

Supervised learning approaches to classifying morphological variation: picking amongst taxonomic hypotheses for the Pacific Pond Turtle (*Emys marmorata*)

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Abstract

We investigate the morphometric identification of cryptic species using machine learning approaches by examining their implications for a recently proposed cryptic turtle species (*Emys pallida*). We collected landmark-based morphometric data from 354 adult *E. marmorata*/"*pallida*" museum specimens. We assigned a classification to each specimen for six different binning schemes based on geographic occurrence data recorded in museum collection archives. We used multiple machine learning methods, both unsupervised and supervised, to compare different classification hypotheses and asked whether it is possible to determine which amongst a set of classification hypotheses is best. In addition, we applied the above approach to two additional datasets: two well-supported subspecies of *Trachemys scripta* and a set of seven unambiguously distinct species closely related to *E. marmorata*. The results of this study indicate that there is no clear grouping of *E. marmorata*/"*pallida*" based on plastron shape. In contrast, the analysis of the other datasets demonstrate a near perfect classification, which demonstrates that application of the methods to plastron shape data can recover correct results in similar situations. Explanations for the lack of grouping in *E. marmorata* include that possibility that genetic differentiation is not associated with plastron

shape variation in this species complex and/or that local selective pressures (e.g., from hydrological regime) overwhelm morphological differentiation. A reconsideration of the methods used to delimit *E. "pallida,"* the lack of barriers to gene flow, the strong evidence for widespread admixture between lineages, and the fact that plastron shape can be used to differentiate other emydid species and subspecies suggest that its lack of diagnosability most likely reflects the non-distinctiveness of this proposed taxon.

INTRODUCTION

Molecular systematics has repeatedly demonstrated the existence of cryptic species that can only be diagnosed using genetic data (Stuart et al. 2006; Bickford et al. 2007; Schilck-Steiner et al. 2007; Pfenninger and Schwenk 2007; Clare 2011; Funk et al. 2012). In attempts to streamline the documentation of biodiversity, several methods of species delimitation that rely almost entirely on genetic data have recently been proposed (Pons et al. 2006; Carstens and Dewey 2010; Hausdorf and Hennig 2010; O'Meara 2010; Yang and Rannala 2010; Huelsenbeck et al. 2011). Although strong caveats on the utility of these methods have been raised (Bauer et al. 2000; Carstens et al. 2013), they are nevertheless being used to name species (Leaché and Fujita 2010; Spinks et al. 2014).

The majority of extant taxa, and almost all extinct taxa, are delimited by morphology alone. This disjunction complicates interpretations of variation and diversity in deep time, as apparent morphological stasis may not reflect the true underlying diversity (Eldredge and Gould 1972; Gould and Eldredge 1977; Hunt 2008; Van Bocxlaer and Hunt 2013). Similarly, for many museum specimens of extant taxa (e.g. those preserved in formalin), it is difficult to acquire the genetic data needed for non-morphological species delimitation methods.

These considerations have sparked interest in whether geometric morphometric analyses can capture fine-scale variation that can be used for identifying cryptic species. This would make the task of identifying and maintaining endangered or conserved groups much easier and could contribute to improved classifications of extinct taxa and populations. Most such studies focus on using morphometrics to discover differences between taxa that were identified by other means (Polly 2003; Zelditch et al. 2004; Gaubert et al. 2005; Gündüz et al. 2007; Polly 2007; Demandt and Bergek 2009). Additionally, there has been work on automated taxon identification and classification of taxa into groups (Baylac et al. 2003; Dobigny et al. 2003; MacLeod 2007; van den Brink and Bokma 2011).

Here, we investigate the morphometric identification of cryptic species using machine learning approaches. In particular, we ask whether it is possible to determine which amongst a set of classification hypotheses is best and examine the implications of the results for a recently proposed set of cryptic turtle species.

Background and study system

Machine learning is an extension of known statistical methodology (Hastie et al. 2009) that emphasizes high predictive accuracy and generality at the expense of the interpretability of individual parameters. The basic statistical mechanics are supplemented by randomization, sorting, and partitioning algorithms, along with the maximization or minimization of summary statistics, in order to best estimate a general model for all data, both sampled and unsampled (Hastie et al. 2009). Machine learning approaches have found use in medical research, epidemiology, economics and automated identification of images such as handwritten zip codes (Hastie et al. 2009). The two major classes of machine learning methods are unsupervised and supervised learning. Unsupervised learning methods are used with unlabeled data where the underlying structure is estimated; they are analogous to clustering and density estimation methods (Kaufman and Rousseeuw 1990). Supervised learning methods are used with labeled data where the final output of data is known and the rules for going from input to output are inferred. These are analogous to classification and regression models (Breiman et al. 1984). Our application of the approaches used in this study illustrates only a sampling of the various methods available for clustering observations and fitting classification models.

Geometric morphometric approaches to identifying differences in morphological variation between different classes, including cryptic species, mostly have used methods like linear discriminate analysis and canonical variates analysis (Polly 2003; Zelditch et al. 2004; Gaubert et al. 2005; Gündüz et al. 2007; Polly 2007; Francoy et al. 2009; Sztencel-Jablonka et al. 2009; Mitrovski-Bogdanovic et al. 2013). Because of their similarity to multivariate approaches like principal components analysis (PCA), these methods are comparatively straightforward ways of understanding the differences in morphology between classes. They also benefit from producing results that can be easily visualized, which aids in the interpretation and presentation of data and results. Most previous morphometric studies did not assess which amongst a set of alternative classification hypotheses was optimal. For example, studies such as those of Caumul and Polly (2005) and Polly (2007) focused on comparing different aspects of morphology and their fidelity to a classification scheme instead of comparing the fidelity of one aspect of morphology to multiple classification schemes. In this context, the study of Cardini et al. (2009) is noteworthy because they compared morphological variation in marmots at the population, regional, and species level and determined the fidelity of shape to divisions at each of these levels.

Here, we used multiple machine learning methods, both unsupervised and supervised, to compare different classification hypotheses. These methods provide different advantages for understanding how to classify taxa, as well as the accuracy of the resulting classifications. Although machine learning methods such as neural networks have been applied to studying shape variation (Baylac et al. 2003; Dobigny et al. 2003; MacLeod 2007; van den Brink and Bokma 2011), including in the context of automated taxon identification and classification of groups, the number of cases remains limited. In the current study, we not only consider pure classification accuracy but also use a statistic of classification strength that reflects the rate at which taxa are both accurately and inaccurately classified.

We analyzed the problem of whether there are distinct subspecies or cryptic species within

the western pond turtle, *Emys marmorata* (Baird and Girard 1852) (formerly *Clemmys marmorata*; see Feldman and Parham 2002). *Emys marmorata* is distributed from northern Washington State, USA to Baja California, Mexico. Traditionally, *E. marmorata* was classified into two named subspecies: the northern *E. marmorata marmorata* and the southern *Emys marmorata pallida* (Seeliger 1945), with a central Californian intergrade zone in between. *Emys marmorata marmorata* is differentiated from *E. marmorata pallida* by the presence of a pair of triangular inguinal scales and darker neck markings. The triangular inguinal plates can sometimes be present in *E. marmorata pallida* although they are considerably smaller. Seeliger (1945) did not formally include the Baja California populations of *E. marmorata* in either taxon, implying the existence of a third distinct but unnamed subspecies.

Previous work on morphological variation in *E. marmorata* has focused primarily on differentiation between populations over a portion of the species' total range (Lubcke and Wilson 2007; Germano and Rathbun 2008; Germano and Bury 2009; Bury et al. 2010); comparatively few studies have included specimens from across the entire range (Holland 1992). Most of these studies considered how local biotic and abiotic factors may contribute to differences in carapace length and found that size can vary greatly between different populations (Lubcke and Wilson 2007; Germano and Rathbun 2008; Germano and Bury 2009). There also has been interest in size-based sexual dimorphism in *E. marmorata* (Holland 1992; Lubcke and Wilson 2007; Germano and Bury 2009), with males being on average larger than females based on total carapace length and other linear measurements. However, the quality of size as a classifier of sex can vary greatly between populations (Holland 1992) because of the magnitude of size differences among populations (Lubcke and Wilson 2007; Germano and Bury 2009). The effect of sexual dimorphism on shape, *sensu* Kendall (1977), has not been assessed (Holland 1992; Lubcke and Wilson 2007; Germano and Rathbun 2008).

Of particular relevance in the context of cryptic diversity in *E. marmorata* is the morphometric analysis of carapace shape carried out by Holland (1992), who compared populations of *E. marmorata* from three areas of the species range. This study concluded that geographic distance was a poor indicator of morphological differentiation, and instead hypothesized that geographic features such as breaks between different drainage basins are probably more important barriers to dispersal and interbreeding. Additionally, Holland (1992) suggested that morphological differences were more pronounced as the magnitude of barriers and distance increased, but this variation required many variables to adequately capture, implying only very subtle morphological differentiation between putatively distinct populations. Finally, Holland concluded that *E. marmorata* is best classified as three distinct species: a northern species, a southern species, and a Columbia Basin species. This classification is similar to that of Seeliger (1945), except elevated to the species level and without recognition of a distinct Baja species.

More recently, the phylogeography of *E. marmorata* and the possibility of cryptic diversity was investigated using molecular data (Spinks and Shaffer 2005; Spinks et al. 2010, 2014). Based on mitochondrial DNA, Spinks and Shaffer (2005) recognized four subclades within *E. marmorata*, a northern clade, a San Joaquin Valley clade, a Santa Barbara clade, and

a southern clade. Analyses with nuclear DNA (Spinks et al. 2010) and single-nucleotide polymorphism (SNP) data suggest a primarily north–south division in *E. marmorata*, although these datasets differed from that of Spinks and Shaffer (2005) in the location of the break point. All three studies discussed the potential taxonomic implications of their results, with Spinks et al. (2014) going so far as to strongly advocate for the recognition of at least two species (*E. marmorata* and *E. pallida*), and a possible third based on populations in Baja California. However, they did not discuss in detail the morphological characters that would help to diagnose these species beyond those specified by Seeliger (1945). Given that these characters are variable within the proposed species, and that Holland (1992) described shell shape variation that might be consistent with this taxonomy, a geometric morphometric analysis of shell shape might provide a reliable way to diagnose groups (whether species or subspecies) within *E. marmorata*.

In this study, we attempt to estimate the best classification scheme of *E. marmorata* based on variation in plastron (ventral shell) shape in order to determine whether this character is consistent with any of the past divisions based on other morphological features or molecular data. We are particularly interested in whether any aspect of plastron shape can be used to reliably diagnose the proposed species of Spinks et al. (2014), and if so, the nature of that shape variation.

WHY DID WE ANALYZE PLASTRON SHAPE? PETER DOESN'T HAVE A GOOD ANSWER.

Because of unclear geographic boundaries between subgroups of *E. marmorata*, we compare multiple hypotheses of morphologically– and molecularly–based classification. We hypothesize that if morphological variation corresponds to class assignment, it should be possible to determine the best classification hypothesis of *E. marmorata* from amongst multiple candidate hypotheses. However, if morphological variation does not correspond to any of the standing hypothesis, then supervised learning model generalization performance will be poor.

MATERIALS AND METHODS

Specimens, sampling, morphometrics

Three different landmark-based morphometric datasets describing plastron variation were assembled for this analysis: specimens from seven distinct emydine species, *T. scripta* specimens from both subspecies, and *E. marmorata* specimens from across its geographic range. We chose to focus on adults because significant changes in plastron shape occur over the course of ontogeny in *E. marmorata* and other emydines (Angielczyk and Feldman 2013).

The first dataset is a compilation of 101 specimens of *T. scripta*: 51 specimens of *T. scripta scripta* and 50 specimens of *T. scripta scripta*. These landmark data are new to this study.

The second dataset, we analyzed 578 total specimens from the following species: *Emys blandingii*, *Terrapene coahuila*, *Clemmys guttata*, *Glyptemys insculpta*, *Glyptemys muhlenbergii*,

Emys orbicularis, and *Terrapene ornata*. Like the first data set, these specimens are a subset of those used in Angielczyk et al. (2011) and Angielczyk and Feldman (2013).

The final dataset included 354 adult *E. marmorata* museum specimens; a subset of those included in Angielczyk and Sheets (2007), Angielczyk et al. (2011), and Angielczyk and Feldman (2013). We assigned a classification to each specimen for the different binning schemes based on geographic occurrence data recorded in museum collection archives. When precise latitude and longitude information were not available we estimated them from locality information. Because Spinks and Shaffer (2005), Spinks et al. (2010), and Spinks et al. (2014) did not use vouchered specimens we were not able to directly sample the individuals in their studies. Therefore our specimen classifications were based solely on the geographic information, not explicit assignment using molecular data. Because the exact barriers between different biogeographic regions are unknown and unclear, we represented some hypothesis with two schemes for a total of six different schemes. These schemes differed based on where geographic boundaries were assigned. This changes the classification of certain individuals near the boundaries between groups, providing a test of the robustness of the classification schemes. Sex information was only known for a subset of the total dataset and was not included as a predictor of classification. Sex information was used to determine if observations cluster by sex or not. The scheme names are as follows: Mito 1 and 2 correspond to Spinks and Shaffer (2005), Mito 3 corresponds to Spinks et al. (2010), Morph 1 and Morph 2 correspond to Holland (1992), and Nuclear corresponds to Spinks et al. (2014).

Following previous work on plastron shape (Angielczyk and Sheets 2007; Angielczyk et al. 2011; Angielczyk and Feldman 2013), we used TpsDig 2.04 (Rohlf 2005) to digitize 19 landmarks (Fig. 1). Seventeen of the landmarks are at the endpoints or intersection of the keratinous plastral scutes that cover the plastron. Twelve of the landmarks were symmetrical across the axis of symmetry. Because damage prevented the digitization of all the symmetric landmarks in some specimens, we reflected landmarks across the axis of symmetry (i.e. midline) prior to analysis and used the average position of each symmetrical pair. In cases where damage or incompleteness prevented symmetric landmarks from being determined, we used only the single member of the pair. We conducted all subsequent analyses on the resulting “half” plastra. We superimposed the plastral landmark configurations using generalized Procrustes analysis (Dryden and Mardia 1998), after which, we calculated the principal components (PC) of shape using the *shapes* package for R (R Core Team 2016; Dryden 2013).

Biasing effects

We estimated the possible effect of digitization error CITATIONS on our results by comparing within (replicated) specimen Procrustes distances to the distances between classification scheme centroids. 10 randomly selected specimen both for this study and an additional four times. These 50 landmark configurations were then Procrustes superimposed. A range of four Procrustes distances were then calculated as the average of the pairwise distances between each of the replicate configurations.

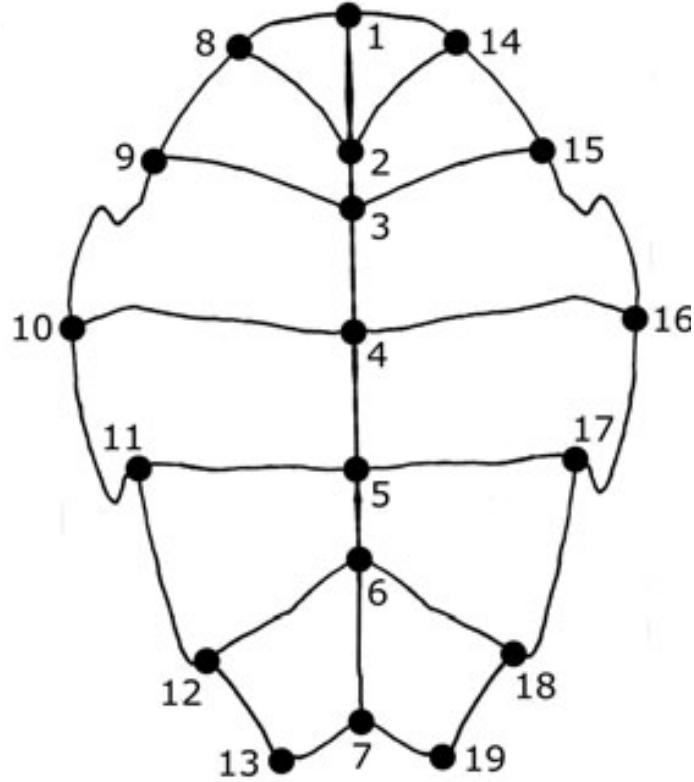


Figure 1: Depiction of general plastral shape of *E. marmorata* and position of the 19 landmark used in this study. Anterior is towards the top of the figure.

The relative magnitude of digitization error was calculated as the ratio between the average of the within-species replicate distances and the average distance between any two configurations in the replicate dataset. The goal of this ratio is to determine if the within group distances are on average smaller than the between individual distances; a value of 0 indicates perfect grouping, a value of 1 indicates no difference between grouping and no grouping, and a value of 1+ indicates that the grouping is counter-intuitive to the data.

Turtles are well known to demonstrate strong sexual dimorphism in carapace shape CITATION. To test for issues surrounding sexual dimorphism in our *E. marmorata* data set, we used a simple permutation test to determine if the distance between the mean female and male shapes is greater than expected when the sex labels are randomly shuffled. Because not all of our specimens have sex identifications associated with them, this analysis was done using a subset of the data.

Supervised learning approaches

The maximum set of possible predictors or features used for any model are the first 25 principal components (PCs), scaled centroid size, and the interaction between scaled centroid

size and PC 1. Size and the interaction between size and PC 1 were included as predictors in order to account for a possible interaction between size and shape over the duration of an individual as well as potential size differences between classes, even if this is unlikely (Seeliger 1945; Holland 1992). We say “maximum set” because the best or selected models based on 5-fold cross-validation does need not to, nor will they likely, include all predictors possible (see below).

This approach is in many ways analogous to PCA regression. PCA regression takes advantage of two aspects of PCA for improving regression fit (Hastie et al. 2009). Because the PCs of shape are by definition orthogonal, allowing them to easily as independent predictors or features of class membership without fear of collinearity.

In classification studies, such as this one, a common metric of performance is the receiver operating characteristic (ROC) which is the relationship between the false and true positive rates (Hastie et al. 2009). The area under the ROC curve (AUC) is then the derived estimate of the model performance; AUC ranges from 0.5 to 1 which corresponding to performance similar to random guesses and perfect classification rates, respectively (Hastie et al. 2009). Both ROC and AUC are preferable to simple classification accuracy when class membership is unbalanced, as it is in these analyses (Hastie et al. 2009). The standard ROC and AUC calculations are defined only for binary classifications, which is not the case for our seven species and *Emys* complex datasets. To generalize this approach for situations with multiple response classes, we used an all-against-one strategy where the model AUC is the average of the AUC values from the multiple binary comparisons of one class compared to all others (Hand and Till 2001).

We adopted a training and testing paradigm for selecting parsimonious models and estimating their overall error rates (Hastie et al. 2009; Kuhn and Johnson 2013). Within-sample model performance is inherently biased upwards, so model evaluation requires overcoming this bias. With very large sample sizes, as in this study, part of the sample can be used as the “training set” and the remainder acts as the “testing set.” In this approach, following all cleaning and vetting, the data is split into a training dataset and a testing dataset. The former is used for fitting the model where as the later is used for measuring model performance, a process called model generalization. In this analysis, we used 80% of samples as the training set while the remaining 20% were used as the testing set.

For a given supervised learning method, we compared the fit of 27 models as the average AUC from 10 rounds of 5-fold cross-validation. Cross-validation is an approach for estimating the average out-of-sample predictive error of a model by simulating out-of-sample data from the training data itself (Hastie et al. 2009). In a single round of k -fold cross-validation, the training data is divided into k blocks where the model is fit to $k - 1$ blocks and the values of the k th block are predicted; this is then repeated for all combinations of blocks. Within each round, the predictive performance metrics is averaged across all folds. Finally, the predictive performance metric is the averaged across all rounds of k -fold cross-validation. This process was implemented using the R package `caret` (Kuhn 2013).

Method name	abbreviation	R package	citation
multinomial logistic regression	MLR	nnet	Venables and Ripley (2002)
linear discriminate analysis	LDA	MASS	Venables and Ripley (2002)
penalized discrminiata analysis	PDA	mda	Hastie et al. (2015)
single-hidden-layer neural network	NN	nnet	Venables and Ripley (2002)
random forests	RF	randomForest	Liaw and Wiener (2002)

Table 1: table of the methods

For a given supervised learning method, the “best” trained model is that the highest mean AUC as estimated from 5-fold cross-validation. The selected or final model, however, is the next most parsimonious model that is within one standard error of the best model; this is a variant on the “one-standard error” rule from Hastie et al. (2009).

Instead of relying on a single supervised learning method, we chose to use an ensemble of multiple approaches so that the congruence between them could be used as a means of “support” for one conclusion or another. The supervised learning methods used here are described in Table 1. Each of these methods makes different assumptions, treat data differently, and can produce different qualities of classification results depending on the nature of the data (Hastie et al. 2009).

RESULTS

Geometric morphometrics

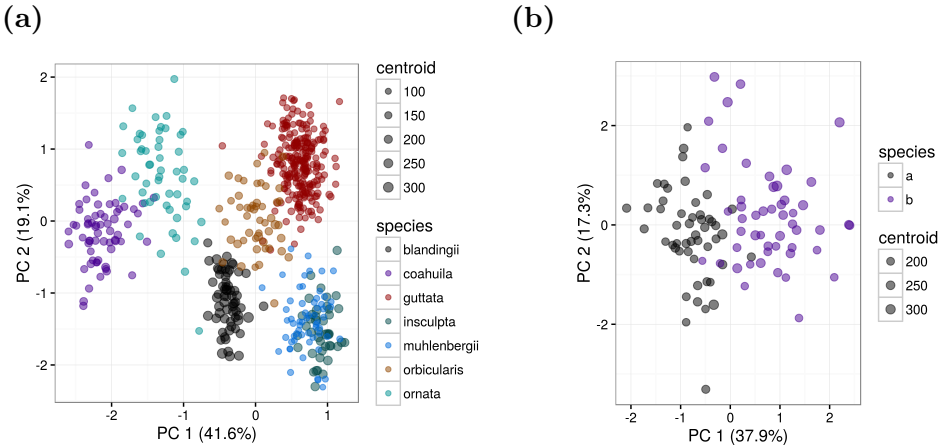


Figure 2: CAPTION

Supervised learning

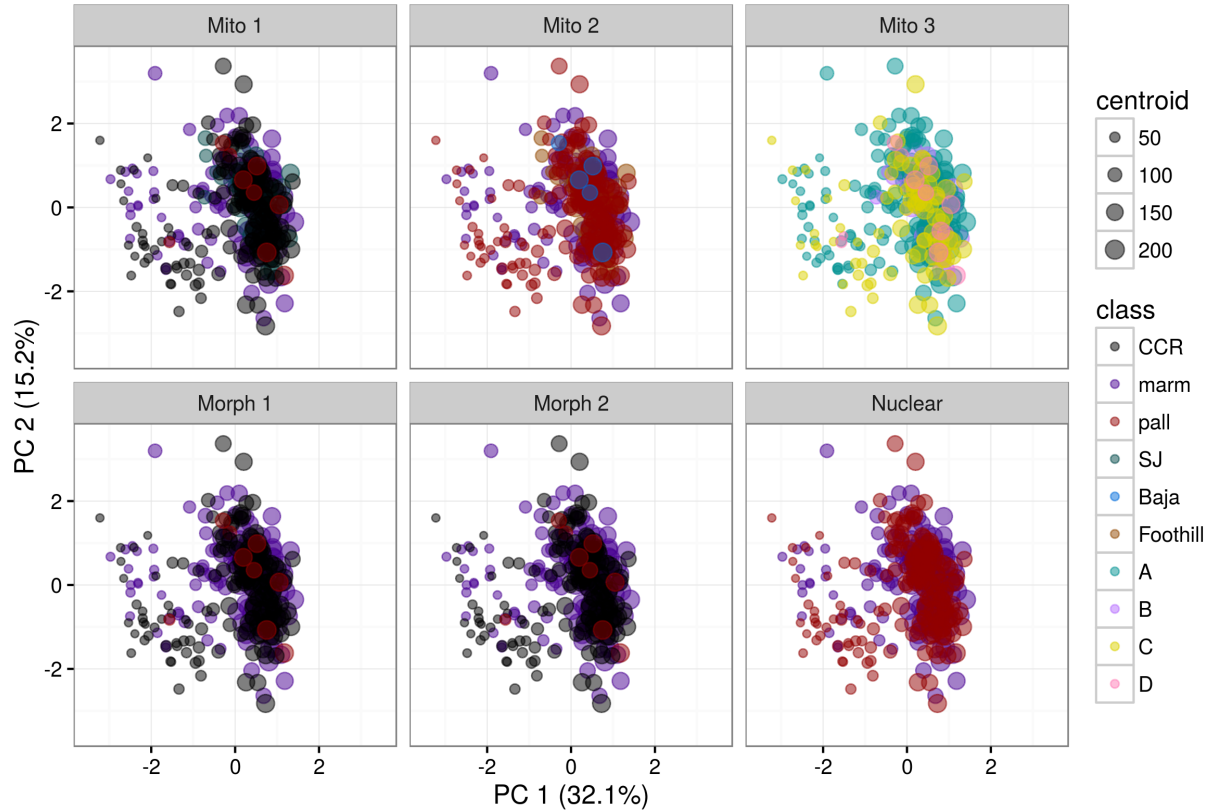


Figure 3: CAPTION

Analysis of the seven morphologically-distinct species and the *T. scripta scripta*–*T. scripta elegans* datasets indicate that these classifications are sufficiently morphologically distinct. Both in-sample and out-of-sample classification have AUC values of approximately 1 for all methods (Fig. 5, 6). For both datasets, the ROC scores from testing datasets are tightly clustered near AUC = 1 (Fig. 6). These results demonstrate that when there are distinctions between the states of the classification schemes, the methods used here can recover them.

AUC-based model selection revealed some important patterns of variation and congruence between the classification schemes and the actual data. Generally, the best performing models tended to include about half the total number of possible PCs (Fig. 7). As was the case with the *Trachemys* dataset (Fig. 5), the neural net models are the least well-performing models compared to all others used (Fig. 7).

Observed AUC values for all of the optimal models are not exceptionally high (Fig. 7). In most cases the different proposed classification schemes are generally poor descriptors of the observed variation. It appears that the data set is overwhelmed by noise, making any

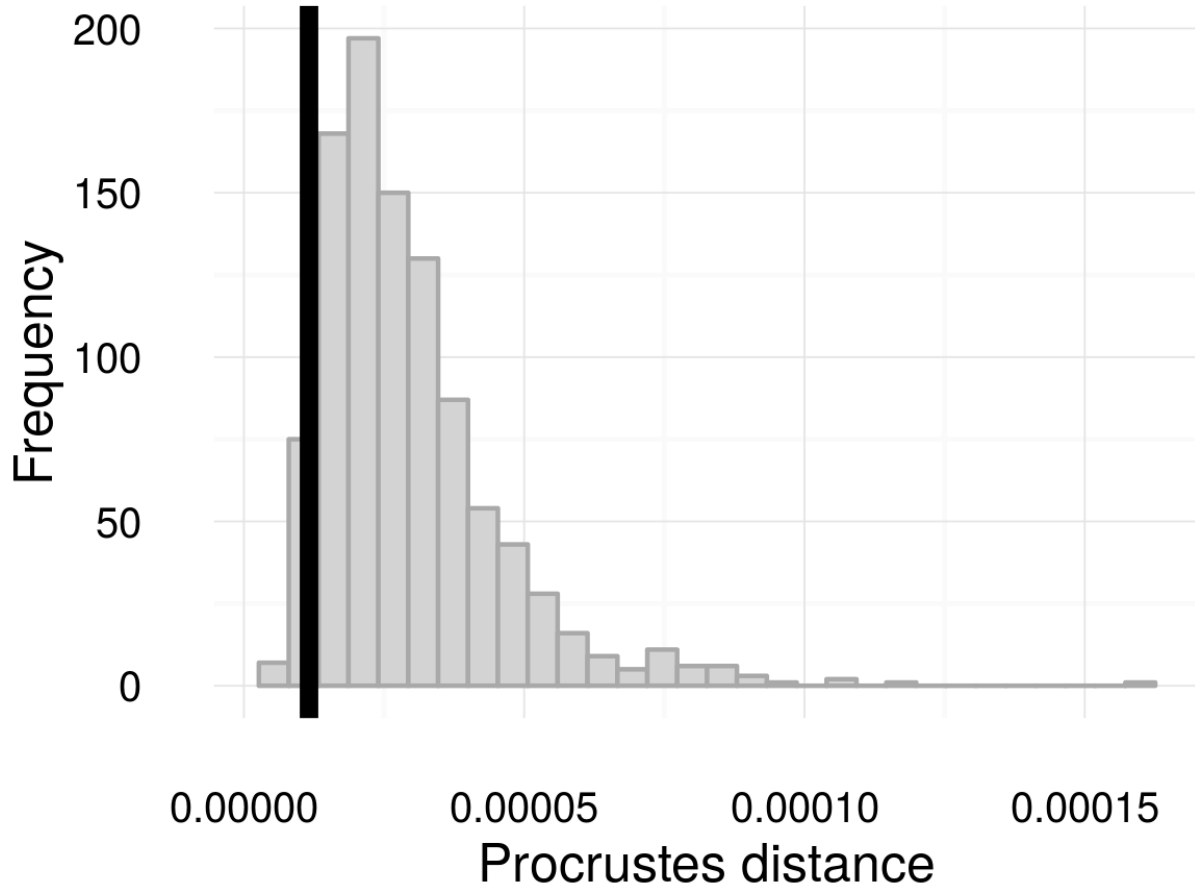


Figure 4: CAPTION

294 accurate classifications difficult at best. This observation is cemented with the generalizations
of the models to the testing data set (Fig. 8).

296 Mean AUC values for the model generalizations, in most cases, are approximately equal to the
observed AUC values from the training data set (Fig. 7, 8). The cases in which the AUC from
298 the generalizations is less than the observed indicate poor model fit and a poor classification
scheme. Comparison of AUC values from the model generalizations do not indicate a clear
300 “best” classification scheme (Fig. 7, 8).

DISCUSSION

302 The results of this study show that there is no clear grouping of *E. marmorata* based on
plastron shape.

304 The unsupervised learning results indicate that no grouping is optimal or particularly better
than a single grouping, which is consistent with the results from the generalizations of

the supervised learning models. The classification schemes used in the supervised learning models correspond, loosely, to unsupervised learning solutions with multiple groups. Because unsupervised learning solutions with multiple groups are poor descriptors of the observed variation, it is important to see this generally supported by the supervised learning results.

The results from fitting the various supervised learning models to each of the classification schemes generally shows that no one scheme is “best.” Possible explanations include that the genetic differentiation is not associated with plastron shape variation and/or that local selective pressures (e.g. from hydrological regime) overwhelm morphological differentiation. This makes sense given that shell shape is influenced by selection for both protection and streamlining, but not necessary mate choice (Rivera 2008; Rivera and Stayton 2011; Stayton 2011; Rivera et al. 2014; Polly et al. 2016) and that shell shape in *E. marmorata* is known to vary among populations inhabiting water bodies with different flow regimes (Holland 1992; Lubcke and Wilson 2007; Germano and Bury 2009). Plastron shape does not seem to preserve a strong phylogenetic signal at the interspecific level in emydine turtles (Angielczyk et al. 2011), and our current results suggest that this may be the case for phylogeographic signal within emydine species as well. A final possibility (explored below) is that the proposed classification schemes themselves do not represent significant evolutionary lineages.

Both the low out-of-sample AUC values (< 0.9) and the significant difference between the correctly and incorrectly classified observations support the conclusion that none of the hypothesized classification schemes are good descriptors of the observed plastral variation within *E. marmorata*.

Nevertheless, it is important to note that plastron shape is an extremely effective method for differentiating classes in the additional datasets we investigated. The magnitude of shape differences between the species (measured as Procrustes distance between species’ mean shapes) is approximately an order of magnitude greater than the differences between the *E. marmorata* subgroups, and the machine learning methods had no trouble accurately classifying the specimens correctly. However, the magnitude of the shape differences between the *T. scripta* subspecies is comparable to those separating the different *E. marmorata* subgroups, yet even in this case the machine learning methods returned an almost perfect classification. These results demonstrate that plastron shape is normally a good marker for differentiating real subgroups in close relatives of *E. marmorata*, and that our lack of results for *E. marmorata* is not simply a shortcoming of the methods we applied. Indeed, they beg the question of what factors have suppressed morphological differentiation of plastron shape in *E. marmorata* and *E. pallida* if they are distinct species. Invoking issues such as the role of the plastron in protection or the need for streamlining are insufficient because the other species are expected to be subject to similar constraints (Stayton 2011; Polly et al. 2016). While it may seem counterintuitive that plastron shape is both useful for species delimitation but has weak or absent phylogenetic signal, it is important to note that these are different goals. While phylogenetically similar species may not be morphologically similar, the variation within a species is much less than the variation between species which leads to plastron shape being a useful tool for species delimitation but not phylogenetic reconstruction.

Is there more than one species of Western Pond Turtle?

The lack of morphological support for the distinctiveness of *E. pallida* does not, on its own, preclude the recognition of this taxon. However, this apparent lack of congruence does prompt a reexamination of the methods and concepts that led to that taxonomic revision, especially considering that plastron shape is demonstrably capable of differentiating species and subspecies among emydids. In other words, before we can assess the significance of the morphological non-diagnosability, it is essential to evaluate the methods and concepts that led to the initial taxonomic revision.

Spinks et al. (2014) elevated *E. pallida* based on a species delimitation analysis of SNP data using BPP (Yang and Rannala 2010). However, Spinks et al. (2014) did not heed the caveats about species delimitation methods raised by Carstens et al. (2013). In addition to specifically addressing the shortcomings of validation methods such as BPP that rely on guide trees and “should be interpreted with caution,” Carstens et al. (2013) also strongly emphasized that “Inferences regarding species boundaries based on genetic data alone are likely inadequate, and species delimitation should be conducted with consideration of the life history, geographical distribution, morphology and behaviour (where applicable) of the focal system. . .” These caveats evoke the development of the Unified Species Concept (Dayrat 2005; De Queiroz 2007), Integrative Taxonomy (Padial et al. 2010), and other pluralist approaches to species delimitation. None of these considerations were brought to bear on the *E. marmorata* system until now, and in doing so we find the proposal that *E. pallida* is a distinct species to be lacking in a normally robust morphological marker.

The natural history and geographical distribution of *E. marmorata* and *E. pallida* also make the recognition of these taxa implausible. The data from Spinks et al. (2014) show extensive introgression and admixture in Central California, which is expected because there are no significant barriers to gene flow in this region. Combined with the well-demonstrated ability for testudinoid turtles, including emydids and even *Emys*, to hybridize (e.g. Buskirk et al. 2005; Spinks and Shaffer 2009; Parham et al. 2013) it is hard to imagine how *E. marmorata* and *E. pallida* could maintain their integrity in the face of such admixture. Because the geography, natural history, demonstrated genetic admixture of *E. marmorata*, and comparisons with other morphologically diagnosable species and subspecies conflict with the recognition of *E. pallida*, we hypothesize that our inability to classify the morphological data by proposed species is because *E. pallida* is not a distinct species.

We fully agree with Spinks et al. (2014) that *E. marmorata* (*sensu lato*) is a species deserving of strong conservation efforts, and we do not wish to trivialize this need. Moreover, the genetic diversity uncovered by the analysis of Spinks et al. (2014) should be explicitly accounted for in any conservation plan. Given the apparent lack of morphological distinction, however, we consider that this diversity should be considered Evolutionary Significant Units or Distinct Population Segments instead of distinct species.

Finally, it is important to note that the data and analyses we present do not let us definitively say whether the apparent lack of morphological divergence within *E. marmorata* truly

reflects the presence of a single species, or if it is an artifact of plastron shape being a poor morphological marker for phylogenetic and phylogeographic divergences in the case of *E. marmorata*, because we could not carry out our morphometric analyses on the specimens from which the genetic data were obtained. The comparisons with the other emydine taxa suggest that it is because *E. marmorata* is a single species. However, tests of both our preferred conclusion (*E. marmorata* as a single species) and that Spinks et al. (2014) should include morphological and molecular analyses of the same set of voucher specimens, as well as additional tests of species delimitation using alternative methods and corroborating evidence as suggested by Carstens et al. (2013). From a morphological standpoint, support for the validity of “*E. pallida*” may come from other aspects of morphology, such as carapace shape or other features. Likewise, further investigation of the phylogeographic utility of plastron shape in other turtle species will help to clarify whether the lack of differentiation seen in *E. marmorata*, and the strong differentiation among the other emydids, is typical or an unusual case.

*

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BIBLIOGRAPHY

- K. D. Angielczyk and C. R. Feldman. Are diminutive turtles miniaturized? The ontogeny of plastron shape in emydine turtles. *Biological Journal of the Linnean Society*, 108(4): 727–755, apr 2013. ISSN 00244066. doi: 10.1111/bij.12010. URL <http://doi.wiley.com/10.1111/bij.12010>.
- K. D. Angielczyk and H. D. Sheets. Investigation of simulated tectonic deformation in fossils using geometric morphometrics. *Paleobiology*, 33(1):125–148, 2007.
- K. D. Angielczyk, C. R. Feldman, and G. R. Miller. Adaptive evolution of plastron shape in emydine turtles. *Evolution*, 65(2):377–394, feb 2011. ISSN 1558-5646. doi: 10.1111/j.1558-5646.2010.01118.x.
- S. F. Baird and C. Girard. Descriptions of new species of reptiles collected by the U.S. Exploring Expedition under the command of Capt. Charles Wilkes. *Proceedings of the National Academy of Sciences Philadelphia*, 6:174–177, 1852.
- A. M. Bauer, J. F. Parham, R. M. Brown, B. L. Stuart, L. Grismer, T. J. Papenfuss, W. Bohme, J. M. Savage, S. Carranza, J. L. Grismer, P. Wagner, A. Schmitz, N. B.

- Ananjeva, and R. F. Inger. Availability of new Bayesian-delimited gecko names and the importance of character-based species descriptions. *Proceedings of the Royal Society B: Biological Sciences*, 278:490–492, 2000. ISSN 07331347. doi: 10.2307/1467045. URL <http://www.jstor.org/stable/1467045?origin=crossref>.
- M. Baylac, C. Villemant, and G. Simbolotti. Combining geometric morphometrics with pattern recognition for the investigation of species complexes. *Biological Journal of the Linnean Society*, 80:89–98, 2003.
- D. Bickford, D. J. Lohman, N. S. Sodhi, P. K. L. Ng, R. Meier, K. Winker, K. K. Ingram, and I. Das. Cryptic species as a window on diversity and conservation. *Trends in ecology & evolution*, 22(3):148–55, mar 2007. ISSN 0169-5347. doi: 10.1016/j.tree.2006.11.004. URL <http://www.ncbi.nlm.nih.gov/pubmed/17129636>.
- L. Breiman, J. Friedman, C. J. Stone, and R. A. Olshen. *Classification and regression trees*. Wadsworth International Group, Belmont, 1984.
- R. B. Bury, D. J. Germano, and G. W. Bury. Population Structure and Growth of the Turtle *Actinemys marmorata* from the KlamathSiskiyou Ecoregion: Age, Not Size, Matters. *Copeia*, 2010(3):443–451, sep 2010. ISSN 0045-8511. doi: 10.1643/CH-08-096. URL <http://www.bioone.org/doi/abs/10.1643/CH-08-096>.
- S. W. Buskirk, J. F. Parham, and C. R. Feldman. On the hybridisation between two distantly related Asian turtles (Testudines: *Scalia* x *Mauremys*). *Salamandra*, 41:21–26, 2005.
- A. Cardini, D. Nagorsen, P. O’Higgins, P. D. Polly, R. W. Thorington Jr, and P. Tongiorgi. Detecting biological distinctiveness using geometric morphometrics: an example case from the Vancouver Island marmot. *Ethology Ecology & Evolution*, 21:209–223, 2009.
- B. C. Carstens and T. A. Dewey. Species Delimitation Using a Combined Coalescent and Information-Theoretic Approach: An Example from North American *Myotis* Bats. *Systematic Biology*, 59(4):400–414, 2010. URL [papers2://publication/doi/10.1093/sysbio/syq024](http://pubs2://publication/doi/10.1093/sysbio/syq024).
- B. C. Carstens, T. a. Pelletier, N. M. Reid, and J. D. Satler. How to fail at species delimitation. *Molecular ecology*, 22(17):4369–83, sep 2013. ISSN 1365-294X. doi: 10.1111/mec.12413. URL <http://www.ncbi.nlm.nih.gov/pubmed/23855767>.
- R. Caumul and P. D. Polly. Phylogenetic and environmental components of morphological variation: skull, mandible, and molar shape in marmots (*Marmota*, Rodentia). *Evolution; international journal of organic evolution*, 59(11):2460–72, nov 2005. ISSN 0014-3820. URL <http://www.ncbi.nlm.nih.gov/pubmed/16396186>.
- E. L. Clare. Cryptic species? Patterns of maternal and paternal gene flow in eight neotropical bats. *PloS one*, 6(7):e21460, jan 2011. ISSN 1932-6203. doi: 10.1371/journal.pone.0021460.
- B. Dayrat. Towards integrative taxonomy. *Biological Journal of the Linnean Society*, 85: 407–415, 2005.

K. De Queiroz. Species concepts and species delimitation. *Systematic Biology*, 56(6):879–86,
dec 2007. ISSN 1063-5157. doi: 10.1080/10635150701701083. URL <http://www.ncbi.nlm.nih.gov/pubmed/18027281>.

M. H. Demandt and S. Bergek. Identification of cyprinid hybrids by using geometric morphometrics and microsatellites. *Journal of Applied Ichthyology*, 25(6):695–701, dec 2009. ISSN 01758659. doi: 10.1111/j.1439-0426.2009.01329.x. URL <http://doi.wiley.com/10.1111/j.1439-0426.2009.01329.x>.

G. Dobigny, L. Granjon, V. Aniskin, K. Ba, and V. Voloboulev. A new sigling species of Taterillus (Muridae, Gerbillinae) from West Agrica. *Mammalian Biology*, 68:299–316, 2003.

I. L. Dryden. *shapes: Statistical shape analysis*, 2013. URL <http://CRAN.R-project.org/package=shapes>. R package version 1.1-8.

I. L. Dryden and K. Y. Mardia. *Statistical shape analysis*. Wiley, New York, 1998.

N. Eldredge and S. J. Gould. Punctuated equilibria: an alternative to phyletic gradualism. In T. J. M. Schopf, editor, *Models in Paleobiology*, pages 82–115. Freeman Cooper, San Francisco, 1972.

C. R. Feldman and J. F. Parham. Molecular phylogenetics of emydine turtles: taxonomic revision and the evolution of shell kinesis. *Molecular Phylogenetics and Evolution*, 22(3): 388–98, mar 2002. ISSN 1055-7903. doi: 10.1006/mpev.2001.1070. URL <http://www.ncbi.nlm.nih.gov/pubmed/11884163>.

T. M. Francoy, R. A. O. Silva, P. Nunes-Silva, C. Menezes, and V. L. Imperatriz-Fonseca. Gender identification of five genera of stingless bees (Apidae, Meliponini) based on wing morphology. *Genetics and molecular research*, 8(1):207–214, 2009.

W. C. Funk, M. Caminer, and S. R. Ron. High levels of cryptic species diversity uncovered in Amazonian frogs. *Proceedings of the Royal Society B: Biological Sciences*, 279(1734): 1806–14, may 2012. ISSN 1471-2954. doi: 10.1098/rspb.2011.1653.

P. Gaubert, P. J. Taylor, C. a. Fernandes, M. W. Bruford, and G. Veron. Patterns of cryptic hybridization revealed using an integrative approach: a case study on genetids (Carnivora, Viverridae, Genetta spp.) from the southern African subregion. *Biological Journal of the Linnean Society*, 86(1):11–33, aug 2005. ISSN 00244066. doi: 10.1111/j.1095-8312.2005.00518.x. URL <http://doi.wiley.com/10.1111/j.1095-8312.2005.00518.x>.

D. J. Germano and R. B. Bury. Variation in body size, growth, and population structure of *Actinemys marmorata* from lentic and lotic habitats in Southern Oregon. *Journal of Herpetology*, 43(3):510–520, 2009.

D. J. Germano and G. B. Rathbun. Growth, population structure, and reproduction of western pond turtles (*Actinemys marmorata*) on the Central Coast of California. *Chelonian Conservation and Biology*, 7(2):188–194, 2008.

S. J. Gould and N. Eldredge. Punctuated equilibria: the tempo and mode of evolution reconsidered. *Paleobiology*, 3(2):115–151, 1977.

I. Gündüz, M. Jaarola, C. Tez, C. Yeniyurt, P. D. Polly, and J. B. Searle. Multigenic and morphometric differentiation of ground squirrels (*Spermophilus*, Scuridae, Rodentia) in Turkey, with a description of a new species. *Molecular phylogenetics and evolution*, 43(3):916–35, jun 2007. ISSN 1055-7903. doi: 10.1016/j.ympev.2007.02.021. URL <http://www.ncbi.nlm.nih.gov/pubmed/17500011>.

D. J. Hand and R. J. Till. A Simple Generalisation of the Area Under the ROC Curve for Multiple Class Classification Problems. *Machine Learning*, 45:171–186, 2001.

T. Hastie, R. Tibshirani, and J. Friedman. *The elements of statistical learning: data mining, inference, and prediction*. Springer, New York, 2nd edition, 2009.

T. Hastie, R. Tibshirani, F. Leisch, K. Hornik, and B. D. Ripley. *mda: Mixture and Flexible Discriminant Analysis*, 2015. URL <https://CRAN.R-project.org/package=mda>. R package version 0.4-8.

B. Hausdorf and C. Hennig. Species delimitation using dominant and codominant multilocus markers. *Systematic biology*, 59(5):491–503, oct 2010. ISSN 1076-836X. doi: 10.1093/sysbio/syq039. URL <http://www.ncbi.nlm.nih.gov/pubmed/20693311>.

D. C. Holland. *Level and pattern in morphological variation: a phylogeographic study of the western pond turtle (Clemmys marmorata)*. PhD thesis, University of Southwestern Louisiana, 1992.

J. P. Huelsenbeck, P. Andolfatto, and E. T. Huelsenbeck. Structurama: bayesian inference of population structure. *Evolutionary bioinformatics online*, 7:55–9, jan 2011. ISSN 1176-9343. doi: 10.4137/EBO.S6761. URL <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3118697&tool=pmcentrez&rendertype=abstract>.

G. Hunt. Gradual or pulsed evolution: when should punctuational explanations be preferred? *Paleobiology*, 34(3):360–377, 2008. doi: 10.1666/07073.1.

L. Kaufman and P. J. Rousseeuw. *Finding groups in data : an introduction to cluster analysis*. Wiley, New York, 1990.

D. G. Kendall. The diffusion of shape. *Advances in Applied Probability*, 9(3):428–430, 1977.

M. Kuhn. *caret: Classification and Regression Training*, 2013. URL <http://CRAN.R-project.org/package=caret>. R package version 5.15-61.

M. Kuhn and K. Johnson. *Applied predictive modeling*. Springer, New York, NY, 2013.

A. D. Leaché and M. K. Fujita. Bayesian species delimitation in West African forest geckos (*Hemidactylus fasciatus*). *Proceedings. Biological sciences / The Royal Society*, 277(1697):3071–7, oct 2010. ISSN 1471-2954. doi: 10.1098/rspb.

2010.0662. URL <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2982061&tool=pmcentrez&rendertype=abstract>.

A. Liaw and M. Wiener. Classification and regression by randomforest. *R News*, 2(3):18–22, 2002. URL <http://CRAN.R-project.org/doc/Rnews/>.

G. M. Lubcke and D. S. Wilson. Variation in shell morphology of the Western Pond Turtle (*Actinemys marmorata* Baird and Giarard) from three aquatic habitats in Northern California. *Journal of Herpetology*, 41(1):107–114, 2007.

N. MacLeod. *Automated taxon identification in systematics: theory, approaches and applications*. CRC Press, Boca Raton, 2007.

A. Mitrovski-Bogdanovic, A. Petrovic, M. Mitrovic, A. Ivanovic, V. Žikic, P. Starý, C. Vorburger, and Ž. Tomanovic. Identification of two cryptic species within the *Praon abjectum* group (Hymenoptera: Braconidae: Aphidiinae) using molecular markers and geometric morphometrics. *Annals of the entomological society of America*, 106(2):170–180, 2013.

B. C. O’Meara. New heuristic methods for joint species delimitation and species tree inference. *Systematic biology*, 59(1):59–73, jan 2010. ISSN 1076-836X. doi: 10.1093/sysbio/syp077. URL <http://www.ncbi.nlm.nih.gov/pubmed/20525620>.

J. M. Padiá, A. Miralles, I. De la Riva, and M. Vences. The integrative future of taxonomy. *Frontiers in Zoology*, 7(16):1–14, 2010.

J. F. Parham, T. J. Papenfuss, P. P. V. Dijk, B. S. Wilson, C. Marte, L. R. Schettino, and W. Brian Simison. Genetic introgression and hybridization in Antillean freshwater turtles (*Trachemys*) revealed by coalescent analyses of mitochondrial and cloned nuclear markers. *Molecular phylogenetics and evolution*, 67(1):176–87, apr 2013. ISSN 1095-9513. doi: 10.1016/j.ympev.2013.01.004. URL <http://www.ncbi.nlm.nih.gov/pubmed/23353072>.

M. Pfenninger and K. Schwenk. Cryptic animal species are homogeneously distributed among taxa and biogeographical regions. *BMC evolutionary biology*, 7:121, jan 2007. ISSN 1471-2148. doi: 10.1186/1471-2148-7-121. URL <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1939701&tool=pmcentrez&rendertype=abstract>.

P. D. Polly. Paleophylogeography of *Sorex araneus*: molar shape as a morphological marker for fossil shrews. *Mammalia*, 68(2):233–243, 2003.

P. D. Polly. Phylogeographic differentiation in *Sorex araneus*: morphology in relation to geography and karyotype. *Russian Journal of Theriology*, 6(1):73–84, 2007.

P. D. Polly, C. T. Stayton, E. R. Dumont, S. E. Pierce, E. J. Rayfield, and K. D. Angielczyk. Combining geometric morphometrics and finite element analysis with evolutionary modeling: towards a synthesis. *Journal of Vertebrate Paleontology*, 4634(March), 2016. ISSN 0272-4634. doi: 10.1080/02724634.2016.1111225.

J. Pons, T. Barraclough, J. Gomez-Zurita, A. Cardoso, D. Duran, S. Hazell, S. Kamoun,

- W. Sumlin, and A. Vogler. Sequence-Based Species Delimitation for the DNA Taxonomy of Undescribed Insects. *Systematic Biology*, 55(4):595–609, aug 2006. ISSN 1063-5157. doi: 10.1080/10635150600852011. URL <http://sysbio.oxfordjournals.org/cgi/doi/10.1080/10635150600852011>.
- R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria, 2016. URL <http://www.R-project.org/>.
- G. Rivera. Ecomorphological variation in shell shape of the freshwater turtle *Pseudemys concinna* inhabiting different aquatic flow regimes. *Integrative and comparative biology*, 48(6):769–87, dec 2008. ISSN 1540-7063. doi: 10.1093/icb/icn088. URL <http://www.ncbi.nlm.nih.gov/pubmed/21669831>.
- G. Rivera and C. T. Stayton. Finite element modeling of shell shape in the freshwater turtle *Pseudemys concinna* reveals a trade-off between mechanical strength and hydrodynamic efficiency. *Journal of morphology*, 272(10):1192–203, oct 2011. ISSN 1097-4687. doi: 10.1002/jmor.10974. URL <http://www.ncbi.nlm.nih.gov/pubmed/21630321>.
- G. Rivera, J. N. Davis, J. C. Godwin, and D. C. Adams. Repeatability of Habitat-Associated Divergence in Shell Shape of Turtles. *Evolutionary Biology*, pages 29–37, jul 2014. ISSN 0071-3260. doi: 10.1007/s11692-013-9243-6. URL <http://link.springer.com/10.1007/s11692-013-9243-6>.
- F. J. Rohlf. TpsDig 2.04, 2005.
- B. C. Schilck-Steiner, B. Seifert, C. Stauffer, E. Christian, R. H. Crozier, and F. M. Steiner. Without morphology, cryptic species stay in taxonomic crypsis following discovery. *Trends in ecology & evolution*, 22(8):391–392, aug 2007. ISSN 0169-5347. doi: 10.1016/j.tree.2007.05.003. URL <http://www.ncbi.nlm.nih.gov/pubmed/17573147>.
- L. M. Seeliger. Variation in the Pacific Mud Turtle. *Copeia*, 1945(3):150–159, 1945.
- P. Q. Spinks and H. B. Shaffer. Range-wide molecular analysis of the western pond turtle (*Emys marmorata*): cryptic variation, isolation by distance, and their conservation implications. *Molecular ecology*, 14(7):2047–64, jun 2005. ISSN 0962-1083. doi: 10.1111/j.1365-294X.2005.02564.x. URL <http://www.ncbi.nlm.nih.gov/pubmed/15910326>.
- P. Q. Spinks and H. B. Shaffer. Conflicting mitochondrial and nuclear phylogenies for the widely disjunct *Emys* (Testudines: Emydidae) species complex, and what they tell us about biogeography and hybridization. *Systematic biology*, 58(1):1–20, feb 2009. ISSN 1076-836X. doi: 10.1093/sysbio/syp005. URL <http://www.ncbi.nlm.nih.gov/pubmed/20525565>.
- P. Q. Spinks, R. C. Thomson, and H. B. Shaffer. Nuclear gene phylogeography reveals the historical legacy of an ancient inland sea on lineages of the western pond turtle, *Emys marmorata* in California. *Molecular ecology*, 19(3):542–56, feb 2010. ISSN 1365-294X. doi: 10.1111/j.1365-294X.2009.04451.x. URL <http://www.ncbi.nlm.nih.gov/pubmed/20051011>.

- P. Q. Spinks, R. C. Thomson, and H. Bradley Shaffer. The advantages of going large: genome wide SNPs clarify the complex population history and systematics of the threatened western pond turtle. *Molecular Ecology*, pages n/a–n/a, mar 2014. ISSN 09621083. doi: 10.1111/mec.12736. URL <http://doi.wiley.com/10.1111/mec.12736>.
- C. T. Stayton. Biomechanics on the half shell: functional performance influences patterns of morphological variation in the emydid turtle carapace. *Zoology (Jena, Germany)*, 114(4):213–23, sep 2011. ISSN 1873-2720. doi: 10.1016/j.zool.2011.03.002. URL <http://www.ncbi.nlm.nih.gov/pubmed/21820295>.
- B. L. Stuart, R. F. Inger, and H. K. Voris. High level of cryptic species diversity revealed by sympatric lineages of Southeast Asian forest frogs. *Biology letters*, 2(3):470–4, sep 2006. ISSN 1744-9561. doi: 10.1098/rsbl.2006.0505. URL <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1686201&tool=pmcentrez&rendertype=abstract>.
- A. Sztencel-Jablonka, G. Jones, and W. Bogdanowicz. Skull Morphology of Two Cryptic Bat Species: *Pipistrellus pipistrellus* and *P. pygmaeus* A 3D Geometric Morphometrics Approach with Landmark Reconstruction. *Acta Chiropterologica*, 11(1):113–126, jun 2009. ISSN 1508-1109. doi: 10.3161/150811009X465730. URL <http://www.bioone.org/doi/abs/10.3161/150811009X465730>.
- B. Van Bocxlaer and G. Hunt. Morphological stasis in an ongoing gastropod radiation from Lake Malawi. *Proceedings of the National Academy of Sciences*, aug 2013. ISSN 0027-8424. doi: 10.1073/pnas.1308588110. URL <http://www.pnas.org/cgi/doi/10.1073/pnas.1308588110>.
- V. van den Brink and F. Bokma. Morphometric shape analysis using learning vector quantization neural networks an example distinguishing two microtine vole species. *Annales Zoologici Fennici*, 48:359–364, 2011.
- W. N. Venables and B. D. Ripley. *Modern Applied Statistics with S*. Springer, New York, fourth edition, 2002. URL <http://www.stats.ox.ac.uk/pub/MASS4>.
- Z. Yang and B. Rannala. Bayesian species delimitation using multilocus sequence data. *Proceedings of the National Academy of Sciences*, 107(20):9264–9, may 2010. ISSN 1091-6490. doi: 10.1073/pnas.0913022107. URL <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2889046&tool=pmcentrez&rendertype=abstract>.
- M. L. Zelditch, D. L. Swiderski, and H. D. Sheets. *Geometric morphometrics for biologists: a primer*. Elsevier Academic Press, Amsterdam, 2004.

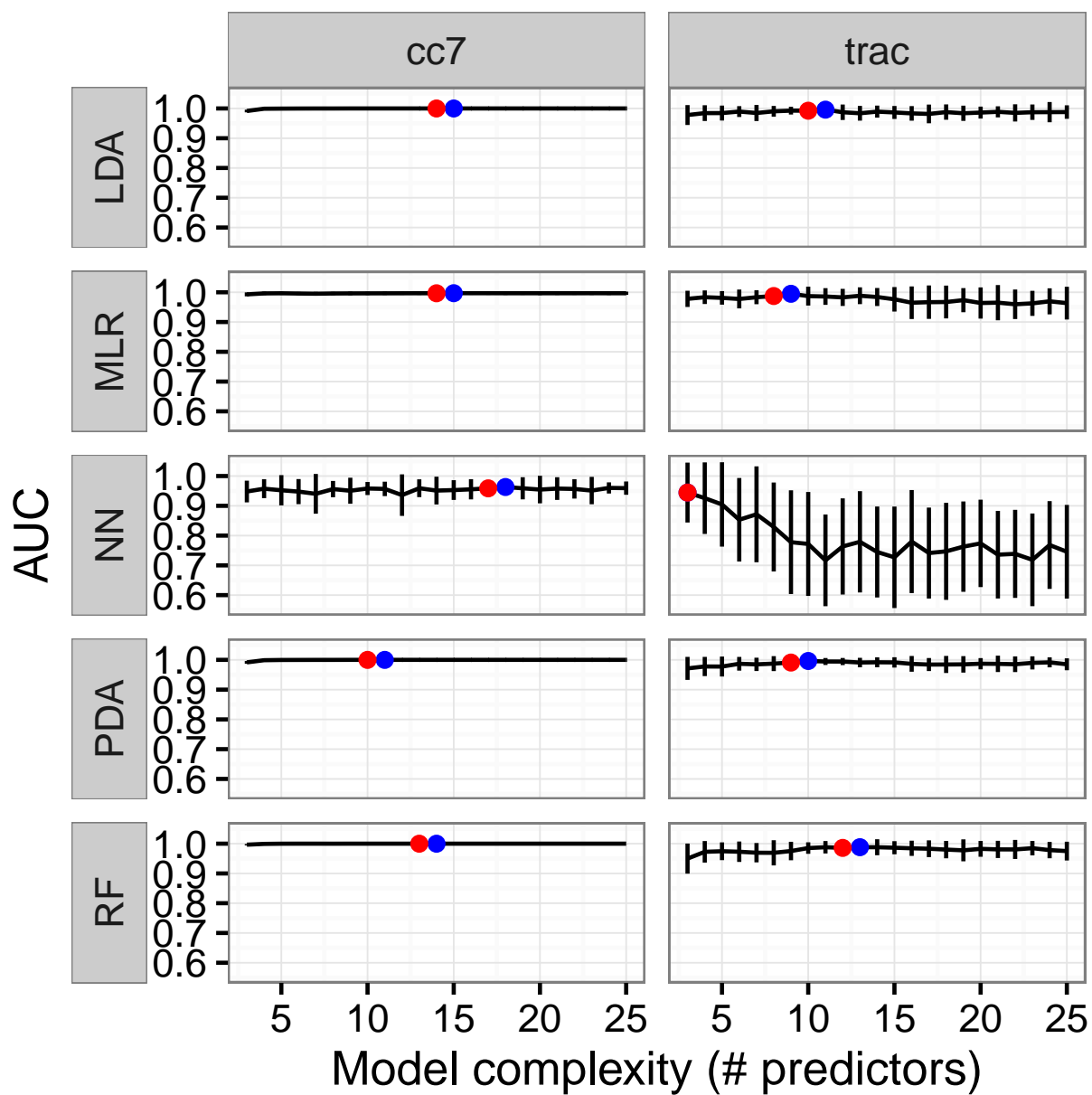


Figure 5: CAPTION

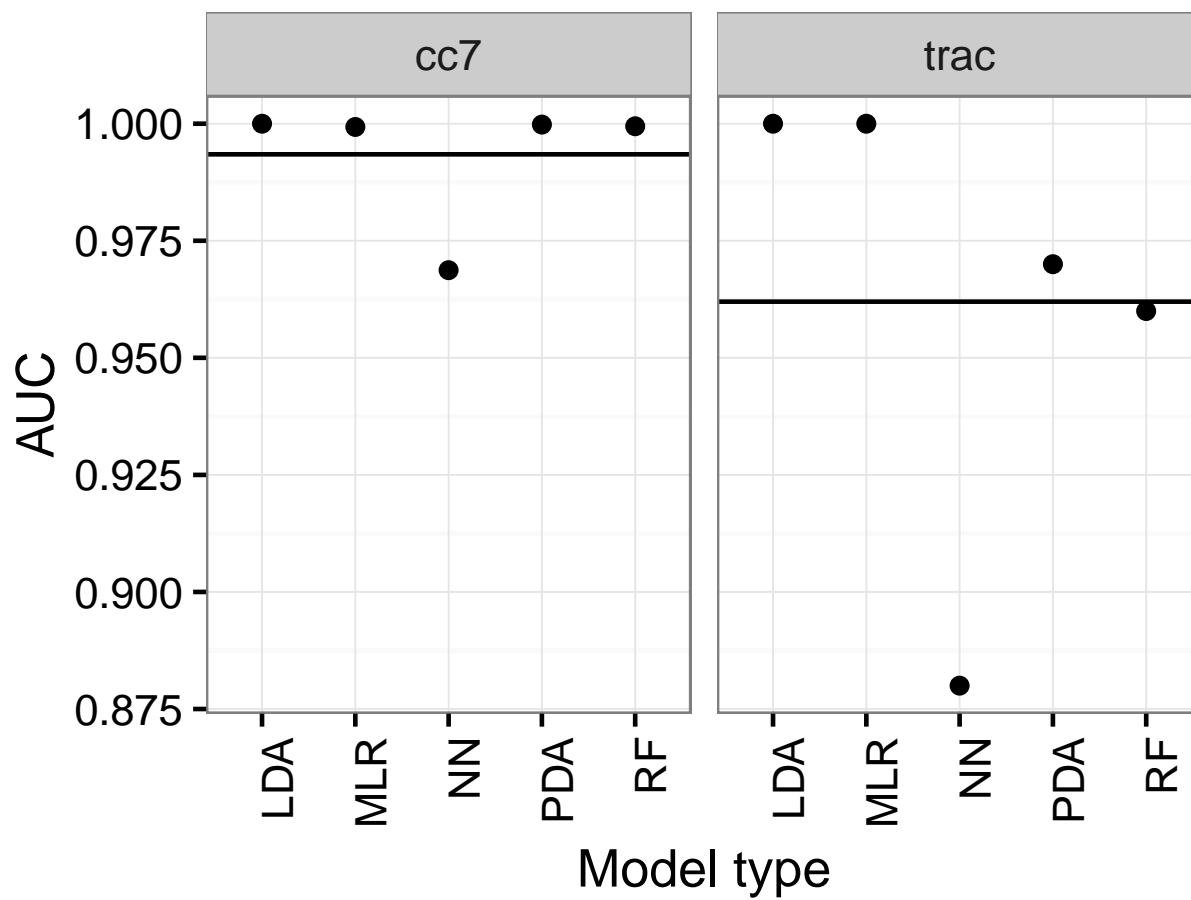


Figure 6: CAPTION

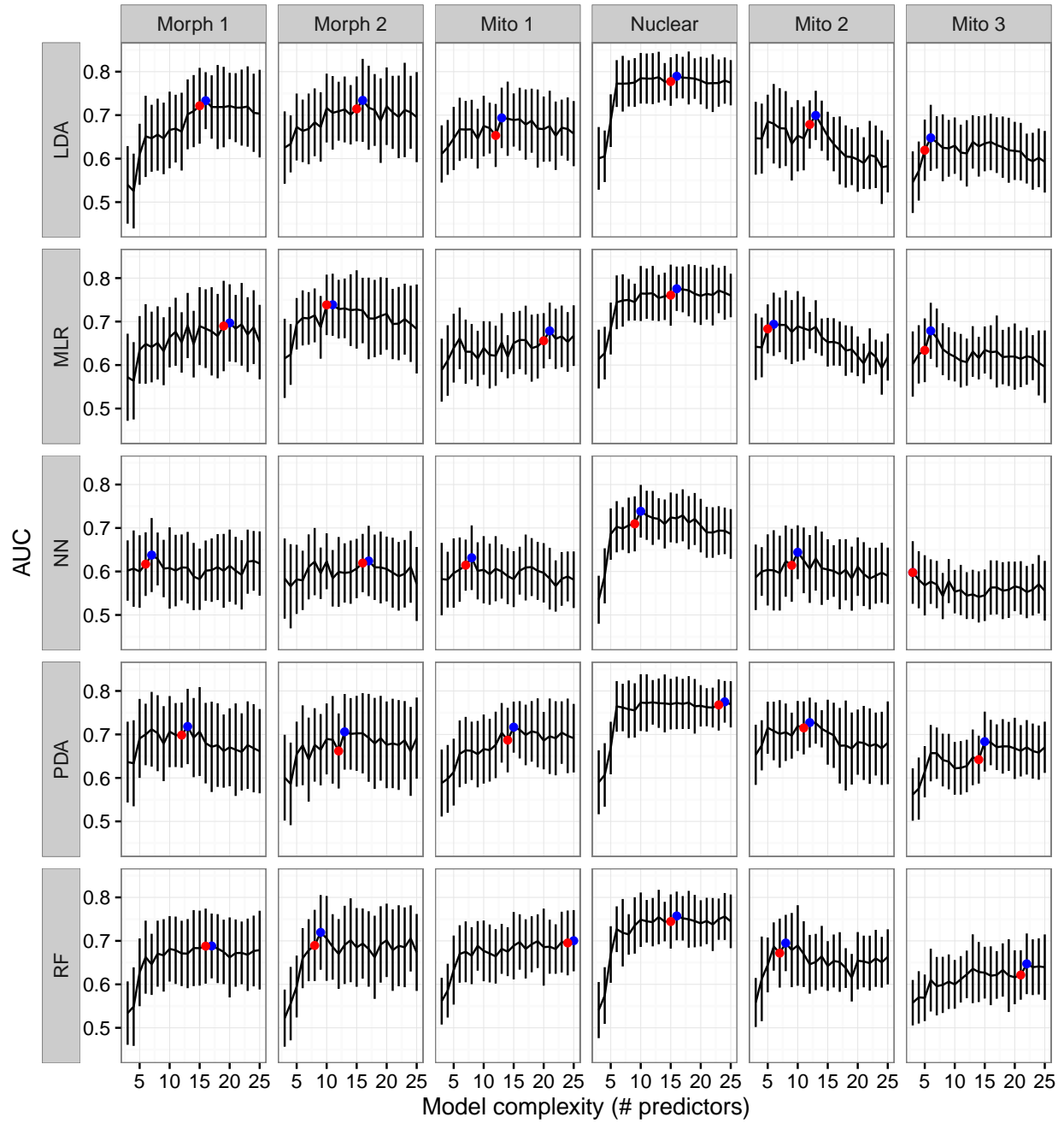


Figure 7: AUC values for models of varying complexity fit to the *Emys marmorata* training datasets for each classification scheme. Standard errors on AUC estimates are calculated from 10 rounds of 5-fold cross-validation. Indicated are the best performing and the selected models, in red and blue respectively. In some cases, there is no difference in complexity between the best and selected models.

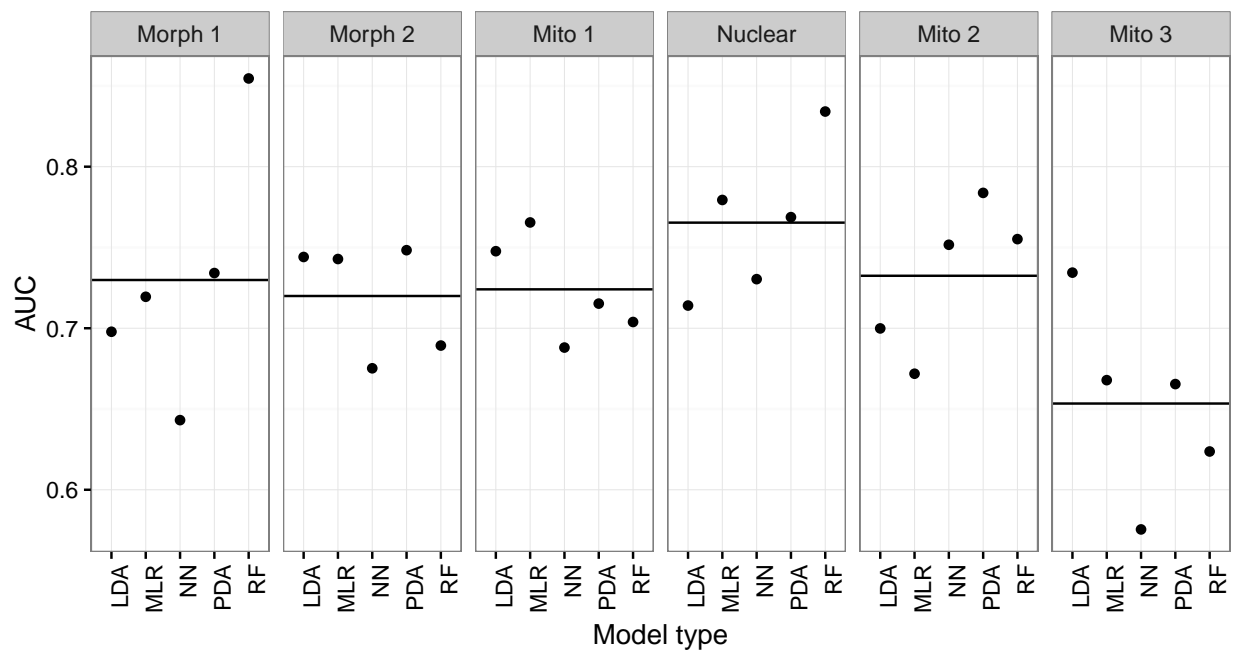


Figure 8: Comparison of out-of-sample AUC estimates from the predictions of selected models (Fig. 7), grouped by classification scheme. The horizontal line in each panel corresponds to the average AUC value across all models of that classification scheme.