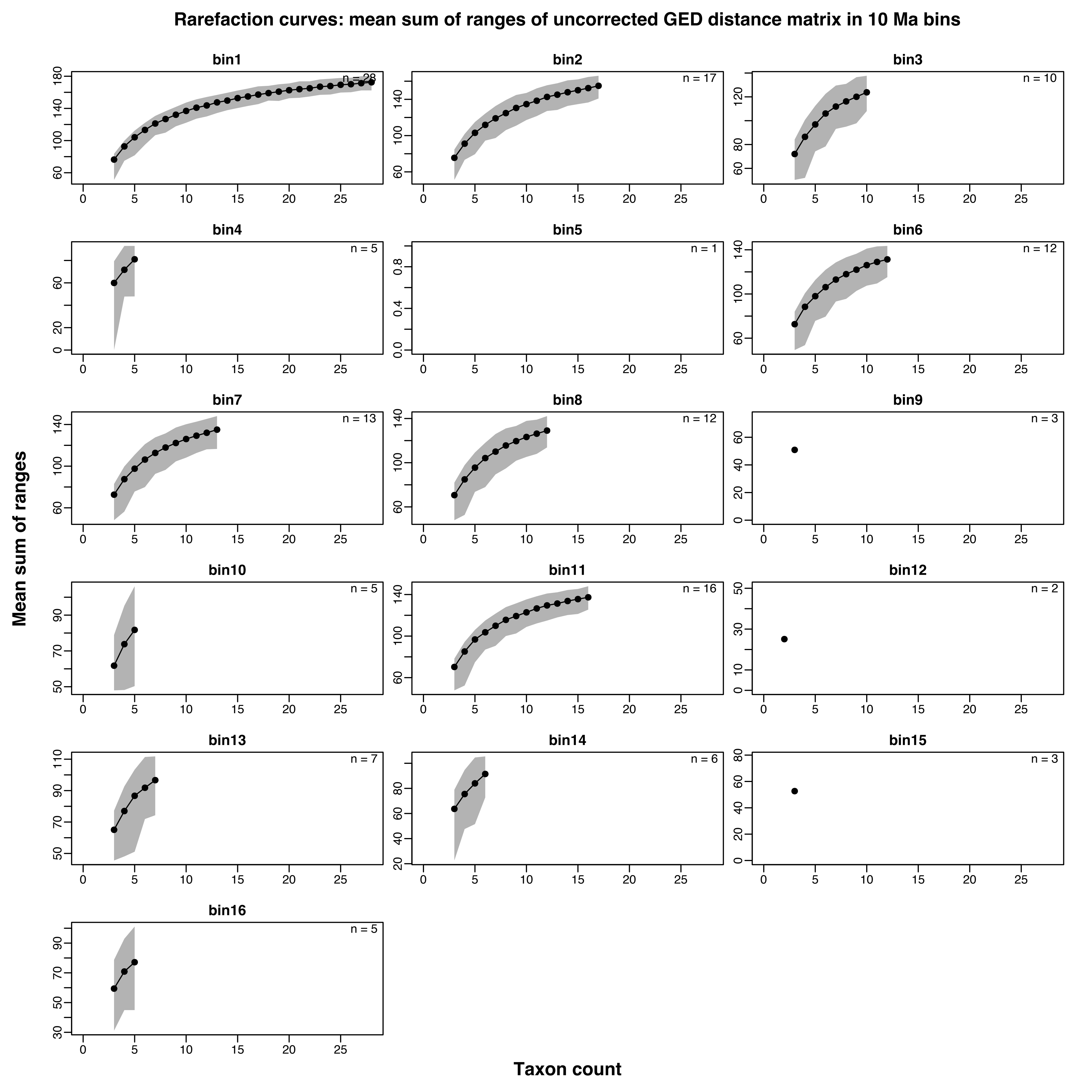


Rarefaction curves: mean sum of ranges of Caillez-corrected GOW distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of ranges
Taxon count

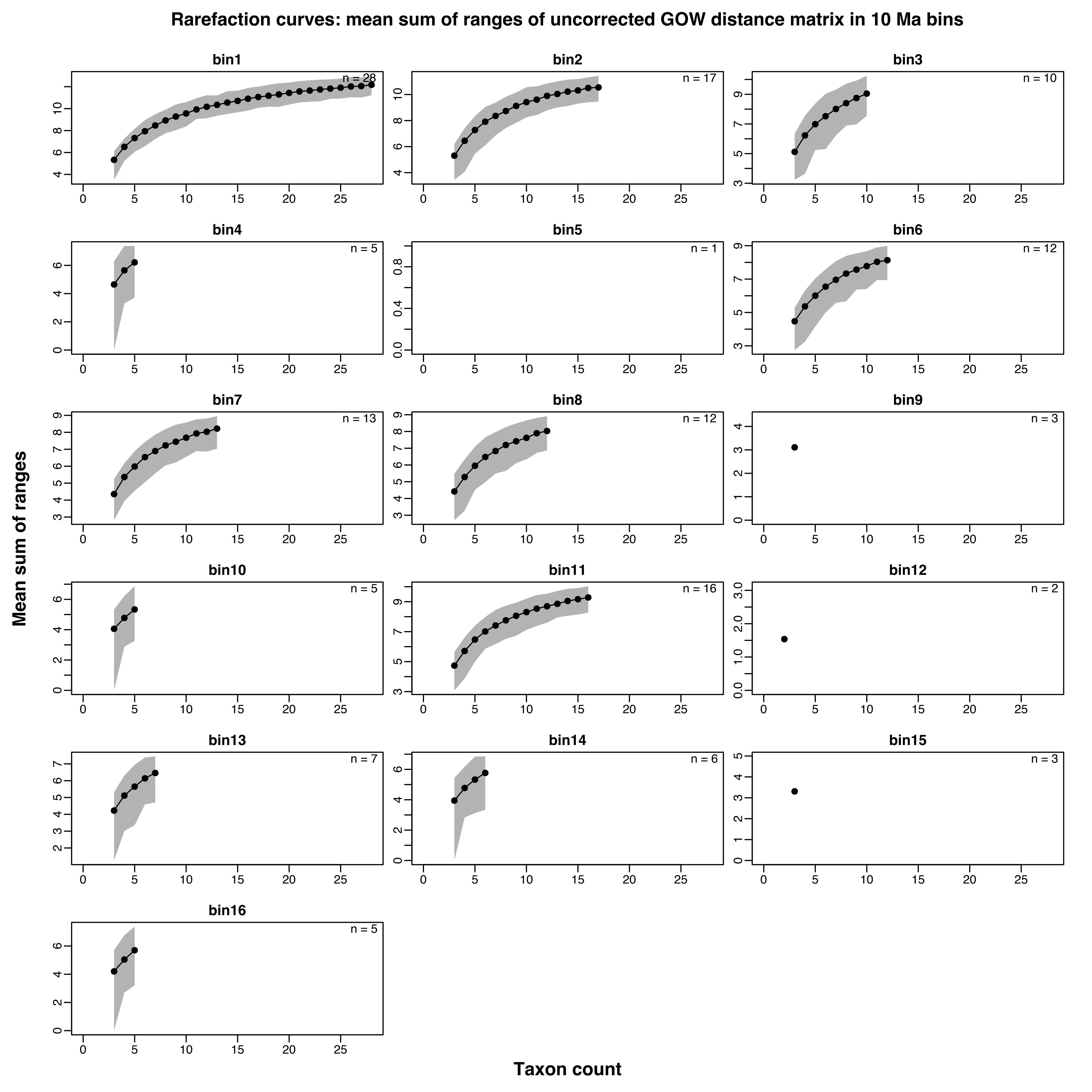

Rarefaction curves: mean sum of ranges of Caillez-corrected MAX distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean sum of ranges
Taxon count

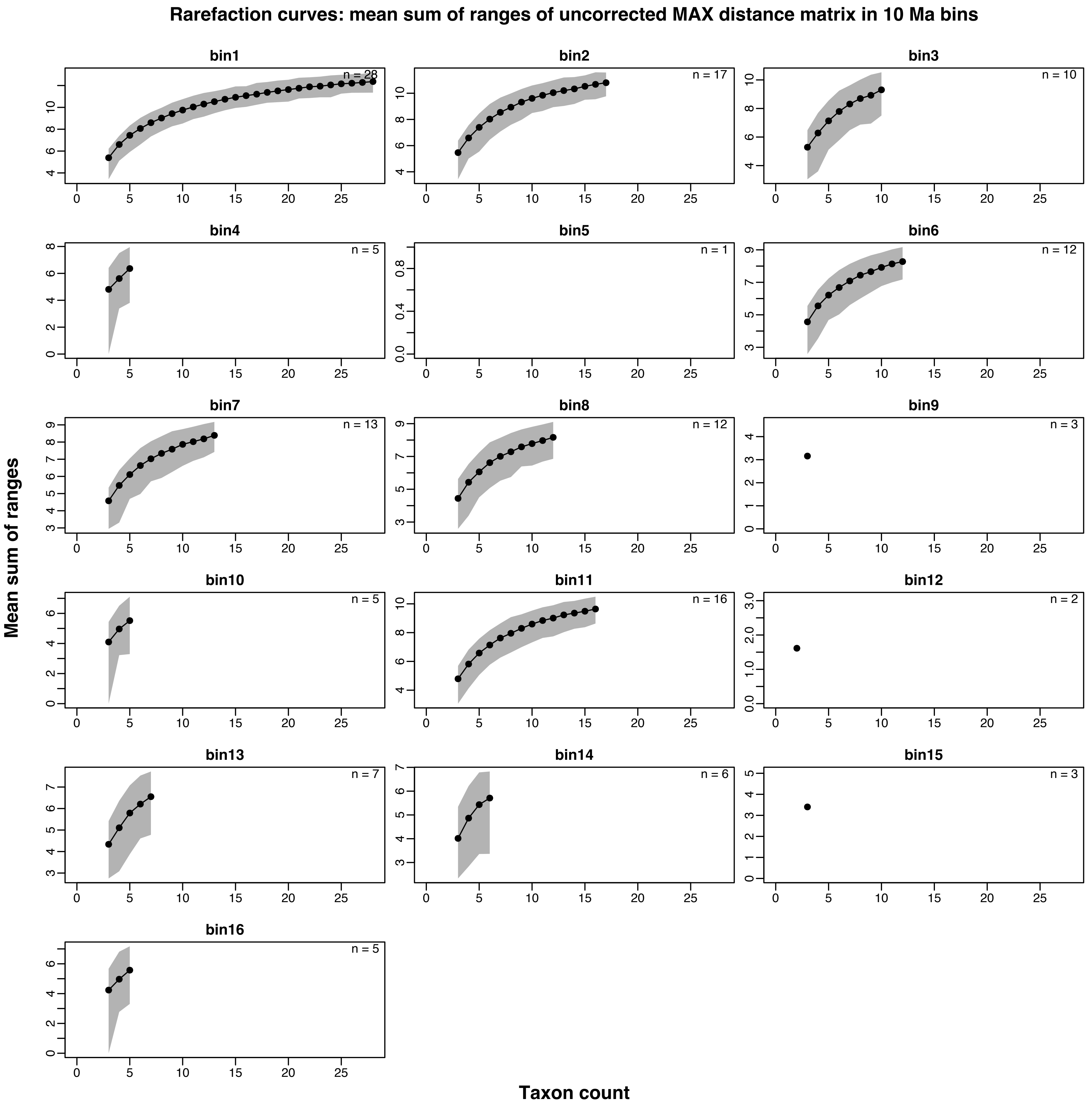


Rarefaction curves: mean sum of ranges of uncorrected RAW distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean sum of ranges
Taxon count

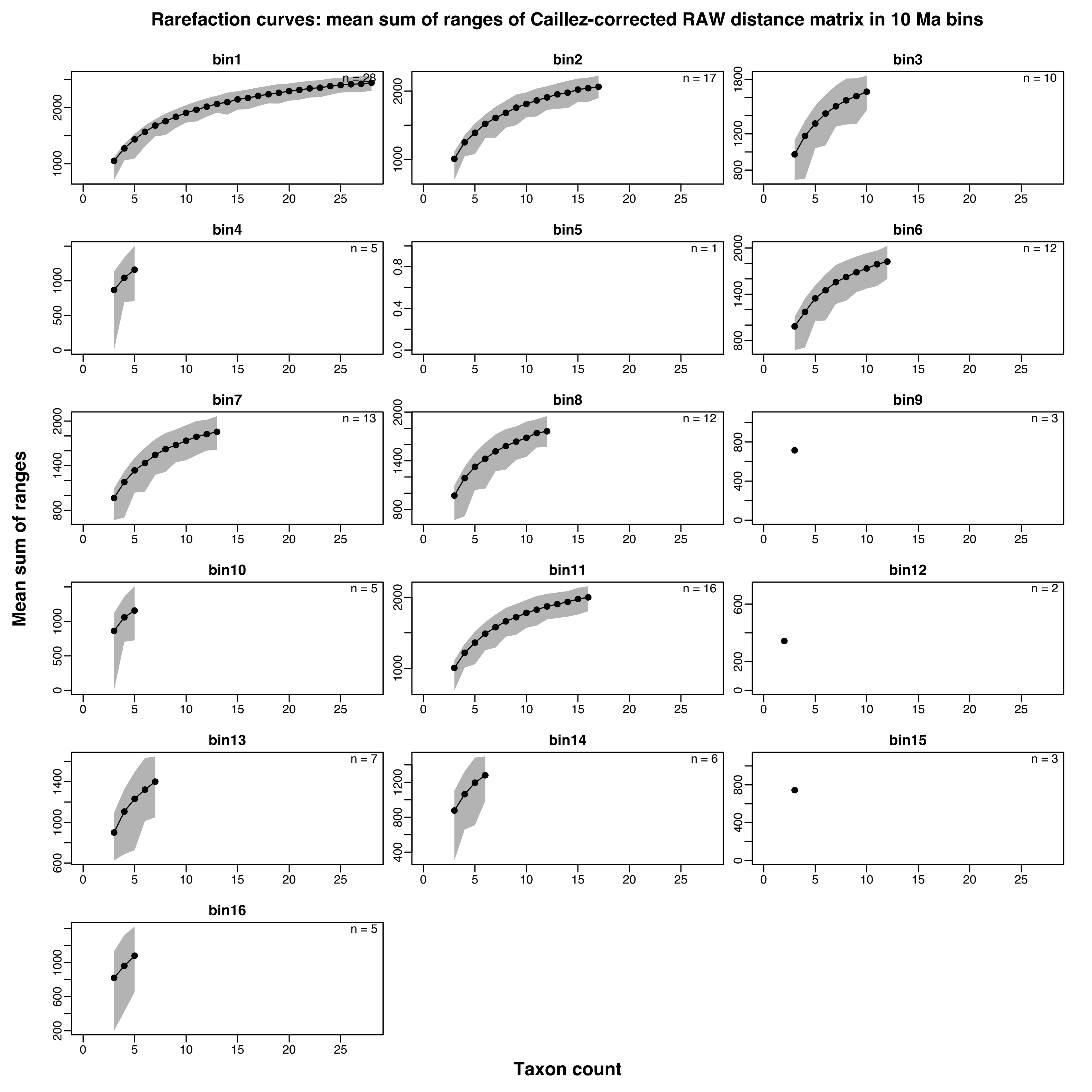


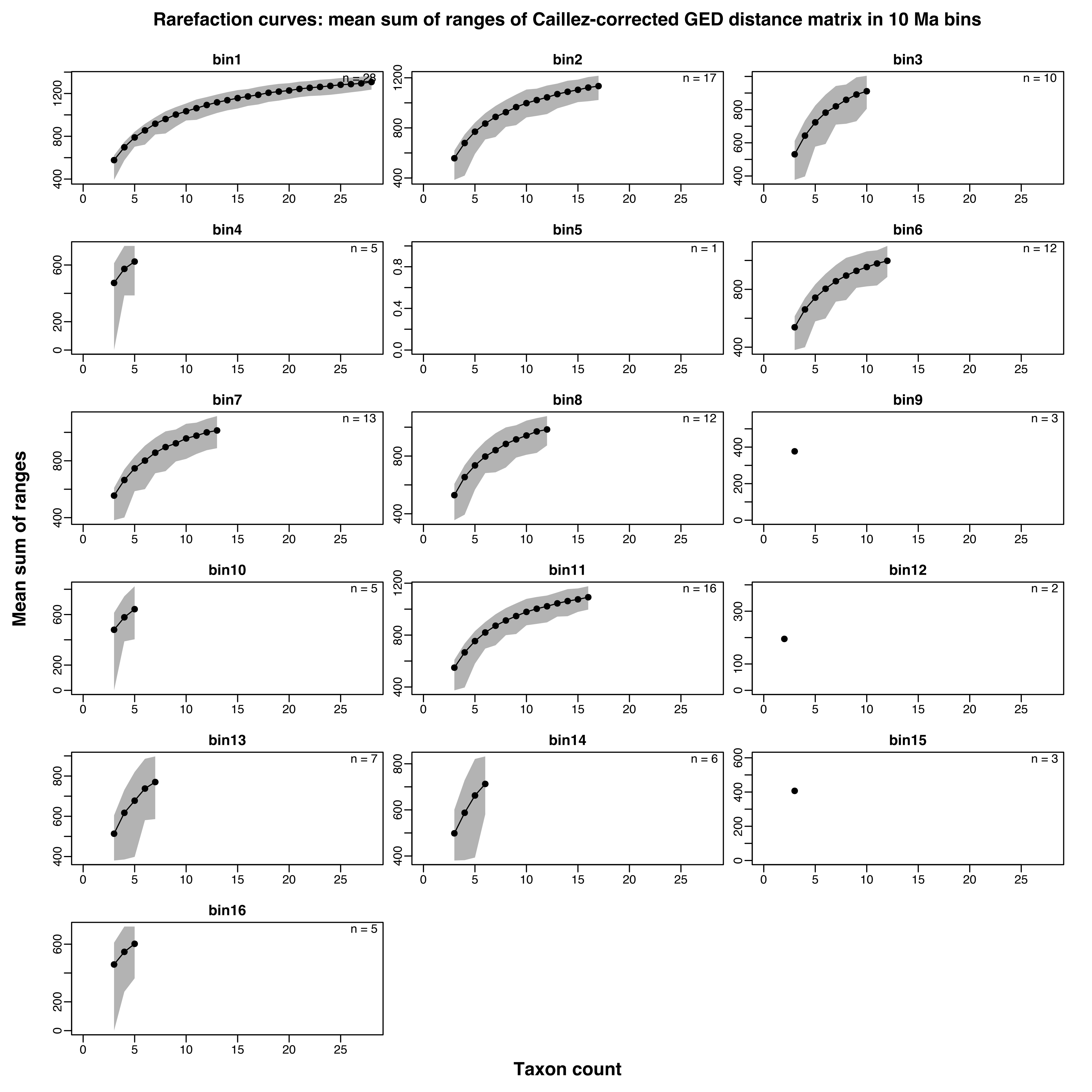
Rarefaction curves: mean sum of ranges of uncorrected GED distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean sum of ranges
Taxon count

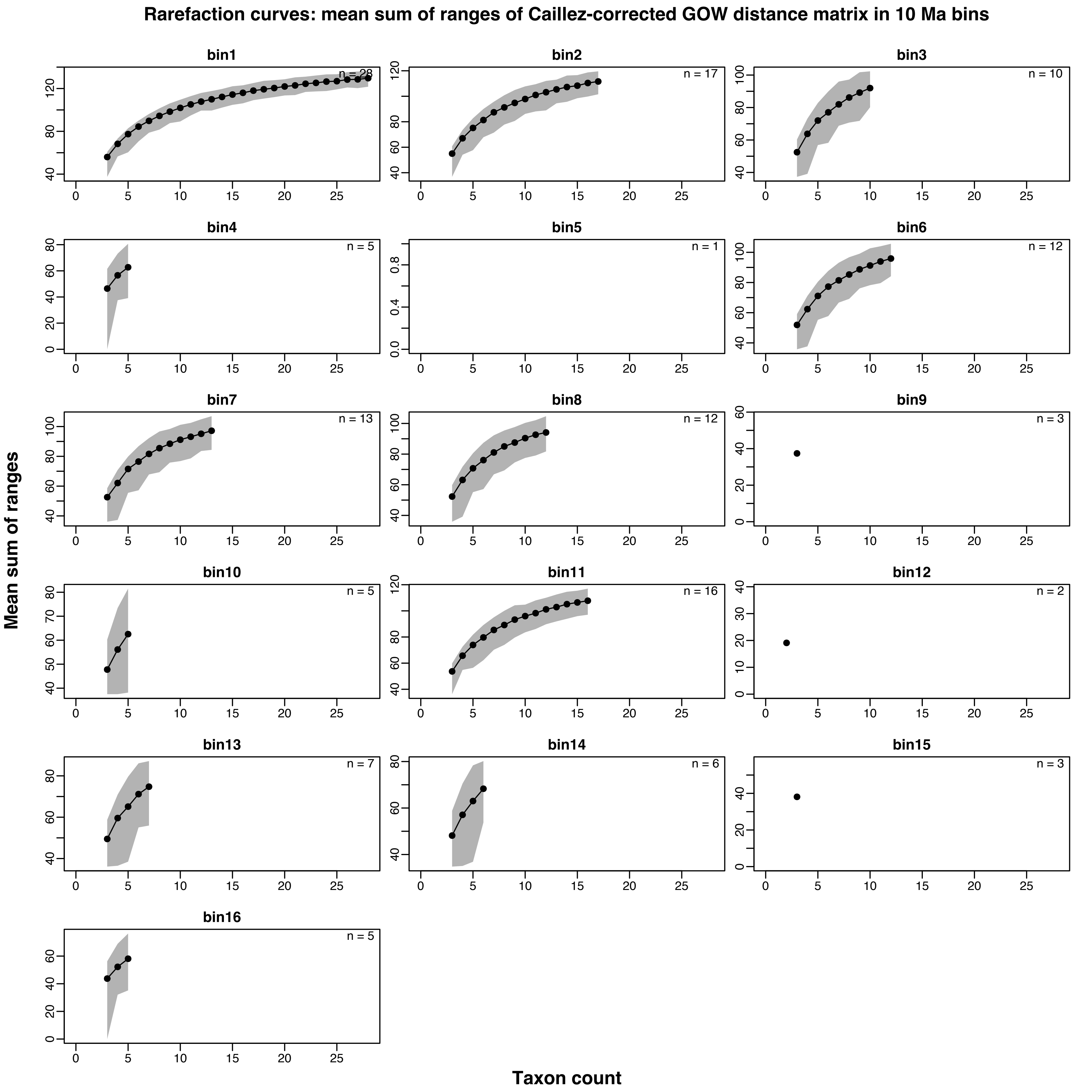

Rarefaction curves: mean sum of ranges of uncorrected GOW distance matrix in 10 Ma bins
Mean sum of ranges
Taxon count
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5

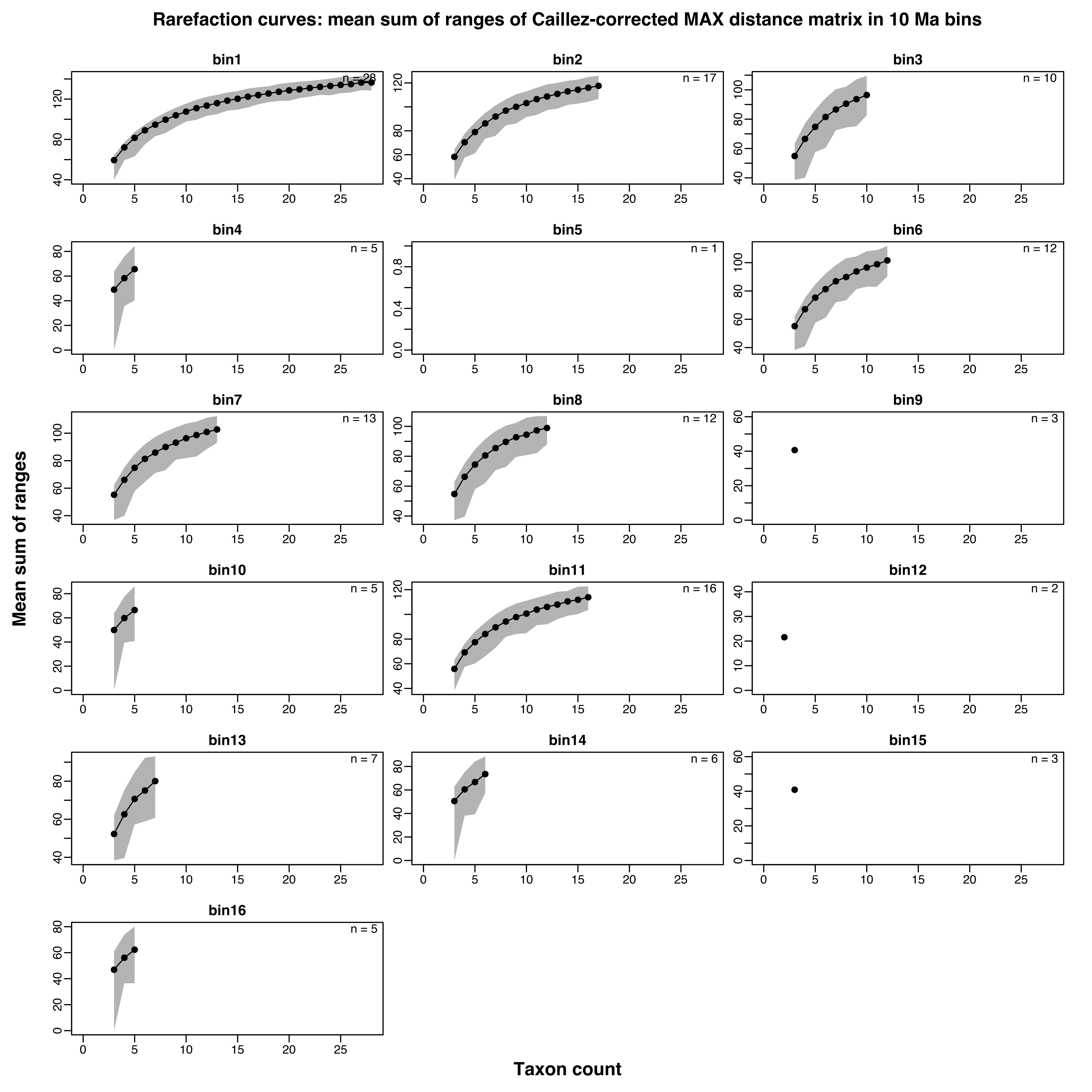


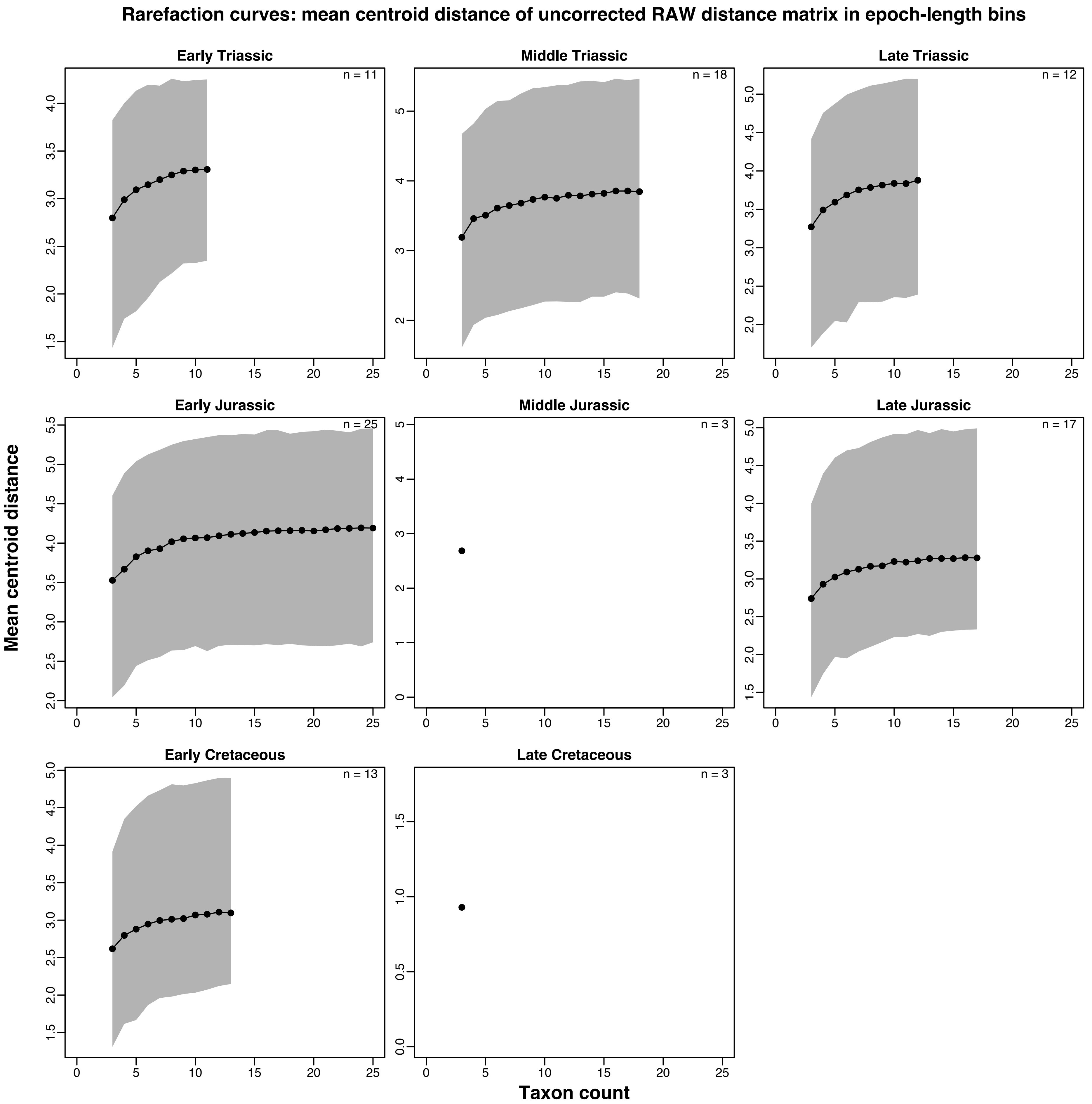
Rarefaction curves: mean sum of ranges of uncorrected MAX distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean sum of ranges
Taxon count


Rarefaction curves: mean sum of ranges of Caillez-corrected RAW distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean sum of ranges
Taxon count

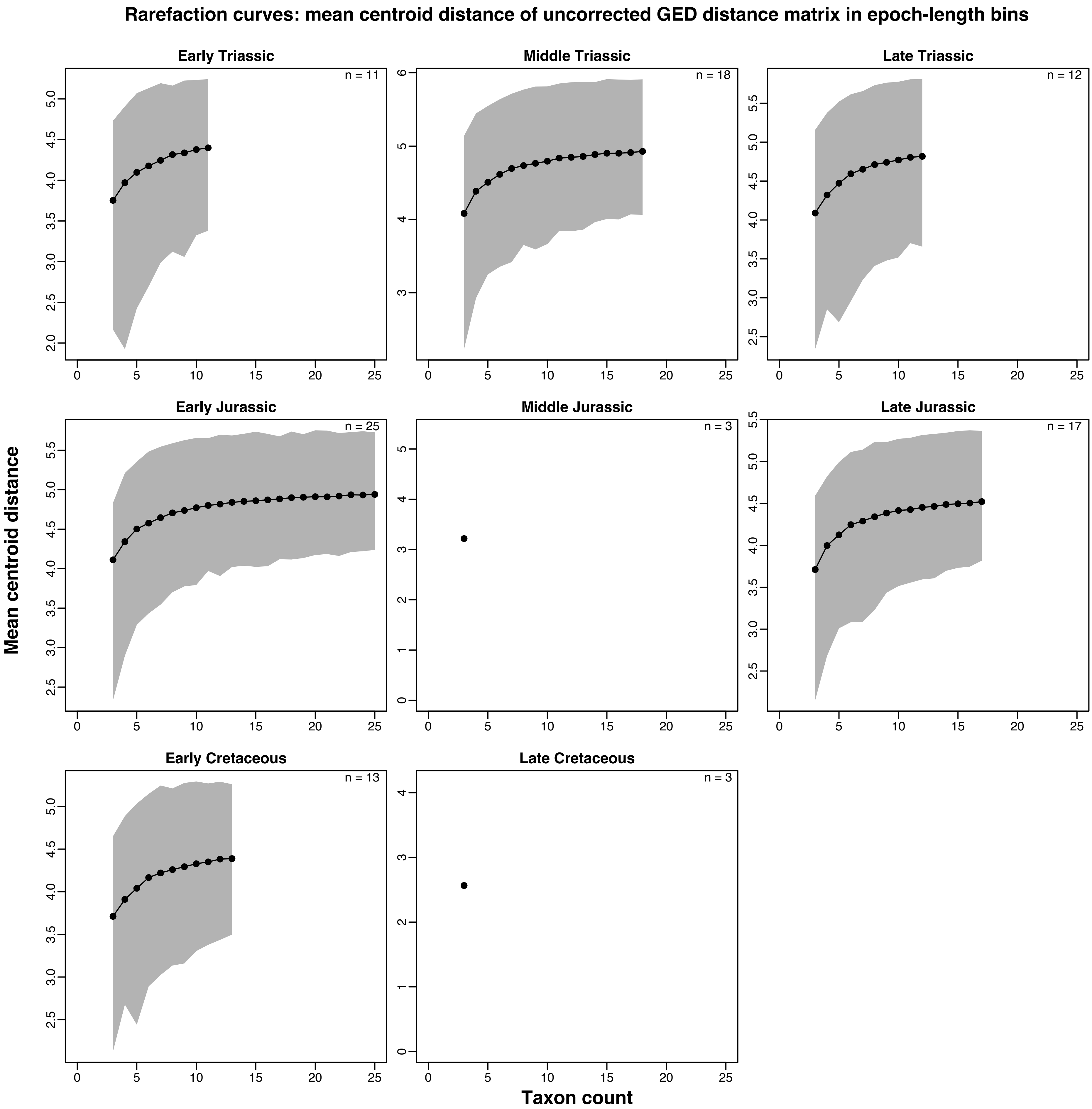

Rarefaction curves: mean sum of ranges of Caillez-corrected GED distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean sum of ranges
Taxon count

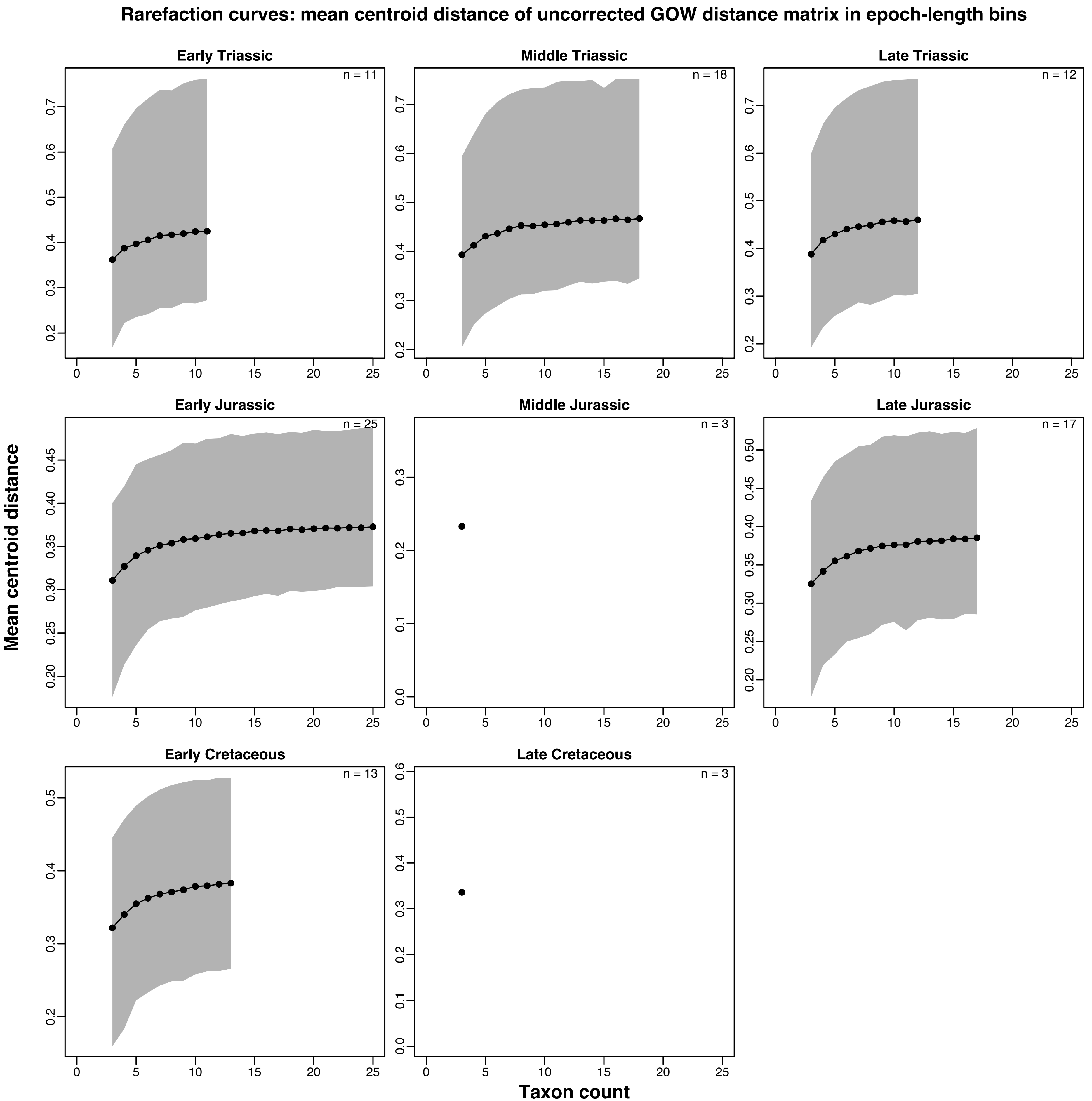

Rarefaction curves: mean sum of ranges of Caillez-corrected GOW distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean sum of ranges
Taxon count

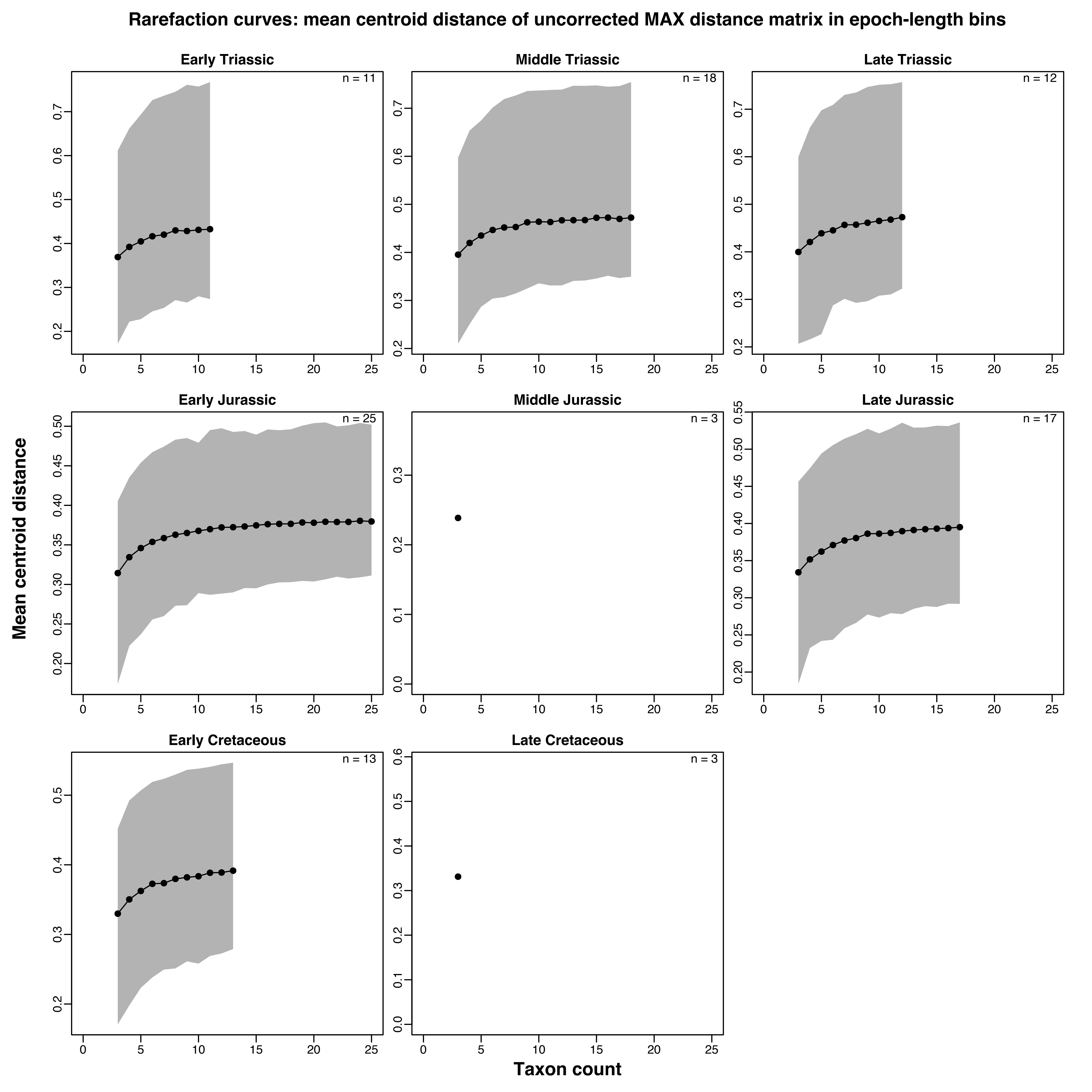

Rarefaction curves: mean sum of ranges of Caillez-corrected MAX distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean sum of ranges
Taxon count



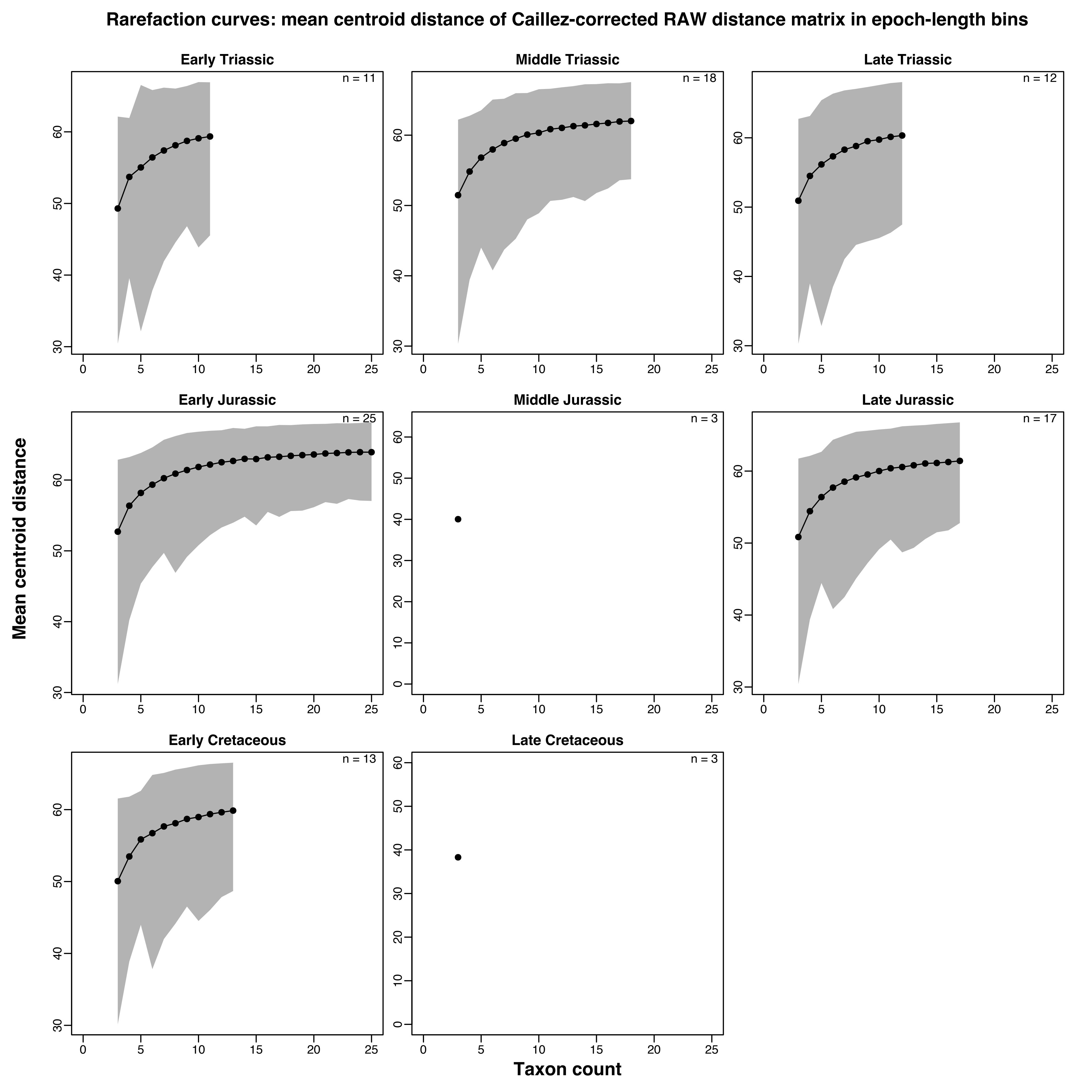
Rarefaction curves: mean centroid distance of uncorrected RAW distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean centroid distance
Taxon count

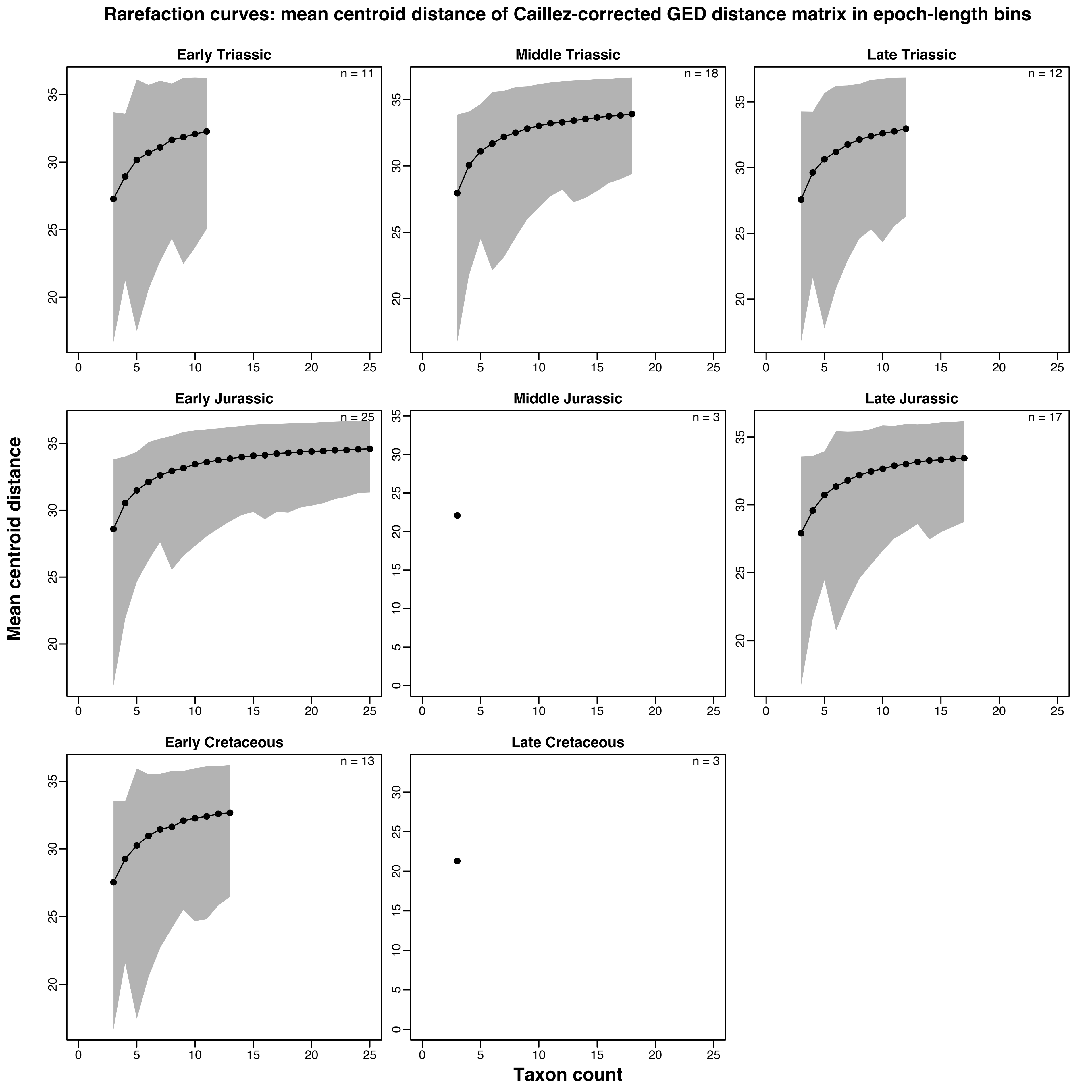

Rarefaction curves: mean centroid distance of uncorrected GED distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean centroid distance
Taxon count

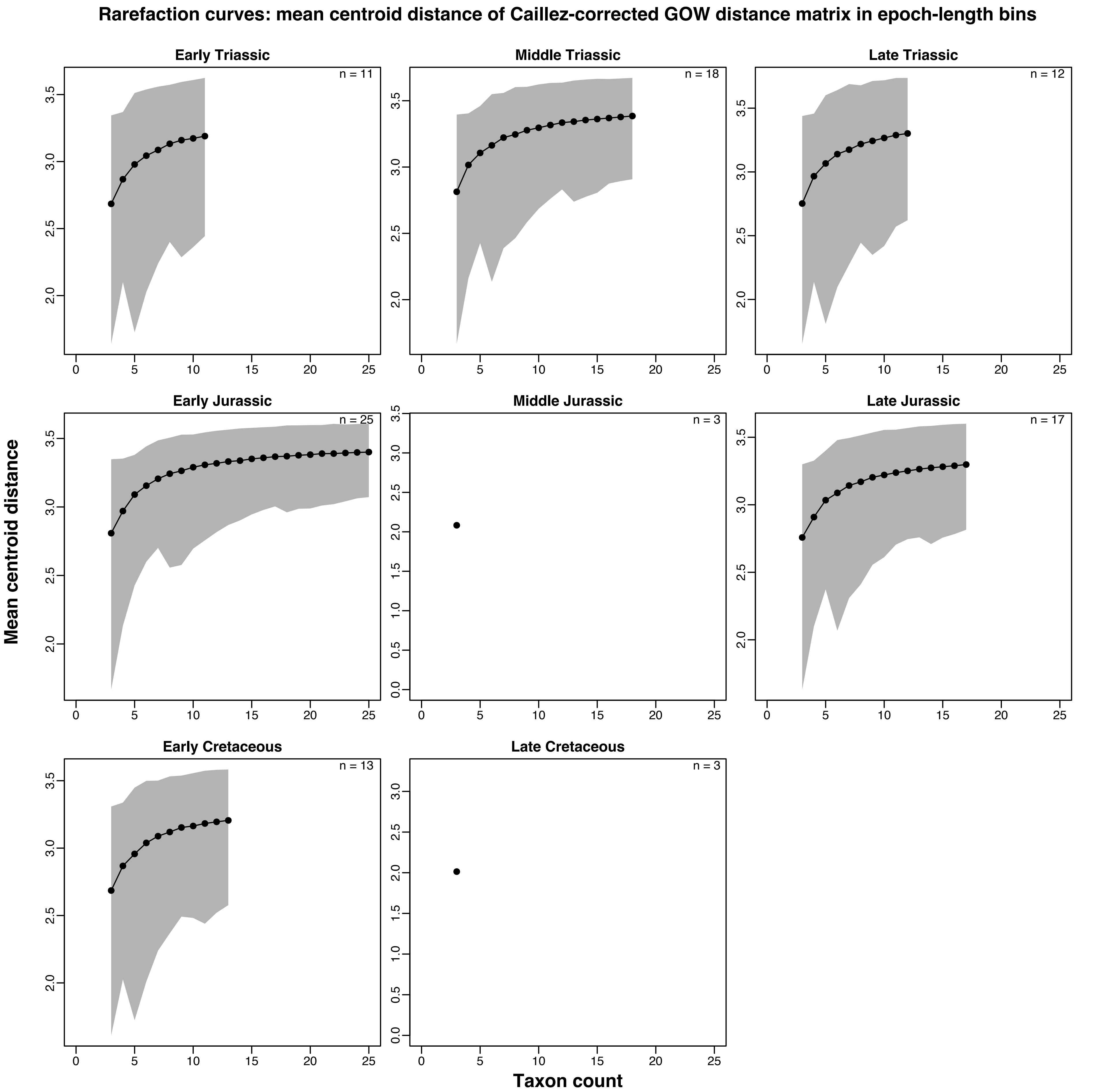

Rarefaction curves: mean centroid distance of uncorrected GOW distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean centroid distance
Taxon count



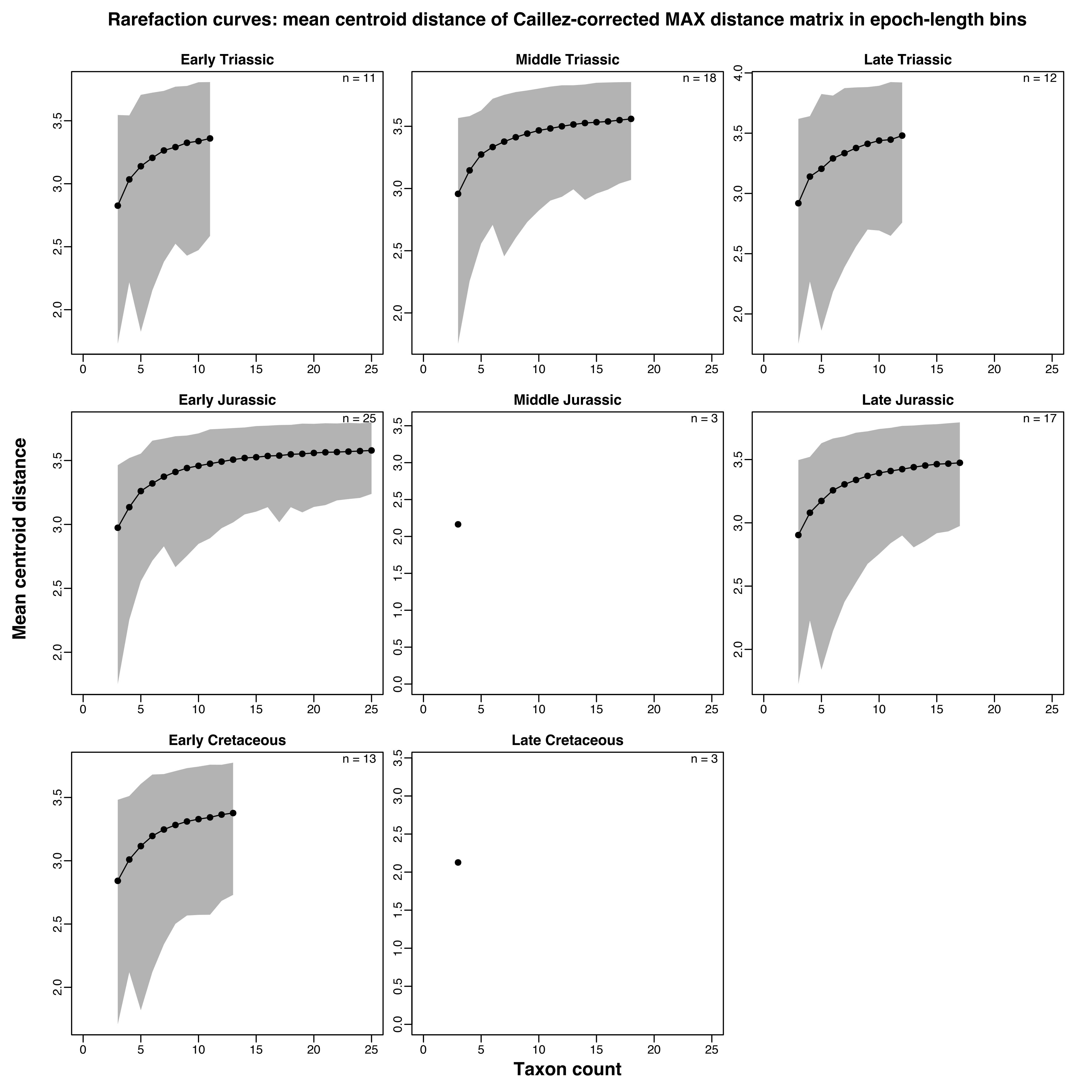
Rarefaction curves: mean centroid distance of uncorrected MAX distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean centroid distance
Taxon count

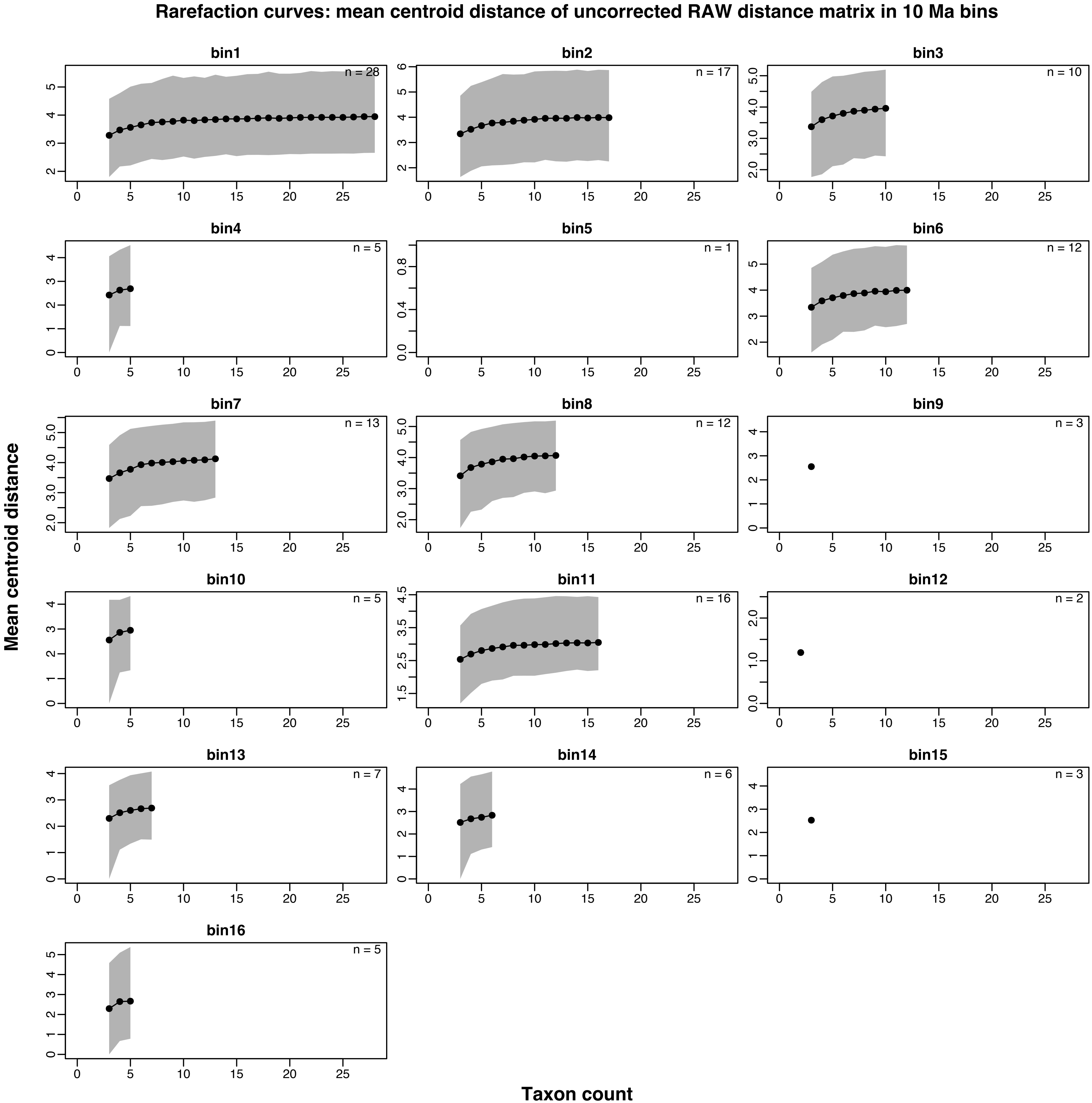

Rarefaction curves: mean centroid distance of Caillez-corrected RAW distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean centroid distance
Taxon count

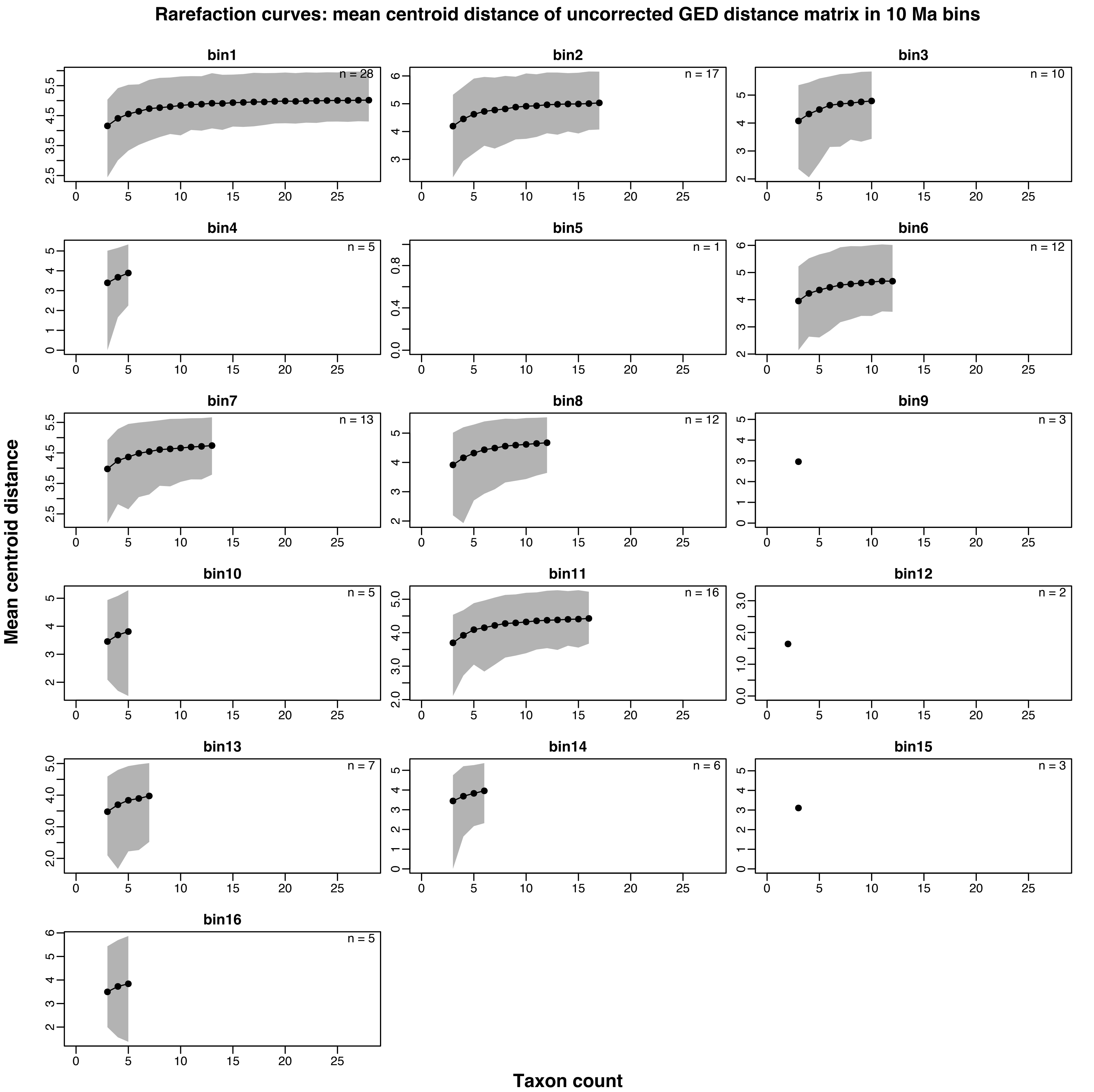

Rarefaction curves: mean centroid distance of Caillez-corrected GED distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean centroid distance
Taxon count



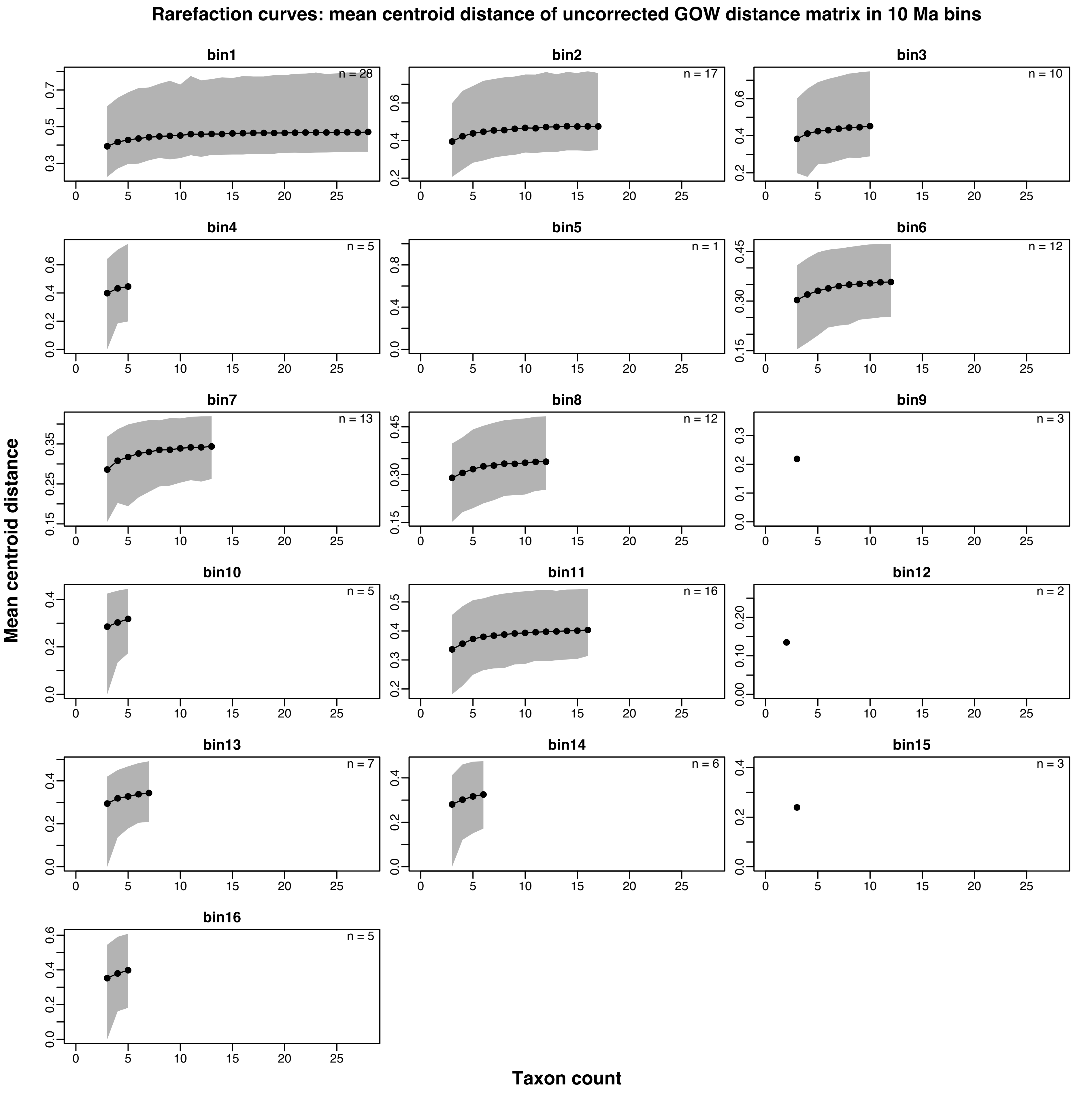
Rarefaction curves: mean centroid distance of Caillez-corrected GOW distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean centroid distance
Taxon count

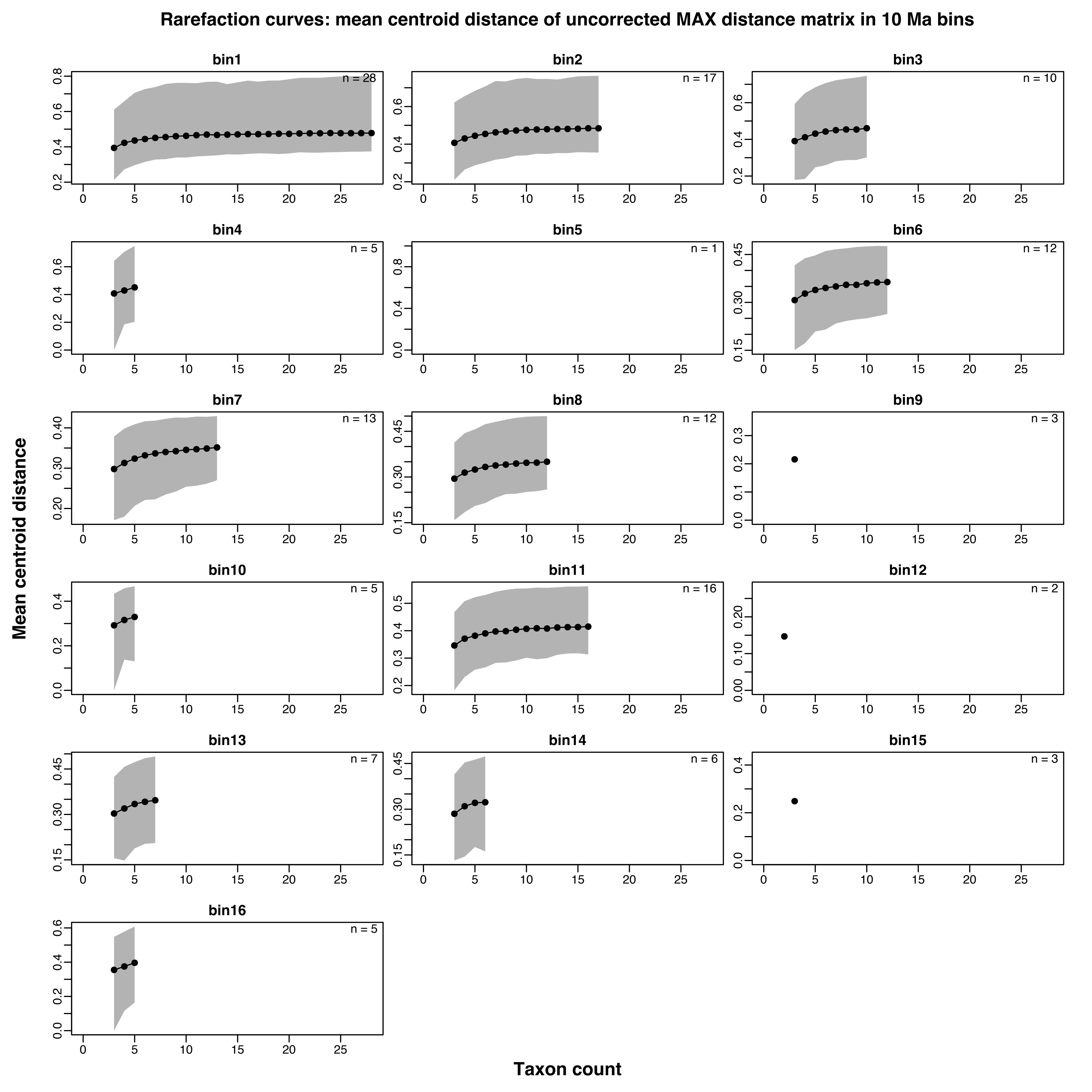

Rarefaction curves: mean centroid distance of Caillez-corrected MAX distance matrix in epoch-length bins
Early Triassic
n = 11
Middle Triassic
n = 18
Late Triassic
n = 12
Early Jurassic
n = 25
Middle Jurassic
n = 3
Late Jurassic
n = 17
Early Cretaceous
n = 13
Late Cretaceous
n = 3
Mean centroid distance
Taxon count


Rarefaction curves: mean centroid distance of uncorrected RAW distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean centroid distance
Taxon count



Rarefaction curves: mean centroid distance of uncorrected GED distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean centroid distance
Taxon count


Rarefaction curves: mean centroid distance of uncorrected GOW distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean centroid distance
Taxon count


Rarefaction curves: mean centroid distance of uncorrected MAX distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
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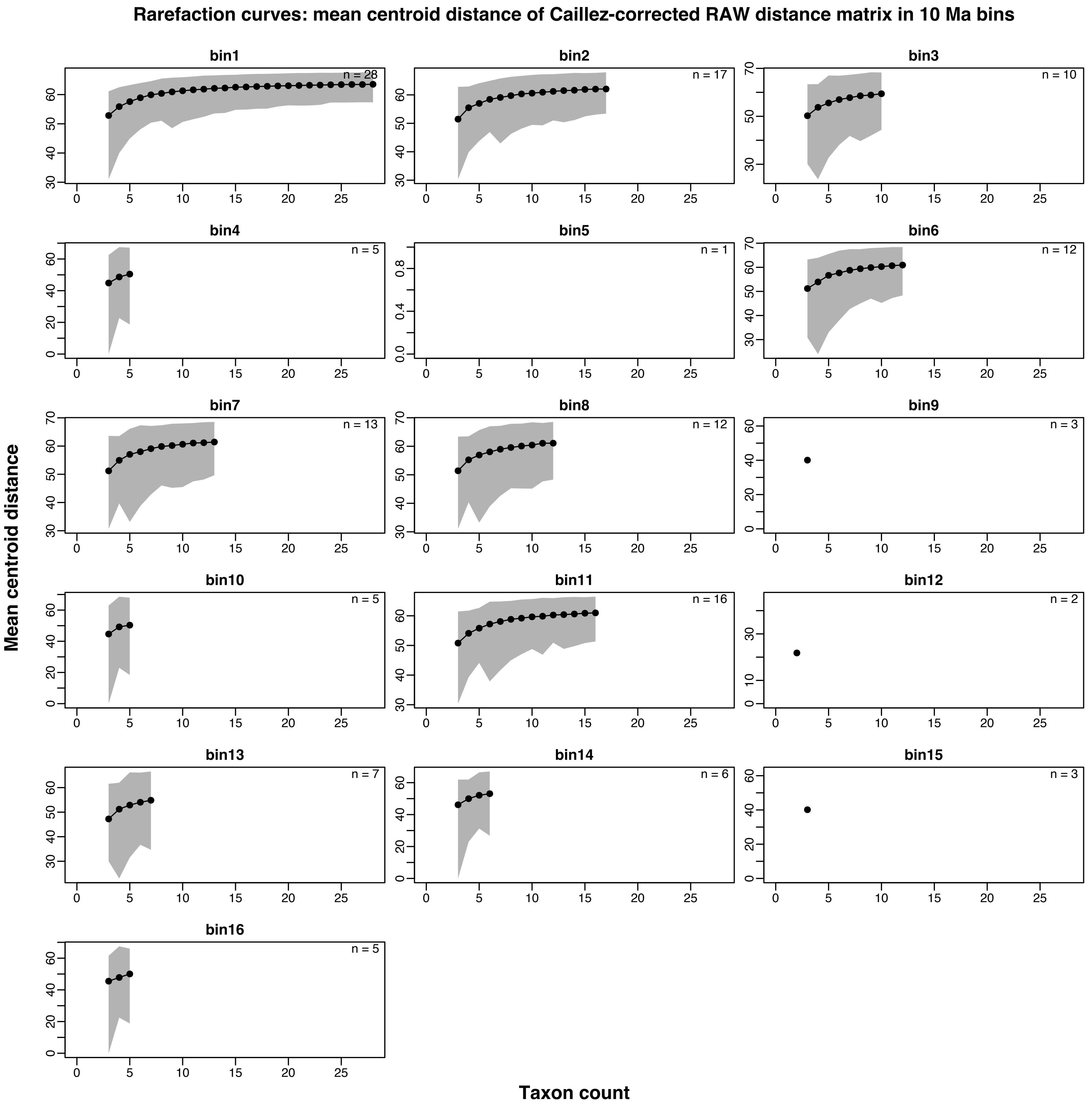
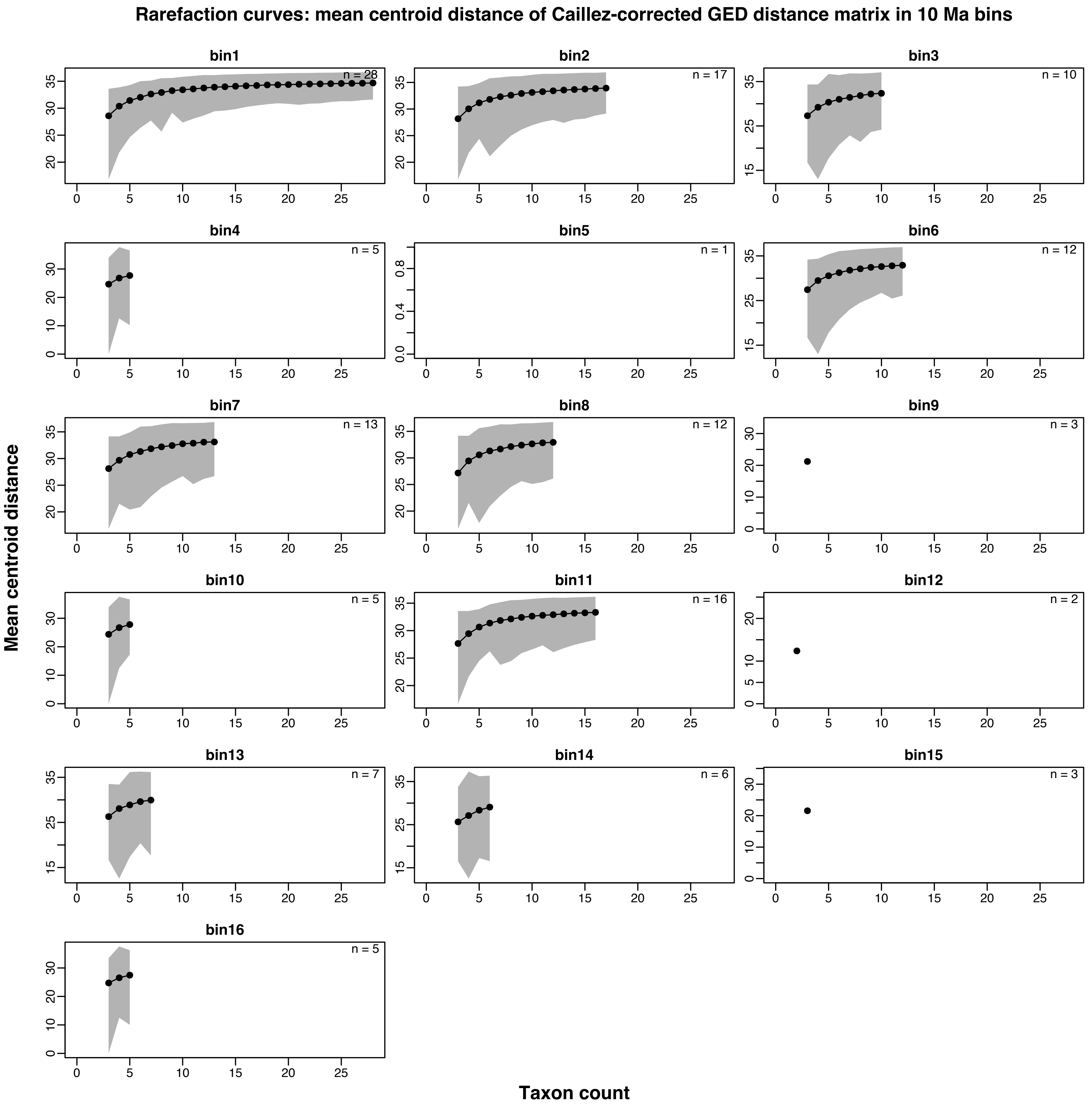
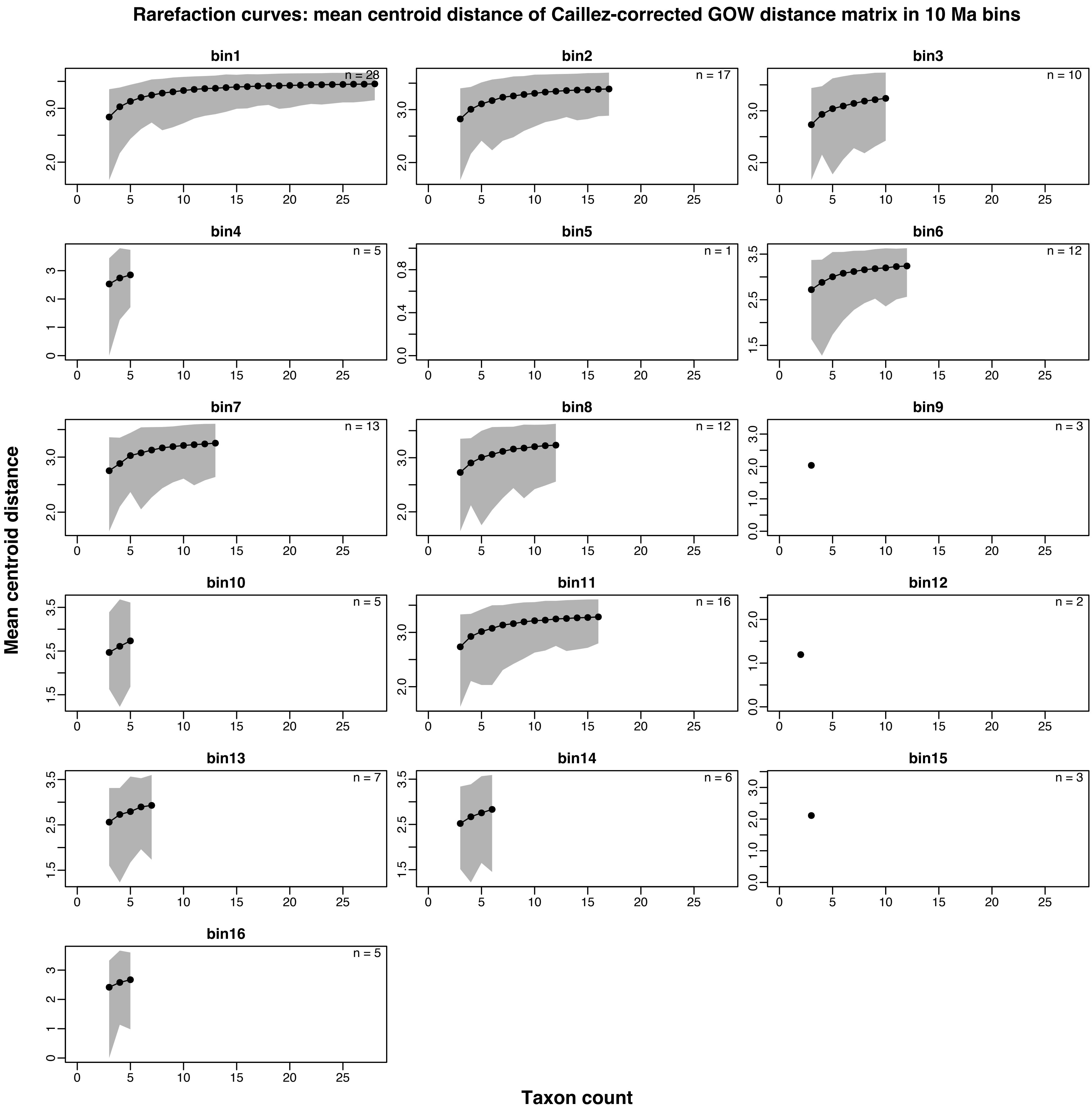
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean centroid distance
Taxon count

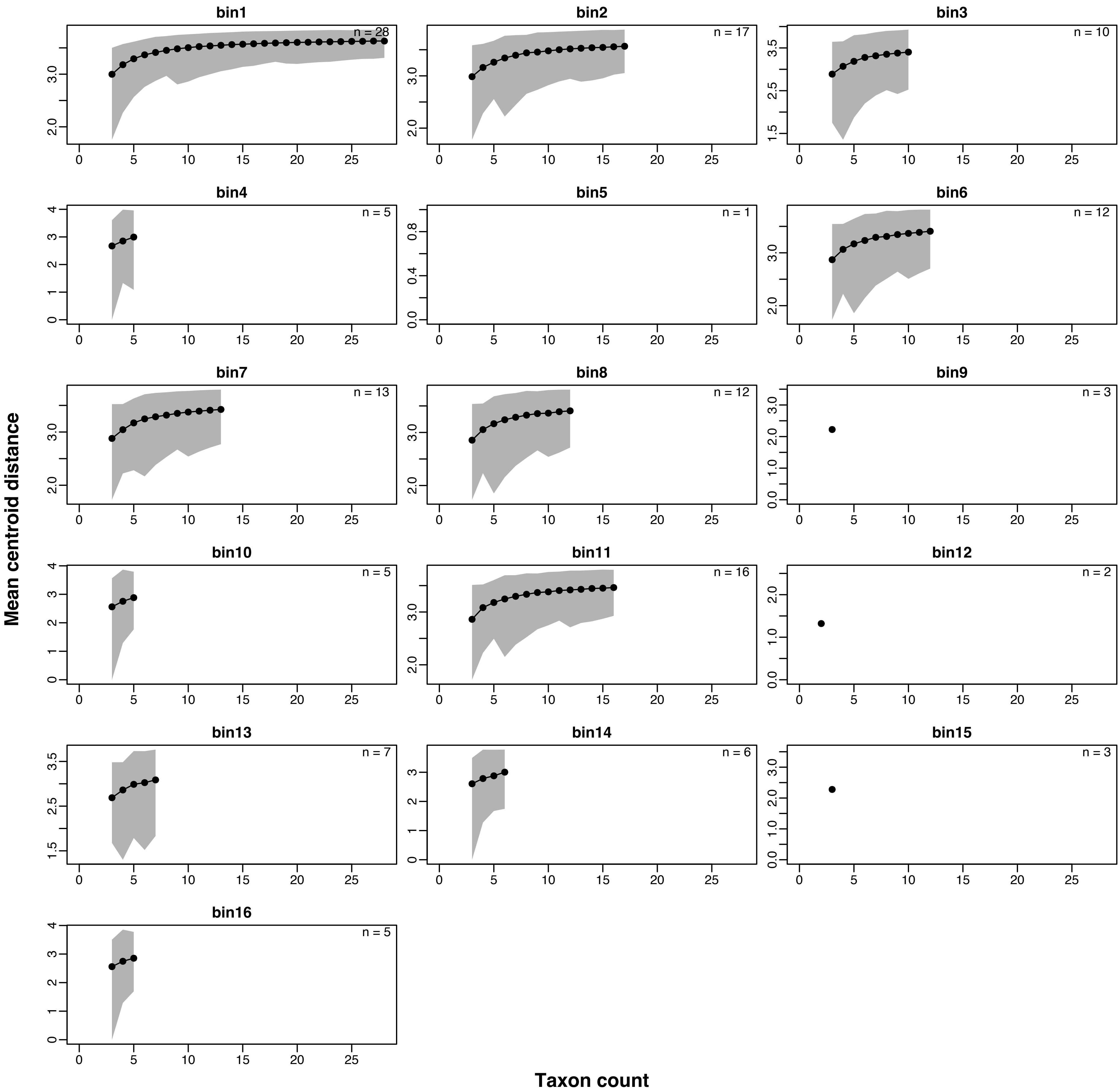

Rarefaction curves: mean centroid distance of Caillez-corrected RAW distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean centroid distance
Taxon count



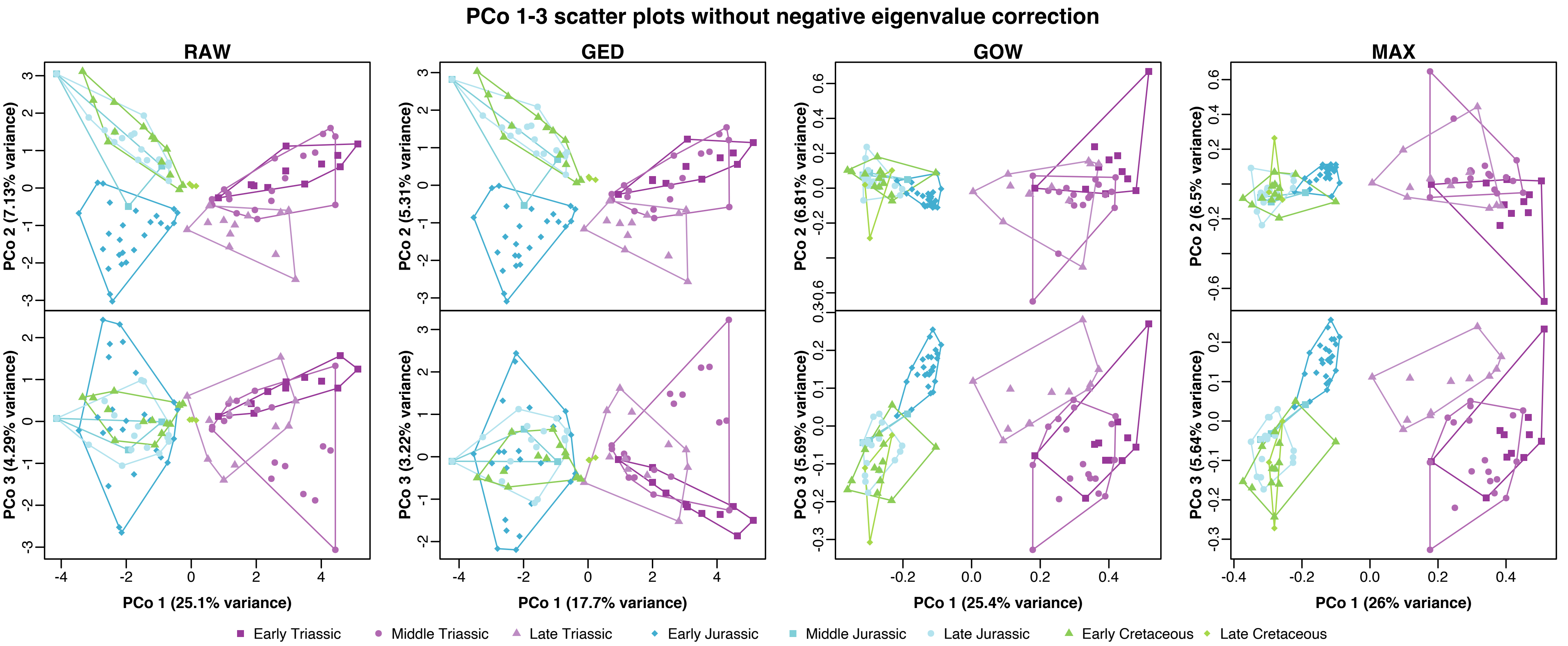
Rarefaction curves: mean centroid distance of Caillez-corrected GED distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean centroid distance
Taxon count


Rarefaction curves: mean centroid distance of Caillez-corrected GOW distance matrix in 10 Ma bins
bin1
n = 28
bin2
n = 17
bin3
n = 10
bin4
n = 5
bin5
n = 1
bin6
n = 12
bin7
n = 13
bin8
n = 12
bin9
n = 3
bin10
n = 5
bin11
n = 16
bin12
n = 2
bin13
n = 7
bin14
n = 6
bin15
n = 3
bin16
n = 5
Mean centroid distance
Taxon count

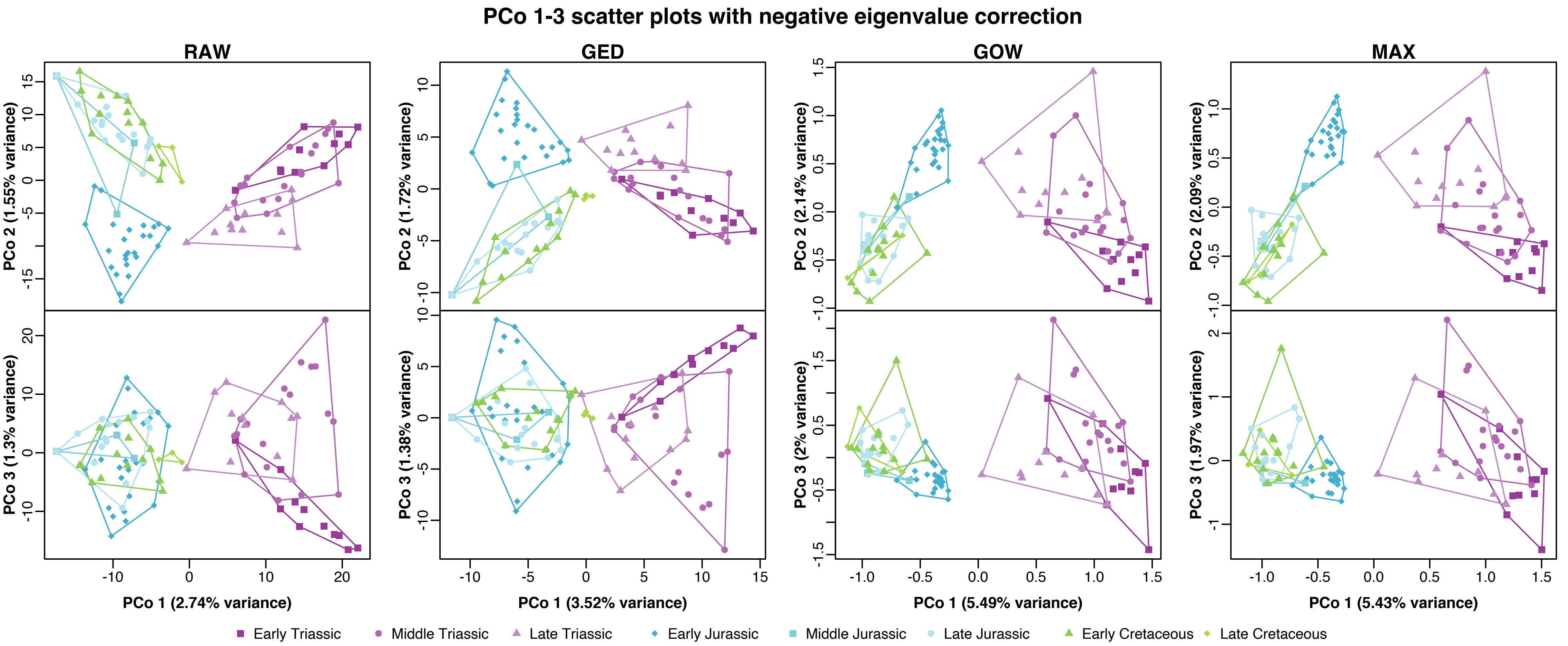
Rarefaction curves: mean centroid distance of Caillez-corrected MAX distance matrix in 10 Ma bins



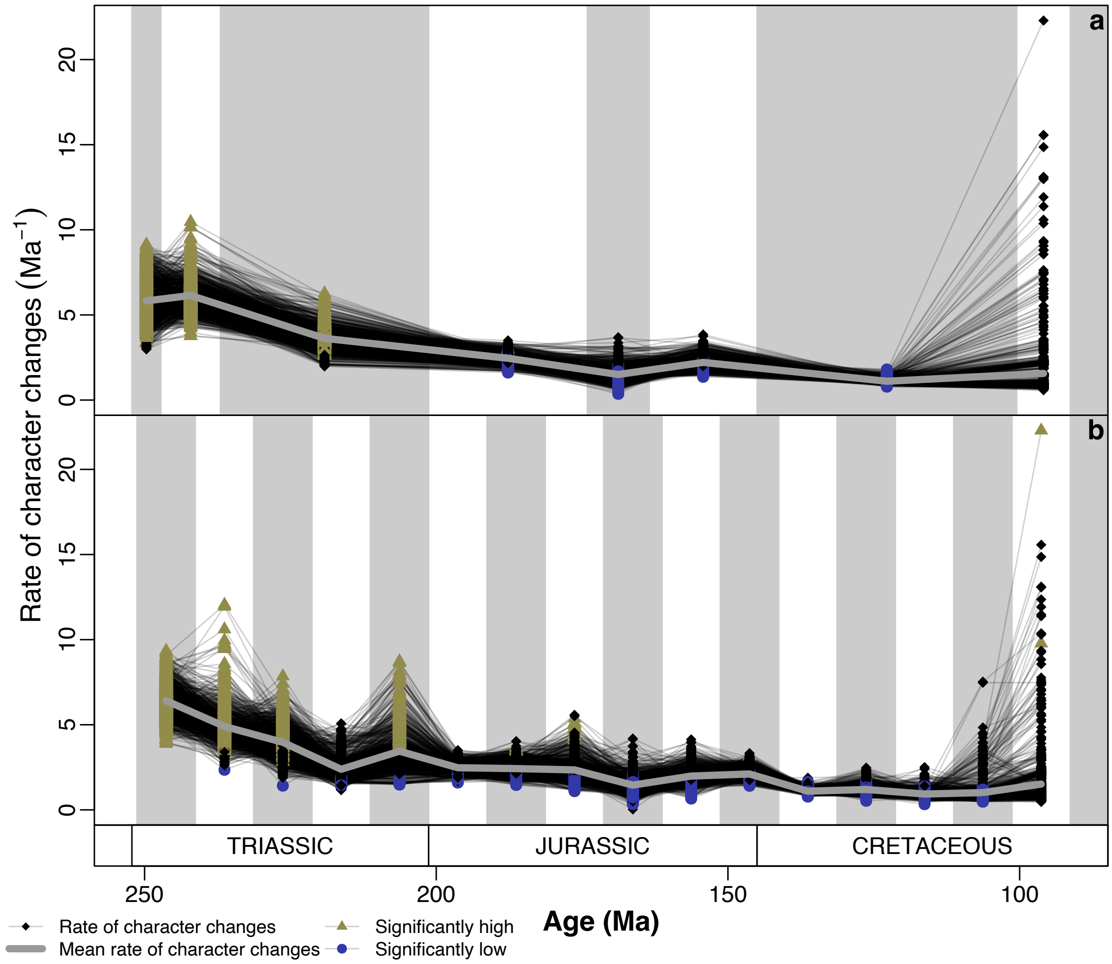
Supplementary figure 6. (following pages) **Morphospace occupation of Ichthyosauriformes through the Mesozoic.** Principal coordinate axis 1 against axes 2 (top row) and 3 (bottom row) from each of eight PCA (four distance matrices: RAW, GED, GOW, MAX; with and without negative eigenvalue correction) on the cladistic matrix of Moon [1] binned into epochs.



PCo 1-3 scatter plots without negative eigenvalue correction
RAW
GED
GOW
MAX
PCo 2 (7.13% variance)
PCo 3 (4.29% variance)
PCo 1 (25.1% variance)
PCo 2 (5.31% variance)
PCo 3 (3.22% variance)
PCo 1 (17.7% variance)
PCo 2 (6.81% variance)
PCo 3 (5.69% variance)
PCo 1 (25.4% variance)
PCo 2 (6.5% variance)
PCo 3 (5.64% variance)
PCo 1 (26% variance)
Early Triassic
Middle Triassic
Late Triassic
Early Jurassic
Middle Jurassic
Late Jurassic
Early Cretaceous
Late Cretaceous



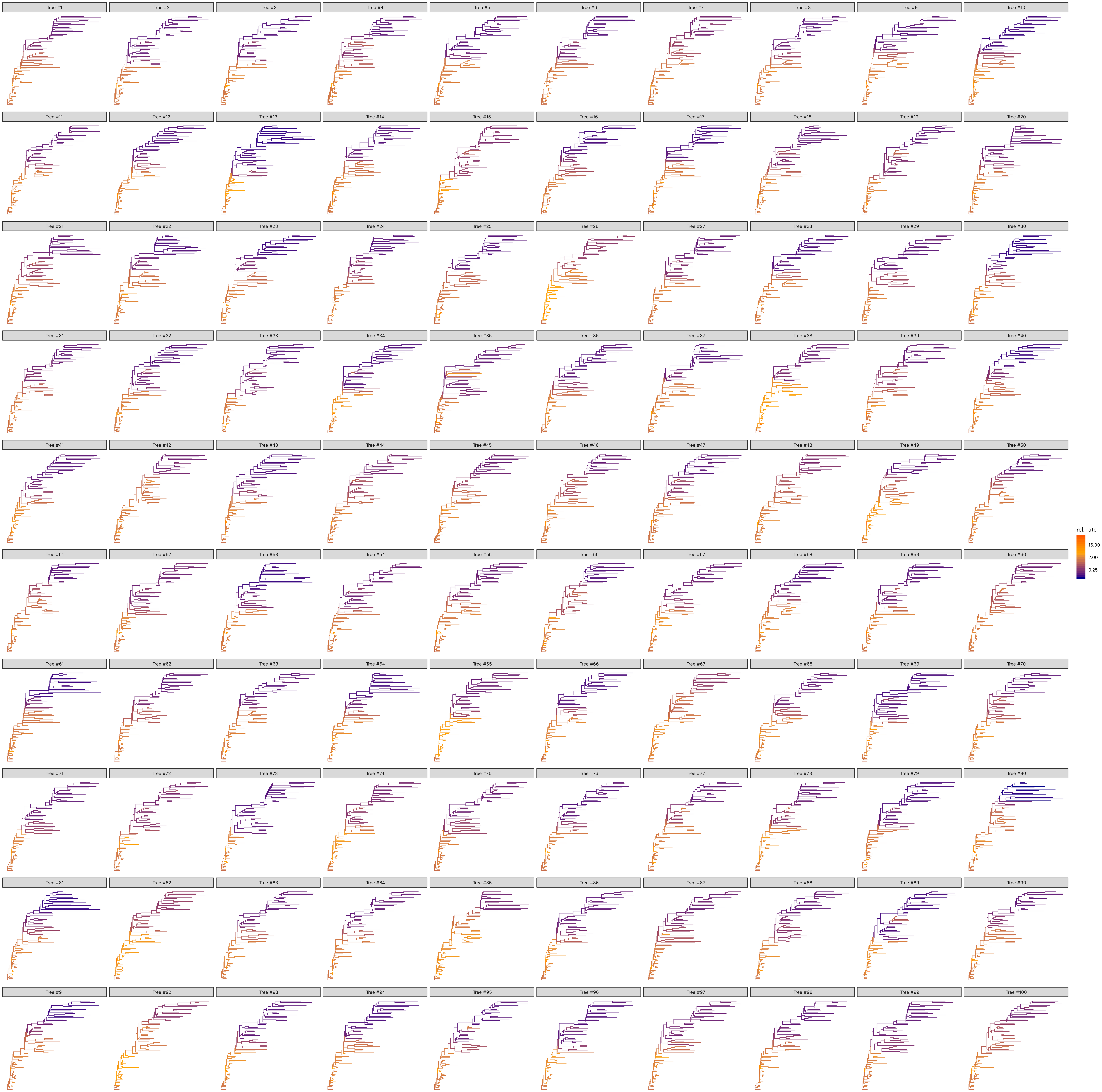
PCo 1-3 scatter plots with negative eigenvalue correction
RAW
GED
GOW
MAX
PCo 2 (1.55% variance)
PCo 3 (1.3% variance)
PCo 1 (2.74% variance)
PCo 2 (1.72% variance)
PCo 3 (1.38% variance)
PCo 1 (3.52% variance)
PCo 2 (2.14% variance)
PCo 3 (2% variance)
PCo 1 (5.49% variance)
PCo 2 (2.09% variance)
PCo 3 (1.97% variance)
PCo 1 (5.43% variance)
Early Triassic
Middle Triassic
Late Triassic
Early Jurassic
Middle Jurassic
Late Jurassic
Early Cretaceous
Late Cretaceous



Supplementary figure 7. **Rates of discrete skeletal character evolution in Ichthyosauriformes.** Calculated from the matrix of Moon [1] using 1000 time-scaled trees from the minimum branch length method. Rates of evolution are plotted in **a**, epoch-bins and **b**, equal-length 10-million-year bins.

Supplementary figure 8. (following page) **Rates of skull size evolution in Ichthyosauriformes.** Evolutionary rate results from 100 Hedman-dated phylogenies. Branches are scaled and branches and taxon names coloured to the rate of skull size change on that branch.

ichthyosaur BayesTraits trees



Supplementary tables

Supplementary table 1. **Bin boundaries of 10 Ma bins used in this study.** Approximate age ranges are given as indicators.

Bin	Start (Ma)	End (Ma)	Approximate age range
1	251.3	241.3	Olenekian–Ladinian
2	241.3	231.3	Ladinian–Carnian
3	231.3	221.3	Carnian–Norian
4	221.3	211.3	Norian
5	211.3	201.3	Norian–Rhaetian
6	201.3	191.3	Hettangian–Sinemurian
7	191.3	181.3	Sinemurian–Toarcian
8	181.3	171.3	Toarcian–Aalenian
9	171.3	161.3	Aalenian–Oxfordian
10	161.3	151.3	Oxfordian–Tithonian
11	151.3	141.3	Tithonian–Berriasian
12	141.3	131.3	Berriasian–Hauterivian
13	131.3	121.3	Hauterivian–Aptian
14	121.3	111.3	Aptian–Albian
15	111.3	101.3	Albian
16	101.3	91.3	Albian–Turonian

Supplementary table 2. **Occurrence dates of outgroup taxa used to date the tree of Ichthyosauriformes.** Stratigraphic occurrence intervals are taken from the given references. Occurrences are converted to absolute ages using Gradstein *et al.* [2]. FAD, first appearance date; FAS, first appearance stratigraphy; LAD, last appearance date; LAS, last appearance stratigraphy.

Taxon	FAD (Ma)	LAD (Ma)	FAS	LAS	Reference
Petrolacosaurus	307.0	298.9	Upper Pennsylvanian	Upper Pennsylvanian	[3, 4]
Hovasaurus	259.8	251.2	Upper Permian	Induan	[5]
Claudiosaurus	253.2	252.17	Late Changsinghian	Late Changinghian	[6]
Thadeosaurus	254.14	252.17	Changsinghian	Changsinghian	[6]
Milleretta	253.2	252.5	Changsinghian	Changsinghian	[7]
Broomia	265.1	260.5	Capitanian	Capitanian	[7]
Mesosaurus	290.1	286	Early Artinskian	Early Artinskian	[7]
Captorhinus	280	270.6	Leonardian	Leonardian	[8]

Supplementary table 3. **Occurrence stratigraphy and dates of Ichthyosauriformes included in the analyses.** Stratographical occurrences are given to the nearest ammonite or conodont biozone horizon where possible. Occurrences are converted to absolute ages using Gradstein *et al.* [2]. FAD, first appearance date; LAD, last appearance date.

Taxon	FAD stratigraphy	LAD stratigraphy	FAD (Ma)	LAD (Ma)	References
Acamptonectes densus	D2D horizon, Speeton Clay Formation, basal Hauterivian	*Simbiskites concinnus/staffi* Biozone, upper Hauterivian, Lower Cretaceous	132.9	129.4	[9]
Aegirosaurus leptospondylus	Malm Zeta2b, early lower Tithonian, Upper Jurassic	Malm Zeta2b, early lower Tithonian, Upper Jurassic	153.96	149.87	[10]
Arthropterygius chrisorum	Oxfordian, Upper Jurassic	Kimmeridgian, Upper Jurassic	163.47	152.06	[11]
Athabascasaurus bitumineus	Lower Albian, Lower Cretaceous	Lower Albian, Lower Cretaceous	113	111.5	[12]
Barracudasauroides panxianensis	*Nicoraella germanicus* Conodont Biozone, Anisian, Middle Triassic	*Nicoraella germanicus* Conodont Biozone, Anisian, Middle Triassic	244.94	243.99	[13]
Besanosaurus leptorhynchus	*Nevadites* Conodont Biozone, uppermost Anisian, Middle Triassic	*Nevadites* Conodont Biozone, uppermost Anisian, Middle Triassic	242.1	241.5	[14]
Brachypterygius extremus	*Pectinatites wheatleyensis* Ammonite Biozone, Tithonian, Upper Jurassic	*Pectinatites hudlestoni* Ammonite Biozone, Tithonian, Upper Jurassic	151	150	[15]
Brachypterygius pseudoscythica	*Ilowaisya pseudoscythica* Ammonite Biozone, Tithonian, Upper Jurassic	*Ilowaisya pseudoscythica* Ammonite Biozone, Tithonian, Upper Jurassic	150.1	149.5	[16]
Californosaurus perrini	*Trachyceras* Beds, Hosselkus Limestone, Carnian	*Trachyceras* Beds, Hosselkus Limestone, Carnian	233.5	228.35	[17, 18]
Callawayia neoscapularis	*Epigondolella triangularis* Conodont Biozone, early Norian, Upper Triassic	*Epigondolella quadrata* Conodont Biozone, early Norian, Upper Triassic	221.5	217.5	[19]
Cartorhynchus lenticarpus	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	247.7	247.2	[20]
Caypullisaurus bonapartei	*Virgatosphinactes mendozanus* Ammonite Biozone, early Tithonian, Upper Jurassic	Berriasian	152.1	139.4	[21]
Chacaicosaurus cayi	*Emileia giebeli* Ammonite Biozone, early Bajocian, Middle Jurassic	*Emileia giebeli* Ammonite Biozone, early Bajocian, Middle Jurassic	170.3	169.45	[22]
Chaohusaurus chaoxianensis	*Procolumbites* Ammonite Biozone, Olenekian, Lower Triassic	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	247.9	247.2	[23, 24]
Chaohusaurus geishanensis	*Procolumbites* Ammonite Biozone, Olenekian, Lower Triassic	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	247.9	247.2	[23, 24]
Chaohusaurus zhangjiawanensis	*Neospathodus homeri* Conodont Biozone, Spathian, Lower Triassic	*Neospathodus triangulus* Conodont Biozone, Spathian, Lower Triassic	247.9	247.2	[25]
Contectopalatus atavus	Pelsonian, Anisian, Middle Triassic	Illyrian, Anisian, Middle Triassic	244.94	241.5	[26]
Cryopterygius kielanae	Middle Volgian, Lower Tithonian, Upper Jurassic	Middle Volgian, Lower Tithonian, Upper Jurassic	149	147	[27]
Cryopterygius kristiansenae	*Dorsoplanites maximus* Ammonite biozone, Tithonian, Upper Jurassic	*Dorsoplanites ilovaiskyi* Ammonite biozone, Tithonian, Upper Jurassic	148.3	147.4	[28]
Cymbospondylus buchseri	Upper Anisian, Middle Triassic	lower Ladinian, Middle Triassic	242.57	240.3	[29]
Cymbospondylus nichollsi	*Kellnerites felsoeoersensis* Ammonite Biozone, Anisian, Middle Triassic	*Kellnerites felsoeoersensis* Ammonite Biozone, Anisian, Middle Triassic	243.99	243.05	[30]

Supplementary table 3 continued

Taxon	FAD stratigraphy	LAD stratigraphy	FAD (Ma)	LAD (Ma)	References
Cymbospondylus petrinus	*Paragondolella* ex gr. *excelsa* Conodont Biozone, Anisian, Middle Triassic	*Paragondolella* ex gr. *excelsa* Conodont Biozone, Anisian, Middle Triassic	243.99	241.5	[18]
Cymbospondylus piscosus	Anisian, Middle Triassic	Anisian, Middle Triassic	247.2	241.5	[18]
Dearcmhara schawcrossi	*Pleydellia aalensis* Ammonite Biozone, Toarcian, Lower Jurassic	*Stephanoceras humphriesianum* Ammonite Biozone, Bajocian, Middle Jurassic	174.43	169.45	[31]
Eurhinosaurus longirostris	*Dactylioceras tenuicostatum* Ammonite Biozone, Toarcian	*Harpoceras falciferum* Ammonite Biozone, Toarcian	182.7	180.36	[32, 33]
Excalibosaurus costini	*Arietites bucklandi* Ammonite Biozone, lower Sinemurian, Lower Jurassic	*Arietites bucklandi* Ammonite Biozone, lower Sinemurian, Lower Jurassic	199.3	197.8	[33, 34]
Gengasaurus nicosiai	Calcari ad aptici e Saccocoma Formation, Late Kimmeridgian, Upper Jurassic	earliest Tithonian, Upper Jurassic	155	150	[35]
Grendelius alekseevi	*Dorsoplanites panderi* Ammonite Biozone, Tithonian, Upper Jurassic	*Dorsoplanites panderi* Ammonite Biozone, Tithonian, Upper Jurassic	149.6	147.9	[36]
Grendelius zhuravlevi	Middle Volgian, Lower Tithonian, Upper Jurassic	Middle Volgian, Lower Tithonian, Upper Jurassic	149.6	147.9	[37]
Grippia longirostris	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	247.7	247.2	[38]
Guizhouichthyosaurus tangae	Carnian, Upper Triassic	Carnian, Upper Triassic	233.5	228.35	[39]
Guizhouichthyosaurus wolonggangense	Carnian, Upper Triassic	Carnian, Upper Triassic	233.5	228.35	[40]
Gulosaurus helmi	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	247.7	247.2	[41, 42]
Hauffiopteryx typicus	*Dactylioceras tenuicostatum*, Ammonite Biozone, Toarcian	*Harpoceras falciferum* Ammonite Biozone, Toarcian	182.7	181.25	[43–45]
Himalayasaurus tibetensis	Norian, Upper Triassic	Norian, Upper Triassic	228.4	209.5	[46]
Hudsonelpidia brevirostris	*Epigondolella quadrata* Conodont Biozone, Norian, Upper Triassic	*Epigondolella quadrata* Conodont Biozone, Norian, Upper Triassic	226.5	221.25	[47]
Hupehsuchus nanchangensis	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	247.9	247.2	[48]
Ichthyosaurus acutirostris	*Hildoceras bifrons* Ammonite Biozone, Toarcian, Lower Jurassic	*Dactylioceras commune* Ammonite Biozone, Toarcian, Lower Jurassic	180.36	175.6	[49]
Ichthyosaurus anningae	Asteroceras obtusum? Ammonite Biozeon, Sinemurian, Lower Jurassic	*Uptonia jamesoni* Ammonite Biozone, Pliensbachian, Lower Jurassic	193.81	189.35	[50]
Ichthyosaurus breviceps	*Schlotheimia angulata* Ammonite Biozone, Sinemurian, Lower Jurassic	*Arnioceras semicostatum* Ammonite Biozone, Sinemurian, Lower Jurassic	200.1	196.31	[51]
Ichthyosaurus communis	Upper Rhaetian, Upper Triassic	*Arnioceras semicostatum* Ammonite Biozone, Lower Jurassic	201.3	196.31	[51]
Ichthyosaurus conybeari	*Schlotheimia angulata* Ammonite Biozone, Hettangian	*Arnioceras semicostatum* Ammonite Biozone, Sinemurian	200.1	196.31	[51]
Ichthyosaurus larkini	Pre-*Planorbis* beds, Hettangian, Lower Jurassic	Pre-*Planorbis* beds, Hettangian, Lower Jurassic	201.3	200.85	[52]
Ichthyosaurus somersetensis	Pre-*Planorbis* beds, Hettangian, Lower Jurassic	Pre-*Planorbis* beds, Hettangian, Lower Jurassic	201.3	200.85	[52]

Supplementary table 3 continued

Taxon	FAD stratigraphy	LAD stratigraphy	FAD (Ma)	LAD (Ma)	References
Isfjordosaurus minor	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	247.7	247.2	[53]
Janusaurus lundi	*Dorsoplanites maximus* Ammonite-Biozone, Tithonian, Upper Jurassic	*Dorsoplanites ilovaiskyi* Ammonite-Biozone, Tithonian, Upper Jurassic	148.3	147.4	[54]
Keilhauia nui	Slottsmøya Member, Agardfjellet Formation, Berriasian, Lower Cretaceous	Slottsmøya Member, Agardfjellet Formation, Berriasian, Lower Cretaceous	145	143	[55]
Leninia stellans	*Deshayesites volgensis* Ammonite Biozone, Lower Aptian, Lower Cretaceous	*Deshayesites volgensis* Ammonite Biozone, Lower Aptian, Lower Cretaceous	126.3	123	[56]
Leptonectes moorei	Lower Pliensbachian, Lower Jurassic	Lower Pliensbachian, Lower Jurassic	190.82	187.56	[57]
Leptonectes solei	*Arnioceras semicostatum* Ammonite Biozone, Sinemurian, Lower Jurassic	*Asteroceras obtusum* Ammonite Biozone, Sinemurian, Lower Jurassic	195.31	193.81	[58]
Leptonectes tenuirostris	Pre-*Planorbis* beds, Hettangian, Lower Jurassic	*Amaltheus margaritatus* Ammonite Biozone, Pliensbachian, Lower Jurassic	201.3	190.8	[49, 59]
Macgowania janiceps	*Epigondolella matthewi* Conodont Biozone, middle Norian, Upper Triassic	*Epigondolella multidentata* Conodont Biozone, middle Norian, Upper Triassic	220	216.9	[60]
Maiaspondylus lindoei	Middle Albian, Lower Cretaceous	Middle Albian, Lower Cretaceous	111.27	110.22	[61]
Malawania anachronus	Late Hauterivian, Early Cretaceous	Barremian, Early Cretaceous	131	125	[62]
Mikadocephalus gracilirostris	Upper Illyrian, Anisian, Middle Triassic	lower Fassinian, Ladinian, Middle Triassic	242.57	240.3	[63]
Mixosaurus cornalianus	Upper Illyrian, Anisian, Middle Triassic	lower Fassinian, Ladinian, Middle Triassic	242.57	240.3	[49, 64]
Mixosaurus kuhnschneyderi	Upper Illyrian, Anisian, Middle Triassic	lower Fassinian, Ladinian, Middle Triassic	242.57	240.3	[65]
Mixosaurus xindianensis	*Nicoraella kockeli* Conodont Biozone, Pelsonian, Anisian, Middle Triassic	*Nicoraella kockeli* Conodont Biozone, Pelsonian, Anisian, Middle Triassic	244.94	241.5	[66]
Mollesaurus periallus	*Emileia giebeli* Ammonite Biozone, early Bajocian, Middle Jurassic	*Emileia giebeli* Ammonite Biozone, early Bajocian, Middle Jurassic	170.3	169.45	[67, 68]
Muiscasaurus catheti	Barremian , Lower Cretaceous	Aptian, Lower Cretaceous	130.77	115.64	[69]
Nannopterygius enthekiodon	*Aulacostephanus* sp. Ammonite Biozone, Kimmeridgian, Upper Jurassic	*Aulacostephanus* sp. Ammonite Biozone, Tithonian, Upper Jurassic	154.6	149.87	[15]
Ophthalmosaurus icenicus	*Kosmoceras jasoni* Ammonite Biozone, Callovian, Upper Jurassic	*Quenstedtoceras mariae* Ammonite Biozone, Oxfordian, Upper Jurassic	165.59	161.39	[70]
Ophthalmosaurus natans	Oxfordian, Late Jurassic	Oxfordian, Late Jurassic	163.5	157.3	[71]
Ophthalmosaurus yasykovi	*Epivirgatites nikitini* Ammonite Biozone, Tithonian, Upper Jurassic	*Craspedites subdites* Ammonite Biozone, Tithonian, Upper Jurassic	147.5	146.4	[72]
Palvennia hoybergeti	*Dorsoplanites maximus* Ammonite Biozone, Tithonian, Upper Jurassic	*Dorsoplanites ilovaiskyi* Ammonite Biozone, Tithonian, Upper Jurassic	148.3	147.4	[28]
Paraophthalmosaurus kabanovi	*Epivirgatites nikitini* Ammonite Biozone, Tithonian, Upper Jurassic	*Epivirgatites nikitini* Ammonite Biozone, Tithonian, Upper Jurassic	147.5	146.9	[72]
Paraophthalmosaurus saveljeviensis	*Dorsoplanites panderi* Ammonite Biozone, Tithonian, Upper Jurassic	*Epivirgatites nikitini* Ammonite Biozone, Tithonian, Upper Jurassic	149.6	146.9	[73]

Supplementary table 3 continued

Taxon	FAD stratigraphy	LAD stratigraphy	FAD (Ma)	LAD (Ma)	References
Parvinatator wapitiensis	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	247.7	247.2	[74]
Pervushovisaurus bannovkensis	Middle Cenomanion, Upper Cretaceous	Middle Cenomanion, Upper Cretaceous	96.24	95.47	[75]
Pervushovisaurus campylodon	Early Cenomanian, Upper Cretaceous	Early Cenomanian, Upper Cretaceous	100.45	96.5	[76]
Pessopteryx nisseri	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	247.7	247.2	[53]
Phalarodon callawayi	Upper Anisian, Middle Triassic	Upper Anisian, Middle Triassic	243.99	239.1	[77]
Phalarodon fraasi	Upper Anisian, Middle Triassic	lower Ladinian, Middle Triassic	244.94	237	[78]
Phalarodon major	Upper Anisian , Middle Triassic	Ladinian, Middle Triassic	244.94	237	[79]
Phantomosaurus neubigi	*pulcher/robustus* Conodont Biozone, Upper Anisian, Middle Triassic	*pulcher/robustus* Conodont Biozone, Upper Anisian, Middle Triassic	244.94	241.5	[80]
Platypterygius americanus	Upper Albian, Lower Cretaceous	Upper Albian, Lower Cretaceous	107.59	100.5	[81]
Platypterygius australis	Albian, Lower Cretaceous	Albian, Lower Cretaceous	113	100.5	[82, 83]
Platypterygius hauthali	*Hatchiceras* Ammonite Biozone, Lower Barremian, Lower Cretaceous	*Hatchiceras* Ammonite Biozone, Lower Barremian, Lower Cretaceous	130.77	129.41	[84]
Platypterygius hercynicus	Aptian, Lower Cretaceous	Aptian, Lower Cretaceous	125	113	[85]
Platypterygius platydactylus	*Hoplites deshayesi* Ammonite Biozone, Aptian, Lower Cretaceous	*Hoplites deshayesi* Ammonite Biozone, Aptian, Lower Cretaceous	125	113	[86]
Platypterygius sachicarum	Barremian, Lower Cretaceous	Aptian, Lower Cretaceous	130.77	113	[87]
Qianichthyosaurus xingyiensis	Ladinian, Middle Triassic	Ladinian, Middle Triassic	241.5	237	[88]
Qianichthyosaurus zhoui	Carnian, Upper Triassic	Carnian, Upper Triassic	237	228.35	[89]
Quasianosteosaurus vikinghoegdai	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	247.7	247.2	[90]
Sclerocormus parviceps	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	247.9	247.7	[91, 92]
Shastasaurus liangae	Upper Carnian, Late Triassic	Upper Carnian, Late Triassic	233.5	228.35	[93]
Shastasaurus pacificus	Upper Carnian, Late Triassic	Upper Carnian, Late Triassic	233.5	228.35	[18]
Shastasaurus sikkaniensis	*Epigondolella postera* conodont Biozone, *Mesohemavatities columbianus* ammonite Biozone, middle Norian, Upper Triassic	*Epigondolella postera* conodont Biozone, *Mesohemavatities columbianus* ammonite Biozone, middle Norian, Upper Triassic	216.9	214.7	[94]
Shonisaurus popularis	Upper Carnian, Late Triassic	Upper Carnian, Late Triassic	233.5	228.35	[95]
Simbirskiasaurus birjukovi	*Praeoxyteuthis pugio* Belemnite Biozone, lower Barremian, Lower Cretaceous	*Praeoxyteuthis pugio* Belemnite Biozone, lower Barremian, Lower Cretaceous	130.77	129.41	[75]
Sisteronia seeleyi	Cambridge Greensand Member, early Cenomanian, Upper Cretaceous	Cambridge Greensand Member, early Cenomanian, Upper Cretaceous	100.5	96.24	[96]
Stenopterygius aaleniensis	*Leioceras opalinum* Ammonite Biozone, Aalenian, Middle Jurassic	*Leioceras opalinum* Ammonite Biozone, Aalenian, Middle Jurassic	174.1	172.13	[97]
Stenopterygius quadriscissus	*Dactylioceras tenuicostatum* Ammonite Biozone, Toarcian, Lower Jurassic	*Harpoceras falciferum* Ammonite Biozone, Toarcian, Lower Jurassic	182.7	180.36	[43, 98]
Stenopterygius triscissus	*Dactylioceras tenuicostatum* Ammonite Biozone, Toarcian, Lower Jurassic	*Harpoceras falciferum* Ammonite Biozone, Toarcian, Lower Jurassic	182.7	180.36	[43, 98]

Supplementary table 3 continued

Taxon	FAD stratigraphy	LAD stratigraphy	FAD (Ma)	LAD (Ma)	References
Stenopterygius uniter	*Harpoceras falciferum* Ammonite Biozone, Toarcian, Lower Jurassic	*Harpoceras falciferum* Ammonite Biozone, Toarcian, Lower Jurassic	181.7	180.36	[43, 98]
Suevoleviathan disinteger	*Dactylioceras tenuicostatum* Ammonite Biozone, Toarcian, Lower Jurassic	*Harpoceras falciferum* Ammonite Biozone, Toarcian, Lower Jurassic	181.7	180.36	[99, 100]
Suevoleviathan integer	*Dactylioceras tenuicostatum* Ammonite Biozone, Toarcian, Lower Jurassic	*Harpoceras falciferum* Ammonite Biozone, Toarcian, Lower Jurassic	181.7	180.36	[99, 100]
Sveltonectes insolitus	Upper Barremian, Cretaceous	Upper Barremian, Cretaceous	129.6	126.3	[101]
Temnodontosaurus azerguensis	*Harpoceras bifrons* Ammonite Biozone, middle Toarcian, Lower Jurassic	*Harpoceras bifrons* Ammonite Biozone, middle Toarcian, Lower Jurassic	180.36	178.24	[102]
Temnodontosaurus crassimanus	*Dactylioceras tenuicostatum* Ammonite Biozone, Toarcian, Lower Jurassic	*Harpoceras falciferum* Ammonite Biozone, Toarcian, Lower Jurassic	182.7	180.36	[103]
Temnodontosaurus eurycephalus	*Arietites bucklandi* Ammonite Biozone, lower Sinemurian, Lower Jurassic	*Arietites bucklandi* Ammonite Biozone, lower Sinemurian, Lower Jurassic	199.3	197.8	[104]
Temnodontosaurus nuertingensis	*Uptonia jamesoni* Ammonite Biozone, Lower Pliensbachian, Lower Jurassic	*Tragophyllocera ibex* Ammonite Biozone, Pliensbachian, Lower Jurassic	190.8	187.56	[105, 106]
Temnodontosaurus platyodon	*Schlotheimia angulata* Ammonite Biozone, Hettangian	*Arnioceras semicostatum* Ammonite Biozone, Sinemurian	200.1	196.31	[104]
Temnodontosaurus trigonodon	*Dactylioceras tenuicostatum* Ammonite Biozone, Toarcian, Lower Jurassic	*Harpoceras falciferum* Ammonite Biozone, Toarcian, Lower Jurassic	182.7	180.36	[99, 107]
Thaisaurus chonglakmanii	Lower Triassic	Lower Triassic	250.01	247.2	[108]
Thalattoarchon saurophagis	*Nevadisculites taylori* Ammonite Biozone, Anisian, Middle Triassic	*Nevadisculites taylori* Ammonite Biozone, Anisian, Middle Triassic	247.2	244.6	[109]
Tholodus schmidi	*Decurtella decurtata* Conodont Biozone, Ladinian (Pelsonian), Middle Triassic	*Judicarites/Neoschizodus orbicularis* Conodont Biozone, Ladinian (Pelsonian), Middle Triassic	241	237	[110]
Toretocnemus californicus	*Metapolygnathus polygnathiformis* Conodont Biozone, Carnian, Upper Triassic	*Metapolygnathus polygnathiformis* Conodont Biozone, Carnian, Upper Triassic	233.5	228.35	[49, 111]
Toretocnemus zitteli	*Metapolygnathus polygnathiformis* Conodont Biozone, Carnian, Upper Triassic	*Metapolygnathus polygnathiformis* Conodont Biozone, Carnian, Upper Triassic	233.5	228.35	[49, 111]
Undorosaurus gorodischensis	*Epivirgatites nikitini*, Virgatites virgatus AmmoniteBiozone, Tithonian, Upper Jurassic	*Epivirgatites nikitini*, Virgatites virgatus AmmoniteBiozone, Tithonian, Upper Jurassic	147.9	146.9	[112]
Undorosaurus trautscholdi	*Epivirgatites nikitini* Ammonite Biozone, Tithonian, Upper Jurassic	*Kachpurites fulgens* Ammonite Biozone, Tithonian, Upper Jurassic	150	144.1	[113]
Utatsusaurus hataii	*Subcolumbites* Ammonite Biozone, Olenekian, Lower Triassic	*Arnautoceratites* Ammonite Biozone, Olenekian, Lower Triassic	247.7	247.2	[114]
Wahlisaurus massarae	Pre-*Planorbis* beds, Hettangian, Lower Jurassic	Pre-*Planorbis* beds, Hettangian, Lower Jurassic	201.3	200.85	[115]
Wimanius odontopalatus	Anisian , Middle Triassic	Ladinian, Middle Triassic	241.5	237	[116]
Xinminosaurus catactes	*Nicoraella kockeli* Conodont Biozone, Pelsonian, Anisian, Middle Triassic	*Nicoraella kockeli* Conodont Biozone, Pelsonian, Anisian, Middle Triassic	244.94	241.5	[117]

Supplementary table 4. **Skull lengths of Ichthyosauriformes included in the analyses.** Logarithm values are shown to 3 d.p.

Taxon	Skull length (mm)	$\log_{10}$ (Skull length (mm))	References
Acamptonectes densus	1000	3.000	[9]
Aegirosaurus leptospondylus	570	2.756	[10]
Barracudasauroides panxianensis	212	2.326	[13]
Besanosaurus leptorhynchus	510	2.708	[14]
Brachypterygius extremus	1155	3.062	[15]
Callawayia neoscapularis	453	2.656	[80, 118]
Cartorhynchus lenticarpus	55	1.740	[20]
Caypullisaurus bonapartei	1300	3.114	[21]
Chacaicosaurus cayi	980	2.991	[22]
Chaohusaurus geishanensis	117	2.068	[23, 24]
Contectopalatus atavus	130	2.114	[26, 119]
Cryopterygius kristiansenae	1220	3.086	[28]
Cymbospondylus petrinus	1166	3.067	[18]
Eurhinosaurus longirostris	1250	3.097	[32, 33]
Excalibosaurus costini	1540	3.188	[33, 34]
Guizhouichthyosaurus tangae	800	2.903	[39]
Guizhouichthyosaurus wolonggangense	645	2.810	[40]
Gulosaurus helmi	87	1.940	[41, 42]
Hauffiopteryx typicus	380	2.580	[43–45]
Hudsonelpidia brevirostris	131	2.117	[47]
Hupehsuchus nanchangensis	126	2.100	[48]
Ichthyosaurus anningae	390	2.591	[50]
Ichthyosaurus breviceps	240	2.380	[51]
Ichthyosaurus communis	256	2.408	[51]
Ichthyosaurus conybeari	216	2.334	[51]
Ichthyosaurus larkini	355	2.550	[52]
Ichthyosaurus somersetensis	438	2.641	[52]
Leptonectes moorei	328	2.516	[57]
Leptonectes solei	1585	3.200	[58]
Leptonectes tenuirostris	523	2.719	[49, 59]
Macgowania janiceps	505	2.703	[60]
Mixosaurus cornalianus	195	2.290	[49, 64]
Mixosaurus kuhnschneyderi	160	2.204	[65]
Mixosaurus xindianensis	223	2.348	[66]
Nannopterygius enthekiodon	600	2.778	[15]
Ophthalmosaurus icenicus	965	2.985	[70]
Ophthalmosaurus natans	1082	3.034	[71]
Palvennia hoybergeti	860	2.934	[28]
Parvinatator wapitiensis	120	2.079	[74]
Phalarodon callawayi	300	2.477	[77]
Phalarodon fraasi	205	2.312	[120, 121]
Phantomosaurus neubigi	550	2.740	[80]
Platypterygius americanus	1250	3.097	[81]
Platypterygius australis	1430	3.155	[82, 83]
Platypterygius hercynicus	1040	3.017	[85]
Platypterygius platydactylus	1170	3.068	[86]
Platypterygius sachicarum	870	2.940	[87]
Qianichthyosaurus xingyiensis	270	2.431	[88]

Supplementary table 4 continued

Taxon	Skull length (mm)	$\log_{10}$ (Skull length (mm))	References
Qianichthyosaurus zhoui	240	2.380	[89]
Sclerocormus parviceps	100	2.000	[91]
Shastasaurus liangae	750	2.875	[93]
Shastasaurus sikkaniensis	3000	3.477	[94]
Shonisaurus popularis	2750	3.439	[95]
Stenopterygius quadriscissus	625	2.796	[43, 98]
Stenopterygius triscissus	634	2.802	[43, 98]
Stenopterygius uniter	537	2.730	[43, 98]
Suevoleviathan disinteger	860	2.934	[99, 100]
Suevoleviathan integer	690	2.839	[99, 100]
Sveltonectes insolitus	570	2.756	[101]
Temnodontosaurus azerguensis	1700	3.230	[102]
Temnodontosaurus eurycephalus	1020	3.009	[104]
Temnodontosaurus platyodon	1790	3.253	[104]
Temnodontosaurus trigonodon	1090	3.037	[99, 107]
Thalattoarchon saurophagis	1200	3.079	[109]
Utatsusaurus hataii	215	2.332	[114]
Wimanius odontopalatus	250	2.398	[116, 122]
Xinminosaurus catactes	290	2.462	[117]

Supplementary code

Code 1 R code implementing the disparity, principal coordinates, diversity, and discrete character rates analyses. This set of five scripts contains the code used to run the main discrete character analyses in R. Outputs include time-scaled trees, discrete rates of evolution, stratigraphic congruence values; PDF files of all figures produced; CSV files of root ages from the time-scaled trees, stratigraphic congruence tests, and statistical tests (pairwise PERMANOVA between epochs for PCA data and pairwise *t*-tests of per-bin disparity).

Code 2 Continuous rates analyses in BayesTraits and plotting in R. Rates analyses were run individually on 100 time-scaled trees then combined into consensus trees with branch rates averaged across all runs. Also includes code to create the traitgram of Fig. 4.

Supplementary methods

Comparison of time-scaling methods To assess the effects of variation in the timing of ichthyosaur evolution on discrete evolutionary rates, we further used the minimum branch length (MBL) tree-scaling method[123,124]. This scales the tree according to occurrence dates, but ensures that each branch length is greater than a given value, rescaling ancestral branches as necessary to ensure this minimum length. Here, we used a MBL of 1 Ma as a reasonable minimum between speciation events and to avoid forcing excessive branch lengths where speciation may occur rapidly. We used the same sample of 120 phylogenetic trees as the main analysis from the Bayesian phylogenetic posterior distribution of Moon [1]. Trees were time-scaled in R[125] using the function `timePaleoPhy` in the package paleotree[123] with point ages sampled from a uniform distribution between their first and last occurrences. Each tree was resampled 10 times to account for the occurrence ranges for each taxon (100 tree topologies × 10 samples = 1000 time-scaled trees total). These MBL time-scaled trees were then used for a further set of discrete character evolutionary rates analyses using function `DiscreteCharacterRate` of R package Claddis[126]. The results of this were used to produce 'spaghetti' plots for epoch-length bins and equal-length bins using modified scripts from Close *et al.* [127]. Code for all these analyses is included in Supplementary Code 1.

Additional disparity metrics Our main results present ichthyosauriform disparity using per-bin pairwise differences between taxa from a distance matrix calculated using maximum observed rescaled distances[126]. Additionally, we compared different distance conversion and disparity metrics.

Claddis provides four distance metrics for discrete character data[126]: raw Euclidean distances (RAW), generalized Euclidean distances (GED)[128], Gower's coefficient (GOW)[129], and maximum observable rescaled distances (MAX)[126]. All four distance metrics were run through the same disparity work flow. Recent studies have shown that GED as implemented in Claddis is susceptible to the completeness of the original data matrix, which may have a strong effect on the resulting disparity[130,131]; therefore we prefer MAX.

Similarly, several different disparity metrics have been developed, each with varying properties. Our main results present mean and weighted mean pairwise distances on MAX as this comes directly from the original data matrix, but we also calculated the pairwise distances for RAW, GED, and GOW distances matrices (Supplementary Figure 1). We ordinated the data using Principal Coordinates Analysis (PCA), both with and without applying a correction to negative eigenvalues[132] and compared the correlation of the PCA data with the original distance matrix.

From the PCA data we used all the resultant axes to calculate per-bin sum of variances, sum of ranges, and centroid distances. These metrics have been used extensively in previous analyses[130,133,134], so we considered it pertinent to compare them. Binning, bootstrap resampling with 500 replicates, and complete rarefaction were completed using the functions `custom.subsets` and `boot.matrix`, and disparity calculations used the function `dispRity`, all from package dispRity[135] in R. Code for this is included in Supplementary Code 1.

Supplementary results

Pairwise disparity Broadly speaking, trends in disparity across all four distance matrices are similar: disparity peaks in the Late Triassic then declines through the Jurassic and Cretaceous (Supplementary Figure 1). The bins that preserve the most completely coded taxa (Supplementary Figure 1 CHAR: Early Jurassic; 201.3 Ma to 171.3 Ma) also show relatively increased disparity in RAW and GED distance matrices compared to GOW and MAX. Indeed, the earliest Jurassic bins are the most disparate for the RAW distance metric with both binning schemes, and for GED the earliest Jurassic bins have relatively higher disparity than GOW and MAX distance matrices. This is most likely a further effect of incompleteness degrading the disparity signal by averaging the difference between taxa[130,131], therefore we prefer the results given by GOW and MAX distance matrices. Rarefying the data shows that maximum disparity is reach quickly with minimal taxa included, and supports using the full taxon sample for each bin (Supplementary Figure 2).

Correlation of ordinated data Negative eigenvalue correction notably decreased the variance described by the first few principal coordinate axes Supplementary Figure 3. The highest correlations between the original and ordinated data were found when including all ordinated axes (Supplementary Figure 3). Without negative eigenvalue correction RAW and GED had the highest correlation, whereas GOW and MAX were reduced to ~0.8. With negative eigenvalue correction the pattern of correlations with increasing number of axes was more complex: RAW gradually increased whereas GED strongly decreased, but both rapidly increased to 1.0 with the last axes; GOW and MAX correlations both immediately decreased, increased to a peak at ~axis 60, then rapidly increased again when including the last axes.

Disparity of ordinated data Wills [133] asserted that variance based disparity metrics are more suited to measuring overall dissimilarity whereas range-based metrics are appropriate for disparity as they are affected by occurrence and thus show the diversification of morphology. In this context, our results support our conclusions that ichthyosaurs represent an early burst of evolution: both of these metrics show initial high disparity from all distance matrices (Supplementary Figure 4). Sum of variances also has a marked increase between the Early to Middle Triassic and a substantial decline in disparity between the Late Triassic–Early Jurassic in the combination of GOW/MAX distance matrix and uncorrected PCO; otherwise all curves follow similar trends. Sum of variances proves more resilient to sample size in rarefaction than either sum of ranges or centroid distance (Supplementary Figure 5).

All sum of ranges curves display the same trends in disparity, differing only in the magnitude. Similarly, we find early high disparity and an increase between the Early–Middle Triassic (Supplementary Figure 4). Disparity decreases substantially through the later Triassic, but broadly recovers in the Early Jurassic before more log-term decline through to the extinction of the ichthyosaurs. Particularly low disparity (e.g. Middle Jurassic; 171.3 Ma to 161.3 Ma) are those bins represented by few taxa and relative incompleteness.

In the case of centroid distance, although this has been shown to be especially susceptible to issues of 'centroid slippage'[130,131], our results show the same trends as for sum of variances: high early disparity that is sustained through to the Late Jurassic/Early Cretaceous before decline, with dips that are most likely related to incompleteness of specimens (Supplementary Figure 4).

Morphospace occupation of ordinated data Morphospace occupation between Triassic and post-Triassic Ichthyosauriformes is separated in almost all cases (Supplementary Figure 6; except RAW and GED distances). Late Triassic taxa are also separated from earlier Triassic taxa in GOW and MAX distance without negative eigenvalue correction, and are consistently positioned more closely towards the Early Jurassic taxa. The variation in Jurassic and Cretaceous taxa is markedly increased in RAW and GED distances relative to GOW and MAX. Differences within Jurassic and Cretaceous taxa are more represented in PCo axis 2 than axis 3 in the RAW and GED morphospace plots, but in a combination of PCO axes 1 and 3 in GOW and MAX. All RAW and GED morphospace plots show more points towards the origins of the plots than GOW and MAX, a results of 'centroid slippage'[130,131]; in particular these represent the least complete taxa.

Time-scaling and rates Using the MBL time-scaling method created trees with a root age of 253.8 Ma to 268.5 Ma; older than the corresponding root ages from the Hedman scaling method. Rates of discrete character evolution are relatively lower for during the Early–Middle Triassic, but these earlier bins nonetheless show significantly higher rates of evolution that subsequent bins (Supplementary Figure 7). Trends across the whole of ichthyosaur evolution remain similar, although there are increased peaks in the later Early Jurassic and the Late Cretaceous bins. Significantly low rates of discrete character evolution are reached in the Early Jurassic (epoch bins) or Late Triassic (10 Ma bins).

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