

INTERACTING ASSOCIATIONS BETWEEN PLOIDY, BREEDING SYSTEM, AND LINEAGE  
DIVERSIFICATION

Rosana Zenil-Ferguson<sup>1,†</sup>, J. Gordon Burleigh<sup>2</sup>, William A. Freyman<sup>3</sup>, Boris Igić<sup>4</sup>, Itay Mayrose<sup>5</sup>, and  
Emma E. Goldberg<sup>3</sup>

<sup>2</sup>Department of Biology, University of Hawai'i Mānoa, Honolulu, HI 96822, U.S.A.

<sup>2</sup>Department of Biology, University of Florida, Gainesville, FL 32611, U.S.A.

<sup>3</sup>Department of Ecology, Evolution, and Behavior, University of Minnesota, Saint Paul, MN 55108, U.S.A.

<sup>4</sup>Department of Biological Sciences, University of Illinois at Chicago, Chicago, IL 60607, U.S.A.

<sup>5</sup>School of Plant Sciences and Food Security, Tel Aviv University, Tel Aviv 6997801, Israel.

<sup>†</sup>*Author for correspondence:.*

*Running head:* Ploidy and Breeding Systems in Solanaceae

*Keywords:* Polyploidy, Breeding System, Diversification, SSE models

## Abstract

If particular traits consistently affect rates of speciation and extinction, broad macroevolutionary patterns can be understood as consequences of selection at high levels of the biological hierarchy. Identifying traits associated with diversification rate differences is tricky, though, because of the many traits available to consider and the statistical challenge of testing for associations from phylogenetic data. Two traits that have been repeatedly suggested as drivers of differential diversification are whether a lineage is diploid or polyploid, and whether it is self-incompatible or self-compatible. We investigate the role of each of these traits, and their interaction, on speciation and extinction rates in Solanaceae. We find that the effect of ploidy can largely be explained by its correlation with breeding system, and that additional unknown factors work with breeding system to determine diversification rates. These results are largely robust to assumptions about whether diploidization occurs. Finally, we show that allowing for state-dependent diversification affects conclusions about the relative contribution of different evolutionary pathways to self-compatible polyploids.

*"Among life history traits, reproductive characters that determine mating system patterns are perhaps the most influential in governing macroevolution."*

Barrett et al. (1996)

## Introduction

Species accumulate within the tree of life at different rates. A possible explanation for this phenomenon is that species possess various traits or character states that may differentially affect rates of diversification.

Dramatic increases in available phylogenetic and phenotypic data as well as methodological advances have greatly accelerated the search for traits that influence diversification traits. Nevertheless, identifying focal traits associated with rates of speciation and extinction remains a difficult statistical problem (e.g., Maddison and FitzJohn 2015; Rabosky and Goldberg 2015; Moore et al. 2016; FitzJohn et al. 2009; Goldberg and Igić 2012; Beaulieu and O'Meara 2016; Rabosky and Goldberg 2017). In part, the difficulties arise because speciation and extinction may not depend on a single trait, and the context in which traits occur can lead to complex interactions resulting in a heterogeneous speciation and extinction rates (Beaulieu and O'Meara 2016; Caetano et al. 2018; Herrera-Alsina et al. 2018). Consequently, examining the association of only one trait with diversification patterns can be misleading.

Whole genome duplication (WGD) is a remarkably common mutation in plants (Husband et al. 2013; Zenil-Ferguson et al. 2017). The widespread prevalence of variation in ploidy has long been considered a salient feature of flowering plant lineages (Stebbins 1938). WGDs have the potential to affect many phenotypes and impact a variety of evolutionary (Ramsey and Schemske 2002) and ecological processes (Sessa 2019). Polyploids have long been thought to have lower rates of net diversification rate than diploids (Mayrose et al. 2011, 2015). Recent studies, however, find common and numerous paleo-polyploidizations, including some preceding the emergence of highly diverse plant clades (Soltis et al. 2014; Landis et al. 2018), suggesting that WGDs have played an important macroevolutionary role driving innovation and diversification in plants. Evidence of paleo-polyploidy within the genomes of diploid extant plants also implies the pervasiveness of diploidization, the return of polyploids to the diploid state throughout the angiosperm phylogeny (Soltis et al. 2015; Dodsworth et al. 2015). Testing for the presence of diploidization in the context of diversification is important because the presence of a positive net diversification rate for diploids can be the result of an ancestrally polyploid lineage. Under this scenario, polyploidy would no longer be considered to reliably slow down diversification, but instead, polyploidy would be the initiator of the diversification process.

Breeding system shifts—changes in the collection of physiological and morphological traits that

determine the likelihood that any two gametes unite—are remarkably common and they crucially affect the distribution and amount of genetic variation in populations (Stebbins 1974; Barrett 2013). In particular, self-incompatibility systems cause a plant to reject its own pollen, and their loss, yielding self-compatibility, is one of the most replicated transitions in flowering plant evolution (Stebbins 1974; Igić et al. 2008). Previous phylogenetic analyses have reported higher rates of diversification for self-incompatible than for self-compatible lineages (Goldberg et al. 2010; de Vos et al. 2014), even when allowing the possibility that hidden states could drive diversification patterns (Freyman and Höhna 2018). However, studying breeding system with other correlated traits and unobserved states driving diversification patterns simultaneously has not yet been explored.

Ploidy may also affect the propensity for self-fertilization (Stebbins 1950). The evidence for correlated shifts in mating system, from outcrossing to selfing, following WGD, appears limited and sometimes contradictory (Barringer 2007; Barrett 2008; Husband et al. 2008). In other cases, however, polyploidy is not only suspected to correlate with breeding system but causes the transition from self-incompatibility (SI) to self-compatibility (SC) (Stout and Chandler 1942; Lewis 1947). Doubled number of alleles in pollen is thought to effect disruption of the genetic mechanisms in gametophytic SI systems, which prevent self-fertilization (Entani et al. 1999; Tsukamoto et al. 2005; Kubo et al. 2010). This creates a correlation between polyploidy and SC by precluding the existence of SI polyploids. In clades with these systems, it is thus natural to consider the simultaneous macroevolution of polyploidy and breeding system.

Given that changes in ploidy and breeding systems may be causally related and have profound effects on the fate of lineages, it seems particularly profitable to examine possible interactions in their macroevolutionary effects. This includes their joint influence on lineage diversification, and also potential patterns in the order of their transitions. For example, it is possible to ask whether losses of SI more commonly occurred tied to polyploidization, or without a ploidy shift. Or whether polyploids have arisen more commonly from self-incompatible than from self-compatible diploids/ Robertson et al. (2011) found that the pathway from self-incompatible diploids to self-compatible polyploids is dominated by loss of self-incompatibility followed later by polyploidization over long timescales, but proceeds in one step via polyploidization of SI species over short timescales. Greatly improved phylogeny and methods that allow for diversification rate differences allow far more powerful approach to such problems.

Two methodological developments are critical for disentangling the complex interactions between two or more traits and their link to diversification. First, the model proposed by FitzJohn (2012) that extended the state-dependent diversification “\*SSE” modeling framework (Maddison et al. 2007), to allow estimating the effect of an arbitrary number of states (enabling multiple states, MuSSE, instead of binary

states, BiSSE). This allows multiple states to represent trait combinations, particularly useful if one is interested in explicitly testing whether combinations of traits non-additively affect speciation or extinction. Second, the model by Beaulieu and O'Meara (2016) HiSSE proposed a first solution to the problem of elevated false positive type I errors found often in the BiSSE framework (Goldberg and Igić 2012). The authors argued that it is unlikely that the variation in speciation and extinction rates is only due to a focal trait but by considering heterogeneity in the diversification process as the null hypothesis, it is possible to parse out the importance of the focal trait in diversification while other unobserved processes can happen. HiSSE models have effectively shown that some traits associated with diversification in BiSSE analyses are actually not associated with the diversification process, and instead a hidden state is linked to differences in the diversification rate. Such results raise the question of the identity of the hidden state, or whether it is an approximation of some unknowable heterogeneity, as well as whether interactions between the known and hidden trait were modeled appropriately. Third, one can simultaneously consider the effects of multiple known traits using MuSSE, especially in systems where multiple traits are suspected to influence diversification, and where interactions between those traits are well understood. However, MuSSE might also suffer from high type I errors if there are other processes shaping diversification other than the traits observed (Caetano et al. 2018). Therefore, a fourth option exists: considering both the presence of multiple known traits linked to the diversification process, but also, some unknown or hidden state changing speciation and extinction rates. These four modeling strategies are proposed here in the context of studying complex interactions among traits, linked diversification.

The focus of our study is the individual role of ploidy and breeding systems, as well as their interaction, on the diversification process in Solanaceae. Using ploidy and breeding system data from species in Solanaceae, and considering possible heterogeneity in the diversification process, we assess the influence of these traits on speciation and extinction rates. First, we present models in which the effect of ploidy and breeding system are considered separately, and compare the inferences to previously published results. Second, we consider the addition of a hidden trait to each of the models that examine traits individually, in order to investigate whether the focal trait directly affects differences in diversification, or if such differences are attributable to unobserved but correlated hidden states. Third, we ask whether the complex interaction between breeding system and ploidy may be explained by the hidden trait states. We evaluate a multi-state model to consider both traits linked to diversification, and then consider whether an additional unobserved trait may be driving differences in diversification. In all these models we also investigate the potential effects of diploidization to explore whether the reversion of polyploidy changes diversification interpretations. Our results highlight the importance of considering non-additive effects of traits on net diversification rates,

especially when there are strong biologically driven correlations amongst them.

## Methods

### Data

Chromosome number data were obtained for all Solanaceae taxa in the Chromosome Counts Database (CCDB; Rice et al. 2015), and the ca. 14,000 records were curated semi-automatically using the CCD-Bcurator R package (Rivero et al. 2019). CCDB contains records from original sources that have multiple  
115 complex symbol patterns denoting multivalence, or irregularities of chromosome counts. After a first full round of curation via CCD-Bcurator, we contrasted results by hand and corrected chromosomes where CCD-Bcurator's output was not able to adequately correct records. Our hand-curated records were also contrasted against the ploidy dataset from Robertson et al. (2011) and against ploidy data in the C-value DNA dataset from Bennett and Leitch (2005). By comparing three different sources of information, we were able to code  
120 taxa as diploid (D) or polyploid (P). For the majority of species, ploidy was assigned according to information from the original publications included in the C-value DNA dataset (Bennett and Leitch 2005). For taxa without ploidy information but with information about chromosome number, we assigned ploidy based on the multiplicity of chromosomes within the genus or based on SI/SC classification. For example, if a species was incompatible without any chromosomal information it was assigned as diploid. This was the  
125 case of *Solanum betaceum* that did not include information about ploidy level but it has 24 chromosomes, since  $x = 12$  is the base chromosome number of the *Solanum* genus (Olmstead and Bohs 2007), we assigned *S. betaceum* as diploid. Species with more than one ploidy level were assigned the most frequent ploidy level recorded or the smallest ploidy in case of frequency ties. Breeding system was scored as self-incompatible (I) or self-compatible (C) based on results curated from the literature and original experimental crosses (as  
130 compiled in Igić et al. 2006; Goldberg et al. 2010; Robertson et al. 2011; Goldberg and Igić 2012). Many species could unambiguously be coded as either I or C (Raduski et al. 2012). But for diploids without breeding system information taxa was coded as both I or C. Following previous work, we coded as I any species with functional I systems, even if C or dioecy was also reported. Dioecious species without functional I were coded as C. To those existing data sets, we added some additional records for chromosome number  
135 and breeding system. The Supplementary Information contains citations for the numerous sources for the added data. Resolution of taxonomic synonymy followed the conventions provided in Solanaceae Source (PBI *Solanum* Project 2012). Hybrids and cultivars were excluded because ploidy and breeding system can be affected by artificial selection during domestication. Following the reasoning outlined in Robertson et al. (2011), we examined closely the few species for which the merged ploidy and breeding system data

indicated the presence of self-incompatible polyploids. Although I populations frequently contain some C individuals, and diploid populations frequently contain some polyploid individuals, in no case did we find a convincing case of a naturally occurring I and polyploid population. The single instance of an I and polyploid individual appears to be an allopolyploid hybrid of *Solanum oplocense* Hawkes x *Solanum gourlayii* Hawkes, reported by Camadro and Peloquin 1981. Under exceedingly rare circumstances, it is possible for polyploids containing multiple copies of S-loci to remain I, so long as they express a single allele at the S-locus (discussed in Robertson et al. 2011). Because of the resulting absence of I and polyploid populations, as well as the linked functional explanation for disabling of gametophytic self-incompatibility systems with non-self recognition, following whole genome duplication (reviewed in Ramsey and Schemske 1998; Stone 2002), we consider only three observed character states: self-incompatible diploids (ID), self-compatible diploids (CD), and polyploids which are always self-compatible (CP).

Matching our character state data to the largest time-calibrated phylogeny of Solanaceae (Särkinen et al. 2013) yielded 595 species with ploidy and/or breeding system information on the tree. Binary or three-state classification of ploidy and breeding system for the 595 taxa is summarized in Fig. 1. We retained all of these species in each of the analyses below because pruning away tips lacking breeding system in the ploidy-only analyses (and vice versa) would discard data that could inform the diversification models. A total of 405 taxa without any information about breeding system or polyploidy were excluded. Including this many more species would have prohibitively slowed our analyses, especially those implementing the most complex models.

### ***Models for ploidy and diversification***

In order to investigate the association between ploidy level and diversification, we first defined a binary state speciation and extinction model (BiSSE, Maddison et al. 2007) in which taxa were classified as diploid (D) or polyploid (P) (Fig. 1). We call this the *D/P ploidy* model. This model is identical to the model proposed by Mayrose et al. (2011, 2015), but inferences were performed in a Bayesian framework. We calculated the posterior probability distributions of speciation rates ( $\lambda_D$ ,  $\lambda_P$ ), extinction rates ( $\mu_D$ ,  $\mu_P$ ), net diversification rates ( $r_D = \lambda_D - \mu_D$ ,  $r_P = \lambda_P - \mu_P$ ), and relative extinction rates ( $v_D = \mu_D/\lambda_D$ ,  $v_P = \mu_P/\lambda_P$ ) associated with each state. Parameter  $\rho$  represents the transition rate from D to P.

Our second model addressed the diversification due to ploidy differences while also parsing out the heterogeneity of diversification rates due a possible unobserved trait. Diversification rate differences explained by some trait other than ploidy were accommodated by adding a hidden state (HiSSE model; Beaulieu and O'Meara 2016). In this model, each of the observed diploid and polyploid states were sub-

divided by a binary hidden trait with states  $A$  and  $B$ . This model was called the *D/P+A/B ploidy and hidden state* model. Posterior probability distributions of speciation rates ( $\lambda_{D_A}$ ,  $\lambda_{D_B}$ ,  $\lambda_{P_A}$ ,  $\lambda_{P_B}$ ), extinction rates ( $\mu_{D_A}$ ,  $\mu_{D_B}$ ,  $\mu_{P_A}$ ,  $\mu_{P_B}$ ), net diversification rates ( $r_{D_A}$ ,  $r_{D_B}$ ,  $r_{P_A}$ ,  $r_{P_B}$ ), and relative extinction rates ( $v_{D_A}$ ,  $v_{D_B}$ ,  $v_{P_A}$ ,  $v_{P_B}$ ) were estimated. In this model polyploidization rate is again represented by  $\rho$  and hidden state rates are symmetrical with parameter  $\alpha$ .

### ***Models for breeding system and diversification***

To assess the effects of breeding system in the diversification process, we first fit model in which the states are self-incompatible (I) or self-compatible (C). This is the same as the analysis of Goldberg et al. (2010), but with an updated phylogeny (Särkinen et al. 2013). We call this BiSSE model the *I/C breeding system* model. To parse out the effect of breeding system on diversification, while allowing for the possibility of heterogeneous diversification rates unrelated to breeding system, we subdivided each of those states into hidden states  $A$  and  $B$ . We call this HiSSE model the *I/C+A/B breeding system and hidden state model*. The I/C+A/B model is equivalent to the model Freyman and Höhna (2017) used to study diversification in Onagraceae, but we restricted the hidden state transition rates to be symmetrical.

Self-incompatibility is homologous in all species in which S-alleles are cloned, and controlled crosses are performed. All species sampled to date, possess a non-self recognition, RNase-based, gametophytic self-incompatibility (shared even with other euasterid families; Ramanauskas and Igić 2017). Furthermore, species that are distantly related within this family carry closely-related alleles, with deep trans-specific polymorphism, at the S-locus, which controls the SI response (Ioerger et al. 1990; Igić et al. 2006). This represents very strong evidence that the self-incompatible mechanism, and our  $I$  state is ancestral to the Solanaceae, and did not arise independently within the family. Therefore, for all breeding system models, we estimated a transition rate from  $I$  to  $C$  but not the reverse ( $q_{CI} = 0$ ).

### ***Models for ploidy, breeding system, and diversification***

Polyploidy and breeding system might have changed lineage diversification individually but these two traits also have complex interactions in Solanaceae species. Therefore, a multi-state model that investigates the contribution of both traits and the possible transitions between them was proposed. Self-incompatible diploids (ID), self-compatible diploids (CD), and polyploids, which are always self-compatible (CP) were used as input for a MuSSE model (FitzJohn 2012). We did not include a state for self-incompatible polyploids because they are not observed in the data, and that trait combination state is mechanistically predicted not to occur. The proposed model is called the *ID/CD/CP ploidy and breeding system* and has six parameters for diversification in each state: ( $\lambda_{ID}$ ,  $\lambda_{CD}$ ,  $\lambda_{CP}$  for speciation,  $\mu_{ID}$ ,  $\mu_{CD}$ ,  $\mu_{CP}$  for extinction), and three



for transitions between states ( $\rho_I$ ,  $\rho_C$  for polyploidization transitions from *ID* and *CD* to *CP*, respectively;  $q_{IC}$  for loss of self-incompatibility without polyploidization, from *ID* to *CD*). The total rate of loss of self-incompatibility, i.e., transitions out of *ID*, is  $q_{IC} + \rho_I$ . Diploidization from *CP* to *ID* is not allowed because  
 205 it would represent a simultaneous regain of SI.

The ID/CD/CP model could also suffer from a high type I error as the regular two state BiSSE model. A hidden factor might alter diversification beyond both ploidy and breeding system misleading inferences (Rabosky and Goldberg 2015). We therefore added a hidden trait layer on top of our three-state model (analogous to Caetano et al. 2018; Huang et al. 2018). We refer to this as the *ID/CD/CP+A/B*  
 210 model. A fully parameterized version of this model would have 26 rate parameters. Because our goal was to look for diversification rate differences associated with ploidy and breeding system rather than the specific effects of the hidden states, we fitted a simplified version with 15 parameters. The reduction in parameter space is achieved by fixing the rates for transitions among hidden states to be equal with rate  $\alpha$ , and fixing the transition rates between observed states to be independent of the hidden state (rates  
 215  $\rho_I$ ,  $\rho_C$ ,  $\delta$ ,  $q_{IC}$  as defined for the ID/CD/CP model). There are additionally twelve diversification rate parameters ( $\lambda_{ID_A}$ ,  $\lambda_{ID_B}$ ,  $\lambda_{CD_A}$ ,  $\lambda_{CD_B}$ ,  $\lambda_{CP_A}$ ,  $\lambda_{CP_B}$ ,  $\mu_{ID_A}$ ,  $\mu_{ID_B}$ ,  $\mu_{CD_A}$ ,  $\mu_{CD_B}$ ,  $\mu_{CP_A}$ ,  $\mu_{CP_B}$ ).

### ***Pathways to polyploidy***

Considering ploidy and breeding system together, there are two evolutionary pathways from SI diploid to SC polyploid (Brunet and Liston 2001; Robertson et al. 2011). In the one-step pathway, the CP state is  
 220 produced directly from the ID state when whole genome duplication disables SI. In the two-step pathway, the CD state is an intermediate: SI is first lost, and later the SC diploid undergoes polyploidization. We quantify the relative contribution of these pathways to polyploidy in two ways, each using the maximum a posteriori (MAP) estimates of rates from the IC/CD/CP model.

Both of our methods are based on a propagation matrix that describes flow from ID to CP, as in  
 225 Robertson et al. (2011). We insert an artificial division in the CP state, so that one substate contains the CP species that arrived via the one-step pathway and the other substate contains the CP species that arrived via the two-step pathway. We consider only unidirectional change along each step of the pathway in order to separate them into clear alternatives, and because in this family there is no support for regain of SI, and not strong support for diploidization. First, we consider only the rates of transitions between these states, placing  
 230 them in the propagation matrix  $Q$ . The matrix  $P = \exp(Qt)$  then provides the probabilities of changing from one state to any other state after time  $t$ . Closed-form solutions for the two pathway probabilities are provided in Robertson et al. (2011). Our results will differ from those of Robertson et al. (2011) because our transition

rate estimates come from a dated phylogeny and a model that allows for state-dependent diversification. Second, we consider not only transitions between states but also diversification within each state. State-dependent diversification can change the relative contributions of the two pathways. In particular, if the net diversification rate is small for CD, the two-step pathway will contribute relatively less. We therefore include the difference between speciation and extinction along the diagonal elements of the propagation matrix. As before, matrix exponentiation provides the relative chance of changing from one state to any other state after time  $t$ . In this case, however, these are not probabilities because diversification changes the number of lineages as time passes. We can still use their ratios to consider the relative contribution of each pathway, though, analogous to the normalized age structure in a growing population.

### ***Diploidization as an exploratory hypothesis***

For all four models that consider ploidy changes, we allowed diploidization by adding a parameter  $\delta$  connecting polyploidy state back to diploid or to self-compatible diploid in the mult-state models (denoted by  $+/delta$  in the models of Table 1). Previous modeling approaches (Mayrose et al. 2011) have argued against inferring diploidization rates when using ploidy data that comes from classifications based on chromosome number multiplicity or chromosome number change models like chromEvol (Mayrose et al. 2010; Glick and Mayrose 2014; Mayrose et al. 2015; Freyman and Höhna 2017). These types of classifications do not allow for a ploidy reversion. Where indicated, the classification of ploidy for the data used in our models was based on chromosome multiplicity at the genus level (data available at <https://www.github.com/roszenil/solploidy/datasets>). However, the majority of the ploidy classifications were adopted from original studies with alternative sources of information (e.g., geographic distribution, genus ploidy distribution) where ploidy was defined by authors that found evidence for it. Since it is not clear whether diploidization can be detected under alternative ploidy classifications or even classifications based on chromosome number multiplicity at the genus level, we also fit the models without diploidization in order to test whether the conclusions about diversification are sensitive to including diploidization. As discussed by Servedio et al. (2014), the presence or absence of a hypothesis can have an exploratory goal. In our case the diploidization parameter (or its absence,  $\delta = 0$ ) in our models is an opportunity to explore an assumption that might be important but that is not the single definitive process to understand the interactions among polyploidy, breeding system, and diversification.

### ***Statistical inference under the models***

Parameters for each of the 10 diversification models were estimated using RevBayes (Höhna et al. 2016). Code for analyses and key results are available at <https://github.com/roszenil/solploidy>. We ac-

counted for incomplete sampling in all analyses by fixing the probability of sampling a species at the present  
 265  $s$  to 595/3000 since the Solanaceae family has approximately 3,000 species as estimated by the Solanaceae  
 Source project (PBI *Solanum* Project 2012). For all 10 models, we assumed that speciation and extinc-  
 tion parameters had log-normal prior distributions with means equal to the expected net diversification rate  
 (number of taxa/[2  $\times$  root age]) and standard deviation 0.5. Priors for parameters defining trait changes  
 were assumed to be gamma distributed with parameters  $k = 0.5$  and  $\theta = 1$ . For each model, a Markov chain  
 270 Monte Carlo (MCMC; Metropolis et al. 1953; Hastings 1970) was run for 96 hours in the high-performance  
 computational cluster at the Minnesota Supercomputing Institute, which allowed for 5,000 generations of  
 burn-in and a minimum of 200,000 generations of MCMC for each of the 10 models. Convergence and  
 mixing of each MCMC was determined by ensuring the effective sample size of each parameter was over  
 200.

275 For each model, ancestral states at each node in the phylogeny were sampled jointly during the  
 MCMC analyses. Ancestral state reconstructions for all models can be found in the supplementary informa-  
 tion and show the maximum a posteriori of the marginal probability distributions for each of the 594 internal  
 nodes for each of the 10 models.

### ***Model selection***

280 We calculated the marginal likelihood for each of the 10 models in RevBayes (Höhna et al. 2016). Marginal  
 likelihoods were calculated using 50 stepping stone steps under the methodology of Xie et al. (2010). Each  
 stepping stone step was found by calculating 500 generations of burn-in followed by a total of 1,000 MCMC  
 steps (Table 1). The calculation of each marginal likelihood ran for 24 hours on a high-performance com-  
 putational cluster.

285 Using the marginal likelihood values, we calculated thirteen different Bayes factors. Six com-  
 pared the models of ploidy against one other (D/P and D/P+A/B, each with or without diploidization), one  
 compared the breeding system models (I/C and I/C+A/B), and six compared the models with both traits  
 (ID/CD/CP and ID/CD/CP+A/B, each with or without diploidization) (Table 2). Other comparisons be-  
 tween these models are not valid because the input data are different under the different state space codings  
 290 (Fig. 1). In mathematical terms, the D/P, I/C, and ID/CD/CP state spaces are not ‘lumpable’ with respect to  
 one another (Tarasov 2018). Each model comparison is reported with a Bayes factor on the natural log scale:  
 the comparison between models  $M_0$  and  $M_1$  is  $BF(M_0, M_1) = \ln[P(\mathbf{X}|M_0) - P(\mathbf{X}|M_1)]$ . There is ‘positive’  
 support for  $M_0$  when this value is more than 2, ‘strong’ support when it is more than 6, and ‘very strong’  
 support when it is more than 10 (Kass and Raftery 1995).

*Traits and diversification*

Individual trait-dependent diversification inference, of ploidy and breeding system considered separately, each showed significant associations with net diversification differences. When considered together, however, the effect of breeding system dominated the effect of ploidy, although hidden factors played an important role as well.

When considering ploidy alone (D/P model), we found a greater net diversification rate for diploids than for polyploids, in agreement with (Mayrose et al. 2011, 2015). This result holds with (Fig. 2A) or without (Fig. 3A) the diploidization parameter, though including diploidization shifts the net diversification rate of polyploids to be non-negative. Incorporating a hidden state, however, removes the clear separation in diversification between diploids and polyploids (D/P+A/B model; Fig. 2B, Fig. 3B). Thus, differences in net diversification are better explained by an unknown factor than by ploidy. Statistical model comparisons show very strong support for including the hidden state and strong support for including diploidization (Table 2).

When considering breeding system alone (I/C model, Fig. 2C), we found a larger net diversification rate for SI than for SC species, in agreement with Goldberg et al. (2010). When a hidden state is included (I/C+A/B model), the large net diversification difference persists for one of the hidden states but is removed for the other (Fig. 2D). Thus, differences in net diversification are best explained by both breeding system and an unknown factor, similar to results found by Freyman and Höhna (2018). The statistical model comparison shows very strong support for including the hidden state (Table 2).

When considering ploidy and breeding system together (ID/CD/CP model), the net diversification rate for SI diploids was greater than for either SC diploids or SC polyploids, with or without diploidization (Fig. 2E, Fig. 3C). It thus appears that the difference in net diversification with breeding system persists when ploidy is included in the model, but not the reverse. The association of ploidy with net diversification in the D/P model (Fig. 2A, Fig. 3A) appears to be driven by the subset of diploids that are SI; among SC species, net diversification rates for diploids and polyploids are similar. When a hidden state is included (IC/CD/CP+A/B model), the same general pattern remains when diploidization is prevented (Fig. 3D), although the higher net diversification rate of ID is less clear within one of the hidden states. With diploidization, the net diversification rate of ID is still greater than CD within each hidden state, but diversification for P is highly uncertain and perhaps bimodal. Statistical model comparisons show very strong support for including the hidden state and at most positive support for including diploidization (Table 2).

### ***Pathways to polyploidy***

Evolution from self-incompatible diploids to self-compatible polyploids can proceed through two different pathways. Determining the relative contribution of these pathways based on our estimated transition rates from the ID/CD/CP model, we find that the one-step pathway is more likely on short timescales and the two-step pathway is more likely on long timescales (Fig. 4, left panels). When not much time has elapsed, the one-step pathway is more likely because only one event need happen. When more time has elapsed, the two-step pathway is more likely because the rate of loss of SI within diploids,  $q_{IC}$ , is greater than the rate of polyploidization for SI species,  $\rho_I$  (Fig. S7). These conclusions are the same as those of Robertson et al. (2011) under one of their branch length approximations.

When rates of lineage diversification are considered, however, the conclusions change. Even over long timescales, the two-step pathway contributes less (Fig. 4, right panels). The lower rate of net diversification in the CD state, relative to ID, means that relatively fewer lineages are available to complete the second step of the two-step pathway.

### ***Diploidization as an exploratory hypothesis***

We considered models both with or without diploidization in order to explore the effects of this process on the estimates of state-dependent diversification. For the two models that only include diploid and polyploid states (D/P and D/P+A/B), the net diversification rate of polyploid lineages is likely negative when diploidization (parameter  $\delta$ ) is excluded but positive when  $\delta$  is included (Fig. 2A versus Fig. 3A). For the two models that also included breeding system (ID/CD/CP and ID/CD/CP+A/B), the main effect of including diploidization is increasing the uncertainty of the estimate of polyploid net diversification rate (Fig. 2EF versus Fig. 3CD). For all models, there is greater uncertainty in the estimate of diploidization rate than polyploidization rate, as judged by the width of the credibility intervals (see supplementary information figures).

## **Discussion**

The present work shows the importance of considering the trait linked diversification patterns under a multivariate approach. Species are created and go extinct based on multiple and often highly correlated phenotypes, understanding the speciation and extinction processes requires understanding of the evolutionary consequences that those trait correlations produce in organisms. In the present work we show how considering both polyploidy and breeding system can disentangle the importance (or the lack of) of polyploidy when confronted with the evidence brought by breeding system.

Using the most complete dataset for polyploidy in a phylogenetic tree in Solanaceae, we were able to replicate the results found by Mayrose et al. (2011), polyploids have a slower net diversification compared to diploids. Furthermore, we also found polyploids had a high probability of having negative diversification which implies that polyploids can become a macroevolutionary dead-end, a result that was also found in the two large angiosperm diversification studies Mayrose et al. (2011) and Mayrose et al. (2015). However, we expanded this study to accommodate background heterogeneity in the diversification process. When adding heterogeneity we found that it was more likely that an unobserved trait linked to diploid state was the one leading the net diversification patterns, and that there were some “second-class” diploids that were not different from polyploids in diversification terms (Figure 2A). This result led us to our central question: *what is that other trait linked diploids that makes them different in the diversification process?*

In Solanaceae, our immediate intuition was to look into breeding system. Previous studies shown that self-incompatible Solanaceae species have also higher rates of diversification compared to their self-compatible counterparts (Goldberg and Igić 2012). Self-incompatible species are diploid in our sample and also expected to be diploid due to ... (citation?). By considering both polyploidy and breeding system simultaneously for every species in our sample, it was possible to disentangle why some diploids were quantitatively different than polyploids. In the three-state diversification model ID/CD/CP, we found that self-incompatible diploids have faster and positive rates than self-compatible diploids and polyploids, and that the difference between the rates of net diversification of self-compatible diploids is not as large (Figures 2C) as first found by binary trait diversification models (Figures 2A). This result is important, since it aligns with the net diversification results of the D/P+A/B model, where a ‘hidden-trait’ seem to be dictating the diversification pattern. By adding breeding system, we were able to hint at which that hidden-trait possibly is. Therefore, we consider that finding a heterogeneous result in the hidden trait approaches should be treated as evidence of a second trait that is necessary to consider. Pursuing knowledge of such trait can result on a clearer picture of the importance of trait linked diversification patterns, but also on a better reconstruction on past events in phylogenies.

Our work shows that a diploid Solanaceae lineage is much more likely to take a one-step ID/CP pathway to polyploidy rather than a two-step ID/CD/CP pathway. We modeled both of these pathways as anagenetic character changes occurring within a species. However Goldberg and Igić (2012) showed that I/C transitions are often associated with speciation events, and similarly Freyman and Höhna (2017) demonstrated that D/P transitions may also be associated with speciation events. Models that fail to consider transitions that occur at speciation (cladogenetic changes) may make misleading estimates of anagenetic transition rates. The HiSSE-based models introduced in our work here could be extended to incorporate

cladogenetic transitions. It is possible that allowing for cladogenetic transitions may enable the one-step pathway to even further dominate over the two-step pathway to polyploidy, but this remains to be tested in future work.

Diploidization needs to be considered in diversification models because higher rates of net diversification (speciation minus extinction) in diploids can be obtained from models that ignore the possibility of a polyploid lineage that has diploidized being the diversification enhancer. Hence, in a diploidization lacking model, diploids will show higher rates of diversification when in fact it is a polyploidy event and its subsequent diploidization that generated higher speciation and less extinction. By adding diploidization to models of polyploidy linked to diversification it is possible to recover this complicated scenario and to reconcile genomic evidence with stochastic models.

Diploidization is widely considered to be relatively rare, compared with polyploidization, but flowering plant lineages are thought to have experienced at least one round of polyploidization in their evolutionary history. As a consequence, it is possible that nearly all extant species classified as “diploid” in our analyses are possibly secondary diploids, having undergone both polyploidization and re-diploidization. Genomic evidence indicates that such an event may have occurred prior to the origin of the family Solanaceae. Ku et al. (2000) and Blanc and Wolfe (2004) posited that the lineage leading to tomato, *Solanum lycopersicum*, may have experienced one or more paleopolyploid events. A subsequent analysis of synteny between grape and *Solanum* genomes, as well as the distribution between inferred paralogs within *Solanum* (tomato and potato) genomes both suggest that this lineage experienced a likely round of ancient genome duplication or triplication (Tomato Genome Consortium 2012). The age of the peak of paralog Ks distances, is approximately 71 million years (Tomato Genome Consortium 2012). If this is the case, then all of the genomes may have been subsequently re-diploidized, because common base chromosome numbers this and related families are  $n=11-12$ . On the other hand, studies comparing map-based genome synteny within the family find no evidence for recent polyploidization-diploidization (Wu and Tanksley 2010). Simple genome re-arrangements appear sufficient to explain chromosomal evolution between a number of species, including all of those in the relatively cytogenetically conserved ‘ $x=12$ ’ group, which includes tomato, potato, eggplant, pepper, and tobacco.

## Acknowledgements

NSF DEB-1655692 to BI, and DEB-1655478 to EEG. The Minnesota Supercomputing Institute (MSI) at the University of Minnesota provided computing resources for this project.

## Literature Cited

- Barrett, S. C., 2008. Major evolutionary transitions in flowering plant reproduction: an overview.
- 420 ———, 2013. The evolution of plant reproductive systems: how often are transitions irreversible? *Proceedings of the Royal Society B: Biological Sciences* 280:20130913.
- Barringer, B. C., 2007. Polyploidy and self-fertilization in flowering plants. *American Journal of Botany* 94:1527–1533.
- Beaulieu, J. M. and B. C. O’Meara, 2016. Detecting hidden diversification shifts in models of trait-dependent  
425 speciation and extinction. *Syst Biol* 65:583–601.
- Bennett, M. D. and I. J. Leitch, 2005. Plant DNA C-values database.
- Blanc, G. and K. H. Wolfe, 2004. Widespread paleopolyploidy in model plant species inferred from age distributions of duplicate genes. *The Plant Cell* 16:1667–1678.
- Brunet, J. and A. Liston, 2001. Technical comment on polyploidy and gender dimorphism. *Science*  
430 291:1441–1442.
- Caetano, D. S., B. C. O’Meara, and J. M. Beaulieu, 2018. Hidden state models improve state-dependent diversification approaches, including biogeographical models. *Evolution* 72:2308–2324.
- Camadro, E. and S. J. Peloquin, 1981. Cross-incompatibility between two sympatric polyploid *Solanum* species. *Theoretical and Applied Genetics* 60:65–70.
- 435 Dodsworth, S., M. W. Chase, and A. R. Leitch, 2015. Is post-polyploidization diploidization the key to the evolutionary success of angiosperms? *Botanical Journal of the Linnean Society* 180:1–5.
- Entani, T., S. Takayama, M. Iwano, H. Shiba, F.-S. Che, and A. Isogai, 1999. Relationship between polyploidy and pollen self-incompatibility phenotype in *Petunia hybrida* Vilm. *Bioscience, Biotechnology, and Agrochemistry* 63:1882–1888.
- 440 FitzJohn, R. G., 2012. Diversitree : comparative phylogenetic analyses of diversification in r. *Methods Ecol Evol* 3:1084–1092.
- FitzJohn, R. G., W. P. Maddison, and S. P. Otto, 2009. Estimating trait-dependent speciation and extinction rates from incompletely resolved phylogenies. *Systematic Biology* 58:595–611.
- Freyman, W. and S. Höhna, 2018. Stochastic character mapping of state-dependent diversification reveals  
445 the tempo of evolutionary decline in self-compatible Onagraceae lineages. *Systematic Biology* syy078.
- Freyman, W. A. and S. Höhna, 2017. Cladogenetic and anagenetic models of chromosome number evolution: A Bayesian model averaging approach. *Systematic Biology* 67:195–215.
- Glick, L. and I. Mayrose, 2014. Chromevol: assessing the pattern of chromosome number evolution and the inference of polyploidy along a phylogeny. *Molecular Biology and Evolution* 31:1914–1922.
- 450 Goldberg, E. E. and B. Igić, 2012. Tempo and mode in plant breeding system evolution. *Evolution* 66:3701–3709.
- Goldberg, E. E., J. R. Kohn, R. Lande, K. A. Robertson, S. A. Smith, and B. Igić, 2010. Species selection maintains self-incompatibility. *Science* 330:493–495.
- Hastings, W. K., 1970. Monte carlo sampling methods using markov chains and their applications.  
455 *Biometrika* 57:97–109.
- Herrera-Alsina, L., P. van Els, and R. S. Etienne, 2018. Detecting the dependence of diversification on multiple traits from phylogenetic trees and trait data. *Systematic biology* .
- Höhna, S., M. J. Landis, T. A. Heath, B. Boussau, N. Lartillot, B. R. Moore, J. P. Huelsenbeck, and F. Ronquist, 2016. Revbayes: Bayesian phylogenetic inference using graphical models and an interactive model-specification language. *Systematic Biology* 65:726–736.  
460
- Huang, D., E. E. Goldberg, L. Chou, and K. Roy, 2018. The origin and evolution of coral species richness in a marine biodiversity hotspot. *Evolution* 72:288–302.
- Husband, B. C., S. J. Baldwin, and J. Suda, 2013. The incidence of polyploidy in natural plant populations:



major patterns and evolutionary processes. Pp. 255–276, in *Plant Genome Diversity Volume 2*. Springer.

465 Husband, B. C., B. Ozimec, S. L. Martin, and L. Pollock, 2008. Mating consequences of polyploid evolution in flowering plants: Current trends and insights from synthetic polyploids. *International Journal of Plant Sciences* 169:195–206.

Igić, B., L. Bohs, and J. R. Kohn, 2006. Ancient polymorphism reveals unidirectional breeding system shifts. *Proc Natl Acad Sci USA* 103:1359–1363.

470 Igić, B., R. Lande, and J. R. Kohn, 2008. Loss of self-incompatibility and its evolutionary consequences. *International Journal of Plant Sciences* 169:93–104.

Ioerger, T. R., A. G. Clark, and T. H. Kao, 1990. Polymorphism at the self-incompatibility locus in *Solanaceae* predates speciation. *Proceedings of the National Academy of Sciences USA* 87:9732–9735.

Kass, R. E. and A. E. Raftery, 1995. Bayes factors. *Journal of the American Statistical Association* 90:773–795.

475 Ku, H. M., T. Vision, J. Liu, and S. D. Tanksley, 2000. Comparing sequenced segments of the tomato and *Arabidopsis* genomes: large-scale duplication followed by selective gene loss creates a network of synteny. *Proceedings of the National Academy of Science, USA* 97:9121–9126.

480 Kubo, K.-i., T. Entani, A. Takara, N. Wang, A. M. Fields, Z. Hua, M. Toyoda, S.-i. Kawashima, T. Ando, A. Isogai, et al., 2010. Collaborative non-self recognition system in s-rnase-based self-incompatibility. *Science* 330:796–799.

Landis, J. B., D. E. Soltis, Z. Li, H. E. Marx, M. S. Barker, D. C. Tank, and P. S. Soltis, 2018. Impact of whole-genome duplication events on diversification rates in angiosperms. *American Journal of Botany* 105:348–363.

485 Lewis, D., 1947. Competition and dominance of incompatibility alleles in diploid pollen. *Heredity* 1:85–108.

Maddison, W. P. and R. G. FitzJohn, 2015. The unsolved challenge to phylogenetic correlation tests for categorical characters. *Systematic Biology* 64:127–136.

Maddison, W. P., P. E. Midford, and S. P. Otto, 2007. Estimating a binary character’s effect on speciation and extinction. *Syst Biol* 56:701–710.

490 Mayrose, I., M. S. Barker, and S. P. Otto, 2010. Probabilistic models of chromosome number evolution and the inference of polyploidy. *Systematic Biology* 59:132–144.

Mayrose, I., S. H. Zhan, C. J. Rothfels, N. Arrigo, M. S. Barker, L. H. Rieseberg, and S. P. Otto, 2015. Methods for studying polyploid diversification and the dead end hypothesis: a reply to soltis et al. (2014). *New Phytol* 206:27–35.

495 Mayrose, I., S. H. Zhan, C. J. Rothfels, K. Magnuson-Ford, M. S. Barker, L. H. Rieseberg, and S. P. Otto, 2011. Recently formed polyploid plants diversify at lower rates. *Science* 333:1257.

Metropolis, N., A. W. Rosenbluth, M. N. Rosenbluth, A. H. Teller, and E. Teller, 1953. Equation of state calculations by fast computing machines. *The Journal of Chemical Physics* 21:1087–1092.

500 Moore, B. R., S. Höhna, M. R. May, B. Rannala, and J. P. Huelsenbeck, 2016. Critically evaluating the theory and performance of bayesian analysis of macroevolutionary mixtures. *Proceedings of the National Academy of Sciences* 113:9569–9574.

Olmstead, R. G. and L. Bohs, 2007. A summary of molecular systematic research in *Solanaceae*: 1982–2006. *Acta Horticulturae* Pp. 255–268.

505 PBI *Solanum* Project, 2012. *Solanaceae Source*: a global taxonomic resource for the nightshade family.

Rabosky, D. L. and E. E. Goldberg, 2015. Model inadequacy and mistaken inferences of trait-dependent speciation. *Systematic Biology* 64:340–355.

———, 2017. Fisse: A simple nonparametric test for the effects of a binary character on lineage diversification rates. *Evolution* 71:1432–1442.

- Raduski, A. R., E. B. Haney, and B. Igić, 2012. The expression of self-incompatibility in angiosperms is bimodal. *Evolution* 66:1275–1283.
- Ramanauskas, K. and B. Igić, 2017. The evolutionary history of plant t2/s-type ribonucleases. *PeerJ* 5:e3790.
- Ramsey, J. and D. W. Schemske, 1998. Pathways, mechanisms, and rates of polyploid formation in flowering plants. *Annual Review of Ecology and Systematics* 29:467–501.
- , 2002. Neopolyploidy in flowering plants. *Annual review of ecology and systematics* 33:589–639.
- Rice, A., L. Glick, S. Abadi, M. Einhorn, N. M. Kopelman, A. Salman-Minkov, J. Mayzel, O. Chay, and I. Mayrose, 2015. The chromosome counts database (CCDB) - a community resource of plant chromosome numbers. *New Phytol* 206:19–26.
- Rivero, R., E. B. Sessa, and R. Zenil-Ferguson, 2019. Eyechrom and ccdb curator: Visualizing chromosome count data from plants. *Applications in Plant Sciences* P. e01207.
- Robertson, K., E. E. Goldberg, and B. Igić, 2011. Comparative evidence for the correlated evolution of polyploidy and self-compatibility in solanaceae. *Evolution* 65:139–155.
- Särkinen, T., L. Bohs, R. G. Olmstead, and S. Knapp, 2013. A phylogenetic framework for evolutionary study of the nightshades (Solanaceae): a dated 1000-tip tree. *BMC Evol Biol* 13:214.
- Servedio, M. R., Y. Brandvain, S. Dhole, C. L. Fitzpatrick, E. E. Goldberg, C. A. Stern, J. Van Cleve, and D. J. Yeh, 2014. Not just a theory? the utility of mathematical models in evolutionary biology. *PLoS biology* 12:e1002017.
- Sessa, E. B., 2019. Polyploidy as a mechanism for surviving global change. *New Phytologist* 221:5–6.
- Soltis, D. E., M. C. Segovia-Salcedo, I. Jordon-Thaden, L. Majure, N. M. Miles, E. V. Mavrodiev, W. Mei, M. B. Cortez, P. S. Soltis, and M. A. Gitzendanner, 2014. Are polyploids really evolutionary dead-ends (again)? a critical reappraisal of mayrose et al.(2011). *New Phytologist* 202:1105–1117.
- Soltis, P. S., D. B. Marchant, Y. Van de Peer, and D. E. Soltis, 2015. Polyploidy and genome evolution in plants. *Current opinion in genetics & development* 35:119–125.
- Stebbins, G. L., 1938. Cytological characteristics associated with the different growth habits in the dicotyledons. *American Journal of Botany* 25:189–198.
- , 1950. *Variation and Evolution in Plants*. Columbia University Press, New York.
- , 1974. *Flowering plants: evolution above the species level*. Belknap Press of Harvard University Press, Cambridge, Mass.
- Stone, J. L., 2002. Molecular mechanisms underlying the breakdown of gametophytic self-incompatibility. *The Quarterly Review of Biology* 77:17–30.
- Stout, A. B. and C. Chandler, 1942. Hereditary transmission of induced tetraploidy and compatibility in fertilization. *Science* 96:257–258.
- Tarasov, S., 2018. Integration of anatomy ontologies and evo-devo using structured markov models suggests a new framework for modeling discrete phenotypic traits. *BioRxiv* P. 188672.
- Tomato Genome Consortium, 2012. The tomato genome sequence provides insights into fleshy fruit evolution. *Nature* 485:635.
- Tsukamoto, T., T. Ando, H. Watanabe, E. Marchesi, and T.-h. Kao, 2005. Duplication of the s-locus f-box gene is associated with breakdown of pollen function in an s-haplotype identified in a natural population of self-incompatible petunia axillaris. *Plant Molecular Biology* 57:141–153.
- de Vos, J. M., C. E. Hughes, G. M. Schneeweiss, B. R. Moore, and E. Conti, 2014. Heterostyly accelerates diversification via reduced extinction in primroses. *Proceedings of the Royal Society B: Biological Sciences* 281:20140075.
- Wu, F. and S. D. Tanksley, 2010. Chromosomal evolution in the plant family solanaceae. *BMC Genomics* 11:182.

- Xie, W., P. O. Lewis, Y. Fan, L. Kuo, and M.-H. Chen, 2010. Improving marginal likelihood estimation for bayesian phylogenetic model selection. *Systematic biology* 60:150–160.
- Zenil-Ferguson, R., J. M. Ponciano, and J. G. Burleigh, 2017. Testing the association of phenotypes with polyploidy: An example using herbaceous and woody eudicots. *Evolution* 71:1138–1148.

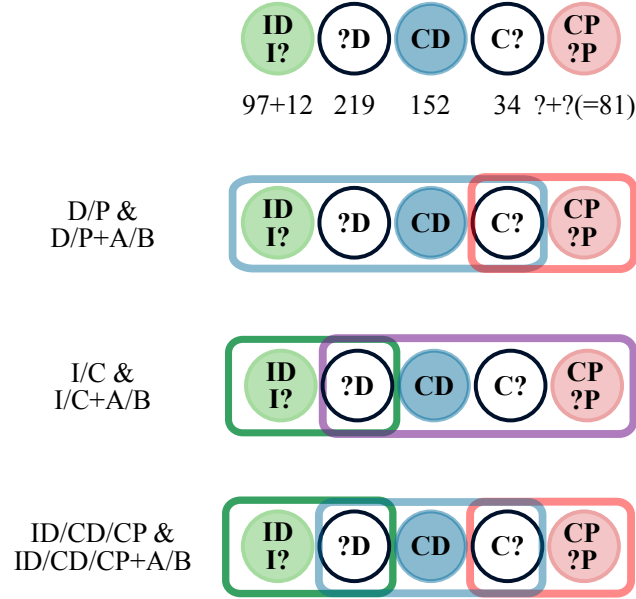


Figure 1: Character states used for each of the models. Each species retained on the tree belonged to one of five possible categories, depending on whether ploidy and/or breeding system were known. The number of species in each is shown under the corresponding circles in the top row. These categories were then grouped in a manner appropriate to the states of each model. For example, there are 34 species that are self-compatible and of unknown ploidy; these are coded as either *D* or *P* in the D/P models (uncertain, or consistent with either state), as *C* in the I/C models, and as either *CD* or *CP* in the ID/CD/CP models. In all cases, species were coded as either *A* or *B* in the hidden state models. The models depicted in the different rows use state spaces that are not comparable with one another. For example, we cannot test whether the D/P model fits better than the I/C model because they use states that are not the same and are not ‘lumpable’ (Tarasov 2018).

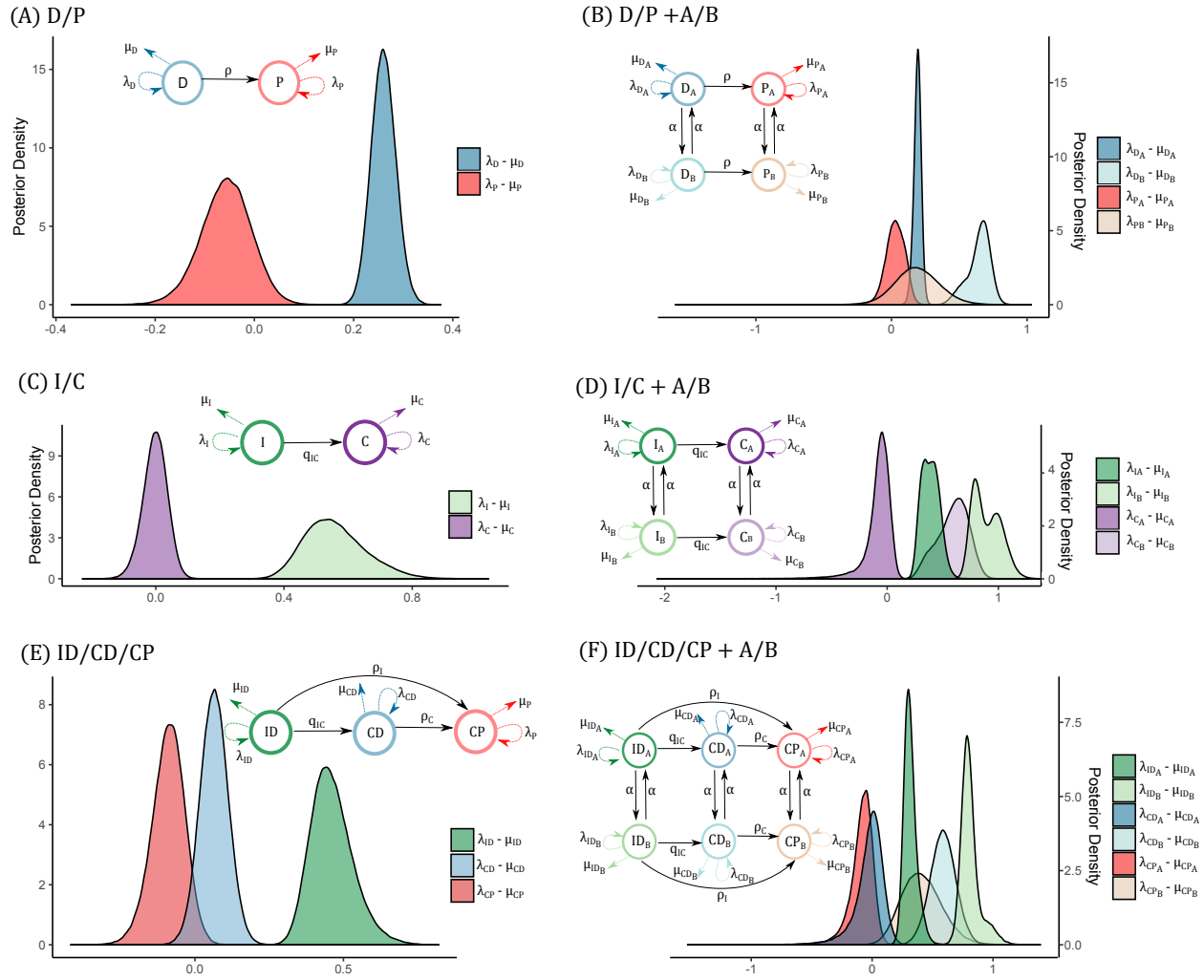


Figure 2: Net diversification rates for all models.

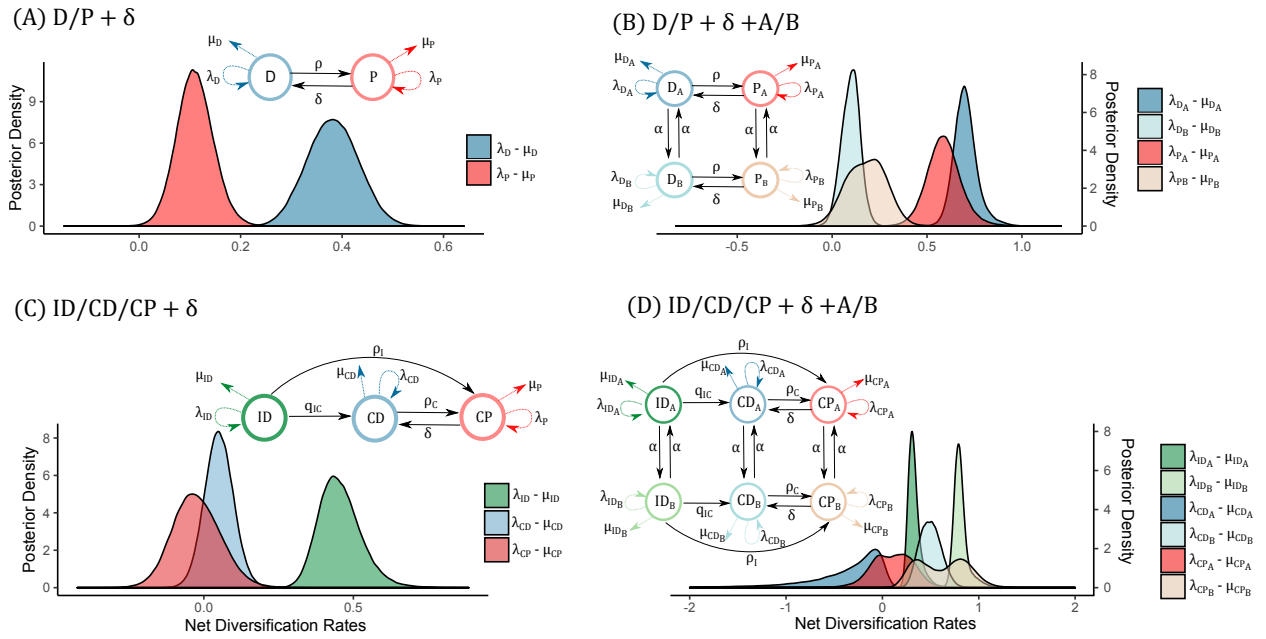


Figure 3: Net diversification rates for all models that include diploidization.

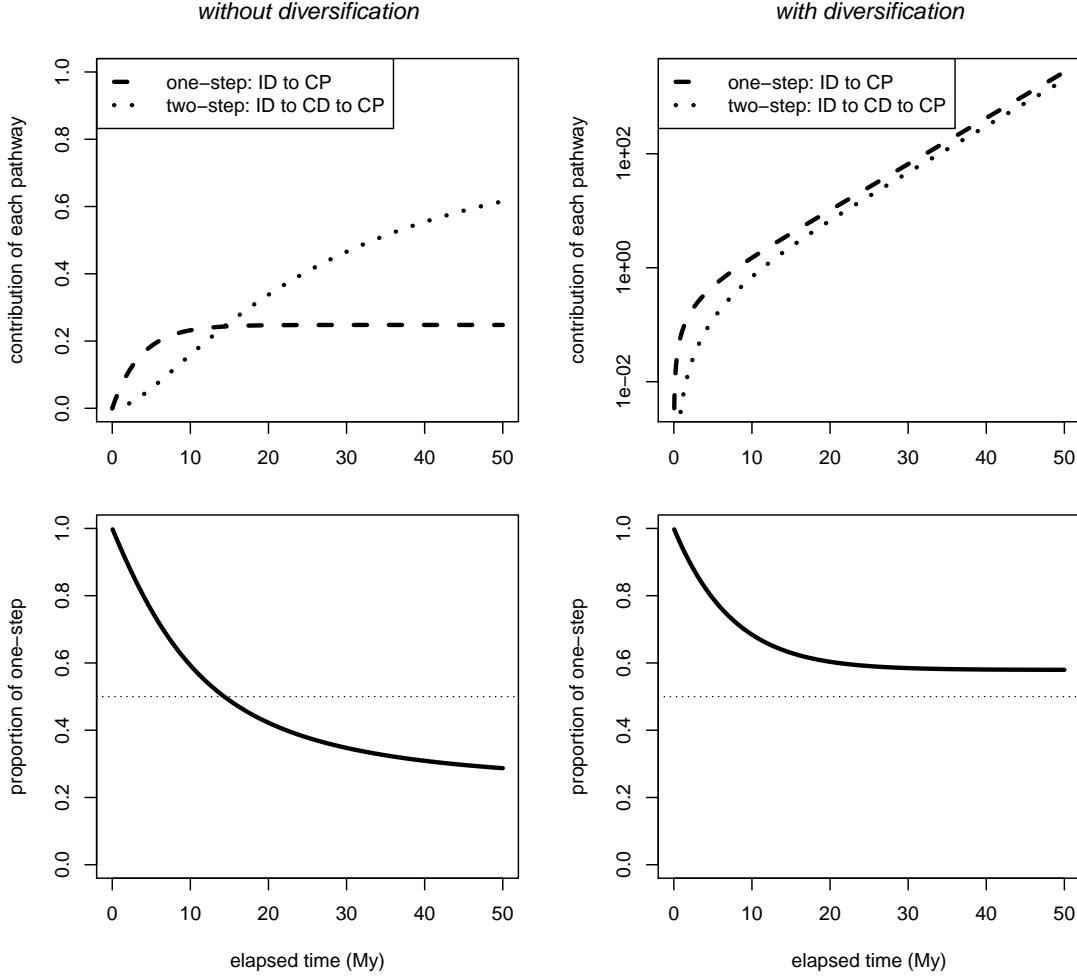


Figure 4: Contributions of the two pathways to polyploidy. The one-step pathway is direct ID→CP transitions. The two-step pathway consists of ID→CD→CP transitions. When considering only rates of transitions among the states (ignoring the diversification rate parameters), the one-step pathway dominates on short timescales and the two-step on long timescales (left panels). When also considering diversification within each state, the one-step pathway, in which polyploidization breaks down SI, dominates over any timescale (right panels). The top panels show the separate contributions of each pathway. The bottom panels show the proportional contribution of the one-step pathway (i.e., one-step / [one-step + two-step]).

Model	Ploidy	Diploidization	Breeding System	Hidden State	Num Parameters	Marginal Log-Likelihood
1. D/P	Yes	No	No	No	5	-1193.66
2. D/P + $\delta$	Yes	Yes	No	No	6	-1182.93
3. D/P+A/B	Yes	No	No	Yes	10	-1150.99
4. D/P+ $\delta$ +A/B	Yes	Yes	No	Yes	11	<b>-1145.69</b>
5. I/C	No	No	Yes	No	5	-1194.80
6. I/C+A/B	No	No	Yes	Yes	10	<b>-1155.37</b>
7. ID/CD/CP	Yes	No	Yes	No	9	-1345.87
8. ID/CD/CP + $\delta$	Yes	Yes	Yes	No	10	-1344.50
9. ID/CD/CP+A/B	Yes	No	Yes	Yes	15	-1303.55
10. ID/CD/CP+ $\delta$ +A/B	Yes	Yes	Yes	Yes	16	<b>-1300.35</b>

Table 1: The ten models and their marginal likelihoods. Values in bold are for the best models within each class that are comparable (see Table 2). Abbreviations are D: diploid, P: polyploid, I: self-incompatible, C: self-compatible, A: one state of hidden trait, B: other state of hidden trait,  $\delta$ : diploidization.



Ploidy Models					Breeding System Models		Ploidy and Breeding System Models					
	1	2	3	4		5	6		7	8	9	10
1. D/P	·	10.72	-37.24	-31.94	5. I/C	·	-39.43	7. ID/CD/CP	·	1.36	-44.15	-40.95
2. D/P no $\delta$	·	·	-47.97	-42.66	<b>6. I/C+A/B</b>	·	·	8. ID/CD/CP no $\delta$	·	·	-45.51	-42.31
<b>3. D/P+A/B</b>	·	·	·	5.30				<b>9. ID/CD/CP+A/B</b>	·	·	·	3.2
4. D/P+A/B no $\delta$	·	·	·	·				10. ID/P/CD no $\delta$ -A/B	·	·	·	·

Table 2: Bayes factors for model comparisons. Each of the three boxes contains models that can be compared with one another, based on the character states they include (see Fig. 1). Models are numbered in as Table 1. Bayes factors are reported on the natural log scale, so numbers greater than +2 mean that the model in the row label has ‘positive’ support relative to the model in the column label; numbers less than −2 mean that model in the column label is the preferred one. Conventional thresholds for ‘strong’ and ‘very strong’ support are 6 and 10, respectively. The best model in each set is written in bold. In each case, it is the most complex model of the set.

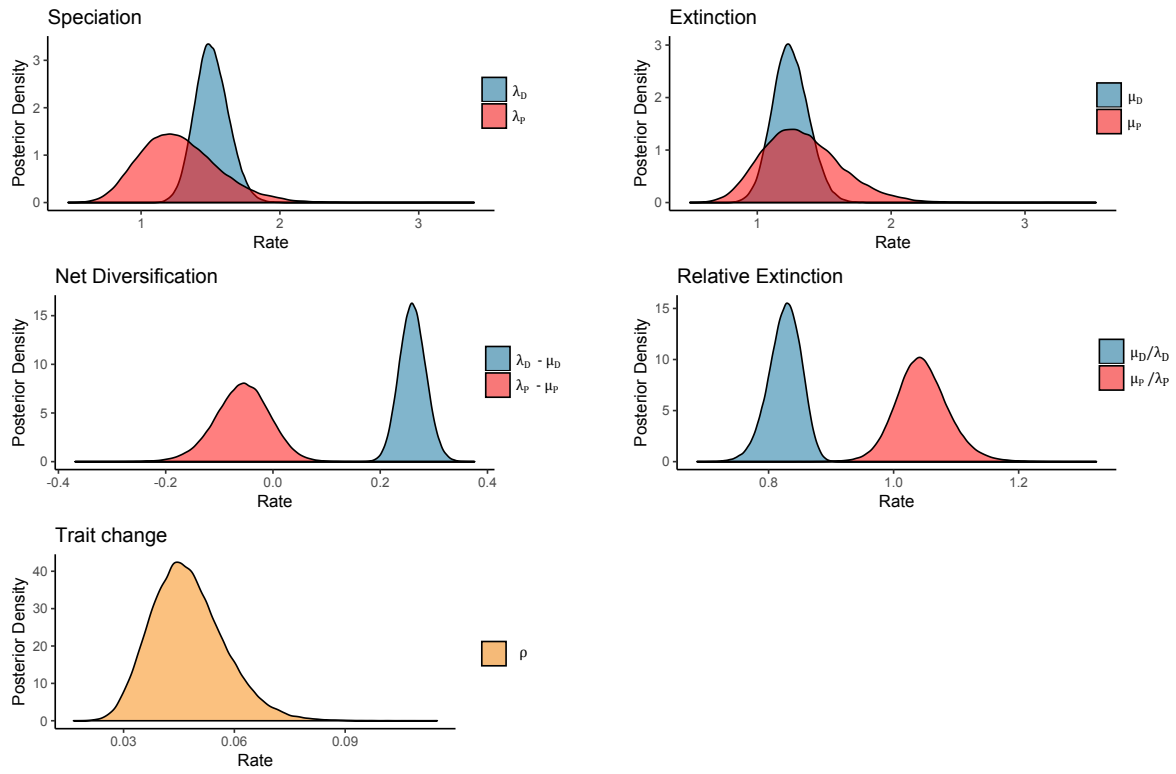


Figure S1: Posterior distribution for each of the parameters in the D/P, polyploidy model

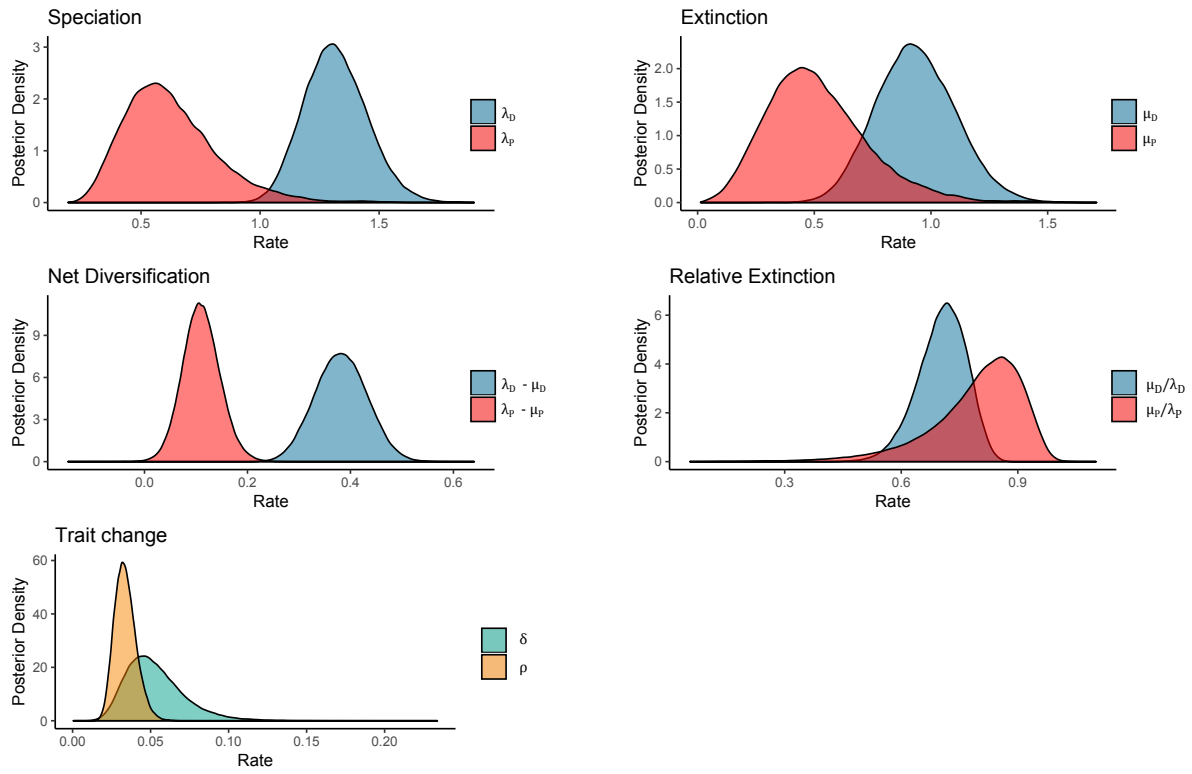


Figure S2: Posterior distribution for each of the parameters in the D/P+  $\delta$ ,polyploidy model

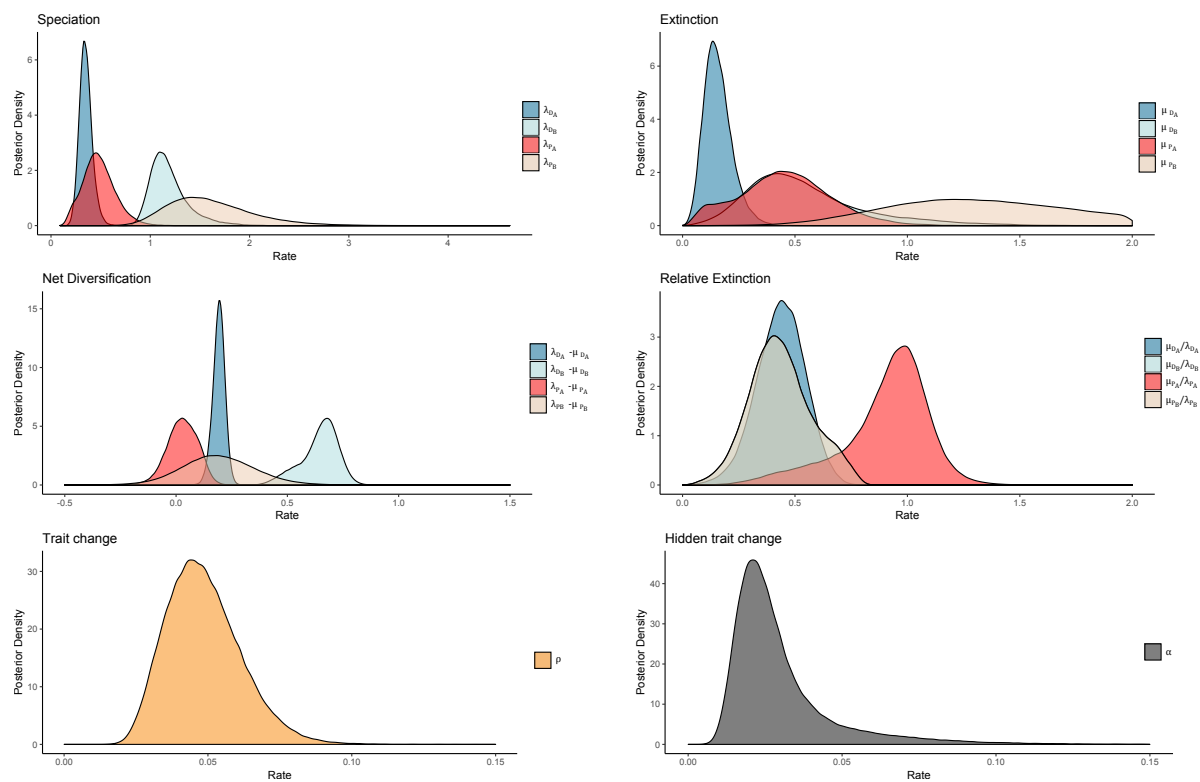


Figure S3: Posterior distribution for each of the parameters in the D/P+A/B, polyploidy model

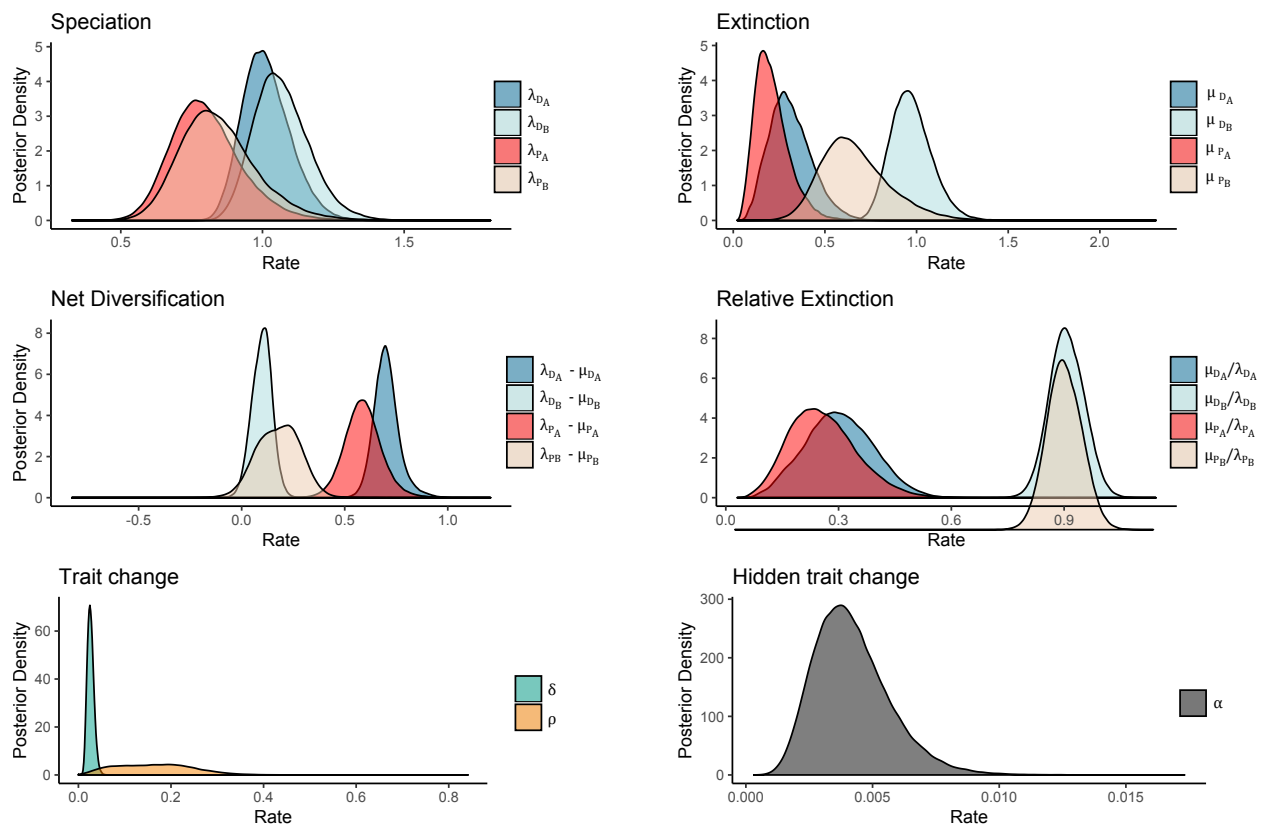


Figure S4: Posterior distribution for each of the parameters in the D/P+ $\delta$ +A/B, polyploidy model. The axis is offset in one location so that the two overlapping distributions can be seen.

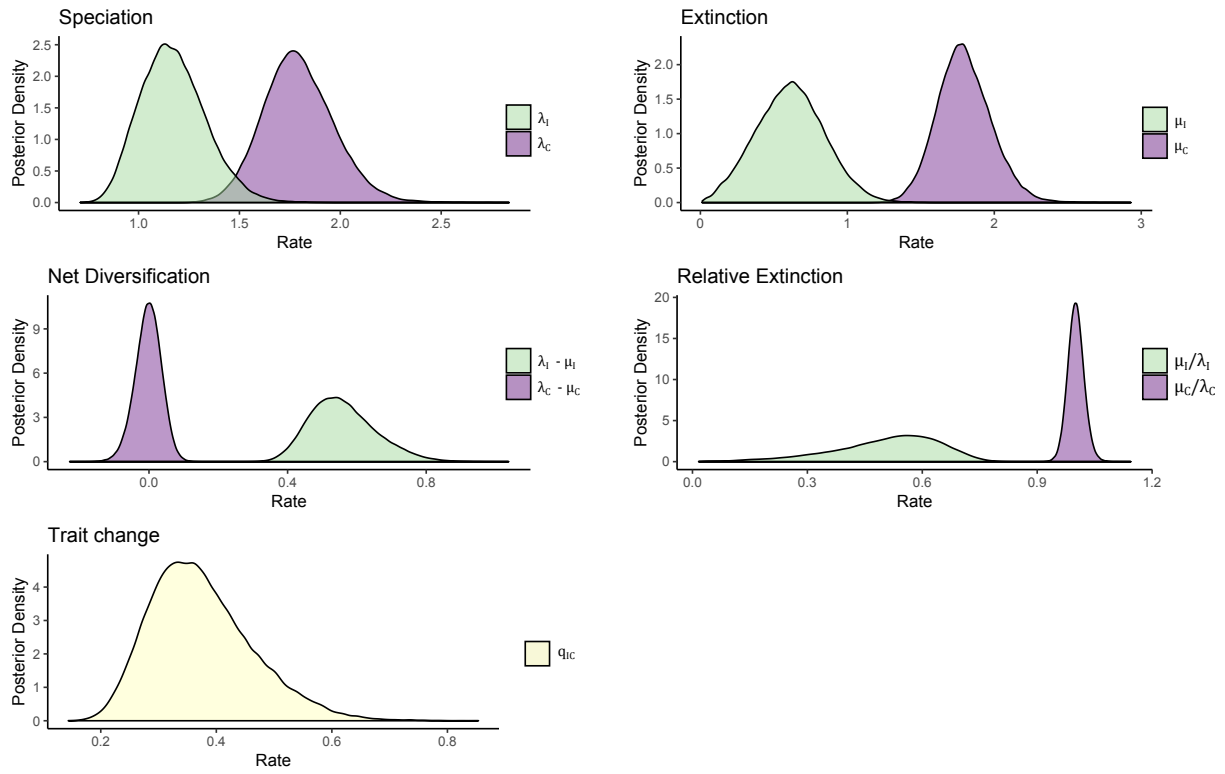


Figure S5: Posterior distribution for each of the parameters in the I/C, breeding system model

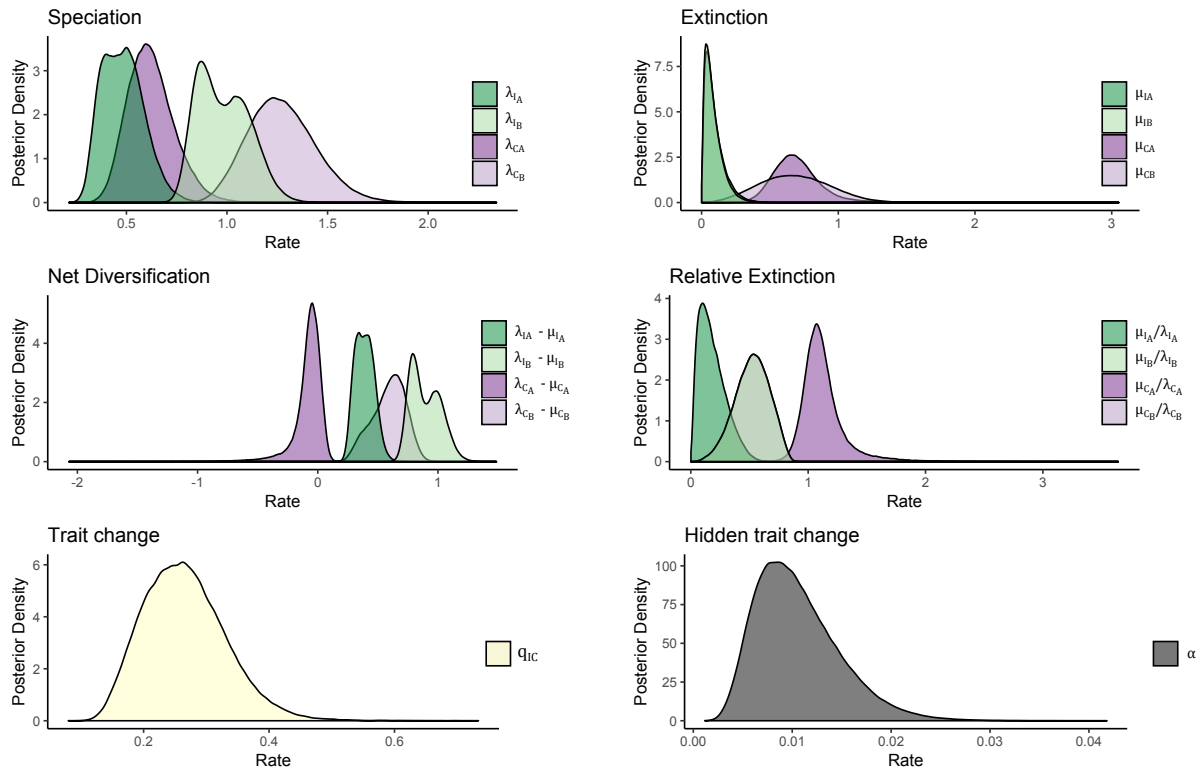


Figure S6: Posterior distribution for each of the parameters in the I/C+A/B, breeding system model

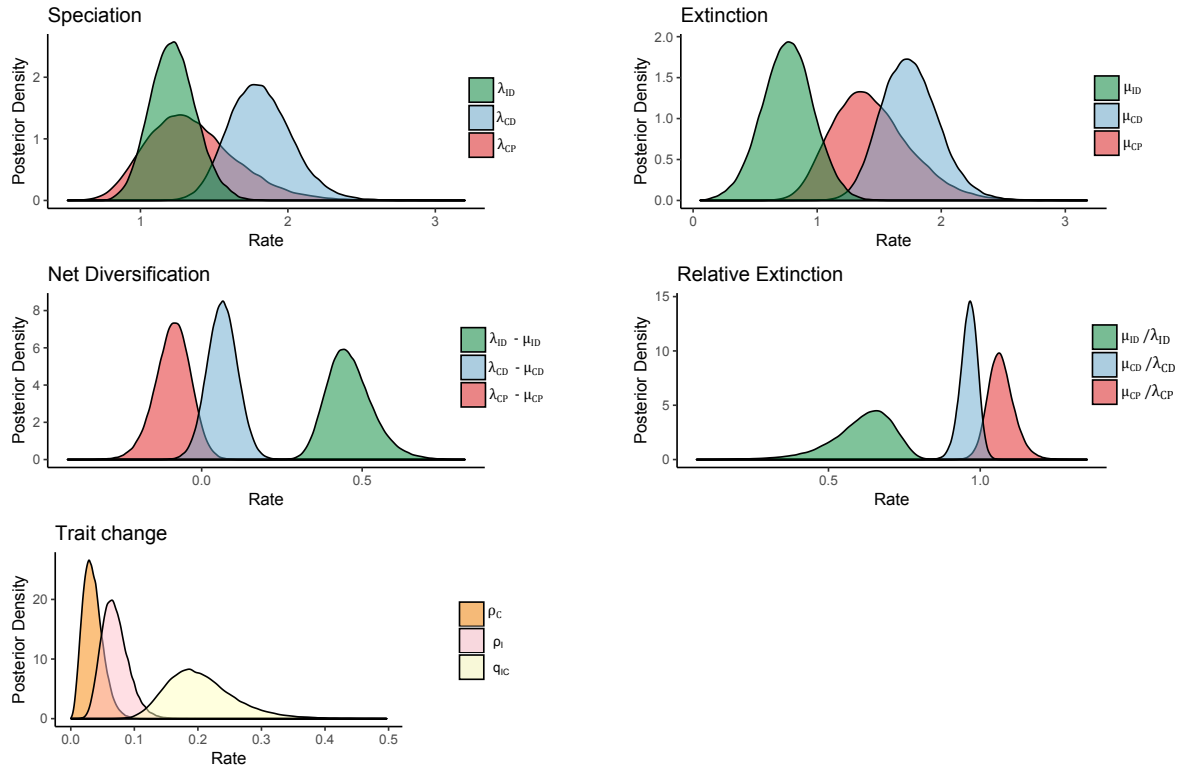


Figure S7: Posterior distribution for each of the parameters in the ID/CD/CP, polyploidy and breeding system model



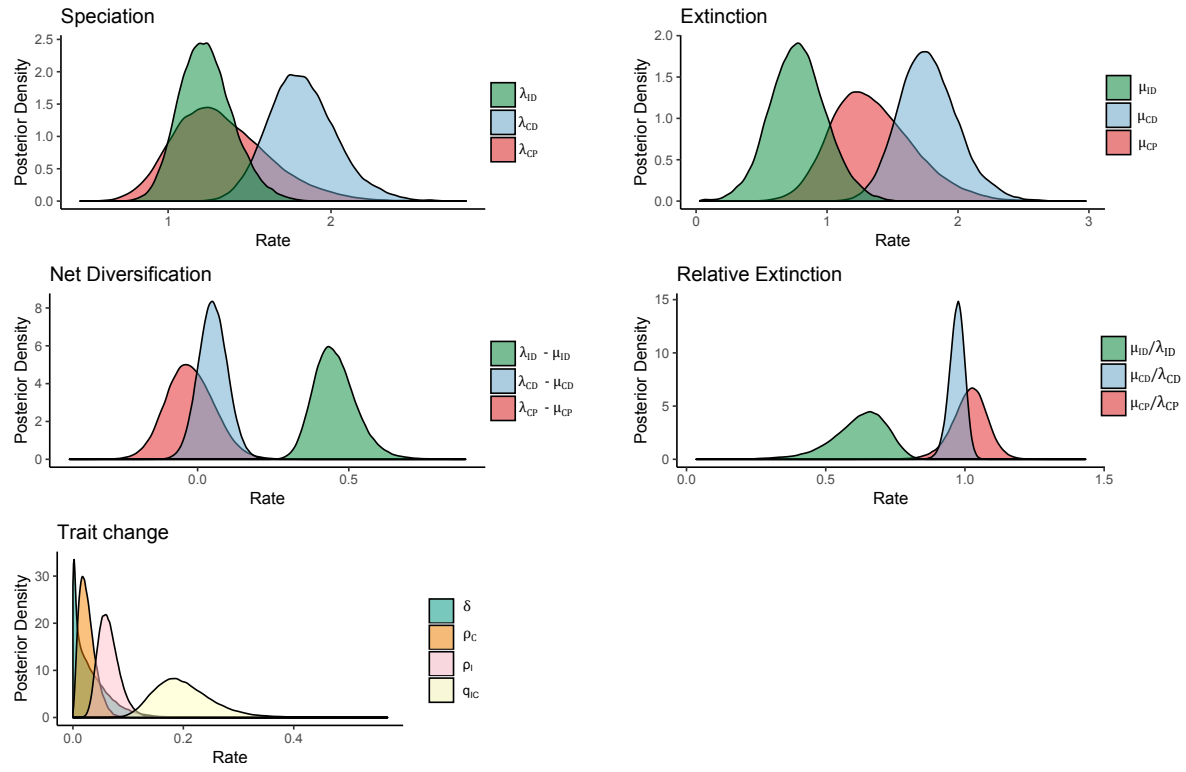


Figure S8: Posterior distribution for each of the parameters in the ID/CD/CP+ $\delta$ , polyploidy and breeding system model

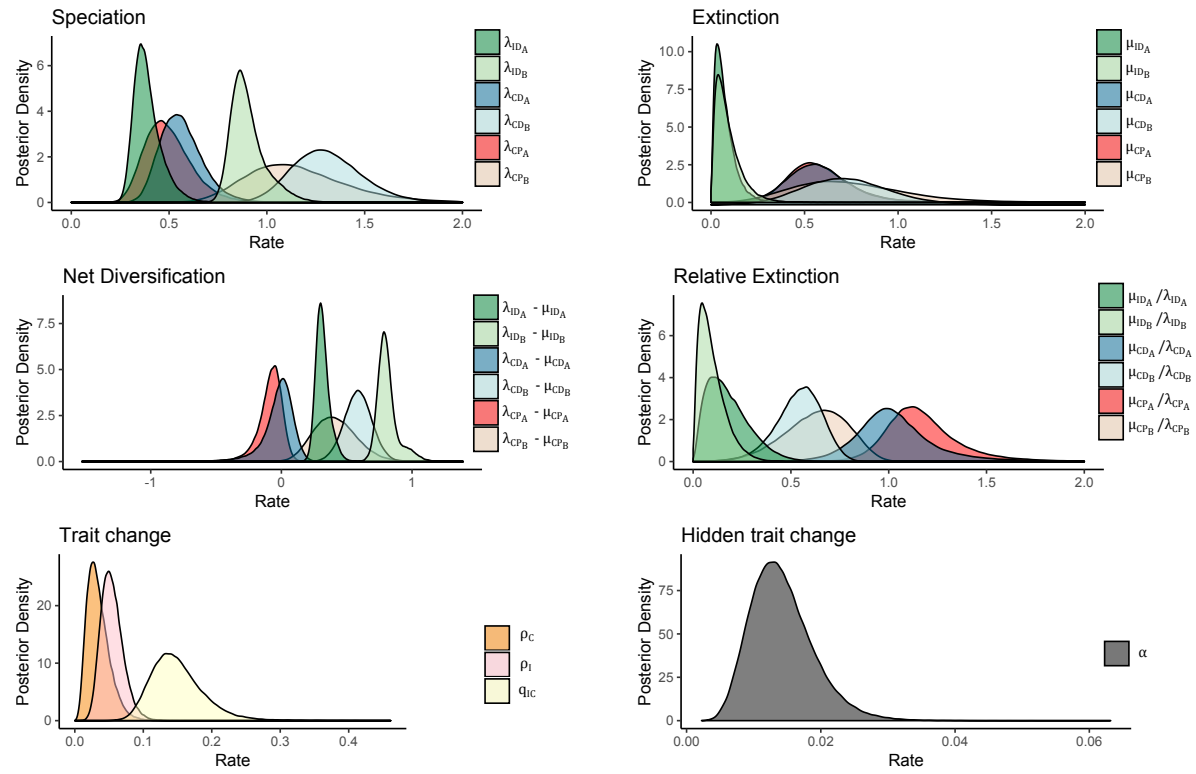


Figure S9: Posterior distribution for each of the parameters in the ID/CD/CP+A/B polyploidy and breeding system model

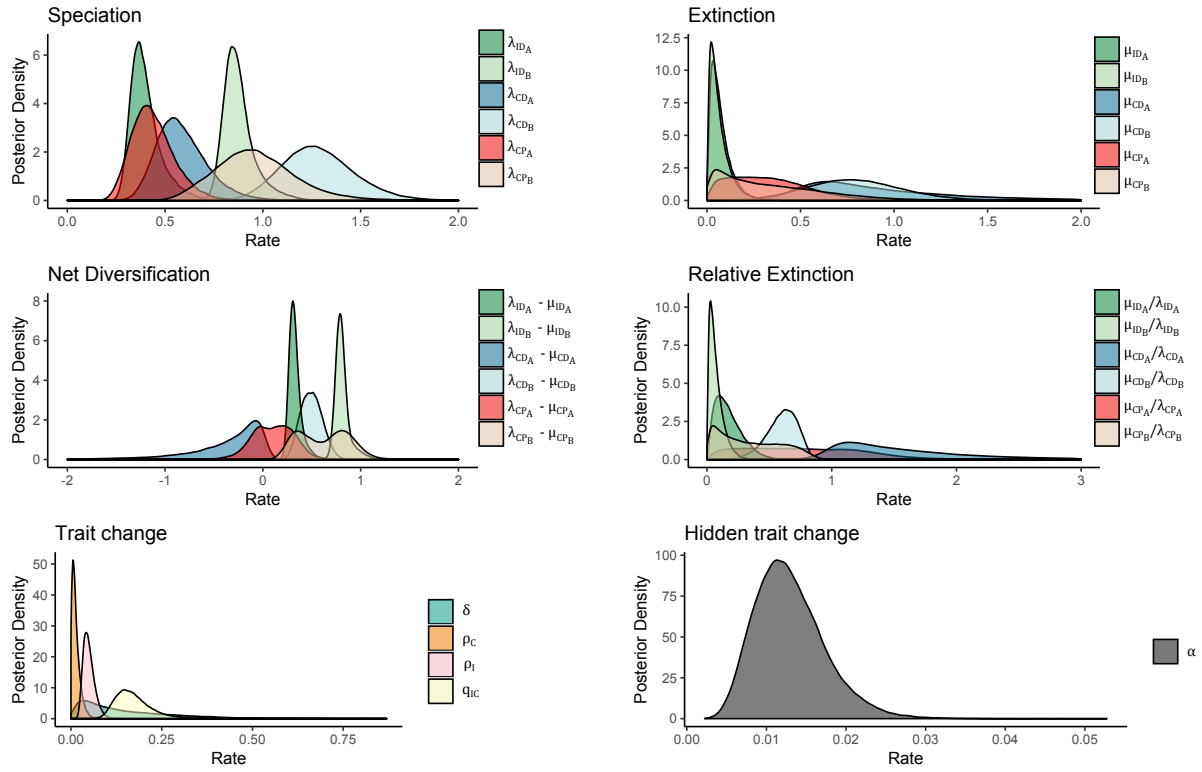


Figure S10: Posterior distribution for each of the parameters in the ID/CD/CP+ $\delta$ +A/B, polyploidy and breeding system model

	D/P	D/P+A/B	ID/CD/CP	ID/CD/CP+A/B
$r_D$	0.260	0.193, 0.658	—	—
$r_P$	-0.056	0.030, 0.187	—	—
$r_I$	—	—	—	—
$r_C$	—	—	—	—
$r_{ID}$	—	—	0.455	0.309, 0.797
$r_{CD}$	—	—	0.065	-0.006, 0.587
$r_{CP}$	—	—	-0.088	-0.074, 0.403
$\rho$	0.047	0.047	—	—
$\rho_I$	—	—	0.067	0.053
$\rho_C$	—	—	0.033	0.032
$q_{IC}$	—	—	0.198	0.145

	D/P	D/P+A/B	I/C	I/C+A/B	ID/CD/CP	ID/CD/CP+A/B
$r_D$	0.382	0.698, 0.100	—	—	—	—
$r_P$	0.109	0.587, 0.182	—	—	—	—
$r_I$	—	—	0.550	0.386, 0.877	—	—
$r_C$	—	—	-0.001	-0.059, 0.606	—	—
$r_{ID}$	—	—	—	—	0.449	0.318, 0.789
$r_{CD}$	—	—	—	—	0.050	-0.248, 0.494
$r_{CP}$	—	—	—	—	-0.027	0.110, 0.634
$\rho$	0.033	0.026	—	—	—	—
$\rho_I$	—	—	—	—	0.063	0.047
$\rho_C$	—	—	—	—	0.024	0.011
$\delta$	0.050	0.162	—	—	0.022	0.107
$q_{IC}$	—	—	0.364	—	0.194	0.164

Table S1: Median rate estimates for all fitted models. Units are per million years. Two comma-separated numbers refer to the *A* and *B* hidden states, and — means the parameter was not present in the model. Net diversification rates ( $r$ ) are subscripted with trait state initials (Diploid, Polyploid, Incompatible, Compatible). Transition rates are  $\rho$  (polyploidization), subscripted with background breeding system state;  $\delta$  (diploidization); and  $q_{IC}$  (loss of self-incompatibility). The upper section is for models without diploidization, and the lower section is for models with diploidization. The supplemental figures show the corresponding distributions of parameter estimates.