Untangling the ecological signal in the dental morphology in the bat superfamily Noctilionoidea

Camilo López-Aguirre[1], Suzanne J Hand[2], Nancy B Simmons[3], Mary T Silcox[1]

[1]Department of Anthropology, University of Toronto Scarborough, Toronto, ON, Canada

[2]Earth & Sustainability Science Research Centre, School of Biological, Earth & Environmental Sciences, University of New South Wales, Sydney, NSW, Australia

[3]Department of Mammalogy, Division of Vertebrate Zoology, The American Museum of Natural History, New York, NY, USA

Abstract

Diet has been linked to the diversification of the bat superfamily Noctilionoidea, a group that underwent an impressive ecological adaptive radiation within Mammalia. For decades, studies have explored morphological adaptations and diversity of noctilionoid bats to reveal macroevolutionary trajectories in their ecological diversity. Surprisingly, despite such interest and recent application of novel techniques, ecomorphological studies have failed to fully resolve the link between diet and a critical component of the feeding apparatus: dental morphology. Using multivariate dental topographic analysis and phylogenetic comparative methods, we examined the phylogenetic, biological and ecological signal in the dental morphology of noctilionoid bats. Analysing the lower first molars of 110 species, we tested the

effect of diet on dental morphology, accounting for three different dimensions of diet (guild, composition and breadth). Phylogenetic and allometric structuring of the dental topography data shows it does not respond only to diet, highlighting the need to account for multiple sources of variation. Frugivorous noctilionoids have sharper molars compared to other frugivorous mammals. Nectarivorous noctilionoids showed reduced lower molar crown height and steepness, whereas animalivorous species had larger molars. Dietary composition suggested that the intensity of exploitation of a resource is also linked to different dimensions of dental morphology. Large molar area positively correlated with increased carnivory, whereas crown height and slope correlated positively with insectivory, and negatively with frugivory and nectarivory. Dietary breadth showed that generalist species had greater molar sharpness and topographic complexity, whereas specialist herbivores and specialist animalivores fell at opposite ends in the range of tooth steepness and crown height. Together, the results suggest that adaptations affecting different attributes of dental morphology likely facilitated the dietary diversity and specialisation found in Noctilionoidea.

Keywords

Introduction

The bat superfamily Noctilionoidea (order Chiroptera) is one of the most ecologically diverse groups of modern mammal, having the broadest range of dietary adaptations within Chiroptera (Rojas et al., 2016). Representing ~17% of modern chiropteran species diversity, noctilionoid bats encompass the entire dietary range found in the more than 1400 species of bats (Rojas et

al., 2016; Simmons and Cirranello, 2021). Feeding ecology (diet and foraging behaviours) has been repeatedly linked to the taxonomic and morphological diversification of this group (Dumont et al., 2012; López-Aguirre et al., 2021a; Monteiro & Nogueira, 2011; Rojas et al., 2018; Rossoni et al., 2019). Stemming from an ancestral insectivorous diet, noctilionoid bats have adapted to feed on blood, seeds, terrestrial vertebrates, fish, fruit, leaves, nectar and pollen (Rojas et al., 2011). Bat dietary adaptations unique to Noctilionoidea include sanguivory (i.e. feeding on blood) in the subfamily Desmodontinae, and granivory (i.e. feeding on seeds) and folivory (i.e. feeding on leaves) in species of the subfamily Stenodermatinae (Duque-Márquez et al., 2019; Nogueira & Peracchi, 2003; Villalobos-Chaves et al., 2016). Levels of omnivory across a herbivory-to-carnivory gradient have also been described in Noctilionoidea and linked to macroevolutionary trajectories during its diversification (Rojas et al., 2018). Most of noctilionoid dietary diversity is concentrated in the Neotropical family Phyllostomidae, with the exception of piscivory which is exclusive to the family Noctilionidae, being common in one species (*Noctilio leporinus*) and perhaps occasionally in another *N. albiventris* (Hood & Pitocchelli, 1983; Brooke, 1994). Species of the families Furipteridae, Mormoopidae, Myzopodidae and Thyropteridae are broadly categorised as insectivores (Arbour et al., 2019; Rojas et al., 2018), whereas species of the family Mystacinidae exhibit a broad omnivorous diet apparently facilitated by terrestrial locomotion (Arkins et al., 1999). There are multiple instances of convergent evolution of some dietary adaptations within Noctilionoidea (e.g. carnivory and nectarivory), highlighting the high ecological adaptability of this group (Datzmann et al., 2010; Santana & Cheung, 2016).

There are multiple dimensions to the dietary diversity of noctilionoid bats, complicating the study of its ecomorphological basis. Comparisons across dietary guilds have been the main tool to quantify morphological differences, reflecting broad similarities across species (e.g. Arbour et al., 2019; Dumont et al., 2012; Monteiro & Nogueira, 2011; Santana & Cheung, 2016). Classifying species into dietary guilds can oversimplify an individual species' diet (Rojas et al., 2012, 2018), potentially underestimating the variety of food items from different guilds that species feed on (herein dietary breadth). For example, *Vampyrum spectrum*, commonly classified as a carnivore, also feeds on insects, fruit and nectar (Rojas et al., 2018; Santana & Cheung, 2016). Additionally, the extent to which species exploit a given resource represents a different dimension of the diet of species (herein diet composition), as it reflects levels of niche partitioning and specialisation across species along a specialisation gradient (Hall et al., *in press*; Rojas et al., 2018). For example, nectarivory is used to different degrees in phyllostomid species that are specialist nectarivores (e.g. *Musonycteris harrisoni*), omnivore herbivores (e.g. *Carollia perspicillata*) and omnivore animalivores (e.g. *Lophostoma silvicolum*), exemplifying different dietary niches (Hall et al., *in press*; Rojas et al., 2018). Articulating the multidimensionality of dietary adaptations within a single comparative framework can better elucidate its ecological and evolutionary drivers (DeCasien et al., 2017; Hall et al., *in press*; Makedonska et al., 2012).

The functional link between the morphological and dietary diversity of extant noctilionoids has been an active area of research for decades (Arbour et al., 2019; Dumont, 2007; Dumont et al., 2012; Freeman, 1981, 1988; Monteiro & Nogueira, 2011; Nogueira et al., 2009; Santana et al., 2011, 2012; Santana & Cheung, 2016). The main area of study with respect to the relationship between diet and form in noctilionoids has been the ecomorphology of the skull, with a strong

correspondence being found between aspects of cranial anatomy and elements of the diet (Arbour et al., 2019; Freeman, 1981; Rossoni et al., 2017, 2019; Santana et al., 2012). Different morphological adaptations have been linked to the exploitation of specific resources: increased body size with carnivory (Freeman, 1988; Santana & Cheung, 2016), elongated rostrum with nectarivory (Arbour et al., 2019; Freeman, 1995), sharpened incisors and reduced post-canine dentition with sanguivory (Arbour et al., 2019; Freeman, 1988), and u-shaped mandible and shorter rostrum with durophagy in frugivory (Arbour et al., 2019; Freeman, 1988; Santana et al., 2012). Moreover, phenotypic specialisations to particular feeding ecologies (e.g. carnivory and nectarivory) have been found to converge across Noctilionoidea (Arbour et al., 2019; Freeman, 1995; Morales et al., 2019; Santana & Cheung, 2016). As such, foraging strategies represent a significant driver of phenotypic variation in bats, with feeding ecology correlating with both cranial and postcranial morphology (Gaudioso et al., 2020; López-Aguirre et al., 2021a; Morales et al., 2019). An emerging body of research has also recently begun to focus on molecular and morphological adaptations in sensory systems associated with adaptation to particular dietary niches (Arbour et al., 2021; Hall et al., *in press*; Leiser-Miller & Santana, 2020).

Despite steady interest in the ecomorphology of diet in bats, dental adaptations and variability in teeth across extant bats remain poorly known and understudied. Freeman (1984, 1988) summarized broad patterns of dental adaptations to diet across bats but primarily considered tooth proportions. Dental traits have often been used to attempt to reconstruct dietary habits of fossil bats (e.g. Hand, 1985; Hand et al., 2018; Simmons et al., 2016) but mostly in a qualitative rather than quantitative fashion. Other studies have looked at teeth and variation in more detail, but often with either very small sample sizes and/or in highly taxonomically

restricted groups. For example, Dumont (1995) evaluated the relationship between enamel thickness and diet in six species of bats as part of a broader study; Santana et al. (2011) explored differences in teeth crown occlusal complexity between dietary guilds; Ghazali and Dzheverin (2013) evaluated correlations between dental form and diet in 9 species of *Myotis*; and a recent study examined dental variation in species of flying foxes and its correlation to diet and phylogenetic relationships (Zuercher et al., 2021). In this context, the goal of the current study was to evaluate dental variation in a much more ecologically diverse clade of bats using larger sample sizes and accounting for three different dimensions of diet (guild, composition, and breadth). To accomplish this, we used methods that serve to quantify multiple aspects of dental variation.

Dental Topographic Analysis (DTA) comprises an increasingly widely used set of metrics that aim to quantify diet-based dental adaptations (Berthaume et al., 2020; Evans et al., 2007; Ledogar et al., 2013; Selig et al., 2021; Ungar et al., 2018). Originally based on geographic information system analysis (e.g., Ungar & M'Kirera, 2003; Evans et al., 2007), DTA has revolutionised the understanding of how the dentition adapts to the biomechanical properties of foodstuff (Bunn et al., 2011; Ledogar et al., 2013; Melstrom & Irmis, 2019; P. S. Ungar et al., 2018). A robust set of DTA metrics has been developed in recent decades, allowing quantification of varying aspects of a complex adaptive landscape (Berthaume et al., 2019a, 2020; Boyer, 2008; Cooke, 2011; Evans et al., 2007; Pineda-Munoz et al., 2017; Winchester et al., 2014). In contrast to geometric morphometrics (another widespread set of morphometric tools), DTA is homology-free, facilitating comparison among a wide range of taxa (Berthaume et al., 2020; Melstrom & Irmis, 2019; Pineda-Munoz et al., 2017). Dental topographic analysis was

126 developed and has been used primarily to study mammal dentitions, most regularly applied to
127 study Primates (e.g., Berthaume et al., 2020; Boyer, 2008; Bunn et al., 2011; Evans et al., 2007;
128 Pineda-Munoz et al., 2017). Comparative studies of modern taxa have successfully elucidated
129 patterns of variation across mammal clades reflecting dietary specialisations (Evans et al., 2007;
130 Lazzari et al., 2008; Pineda-Munoz et al., 2017; Selig et al., 2019). General predictive patterns
131 also posit ecological and evolutionary drivers for common mammalian patterns (Selig et al.,
132 2021). Dental topography has also been an informative tool to reconstruct the diet of extinct
133 mammals and to discover and document macroecological patterns (López-Torres et al., 2018;
134 Prufrock et al., 2016; Selig et al., 2020; Ungar, 2004). In bats, DTA has only been applied in two
135 studies (López-Aguirre et al., 2021b; Santana et al., 2011). Santana et al. (2011) explored
136 differences between bat insectivores, omnivores and herbivores, finding higher topographic
137 complexity in frugivores. Comparisons of values of DTA in modern bats to reconstruct the diet
138 of the fossil species *Notonycteris magdalenensis* suggests DTA can reflect the diet of bats
139 (López-Aguirre et al., 2021b). These studies revealed an increase in dental complexity and
140 sharpness in frugivorous noctilionoids and a decrease in species with liquid diets (i.e.
141 nectarivory and sanguivory). However, broader patterns that indicate common pathways of
142 dental morphological adaptation to exploit different dietary resources largely remain to be
143 explored in bats.

144 In this study we aimed to trace the ecomorphological connection between dental morphology
145 and diet in noctilionoid bats. Using a battery of DTA metrics, we quantified aspects of the
146 dental morphology for 110 noctilionoid species representing the range and multidimensionality
147 of dietary adaptations. Three-dimensional models of lower first molars were analysed within a

multivariate statistical framework using phylogenetic comparative methods, accounting for the effect of evolutionary kinship and body mass in our data. We represented diet in three dimensions (guild, composition and breadth) and tested how dental morphology is related to each parameter. Considering the repeated evolution of various noctilionoid lineages to occupy the same dietary guilds, we hypothesised that 1) bat dental morphology does not have strong phylogenetic structuring; 2) noctilionoid bats show a significant allometric effect on dental morphology, following a general mammalian pattern in molar size (Billet & Bardin, 2021); 3) topographic complexity increases in guilds representing biomechanically demanding diets (i.e. frugivory and animalivory); and 4) dietary composition will reveal patterns of variation in the DTA metrics that reflect the level of intensity with which species exploit different food items. In particular, we predicted that we would find higher values of OPCR and DNE in animalivore and frugivore diets and higher values of RFI and slope in species with liquid diets. Given that most species are known to feed on a variety of resources (despite extreme diet-based morphological specialisations), we did not expect to see a pattern in DTA in response to dietary breadth.

Methods

Sample composition

Our sample consisted of 90 specimens representing 85 noctilionoid species (Supplementary Table 1). Data for an additional 25 species were retrieved from the literature to complete a total of 115 samples and 110 species. Species were represented by one to five specimens, with average values being used in analyses for species represented by more than one specimen. We sampled all noctilionoid families (Furipteridae, Mormoopidae, Mystacinidae, Myzopodidae,

Noctilionidae, Phyllostomidae and Thyropteridae), 44% of currently recognized noctilionoid species and the entire dietary range found in Chiroptera (Fig. 1). The majority of µCT scans of specimens were retrieved from the Digitizing Extant Bat Diversity Project (Shi et al., 2018) and more generally from MorphoSource. To complement our sampling of rare lineages (e.g. Myzopodidae), additional specimens were sourced from Digimorph (Supplementary Table 1). Data we retrieved from the literature were extracted from specimens that were also sourced from (Shi et al., 2018), ensuring that the imaging protocols were generally consistent across our sample. Only specimens without excessive wear (no dentine exposed in occlusal view) were selected. Each specimen was represented by a single lower left first molar (m1). Lower first molars have been proposed as an effective proxy to test dietary diversity in bats based on DTA (Berthaume et al., 2020). Freeware 3D Slicer was used to process raw scan data and to segment individual m1s (Fedorov et al., 2012). Meshlab was used to process 3D meshes of individual m1s (Cignoni et al., 2008), cropping each crown below the cingulid (following established protocols for DTA in mammals and bats) (Berthaume et al., 2019b). To standardise our 3D models, individual meshes were simplified to 10,000 faces and smoothed using 3 iterations of the Laplacian Smoothing filter in Meshlab (Berthaume et al., 2019b).

Figure 1

Dental morphology quantification

Data for five DTA metrics were collected (Fig. 2): Dirichlet Normal Energy (DNE, Bunn et al., 2011), Orientated Patch Count Rotated (OPCR, Evans et al., 2007), Relief Index (RFI, Boyer, 2008), slope (Ungar & M'Kirera, 2003) and molar area (MS). Dirichlet Normal Energy uses

changes in normal vectors generated for individual faces in the mesh to quantify curvature of the crown (Bunn et al., 2011). Higher values of DNE are usually associated with greater shearing capacity and animalivory in mammals (Ledogar et al., 2013, 2018; López-Torres et al., 2018; Selig et al., 2021). Oriented Patch Count Rotated estimates surface complexity by quantifying the number of clusters of faces (i.e. patches) in the mesh that are similarly oriented in space (Evans et al., 2007). High OPCR values are interpreted as a representing a greater set of tools for processing biomechanically demanding diets (e.g. folivory and animalivory, (Evans et al., 2007)). Relief Index is the ratio of 3D-to-2D area of the tooth crown, representing an index of crown height (Allen et al., 2015; Boyer, 2008; Cooke, 2011). Low RFI values associated with flat tooth crowns have been found in mammalian frugivores and high RFI values with tall cusps in folivores and animalivores (Pampush, Spradley, et al., 2016). Slope is the mean slope across the surface in occlusal view, averaging the slope of all faces of the mesh (P. S. Ungar & M'Kirera, 2003). Molar area was estimated as the 2D surface area of a mesh. All DTA metrics were calculated using the R package *molaR* (Pampush, Winchester, et al., 2016).

Figure 2

Body mass and dietary data acquisition

Body mass of species was compiled from the literature and averages were used in further studies (Giannini et al., 2020; Moyers Arévalo et al., 2018). Noctilionoid bats show the greatest range of dietary adaptations among mammals (Arbour et al., 2019; Rossoni et al., 2017), but also a high degree of plasticity, with species feeding on a variety of items (Rojas et al., 2011, 2012, 2018). To capture the dietary complexity of noctilionoid bats, we quantified three

211 dimensions of dietary specialisation: 1) guild, 2) composition and 3) breadth. Species were
212 assigned to one of seven dietary guilds previously used to study dietary adaptations in bats (e.g.
213 by Arbour et al., 2019; Monteiro & Nogueira, 2011; Rossoni et al., 2019), grouping species
214 based on broad dietary similarities: carnivory, frugivory, insectivory, nectarivory, omnivory,
215 piscivory and sanguivory. Use of dietary guilds alone can oversimplify the diets of species that
216 differ in the intensity of exploitation of a given item (e.g. strict frugivores versus facultative
217 frugivores) and the variety of food items exploited (Rojas et al., 2018). Therefore, we also
218 gathered data on dietary composition and dietary breadth. For dietary composition, food items
219 were classified into seven categories: arthropods, blood, terrestrial vertebrates, fish, flower
220 pieces, pollen and nectar, fruit and seeds (Rojas et al., 2011, 2012, 2018). For each species, the
221 relative importance of each food item was codified as either: absent (one), complementary
222 (two), predominant (three), or exclusive (four), following Rojas et al. (2011, 2012, 2018).
223 Quantifying diet composition of each species and the relative importance of each item allows
224 the comparison of species across a range of intensity of exploitation of a given resource. Finally,
225 dietary breath was compiled as the marginality index developed by (Rojas et al., 2018) based on
226 the diet composition data described above. This marginality index places species within a range
227 of values between zero and one, representing a gradient of specialisation from herbivory to
228 carnivory. Species with values close to zero indicate a specialised herbivore diet, values close to
229 one indicate a specialised animalivore diet, whereas species with values close to 0.5 represent
230 generalist species capable of both herbivory and animalivory. Marginality calculates diet as a
231 continuous numerical variable that can be included as a factor in statistical analyses that can
232 facilitate the reconstruction of an ecological transition from strict herbivory to strict

animalivory. A caveat with this approach is that it obscures dietary subguilds at the extremes of the range of marginality values (e.g. frugivory and nectarivory within herbivory). Data for dietary composition and breadth were retrieved from (Rojas et al., 2011, 2012, 2018), whereas dietary guild data were retrieved from (Monteiro & Nogueira, 2011; Rossoni et al., 2019).

Statistical analyses

We used the phylogeny of (Shi & Rabosky, 2015) to test the effect of evolutionary kinship in our data, pruning the phylogeny to match our sample composition. We tested for the presence of phylogenetic signal using the K–statistic implemented in the "phylosig" function in the R package *phytools* (Revell, 2012). Before testing the effect of body mass on dental topography, we first tested for autocorrelation between body mass and diet using a phylogenetic linear model (log(BM)~Marginality). A weak but significant correlation was found, marginality explaining less than 4% of variation in body mass (R^2= 0.031, P= 0.035). In light of this result, all further analyses were performed with log-transformed body mass. Phylogenetic ANOVAs were used to test for statistical differences in DTA metrics across dietary guilds using the "procD.pgls" function in the R package *Geomorph* (Adams et al., 2013). Tukey post hoc tests were used to further explore pairwise differences between dietary guilds, using a Bonferroni correction to account for autocorrelation between multiple comparisons. Boxplots were generated to visually explore patterns of variation in DTA metrics across guilds. A principal components analysis was performed to explore multivariate patterns of variation in DTA, reducing the dimensionality of our data. Additionally, we performed a phylogenetic principal component analysis to account for the phylogenetic structuring (i.e. significant phylogenetic

signal) of our data, using the "phyl.pca" function in *phytools* (Revell, 2012). We calculated the dental topographic disparity (quantified as the sum of variances across DTA metrics) per guild and tested for significant differences across guilds using the R package *dispRity* (Guillerme, 2018). Per guild sum of variances across DTA metrics was used as a disparity metric and a Wilcoxon test was applied for pairwise comparisons across guilds with a Bonferroni correction.

Next, the association between diet composition and dental morphology was assessed. Dietary composition (measured as the relative importance of a given resource) allowed us to test how DTA metrics may differentially correlate with specialisation for feeding on a particular type of resource. We focused on dietary guilds that show a range in the intensity of exploitation of the resource that characterises that guild (i.e. carnivory, insectivory, frugivory and nectarivory). Phylogenetic regression models were used to quantify the relative association of each DTA metric with increasing exploitation of a given resource. The relative importance of each DTA metric in each model was estimated using the lmg metric implemented in the "relaimpo" function in the R package *relaimpo* (Groemping, 2006). The lmg metric deconstructs the variance explained by a model, averaging the marginal contribution of each predictor over all orderings of predictors (Groemping, 2006). Barplots were used to visualise the relative importance of each DTA metric for the increasing exploitation of a resource. Finally, we analysed the influence of dietary breadth on dental morphology. Phylogenetic regression models were used to discern the relative effect of body mass and dietary breadth (marginality) on each DTA metric (log(DTA)~log(BM)+Marginality), using the "procD.pgls" function in *Geomorph* (Adams et al., 2013). Biplots were used to visualise patterns of association between DTA metrics and marginality.

Results

Differences across dietary guilds

A significant phylogenetic signal was detected for all five DTA metrics, OPCR showing the weakest signal and RFI the strongest (Table 1). Boxplots revealed differences in DTA metrics between dietary guilds (Fig. 3 left column). Dirichlet Normal Energy was markedly high in the piscivorous species, followed by frugivorous, insectivorous, omnivorous and carnivorous species and lower in species with liquid diets (i.e. nectarivorous and sanguivorous, Fig. 3). A similar pattern was found in OPCR values, with the piscivore showing similar values to carnivores, frugivores and insectivores, and with lower values found in species with liquid diets (Fig. 3). In contrast, sanguivorous and piscivorous species showed the highest values of RFI and slope, whereas the lowest values for those two metrics were found in frugivorous species, followed by nectarivorous species (Fig. 3). Molar area was noticeably greater in carnivorous and piscivorous species and lower in species with liquid diets (Fig. 3).

Figure 3

Phylogenetic ANOVAs indicated statistically significant differences between dietary guilds across all DTA metrics (Table 2). Pairwise comparisons revealed slope and RFI in frugivorous species were significantly different from all other guilds, whereas OPCR and DNE in species with liquid diets were significantly different from all other guilds with solid diets (Supplementary Table 2).

Dental topographic disparity was found to be higher in noctilionoid omnivores and frugivores and lower in nectarivores and sanguivores (Fig. 4). Wilcoxon pairwise comparisons showed statistical differences in disparity between all guilds but not between frugivores and omnivores (Table 3).

Figure 4

The first two principal components of dental morphospace (based on principal component analysis) explained 83.79% of variation (Fig. 5 left). Piscivorous and sanguivorous species were the only taxa occupying non-overlapping subspaces, whereas frugivores showed the greatest dispersion across morphospace and the greatest overlap with other guilds. Low values of Principal Component 1 were correlated with high values of OPCR and DNE, separating species that feed on vertebrates (i.e. piscivory and carnivory) from those with liquid diets. High values of Principal Component 2 were associated with low values of slope and RFI. A similar pattern was found in phylomorphospace (based on phylogenetic principal component analysis), with the first two components explaining 78.52% of variation (Fig. 5 right) and the same pattern of correlation with the various DTA metrics.

Figure 5

Dietary composition and level of specialisation

Comparing dental morphology along trajectories of increasing importance of a given resource in a species' diet showed decoupled patterns across DTA metrics (Fig. 6). Mean DNE values increased with the increasing importance of carnivory, frugivory and insectivory, and mean

values decreased as nectarivory increased. Values of OPCR increased as degrees of carnivory and frugivory increased, remained stable across varying relative amounts of insectivory and values decreased as nectarivory increased. Values of RFI and slope increased as amounts of carnivory and insectivory increased and both values and slope decreased as degree of frugivory and nectarivory decreased. Molar area showed a dramatic increase with increasing levels of carnivory, remained relatively stable for differing degrees of frugivory and insectivory, and decreased with increasing nectarivory. Relief Index had the greatest relative importance in our models of increasing specialisation to frugivory, insectivory and nectarivory (Fig. 7). Molar area was the most highly correlated metric with specialising carnivory, followed by RFI. Slope was the second-most highly correlated metric with specialising to frugivory and insectivory, whereas DNE and slope were equally correlated to specialising to nectarivory. Phylogenetic regression models confirmed the diverging association of different DTA metrics with specialisation for different diets (Supplementary Table 3).

Figure 6

Effect of dietary breadth

Phylogenetic linear models revealed a significant effect of body mass and marginality (degree of herbivory vs animalivory) on all DTA metrics, with body mass explaining on average 19.94% of variation and marginality explaining 20.37% (Table 4). Body mass correlated more strongly with molar area (explaining 38.86% of variation), whereas marginality correlated more strongly with RFI and slope (explaining 39.91% and 25.74% of variation, respectively). Slope and BM did not significantly correlate with body mass and marginality, respectively. Biplots show the strong

correspondence between RFI and slope and marginality, with specialist herbivores having the lowest values of both metrics and specialist animalivores the highest values (Fig. 3).

Figure 7

Discussion

Multivariate DTA strongly supports a functional link between dental phenotypic variation and dietary complexity in Noctilionoidea. Statistically significant allometry and phylogenetic signal indicate dental morphology is also influenced by body mass and evolutionary relatedness, contrary to our prediction of a lack of phylogenetic structuring. After controlling for phylogenetic structuring and allometry, retrieved patterns of DTA variation showed differential effects of dietary guild, composition and breadth, suggesting there are different evolutionary pathways for dental morphology to facilitate and/or reflect diet. Differences in DTA metrics across dietary guilds reflect biomechanical differences between diets (e.g. liquid diets vs. solid diets). Higher OPCR and DNE in frugivorous and animalivorous species supported our hypothesis of increased complexity and sharpness in biomechanically demanding diets. RFI and slope were the variables most highly correlated with specialisation for insectivory, frugivory, or nectarivory, whereas molar area was found to be the main covariate associated with carnivory in noctilionoid bats. Contrary to our prediction, aspects of dental morphology correlated with dietary breadth, RFI and occlusal slope showing the most significant associations, with values that decrease as diet narrows to specialise for herbivory and increase as diet narrows to specialise for animalivory.

Differences between dietary guilds

Consistent with previous studies of DTA in bats, we found a significant phylogenetic and ecological signal in dental morphology, reflecting both dietary adaptations and evolutionary relatedness (López-Aguirre et al., 2021b). Differences in dental morphology across noctilionoid bats revealed biomechanical similarities in foodstuff processing within dietary guilds, following patterns previously reported in other bats and mammals (López-Aguirre et al., 2021b; Pineda-Munoz et al., 2017; Santana et al., 2011; Winchester et al., 2014). General patterns in diet-based variation in DNE among mammals typically suggest a negative correlation between DNE and frugivory, and an increase in DNE in omnivorous and insectivorous taxa (Berthaume et al., 2019a; Fulwood et al.,2021; Winchester et al., 2014). Our finding that values of DNE are instead broadly similar in frugivorous, insectivorous and omnivorous noctilionoid bats confirms previous findings from a smaller sample of species (López-Aguirre et al., 2021b), indicating a clear deviation from the general mammalian pattern in these bats (Fulwood et al., 2021; Pérez-Ramos et al., 2020; Winchester et al., 2014). This suggests a unique pattern morphological adaptation to frugivory in bats, at least in the dentition.

Dirichlet Normal Energy has usually been interpreted as a measure of tooth sharpness, so our findings suggest frugivorous noctilionoids have sharper molars than the average frugivorous mammal. We hypothesise that the reduced capacity that bats have to handle fruits with their forelimbs and the fact they feed either perched upside down or during flight represented a selective pressure for sharper molars to optimise food processing, due to a reduced potential for pre-ingestion foodstuff processing (Aguirre et al., 2003; Santana et al., 2011; Santana &

377 Dumont, 2009). However, to our knowledge our study is only the second one to investigate
378 DNE in bats, so further studies are required to determine if this is a chiropteran feature or
379 something specific to noctilionoids.

380 Higher dental complexity has been proposed as a common adaptation for frugivory in bats
381 (López-Aguirre et al., 2021b; Santana et al., 2011), contrary to recent studies that have found an
382 opposite pattern in ursid carnivorans and strepsirrhine primates (Fulwood et al., 2021; Pérez-
383 Ramos et al., 2020). Our results support the general chiropteran pattern of higher dental
384 complexity in frugivores, as indicated by our results of OPCR in noctilionoid bats. Values of RFI
385 increased on the scale from herbivory to animalivory, similar to previous findings in primates.
386 Values calculated for RFI were higher in nectarivorous bats than in frugivorous bats, which
387 would seem to be in opposition to the hypothesis that high RFI necessarily means more
388 mastication surface area by Pineda-Munoz et al. (2017). Additionally, we found high slope and
389 RFI showed a marked association with liquid diets, confirming previous findings in bats (López-
390 Aguirre et al., 2021b). Reduction of size in postcanine dentition has been proposed as a
391 common adaptation in mammals specialised to different liquid diets (e.g. sanguivory and
392 exudativory; (Burrows et al., 2020)). Compared to gummivore and exudativore primates
393 (Burrows et al., 2020; Burrows & Nash, 2010; Pineda-Munoz et al., 2017), noctilionoid bats with
394 liquid diets have laterally compressed molars, which reduces the 2D area of the crown and
395 inflates RFI and slope (see Fig. 2).

396 In terms of dental disparity, the significantly greater dental variability in frugivorous and
397 omnivorous noctilionoid bats showcases the extreme phenotypic diversity found associated

with frugivory, reflecting previous findings supporting the importance that shifts to feeding on fruit apparently had on morphological and taxonomic diversification of bats (Arbour et al., 2019; Monteiro & Nogueira, 2011; Rojas et al., 2012; Rossoni et al., 2019). Overall, our results reveal noctilionoid bats do not follow the general mammalian pattern of OPCR variation across dietary guilds. Further, DNE in noctilionoid frugivores and RFI and slope in species with liquid diets showed deviations from the previous findings in mammals.

DTA and dietary composition

Patterns of DTA based on the intensity of exploitation of different resources supported our hypothesis that dietary composition, in addition to putative guild, has an effect on dental morphology. Increasing values of DNE in species that rely more on fruit supports our previous findings that frugivorous noctilionoids tend to have sharper molars, possibly to optimise food handling (López-Aguirre et al., 2021b). This seems to be correlated with the evolution of a labial rim on the molars, formed by the displacement of the paracone and metacone from a central position in the occlusal surface of the molar (i.e. dilambdodonty) to the labial edge of the tooth, a trait which is found in specialised frugivore noctilionoids (Freeman, 1988). Decreasing values of DNE and OPCR associated with increasing amounts of nectarivory also support our prediction that species with liquid diets have less biomechanically demanding food processing needs, in accordance with previous findings (Freeman, 1995). All DTA metrics tended to increase with intensified carnivory, suggesting that evolution of specialized carnivory represents a multifaceted adaptation process, rather than encompassing change in a single dimension of dental morphology that facilitated the colonisation of this dietary niche (Freeman, 1988;

Norberg & Fenton, 1988; Santana & Cheung, 2016). The difference in the relative importance of DTA metrics in our different models of intensifying exploitation showed decoupled patterns of ecomorphological adaptation. Molar area explaining the greatest proportion of variance in the model of intensifying carnivory reflects previous findings on the importance of increased body size for the adoption of carnivory in Chiroptera (Freeman, 1988; Norberg & Fenton, 1988; Santana & Cheung, 2016). It has been suggested that increased body size was the primary adaption required for carnivory during the evolution of noctilionoid bats (Freeman, 1988; Giannini et al., 2020; Norberg & Fenton, 1988), predating other dental or skeletal adaptations (López-Aguirre et al., 2021b). Relief Index had the highest explicatory power in our models of intensifying frugivory, insectivory and nectarivory, suggesting that crown height had high evolutionary lability with changes in diet during the diversification of Chiroptera (Freeman, 1981, 1988, 1995). Slope had the second-highest explicatory power in our models of intensifying frugivory and insectivory, possibly reflecting opposite extremes of crown steepness, with that feature increasing with greater insectivory and decreasing with greater frugivory. It is interesting that DNE had the second-highest explicatory power in our model of intensifying nectarivory, suggesting that reduction in molar sharpness played a major role during the adoption of nectarivory in Noctilionoidea.

DTA and dietary breadth

Contrary to our prediction, all DTA metrics with the exception of molar area showed a significant association with dietary breadth, revealing that the diversity in species' diets is also reflected in dental morphology. Nevertheless, the variation in the strength and direction of the

association across DTA metrics indicates different pathways shaping phenotypic adaptions to generalist and specialist diets. The stronger linear correlation between slope, RFI and marginality points to a common path of specialisation for herbivory on the one hand and animalivory on the other. The pattern of values of slope and RFI decreasing in species with narrow herbivorous diets and increasing in those that have narrow animalivorous diets underscore previous findings regarding dietary guilds and diet composition (López-Aguirre et al., 2021b). Wider molar occlusal surfaces are commonly found in frugivorous noctilionoids (particularly in the subfamily Stenodermatinae, comprised largely of specialised frugivores), whereas taller and steeper molar crowns are characteristic of animalivorous bats (Freeman, 1981, 1988, 1995; Santana & Cheung, 2016). Biplots of marginality and DNE, OPCR and molar area suggest higher values of these three metrics in species with broader diets (i.e. generalist omnivores), explaining the weaker linear correlation between the three metrics and marginality. More omnivorous species face the challenge of consuming a wider range of foodstuffs that present a myriad of biomechanical challenges (Aguirre et al., 2003; Santana et al., 2011; Santana & Dumont, 2009). Higher DNE and OPCR values suggest that omnivory exerts a functional selective pressure towards increased molar sharpness and topographic complexity (Rojas et al., 2018). We hypothesise that increased DNE and OPCR equip generalist species with the dental tools necessary to process a variety of foods with different biomechanical properties. Combined, our results suggest that variability in RFI and slope provide evolutionary pathways to specialist diets, whereas increases in DNE and OPCR represent adaptations to omnivory.

Conclusions

Using phylogenetic comparative methods and multivariate DTA, we deconstructed variation in noctilionoid dental morphology into its phylogenetic, ecological and biological components. Our finding of significant phylogenetic and allometric structuring in DTA indicates that dental topography does not respond only to diet-related functional demands, but also to phylogenetic relatedness, highlighting the need to account for multiple sources of variation. Our results suggest frugivorous noctilionoids have sharper molars (higher DNE values) than expected compared with other frugivorous mammals, that species with liquid diets show increased molar crown height and steepness, and that animalivorous noctilionoids have relatively larger molars than herbivorous taxa. We also recovered DTA adaptations to dietary composition, revealing that the intensity of exploitation of a resource also correlates with dental morphology. Molar area was the trait most strongly associated with carnivory, whereas RFI and slope explained the greatest variation in our models of increasing insectivory, frugivory and nectarivory. Finally, generalist noctilionoids were found to have higher DNE and OPCR, whereas the range of RFI and slope values revealed a base point for the transitions to specialist herbivory and specialist animalivory. Incorporating data on biomechanical properties of food items (e.g. item hardness and size) in futures studies could further elucidate still unexplored patterns of dental variation in bats.

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Figure captions

Figure 1. Evolutionary relationships of species sampled, based on a modified version of Shi & Rabosky (2015)'s phylogeny. Tip colours indicate dietary guilds.

Figure 2. Diversity of dental morphology across the dietary range found in Noctilionoidea, exemplified with DTA metrics; DNE, OPCR and slope. 3D meshes not to scale. Low DNE and slope values in blue and high values in red. For 3D-OPCR, differences in colour relate to the orientation of patches with respect to the 8 cardinal directions.

Figure 3. Variation in dental complexity across Noctilionoidea based on diet. Boxplots comparing DTA metrics across different dietary guilds (left column), and scatterplots showing linear regressions of DTA metrics against marginality (i.e. dietary breadth). Marginality values close to zero represent specialist herbivorous diets, whereas values close to one represent specialist animalivorous diets.

Figure 4. Boxplots of dental topographic disparity (quantified as the sum of variances across DTA metrics) across dietary guilds, based on 100 resampling iterations.

Figure 5. Dental morphospace (based on principal component analysis) and phylomorphospace (based on phylogenetic principal component analysis).

Figure 6. Trajectories of mean values of DTA metrics along a gradient of increasing intensity of exploitation of a given dietary resource in noctilionoid bats.

Figure 7. Relative importance of DTA metrics on a linear regression model of increasing intensity of exploitation of a dietary resource, expressed as the percentage of R^2 of the model explained by each DTA metric.

Table captions

Table 1. Statistical test of phylogenetic signal on each DTA metric, based on 10000 iterations.

Table 2. Phylogenetic ANOVAs of differences in DTA metrics between dietary guilds, based on 10,000 iterations.

Table 3. Wilcoxon test of pairwise comparisons of dental disparity across noctilionoid dietary guilds.

Table 4. Phylogenetic linear regression models of the effect of body mass (BM) and dietary breadth (marginality) on DTA metrics, based on 10,000 iterations.

Table 1. Statistical test of phylogenetic signal on each DTA metric, based on 10000 iterations.

	K-	*P*
DNE	0.513	<0.0001
OPCR	0.299	0.049
RFI	1.553	0.0001
Slope	0.848	0.0001
Molar size	0.754	0.0002

Table 2. Phylogenetic ANOVAs of differences in DTA metrics between dietary guilds, based on 10,000 iterations.

	df	SS	MS	F	*P*
DNE	6	6.135	1.023	8.986	<0.0001
RFI	6	2.402	0.400	29.11	<0.0001
OPCR	6	3.285	0.546	4.064	0.001
Slope	6	0.273	0.045	12.61	<0.0001
MS	6	34.08	5.680	7.798	<0.0001

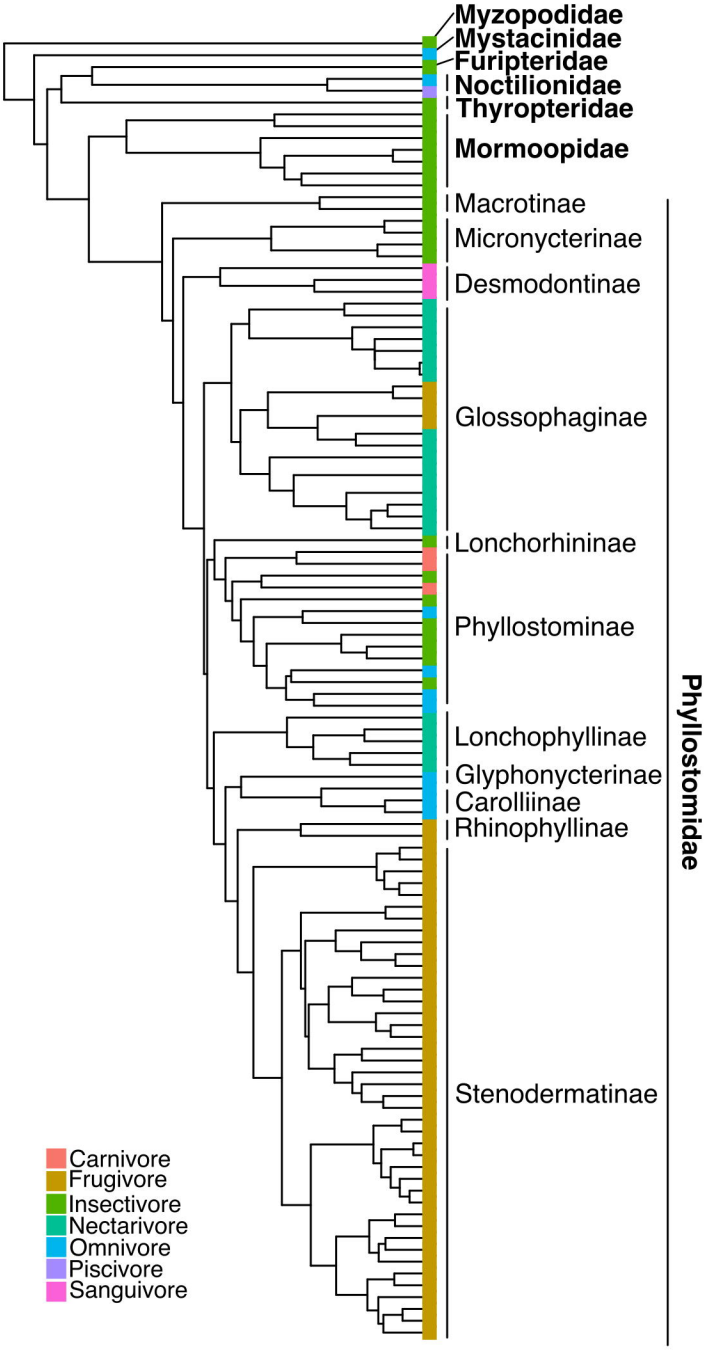
Table 3. Wilcoxon test of pairwise comparisons of dental disparity across noctilionoid dietary guilds.

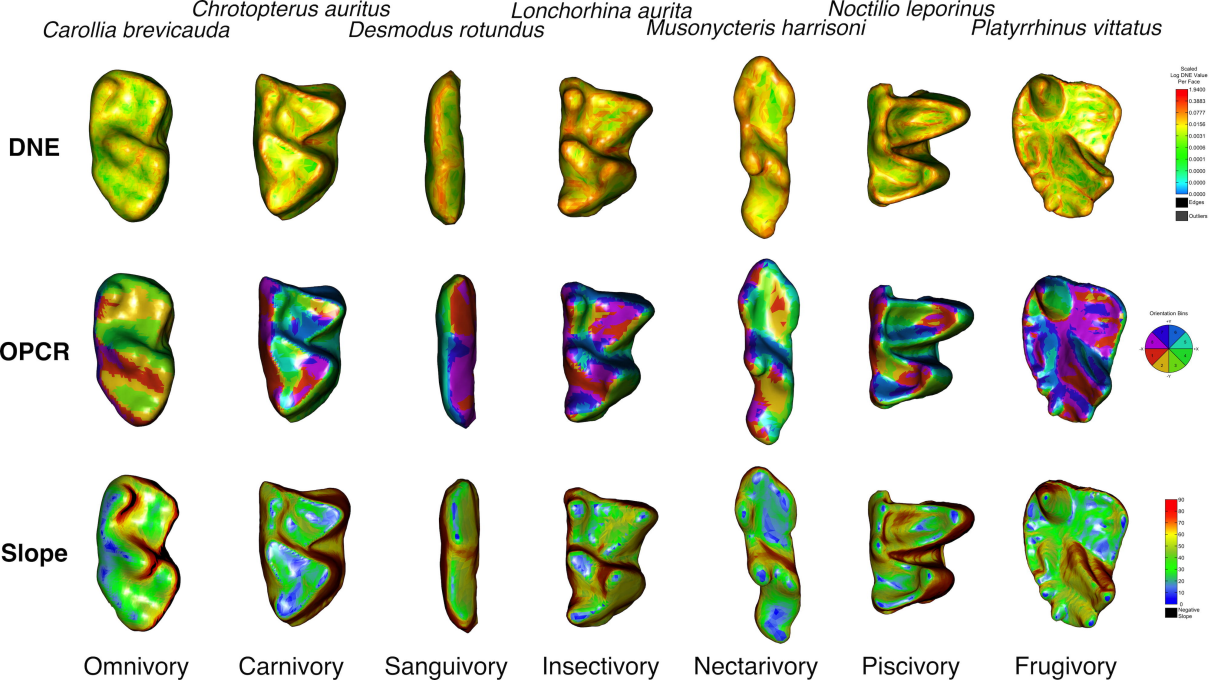
	W statistic	*P*
Carnivore : Frugivore	48	<0.0001
Carnivore : Insectivore	2367	<0.0001
Carnivore : Nectarivore	6932	<0.0001
Carnivore : Omnivore	200	<0.0001
Carnivore : Sanguivore	8759	<0.0001
Frugivore : Insectivore	8801	<0.0001
Frugivore : Nectarivore	10000	<0.0001
Frugivore : Omnivore	4282	1.000
Frugivore : Sanguivore	10000	<0.0001
Insectivore : Nectarivore	9660	<0.0001
Insectivore : Omnivore	1290	<0.0001
Insectivore : Sanguivore	10000	<0.0001
Nectarivore : Omnivore	0	<0.0001
Nectarivore : Sanguivore	9946	<0.0001
Omnivore : Sanguivore	10000	<0.0001

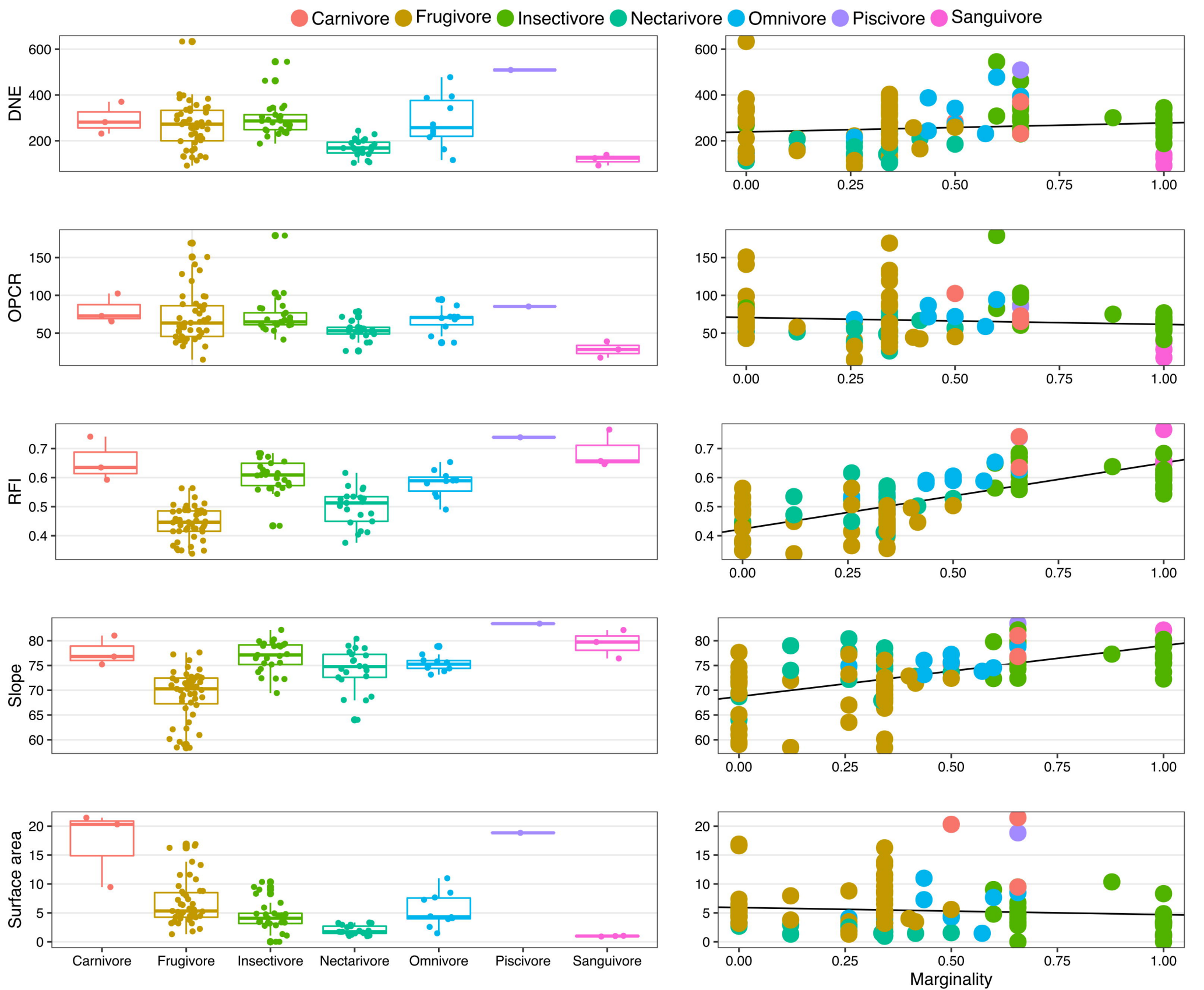
767 **Table 4.** Phylogenetic linear regression models of the effect of body mass (BM) and dietary
768 breadth (marginality) on DTA metrics, based on 10,000 iterations.

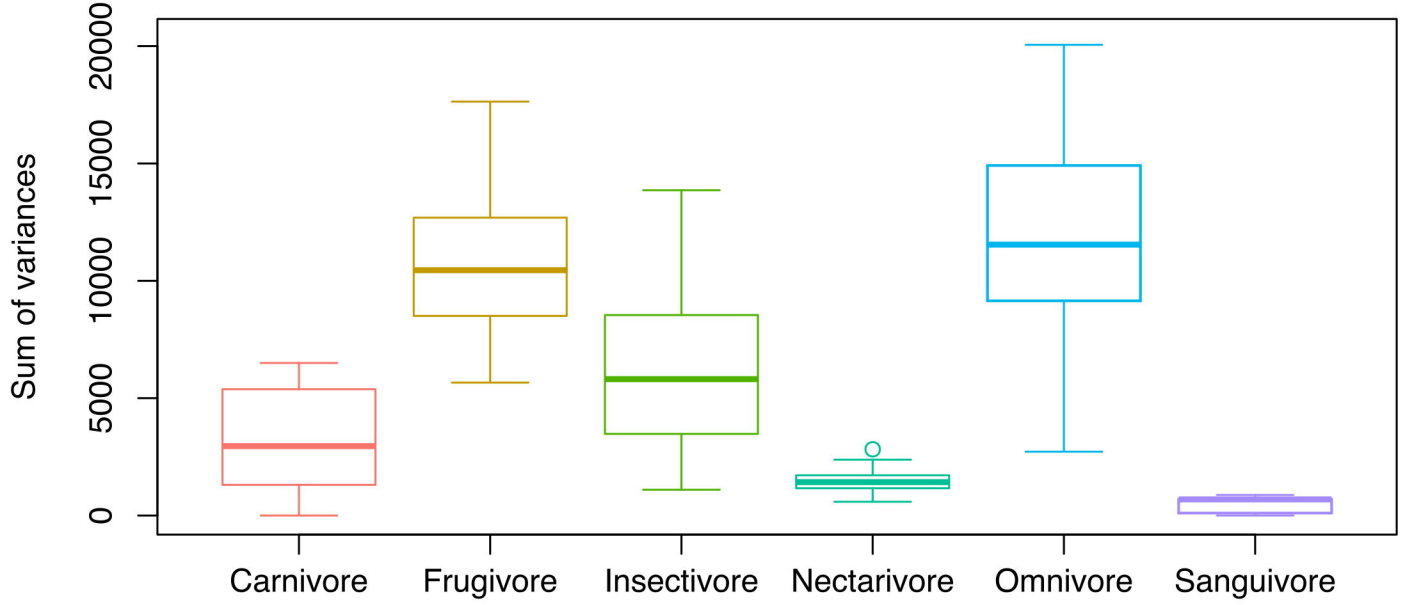
		df	SS	MS	R^2	F	Z	*P*
DNE	BM	1	0.30209	0.302091	0.18349	25.1161	1.9893	0.0001
	Marginality	1	0.05727	0.057273	0.03479	4.7617	1.27	0.0296
OPCR	BM	1	0.25076	0.25076	0.16837	25.452	2.0276	0.0001
	Marginality	1	0.18435	0.184348	0.12378	18.711	1.8726	0.0001
RFI	BM	1	0.017814	0.017814	0.05721	11.261	1.6139	0.0017
	Marginality	1	0.124275	0.124275	0.39914	78.558	2.5358	0.0001
Slope	BM	1	0.000624	0.0006242	0.01215	1.7798	0.8305	0.1829
	Marginality	1	0.013224	0.0132238	0.25741	37.7071	2.211	0.0001
MS	BM	1	3.1885	3.1885	0.3886	69.4906	2.4991	0.0001
	Marginality	1	0.107	0.107	0.01304	2.3321	0.9646	0.1255

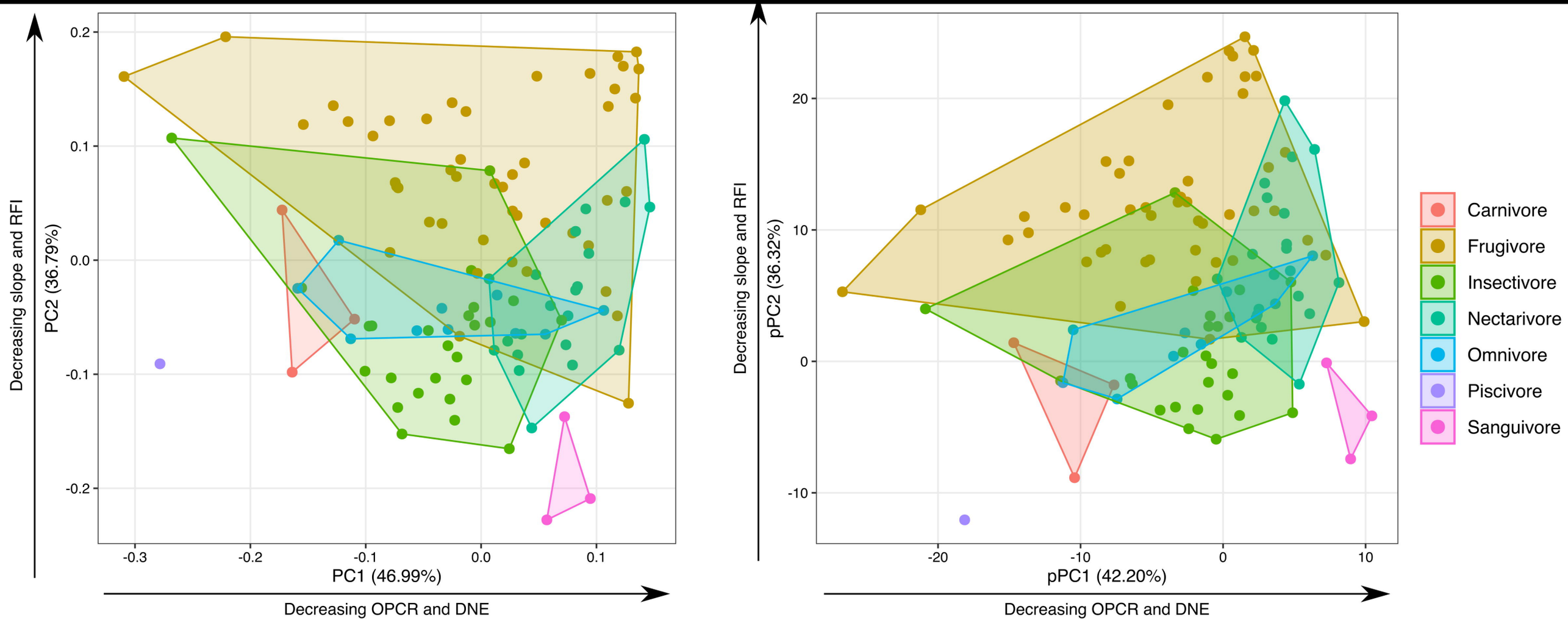
769
770

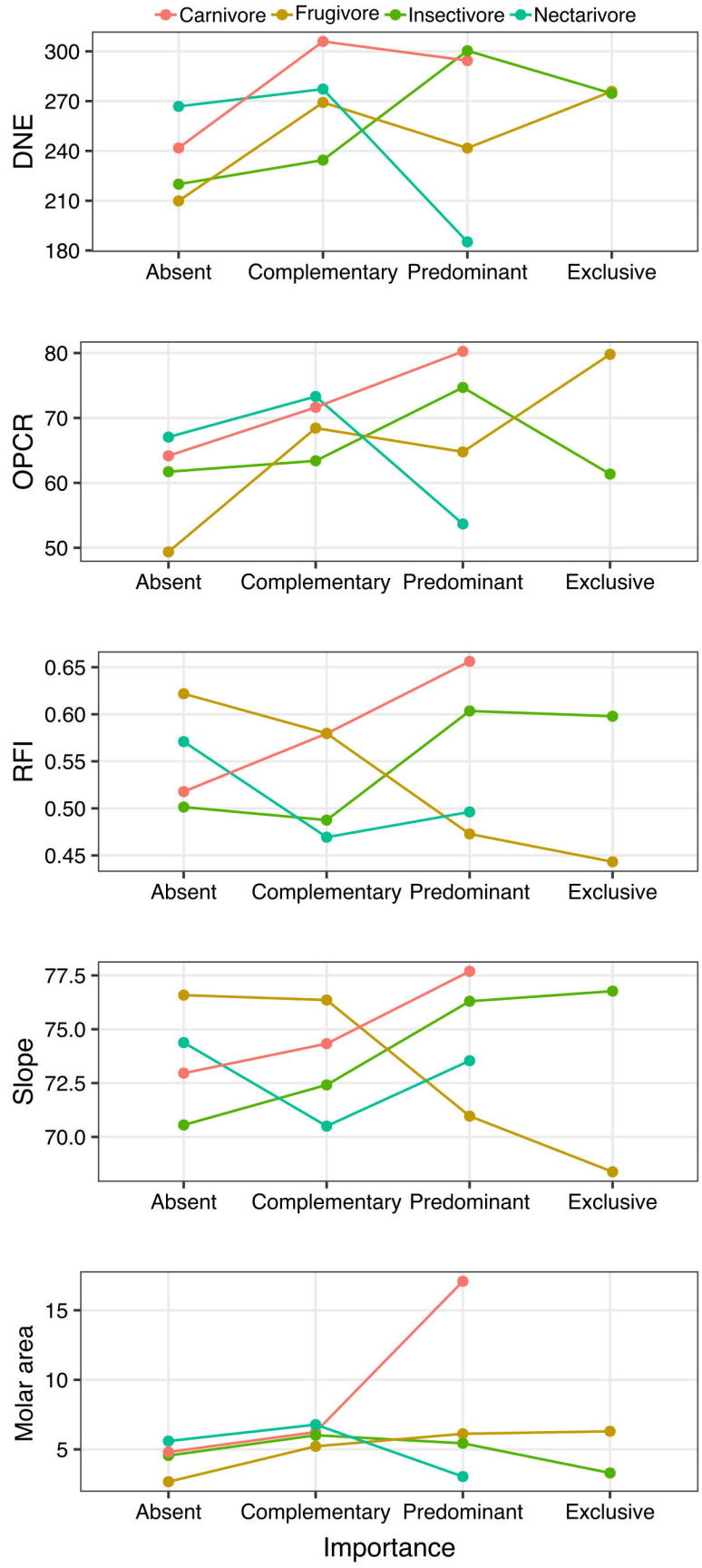

Myzopodidae
Mystacinidae
Furipteridae
Noctilionidae
Thyropteridae
Mormoopidae
Macrotinae
Micronycterinae
Desmodontinae
Glossophaginae
Lonchorhininae
Phyllostominae
Lonchophyllinae
Glyphonycterinae
Carolliinae
Rhinophyllinae
Stenodermatinae
Phyllostomidae
Carnivore
Frugivore
Insectivore
Nectarivore
Omnivore
Piscivore
Sanguivore

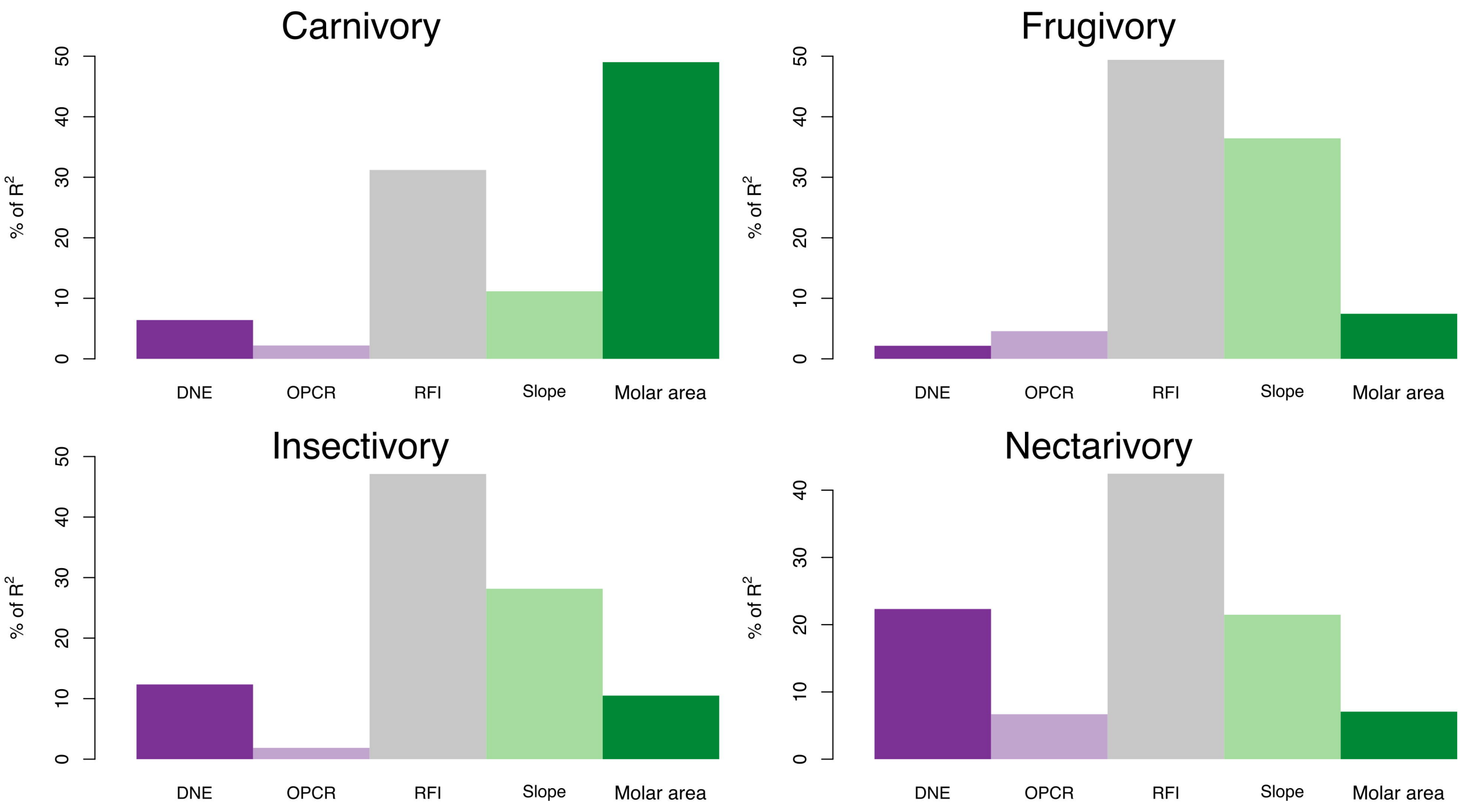

Carollia brevicauda
Chrotopterus auritus
Desmodus rotundus
Lonchorhina aurita
Musonycteris harrisoni
Noctilio leporinus
Platyrrhinus vittatus
DNE
OPCR
Slope
Scaled Log DNE Value Per Face
1.9400
0.3883
0.0777
0.0156
0.0031
0.0006
0.0001
0.0000
0.0000
0.0000
Edges
Outliers
Orientation Bins
90
80
70
60
50
40
30
20
10
0
Negative Slope
Omnivory
Carnivory
Sanguivory
Insectivory
Nectarivory
Piscivory
Frugivory


Carnivore
Frugivore
Insectivore
Nectarivore
Omnivore
Piscivore
Sanguivore
DNE
OPCR
RFI
Slope
Surface area
Carnivore
Frugivore
Insectivore
Nectarivore
Omnivore
Piscivore
Sanguivore
Marginality


Sum of variances
0
5000
10000
15000
20000
Carnivore
Frugivore
Insectivore
Nectarivore
Omnivore
Sanguivore


Decreasing slope and RFI
PC2 (36.79%)
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.2
-0.1
0.0
0.1
PC1 (46.99%)
Decreasing OPCR and DNE
Decreasing slope and RFI
pPC2 (36.32%)
20
10
0
-10
-20
-10
0
10
pPC1 (42.20%)
Decreasing OPCR and DNE
Carnivore
Frugivore
Insectivore
Nectarivore
Omnivore
Piscivore
Sanguivore


Carnivore
Frugivore
Insectivore
Nectarivore
DNE
300
270
240
210
180
Absent
Complementary
Predominant
Exclusive
OPCR
80
70
60
50
RFI
0.65
0.60
0.55
0.50
0.45
Slope
77.5
75.0
72.5
70.0
Molar area
15
10
5
Importance


Carnivory
Frugivory
Insectivory
Nectarivory
% of R2
0
10
20
30
40
50
DNE
OPCR
RFI
Slope
Molar area