A Standardized Effect Size for Evaluating the Strength of Phylogenetic Signal, and Why Lambda is not Appropriate

Abstract

Macroevolutionary studies frequently characterize the phylogenetic signal in phenotypes, and wish to compare the strength of that signal across traits. However, analytical tools for such comparisons have largely remained underdeveloped. In this study, we evaluated the efficacy of one commonly used parameter (Pagel's λ) to estimate the strength of phylogenetic signal in phenotypic traits, and evaluate the degree to which λ correctly identifies known levels of phylogenetic signal. We find that the precision of λ in estimating actual levels of phylogenetic signal is often inaccurate, and that biological interpretations of the strength of phylogenetic signal based on λ are therefore compromised. We then propose a standardized effect size based on *Kappa* (Z_K), which measures the strength of phylogenetic signal, and places it on a common scale for statistical comparison. Tests based on Z_K provide a mechanism for formally comparing the strength of phylogenetic signal across datasets, in much the same manner as effect sizes may be used to summarize patterns in quantitative meta-analysis. Our approach extends the phylogenetic comparative toolkit to address hypotheses that compare the strength of phylogenetic signal various phenotypic traits, even when those traits are found in different evolutionary lineages or of in different units or scale.

Introduction

Investigating macroevolutionary patterns of trait variation requires a phylogenetic perspective, because the shared ancestry among species generates statistical non-independence (Felsenstein 1985; Harvey and Pagel 1991). Accounting for this evolutionary non-independence is the purview of *phylogenetic comparative methods* (PCMs); a suite of analytical tools that condition the data on the phylogeny through the course of statisical evaluations of phenotypic trends (e.g., Grafen 1989; Garland and Ives 2000; Rohlf 2001; Butler and King 2004). The past several decades have witnessed a rapid expansion in the development of PCMs to address an ever-growing set of macroevolutionary hypotheses (Martins and Hansen 1997; O'Meara et al. 2006; Revell and Harmon 2008; Beaulieu et al. 2012; Adams 2014b,a; Adams and Collyer 2018). These methods are predicated on the notion that phylogenetic signal – the tendancy for closely related species to display similar trait values – is present in cross-species datasets (Felsenstein 1985; Pagel 1999; Blomberg et al. 2003). Indeed, under numerous evolutionary models, phylogenetic signal is to be expected, as stochastic character change along the hierarchical structure of the tree of life generates trait covaration among related taxa (see Felsenstein 1985; Blomberg et al. 2003; Revell et al. 2008).

Several analytical tools have been developed to quantify phylogenetic signal in phenotypic datasets, including measures of serial independence (**C**: Abouheif 1999), autocorrelation estimates (I: Gittleman and Kot 1990), statistical ratios of trait variation relative to what is expected given the phylogeny ($Kappa$: Blomberg et al. 2003; Adams 2014a), and scaling parameters used in maximum likelihood fitting of the data to the phylogeny (λ: Pagel 1999), among others (e.g., Klingenberg and Gidaszewski 2010). The statistical properties of these methods – namely type I error rates and power – have also been investigated to determine when phylogenetic signal can be detected and under what conditions (e.g., Munkemuller et al. 2012; Pavoine and Ricotta 2012; Diniz-Filho et al. 2012; Adams 2014a; Molina-Venegas and Rodriguez 2017; see also Revell et al. 2008; Revell 2010). One of the most widely used methods for characterizing phylogenetic signal in macroevolutionary studies is Pagel's λ (Pagel 1999). Here, maximum likelihood is used to fit the data to the phylogeny under a Brownian motion model of evolution. A parameter (λ) is included, which transforms the lengths of the internal branches of the phylogeny to improve the fit (Pagel 1999; Freckleton et al. 2002). Pagel's λ ranges from $0 \rightarrow 1$, with larger values signifying a greater dependence of observed trait variation on the phylogeny. Pagel's λ also has the appeal that it may be included in phylogenetic regression (PGLS) to account for the degree of phylogenetic signal in comparative analyses (see Freckleton et al. 2002).

Evolutionary biologists commonly seek to describe the relative strength of phylogenetic signal in phenotypic traits, to determine the extent to which shared evolutionary history has influenced trait covariation among taxa. This is often accomplished by interpreting empirical estimates of λ; with smaller values signifying 'weak' phylogenetic signal, while larger values are interpreted as 'strong' phylogenetic signal (e.g., De Meester et al. 2019; Pintanel et al. 2019; Su et al. 2019). Other approaches for interpreting λ are more statistical. For instance, some have evaluated whether the observed λ differs from some expected value through the use of confidence intervals (Vandelook et al. 2019) or by performing likelihood ratio tests that compare the observed model fit to that obtained when $\lambda = 0$ or $\lambda = 1$ (Freckleton et al. 2002; Cooper et al. 2010; Bose et al. 2019). Additionally, qualitative comparisons of λ estimates obtained from multiple phenotypic traits have been used to infer whether the strength of phylogenetic signal is greater in one trait as compared to another (e.g., Liu et al. 2019; Bai et al. 2019). Indeed, statements regarding the strength of phylogenetic signal based on λ are rather common in the evolutionary literature. For instance, of the 204 papers published in 2019 that estimated and reported Pagel's λ (found in Google.scholar), 40% interpreted the strength of phylogenetic signal for at least one phenotypic trait. Further, because nearly half of the 1,572 λ values reported were near 0 or 1 (Figure 1) where the biological interpretation of λ is known, this percentage is even higher.

[insert Figure 1 here]

It seems intuitive to interpret the strength of phylogenetic signal based on the value of λ, as λ is a parameter on a bounded scale ($0 \rightarrow 1$) for which interpretation of its extremal points are understood. Specifically, $\lambda = 0$ represents no phylogenetic signal, while $\lambda = 1$ is phylogenetic signal as expected under Brownian motion. However, equating values of λ directly to the strength of phylogenetic signal presumes two important statistical properties that have not been fully explored. First, it presumes that values of λ can be precisely estimated, as biological inferences regarding the strength of phylogenetic signal depend on high accuracy in its estimation. Therefore, understanding the precision in estimating λ is paramount. One study (Boettiger et al. 2012) found that estimates of Pagel's λ displayed less variation (i.e., greater precision) when data were simulated on a large phylogeny ($N = 281$) as compared to a small one ($N = 13$). From this observation it was concluded that insufficient data (i.e., the number of species) was the underlying cause of the increased variation across parameter estimates (Boettiger et al. 2012). Indeed, such a pattern is common with statistical estimators, as summary statistics and parameters are often more precise at greater sample sizes (Cohen 1988). However, this conclusion also implies that the precision of λ remains constant across its range

($\lambda = 0 \rightarrow 1$); an assumption that to date, has not been verified. Thus, despite widespread use of Pagel's (1999) λ in macroevolutionary studies, at present, we lack a general understanding of the precision with which λ can estimate levels of phylogenetic signal in phenotypic datasets.

Second, while estimates of λ are within a bounded scale ($0 \rightarrow 1$), this does not *de-facto* imply that the estimated values of this parameter correspond to the actual strength of the underlying input signal in the data. For this to be the case, λ must be a statistical effect size. Effect sizes are a measure the magnitude of a statistical effect in data, represented on a common scale (Glass 1976; Cohen 1988). Effect sizes have widespread use in many areas of the quantiative sciences, as they represent measures that may be readily summarized across datasets as in meta-analyses (Glass 1976; Hedges and Olkin 1985; Arnqvist and Wooster 1995), or compared among datasets (e.g., Adams and Collyer 2016, 2019a). Unfortunatley, not all model parameters and test statistics are effect sizes, and thus many summary measures must first be converted to standardized units (i.e., an effect size) for meaningful comparison (see Rosenthal 1994). As a consequence, it follows that only if λ is a statistical effect size can comparisons of estimates across datasets be interpretable. For the case of λ, this has not yet been explored.

In this study, we evaluate the precision of Pagel's λ for estimating known levels of phylogenetic signal in phenotypic data. We use computer simulations with differing numbers of species, differently shaped phylogenies, and differing input levels of phylogenetic signal, to explore the degree to which λ correctly identifies known levels of phylogenetic signal, and under what circumstances. We find that estimates of λ vary widely for a given input value of phylogenetic signal, and that the precision in estimating λ is not constant across its range. Rather, there is decreased precision when input levels of phylogenetic signal are of intermediate strength. Additionally, the same estimated values of λ may be obtained from datasets containing vastly different input levels of phylogenetic signal. Thus, λ is not a reliable indicator of the strength of phylogenetic signal in phenotypic data. We then describe a standardized effect size for measuring the strength of phylogenetic signal in phenotypic datasets, and apply the concept to two common measures of phylogenetic signal: λ and $Kappa$. Through simulations we find that the precision of effect sizes based on λ (Z_λ) are less reliable than that those based on $Kappa$ (Z_K), implying that Z_K is a more robust effect size measure. We also propose a two-sample test statistic that may be used to compare the strength of phylogenetic signal among datasets, and provide an empirical example to demonstrate its use. We conclude that estimates of phylogenetic signal using Pagel's λ are often inaccurate, and thus interpreting strength of phylogenetic signal in phenotypic datasets based on this measure is compromised. By contrast, effect sizes obtained from $Kappa$

hold promise for characterizing phylogenetic signal, and for comparing the strength of phylogenetic signal across datasets.

Methods and Results

The Precision of λ is Variable

We conducted a series of computer simulations to evaluate the precision of Pagel's λ. Our primary simulations were based on pure-birth phylogenies; however, we also evaluated patterns on both balanced and pectinate trees to determine whether tree shape affected our findings (see Supporting Information). First we generated 50 pure-birth phylogenies at each of six different tree sizes, ranging from 32 to 1024 taxa ($n = 2^5 - 2^{10}$). Next, we rescaled the simulated phylogenies by multiplying the internal branches by λ_{in}, using 21 intervals of 0.05 units across its range ($\lambda_{in} = 0.0 \rightarrow 1.0$), resulting in 1050 scaled phylogenies at each level of species richness (n). Continuous traits were then simulated on each phylogeny under a Brownian motion model of evolution to obtain datasets with differing levels of phylogenetic signal, that ranged from no phylogenetic signal (when $\lambda_{in} = 0$), to phylogenetic signal reflecting Brownian motion (when $\lambda_{in} = 1$). For each dataset we then estimated phylogenetic signal (λ_{est}), and calculated the variance of λ (σ^2_λ) across datasets at each input level of phylogenetic signal and level of species richness as an estimate of precision.

We also evaluated the precision of λ when estimated in PGLS regression and ANOVA (i.e., $Y \sim X$). Here, an independent variable X was simulated on each rescaled phylogeny under a Brownian motion model of evolution (for PGLS regression). For phylogenetic ANOVA, random groups (X) were obtained by simulating a discrete (binary) character on each phylogeny. Next, the dependent variable was simulated in such a manner as to contain a known relationship with X plus random error containing phylogenetic signal. This was accomplished as: $Y = \beta X + \epsilon$. Here, the association between Y and X was modeled using a range of values: $\beta = (0.0, 0.25, 0.5, 0.75, 1.0)$, and the residual error was modeled to contain phylogenetic signal simulated under a Brownian motion model of evolution on each rescaled phylogeny: $\epsilon = \mathcal{N}(\mu = 0, \sigma = \sigma^2\mathbf{C})$: (see Revell 2010 for a similar simulation design). The fit of the phylogenetic regression was estimated using maximum likelihood, and parameter estimates (β_{est} and λ_{est}) were obtained. We then calculated precision estimates (σ^2_λ) at each input level of phylogenetic signal and level of species richness.

All analyses were performed in R v3.6.0 (R Core Team 2019) using the packages `geiger` (Harmon et al.

2008), `caper` (Orme et al. 2013), `phytools` (Revell 2012), and `geomorph` 3.2.1 (Adams and Otárola-Castillo 2013; Adams et al. 2020). R-scripts are found in the Supporting Information.

Results. We found that the precision of λ_{est} varied widely across simulation conditions. Predictably, precision improved as the number of species increased (Figure 2). This confirmed earlier findings of Boettiger et al. (2012), and adhered to parametric statistical theory. However, in many cases the set of λ_{est} spanned nearly the entire range of possible values (e.g., $n = 32$; $\lambda_{in} = 0.5$: $\lambda_{est} = 0.0 \rightarrow 0.985$), revealing that estimates of λ were not a reliable indicator of input phylogenetic signal. Importantly, the precision of λ_{est} was not uniform across all levels of phylogenetic signal. The worst precision was observed at intermediate levels of phylogenetic signal ($\lambda_{in} \approx 0.5$), while precision improved as input levels approached the extremes of λ's range (i.e., $\lambda_{in} \rightarrow 0$ & $\lambda_{in} \rightarrow 1$). Thus, estimates of λ were least reflective of the true input signal at intermediate values. Additionally, even at large levels of species richness, we found that the range of λ_{est} still encompassed a substantial portion of possible values (e.g., $n = 512$; $\lambda_{in} = 0.5$: $\lambda_{est} = 0.32 \rightarrow 0.68$). Likewise, the same λ_{est} could be obtained from datasets containing vastly different input levels of phylogenetic signal (e.g., $n = 512$; $\lambda_{est} = 0.5$; $\lambda_{in} = 0.25 \rightarrow 0.65$). These findings were particularly unsettling when considered in light of our literature survey. Over one quarter of the λ estimates obtained in empirical studies (421 of 1,572) were between $\lambda = 0.25$ and $\lambda = 0.75$ (Figure 1). This range reflected the region that our simulations identified as being the least reliable in terms of accurately characterizing levels of phylogenetic signal, yet 30% of these mid-range empirical estimates were explicitly interpreted in terms of the strength of phylogenetic signal that they represented (i.e., weak, intermediate, strong phylogenetic signal).

Finally, when λ was co-estimated with regression parameters in PGLS regression and ANOVA, the results of our simulations were quite similar. Here, regression parameters (β) were accurately estimated, confirming earlier findings of Revell (2010) (see Supporting Information). However, estimates of phylogenetic signal (λ) were less precise (Figure 3; see also Supporting Information), and the spread of λ_{est} was similar to that observed when λ was estimated for only the dependent variable, as in Figure 2. Taken together, these findings reveal that λ_{est} does not precisely characterize observed levels of phylogenetic signal in phenotypic datasets, and that biological interpretations of the strength of phylogenetic signal based on λ may be highly inaccurate.

[insert Figure 2 here]

[insert Figure 3 here]

A Standardized Effect Size for Phylogenetic Signal

The results above demonstate that λ is not a reliable estimate of the phylogenetic signal in phenotypic data. As such, biological interpretations of the strength of phylogenetic signal, and comparisons of the magnitude of such effects across datasets are severely compromised when based on this parameter. As an alternative, we propose that summary estimates of phylogenetic signal be converted to effect sizes for interpretation and comparison of the relative strength of phylogenetic signal in phenotypic datasets. Statistically, a standardized effect size may be found as:

$$Z_\theta = \frac{\theta_{obs} - E(\theta)}{\sigma_\theta} \tag{1}$$

where θ_{obs} is the observed test statistic, $E(\theta)$ is its expected value under the null hypothesis, and σ_θ is its standard error (Glass 1976; Cohen 1988; Rosenthal 1994). Z_θ expresses the magnitude of the effect in θ_{obs} by transforming the original test statistic to its standard normal deviate (Glass 1976; Kelley and Preacher 2012). Typically, θ_{obs} and σ_θ are estimated from the data, while $E(\theta)$ is obtained from the distribution of θ derived from parametric theory. However, recent advances in resampling theory (Collyer et al. 2015; Adams and Collyer 2016, 2019a) have shown that $E(\theta)$ and σ_θ may also be obtained from an empirical sampling distribution of θ obtained from permutation procedures.

Adams and Collyer (2019b) suggested that the strength of phylogenetic signal could be represented as an effect size based on the $Kappa$ statistic and its empirical sampling distribution from permutation. Here we formalize that suggestion, resulting in an effect size of:

$$Z_K = \frac{log(K_{obs}) - \hat{\mu}_{log(K)}}{\hat{\sigma}_{log(K)}} \tag{2}$$

where K_{obs} is the observed phylogenetic signal, and $\hat{\mu}_K$ and $\hat{\sigma}_K$ are the mean and standard deviation of the empirical sampling distribution of $log(Kappa)$ obtained via permutation. Here the logarithm was used because $Kappa$ takes only positive values ($0 \rightarrow \infty$) and its sampling distribution is log-normally distributed

(for a similar transformation when calculating multivariate effect sizes see: Appendix 1 of Collyer and Adams 2018). Similarly, an effect size based on λ could be envisioned as:

$$Z_\lambda = \frac{\lambda_{obs} - 0}{\hat{\sigma}_\lambda}. \tag{3}$$

In this case, λ_{obs} and $\hat{\sigma}_\lambda$ are empirically derived using maximum likelihood, as permutation approaches have not been developed for evaluating λ. Note also that under the null hypothesis, no phylogenetic signal is expected (Freckleton et al. 2002), and thus $E(\lambda) = 0$ under this condition.

To evaluate the utility of Z_K and Z_λ we calculated both effect sizes for the simulated datasets generated above, and summarized the precision of each using its variance ($\sigma^2_{Z_K}$ and $\sigma^2_{Z_\lambda}$). Results are found in Figure 4 (additional results are found in the Supporting Information). Here two things are evident. First, estimates of Z_K track the input phylogenetic signal in a more linear fashion than do estimates of Z_λ (Figure 4A,B). Thus, actual changes in the strength of phylogenetic signal are reflected more evenly in the corresponding values of the effect size Z_K. Second, the precision of Z_K is considerably more stable as compared with Z_λ. This may be seen by calculating the coefficients of variation for the set of precision estimates (i.e., $\sigma^2_{Z_K}$ and $\sigma^2_{Z_\lambda}$) across input levels of phylogenetic signal. Here coefficients of variation in the precision of Z_K were an order of magnitude smaller for than for Z_λ (Figure 4C). This implied that estimates of the strength of phylogenetic signal were more reliable and robust when using Z_K as compared with Z_λ.

[insert Figure 4 here]

Statistical Comparisons of Phylogenetic Signal

Once the magnitude of phylogenetic signal is characterized using Z_K, one may wish to compare such measures across datasets, to determine whether the strength of phylogenetic signal is significantly greater in one phenotypic trait as compared to another. As with other effect sizes derived from permutation distributions (e.g., Adams and Collyer 2016, 2019a), a two-sample test statistic may be calculated as:

$$\hat{Z}_{12} = \frac{|(K_1 - \hat{\mu}_{K_1}) - (K_2 - \hat{\mu}_{K_2})|}{\sqrt{\hat{\sigma}^2_{K_1} + \hat{\sigma}^2_{K_2}}} \quad (4)$$

where K_1, K_2, $\hat{\mu}_{K_1}$, $\hat{\mu}_{K_2}$, $\hat{\sigma}_{K_1}$, and $\hat{\sigma}_{K_2}$ are as defined above for equation 2. Estimates of significance of $\hat{Z}_{12}$ may be obtained from a standard normal distribution. Typically, $\hat{Z}_{12}$ is considered a two-tailed test, however directional (one-tailed) tests may be specified should the empirical situation require it (see Adams and Collyer 2016, 2019a).

Empirical Example

To demonstrate the utility of $\hat{Z}_{12}$ we performed an analysis of the strength of phylogenetic signal in two phenotypic datasets from species of plethodontid salamander. The data were part of a series of studies examining macroevolutionary trends in phenotypic diversification in this group (Baken and Adams 2019; Baken et al. 2020). Our dataset contained surface area to volume ratios (SA:V) and relative body width ($\frac{BW}{SVL}$) for 305 species (Figure 5A). For SA:V, 11 linear body measurements from 2,781 individuals were taken, from which estimates of the surface area and volume of the head, body, and tail were calculated and subsequently combined to arrive at the SA:V for each indiviual (for mathematical details see Baken et al. 2020). Species means were then obtained. Likewise, body size (SVL) and body width (BW) measurements were taken from 3,371 individuals, and species means of relative body width ($\frac{BW}{SVL}$) were calculated (data from Baken and Adams 2019). A time-dated molecular phylogeny for the group (Bonett and Blair 2017) was then pruned to match the species in the dataset, resulting in a phylogeny and corresponding phenotypic dataset containing 305 species. The phylogenetic signal in each trait was then characterized using $Kappa$, which was converted to its effect size (Z_K) using `geomorph` 3.2.1 (Adams and Otárola-Castillo 2013; Adams et al. 2020). Finally, the strength of phylogenetic signal was compared across traits using $\hat{Z}_{12}$ as described above (**to be incorporated in `geomorph` upon manuscript acceptance**).

Results. Both SA:V and relative body width displayed significant phylogenetic signal ($Kappa_{SA:V} = 0.7608$; $P = 0.001$; $Kappa_{BW/SVL} = 0.2515$; $P = 0.001$). For both phenotypic traits, K_{obs} differed markedly from their corresponding permutation distributions, which were found to overlap almost perfectly (Figure 5B). However, while both traits displayed significant phylogenetic signal, there was nearly a four-fold difference

in the magnitude of their effect sizes, with SA:V displaying the greater phylogenetic signal (Figure 5C). Using the two-sample test statistic above, this difference was found to be highly significant ($\hat{Z}_{12} = 4.13$; $P = 0.000036$). Thus it may be concluded that SA:V displays significantly stronger phylogenetic signal than does relative body width, and that shared evolutionary history has strongly influenced trait covariation among taxa for SA:V. Biologically, this observation corresponds with the fact that tropical species – which form a monophyletic group within plethodontids – display greater variation in SA:V which covaries with disparity in their climatic niches (Baken et al. 2020). Thus, because of this macroevolutionary association, strong phylogenetic signal in SA:V is to be expected.

Discussion

It is common in comparative evolutionary studies to characterize the phylogenetic signal in phenotypic traits to determine the extent to which shared evolutionary history has generated trait covariation among taxa. However, while numerous analytical approaches may be used to quantify phylogenetic signal (e.g., Abouheif 1999; Gittleman and Kot 1990; Pagel 1999; Blomberg et al. 2003; Adams 2014a), methods that explicitly measure the strength of phylogenetic signal, or facilitate comparisons among datasets, have remained underdeveloped. In this study, we evaluated the precision of one common measure, Pagel's λ, and explored its efficacy for characterizing the strength of phylogenetic signal in phenotypic data. Using computer simulations, we found that the precision of λ increased with increasing sample sizes; a pattern noted previously (Boettiger et al. 2012), and one that conformed with parametric statistical theory (Cohen 1988). However, we also found that vastly different λ estimates could be obtained from data containing the same level of phylogenetic signal, and that similar λ estimates may be obtained from data containing differing levels of phylogenetic signal. Further, the precision of λ varied with the strength of phylogenetic signal, where lower precision was observed when in data whose phylogenetic signal was of intemediate strength. From these findings we conclude that λ is not a reliable indicator of the observed strength of phylogenetic signal in phenoytpic datasets, and that biological interpretations of the strength of signal based on this parameter may innacurately characterize such effects.

As an alternative, we described a standardized effect size (Z) for assessing the strength of phylogenetic signal. Z expresses the magnitude of phylogenetic signal as a standard normal deviate, which is easily interpretable as the strength of phylogenetic signal relative to the mean. We applied this concept to both λ and $Kappa$, and found that Z_K was a better estimate of the strength of phylogenetic signal in phenotypic data. First, Z_K was more precise than Z_λ, and variation in this precision was more consistent across the range of input levels

of phylogenetic signal. Additionally, values of Z_K more accurately tracked known levels of phylogenetic signal, with changes in the actual strength of phylogenetic signal reflected in a more linear fashion by concomite changes in the values of Z_K. Thus, Z_K holds promise as a measure of the relative strength of phylogenetic signal that reflects the magnitude of this effect in phenotypic data. We therefore recommend that future studies interested in the strength of phylogenetic signal incorporate Z_K as a statistical measure of this effect.

Based on the effect size Z_K, we then proposed a two-sample test, which provides a statistical means of determining whether the strength of phylogenetic signal is greater in one phenotypic trait as compared to another. Prior studies have summarized patterns of variation in phylogenetic signal across datasets using summary test values, such as $Kappa$ (e.g., Blomberg et al. 2003). However, $Kappa$ does not scale linearly with input levels of phylogenetic signal, and its variance increases (i.e., precision decreases) with increasing strength of phylogenetic signal (Munkemuller et al. 2012; Diniz-Filho et al. 2012: see also Supporting Information). Thus, $Kappa$ should not be considered a standardized effect size that measures the strength of phylogenetic signal on a common scale. By contrast, converting $Kappa$ to Z_K (via equation 2) alleviates these concerns, and facilitates formal statistical comparisons of the strength of signal across datasets. Thus when viewed from this perspective, the approach developed here is statistically aligned with other statistical approaches such as meta-analysis (sensu Hedges and Olkin 1985; Glass 1976; Arnqvist and Wooster 1995), where summary statistics across datasets are converted to standardized effect sizes for subsequent 'higher order' statistical summaries or comparisons. As such our approach enables evolutionary biologists to quantitatively examine the relative strength of phylogenetic signal across a wide range of phenotypic traits, and thus opens the door for future discoveries that inform on how phenotypic diversity accumulates in macroevolutionary time across the tree of life.

One important advantage of the approach advocated here is that the resulting effect sizes (Z_K) are dimensionless, as the units of measurement cancel out during the calculation of Z (Sokal and Rohlf 2012). Thus, Z_K represents the strength of phylogenetic signal on a common and comparable scale – measured in standard deviation units – regardless of the initial units and original scale of the phenotypic variables under investigation. This means that the strength of phylogenetic signal may be compared across datsets for continuous phenotypic traits measured in different units and scale, because those units have been standardized through their conversion to Z_K. For example, our approach could be utilized to determine whether the strength of phylogenetic signal (say, in response to ecological differentiation) is stronger in morphological traits (linear traits: mm), physiological traits (metabolic rate: $\frac{O^2}{min}$), or behavioral traits

(aggression: $\frac{\#displays}{second}$). Additionally, our method is capable of comparing the strength of phylogenetic signal in traits of different dimensionality, as estimates of phylogenetic signal using $Kappa$ have been generalized for multivariate data (K_{mult}: see Adams 2014a). Likewise, as Z_K is a standard deviation unit (which accounts for variation, sample size, and the phylogeny), tests based on $\hat{Z}_{12}$ may be utilized for comparing the strength of phylogenetic signal across datasets containing a different number of species, and even for phenotypes obtained from species in different lineages, because their phylogenetic non-independence, and observed variation, are taken into account in the generation of the empirical sampling distribution via permutation.

** Finally... Need Closing paragraph. **

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Figure Legends

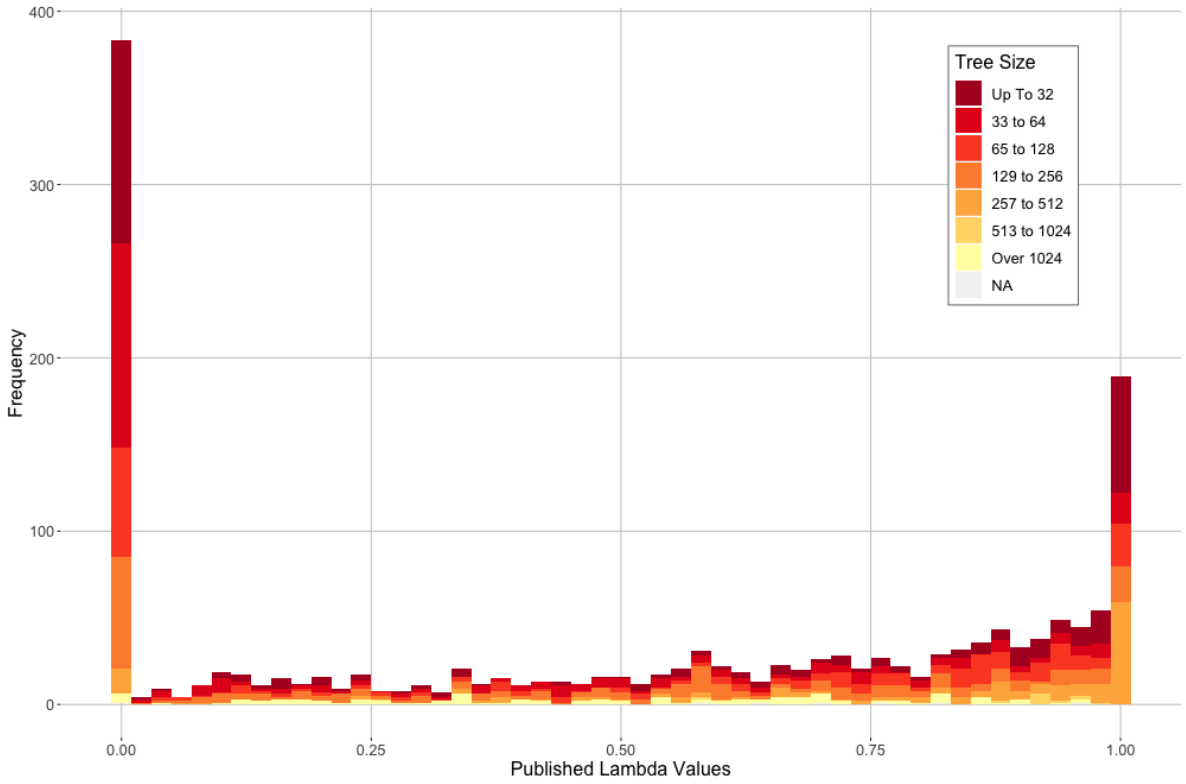
Figure 1. Frequency distribution of λ estimates published in 2019. The majority of these values were close to 0 or 1, and from phylogenies with fewer than 200 taxa.

Figure 2. Precision of Pagel's λ across known levels of input phylogenetic signal (λ_{in}) on phylogenies of various sizes. As phylogenies increase in size, variation in λ_{in} decreases; however the precision is not constant across the range of input levels ($\lambda_{in} : 0 \rightarrow 1$), and is highest at intermediate levels of phylogenetic signal.

Figure 3. Precision of Pagel's λ when incorporated in phylogenetic regression ($Y \sim X$), across known levels of input phylogenetic signal (λ_{in}) on phylogenies of various sizes. As phylogenies increase in size, variation in λ_{in} decreases; however the precision is not constant across the range of input levels ($\lambda_{in} : 0 \rightarrow 1$), and is highest at intermediate levels of phylogenetic signal.

Figure 4. Variation in effect size estimates of phylogenetic signal across input levels of phylogenetic signal. (A) Estimates Z_λ for data simulated on phylogenies with 32 taxa ($n = 32$), (B) Estimates of Z_K for data simulated on phylogenies with 32 taxa ($n = 32$), (C) Coefficients of variation of precision estimates of Z_λ and Z_K across input levels of phylogenetic signal, estimated on phylogenies containing differing numbers of species.

Figure 5. (A) Linear measures for relative body size, and regions of the body used to estimate surface area to volume (SA:V) ratios. (B) Permutation distributions of phylogenetic signal for SA:V and $\frac{BW}{SVL}$, with observed values shown as vertical bars. (C) Effect sizes (Z_K) for SA:V and $\frac{BW}{SVL}$, with their 95% confidence intervals (CI not standardized by $\sqrt{(n)}$).



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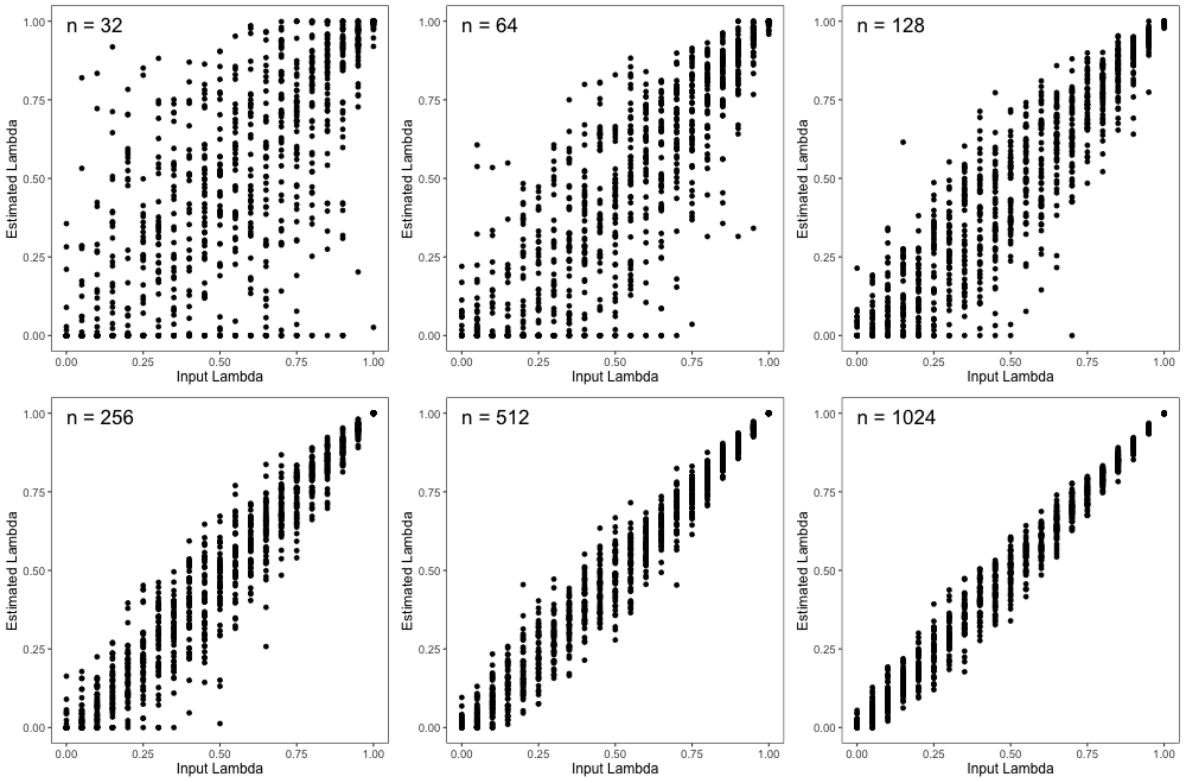

452

453 **Figure 2**. Precision of Pagel's λ across known levels of input phylogenetic signal (λ_{in}) on phylogenies of
454 various sizes. As phylogenies increase in size, variation in λ_{in} decreases; however the precision is not
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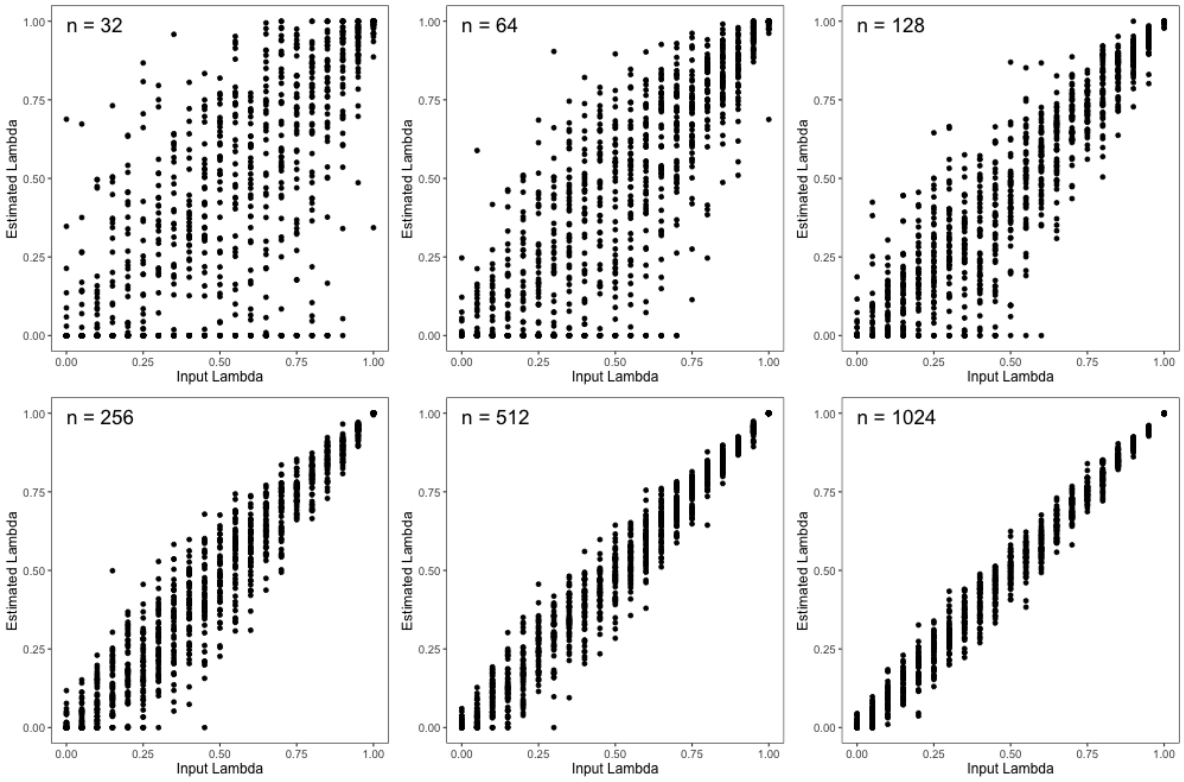

457

458 **Figure 3**. Precision of Pagel's λ when incorporated in phylogenetic regression ($Y \sim X$), across known levels
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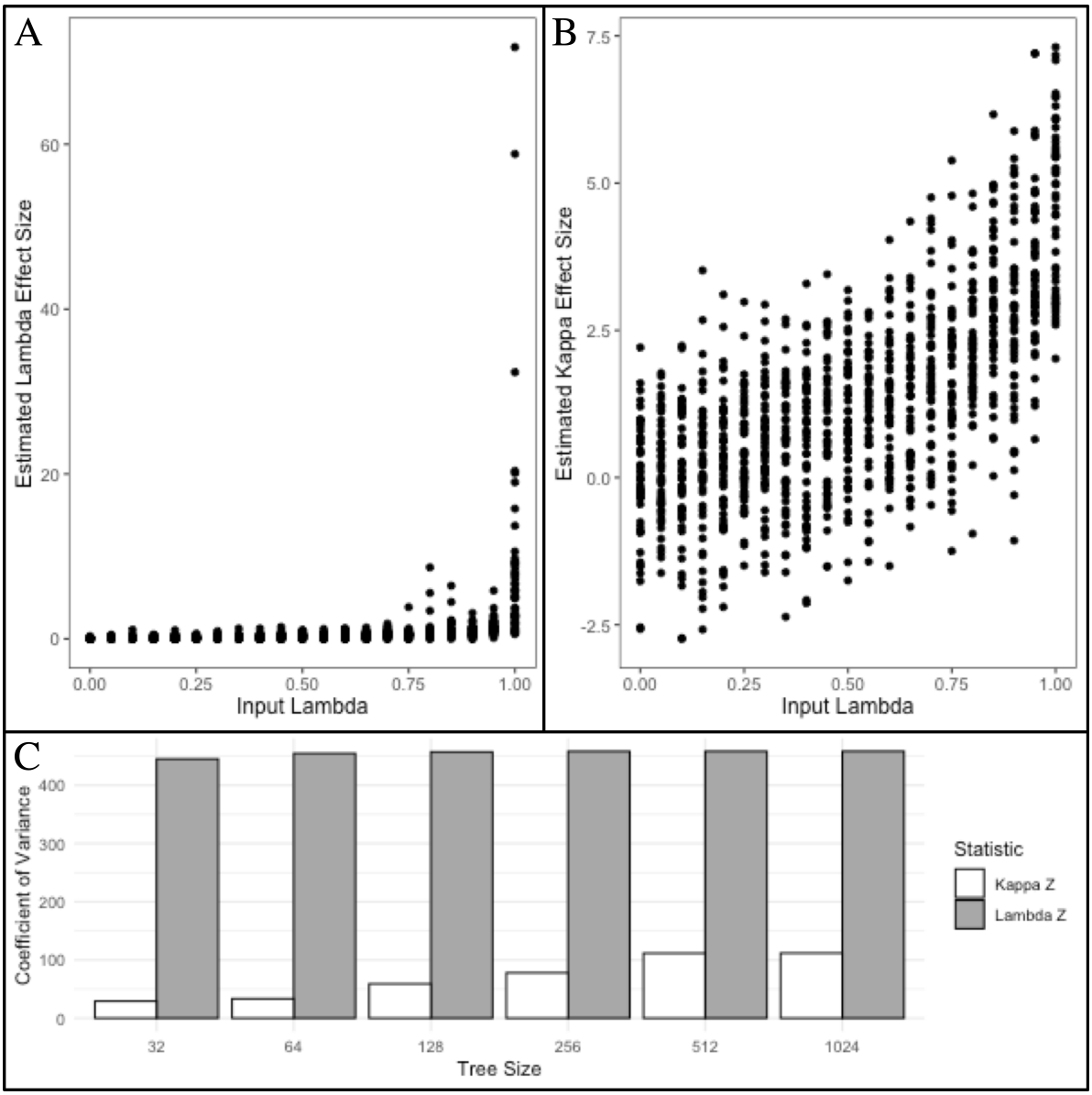

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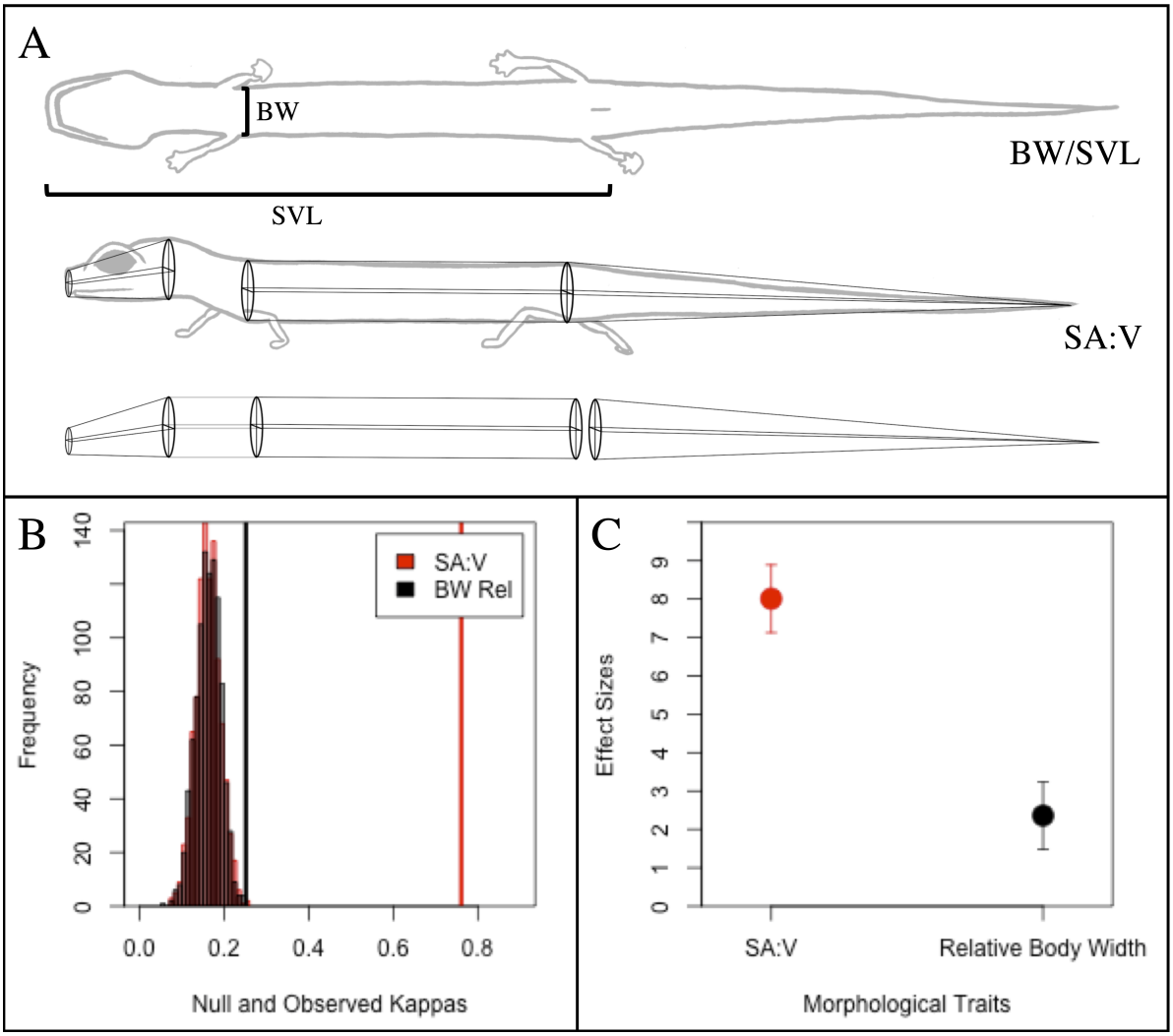

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