

1 Title: **Phylogeographic Inference Using Approximate Likelihoods**

2 Running Title: **Phylogeography with Approximate Likelihoods**

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24 **Abstract**

25 The demographic history of most species is complex, with multiple evolutionary  
26 processes combining to shape the observed patterns of genetic diversity. To infer this  
27 history, the discipline of phylogeography has (to date) used models that simplify the  
28 historical demography of the focal organism, for example by assuming or ignoring  
29 ongoing gene flow between populations or by requiring *a priori* specification of  
30 divergence history. Since no single model incorporates every possible evolutionary  
31 process, researchers rely on intuition to choose the models that they use to analyze their  
32 data. Here, we develop an approach to circumvent this reliance on intuition. PHRAPL  
33 allows users to calculate the probability of a large number of demographic histories given  
34 their data, enabling them to identify the optimal model and produce accurate parameter  
35 estimates for a given system. Using PHRAPL, we reanalyze data from 19 recent  
36 phylogeographic investigations. Results indicate that the optimal models for most  
37 datasets parameterize both gene flow and population divergence, and suggest that species  
38 tree methods (which do not consider gene flow) are overly simplistic for most  
39 phylogeographic systems. These results highlight the importance of phylogeographic  
40 model selection, and reinforce the role of phylogeography as a bridge between population  
41 genetics and phylogenetics.

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43 **Key words:** Phylogeography, PHRAPL, isolation, gene flow, parametric approaches

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45 **Data archival location:** Dryad once possible.

46 Phylogeographic investigations operate at the scale where population-level processes  
47 begin to form phylogenetic patterns. As such, the field can act as a bridge between  
48 population genetics and phylogenetics (Avice et al. 1987), and provide valuable  
49 information about the early stages of speciation (Moritz 1994). While early  
50 phylogeographic studies were conducted largely from a phylogenetic perspective  
51 (Crandall and Templeton 1996; Sullivan et al. 2000), the incorporation of coalescent  
52 theory (Kingman 1982) has provided a theoretical basis for incorporating population  
53 level processes such as gene flow, genetic drift, and population size change into empirical  
54 investigations. This expansion of the evolutionary processes considered by  
55 phylogeography has improved the discipline immensely, with recent studies providing  
56 clear examples of the importance of processes such as range expansion and gene flow  
57 (e.g., Khatchikian et al. 2015; Weir et al. 2015). However, increasing the complexity of  
58 the historical models considered by phylogeographic research has an associated cost; in  
59 general, analytical solutions are not available for these models, and thus complex  
60 computational machinery such as Markov chain Monte Carlo (MCMC) are required to  
61 estimate parameters that quantify processes such as gene flow.

62         Researchers can choose among a wide range of software packages that implement  
63 powerful phylogeographic models; however, due to their inherent complexity, most of  
64 these methods impose limits on the parameter space under consideration. For example,  
65 the classic island model (Wright 1931) can be used to estimate gene flow using several  
66 methods. The popular program *Migrate-n* (Beerli and Felsenstein 2001) allows  
67 researchers to estimate rates of gene flow among  $n$  populations, but assumes that allele  
68 coalescence among populations is due to migration (i.e., it does not consider the temporal

69 divergence among populations). This assumption is counter to those of species tree  
70 methods which estimate the branching history among populations, but under the  
71 assumption of no gene flow (see Edwards 2009). Because many phylogeographic  
72 investigations are concerned with both processes, so researchers have turned to isolation-  
73 with-migration (IM) models (Nielsen and Wakeley 2001), particularly IMA2 (Hey and  
74 Nielsen 2007; Hey 2010), which considers multiple populations. Such models approach  
75 the phylogenetic models that have long been applied to phylogeographic datasets, and  
76 may be particularly well suited to incipient phylogenetic systems (Hey and Nielsen  
77 2004). However, IMA2 still imposes an important limit on the historical demography of  
78 the focal system; it does not infer the relationships among lineages. Given theoretical  
79 findings that demonstrate how gene flow can decrease the accuracy of species tree  
80 inference (Eckert and Carstens 2008; Leaché et al. 2014), an ideal method would estimate  
81 gene flow in addition to the pattern and timing of population isolation.

82         Phylogeographic methods derive signal from patterns of genetic variation inherent  
83 to the empirical data. Parameters estimated from the data are thus contingent on the  
84 parameterization of the model used to estimate a particular set of parameters, and  
85 consequently conflicting inferences can follow from analysis of the same data using  
86 different models (i.e., differing sets of parameters). Consider the example of *Myotis*  
87 *lucifugus*, a vespertilionid bat distributed throughout most of North America. Several  
88 subspecies of this bat have been described, and species delimitation analyses indicate that  
89 these subspecies are independent evolutionary lineages (Carstens and Dewey 2010; Fig.  
90 S1). However, analysis of these data using an *n*-island model (Migrate-*n*) support gene  
91 flow among 3 of the 4 subspecies (Table S1), while analyses using an IM model produce

92 substantial estimates of gene flow among diverging lineages (Carstens and Dewey 2010).  
93 Thus, *M. lucifugus* subspecies are inferred to be independent evolutionary lineages if  
94 species tree models are used to analyze the data, or populations within a species that  
95 exchange alleles when an *n*-island model is used to analyze the data. Parameter estimates  
96 using an IM model suggest that both processes (i.e., gene flow and population  
97 divergence) are important, but this also suggests the possibility that estimates of lineage  
98 phylogeny could be misled by not accounting for gene flow. While assessing the extent  
99 of gene flow among populations has long been a critical aspect of speciation research  
100 (Dobzhansky 1937; Mayr 1963), results such as these are difficult to resolve unless the  
101 statistical fit of the underlying models can be evaluated. Absent a framework for  
102 evaluating model fit, researchers have been forced to reconcile conflicting parameter  
103 estimates on a *post hoc* basis (Koopman and Carstens 2010).

104 In this report, we introduce a novel method (PHRAPL) that calculates the  
105 approximate likelihood of a large number of demographic models given the data, and  
106 demonstrate that it provides a suitable framework for assessing the statistical fit of the  
107 models commonly used in phylogeographic research. PHRAPL compares the topology of  
108 gene trees estimated from empirical data to those simulated under various demographic  
109 models. It then approximates the probability of the data given those demographic models  
110 by calculating the proportion of times that simulated gene tree topologies match the  
111 empirical topologies (O’Meara 2010), and adopts a multiple model inference framework  
112 (Burnham and Anderson, 2004) to quantify the support for each model in the comparison  
113 set. When applied to empirical systems such as *Myotis*, it enables researchers to identify  
114 *which* parameters are essential to estimate. PHRAPL is also likely to be useful as a tool

115 for data exploration, particularly in systems that lack previous phylogeographic  
116 investigation.

117 To date, phylogeographic inference has been almost entirely based on a  
118 qualitative interpretation of parameters that were estimated using models that were  
119 selected based on the intuition of the researchers. Consequently, it is not clear if and how  
120 incorrect phylogeographic model choice has misled researchers. To explore this question,  
121 we reanalyze recently published data (Table S2) and compare the demographic models  
122 selected by PHRAPL to those chosen by researchers.

123

## 124 **Methods**

125

126 *Description of the phylogeographic approximate likelihood method.*

127 PHRAPL inputs gene tree topologies (without branch lengths) estimated from empirical  
128 data, as well as an association file that maps sampled individuals to populations. It  
129 assumes that recombination within genes can be ignored and that gene trees from  
130 different genes are effectively unlinked. The maximum number of free parameters (which  
131 determines the size of the set of possible models) must also be defined, either by the user  
132 or automatically. PHRAPL then creates a list of the possible demographic histories that  
133 can describe these populations. All models contain some combination of parameters that  
134 describe the time of population coalescence ( $t$ ) and/or the migration rate ( $M = 4Nm$ )  
135 among some number of populations. Models with any combination of migration rates are  
136 possible; for example, one possible model could parameterize gene flow from population  
137 A to B as parameter  $M_1$ , gene flow from population C to B and C to A as  $M_2$ , and set all

138 other migration rates set to zero. In addition, users can apply filters to simplify model  
139 space: for example, one can limit models to a maximum of two different population sizes,  
140 consider only models in which all populations coalesce, and so forth. While any  
141 restriction of model space is an exchange of generality for computational efficiency, such  
142 restrictions allow for flexible incorporation of existing knowledge, and enables  
143 researchers to use PHRAPL in either a completely agnostic manner or as a tool to  
144 evaluate specific biogeographic hypotheses. The current implementation of PHRAPL  
145 assumes constant population size during a given time interval (i.e., between population  
146 splitting events), but future implementations could relax this assumption to allow  
147 exponential population growth or decline. Once the complete list of models is specified  
148 by PHRAPL, each is converted into a command for the program *ms* (Hudson 2002),  
149 which is then used to simulate gene trees under the various models with particular  
150 numeric values of parameters. Log-likelihoods are approximated from the proportion of  
151 simulated topologies that match the observed ones, described in more detail below.

152       Rather than a full optimization search of parameter space, we present in this paper  
153 analyses that were conducted using a grid of parameter values. This was found in initial  
154 explorations to be more efficient than optimization (Fig. S2) and provides a better sense  
155 of the confidence intervals of parameter values than can be achieved with typical  
156 numerical optimization. Note that both a grid and continuous parameter optimization are  
157 available as options to users, although we recommend seeding optimization searches with  
158 values obtained from a preliminary grid search. Preliminary searches using a coarse grid  
159 (i.e., with large increments between proposed values) may be used to construct finer grids  
160 for subsequent analyses. In addition, if the optimal value is found to be at the extreme

161 edge of a grid, further searches should be conducted to include more extreme values.  
162 Although the grid is composed of discrete values, parameter estimates from a given  
163 model are obtained by model averaging across the grid, and thus parameter estimates are  
164 continuous and not confined to taking on values included in the grid. Because the size of  
165 the grid rapidly expands with additional parameters, the coarseness of the grid must be  
166 balanced with desired model complexity, and it will be computationally difficult to  
167 search over using either a grid or optimization for models with large numbers of  
168 parameters (e.g. > 10).

169 PHRAPL is written in R, and is available at <https://github.com/bomeara/phrapl>.

170

171 *Strategies for increasing the efficiency of calculating approximate likelihoods of*  
172 *demographic models*

173 One obvious challenge for PHRAPL is effectively searching the large set of possible  
174 gene trees. For just seven sampled alleles, there are 10,395 binary gene trees; this number  
175 increases to  $>10^{21}$  trees when 20 alleles are sampled and would exceed the square of the  
176 number of atoms in the universe when more than 100 alleles are sampled. On the surface,  
177 this would seem to preclude a method that calculates probability based on the proportion  
178 of gene trees that match a given history, but PHRAPL uses several strategies to  
179 circumvent this difficulty.

180 First, when comparing the empirical gene tree to the simulated gene trees,  
181 PHRAPL assumes that samples from within a population are interchangeable, and then  
182 corrects for this assumption. This allows PHRAPL to switch labels within a population: if  
183 the observed gene tree is  $((A1,A2),A3),(B1,C1))$ , where letters indicate populations, and



184 numbers indicate alleles sampled from that population, the simulated gene tree  
185 (((A3,A2),A1),(B1,C1)) matches the observed gene tree except for the switching of the  
186 labels within population A. Thus, when scoring matches, PHRAPL automatically  
187 considers all possible assignments of individual labels within populations and corrects for  
188 the number of such samplings (for example, in this case, there are six possible assignment  
189 permutations of labels A1, A2, and A3, so these are all tried and a match is counted as  
190 1/6 of a possible match, as the expectation is that 1/6 of the simulations would result in a  
191 perfect match). This removes the stochastic factor of intrapopulation labeling on  
192 detecting matches, and results in a more efficient matching algorithm, particularly as the  
193 number of samples increases.

194         Second, although there may be millions of possible gene trees under a given  
195 demographic history, these do not occur at equal probability. For example, in cases of  
196 small populations that have been isolated for many generations, congruence between the  
197 gene tree and population tree occurs at a relatively high frequency (Hudson and Turelli  
198 2003), so many gene trees will have the same interpopulation branches, leaving only  
199 intrapopulation disagreements. This non-uniform distribution of gene tree probabilities  
200 (Degnan and Salter 2005) enables a far more efficient PHRAPL inference: the main  
201 differences between models will come in the relative probabilities of fairly common  
202 trees, rather than in the relative probabilities of trees in the tail, so PHRAPL can achieve  
203 reasonable degrees of accuracy in assessing model fit with a feasible number of  
204 simulations.

205         Third, we implement subsampling of individuals within putative populations,  
206 which has been shown to be an effective strategy for estimating species trees from

207 phylogeographic data (Hird et al. 2010). Even with full resolution, having tens to  
208 hundreds of samples within a population may not provide much more information than  
209 having fewer samples because most coalescent events occur very recently in the tip  
210 populations, but will require far greater computation time. PHRAPL randomly samples  
211 individuals from all populations (with number of samples per population and number of  
212 replicates specified by the user) and then analyzes these subsampled gene trees against  
213 the model set. Multiple sampling strategies are possible, although preliminary  
214 explorations have shown that subsampling three or four alleles per population yields the  
215 best balance between adequate information content and computational efficiency.

216 Finally, given that the approximate likelihood is calculated by counting matches,  
217 with a finite number of simulated trees there is some probability that none of them have  
218 matched a particular observed tree. This produces a point estimate of the likelihood of the  
219 model equal to zero, or a log likelihood of negative infinity. In practice, we know that all  
220 gene topologies have a nonzero, albeit sometimes very small, probability, but having one  
221 or more negative infinities in the log likelihood prevents the calculation of the overall  
222 AIC. Put another way, our estimate of the probability of a gene tree naturally comes from  
223 the maximum likelihood estimate of the probability of successes in a binomial  
224 distribution, but this estimate prohibits calculation of the approximate likelihood if it is  
225 exactly zero. We thus incorporate this small bit of prior information. Absent data, we  
226 expect the probability that an observed tree will match a given random tree is just one  
227 over the number of possible random trees with the same number of tips. We chose to give  
228 the prior a small weight: though we simulate thousands of trees, by default (this can be  
229 adjusted by the user) the prior only has as much weight as 100 additional simulated trees

230 ( $nEq$ ). In practice, this gives the approximate likelihood a tiny nudge away from exactly  
231 zero in the case of no matches, making the log likelihood finite, while having little effect  
232 in cases where there are observed matches. Our overall estimate of the likelihood of a  
233 gene tree  $G$  given the model (including parameters)  $M$  is not simply the number of  
234 matches ( $nMatch$ ) divided by the number of simulated trees ( $nSim$ ) but rather comes from  
235 a beta-binomial distribution:

$$236 \quad \alpha = (nEq - 1) \div nPossibleTrees$$

$$237 \quad \beta = nEq - \alpha - 1$$

$$238 \quad P(G | M) = (nMatch - \alpha) \div (nSim + \alpha + \beta)$$

239 The effect of this change is relatively minor. Given 20 taxon gene trees, 10,000 simulated  
240 trees, and five gene trees that match, respectively, 1, 2, 0, 3, 0 times, this changes the  
241 likelihood estimate for each gene tree from 0.000100, 0.000200, 0.000000, 0.000300, and  
242 0.000000, to 0.000099, 0.000198,  $1.195e^{-24}$ , 0.000297, and  $1.195e^{-24}$ , resulting in finite  
243 log-likelihoods and calculable approximate likelihoods.

244

245 *Demographic histories and model space.*

246 One challenge to phylogeographic model selection is defining the complexity of the  
247 model space. The possible number of topologies for  $n$  sampled populations is slightly  
248 higher than the number of resolved and unresolved phylogenetic trees for the same  
249 number of OTUs (the difference comes from allowing histories with at least some non-  
250 coalescing populations as in a typical island population model). This number grows  
251 factorially with  $n$ , and can be large, even with only a few free parameters. For example,  
252 an empirical dataset with 3 populations, up to 2 population divergence events, and 1

253 migration rate would have 1,462 possible histories. To reduce the complexity of model  
254 space, constraints can be added; for example users can specify that population merging is  
255 to occur only between geographically proximate populations. At most, there will be  $n-1$   
256 possible free parameters for divergence times,  $2n-2$  possible population sizes at nodes  
257 (including terminal nodes) (not  $2n-1$ , as the initial population size is fixed in all the  
258 models),  $2 \sum_{i=2}^n \binom{i}{2}$  possible migration rates, and  $2n-1$  possible population growth rates.  
259 This explicit focus on the number of free parameters has an auxiliary benefit: since the  
260 number of possible parameters scales with the number of loci and the number of samples,  
261 users should explore tradeoffs in resource allocation and may be discouraged from  
262 proposing overly-complex demographic scenarios, a common problem in  
263 phylogeography (Knowles and Maddison 2002).

264         While PHRAPL is not essentially a Bayesian approach, it shares some similarities  
265 with approximate Bayesian computation (ABC; Beaumont et al. 2002), which has also  
266 been applied to phylogeographic model selection (e.g., Fagundes et al. 2007; Peter et al.  
267 2010). In the absence of an analytical solution, both rely on data simulated under specific  
268 demographic scenarios, and evaluate these data by comparing them to the observed data.  
269 However, PHRAPL uses likelihood rather than a Bayesian criterion. It thus seeks the  
270 model (i.e., demographic history + parameter estimates) that maximizes the probability of  
271 the data, rather than integrating over parameter space to calculate posterior probability. In  
272 ABC, prior beliefs about the distribution are required for parameter values (in some  
273 cases, these could be set to uninformative priors), and in some cases the priors can affect  
274 the final results (e.g., Oaks et al. 2013). PHRAPL does not use priors, but does require  
275 some specification of the region of parameter space to explore. PHRAPL also differs

276 from ABC in how it evaluates similarity between the simulated and the observed data.  
277 ABC approaches typically use a variety of summary statistics and require specification of  
278 an epsilon value to describe how close a simulated value has to be to an empirical value  
279 to count as a “match”. PHRAPL uses discrete gene topologies in effectively the same  
280 way, as a summary statistic, but does not require specification of an epsilon value  
281 because topology is a discrete parameter. We have observed that log-likelihoods  
282 calculated using PHRAPL are generally good approximations of analytical log-likelihood  
283 estimates (Fig. S3), at least for those demographic models which have analytical  
284 solutions. Finally, PHRAPL is explicitly tailored for model selection. It calculates AIC  
285 scores for each model (Akaike 1973) and then applies information theory (Burnham and  
286 Anderson 1998) to assess the relative support of these models given a particular dataset.  
287 This enables model selection from a large set of demographic models, an objective that is  
288 empirically difficult when using ABC for model choice (Pelletier and Carstens 2014).

289

#### 290 *Analyses with simulated data*

291 We tested the performance of PHRAPL using simulated datasets for which the  
292 underlying history is known. We focused on four demographic histories (Fig. 1) each  
293 consisting of three populations: an isolation only (IO) model, isolation with migration  
294 (IM) model,  $n$ -island migration only (MO) model, and a mixed (MX) model which was  
295 intermediate to IM and MO models and included one population coalescent event, with  
296 migration between some, but not all populations. For IO and IM models, we considered  
297 three divergence depths (shallow, medium, and deep), yielding eight histories (Fig. 1).  
298 Under each history we simulated gene trees using ms for five different dataset sizes (1, 5,

299 10, 50, and 100 loci), with 20 replicates for each treatment (for a total of 480 datasets).  
300 Parameter values span an order of magnitude of migration rates and divergence times and  
301 were chosen to reflect the breadth of variation commonly observed within  
302 phylogeographic datasets.

303 We analyzed these simulated datasets against two different model sets. First, we  
304 assembled a small model set (11 models) containing (i) the full true underlying models  
305 (four models), (ii) a set of simplified IM, MO, and MX models (three models, which are  
306 identical to the full true models except that they include only a single shared migration  
307 rate), and (iii) IO and IM models that reflect alternative branching histories (four  
308 models). Secondly, we analyzed simulated datasets against a large model set consisting of  
309 a filtered set of all possible demographic models that include one, two, or three free  
310 parameters ( $\text{maxK} = 3$ ). To reduce model space we assumed a shared, constant  
311 population size across populations, set the maximum number of migration parameters to  
312 one, and considered only models in which migration parameters were symmetric between  
313 populations (e.g., if there is migration from population A to population B, there must also  
314 be migration from B to A). For three populations, the three available free parameters  
315 could thus be allotted to zero, one, or two possible population coalescence events and/or  
316 to one possible migration rate, in all possible combinations. After adding in three missing  
317 full models from the small model set, this yielded a total of 81 models. We also repeated  
318 all the above analyses (for 10 replicates and for only three of the five dataset sizes) using  
319 genealogies inferred from sequence data, which we evolved along all simulated  
320 genealogies using Seq-Gen (Rambaut and Grassley 1997; Figs. S4-S5). These analyses

321 were designed to assess how the stochastic process of mutation influences PHRAPL  
322 inferences.

323 For each dataset, model, and value combination in the specified parameter grid,  
324 we simulated 10,000 gene trees. For the grid, we considered seven values of time to  
325 population coalescence ( $t$ ) (0.30, 0.58, 1.11, 2.12, 4.07, 7.81, and 15.00) and six values of  
326 migration rate ( $M$ ) (0.10, 0.22, 0.46, 1.00, 2.15, 4.64). For each simulation, the  
327 approximate log-likelihood of a dataset under a given model was calculated using the  
328 mean log-likelihood across subsampled trees for a given locus, and summing these across  
329 loci. We performed PHRAPL analyses on 10 iterative subsamples of each dataset,  
330 subsampling 4 individuals per population (resulting in 12 tip trees).

331

### 332 *Analyses with empirical data*

333 Data were kindly provided by the corresponding authors of 19 recently-published  
334 phylogeographic investigations (Barker et al. 2012, Camargo et al. 2012, Harrington and  
335 Near 2012, Hung et al. 2012, Jackson and Austin 2012, Muir et al. 2012, Werneck et al.  
336 2012, Carstens et al. 2013, Dhimi et al. 2013, Duvernell et al. 2013, Fernandez-  
337 Mazuecos and Vargas 2013, Hamback et al. 2013, Leaché et al. 2013, Reilly et al. 2013,  
338 Satler et al. 2013, Talavera et al. 2013, Tsai and Carstens 2013; Wielstra et al. 2013,  
339 Giaria et al. 2014, Halas and Simons 2014; see Table S2 for specifications of included  
340 datasets). We selected studies (i) that were published or in press between January 2012  
341 and October 2013; (ii) that used \*BEAST (Heled and Drummond 2010) or IMA2 (Hey  
342 2010), two of the most commonly applied methods for inferring evolutionary parameters  
343 of interest in phylogeographic datasets; (iii) that used sequence data from multiple loci

344 that were either available to us from the authors or from public databases; (iv) that  
345 analyzed their data using three defined lineages (to allow for the same, moderately sized  
346 model set to be used for all datasets); and (v) sampled four or more individuals per  
347 population. If a dataset lacked an outgroup sequence, we obtained one from GenBank. If  
348 needed, datasets were aligned using MUSCLE (Edgar 2004). For each dataset and locus,  
349 we estimated a maximum likelihood tree using the rapid hill-climbing algorithm (10  
350 replicate searches) and GTRGAMMA model implemented in RaxML-HPC v7.2.6  
351 (Stamatakis 2006).

352 We analyzed each empirical dataset using the larger (81) model set used for the  
353 simulated data, except we removed the three models that contained more than one  
354 migration rate (for a total of 78 models). 200 subsample iterations were used for each  
355 dataset, with three individuals per population subsampled for each iteration (i.e., nine tip  
356 trees), as this yielded better AIC consistency across replicate runs of these datasets than  
357 was observed by subsampling four (Figs. S6-S7). The number of trees simulated per  
358 cycle was set to 100,000. The parameter grid was identical to that used for the simulated  
359 datasets, except that we added one additional migration rate ( $4Nm = 10$ ). Parameter  
360 estimates for mtDNA were scaled to account for their  $\frac{1}{4}$  effective population size.

361 In addition, we analyzed the *Myotis* dataset (Carstens and Dewey 2010) that  
362 contained four populations (one corresponding to each subspecies) using 216 total  
363 models. These models were filtered to include only those with a fully resolved population  
364 history, but varied in topology and presence and direction of migration.

365

366 **Results and Discussion**



367 *Performance with simulated datasets*

368 At moderate to deep levels of divergence, PHRAPL is generally accurate at identifying  
369 the 'true' model (i.e., the model used to generate the data), although in some cases, this is  
370 contingent upon sampling many loci (Fig. 2). In cases where the generating model does  
371 not have the highest AIC score, this model is often ranked second-best and is surpassed  
372 by a model with a similar set of parameters. As with many phylogeographic methods, the  
373 accuracy of PHRAPL improves as the size of the dataset increases. While we report  
374 results for up to 100 loci, PHRAPL scales efficiently with genomic datasets because the  
375 gene trees estimated from 100s to 10,000s of loci are compared to the same simulated  
376 gene tree distributions to calculate the approximate likelihood. Performance decreases  
377 slightly when using gene trees estimated from simulated sequence data rather than the  
378 original genealogies, particularly in the case of isolation only datasets (Figs. S4-S5).  
379 Parameter estimates are generally accurate (Figs. S8-S9 and Table S3), with the  
380 exception of estimates of migration between ancestral populations, which were typically  
381 overestimated. We suspect that ancestral migration is difficult to estimate in general, as  
382 more recent events tend to erase this history.

383       The number of models considered by a PHRAPL analysis also affects accuracy,  
384 particularly for IM models or IO models with shallow divergence, where accuracy  
385 declines with increases in the number of models considered by the analysis. Due to the  
386 nature of the model space, our large model set is predominately composed of IM models  
387 with subtle differences among migration matrices. Thus, with fewer loci or less time for  
388 lineage sorting, it becomes a challenge to consistently distinguish among models that  
389 include slight variations on the true migration scheme. We suggest that users evaluate

390 parameter estimates in such cases. For example, although IM models were incorrectly  
391 inferred for many shallow isolation only datasets (although usually with the correct  
392 population topology; Fig. 2A), the estimated migration rates in these models were  
393 generally near zero (Fig. S8-S9 and Table S3). In practice, such a result would likely lead  
394 researchers (albeit in a circuitous way) to the correct inference (i.e., that migration is not  
395 very important for these datasets). The similarity in parameter values estimated using the  
396 small and large model sets (Fig. S8-S9) suggests that researchers do not necessarily need  
397 to identify the exact true model to accurately quantify the underlying processes. Rather,  
398 in keeping with the spirit of model-based inferences (e.g., Anderson 2008), it is perhaps  
399 best to view PHRAPL as a tool that is likely to identify the processes that have left a  
400 noticeable signal in the data. Parameters included in the models with the best AIC scores  
401 are those that reflect the dominant evolutionary processes that gave rise to the observed  
402 genetic patterns (Carstens et al. 2009).

403         The one scenario under which model inference was poor regardless of model set  
404 size was when the true model was an  $n$ -island model (Fig. 2C). In such a case, the models  
405 with the best AIC value usually included one or two divergence parameters in addition to  
406 full migration. This suggests that PHRAPL is biased towards IM models, which is  
407 worrisome for systems in which migration is so important as to have swamped out the  
408 genetic signal of the underlying divergence history. Phylogeography has been criticized  
409 for being overly reliant on tree thinking (Smouse 2008), and this aspect of PHRAPL's  
410 performance should be improved. Nevertheless, high accuracy in migration rate estimates  
411 was still observed for these datasets (Fig. S8-S9), so it is unlikely that researchers would  
412 ignore migration in such systems altogether.

413           When parameters are estimated using model averaging, PHRAPL is precise in  
414 most cases (Fig. S8-S9). The exceptions are the timing of divergence and gene flow  
415 among ancestral lineages. In both cases, PHRAPL tends to overestimate these values,  
416 suggesting that genetic data contains less information about earlier processes than about  
417 more recent ones. In light of these results, PHRAPL is best suited to be used as a tool for  
418 identifying the optimal model for a given empirical system. Users should devote more  
419 effort to parameter estimation after an optimal model is identified, either by using a finer  
420 parameter grid within PHRAPL or by analyzing their data using an alternative method  
421 that implements the chosen model(s) in a full probabilistic framework.

422           Molecular systematists should be familiar with this relationship between model  
423 selection and parameter estimation; to estimate phylogenetic trees from sequence data  
424 researchers first use a program such as MODELTEST (Posada and Crandall 1998) to  
425 objectively choose a model of sequence evolution, and then other software to generate a  
426 precise estimate of the parameter in question (i.e., the phylogeny and branch lengths).  
427 However, it is worth noting that this workflow was not always in place. Prior to the  
428 widespread use of model selection, papers were routinely published that promoted  
429 unconventional relationships on the basis of phylogenetic trees that were likely poor  
430 estimates of the true parameter because they were estimated using inappropriate models  
431 (e.g., D'Erchia et al. 1996). In molecular systematics, parameters such as gamma for rate  
432 heterogeneity (Yang 1996) are important because they allow phylogeny (the true  
433 parameter of interest) to be estimated accurately, but are essentially nuisance parameters  
434 in terms of the inferences that result from the phylogeny estimate. In phylogeographic  
435 research, some parameters inherent to the models used to analyze the data are decidedly

436 not nuisance parameters, particularly those that model evolutionary processes such as  
437 gene flow, genetic drift, or population history.

438         One criticism that could be made against PHRAPL is that it does not analyze all  
439 of the data. For example, it does not use raw gene sequences, nor does it use gene tree  
440 branch lengths. This is a compromise necessitated by its use of a discrete parameter to  
441 evaluate matches. In addition, it is often difficult to estimate a topology and branch  
442 lengths accurately using intraspecific data (Harding 1996), and thus branch length  
443 information would likely be noisy. Finally, there are the practical results: using just  
444 topologies, PHRAPL performs reasonably well in many cases. While we hope for  
445 methods in the future that can use more of the data, the results presented here suggest that  
446 topologies alone contain sufficient information to make inferences about important  
447 population-level evolutionary processes.

448

#### 449 *Computation time required by PHRAPL*

450 The computational time requirements of PHRAPL are similar to those of other methods  
451 commonly used by phylogeographers. Using a single core, individual models required 2.3  
452 hours on average for the analysis of empirical data, resulting in a median time of 198  
453 hours (8.2 computer-days) for the total model set (78 models). However, variance around  
454 this value was high (2.6 to 31 computer-days). Notably, PHRAPL is a method that is easy  
455 to implement in parallel because only the input data are shared between models, and  
456 substantial time savings can be accomplished by analyzing models across multiple cores  
457 on a single computer or split across several computers.

458

459 *Empirical studies*

460 The reanalysis of recently published data suggests that the process of gene flow has been  
461 underappreciated by phylogeographic investigations. It is almost always implicated as an  
462 important evolutionary process by PHRAPL (Fig. 3 and Fig. S10), despite the fact that  
463 many of the original studies only considered species tree models (Table S2). Note that  
464 while the number of possible IM histories is inherently much larger than the number of  
465 MO and IO histories (90% of the model set was composed of IM models, whereas IO and  
466 MO models made up only 5% each), we normalized the model class probabilities  
467 depicted in Fig. 3 based on the frequency of each model class to account for this bias.  
468 The absence of support for isolation only models among empirical datasets suggests that  
469 reliance on species tree approaches (in our sample, the most commonly applied model to  
470 phylogeographic systems) may fail to account for important evolutionary processes.  
471 Moreover, parameter estimates of non-migration parameters can be affected when  
472 migration is ignored. For each of our 20 empirical datasets (including *Myotis*), there were  
473 four tree structures (polytomy and all three resolved trees) that were analyzed with and  
474 without migration. In 79 out of these 80 examples, the no-migration model had  
475 divergence times lower, often much lower, than the divergence times in the best fitting  
476 corresponding migration model. Over all the 80 pairs, the median branch length under a  
477 no-migration model was just 13% of the corresponding branch length for the best  
478 migration model. Thus, for empirical datasets, ignoring migration can have a significant  
479 effect on the resulting inference, even if it is not a parameter of interest *per se*.

480         Results from *Myotis lucifigus* mirror those seen in the analysis of the other  
481 empirical data. Of the 216 models included in the analysis, roughly 98.5 of the total

482 model probability was represented by isolation-with-migration models (Table 1). The  
483 inferred topology matches the topology estimated using \*BEAST (not shown), but gene  
484 flow is clearly a process that should be considered to understand the evolutionary history  
485 of this group. These results imply either that species delimitation approaches such as BPP  
486 (Yang and Ranalla 2010) and spedeSTEM (Ence and Carstens 2011) can accurately  
487 delimit lineages in the presence of moderate gene flow, or that they falsely delimit  
488 lineages by treating all shared polymorphism as the product of ancestral lineage sorting.  
489 Differentiating these scenarios would require a more nuanced understanding of both the  
490 timing of diversification and gene flow than can likely be provided by the PHRAPL  
491 analysis of the data analyzed here.

492

### 493 **Conclusion**

494 Our reanalysis of 20 empirical datasets highlights the utility of phylogeographic model  
495 selection by demonstrating that the intuition of researchers (inclusive to some of the  
496 authors of this paper) is sometimes flawed in choosing the models used to analyze data  
497 from empirical systems. Optimal models for most datasets parameterize both gene flow  
498 and population divergence, suggesting that species tree methods (which do not consider  
499 gene flow) are over-simplifications for phylogeographic systems. Phylogeography has  
500 long been promoted as a 'bridge' between population genetics and systematics (Avise et  
501 al. 1987), but the reliance on the species tree has constrained the field to one side of this  
502 continuum. For the first time, PHRAPL enables researchers to select demographic  
503 models without relying on their intuition about the processes likely to be important to  
504 their systems. By allowing a direct probabilistic assessment of nearly any coalescent

505 model to the empirical data, PHRAPL represents a substantial addition to the  
506 methodological toolbox available to phylogeographers.

507

508 **Acknowledgements.**

509 PHRAPL is funded by the National Science Foundation (DEB 1257669 / DEB-1257784).

510 We thank the authors who generously provided empirical data. We thank Jack Sullivan,

511 Darin Rokyta, members of the Carstens and O'Meara labs, as well as students in the first

512 PHRAPL workshop for conversations related to this work.

513

514 **Data Archiving:** Dryad once possible.

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703 **Figure Legends**

704

705 **Fig. 1.** Histories used for simulation testing. Four types of histories were simulated, each  
706 involving three populations: A: isolation only models, which exhibit two collapse events,  
707  $t_1$  and  $t_2$  (three time depths were simulated; times are given in units of  $4N$ ); B: isolation  
708 with migration models (migration rates above arrows are given in units of  $4Nm$ ); C: a  
709 migration only model; and D: a mixed model, which includes one collapse event and  
710 migration in some, but not all directions.

711

712

713 **Fig. 2.** PHRAPL results from analysis of four types of simulated models (depicted in Fig.  
714 1. A: isolation only; B isolation with migration; C: migration only; D: mixed). Results are  
715 shown for the entire model set (81 models) and for a reduced model set (11 models).  
716 Black bars give the proportion of 20 replicate analyses in which the true model garnered  
717 the highest AIC weight; grey bars give the proportion where the true model garnered the  
718 second highest AIC weight.

719

720

721 **Fig. 3.** Triangle plot showing the weighted probabilities from PHRAPL analysis of 19  
722 datasets. Each of the three vertices represents a commonly used approach to  
723 phylogeographic data analysis. The top corresponds to IMa2 (Hey 2010), the lower right  
724 to Migrate-n (Beerli and Felsenstein 2001) and the lower left to a species tree analysis  
725 (i.e., \*BEAST; Heled and Drummond 2010). The probabilities of each analysis are

726 shown decreasing from the respective vertex in increments of 0.1. Weighted probabilities  
727 were corrected for the unevenness of the model space in respect to the three model  
728 classes such that a dataset with equivalent probability for each of the models would  
729 appear in the center of the triangle (marked with a small yellow circle). Results indicate  
730 that there is very little support for the isolation-only model in these phylogeographic  
731 investigations. Percentages at the triangle tips give the proportion of the empirical studies  
732 that applied the corresponding model to the data.

733

734 **Table 1.** Model selection results in *Myotis lucifugus*. Data from 4 subspecies (*a*lacensis,  
735 *c*arissima, *l*ucifugus, *r*elictus) were analyzed using PHRAPL and 216 models. Shown are  
736 the model (letters with 'M' represent models that included migration among the identified  
737 subspecies), the topology of the population tree, the number of parameters (*K*), the  
738 Akaike Information Criterion (Akaike 1973) score (AIC), and the model likelihood  
739 (Burnham and Anderson 1998). Subspecies are identified using the first letter of  
740 subspecies names.

741

model	topology	K	AIC	wAIC
c - l M	(((a,l)r)c)	4	123.23	0.405
c - r M	(((a,l)r)c)	4	123.51	0.352
a - c M	(((a,l)r)c)	4	126.11	0.096
a - c - l M	(((a,l)r)c)	4	126.72	0.071
a - l M	(((a,l)r)c)	4	127.06	0.060
species tree	(((a,l)r)c)	3	129.87	0.015
symmetric M	(((a,l)r)c)	4	135.03	0.001

742





