

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

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Supplemental 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^{1,2}. 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 [3]. Trees were time-scaled in R⁴ using the function `timePaleoPhy` in the package `paleotree`¹ 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 (120 tree topologies × 10 samples = 1200 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`⁵. 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.* [6]. Code for all these analyses is included in Supplemental Code S1.

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 distances⁵. Additionally, we compared different distance conversion and disparity metrics.

Claddis provides four distance metrics for discrete character data⁵: raw Euclidean distances (RAW), generalized Euclidean distances (GED)⁷, Gower's coefficient (GOW)⁸, and maximum observable rescaled distances (MAX)⁵. 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^{9,10}; 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 distance matrices (fig. 1). We ordinated the data using Principal Coordinates Analysis (PCA), both with and without applying a correction to negative eigenvalues¹¹ 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^{9,12,13}, so we considered it pertinent to compare them. Binning, bootstrap resampling with 10 000 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`¹⁴ in R. Code for this is included in Supplemental Code S1.

Supplemental 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 (fig. 1). The bins that preserve the most completely coded taxa (fig. 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^{9,10}, therefore we prefer the results given by GOW and MAX distance matrices.

Correlation of ordinated data Negative eigenvalue correction notably decreased the variance described by the first few principal coordinate axes. The highest correlations between the original and ordinated data were found when including all ordinated axes (??). 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 [12] 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 (fig. 2). 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 (fig. 3).

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 (fig. 2). Disparity decreases substantially through the later Triassic, but broadly recovers in the Early Jurassic before more long-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’^{9,10}, 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 (fig. 2).

Morphospace occupation of ordinated data Morphospace occupation between Triassic and post-Triassic Ichthyosauriformes is separated in almost all cases (fig. 4; 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 result of ‘centroid slippage’^{9,10}; 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 than subsequent bins (fig. 5). 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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Ichthyosaur disparity (mean pairwise dissimilarity) through time

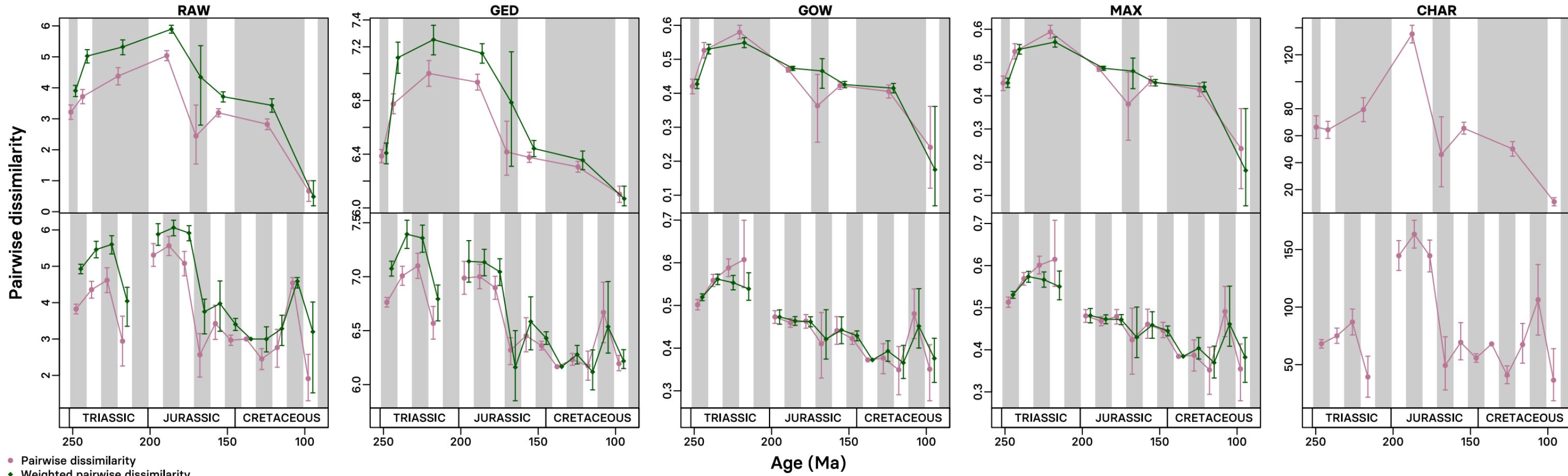
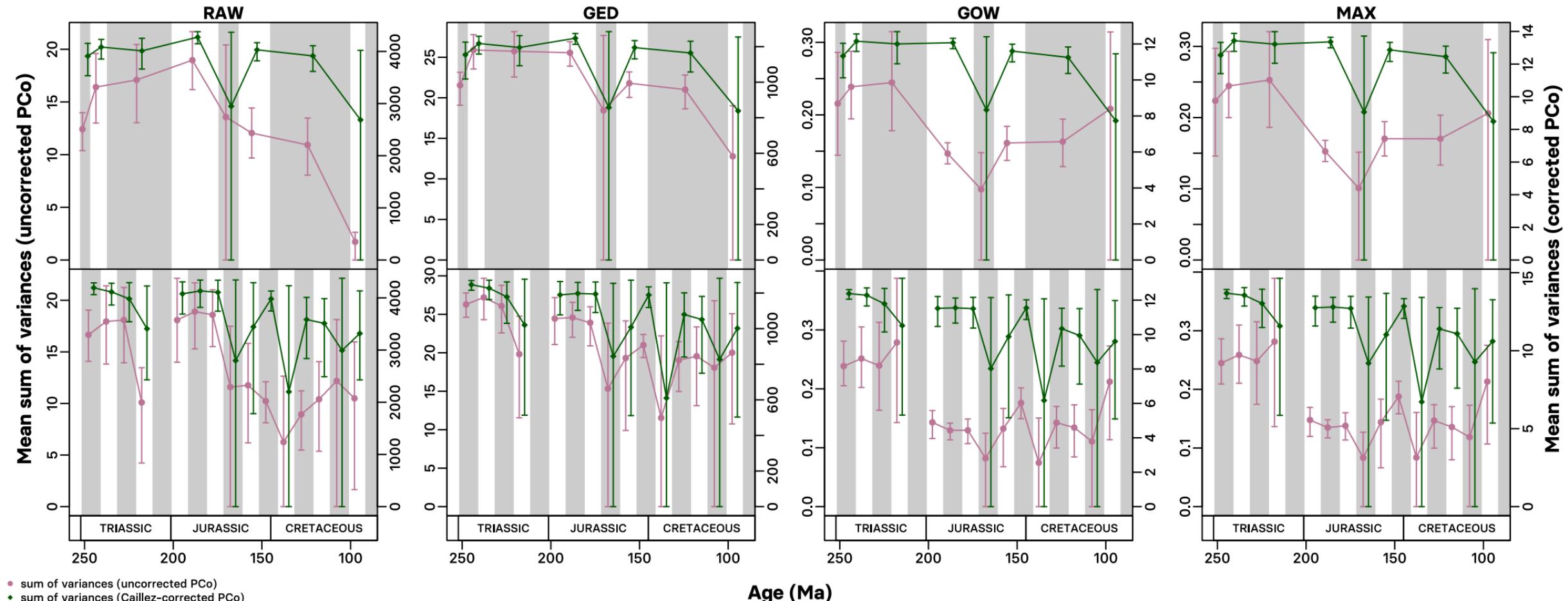
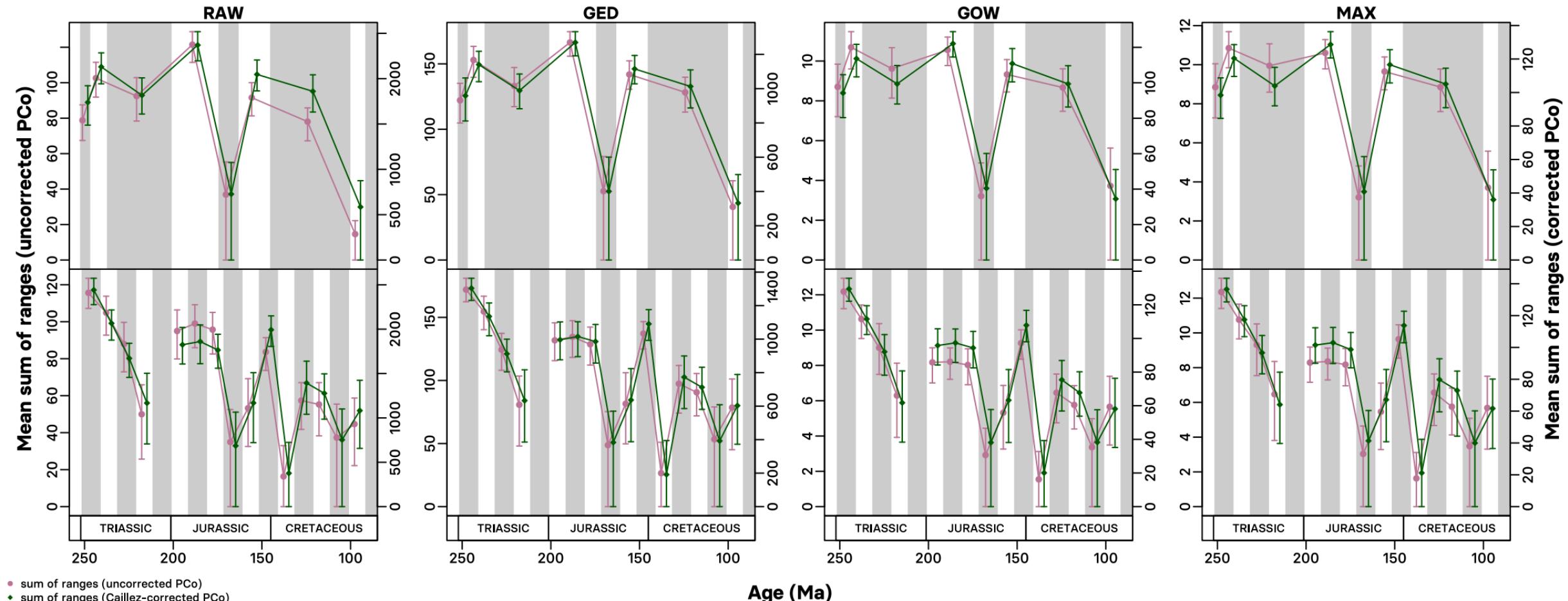


Figure 2: (following pages) **Per-bin discrete skeletal disparity of Ichthyosauriformes through the Mesozoic from ordinated data.** Ichthyosaur disparity represented by mean sum of variances, mean sum of ranges, and mean centroid distance from each of eight PCA (four distance matrices: RAW, GED, GOW, MAX; with and without negative eigenvalue correction) on the cladistic matrix of Moon [3]. Error bars show 95% confidence intervals from 10,000 bootstrap replicates.

Ichthyosaur disparity (mean sum of variances) through time



Ichthyosaur disparity (mean sum of ranges) through time



Ichthyosaur disparity (mean centroid distance) through time

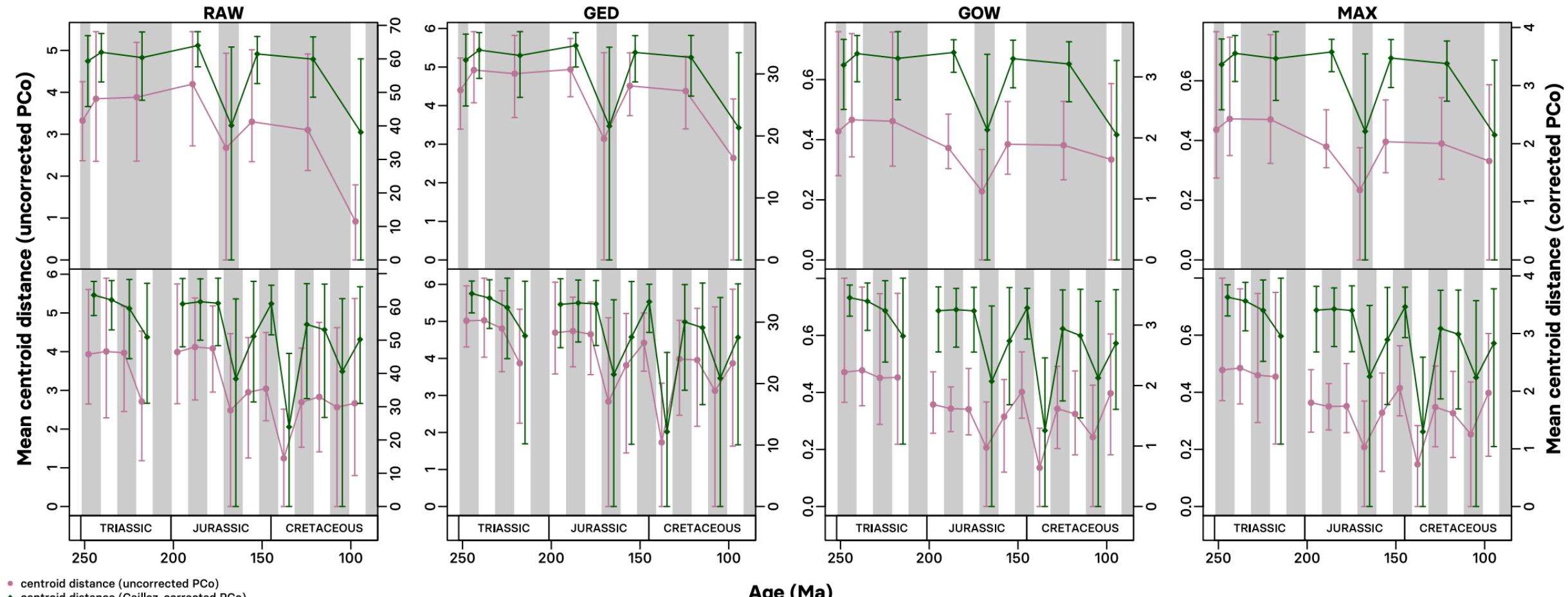
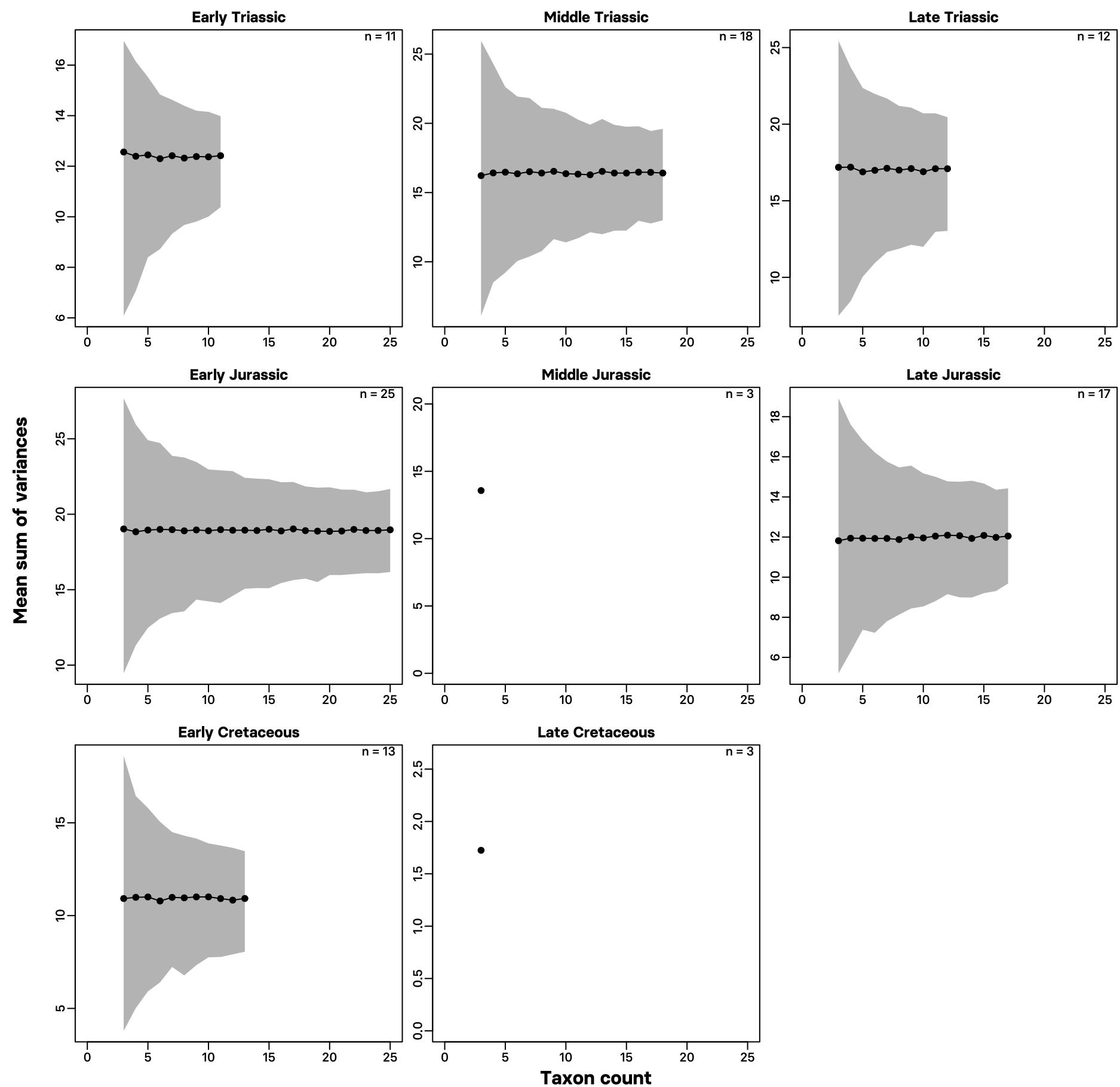
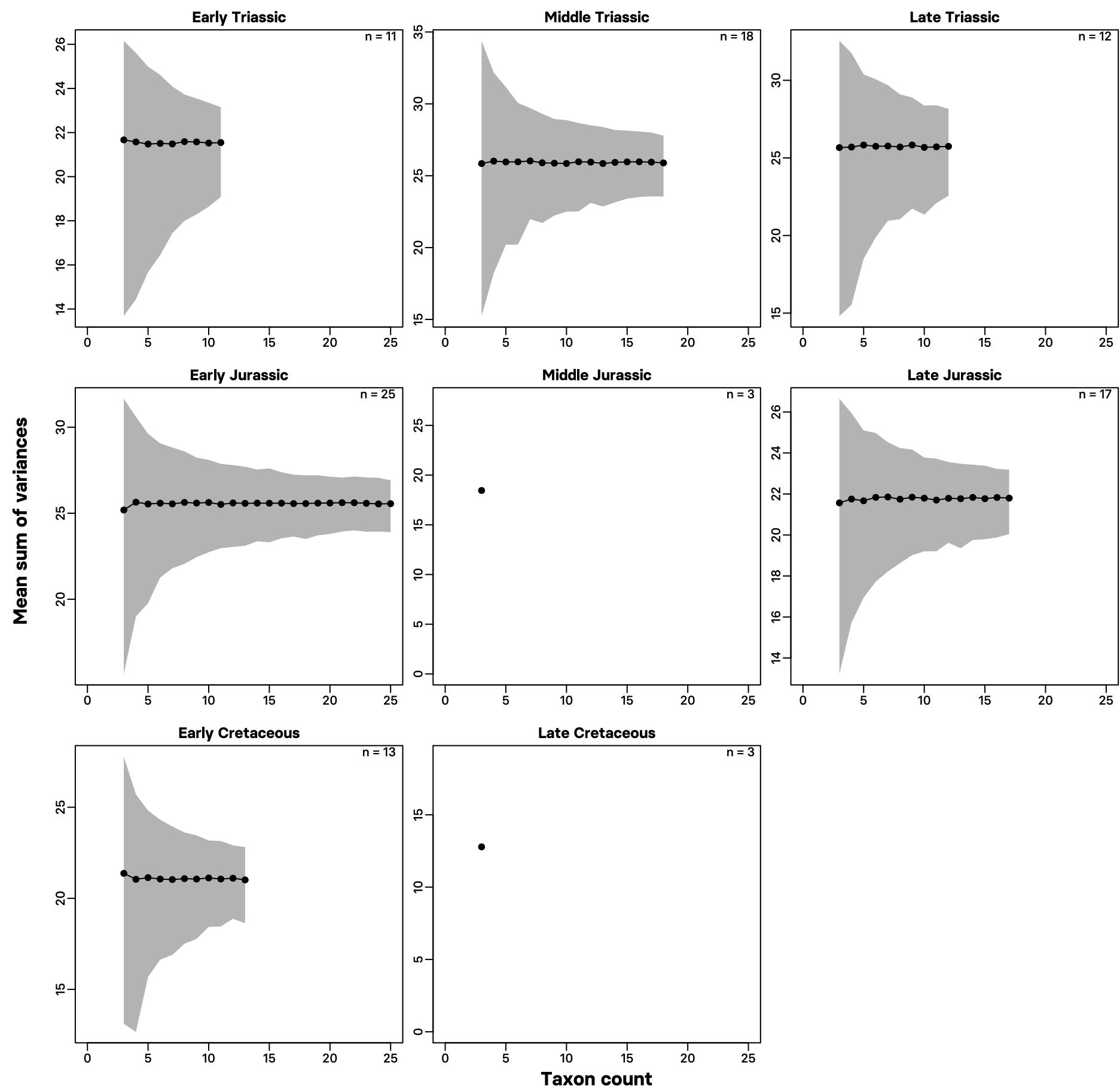


Figure 3: (following pages) **Per-bin rarefaction curves for each disparity-time curve shown in fig. 2** Disparity for each bin is sequentially rarefied on taxon occurrences. Error polygon gives 95% confidence interval from 10,000 bootstrap replicates.

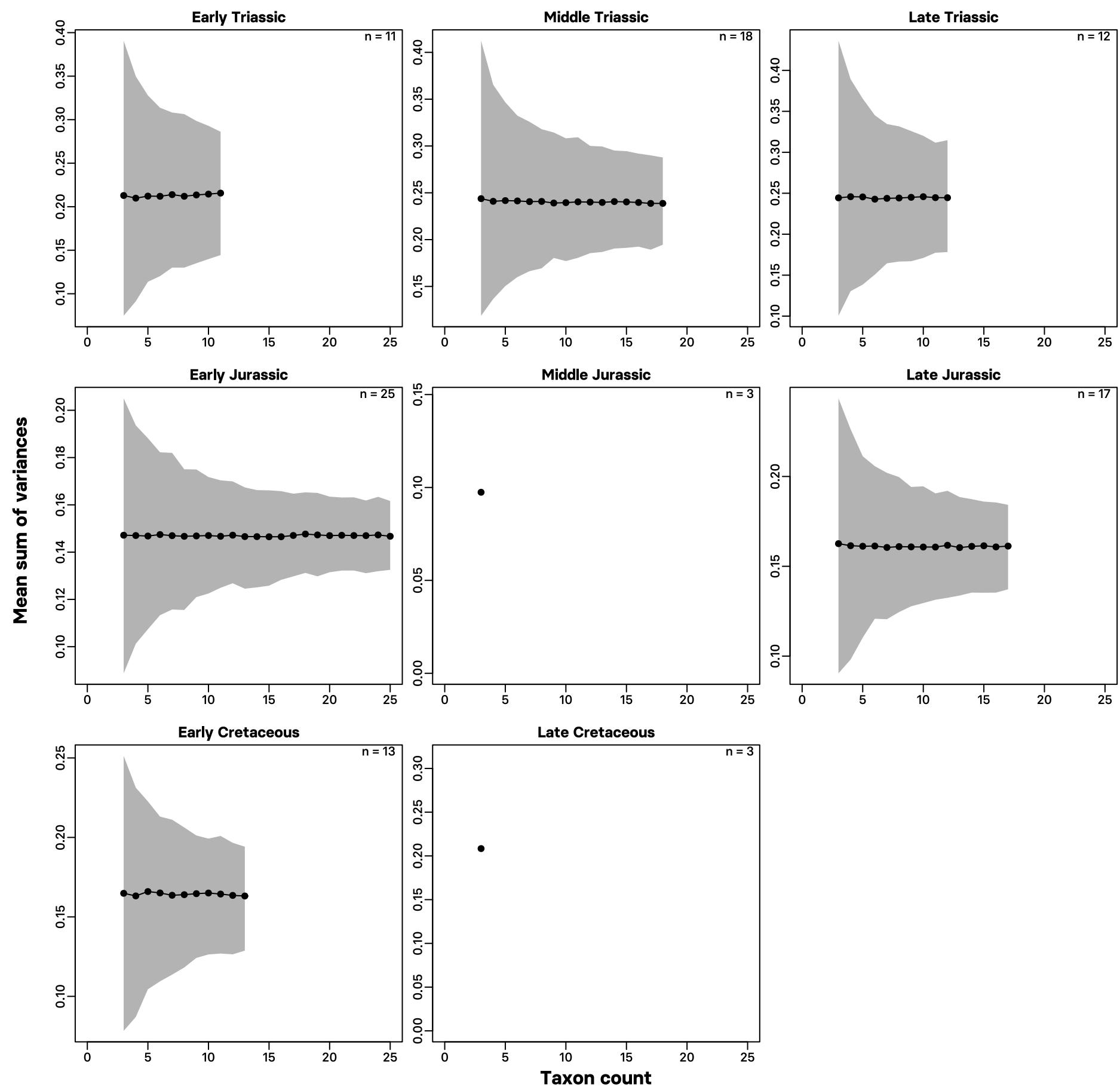
Rarefaction curves: mean sum of variances of uncorrected RAW distance matrix in epoch-length bins



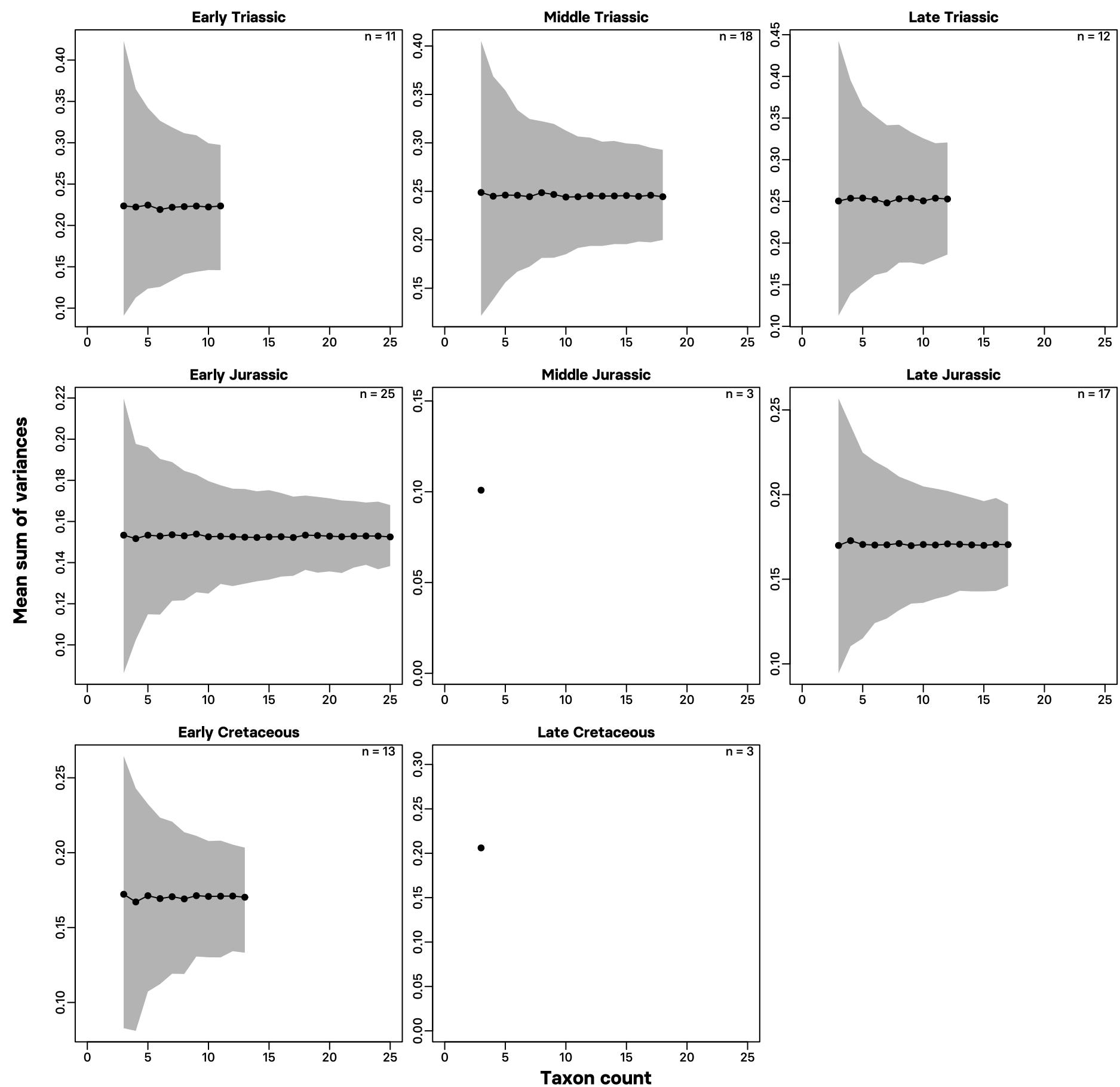
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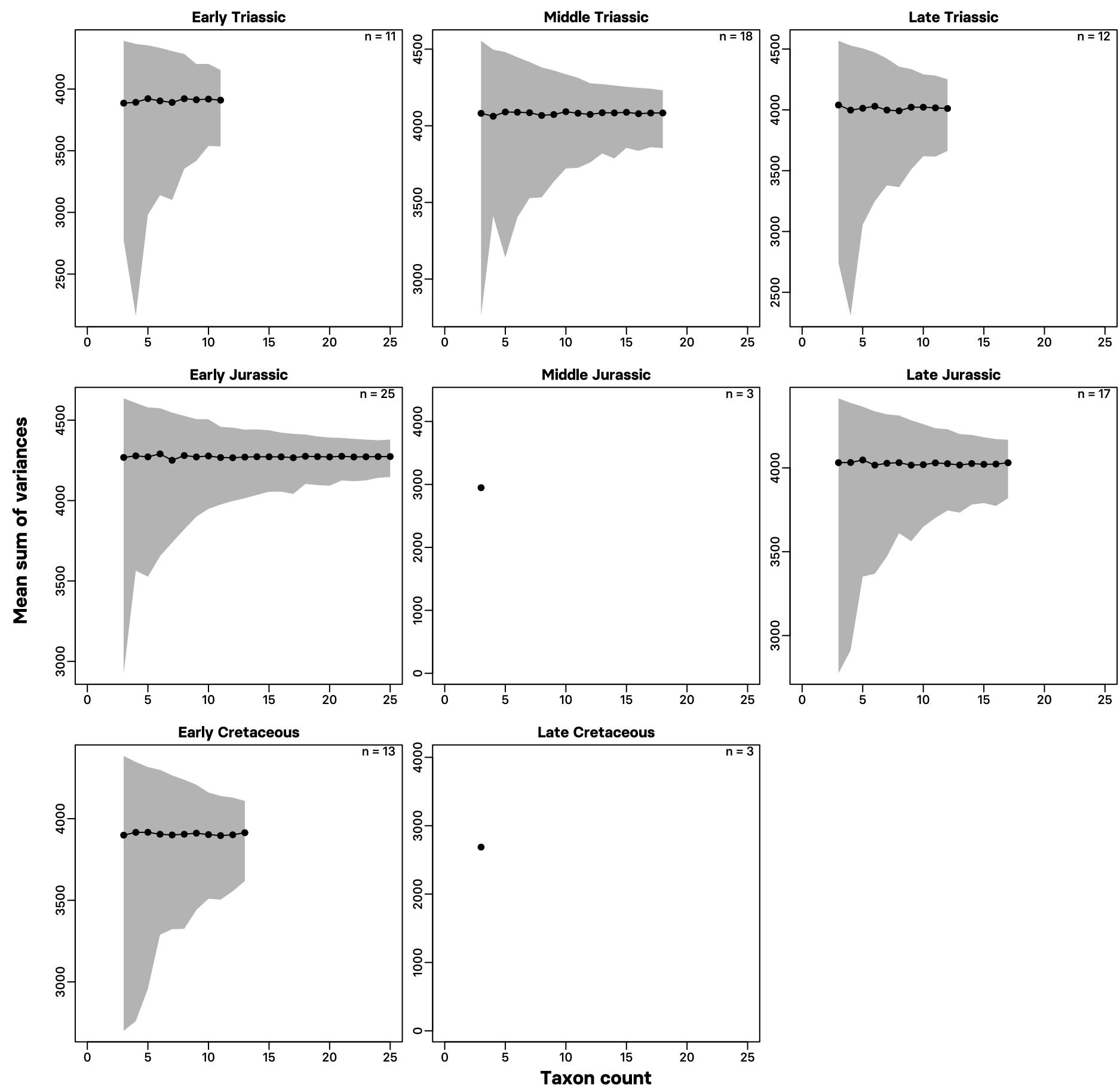
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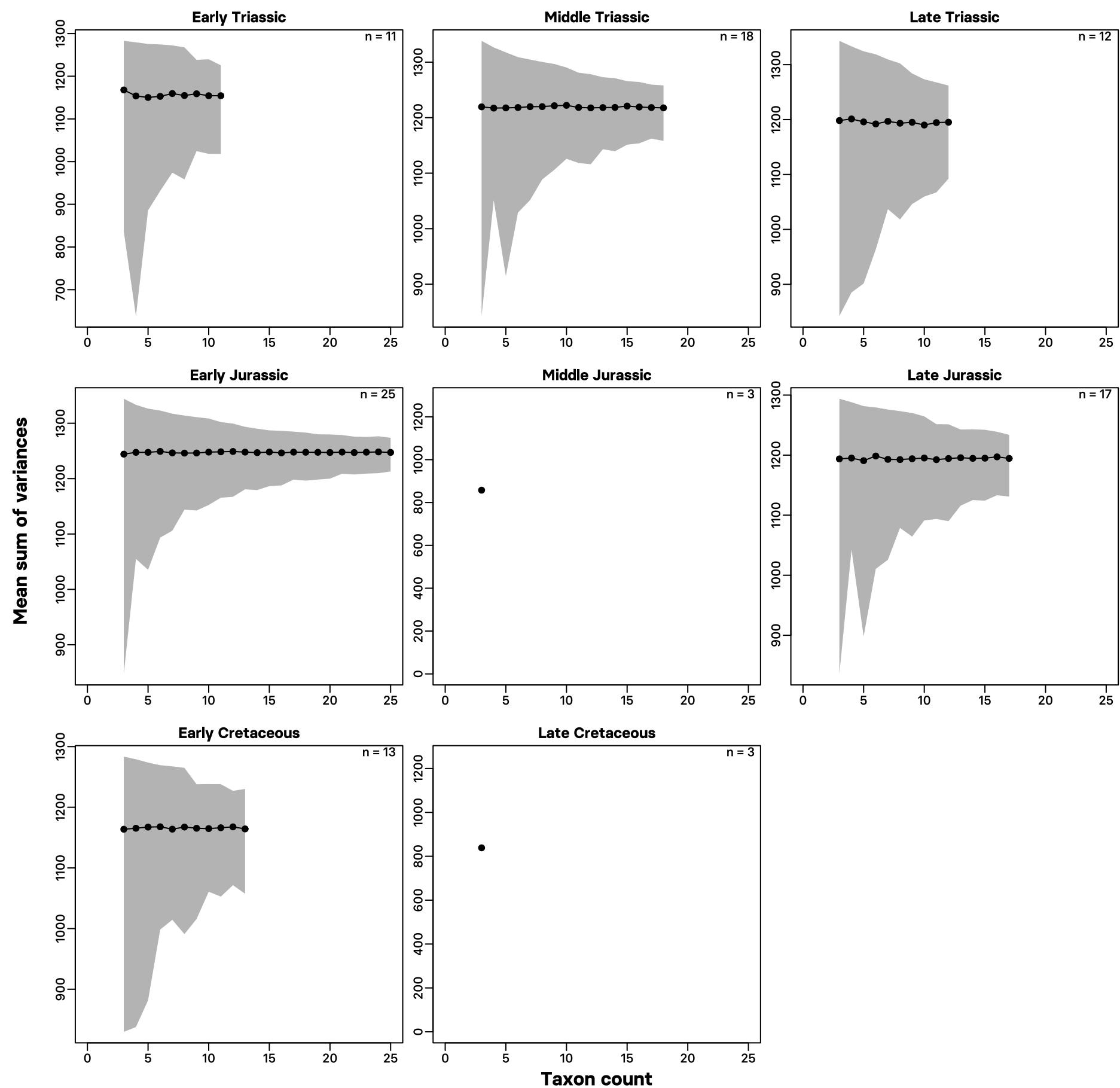
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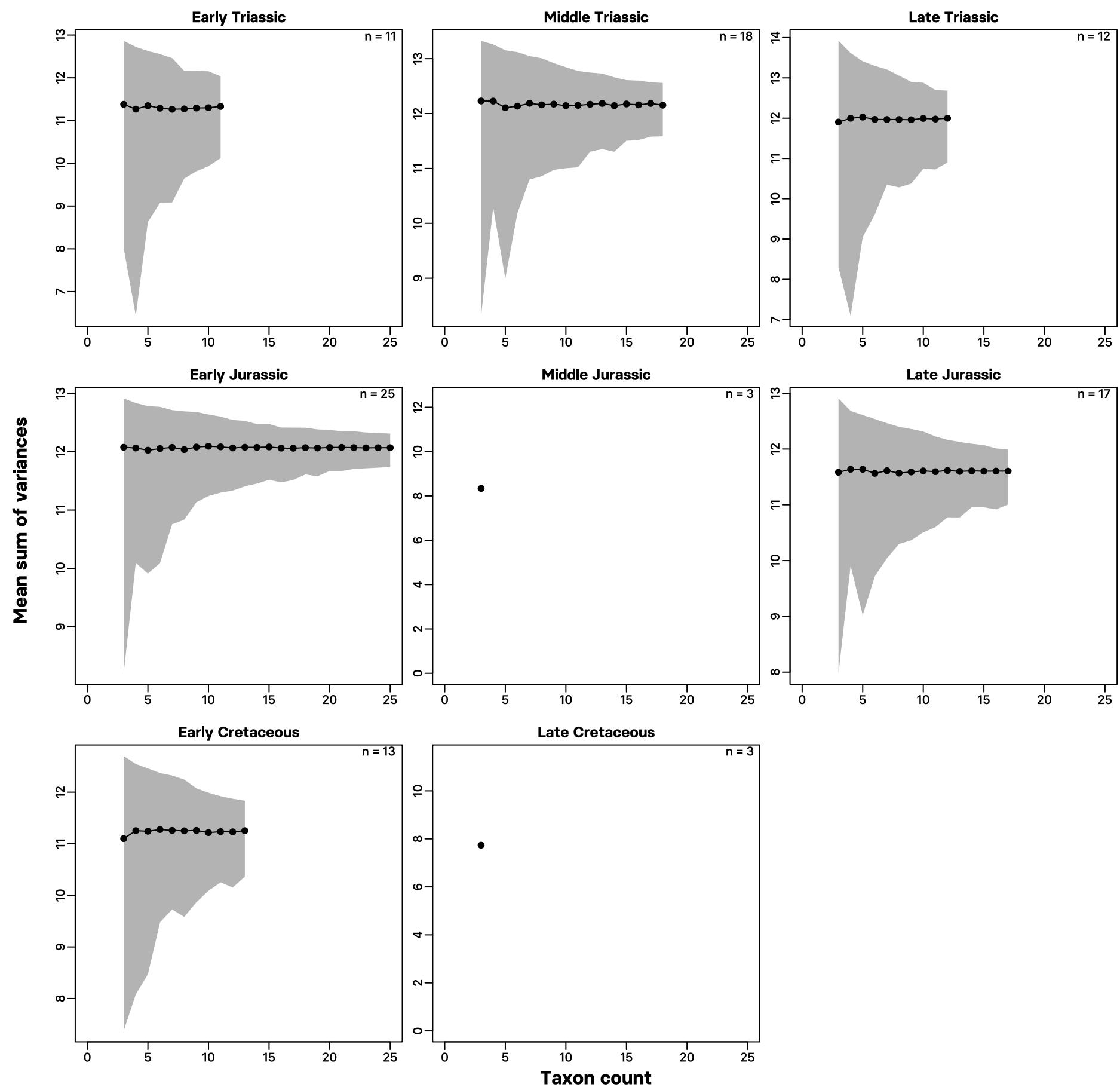
Rarefaction curves: mean sum of variances of Cailleuz-corrected RAW distance matrix in epoch-length bins



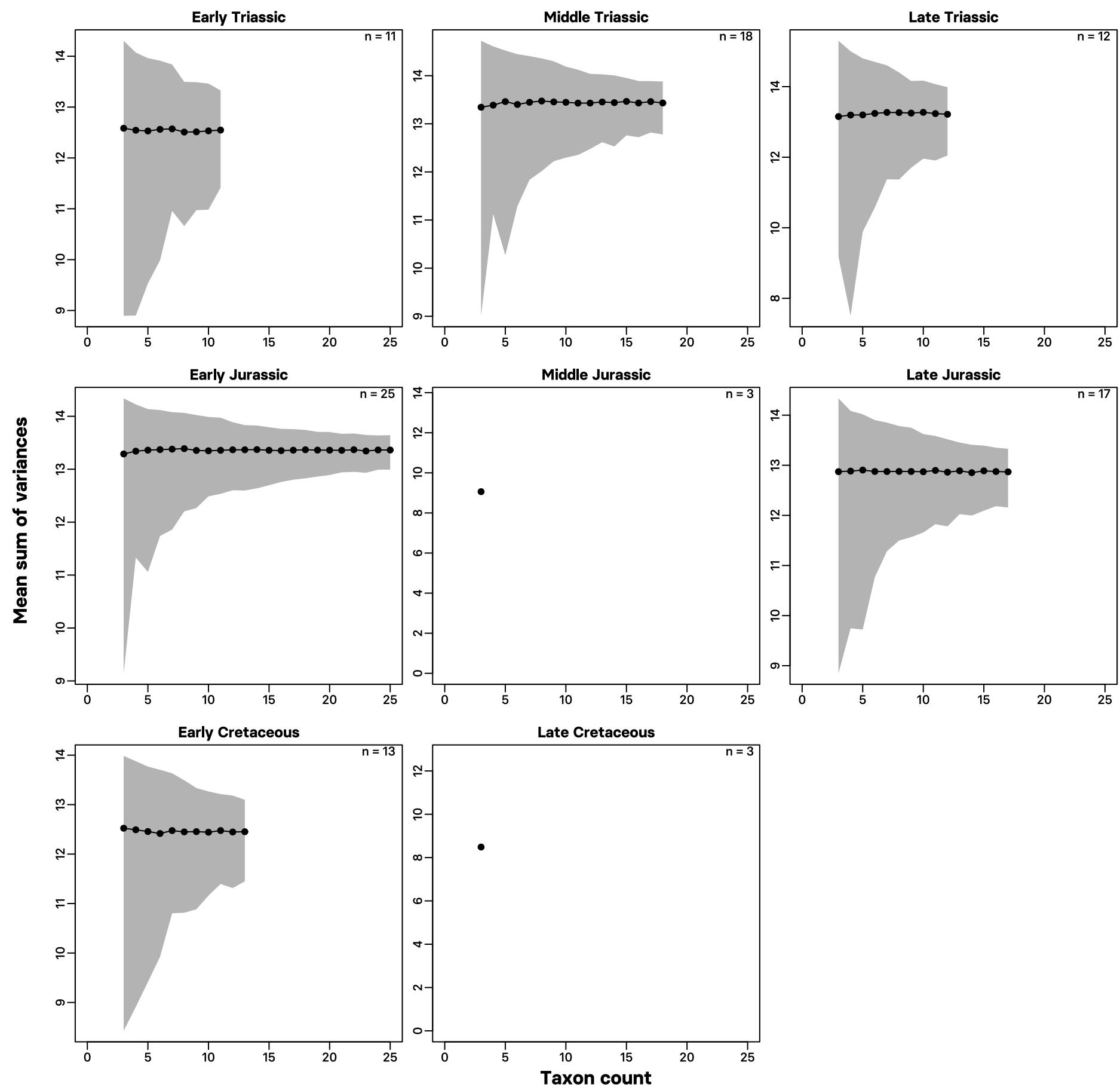
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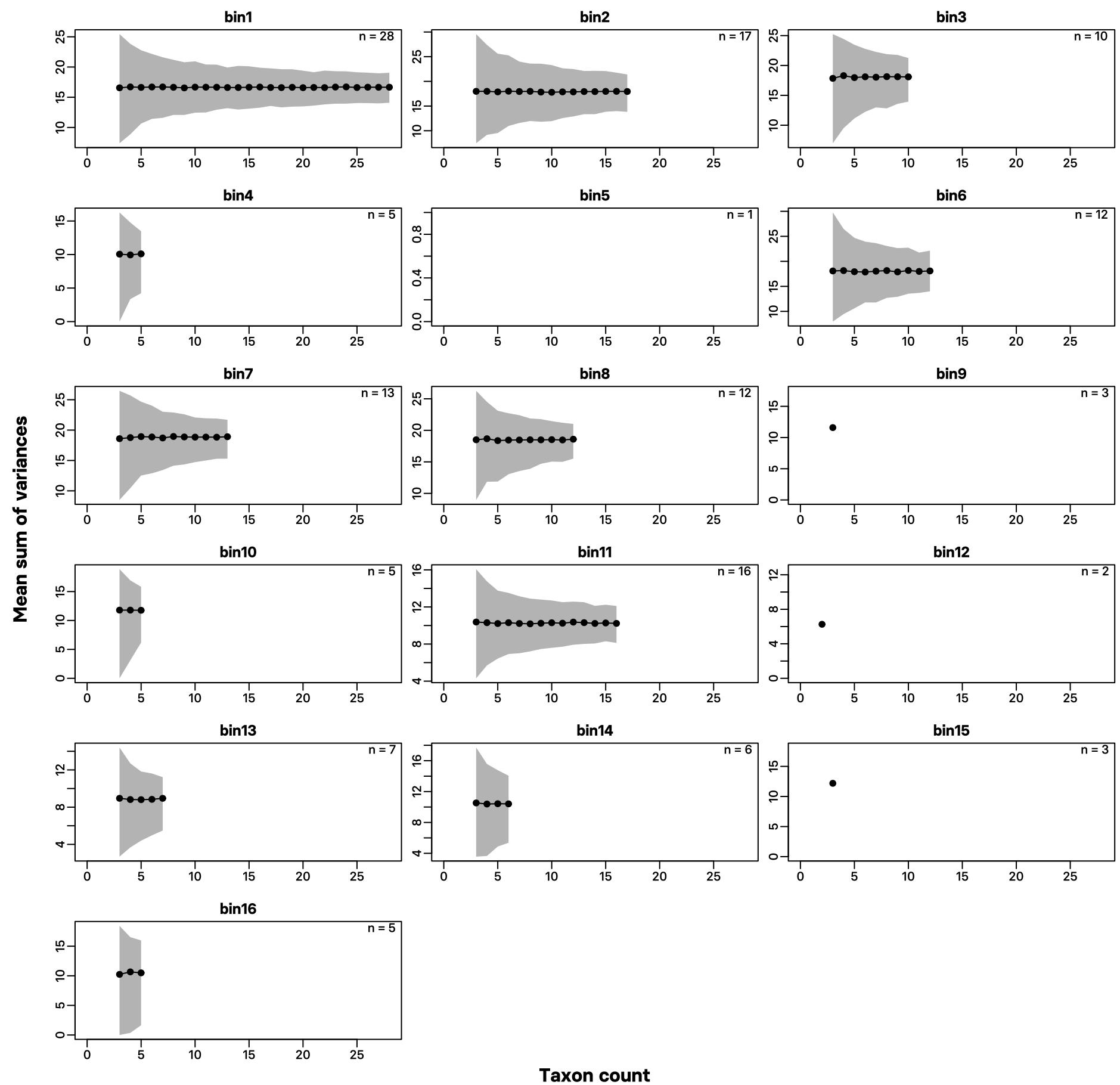
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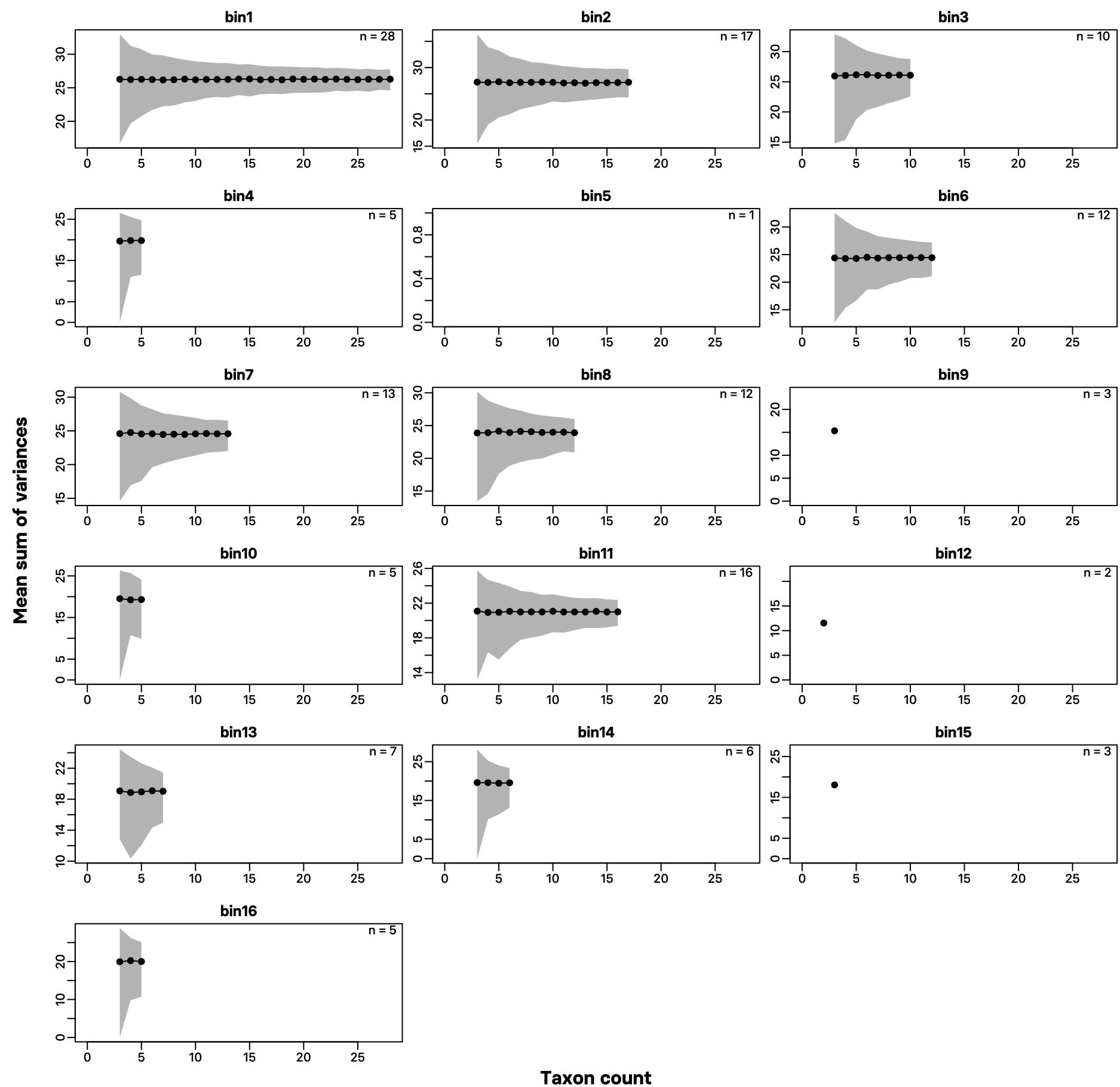
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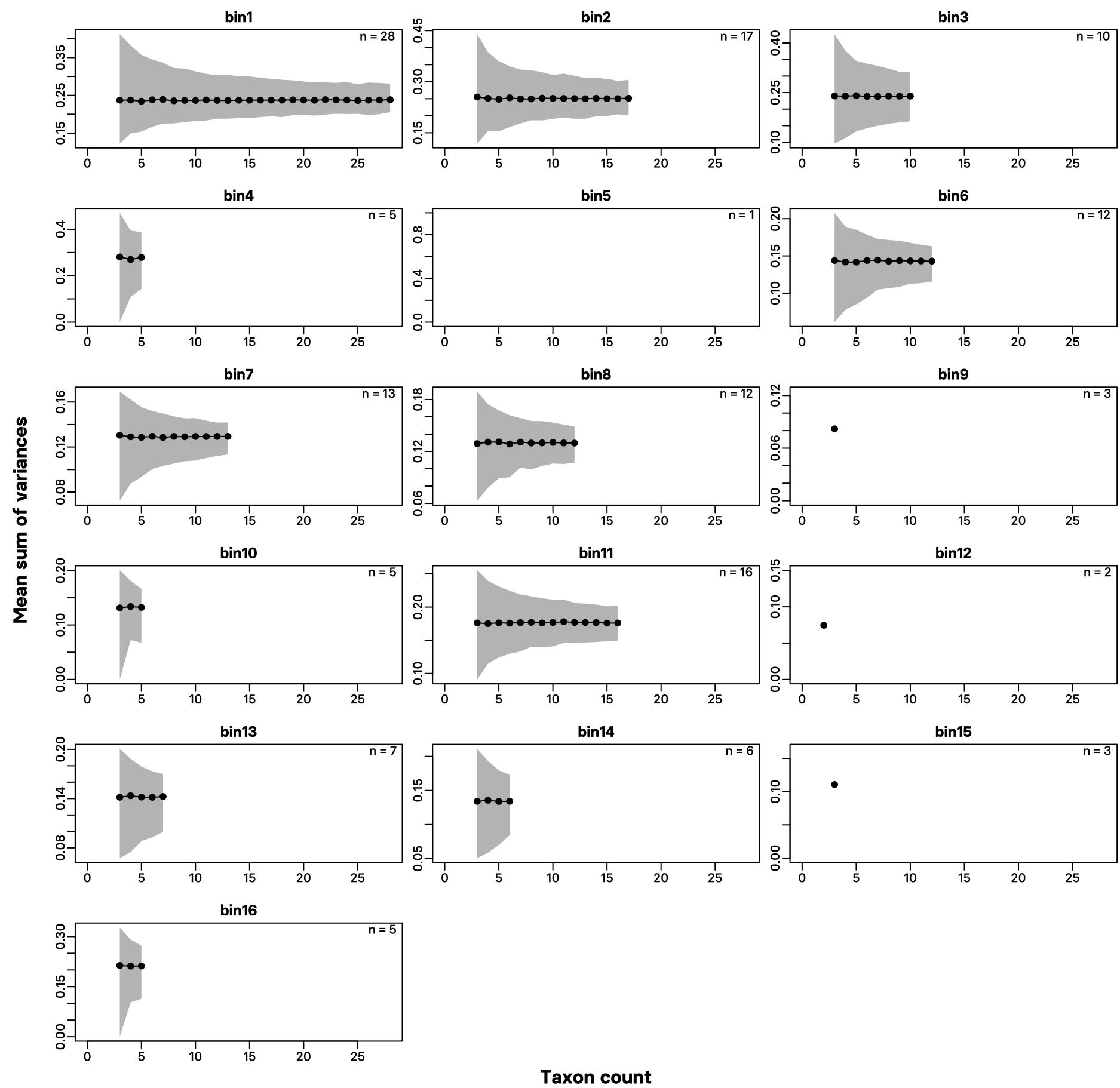
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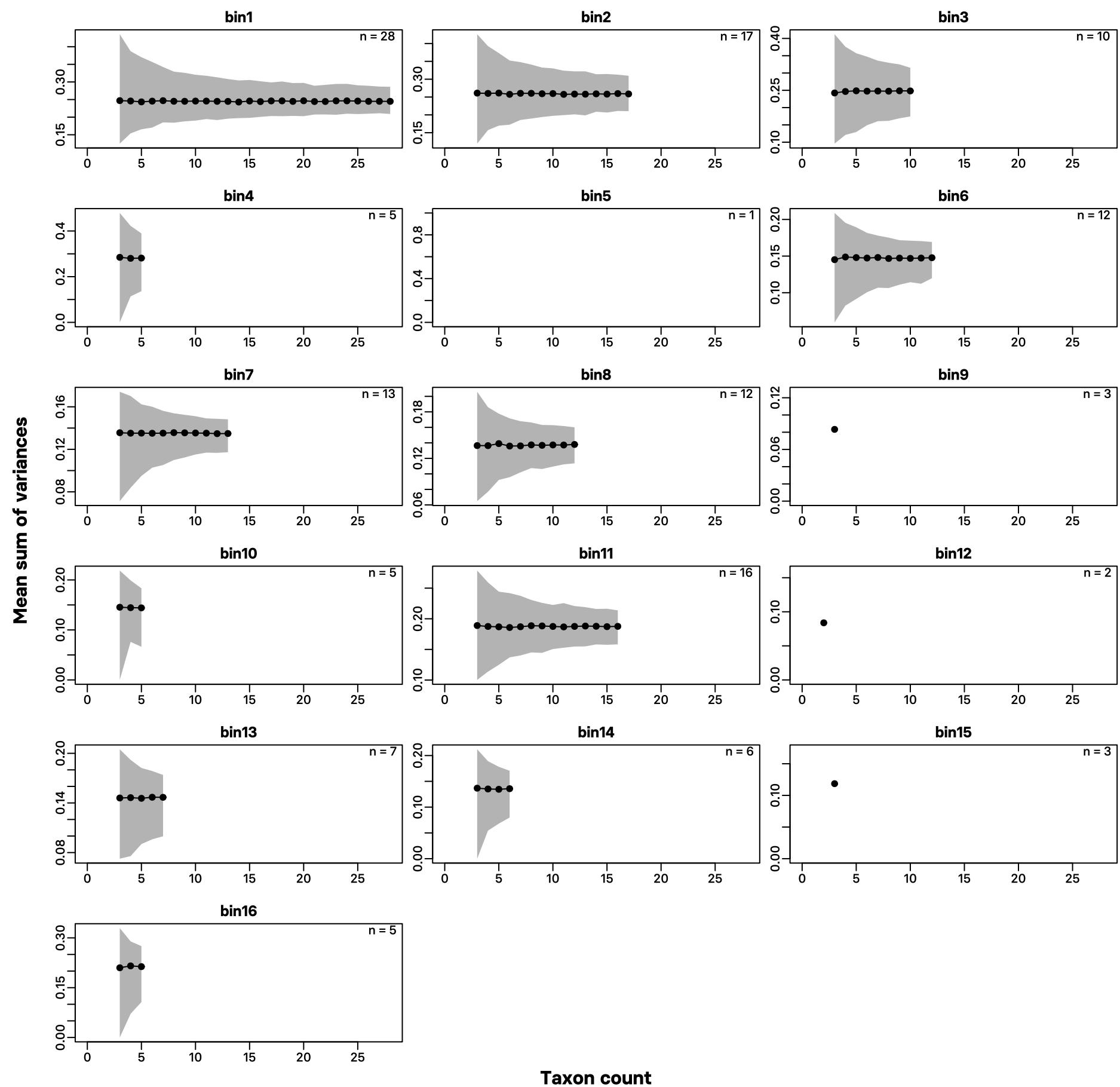
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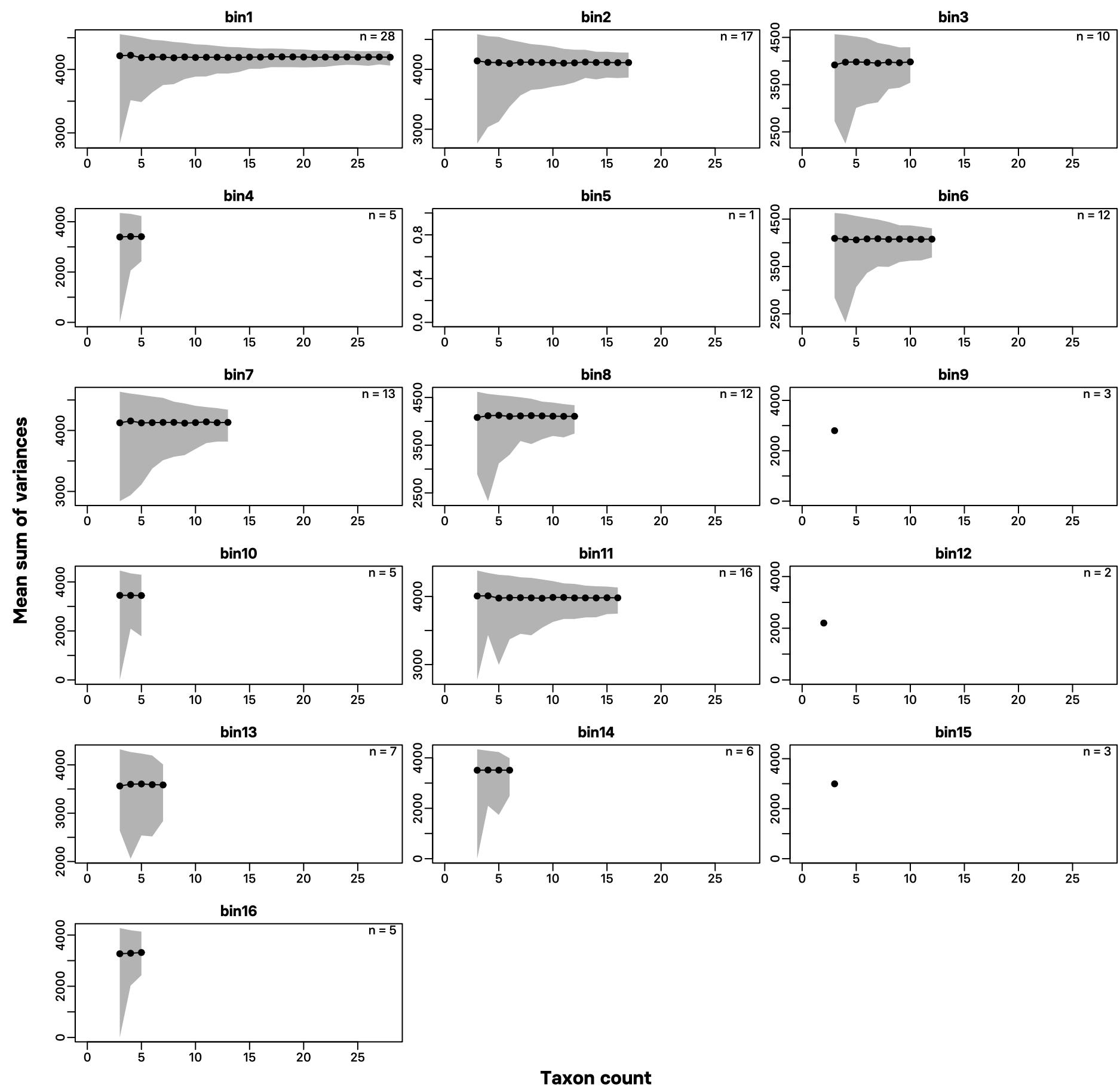
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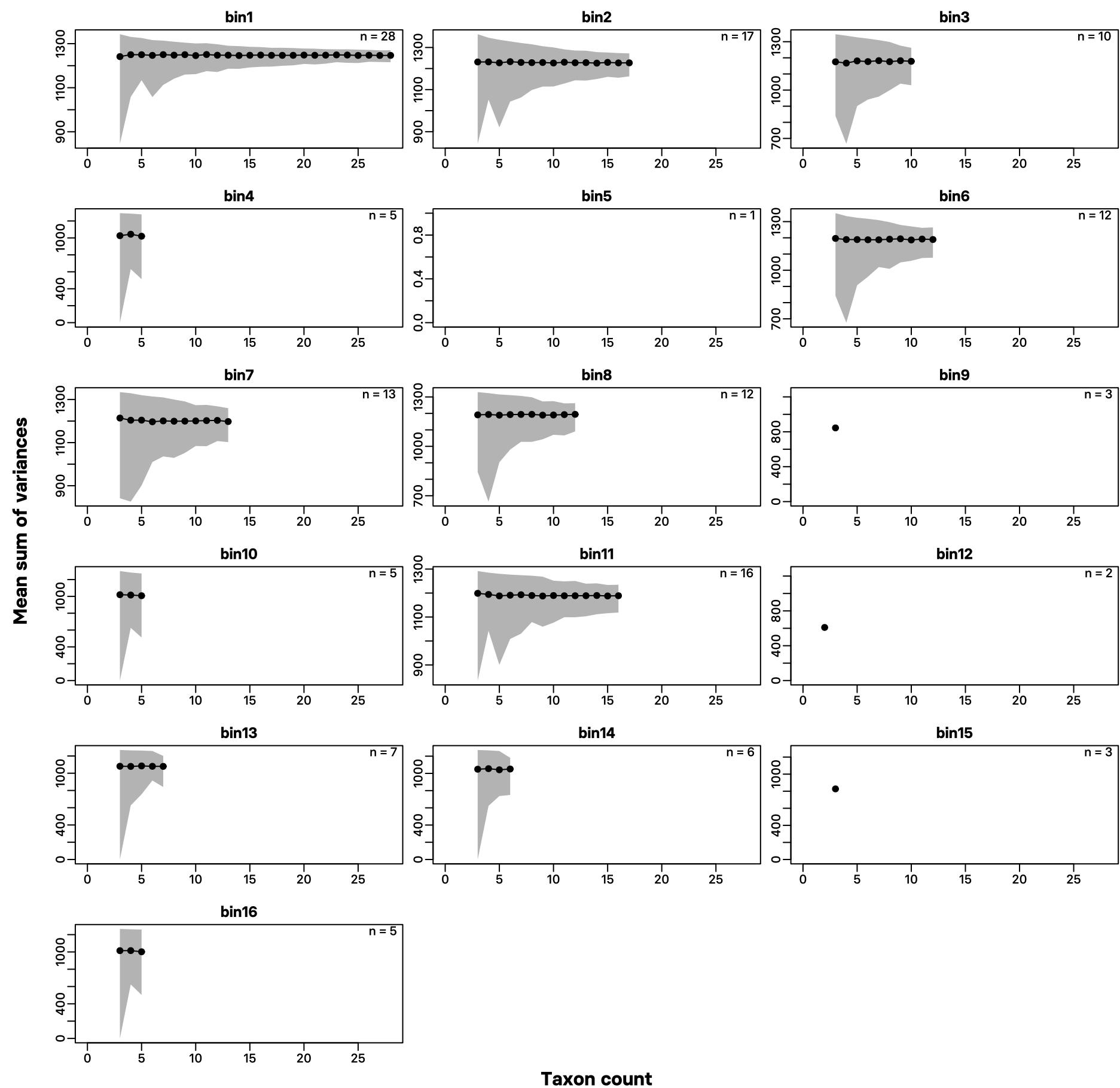
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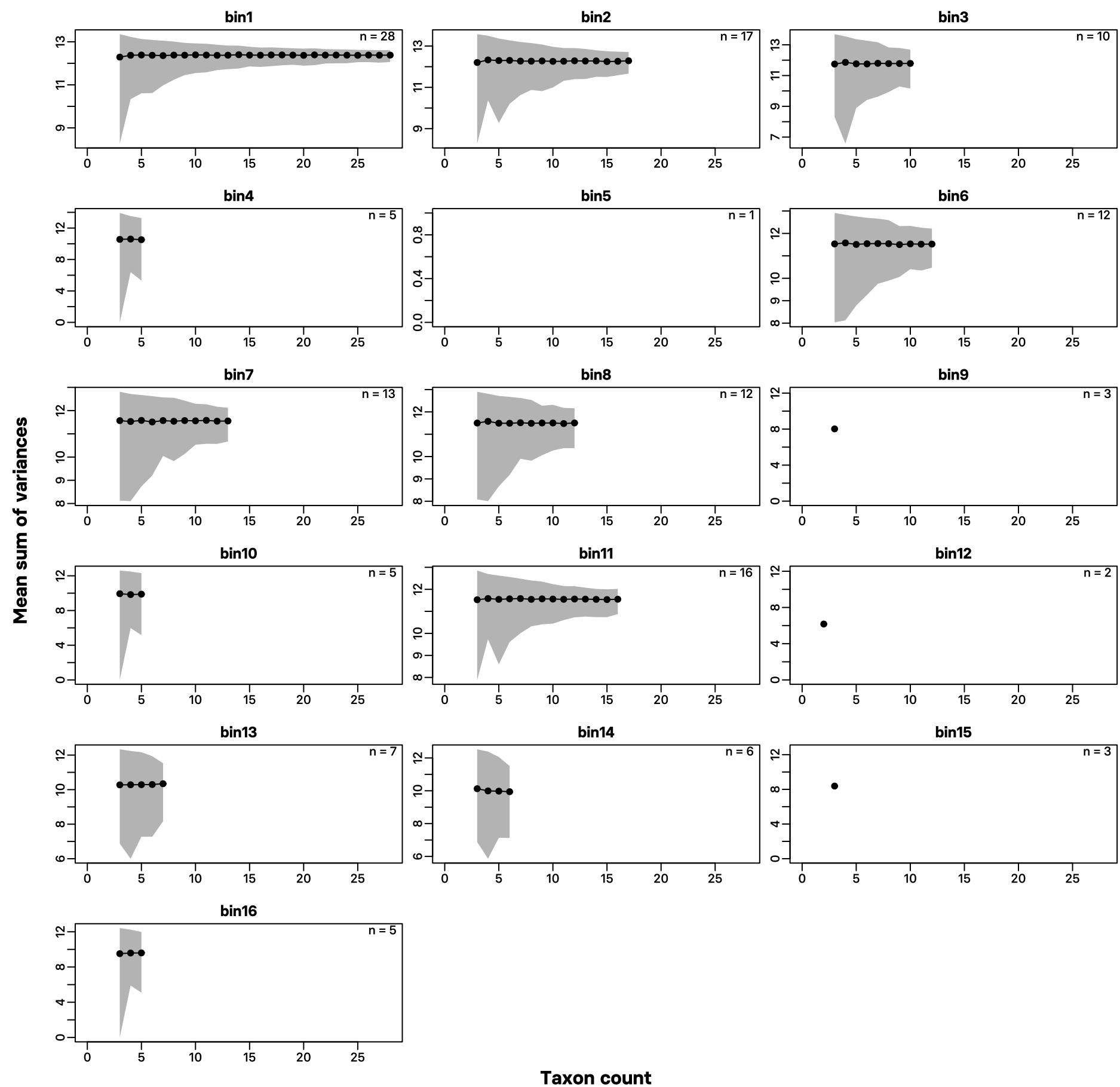
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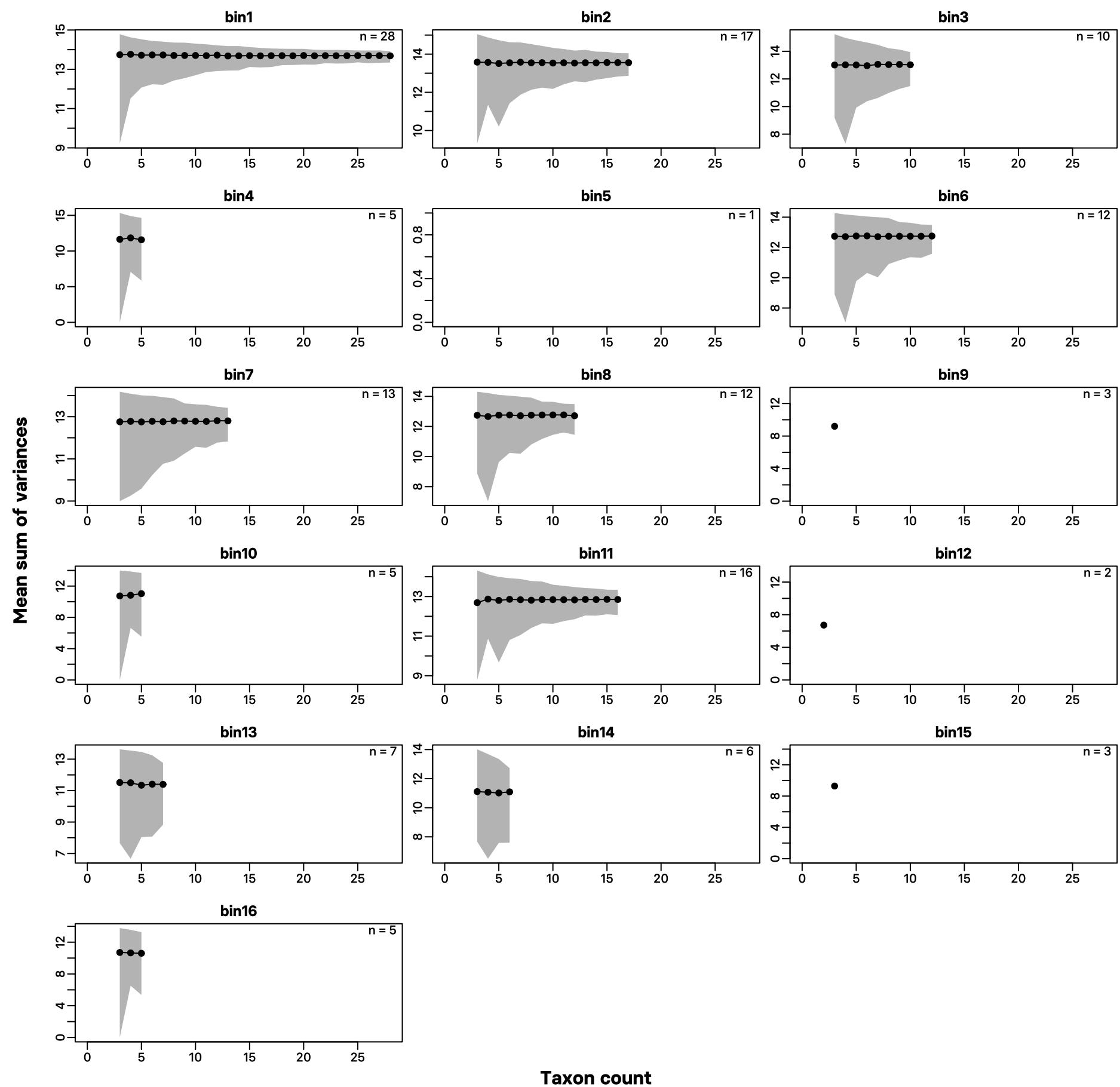
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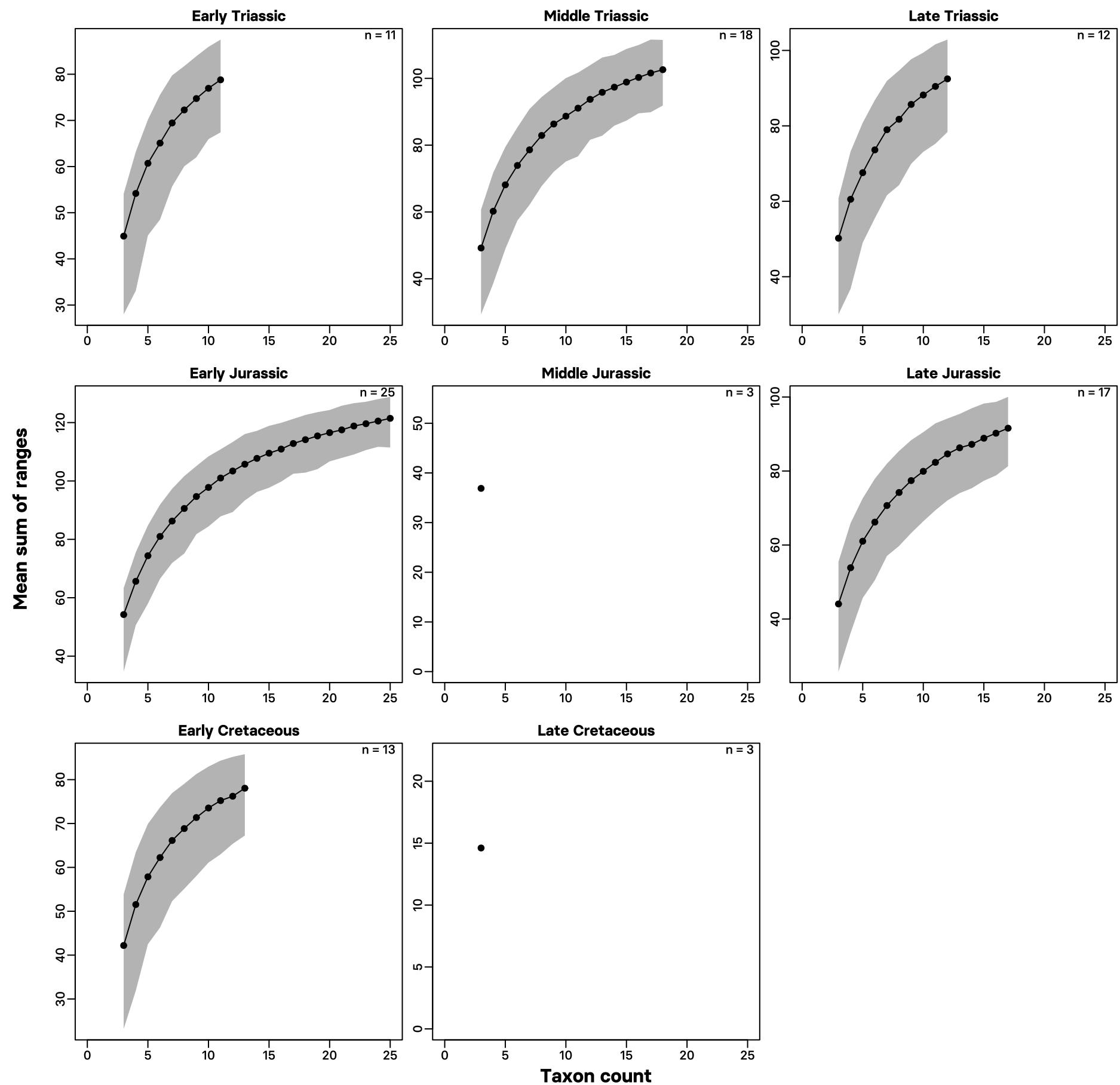
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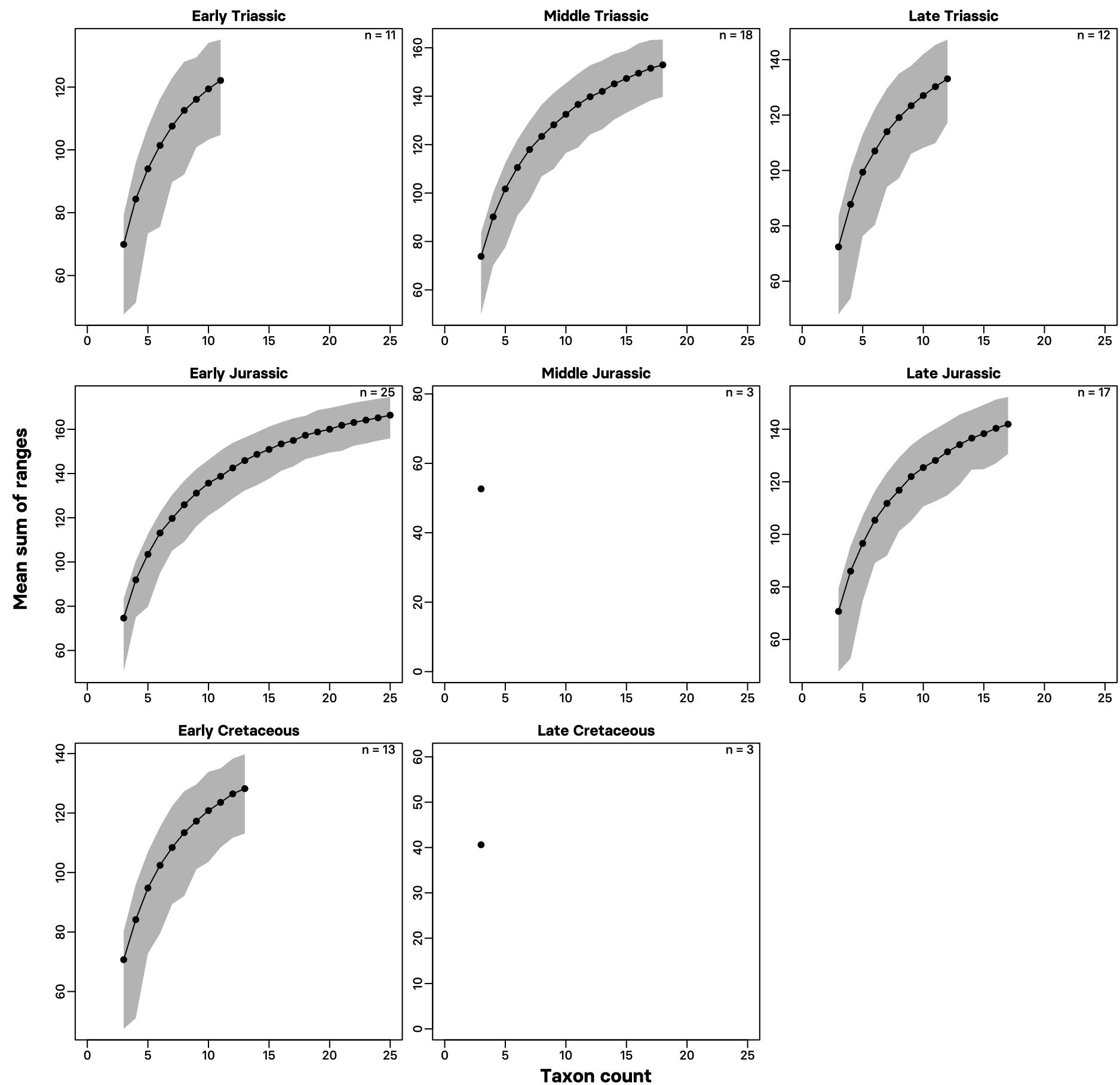
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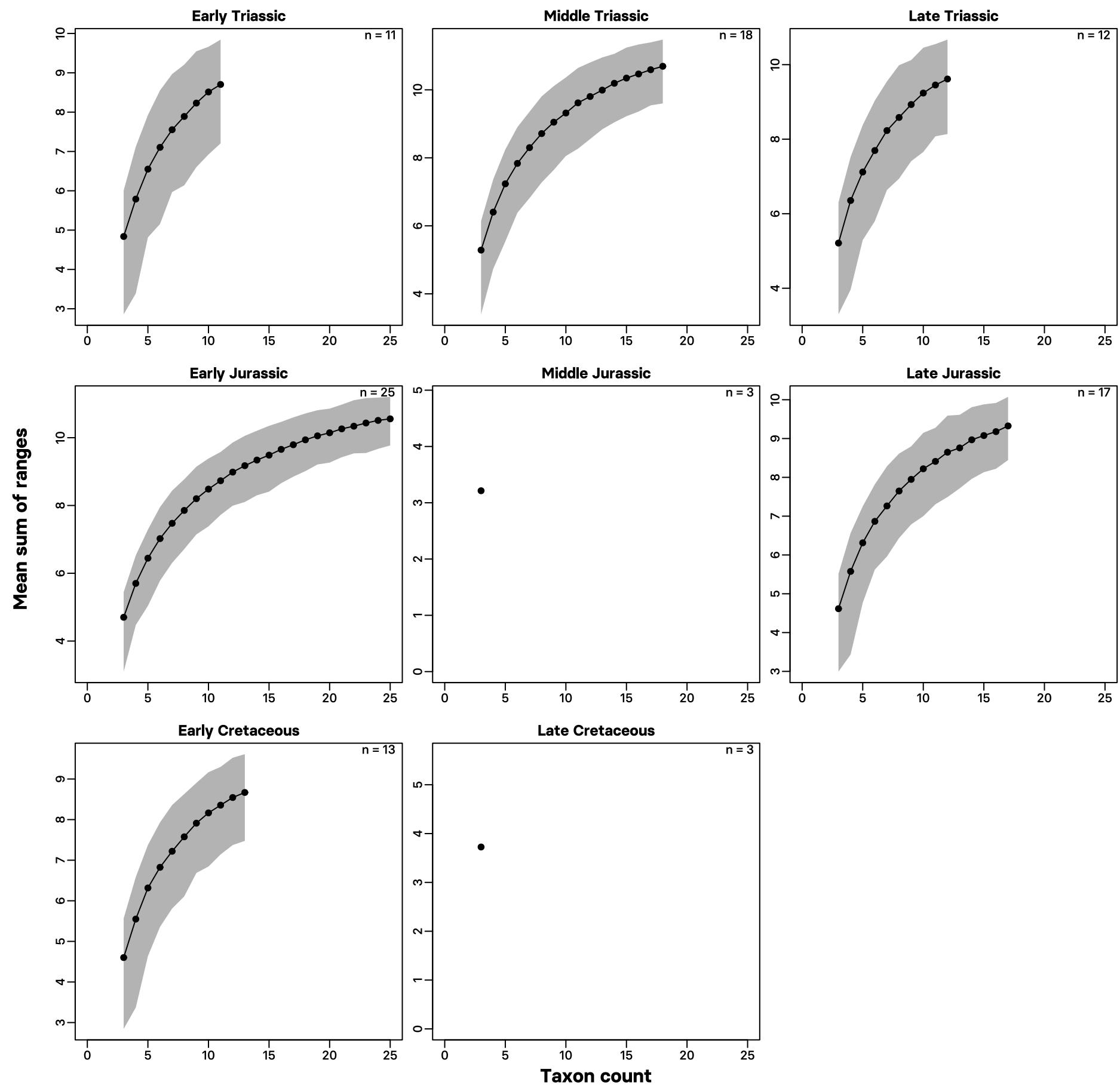
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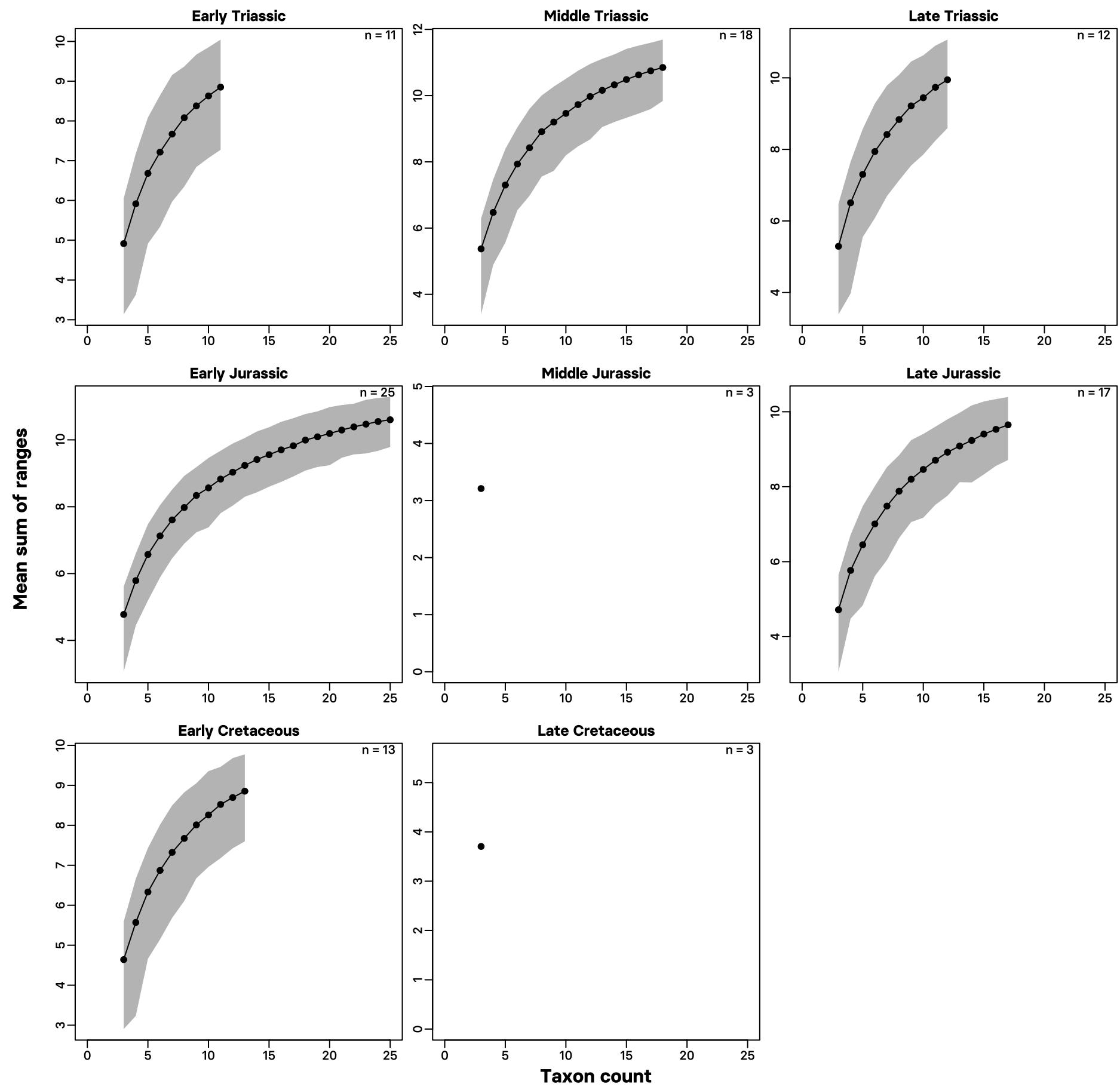
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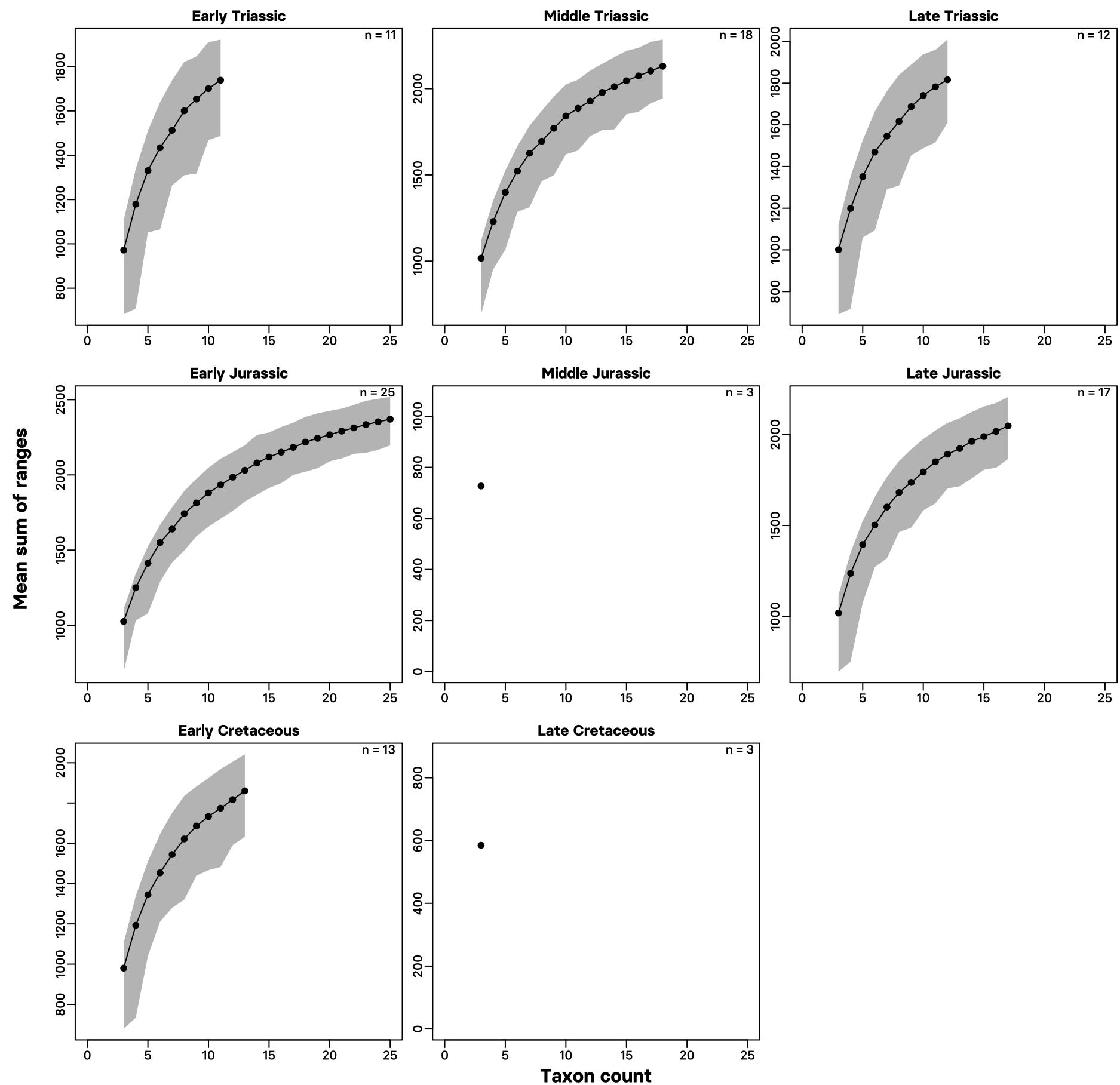
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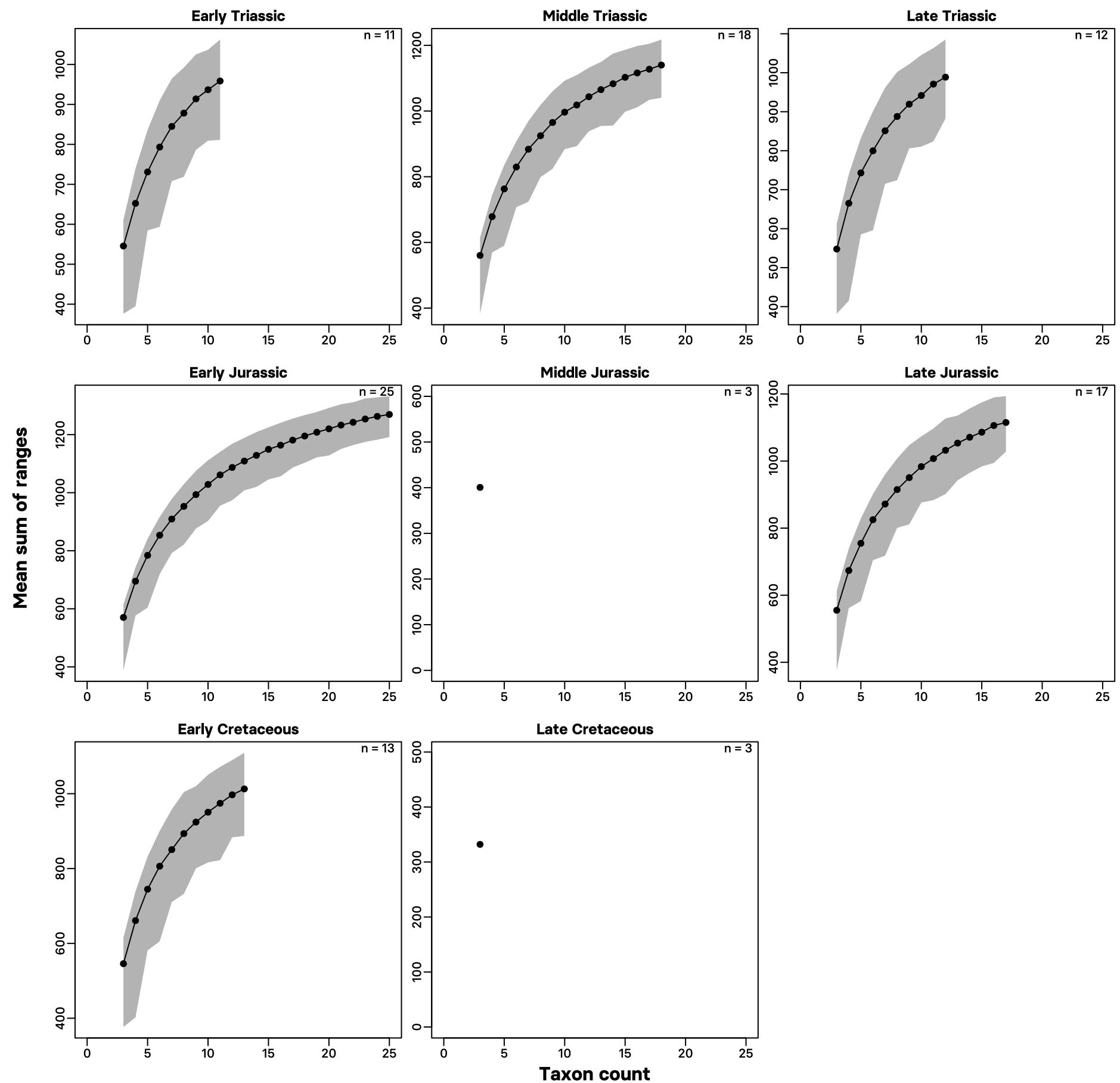
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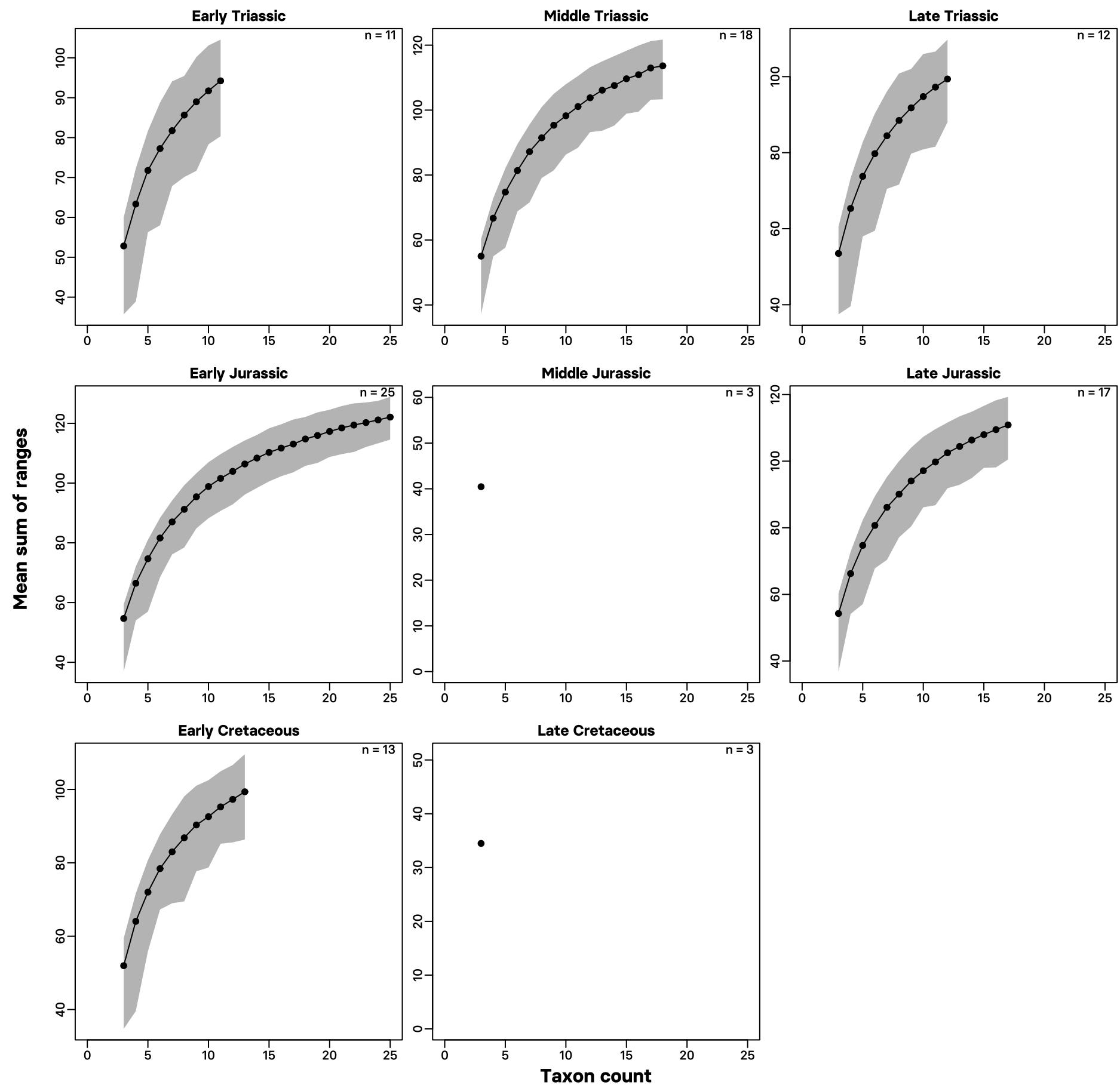
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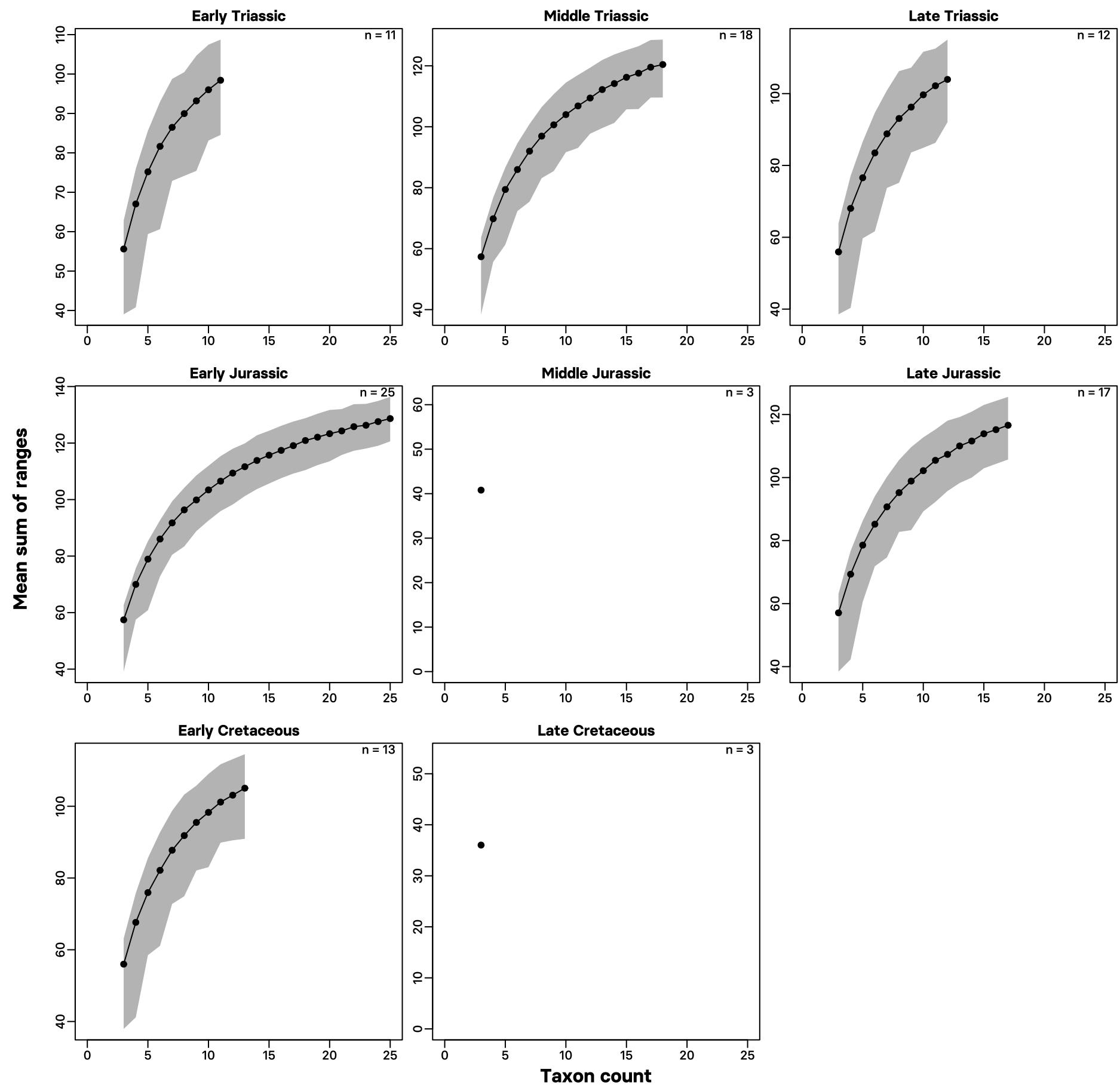
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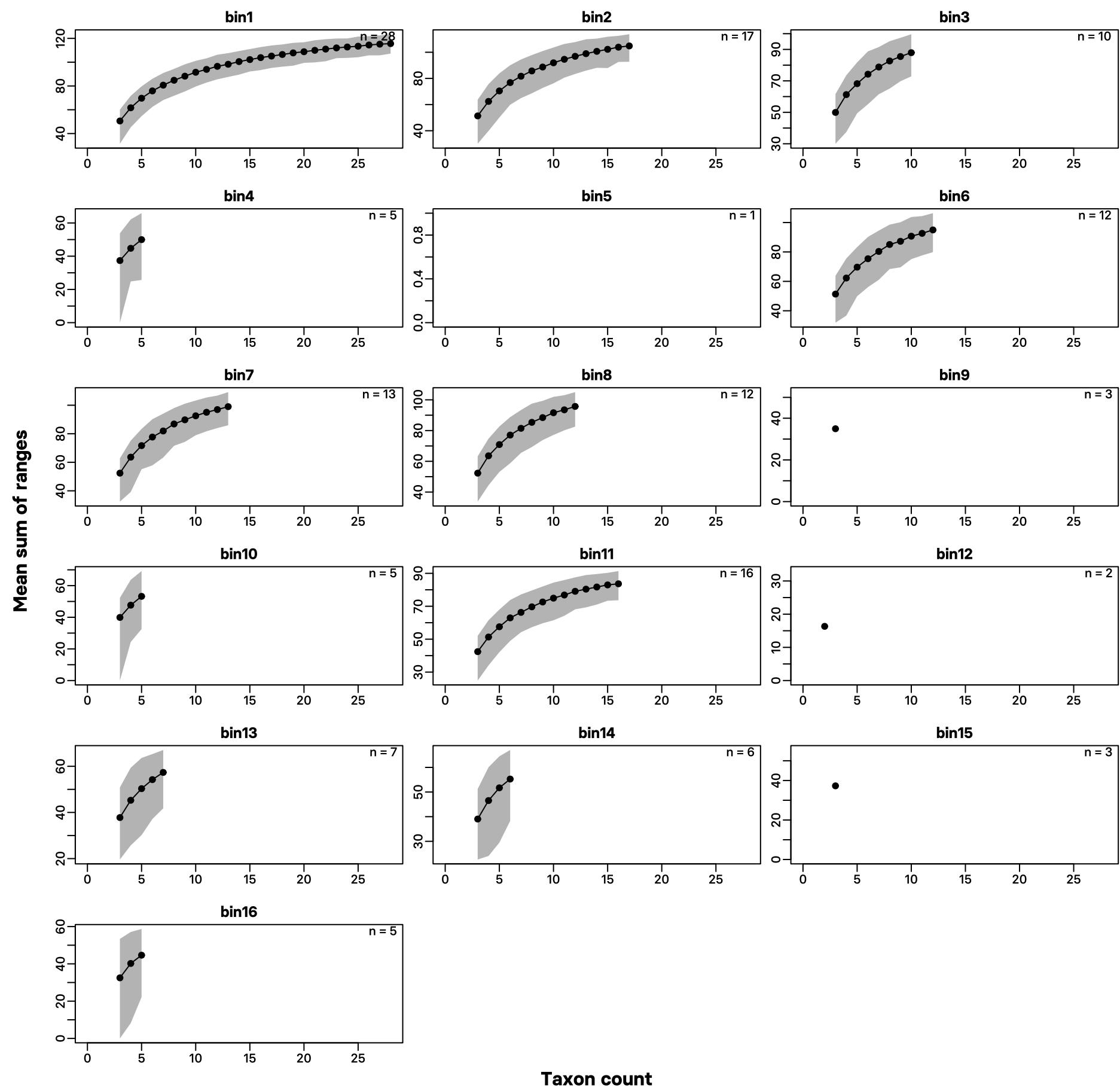
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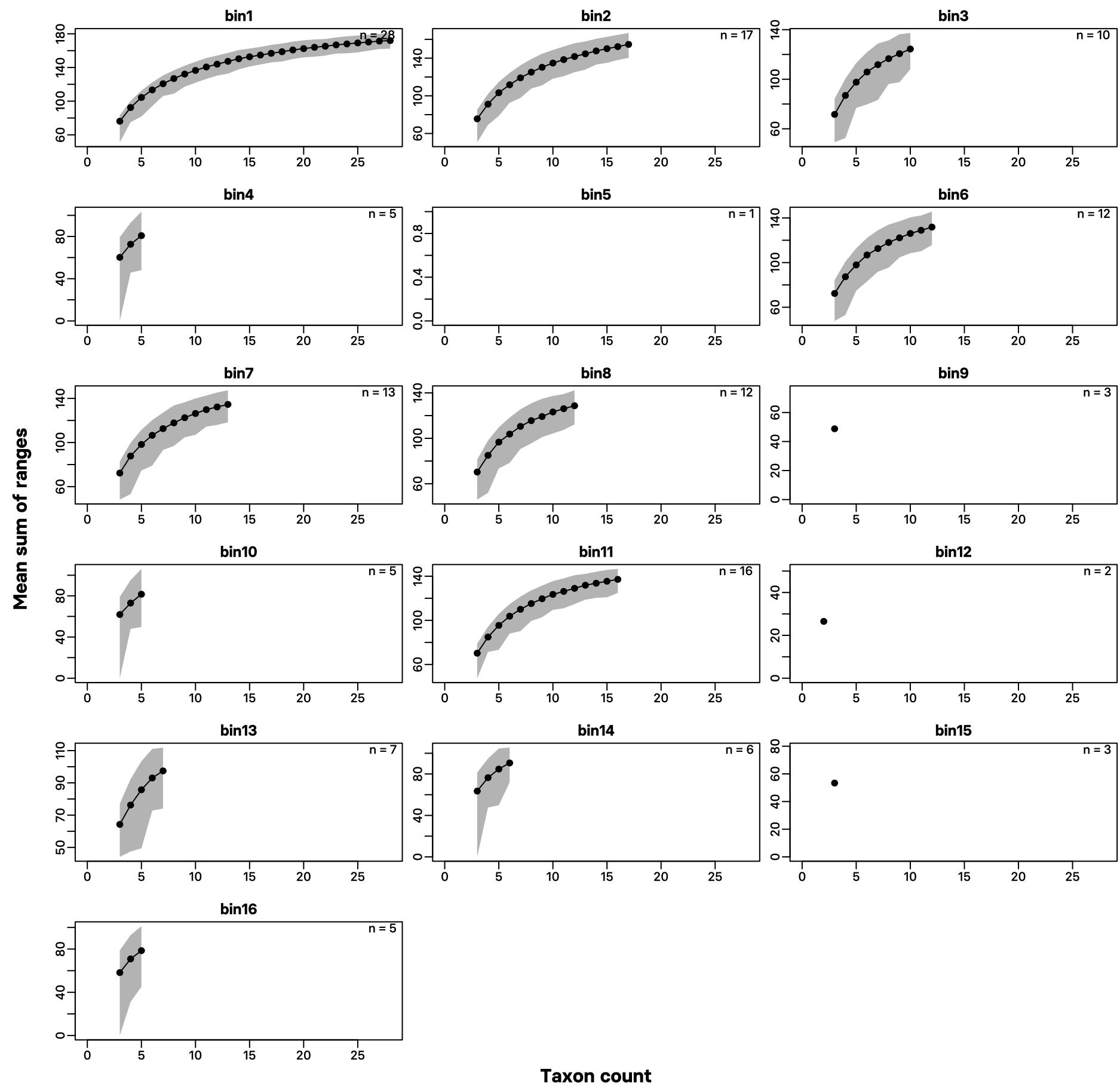
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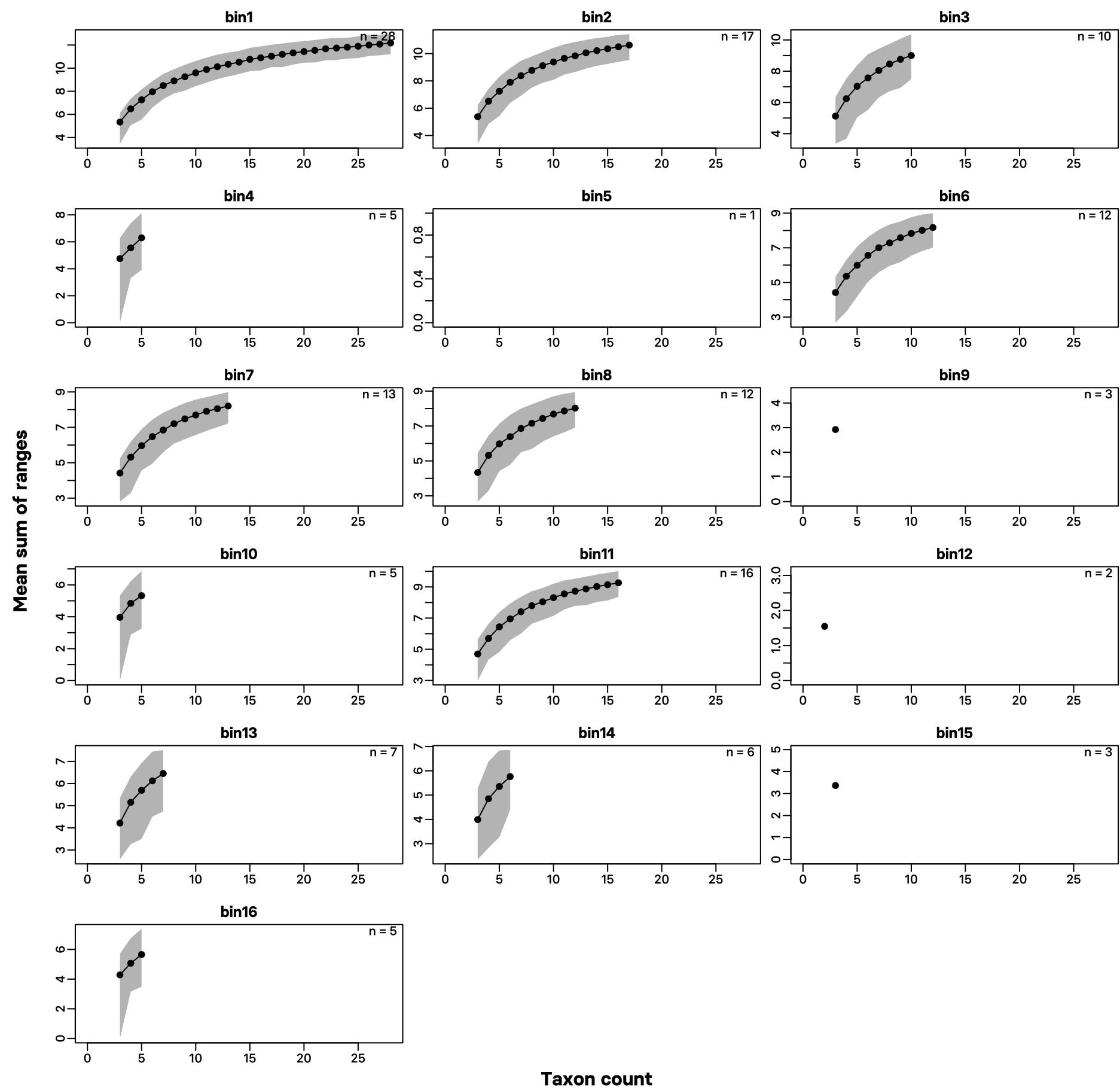
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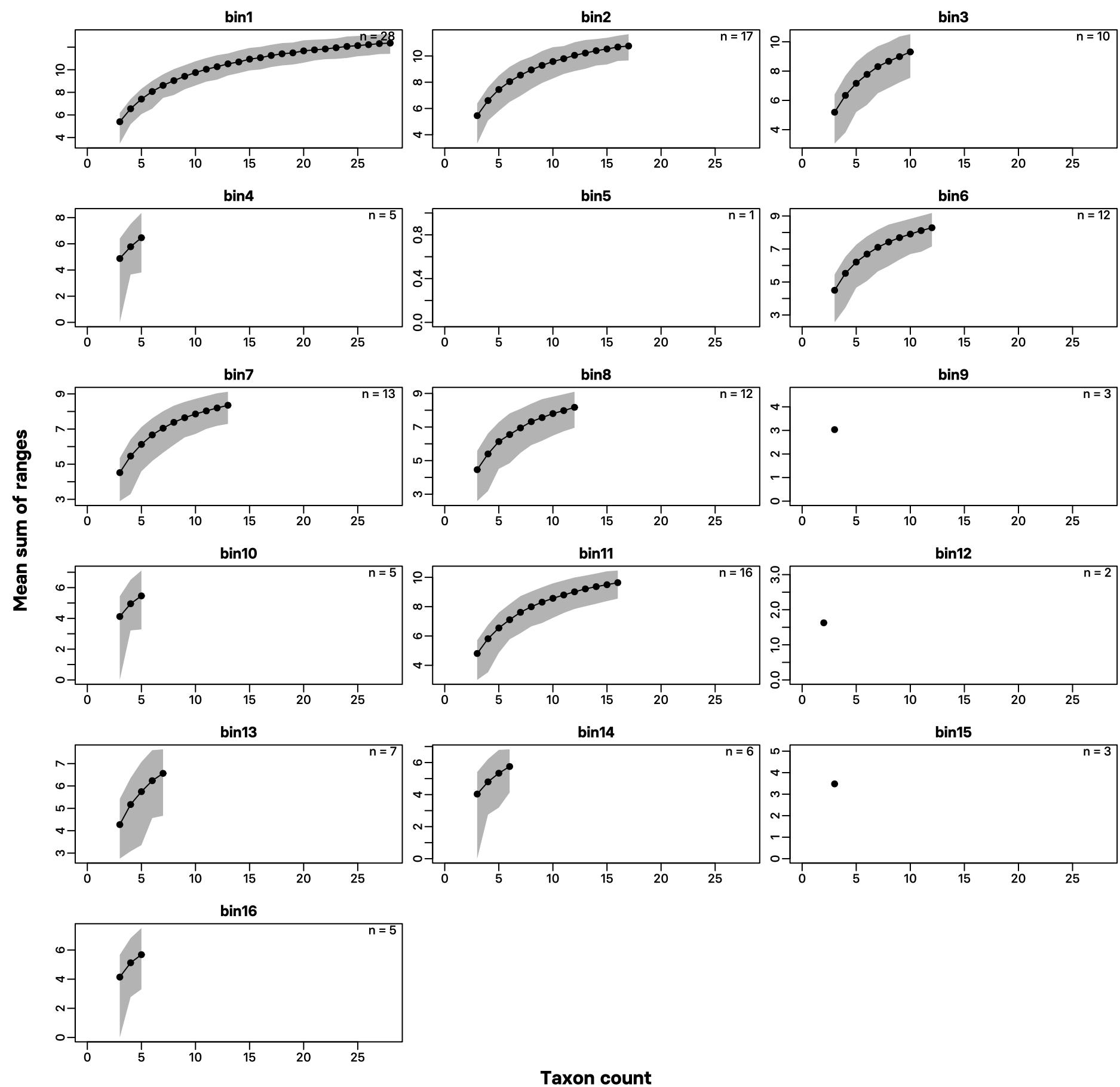
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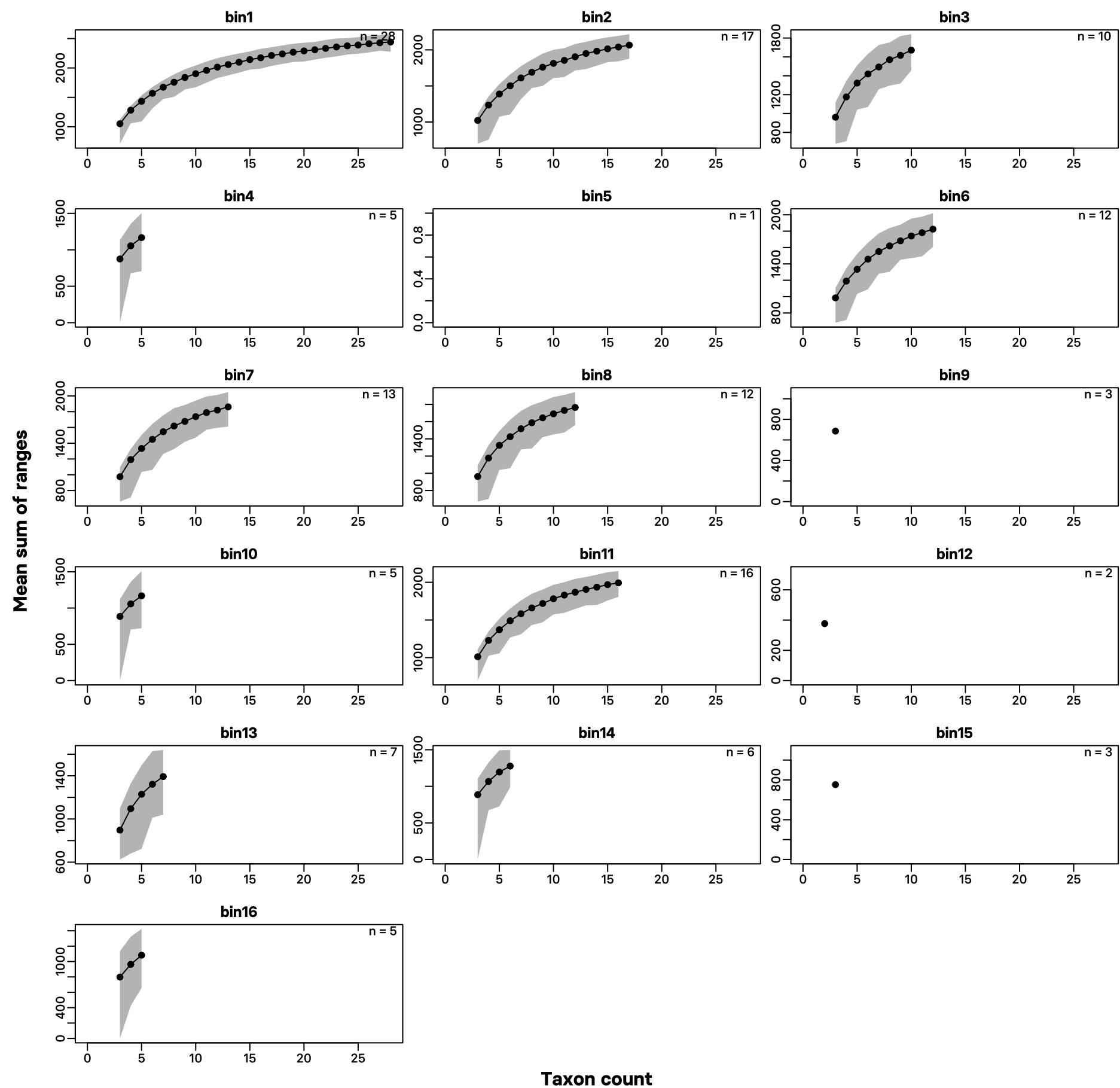
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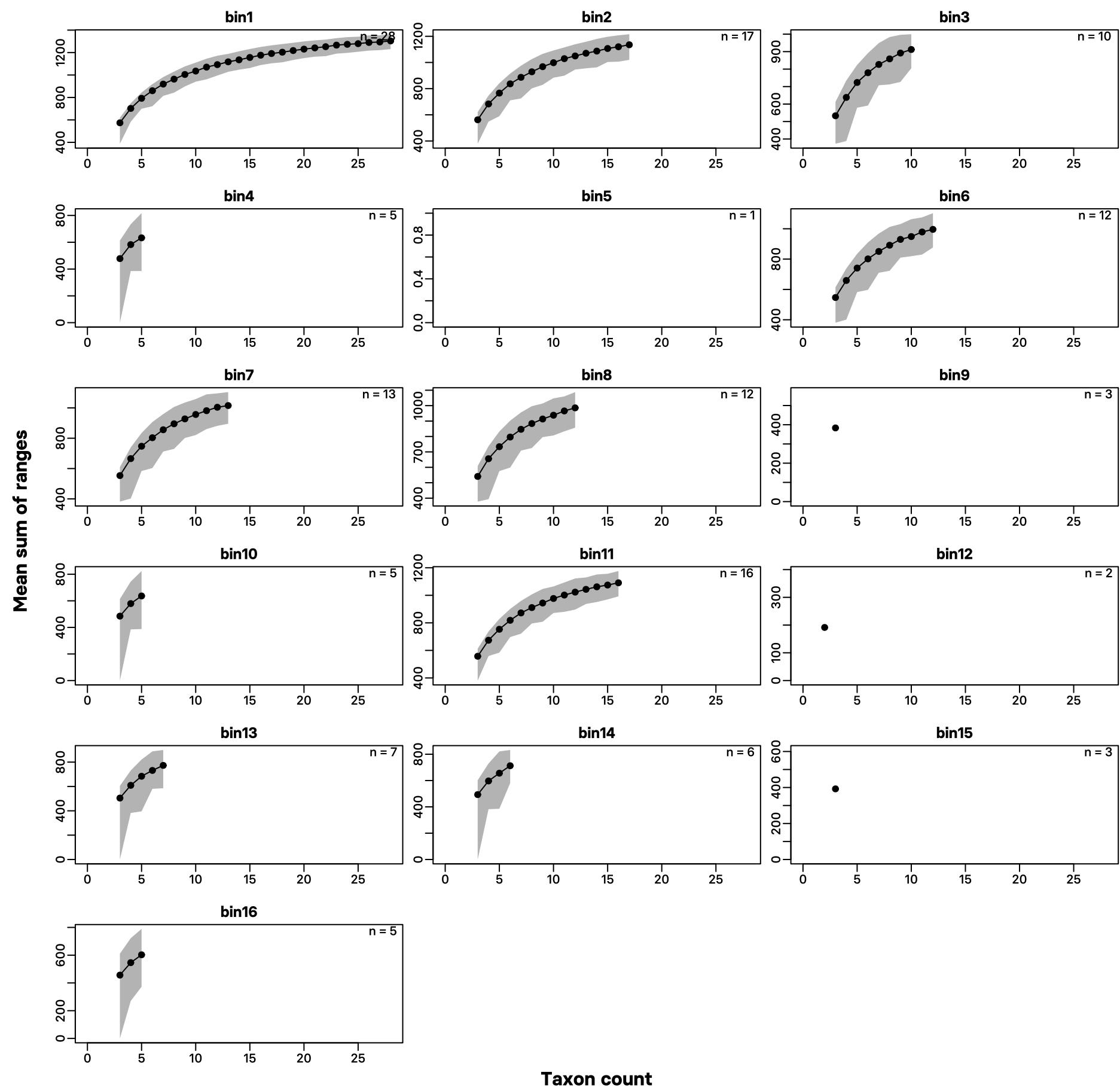
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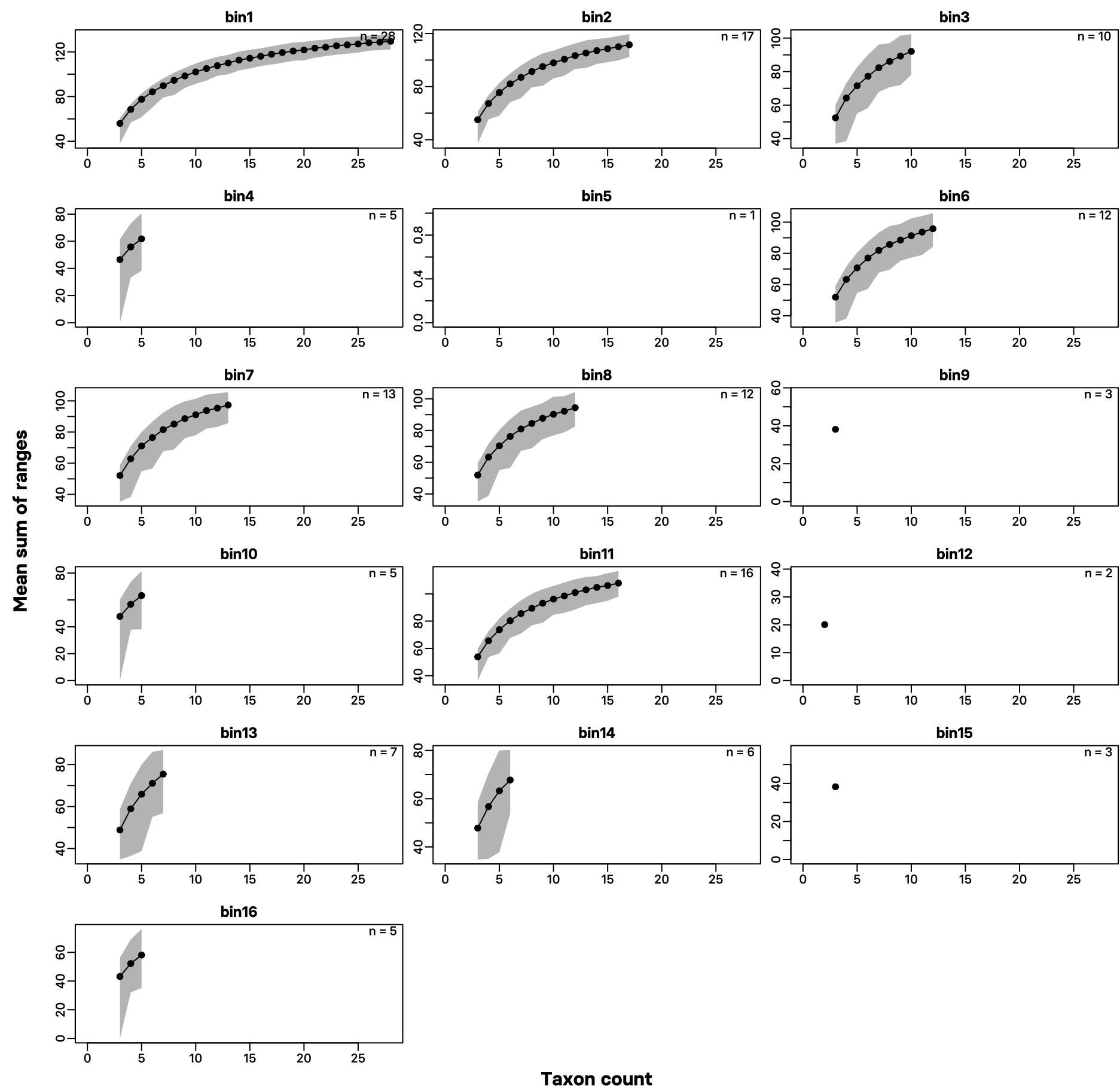
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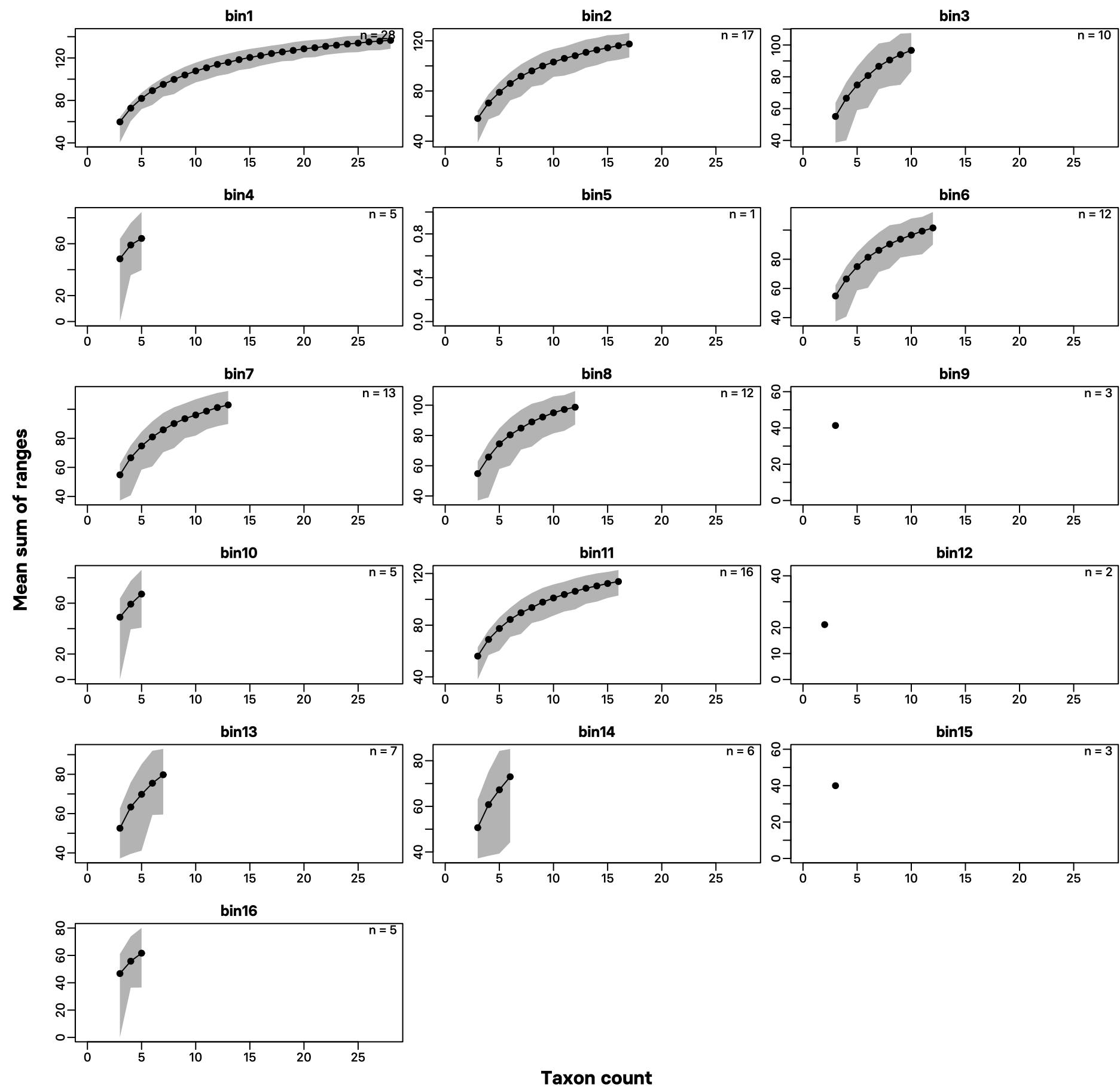
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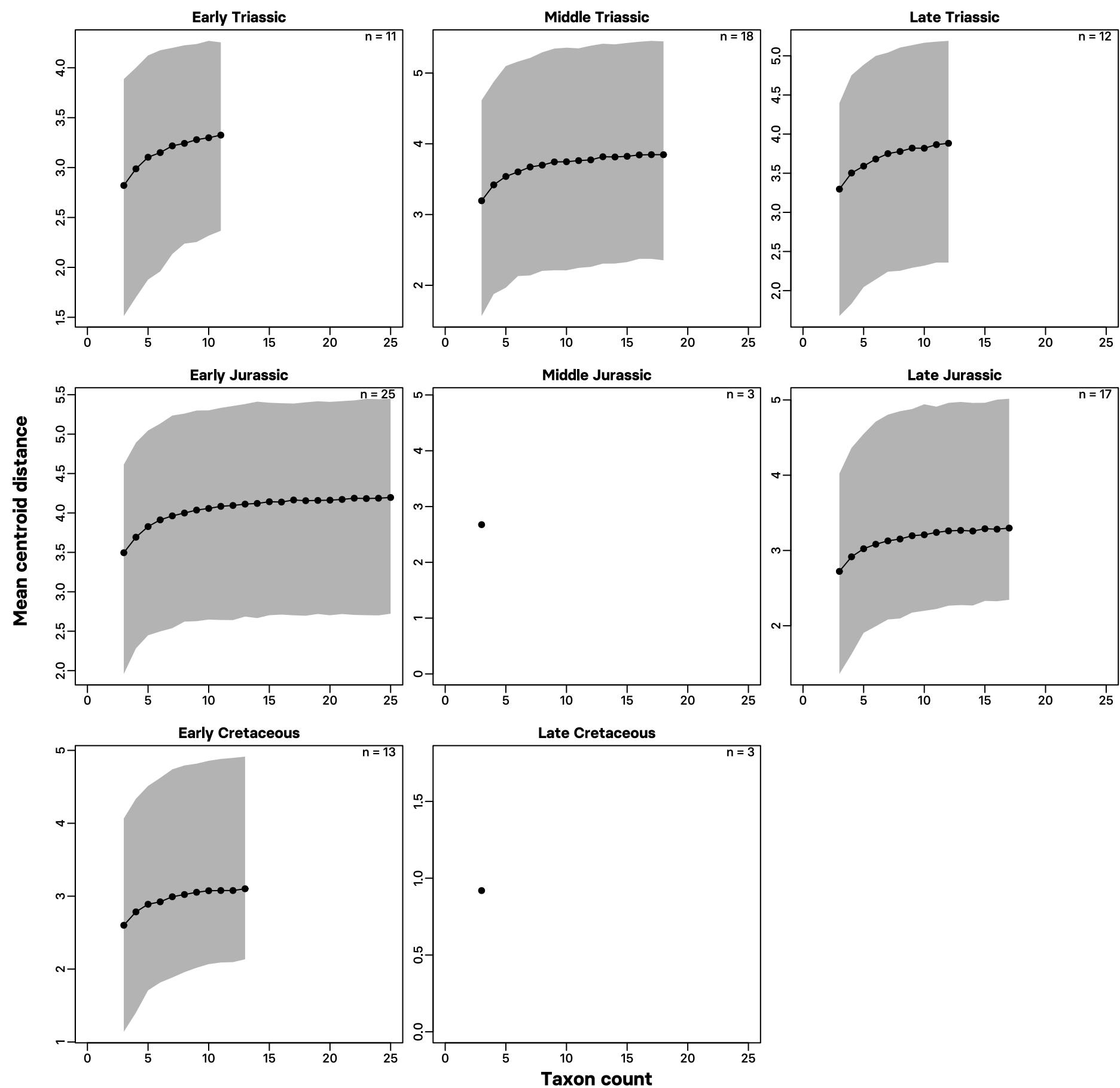
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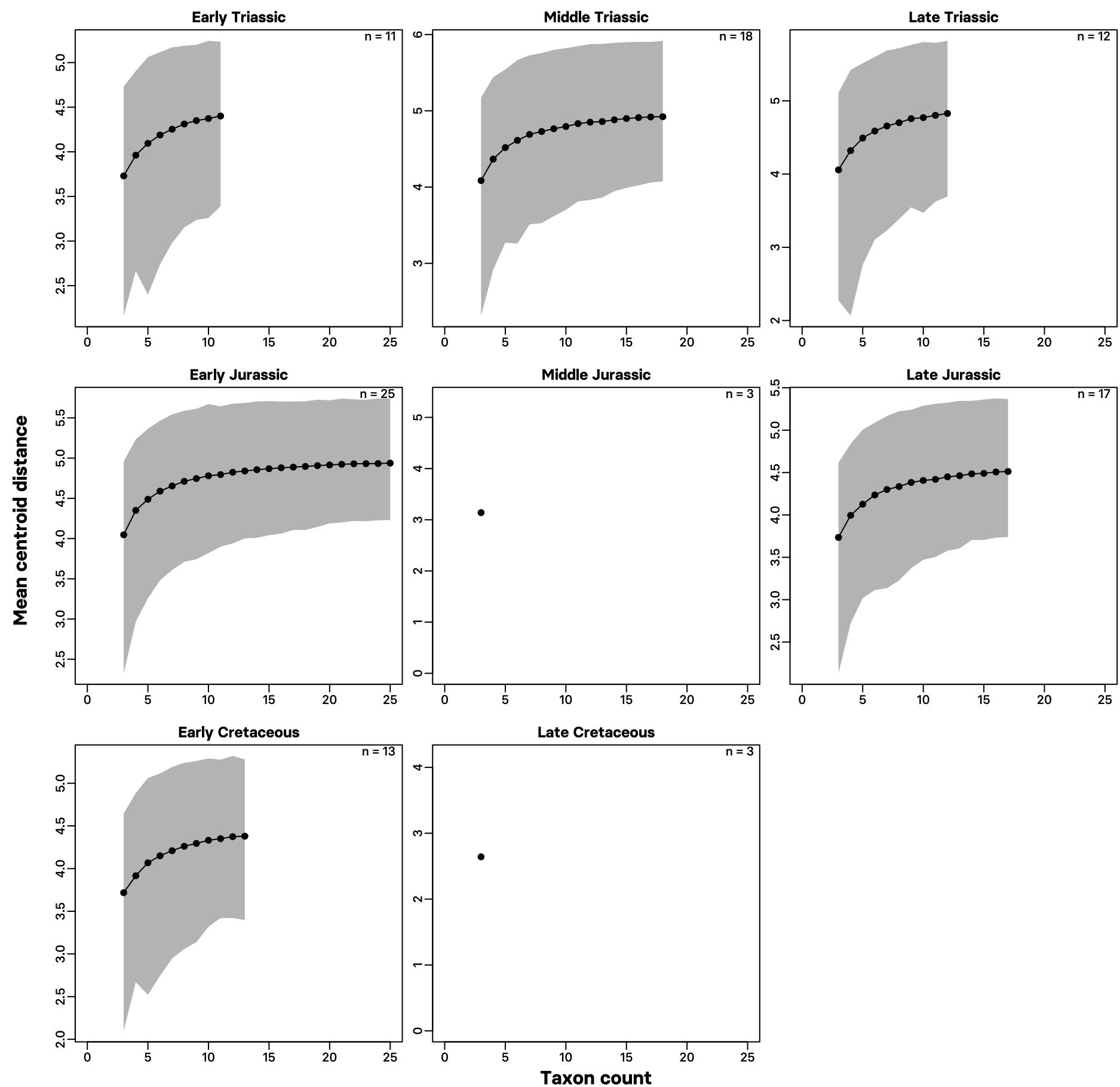
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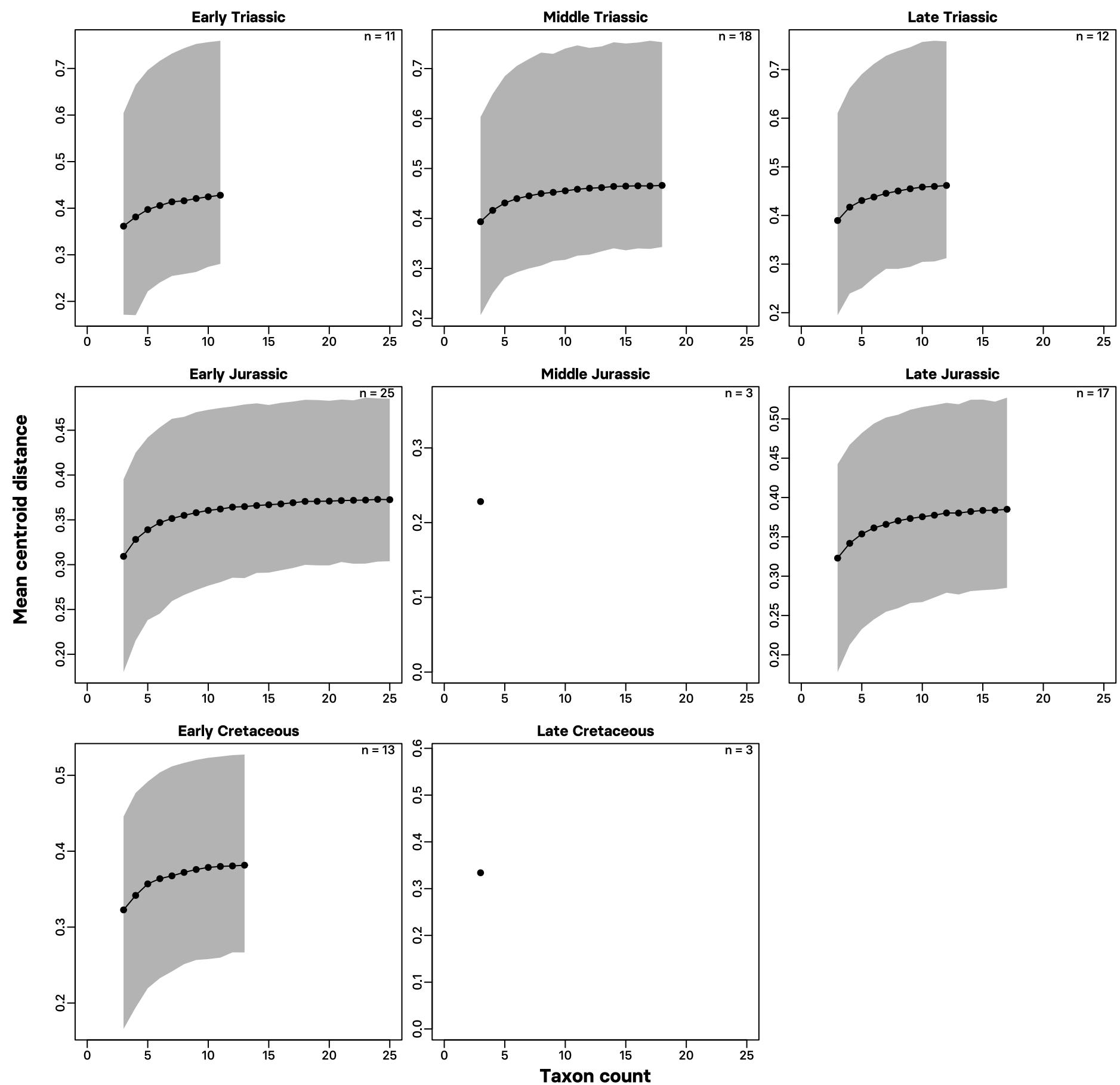
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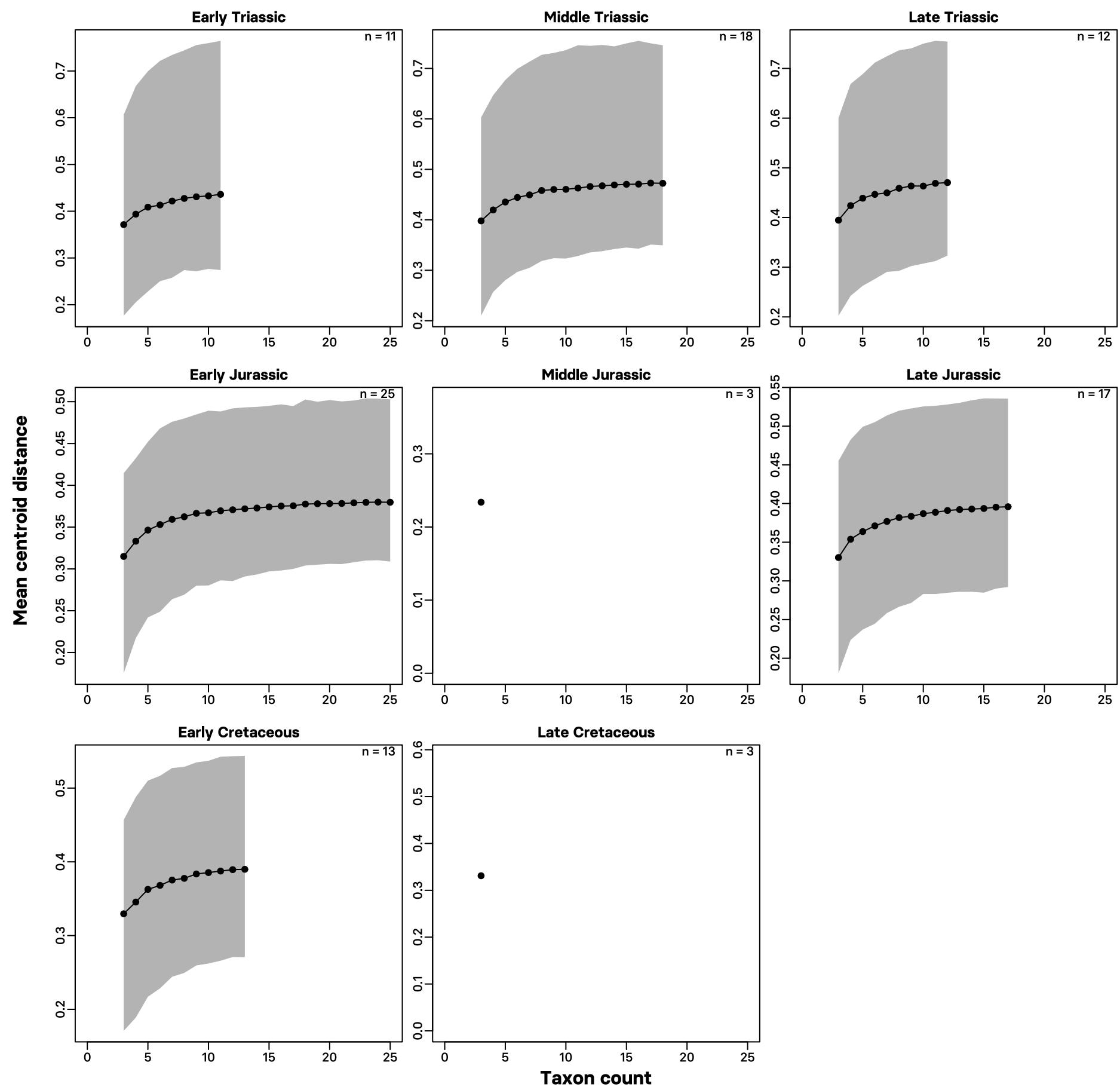
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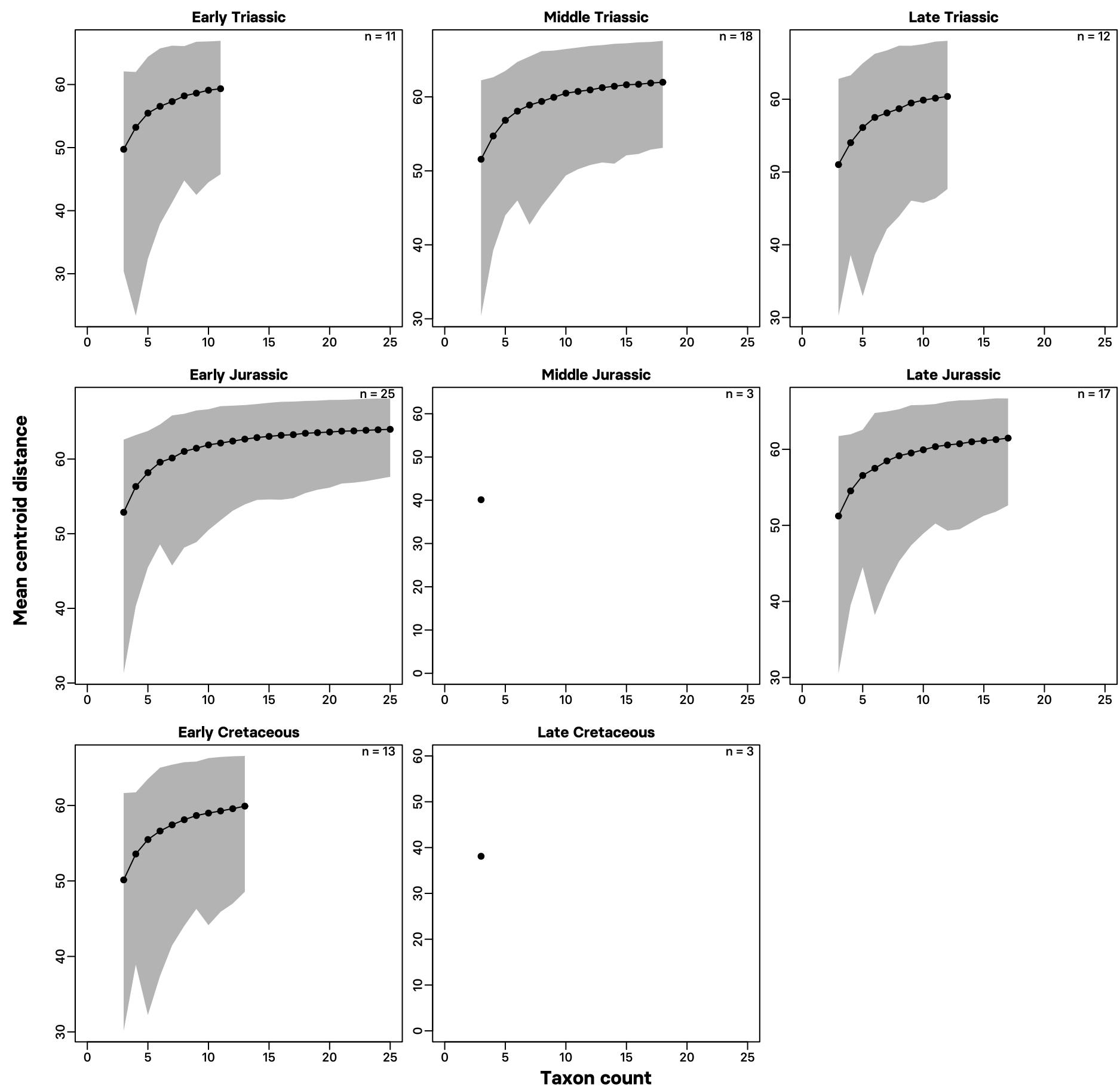
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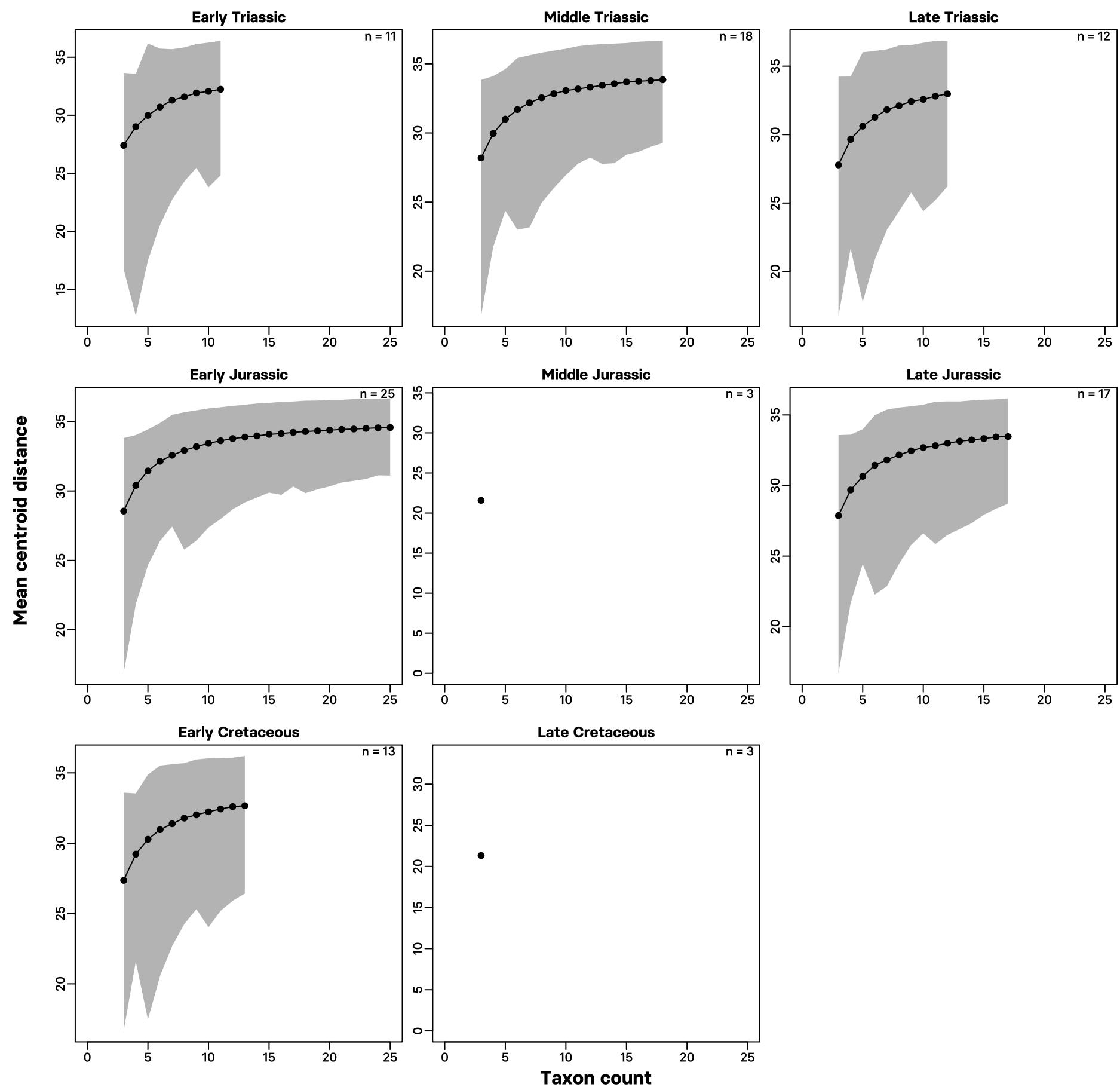
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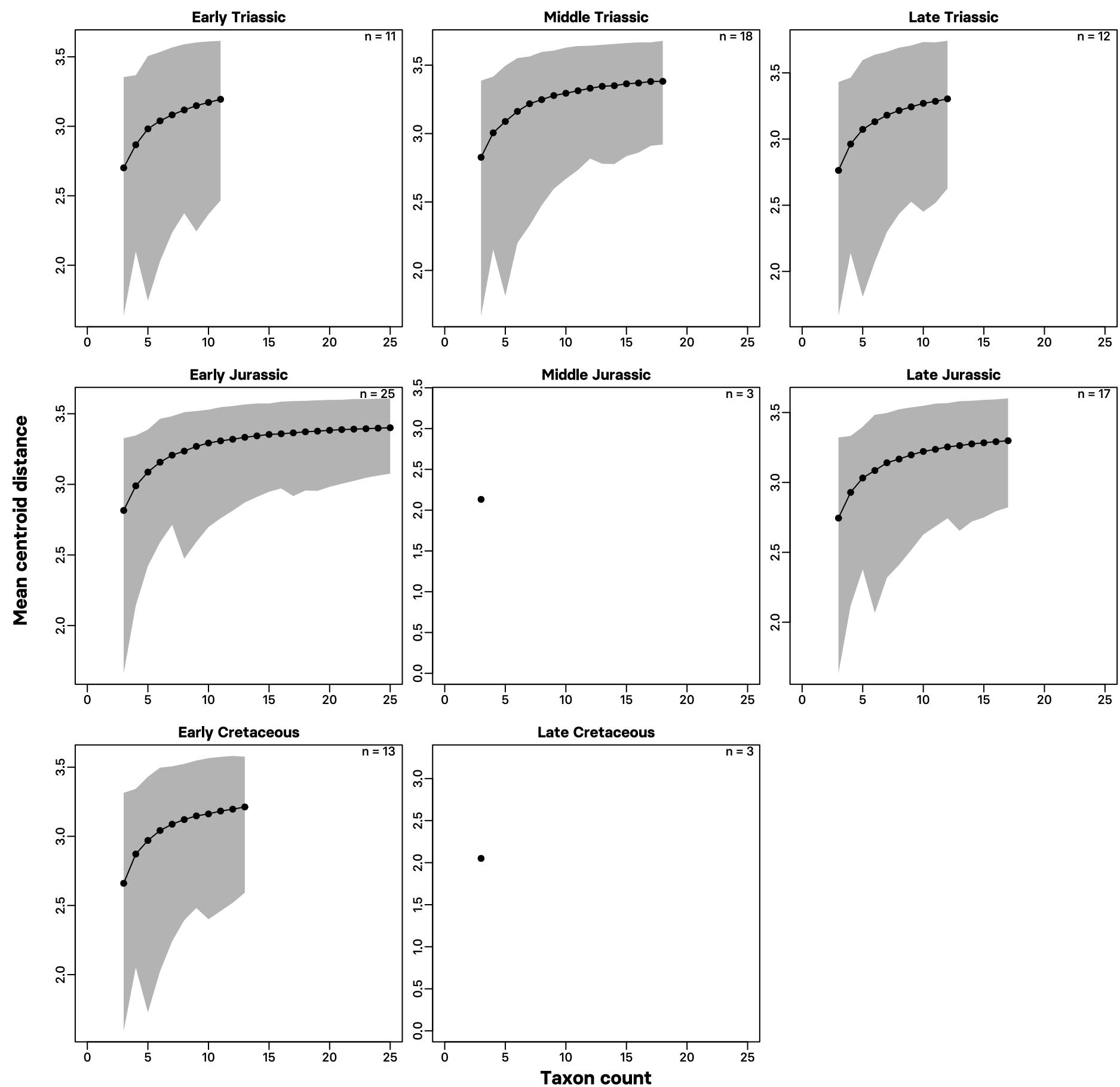
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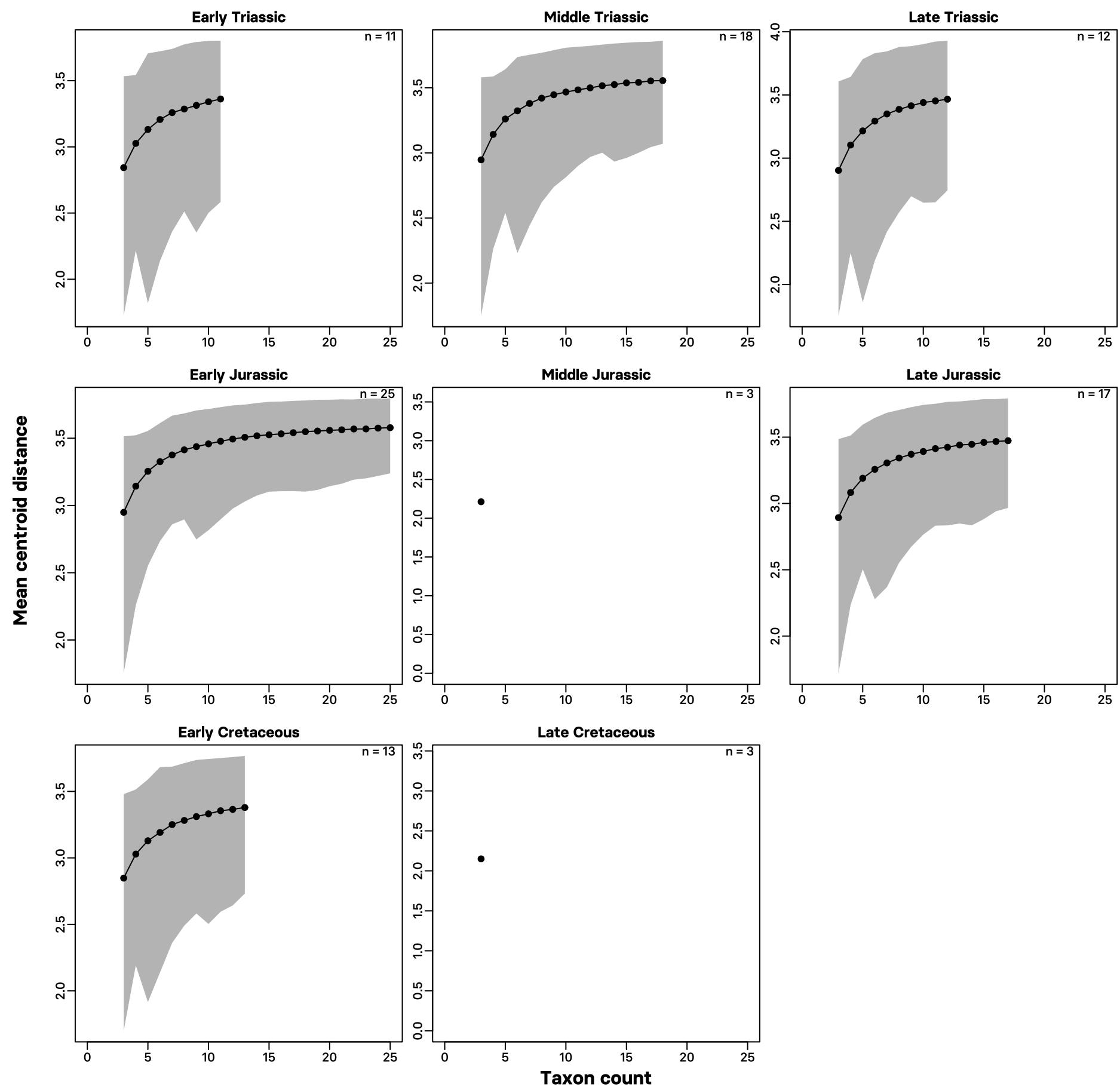
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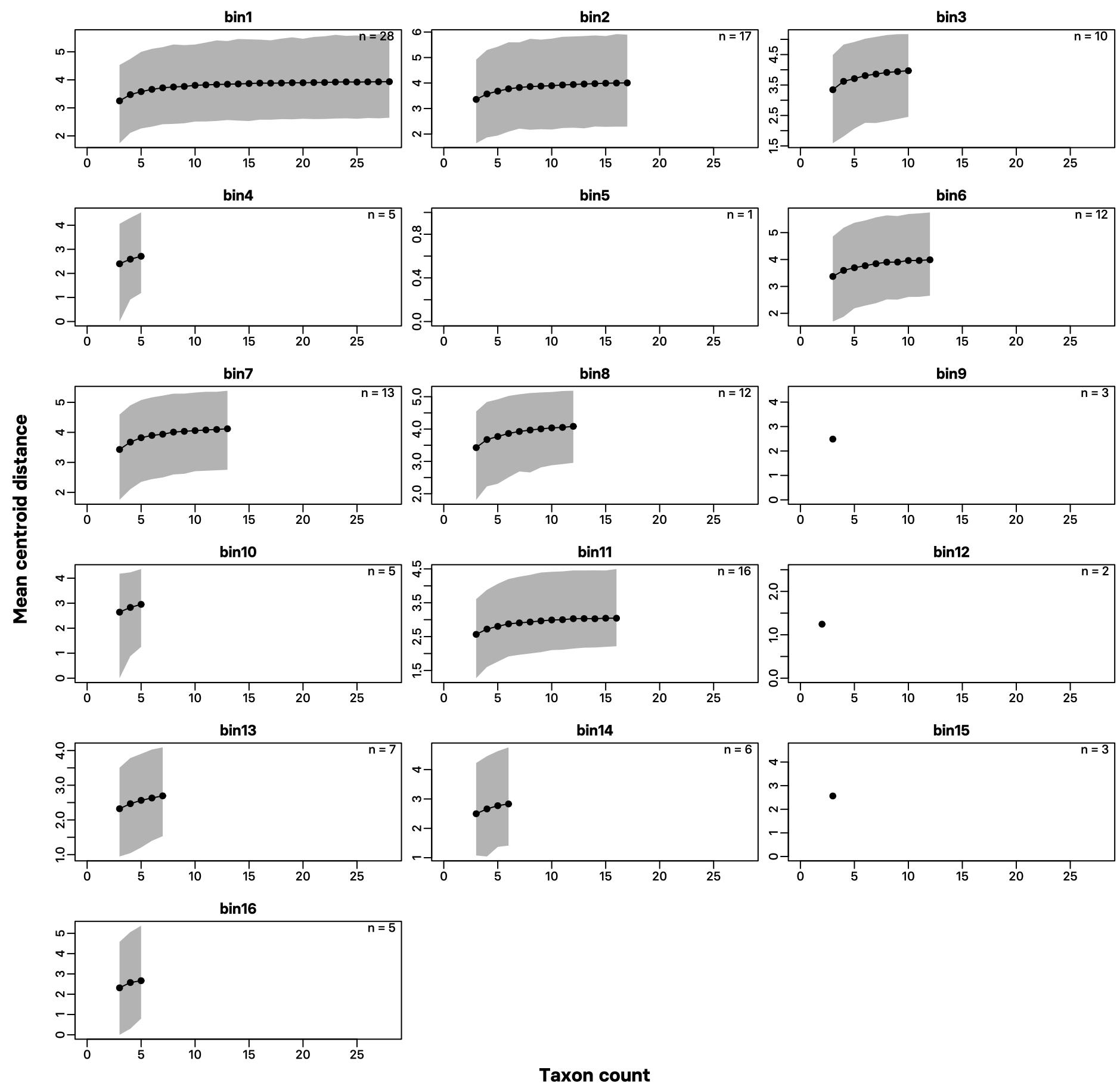
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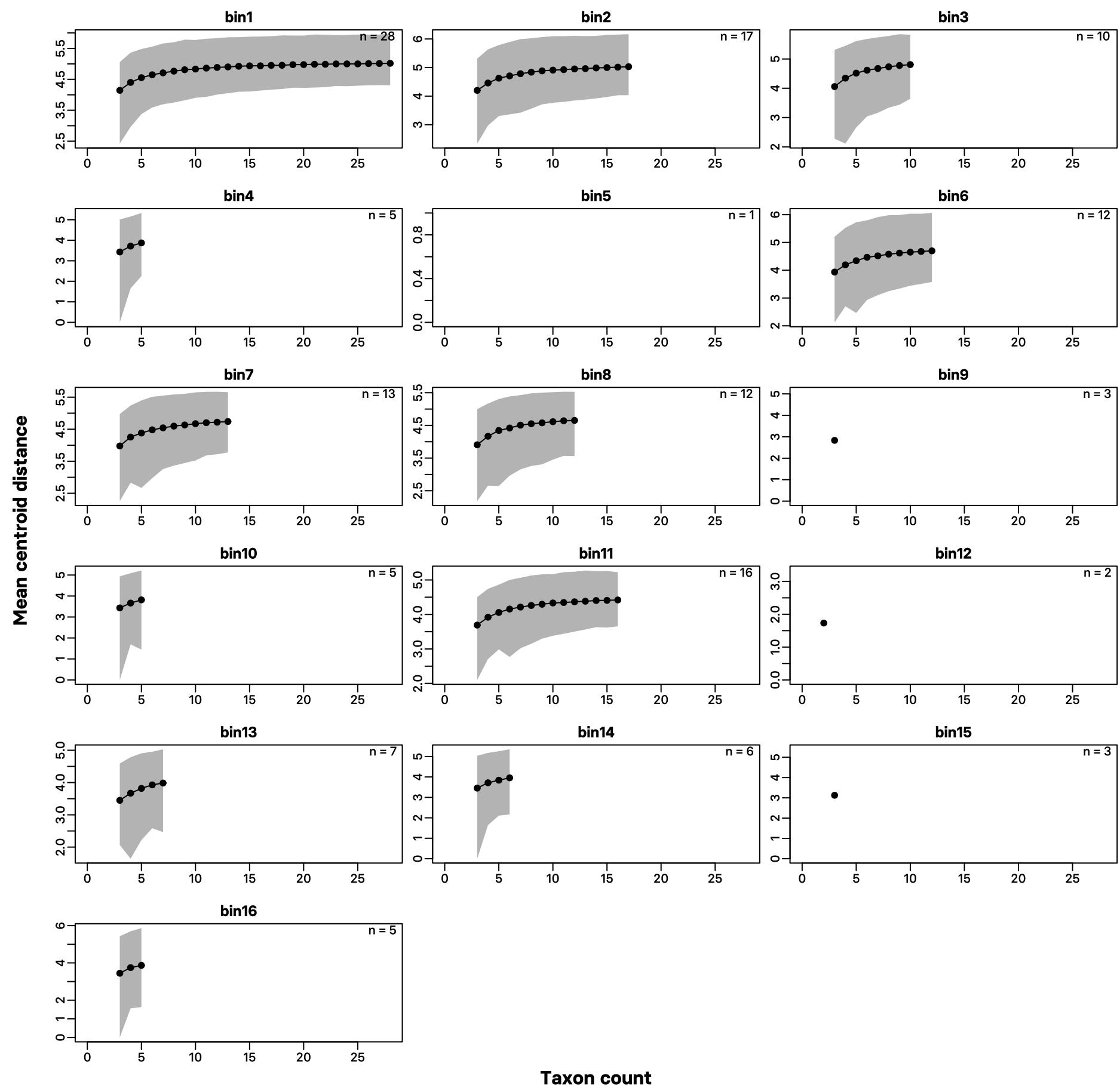
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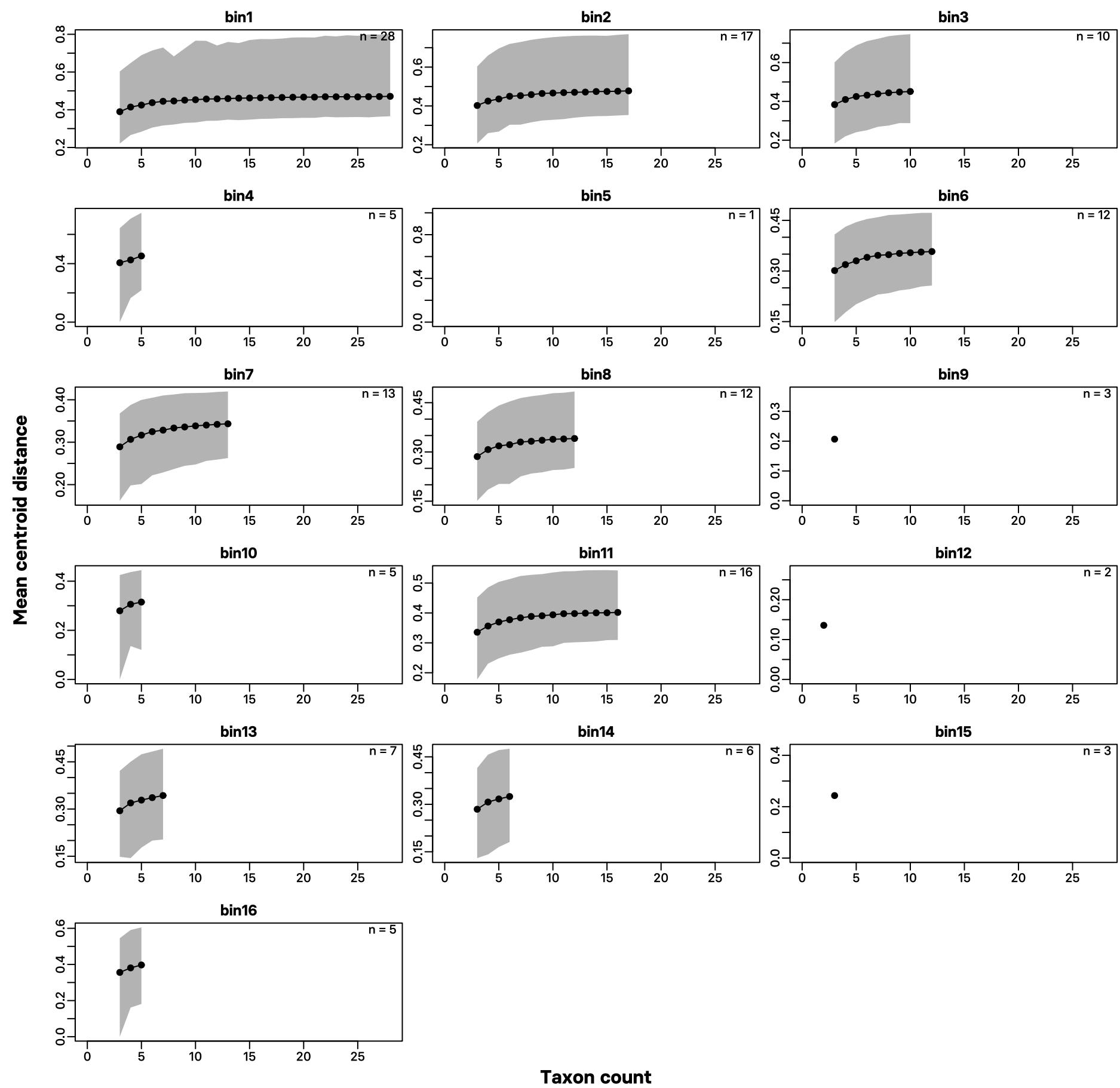
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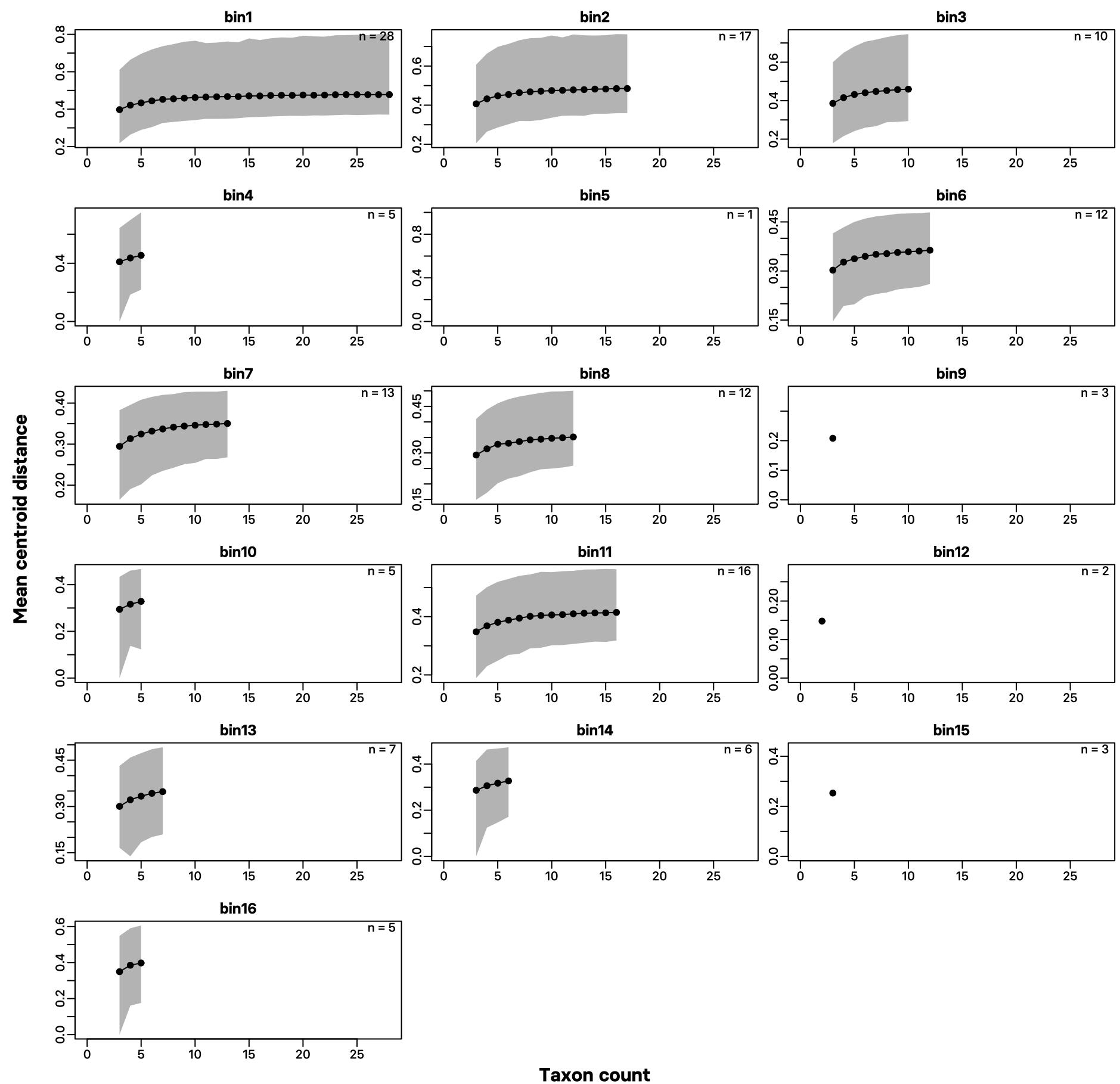
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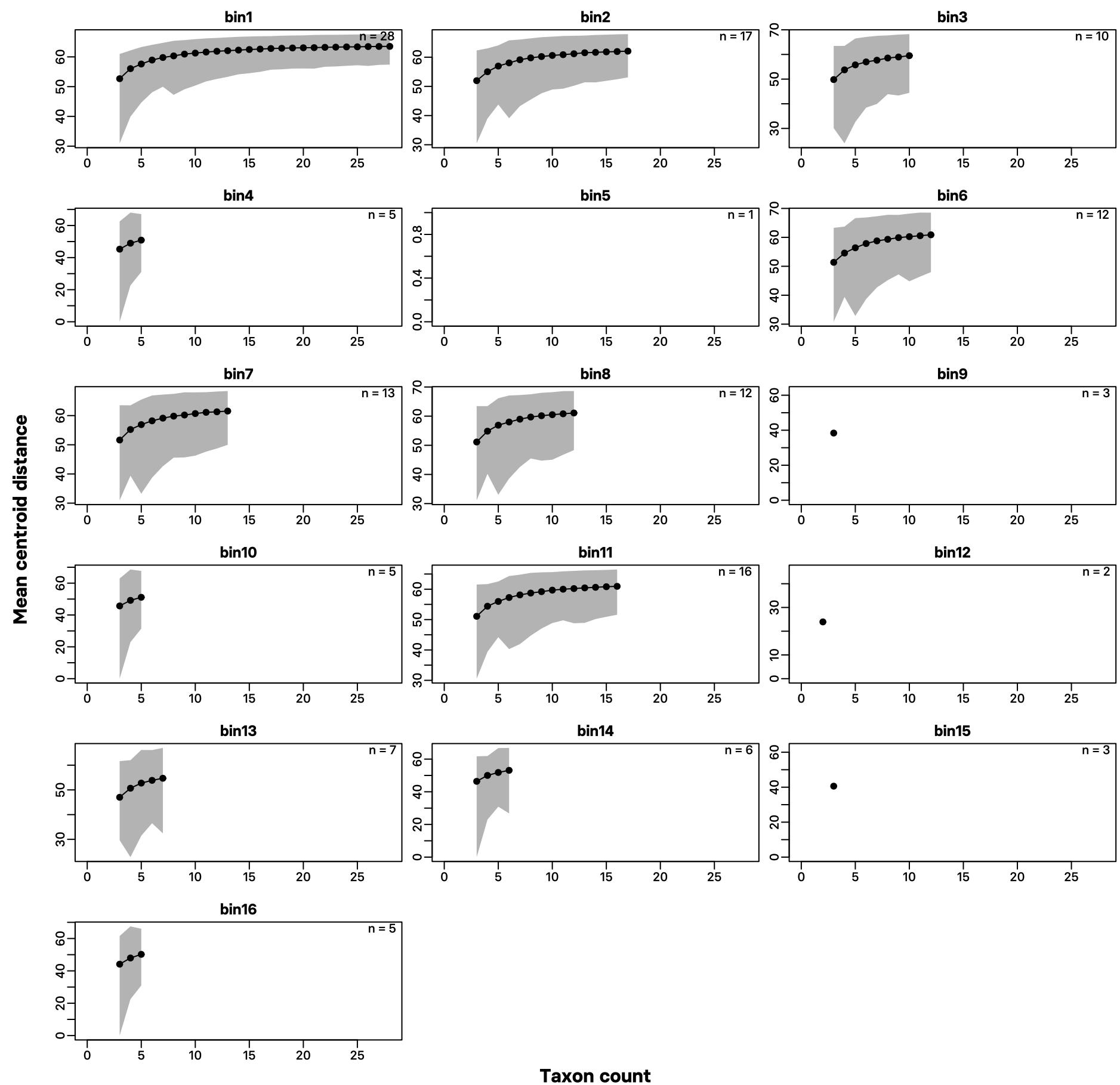
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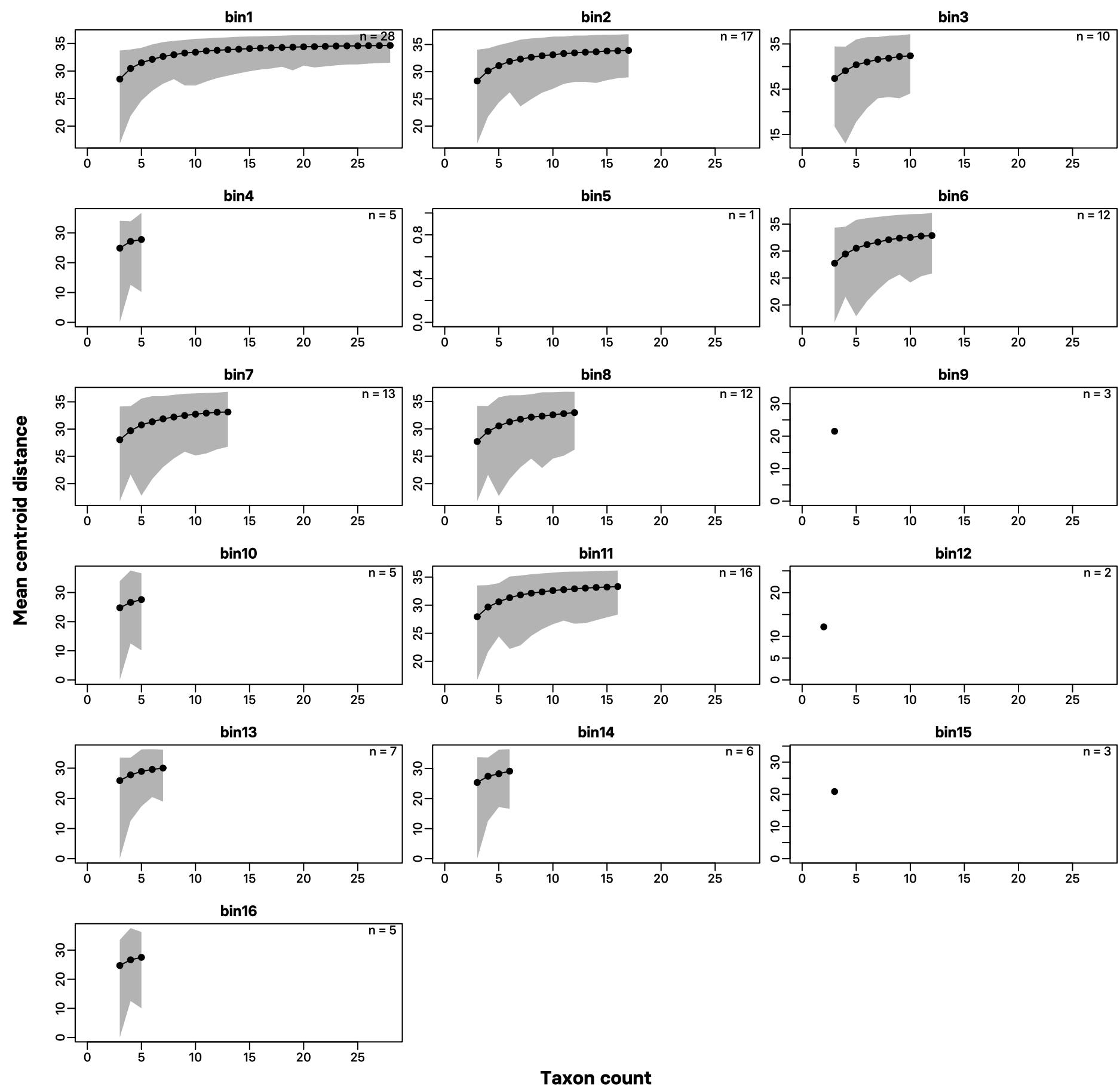
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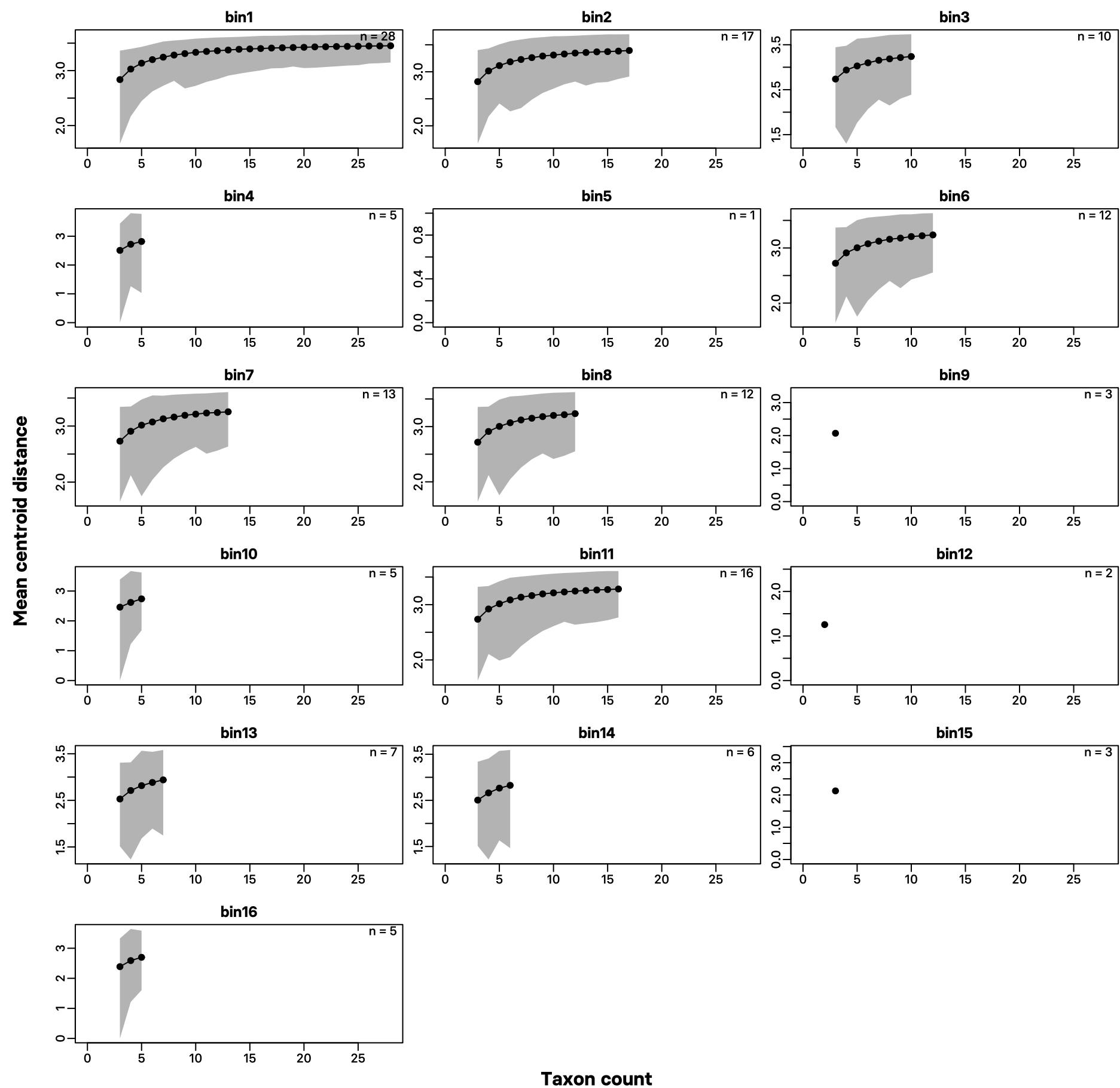
Rarefaction curves: mean centroid distance of Cailleuz-corrected RAW distance matrix in 10 Ma bins



Rarefaction curves: mean centroid distance of Cailleuz-corrected GED distance matrix in 10 Ma bins



Rarefaction curves: mean centroid distance of Cailleuz-corrected GOW distance matrix in 10 Ma bins



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

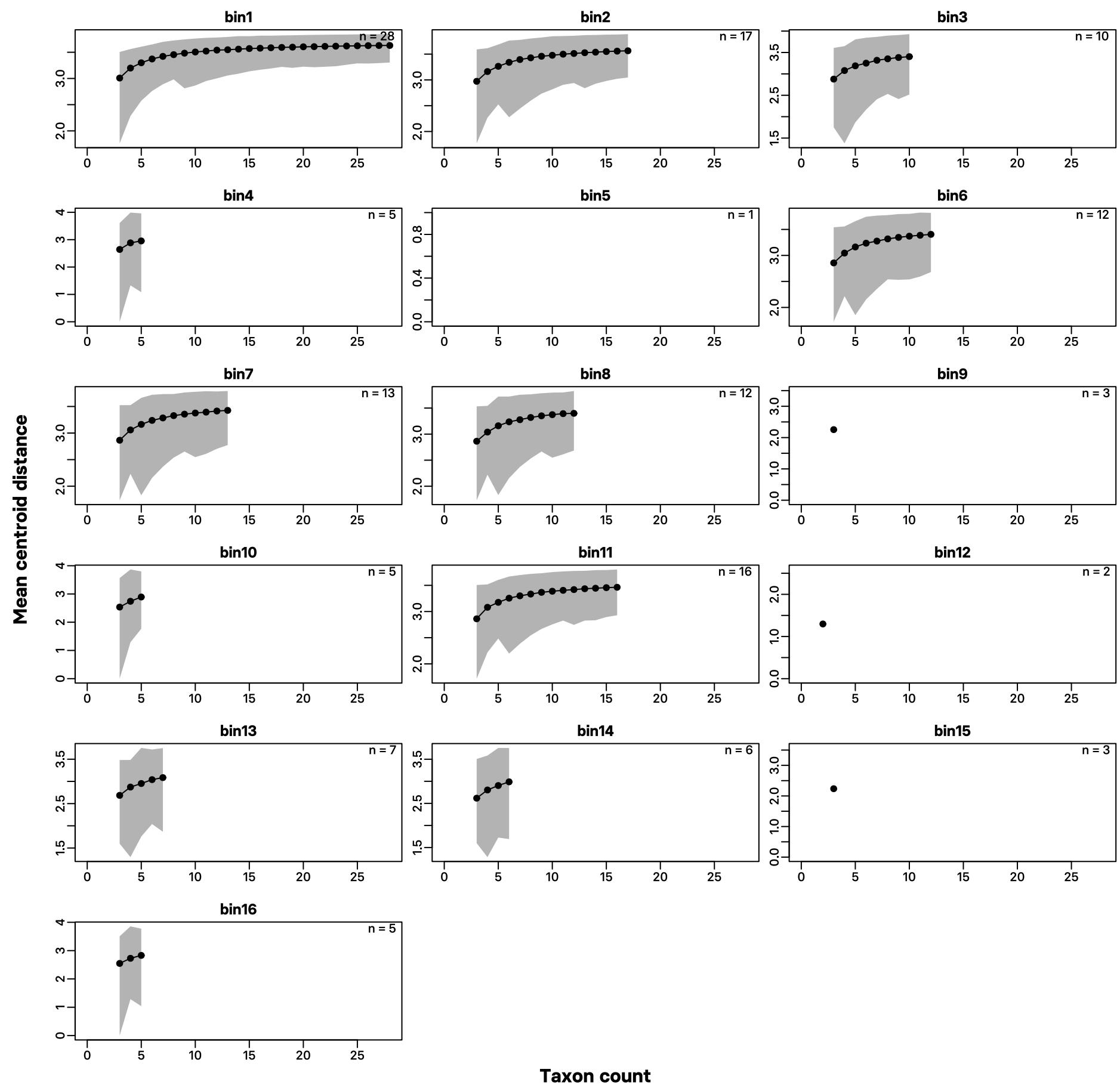
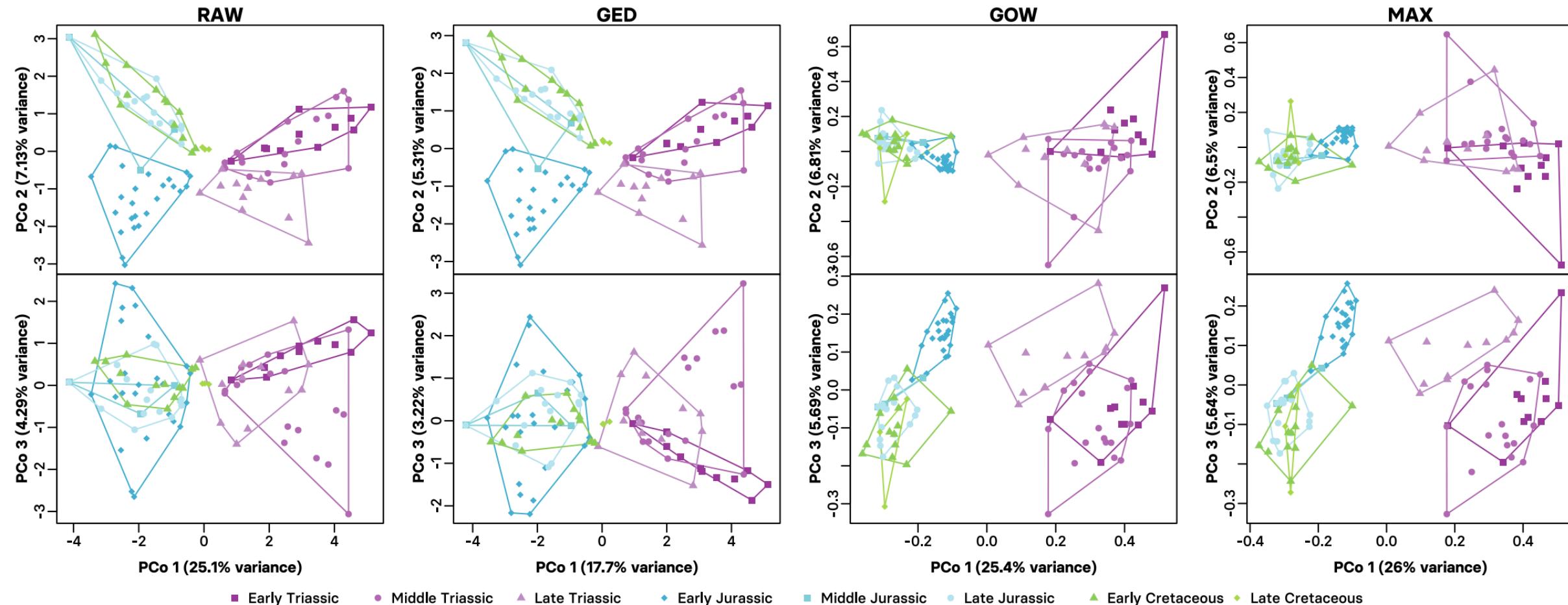


Figure 4: (following pages) **Morphospace occupation of Ichthyosauriformes through the Mesozoic.** Principal coordinate axis 1 against axes 2 (top row) and 3 (bottom row) from each of eight PCA (four distance matrices: RAW, GED, GOW, MAX; with and without negative eigenvalue correction) on the cladistic matrix of Moon [3] binned into epochs.

PCo 1-3 scatter plots without negative eigenvalue correction



PCo 1-3 scatter plots with negative eigenvalue correction

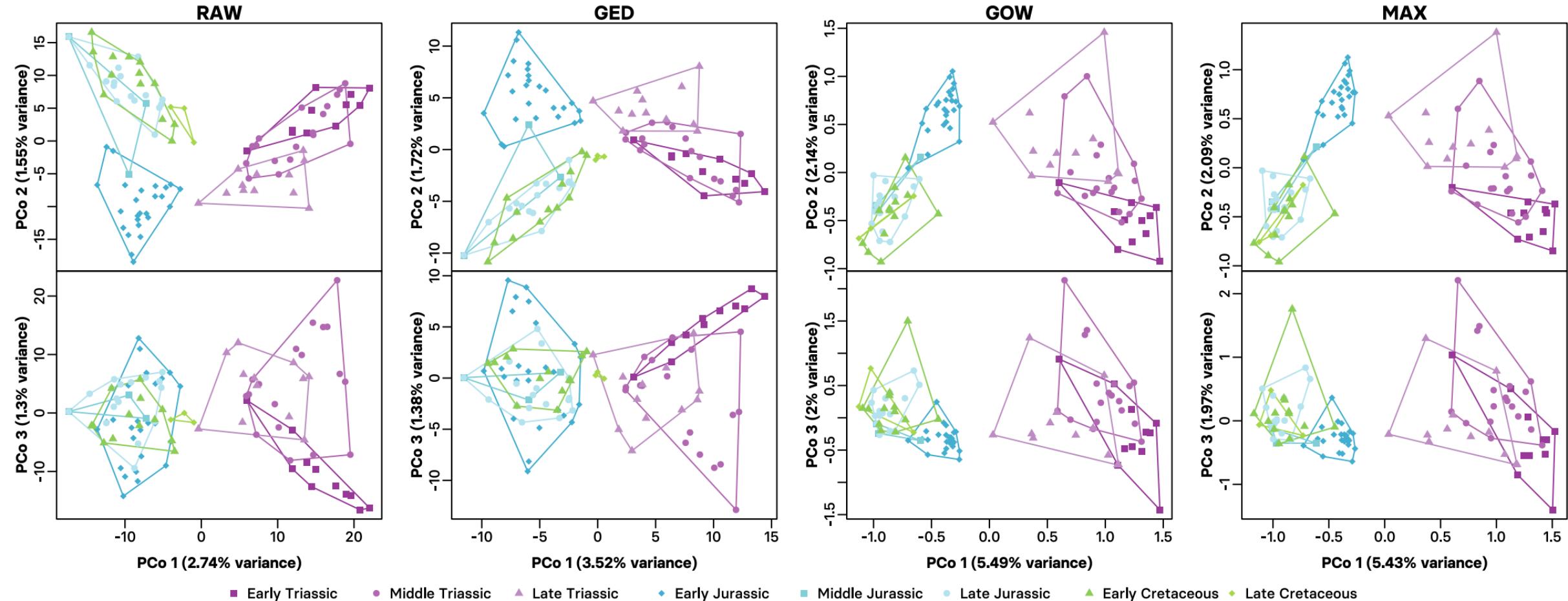


Figure 1: (following page) **Per-bin discrete skeletal disparity of Ichthyosauriformes through the Mesozoic.** Pairwise and weighted pairwise dissimilarity measured from raw Euclidean (RAW), generalised Euclidean (GED), Gower (GOW), and maximum observed rescaled (MAX) distances between taxa in the cladistic dataset of Moon [3] 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 10,000 bootstrap replicates.

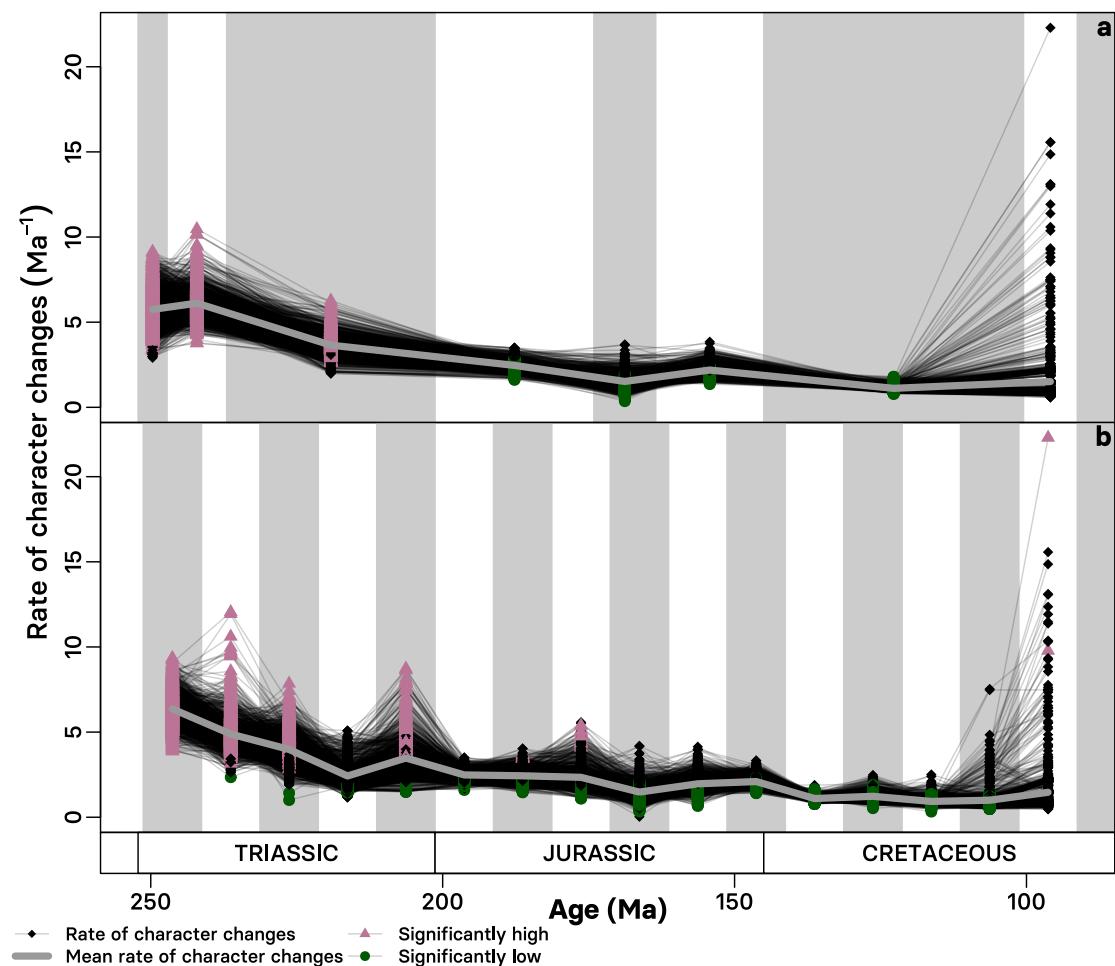
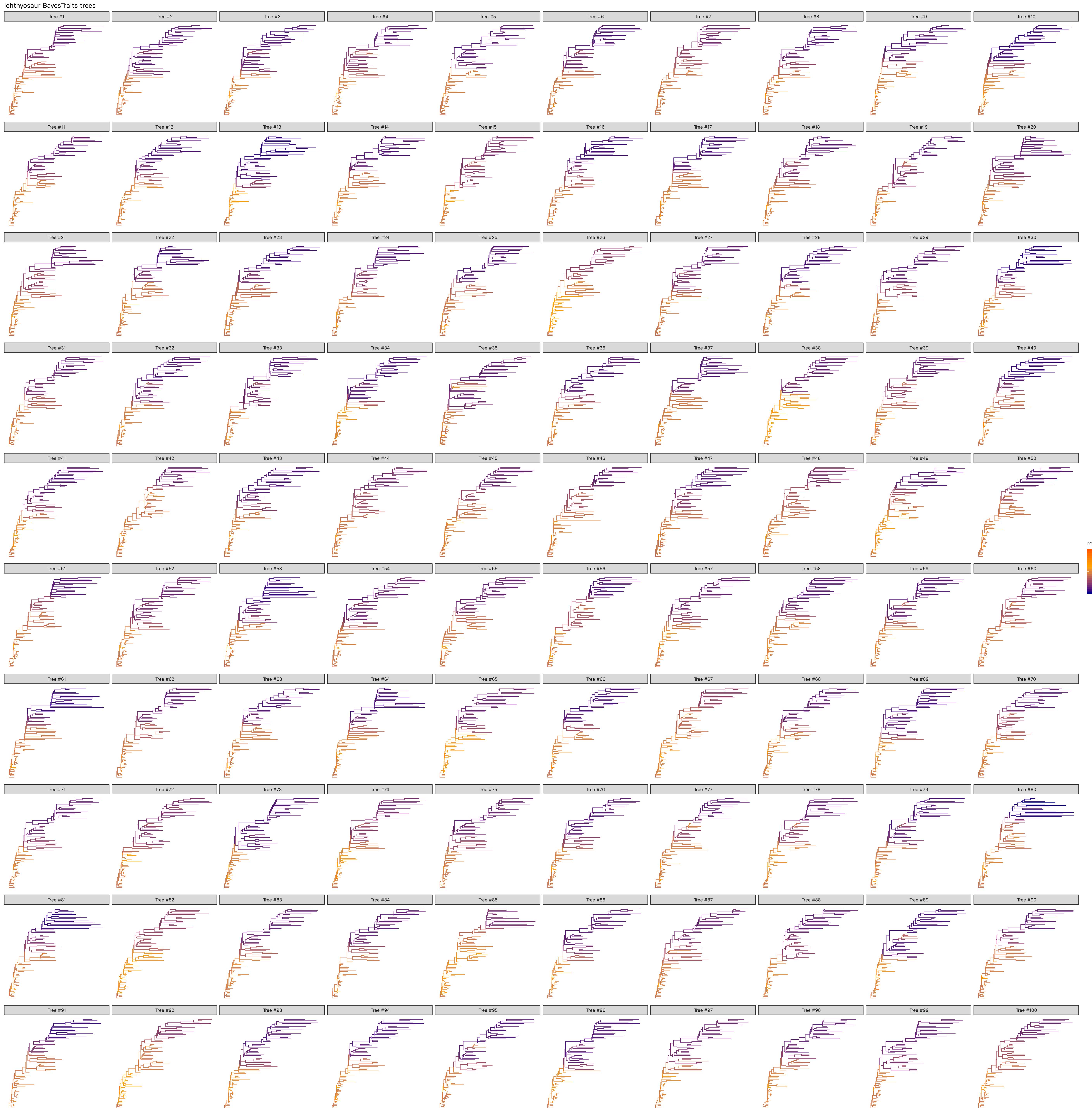


Figure 5: **Rates of discrete skeletal character evolution in Ichthyosauriformes.** Calculated from the matrix of Moon [3] using 1200 time-scaled trees from the minimum branch length method. Rates of evolution are plotted in **a**, epoch-bins and **b**, equal-length 10-million-year bins.

Figure 6: (previous 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.



Supplementary tables

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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

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.* [15]. FAD, first appearance date; FAS, first appearance stratigraphy; LAD, last appearance date; LAS, last appearance stratigraphy.

Taxon	FAD (Ma)	LAD (Ma)	FAS	LAS	Reference
<i>Petrolacosaurus</i>	307.0	298.9	Upper Pennsylvanian	Upper Pennsylvanian	[16, 17]
<i>Hovasaurus</i>	259.8	251.2	Upper Permian	Induan	[18]
<i>Claudiosaurus</i>	253.2	252.17	Late Changsinghian	Late Changsinghian	[19]
<i>Thadeosaurus</i>	254.14	252.17	Changsinghian	Changsinghian	[19]
<i>Milleretta</i>	253.2	252.5	Changsinghian	Changsinghian	[20]
<i>Broomia</i>	265.1	260.5	Capitanian	Capitanian	[20]
<i>Mesosaurus</i>	290.1	286	Early Artinskian	Early Artinskian	[20]
<i>Captorhinus</i>	280	270.6	Leonardian	Leonardian	[21]

Table 3: Occurrence stratigraphy and dates of Ichthyosauriformes included in the analyses. Stratigraphical occurrences are given to the nearest ammonite or conodont biozone horizon where possible. Occurrences are converted to absolute ages using Gradstein *et al.* [15]. FAD, first appearance date; LAD, last appearance date.

Taxon	FAD stratigraphy	LAD stratigraphy	FAD (Ma)	LAD (Ma)	References
<i>Acciptonectes densus</i>	D2D horizon, Speeton Clay Formation, basal Hauterivian	<i>Simikites concinnus/staffi</i> Biozone, upper Kimmeridgian, Upper Jurassic	132.9	129.4	[22]
<i>Aegirosaurus leptospondylus</i>	Malm Zeta2b, early lower Tithonian, Upper Jurassic	Lower Cretaceous	153.96	149.87	[23]
<i>Arthropterygius chirosum</i>	Oxfordian, Upper Jurassic	Lower Albian, Lower Cretaceous	163.47	152.06	[24]
<i>Athabascasaurus bitumineus</i>	Lower Albian, Lower Cretaceous	<i>Nicarella germanicus</i> Conodont Biozone, Anisian, Middle Triassic	113	111.5	[25]
<i>Barracudasauroides paxaniensis</i>	<i>Nicarella germanicus</i> Conodont Biozone, Anisian, Middle Triassic	Anisian, Middle Triassic	244.94	243.99	[26]
<i>Besanosaurus leptorhynchus</i>	<i>Nevadites</i> Conodont Biozone, uppermost Anisian, Middle Triassic	<i>Nevadites</i> Conodont Biozone, uppermost Anisian, Middle Triassic	242.1	241.5	[27]
<i>Brachypterygius extremus</i>	<i>Pectinatites wheatleyensis</i> Ammonite Biozone, Tithonian, Upper Jurassic	<i>Pectinatites hudsoni</i> Ammonite Biozone, Tithonian, Upper Jurassic	151	150	[28]
<i>Brachypterygius pseudoscythica</i>	<i>Ilowaisya pseudoscythica</i> Ammonite Biozone, Tithonian, Upper Jurassic	<i>Ilowaisya pseudoscythica</i> Ammonite Biozone, Tithonian, Upper Jurassic	150.1	149.5	[29]
<i>Californosaurus perrini</i>	Trachyceras Beds, Hosselkus Limestone, Carnian	Trachyceras Beds, Hosselkus Limestone, Carnian	233.5	228.35	[30, 31]
<i>Callawayia neoscacularis</i>	<i>Epigondolella triangularis</i> Conodont Biozone, early Norian, Upper Triassic	<i>Epigondolella quadrata</i> Conodont Biozone, early Norian, Upper Triassic	221.5	217.5	[32]
<i>Cartonychus lenticarpus</i>	Subcolumbites Ammonite Biozone, Olenian, Lower Triassic	Subcolumbites Ammonite Biozone, Olenian, Lower Triassic	247.7	247.2	[33]
<i>Caypullisaurus bonapartei</i>	<i>Virgatosphinctes mendozanus</i> Ammonite Biozone, early Tithonian, Upper Jurassic	<i>Emileia giebelii</i> Ammonite Biozone, early Bajocian, Middle Jurassic	152.1	139.4	[34]
<i>Chacaicosaurus capi</i>	<i>Emileia giebelii</i> Ammonite Biozone, early Bajocian, Middle Jurassic	<i>Emileia giebelii</i> Ammonite Biozone, early Bajocian, Middle Jurassic	170.3	169.45	[35]
<i>Chaohusaurus chaoxianensis</i>	<i>Procolumnites ammonite</i> Biozone, Olenian, Lower Triassic	<i>Subcolumbites ammonite</i> Biozone, Olenian, Lower Triassic	247.9	247.2	[36, 37]
<i>Chaohusaurus geishanensis</i>	<i>Procolumnites ammonite</i> Biozone, Olenian, Lower Triassic	<i>Subcolumbites ammonite</i> Biozone, Olenian, Lower Triassic	247.9	247.2	[36, 37]
<i>Chaohusaurus zhangjiawanensis</i>	<i>Neospathodus homeri</i> Conodont Biozone, Spathian, Lower Triassic	<i>Neospathodus triangulus</i> Conodont Biozone, Spathian, Lower Triassic	247.9	247.2	[38]
<i>Contectoplatlatus atavus</i>	<i>Procolumbites ammonite</i> Biozone, Olenian, Lower Triassic	Illyrian, Anisian, Middle Triassic	244.94	241.5	[39]
<i>Cryptopterygius kielanae</i>	Middle Volgian, Lower Tithonian, Upper Jurassic	Middle Volgian, Lower Tithonian, Upper Jurassic	149	147	[40]
<i>Dorsoplantites maximus</i>	<i>Dorsoplantites maximus</i> Ammonite Biozone, Tithonian, Upper Jurassic	<i>Dorsoplantites ilovaiskyi</i> Ammonite Biozone, Tithonian, Upper Jurassic	148.3	147.4	[41]
<i>Cymbospondylus buchseri</i>	Upper Anisian, Middle Triassic	lower Ladinian, Middle Triassic	242.57	240.3	[42]

Table 3 continued

Taxon	FAD stratigraphy	LAD stratigraphy	FAD (Ma)	LAD (Ma)	References
<i>Cymbospondylus nicholisi</i>	<i>Kellnerites felsoeversensis</i> Ammonite Biozone, Anisian, Middle Triassic	<i>Kellnerites felsoeversensis</i> Ammonite Biozone, Anisian, Middle Triassic	243.99	243.05	[43]
<i>Cymbospondylus petrinus</i>	<i>Paragonioidella ex gr. excelsa</i> Conodont Biozone, Anisian, Middle Triassic	<i>Paragonioidella ex gr. excelsa</i> Conodont Biozone, Anisian, Middle Triassic	243.99	241.5	[31]
<i>Cymbospondylus piscoensis</i>	Anisian, Middle Triassic	Anisian, Middle Triassic	241.5	241.5	[31]
<i>Dearcmhara schawcrossi</i>	<i>Pleydella aadensis</i> Ammonite Biozone, Toarcian, Lower Jurassic	<i>Stephanoceras humphriesianum</i> Ammonite Biozone, Bajocian, Middle Jurassic	174.43	169.45	[44]
<i>Eurhinosaurus longirostris</i>	<i>Dactylioceras tenuicostatum</i> Ammonite Biozone, Toarcian	<i>Harpoceras falciferum</i> Ammonite Biozone, Toarcian	182.7	180.36	[45, 46]
<i>Excitibosaurus costini</i>	<i>Arietites bucklandi</i> Ammonite Biozone, lower Sinemurian, Lower Jurassic earliest Tithonian, Upper Jurassic	<i>Arietites bucklandi</i> Ammonite Biozone, lower Sinemurian, Lower Jurassic earliest Tithonian, Upper Jurassic	199.3	197.8	[46, 47]
<i>Gengasaurus nicostai</i>	Calcaria ad apiculae Saccocoma Formation, Late Kimmeridgian, Upper Jurassic		155	150	[48]
<i>Grendelius alekseevi</i>	<i>Dorsoplaniites panderi</i> Ammonite Biozone, Tithonian, Upper Jurassic	<i>Dorsoplaniites panderi</i> Ammonite Biozone, Tithonian, Upper Jurassic	149.6	147.9	[49]
<i>Grendelius zhuravlevi</i>	Middle Volgian, Lower Tithonian, Upper Jurassic	Middle Volgian, Lower Tithonian, Upper Jurassic	149.6	147.9	[50]
<i>Grippia longirostris</i>	<i>Subcolumnites ammoniticus</i> Biozone, Olenekian, Lower Triassic	<i>Subcolumnites ammoniticus</i> Biozone, Olenekian, Lower Triassic	247.7	247.2	[51]
<i>Guizhouichthyosaurus tangae</i>	Carnian, Upper Triassic	Carnian, Upper Triassic	233.5	228.35	[52]
<i>Guizhouichthyosaurus wolonggangense</i>	Carnian, Upper Triassic	<i>Subcolumnites ammoniticus</i> Biozone, Olenekian, Lower Triassic	233.5	228.35	[53]
<i>Gulosaurus hemi</i>	<i>Subcolumnites ammoniticus</i> Biozone, Olenekian, Lower Triassic	<i>Subcolumnites ammoniticus</i> Biozone, Olenekian, Lower Triassic	247.7	247.2	[54, 55]
<i>Hauffiopteryx typicus</i>	<i>Dactylioceras tenuicostatum</i> , Ammonite Biozone, Toarcian	<i>Harpoceras falciferum</i> Ammonite Biozone, Toarcian	182.7	181.25	[56–58]
<i>Himalayasaurus tibetensis</i>	Norian, Upper Triassic	Norian, Upper Triassic	228.4	209.5	[59]
<i>Hudsonelpidia brevirostris</i>	<i>Epigondioidella quadrata</i> Conodont Biozone, Norian, Upper Triassic	<i>Epigondioidella quadrata</i> Conodont Biozone, Norian, Upper Triassic	226.5	221.25	[60]
<i>Hupehsuchus nanchangensis</i>	<i>Hildoceras bifrons</i> Ammonite Biozone, Olenekian, Lower Triassic	<i>Subcolumnites ammoniticus</i> Biozone, Olenekian, Lower Triassic	247.9	247.2	[61]
<i>Ichthyosaurus acutirostris</i>	Toarcian, Lower Jurassic	<i>Dactylioceras commune</i> Ammonite Biozone, Norian, Upper Triassic	180.36	175.6	[62]
<i>Ichthyosaurus anningae</i>	<i>Asteroceras obtusum?</i> Ammonite Biozon, Sinemurian, Lower Jurassic	<i>Upotonia janesoni</i> Ammonite Biozone, Pliensbachian, Lower Jurassic	193.81	189.35	[63]
<i>Ichthyosaurus breviceps</i>	<i>Schlotheimia angulata</i> Ammonite Biozone, Sinemurian, Lower Jurassic	<i>Arnioceras semicostatum</i> Ammonite Biozone, Sinemurian, Lower Jurassic	200.1	196.31	[64]
<i>Ichthyosaurus communis</i>	Upper Rhaetian, Upper Triassic	<i>Arnioceras semicostatum</i> Ammonite Biozone, Lower Jurassic	201.3	196.31	[64]
<i>Ichthyosaurus conybeari</i>	<i>Schlotheimia angulata</i> Ammonite Biozone, Hettangian	<i>Arnioceras semicostatum</i> Ammonite Biozone, Sinemurian	200.1	196.31	[64]
<i>Ichthyosaurus larkini</i>	Pre-Planorbis beds, Hettangian, Lower Jurassic	Pre-Planorbis beds, Hettangian, Lower Jurassic	201.3	200.85	[65]

Table 3 continued

Taxon	FAD stratigraphy	LAD stratigraphy	FAD (Ma)	LAD (Ma)	References
<i>Ichthyosaurus somersetensis</i>	Pre- <i>Planorbis</i> beds, Hettangian, Lower Jurassic	Pre- <i>Planorbis</i> beds, Hettangian, Lower Jurassic	201.3	200.85	[65]
<i>Isfjordosaurus minor</i>	Subcolumnites Ammonite Biozone, Ole-nelian, Lower Triassic	Subcolumnites Ammonite Biozone, Ole-nelian, Lower Triassic	247.7	247.2	[66]
<i>Janusaurus fundi</i>	<i>Dorsoplantis maximus</i> Ammonite Biozone, Tithonian, Upper Jurassic	<i>Dorsoplantis ilovaiskyi</i> Ammonite Biozone, Tithonian, Upper Jurassic	148.3	147.4	[67]
<i>Keihauia nui</i>	Slottsmøya Member, Agardfjellet Formation, Berriasian, Lower Cretaceous	Slottsmøya Member, Agardfjellet Formation, Berriasian, Lower Cretaceous	145	143	[68]
<i>Leniniastellans</i>	<i>Deshayesites vogensis</i> Ammonite Biozone, Lower Aptian, Lower Cretaceous	<i>Deshayesites vogensis</i> Ammonite Biozone, Lower Aptian, Lower Cretaceous	126.3	123	[69]
<i>Leptonectes moorei</i>	Lower Pliensbachian, Lower Jurassic	Lower Pliensbachian, Lower Jurassic	190.82	187.56	[70]
<i>Leptonectes solei</i>	<i>Amioceras semicostatum</i> Ammonite Biozone, Sinemurian, Lower Jurassic	<i>Asteroceras obtusum</i> Ammonite Biozone, Sinemurian, Lower Jurassic	195.31	193.81	[71]
<i>Leptonectes tenuirostris</i>	Pre- <i>Planorbis</i> beds, Hettangian, Lower Jurassic	<i>Amaltheus margaritatus</i> Ammonite Biozone, Piensbachian, Lower Jurassic	201.3	190.8	[62, 72]
<i>Macgowania janiceps</i>	<i>Epigondolella matthewi</i> Conodont Biozone, middle Norian, Upper Triassic	<i>Epigondolella multidentata</i> Conodont Biozone, middle Norian, Upper Triassic	220	216.9	[73]
<i>Maiaspondylus lindoei</i>	Middle Albian, Lower Cretaceous	Middle Albian, Lower Cretaceous	111.27	110.22	[74]
<i>Malawania anachronus</i>	Late Hauterivian, Early Cretaceous	Barremian, Early Cretaceous	131	125	[75]
<i>Mikadocephalus gracilirostris</i>	Upper Illyrian, Anisan, Middle Triassic	lower Fassinián, Ladinian, Middle Triassic	242.57	240.3	[76]
<i>Mixosaurus cornalianus</i>	Upper Illyrian, Anisan, Middle Triassic	lower Fassinián, Ladinian, Middle Triassic	242.57	240.3	[62, 77]
<i>Mixosaurus kuhnschneyderi</i>	Upper Illyrian, Anisan, Middle Triassic	lower Fassinián, Ladinian, Middle Triassic	242.57	240.3	[78]
<i>Mixosaurus xindianensis</i>	<i>Nicraella kockeli</i> Conodont Biozone, Pel-sonian, Anisan, Middle Triassic	<i>Nicraella kockeli</i> Conodont Biozone, Pel-sonian, Anisan, Middle Triassic	244.94	241.5	[79]
<i>Mollesaurus penitus</i>	<i>Emilia giebelii</i> Ammonite Biozone, early Barremian, Middle Jurassic	<i>Emilia giebelii</i> Ammonite Biozone, early Barremian, Middle Jurassic	170.3	169.45	[80, 81]
<i>Muiscasaurus catheti</i>	<i>Aulacostephanus</i> sp. Ammonite Biozone, Kimmeridgian, Upper Jurassic	<i>Aulacostephanus</i> sp. Ammonite Biozone, Kimmeridgian, Upper Jurassic	130.77	115.64	[82]
<i>Nannopterygius entektodon</i>	<i>Kosmoceras jasoni</i> Ammonite Biozone, Callovian, Upper Jurassic	<i>Quenstedtoceras mariae</i> Ammonite Biozone, Oxfordian, Upper Jurassic	154.6	149.87	[28]
<i>Ophthalmosaurus icenicus</i>	Oxfordian, Late Jurassic	Oxfordian, Late Jurassic	163.5	157.3	[84]
<i>Ophthalmosaurus natans</i>	<i>Epivirgatites nikitinii</i> Ammonite Biozone, Tithonian, Upper Jurassic	<i>Craspedites subdites</i> Ammonite Biozone, Tithonian, Upper Jurassic	147.5	146.4	[85]
<i>Ophthalmosaurus yasykovi</i>	<i>Dorsoplantis maximus</i> Ammonite Biozone, Tithonian, Upper Jurassic	<i>Dorsoplantis ilovaiskyi</i> Ammonite Biozone, Tithonian, Upper Jurassic	148.3	147.4	[41]
<i>Pahennia hoybergi</i>	<i>Epivirgatites nikitinii</i> Ammonite Biozone, Tithonian, Upper Jurassic	<i>Epivirgatites nikitinii</i> Ammonite Biozone, Tithonian, Upper Jurassic	147.5	146.9	[85]
<i>Paraophthalmosaurus kabanoi</i>	<i>Dorsoplantes panderi</i> Ammonite Biozone, Tithonian, Upper Jurassic	<i>Epivirgatites nikitinii</i> Ammonite Biozone, Tithonian, Upper Jurassic	149.6	146.9	[86]
<i>Paraophthalmosaurus savejvensis</i>					

Table 3 continued

Taxon	FAD stratigraphy	LAD stratigraphy	FAD (Ma)	LAD (Ma)	References
<i>Pervinitator wapitiensis</i>	<i>Subcolumbites</i> Ammonite Biozone, Olenekian, Lower Triassic	<i>Subcolumbites</i> Ammonite Biozone, Olenekian, Lower Triassic	247.7	247.2	[87]
<i>Pervushovisaurus bannovkensis</i>	Middle Cenomanian, Upper Cretaceous	Middle Cenomanian, Upper Cretaceous	96.24	95.47	[88]
<i>Pervushovisaurus campylodon</i>	Early Cenomanian, Upper Cretaceous	Early Cenomanian, Upper Cretaceous	100.45	96.5	[89]
<i>Pesospteryx nisseri</i>	<i>Subcolumbites</i> Ammonite Biozone, Olenekian, Lower Triassic	<i>Subcolumbites</i> Ammonite Biozone, Olenekian, Lower Triassic	247.7	247.2	[66]
<i>Phalarodon callawayi</i>	Upper Anisian, Middle Triassic	Upper Anisian, Middle Triassic	243.99	239.1	[90]
<i>Phalarodon fractasi</i>	Upper Anisian, Middle Triassic	lower Ladinian, Middle Triassic	244.94	237	[91]
<i>Phalarodon major</i>	Upper Anisian, Middle Triassic	Ladinian, Middle Triassic	244.94	237	[92]
<i>Phantomosaurus neubigi</i>	<i>pulcher/robustus</i> Conodont Biozone, Upper Anisian, Middle Triassic	<i>pulcher/robustus</i> Conodont Biozone, Upper Anisian, Middle Triassic	244.94	241.5	[93]
<i>Platyptyerius americanus</i>	Upper Albian, Lower Cretaceous	Upper Albian, Lower Cretaceous	107.59	100.5	[94]
<i>Platyptyerius australis</i>	Albian, Lower Cretaceous	Albian, Lower Cretaceous	113	100.5	[95, 96]
<i>Platyptyerius kauthali</i>	<i>Hatchiceras</i> Ammonite Biozone, Lower Barremian, Lower Cretaceous	<i>Hatchiceras</i> Ammonite Biozone, Lower Barremian, Lower Cretaceous	139.77	129.41	[97]
<i>Platyptyerius hercynicus</i>	Barremian, Lower Cretaceous	Apitan, Lower Cretaceous	125	113	[98]
<i>Platyptyerius platyptychylus</i>	Apitan, Lower Cretaceous	<i>Hoplites deshayesi</i> Ammonite Biozone, Apitan, Lower Cretaceous	125	113	[99]
<i>Platyptyerius sachiticum</i>	Barremian, Lower Cretaceous	Apitan, Lower Cretaceous	130.77	113	[100]
<i>Qianichthyosaurus xingyiensis</i>	Ladinian, Middle Triassic	Ladinian, Middle Triassic	241.5	237	[101]
<i>Qianichthyosaurus zhoui</i>	Carnian, Upper Triassic	Carnian, Upper Triassic	237	228.35	[102]
<i>Quasianosteosaurus vikinghoegdai</i>	<i>Subcolumbites</i> Ammonite Biozone, Olenekian, Lower Triassic	<i>Subcolumbites</i> Ammonite Biozone, Olenekian, Lower Triassic	247.7	247.2	[103]
<i>Selerocormus parviceps</i>	<i>Subcolumbites</i> Ammonite Biozone, Olenekian, Lower Triassic	<i>Subcolumbites</i> Ammonite Biozone, Olenekian, Lower Triassic	247.9	247.7	[104, 105]
<i>Shastasaurus liangae</i>	Upper Carnian, Late Triassic	Upper Carnian, Late Triassic	233.5	228.35	[106]
<i>Shastasaurus pacificus</i>	Upper Carnian, Late Triassic	Upper Carnian, Late Triassic	233.5	228.35	[31]
<i>Shastasaurus sikkimensis</i>	<i>Epigondolella postera</i> conodont Biozone, Mesohemimatis <i>columbianus</i> ammonite Biozone, middle Norian, Upper Triassic	<i>Epigondolella postera</i> conodont Biozone, Mesohemimatis <i>columbianus</i> ammonite Biozone, middle Norian, Upper Triassic	216.9	214.7	[107]
<i>Shonisaurus popularis</i>	Upper Carnian, Late Triassic	Upper Carnian, Late Triassic	233.5	228.35	[108]
<i>Simbirskiasaurus birjukovi</i>	<i>Praeoxyteuthis pugio</i> Belemnite Biozone, lower Barremian, Lower Cretaceous	<i>Praeoxyteuthis pugio</i> Belemnite Biozone, lower Barremian, Lower Cretaceous	130.77	129.41	[88]
<i>Sisteronia seeleyi</i>	Cambridge Greensand Member, early Cenomanian, Upper Cretaceous	Cambridge Greensand Member, early Cenomanian, Upper Cretaceous	100.5	96.24	[109]
<i>Stenopterygius allenensis</i>	<i>Leioceras opalinum</i> Ammonite Biozone, Allenian, Middle Jurassic	<i>Leioceras opalinum</i> Ammonite Biozone, Allenian, Middle Jurassic	174.1	172.13	[110]
<i>Stenopterygius quadriserratus</i>	<i>Dactylioceras tenuicostatum</i> Ammonite Biozone, Toarcian, Lower Jurassic	<i>Harpoceras falciferum</i> Ammonite Biozone, Toarcian, Lower Jurassic	182.7	180.36	[56, 111]
<i>Stenopterygius triserratus</i>	<i>Dactylioceras tenuicostatum</i> Ammonite Biozone, Toarcian, Lower Jurassic	<i>Harpoceras falciferum</i> Ammonite Biozone, Toarcian, Lower Jurassic	182.7	180.36	[56, 111]

Table 3 continued

Taxon	FAD stratigraphy	LAD stratigraphy	FAD (Ma)	LAD (Ma)	References
<i>Synopterygius uniter</i>	<i>Harpoceras falciferum</i> Ammonite Biozone, Toarcian, Lower Jurassic	<i>Harpoceras falciferum</i> Ammonite Biozone, Toarcian, Lower Jurassic	181.7	180.36	[56, 111]
<i>Suevoleviathan disintegrer</i>	<i>Dactylioceras tenuicostatum</i> Ammonite Biozone, Toarcian, Lower Jurassic	<i>Harpoceras falciferum</i> Ammonite Biozone, Toarcian, Lower Jurassic	181.7	180.36	[112, 113]
<i>Suevoleviathan integer</i>	<i>Dactylioceras tenuicostatum</i> Ammonite Biozone, Toarcian, Lower Jurassic	<i>Harpoceras falciferum</i> Ammonite Biozone, Toarcian, Lower Jurassic	181.7	180.36	[112, 113]
<i>Svetlonectes insolitus</i>	<i>Dactylioceras tenuicostatum</i> Ammonite Biozone, Upper Barremian, Cretaceous	<i>Harpoceras bifrons</i> Ammonite Biozone, middle Toarcian, Lower Jurassic	129.6	126.3	[114]
<i>Tennodontosaurus azerguenensis</i>	<i>Harpoceras bifrons</i> Ammonite Biozone, middle Toarcian, Lower Jurassic	<i>Harpoceras bifrons</i> Ammonite Biozone, middle Toarcian, Lower Jurassic	180.36	178.24	[115]
<i>Tennodontosaurus crassimanus</i>	<i>Dactylioceras tenuicostatum</i> Ammonite Biozone, Toarcian, Lower Jurassic	<i>Harpoceras falciferum</i> Ammonite Biozone, Toarcian, Lower Jurassic	182.7	180.36	[116]
<i>Tennodontosaurus eurycephalus</i>	<i>Arietites bucklandi</i> Ammonite Biozone, lower Sinemurian, Lower Jurassic	<i>Arietites bucklandi</i> Ammonite Biozone, lower Sinemurian, Lower Jurassic	199.3	197.8	[117]
<i>Tennodontosaurus nuertingensis</i>	<i>Uptonia jamesoni</i> Ammonite Biozone, Lower Pliensbachian, Lower Jurassic	<i>Tragophyllocera ibex</i> Ammonite Biozone, Piensbachian, Lower Jurassic	190.8	187.56	[118, 119]
<i>Tennodontosaurus platyodon</i>	<i>Schlotheimia angulata</i> Ammonite Biozone, Hettangian	<i>Amioceras semicostatum</i> Ammonite Biozone, Sinemurian	200.1	196.31	[117]
<i>Tennodontosaurus trigonodon</i>	<i>Dactylioceras tenuicostatum</i> Ammonite Biozone, Toarcian, Lower Jurassic	<i>Harpoceras falciferum</i> Ammonite Biozone, Toarcian, Lower Jurassic	182.7	180.36	[112, 120]
<i>Thaisaurus chonglakmanii</i>	Lower Triassic	Lower Triassic	250.01	247.2	[121]
<i>Thalattoarchon saurophagus</i>	Nevadiscultites <i>taylori</i> Ammonite Biozone, Anisian, Middle Triassic	Nevadiscultites <i>taylori</i> Ammonite Biozone, Anisian, Middle Triassic	247.2	244.6	[122]
<i>Thlobodus schmidti</i>	<i>Decurrella decurriata</i> Conodont Biozone, Ladinian (Pelsonian), Middle Triassic	<i>Judicarites/Neoschizodus orbicularis</i> Conodont Biozone, Ladinian (Pelsonian), Middle Triassic	241	237	[123]
<i>Toretocnemus californicus</i>	<i>Metapolygnathus polygnathiformis</i> Conodont Biozone, Carnian, Upper Triassic	<i>Metapolygnathus polygnathiformis</i> Conodont Biozone, Carnian, Upper Triassic	233.5	228.35	[62, 124]
<i>Toretocnemus zitteli</i>	<i>Metapolygnathus polygnathiformis</i> Conodont Biozone, Carnian, Upper Triassic	<i>Metapolygnathus polygnathiformis</i> Conodont Biozone, Carnian, Upper Triassic	233.5	228.35	[62, 124]
<i>Undorosaurus gorodischensis</i>	<i>Epivirgatites nikitinii</i> , <i>Virgatites virgatus</i> Ammonite Biozone, Tithonian, Upper Jurassic	<i>Epivirgatites nikitinii</i> , <i>Virgatites virgatus</i> Ammonite Biozone, Tithonian, Upper Jurassic	147.9	146.9	[125]
<i>Undorosaurus trautscholdi</i>	<i>Kachipurites fulgens</i> Ammonite Biozone, Tithonian, Upper Jurassic	<i>Kachipurites fulgens</i> Ammonite Biozone, Tithonian, Upper Jurassic	150	144.1	[126]
<i>Uttatsusaurus hataii</i>	<i>Subcolumnites</i> Ammonite Biozone, Olenekian, Lower Triassic	<i>Artautoceratites</i> Ammonite Biozone, Olenekian, Lower Triassic	247.7	247.2	[127]
<i>Wahisaurus massarae</i>	Lower Triassic	Pre-Planorbis beds, Hettangian, Lower Jurassic	201.3	200.85	[128]
<i>Wimanius odontopalatus</i>	Anisian, Middle Triassic	Ladinian, Middle Triassic	241.5	237	[129]
<i>Xirimnosaurus cataxes</i>	<i>Nicarella rockei</i> Conodont Biozone, Pelsonian, Anisian, Middle Triassic	<i>Nicarella rockei</i> Conodont Biozone, Pelsonian, Anisian, Middle Triassic	244.94	241.5	[130]

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
<i>Acamptonectes densus</i>	1000	3.000	[22]
<i>Aegirosaurus leptospondylus</i>	570	2.756	[23]
<i>Barracudasauroides paxianensis</i>	212	2.326	[26]
<i>Besanosaurus leptorhynchus</i>	510	2.708	[27]
<i>Brachypterygius extremus</i>	1155	3.062	[28]
<i>Callawayia neoscapularis</i>	453	2.656	[93, 131]
<i>Cartorhynchus lenticarpus</i>	55	1.740	[33]
<i>Caypullisaurus bonapartei</i>	1300	3.114	[34]
<i>Chacaicosaurus cayi</i>	980	2.991	[35]
<i>Chaohusaurus geishanensis</i>	117	2.068	[36, 37]
<i>Contectopalatus atavus</i>	130	2.114	[39, 132]
<i>Cryopterygius kristiansenae</i>	1220	3.086	[41]
<i>Cymbospondylus petrinus</i>	1166	3.067	[31]
<i>Eurhinosaurus longirostris</i>	1250	3.097	[45, 46]
<i>Excalibosaurus costini</i>	1540	3.188	[46, 47]
<i>Guizhouichthysaurus tangae</i>	800	2.903	[52]
<i>Guizhouichthysaurus wolonggangense</i>	645	2.810	[53]
<i>Gulosaurus helmi</i>	87	1.940	[54, 55]
<i>Hauffiopteryx typicus</i>	380	2.580	[56–58]
<i>Hudsonelpidia brevirostris</i>	131	2.117	[60]
<i>Hupehsuchus nanchangensis</i>	126	2.100	[61]
<i>Ichthyosaurus anningae</i>	390	2.591	[63]
<i>Ichthyosaurus breviceps</i>	240	2.380	[64]
<i>Ichthyosaurus communis</i>	256	2.408	[64]
<i>Ichthyosaurus conybeari</i>	216	2.334	[64]
<i>Ichthyosaurus larkini</i>	355	2.550	[65]
<i>Ichthyosaurus somersetensis</i>	438	2.641	[65]
<i>Leptonectes moorei</i>	328	2.516	[70]
<i>Leptonectes solei</i>	1585	3.200	[71]
<i>Leptonectes tenuirostris</i>	523	2.719	[62, 72]
<i>Macgowania janiceps</i>	505	2.703	[73]
<i>Mixosaurus cornalianus</i>	195	2.290	[62, 77]
<i>Mixosaurus kuhnschneyderi</i>	160	2.204	[78]
<i>Mixosaurus xindianensis</i>	223	2.348	[79]
<i>Nannopterygius enthekiodon</i>	600	2.778	[28]
<i>Ophthalmosaurus icenicus</i>	965	2.985	[83]
<i>Ophthalmosaurus natans</i>	1082	3.034	[84]
<i>Palvennia hoybergeti</i>	860	2.934	[41]
<i>Parvinatator wapitiensis</i>	120	2.079	[87]
<i>Phalarodon callawayi</i>	300	2.477	[90]
<i>Phalarodon fraasi</i>	205	2.312	[133, 134]
<i>Phantomosaurus neubigi</i>	550	2.740	[93]
<i>Platypterygius americanus</i>	1250	3.097	[94]
<i>Platypterygius australis</i>	1430	3.155	[95, 96]
<i>Platypterygius hercynicus</i>	1040	3.017	[98]
<i>Platypterygius platydactylus</i>	1170	3.068	[99]
<i>Platypterygius sachicarum</i>	870	2.940	[100]
<i>Qianichthysaurus xingyiensis</i>	270	2.431	[101]

Table 4 continued

Taxon	Skull length (mm)	\log_{10} (Skull length (mm))	References
<i>Qianichthyosaurus zhoui</i>	240	2.380	[102]
<i>Sclerocormus parviceps</i>	100	2.000	[104]
<i>Shastasaurus liangae</i>	750	2.875	[106]
<i>Shastasaurus sikkaniensis</i>	3000	3.477	[107]
<i>Shonisaurus popularis</i>	2750	3.439	[108]
<i>Stenopterygius quadriscissus</i>	625	2.796	[56, 111]
<i>Stenopterygius triscissus</i>	634	2.802	[56, 111]
<i>Stenopterygius uniter</i>	537	2.730	[56, 111]
<i>Suevoleiathan disinteger</i>	860	2.934	[112, 113]
<i>Suevoleiathan integer</i>	690	2.839	[112, 113]
<i>Sveltonectes insolitus</i>	570	2.756	[114]
<i>Temnodontosaurus azerguensis</i>	1700	3.230	[115]
<i>Temnodontosaurus eurycephalus</i>	1020	3.009	[117]
<i>Temnodontosaurus platyodon</i>	1790	3.253	[117]
<i>Temnodontosaurus trigonodon</i>	1090	3.037	[112, 120]
<i>Thalattoarchon saurophagus</i>	1200	3.079	[122]
<i>Utatsusaurus hataii</i>	215	2.332	[127]
<i>Wimanius odontopalatus</i>	250	2.398	[129, 135]
<i>Xinminosaurus catactes</i>	290	2.462	[130]

Supplemental code

Code S1 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 S2 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.

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