

**When your favorite trait is not enough to explain diversification: An example of diversification
linked to polyploidy and breeding system in Solanaceae**

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Abstract

The effect of polyploidy in diversification remains a contentious issue. On the one hand, recent studies that found that polyploids have slower speciation rates and higher extinction rates than diploids left scientist wondering if polyploidy is truly an evolutionary dead-end. On the other hand, botanist have found strong
5 molecular support of multiple polyploidy events at the root of highly diverse clades which challenges the evolutionary dead-end conclusions reached by modeling approaches. We re-investigate the role of polyploidy in speciation and extinction from a new modeling perspective considering that patterns found in diversification models can be misleading and incorrectly attributed to polyploidy when other observed and unobserved plant traits are responsible of shaping diversification. Using statistically robust comparative
10 phylogenetic approaches, we show that it is possible to detect whether the contribution of polyploidy to speciation and extinction is significant under the presence of other potential traits also affect diversification. We use the phylogeny, polyploidy, and breeding system data of 595 Solanaceae species to understand the contribution of polyploidy to diversification. We ask if Solanaceae polyploids are evolutionary dead-ends, and whether breeding system or some other unobserved traits are responsible of the patterns of diversification
15 observed in the phylogeny.

Introduction

Studying diversification linked to trait evolution

The prevalence of polyploidy and its detection across multiple and highly diverse clades of angiosperms inevitably lead to the hypothesis of the importance of polyploidy in the speciation and extinction patterns observed across the flowering plant phylogeny. At the same time, a similar question has been asked in the breeding system world, where self-compatibility has evolved multiple times in flowering plants. However, the influence in diversification using both polyploidy and self-compatibility information has not been studied simultaneously.

- Why polyploidy and self-compatibility in particular makes for an interesting study in the context of diversification

In the polyploidy world, an important debate regarding the diversification of angiosperms has been ongoing since the publication of Mayrose et al. (2011). The authors discovered that using the latest diversification model linked to two states diploid and polyploid, the net diversification of polyploids was much slower than the net diversification rate than polyploids. This result was surprising and sparked a discussion about the long-term evolutionary consequences of polyploidy. Soltis et al. (2014) questioned if polyploidy should be regarded as an evolutionary dead-end since the net diversification of polyploids was negative, despite overwhelming evidence about the incidence of polyploidy especially at the root of highly diverse angiosperm claims (ref here). A year later, diversification models were re-tested and corrected, and still found the same pattern (Mayrose et al. 2015), to the disappointment of plenty of botanists there was no denying of the weak trend of diversification that polyploids left behind. The most recent study by Landis et al. (2018) that used not only the presence of polyploidy in the tips but also the number of whole genome duplications in a taxon lineage found that...

Meanwhile, studies focusing on diversification patterns and breeding system have consistently found that self-incompatible plants often have higher net diversification rates compare to their self-compatible counterparts (Emma and Boris' papers here, what about papers that are not solanaceae?)

- Why other traits need to be considered as well

- What other models and studies have done in the past

- What is lacking from past approaches?

There are two key questions that at the time of the polyploidy debate were difficult to ask. The first is if

the models used to measure the diversification of polyploids were correct, and the second question is if the models have potentially included more evidence and potential traits that are not polyploidy or other lines of evidence that could be driving the patterns. At the time, in a different context Beaulieu and O'Meara (2016) were finding an alternative solution to the first question, coming up with a new model that could represent the broad heterogeneity of the diversification process and parse out the signal between the trait of interest and the noise in diversification. Their model, the hidden state speciation and extinction model is a key component to detect whether polyploidy or something else unknown but related to it is driving the speciation and extinction patterns that we see in angiosperms.

-What is our proposal to tackle this problem?

- How this paper is structured

The second question (talk here about breeding system and polyploidy, and how this could be different across clades and this is one of the reasons why we focused on Solanaceae). -Diversification and breeding systems

Goldberg and Igić 2012, different perspectives

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Methods

Data

Chromosome number data were obtained for all Solanaceae taxa in the the Chromosome Counts Database (CCDB; Rice et al. 2015), and the ca. 14,000 records were cleaned semi-automatically using the CCDBcurator R package (Rivero et al. 2019). This large dataset includes the compilation of Solanaceae ploidy states from Robertson et al. (2011). Species were coded as either diploid (D) or polyploid (P). For the majority of species, ploidy was assigned according to information from the original publications and the Kew Royal Botanic Gardens C-value DNA resource (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. For example, *Solanum betaceum* did not include information about ploidy level but it has 24 chromosomes, so because $x = 12$ 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

smallest and most frequent ploidy level recorded. Breeding system was scored as self-incompatible (I) or self-compatible (C) based on results curated from the literature and original experimental crosses (as compiled in Igić et al. 2006; Goldberg et al. 2010; Robertson et al. 2011; Goldberg and Igić 2012). Most species could unambiguously be coded as either I or C (Raduski et al. 2012). 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 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 SI populations frequently contain some SC individuals, and diploid populations frequently contain some polyploid individuals, in no case did we find a convincing case of a naturally occurring SI and polyploid population. The single instance of an SI and polyploid individual appears to be an allopolyploid hybrid of *Solanum oplocense* Hawkes x *Solanum gourlayii* Hawkes, reported by Camadro and Peloquin 1981.

Because of this empirical observation and the functional explanation for whole genome duplication disabling gametophytic self-incompatibility (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. Tips without trait data are much less informative for diversification parameters linked to trait values, and including this many more species would have prohibitively slowed our analyses, especially for the most complex models.

Models for ploidy and diversification

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. In a Bayesian framework, we obtained posterior probability distributions of speciation rates (λ_D, λ_P), extinction rates (μ_D, μ_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. This analysis explores the same question as Mayrose et al. (2011, 2015), but our analyses differ because we include not only polyploidization (parameter ρ , the transition rate from *D* to *P*), but also diploidization (parameter δ , the transition rate from *P* to *D*).

Our second model assesses the the signal of diversification due to ploidy while also parsing out the heterogeneity of diversification rates due a possible unobserved trait. BiSSE-like models can suffer from a large false discovery rate because they fail to account for diversification rate changes that do not directly depend on the trait of interest (Rabosky and Goldberg 2015; Beaulieu and O’Meara 2016). To allow for diversification rate differences explained by something other than ploidy, we added a hidden state (HiSSE model; Beaulieu and O’Meara 2016). In this model, each of the observed diploid and polyploid states is subdivided by a binary hidden trait with states *A* and *B*. We call this the D/P–A/B ploidy and hidden state model. We estimated the posterior probability distributions of speciation rates ($\lambda_{DA}, \lambda_{DB}, \lambda_{PA}, \lambda_{PB}$), extinction rates ($\mu_{DA}, \mu_{DB}, \mu_{PA}, \mu_{PB}$), net diversification rates ($r_{DA}, r_{DB}, r_{PA}, r_{PB}$), and relative extinction rates ($v_{DA}, v_{DB}, v_{PA}, v_{PB}$). In this model polyploidization rate ρ and diploidization rate δ are also included, and changes between hidden states are symmetrical with rate α .

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), though 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 in 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.

For these and the subsequent models including breeding system, we allow transitions from *I* to *C* (at rate q_{IC}) but not the reverse. Within Solanaceae, self-incompatibility in species that possess it is a homologous form of gametophytic SI (shared even shared even with other dicot families; Igić and Kohn 2001; Steinbachs and Holsinger 2002). Furthermore, species that are distantly related within the family

carry several closely-related alleles at the locus that controls the SI response (Ioerger et al. 1990; Igić et al. 2006). This is very strong evidence that the SI mechanism is ancestral in Solanaceae and has not re-evolved within the family.

Models for ploidy, breeding system, and diversification

If both ploidy and breeding system have the potential to influence lineage diversification, we should logically consider their effects jointly. We thus fit a model that includes both traits (MuSSE, FitzJohn 2012). The three states in this model are self-incompatible diploids (ID), self-compatible diploids (CD), and polyploids, which are always self-compatible (CP). We did not include a state for self-incompatible polyploids because they are not present in the data, and because that trait combination is logically expected not to occur (as explained above). We call this the ID/CD/CP ploidy and breeding system model. It has ten parameters, six for diversification in each state (λ_{ID} , λ_{CD} , λ_{CP} for speciation, μ_{ID} , μ_{CD} , μ_{CP} for extinction) and four for transitions between states (ρ_I , ρ_C for polyploidization transitions from ID and CD to CP, respectively; δ for diploidization from CP to CD; 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 it would be a regain of self-incompatibility.

The ID/CD/CP model could potentially capture similar dynamics as earlier models, if the hidden state in D/P–A/B was effectively breeding system, and the hidden state in I/C–A/B was effectively ploidy. There is also the potential, however, for a hidden factor to be influencing diversification even beyond both of our focal traits, and this could again mislead inferences. We therefore added a hidden trait layer on top of our three-state model (analogous to Caetano et al. 2018; Herrera-Alsina et al. 2018; Huang et al. 2018). We refer to this as the ID/CD/CP–A/B model. A fully parameterized version of this model would have 26 rate parameters (Herrera-Alsina et al. 2018). 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 16 parameters. The reduction in parameter space is achieved by fixing the rates for transitions among hidden states to be equal with rate α , and fixing the transition rates between observed states to be independent of the hidden state (rates ρ_I , ρ_C , δ , q_{IC} as defined for the ID/CD/CP model). There are additionally twelve diversification rate parameters (λ_{IDA} , λ_{IDB} , λ_{CDA} , λ_{CDB} , λ_{CPA} , λ_{CPB} , μ_{IDA} , μ_{IDB} , μ_{CDA} , μ_{CDB} , μ_{CPA} , μ_{CPB}).

Diploidization as an exploratory hypothesis

For all four models that consider ploidy changes, we allowed that diploidization could happen. 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). 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. 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 ten diversification models were performed using custom code in the RevBayes (Höhna et al. 2016) environment. Code and results for all analyses is available at <https://github.com/roszenil/solploidy>. For all analyses, a correction for incomplete sampling was included, based on assuming that the Solanaceae family has approximately 3,000 species ($s = 595/3000$) as estimated by the Solanaceae Source project (PBI *Solanum* Project 2012). For all ten models, we assumed that speciation and extinction parameters had log-normal prior distributions with means equal to the expected net diversification rate (number of taxa/ $[2 \times \text{root age}]$) 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, an MCMC chain was run for 96 hours in the high-performance computational cluster at Minnesota Supercomputing Institute, which allowed for 5,000 generation of burn-in and a minimum of 200,000 generations of MCMC for each of the 6 models. For each model, convergence and mixing of the MCMC was tested using the R package coda and the software Tracer (see supplementary information for convergence plots).

Model selection

We calculated the marginal likelihood for each of the ten 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 1000 MCMC steps (Table 1). The calculation of each marginal likelihood ran for 24 hours on a high-performance com-

putational cluster.

Using the marginal likelihood values, we calculated thirteen different Bayes factors. Six compared the models of polyploidy against each 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 between these models are not valid because the input data are different under the different state space codings (Fig. 1). In essence, the D/P, I/C, and ID/CD/CP state spaces are not lumpable with respect to one another (Tarasov 2018).

Results

Polyploidy and Diversification Models

Similarly to the results obtained by Mayrose et al. (2011) and Mayrose et al. (2015), we found that in the D/P polyploidy model the net diversification of diploids is larger than the net diversification of polyploids since the net diversification distributions do not overlap (Figure 2(A)). This result holds true whether or not the diploidization parameter is present. However in the presence of the diploidization parameter the net diversification rate of polyploids is nonnegative with probability 1 (Figure 2(A)), whereas in the absence of diploidization the net diversification rate of polyploids can be negative with a probability (HERE verify the quantile) (FIGURE 3(A)). In terms of the relative extinction, when the diploidization parameter is present both polyploids and diploids have posterior distributions that overlap, but that pattern changes in the absence of the diploidization parameter leading to a significant difference between relative extinction where polyploids have a significant higher relative extinction rate (see Supplementary Information).

For the D/P- A/B model with diploidization the diploid and polyploid net diversification rates are overlapping for both state A and B of the hidden trait (Figure 2(B)). In this model, the differences in net diversification are due to the presence of a hidden trait and not to the differences in ploidy. When diploidization parameter is absent the hidden state is still driving the differences in diversification rates (Figure 3(B)).

Breeding System and Diversification models

In the I/C breeding system model we found that the net diversification rate for self-incompatible state is larger than the net diversification rate for self-compatible state (Figure 2(C)). The net diversification rate for self-compatible has a probability distribution centered at zero.

When a hidden state is added in the I/C-A/B model, we found that under the hidden state A the self-compatible and self-incompatible net diversification rates are different. Under the hidden state B, those two rates overlap with a probability (HERE CALCULATE THAT) meaning that they are different with probability (CALCULATE) (Figure 2(D)). These results agree with previous results found by Goldberg and Igić (2012). However, Goldberg and Igić (2012) used a ClaSSE approach since they were interested in anagenetic and cladogenetic changes for self-incompatibility using a smaller subset of the data presented in the current work.

Polyploidy and Breeding Sytem models

In the ID/P/CD model we found that self-incompatible and diploid state has a significantly larger net diversification rate compare to both self-compatible diploid and polyploid rates. Meanwhile, both self-compatible diploid and polyploid posterior distributions of net diversification rates completely overlap (Figure 2(E)). When hidden state was added in the ID/P/CD-A/B model, we observed significant differences between self-compatible and self-incompatible diploids for both A and B values of the hidden state. Self-incompatible state had a larger net diversification rate than self compatible for both A and B states. However, the posterior distribution for the net diversification rate of polyploids overlaps with both the self-compatible and self-incompatible posterior distributions for each value of the hidden state(Figure 2F) meaning that polyploidy state is not significantly different from diploid in net diversification terms. The resulting effect of adding the hidden state values is significant

Diploidization as an exploratory hypothesis

In the D/P model the diploidization rate δ and polyploidization rate ρ are different from zero with probability 1. Diploidization rate is more uncertain than polyploidization. For the D/P no δ model, the polyploidization rate is still different from zero but has a wider 95% credible interval (see Supplementary Information). In the D/P-A/B model the diploidization rate remains positive but there rate of polyploidization becomes really uncertain. Whereas, in the absence of diploidization (D/P no δ A/B) the rate of polyploidy has a small credible interval

For the model ID/P/CD containing both polyploidy and breeding system traits, we found that the diploidization rate is really uncertain with a MAP that is (CALCULATE VALUE HERE- close to zero). The polyploidization rate from self-incompatible diploid ρ_I is slightly faster than the polyploidization rate from self-compatible diploid ρ_C and that pattern remains the same for the ID/P no δ /CD model(see supplementary information).

Model selection

In Table 1 we list the marginal likelihood in log scale for each of the models tested. In the table we show what are the different components included and excluded for each model as a summary of the diagrams from Fig. 2. From the marginal likelihoods in log scale, the Bayes factors in log-scale were calculated as shown in table Table 2. After testing every single pair of polyploidy modes (1-4) we found overwhelming evidence that the best polyploidy model is always the D/P-A/B, that is the model with hidden state and diploidization.

For the two models following the evolution of breeding system, the I/C-A/B is the best choice between models 3 and 4.

The models that follow the diversification linked to both polyploidy and breeding system are the last 4 (models 5-8). When comparing using Bayes factors every two models we found that the IC/P/CD-A/B is always preferred over the rest, meaning that the model that has a hidden state and diploidization is chosen over the ones that lack either of both of those options.

Therefore, the models that were chosen were always the ones containing a hidden trait, and in the case of polyploidy models, the ones containing a diploidization parameter δ are preferable.

Discussion

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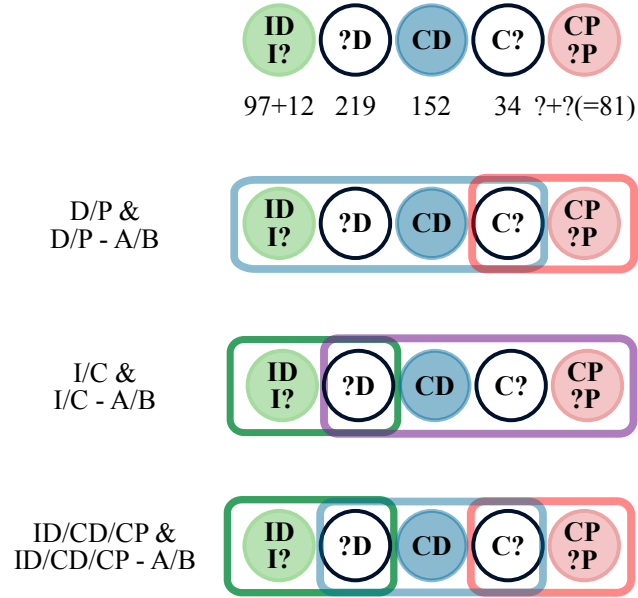


Figure 1: Character states used for each of the models. Each species retained on the tree belonged to one of five possible categories, depending on whether ploidy and/or breeding system were known. The number of species in each is shown under the corresponding circles in the top row. These categories 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.

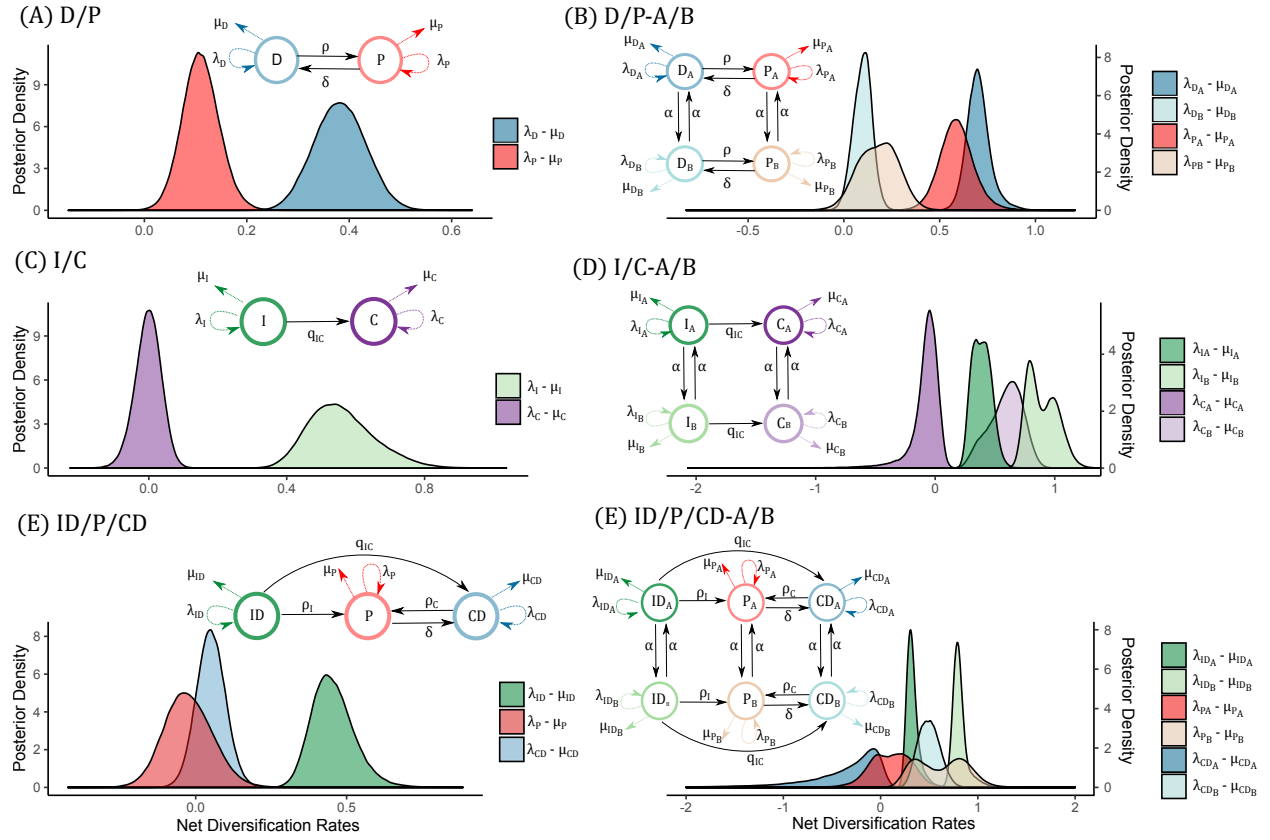


Figure 2: Net diversification rates for all models that include diploidization.

Model	Model Type	Ploidy	Diploidization	Breeding System	Hidden State	Parameters	Marginal Log- Likelihood
1. D/P	BiSSE	Yes	Yes	No	No	6	-1182.93
2. D/P no δ	BiSSE	Yes	No	No	No	5	-1193.66
3. D/P- A/B	HiSSE	Yes	Yes	No	Yes	11	-1145.69
4. D/P no δ -A/B	HiSSE	Yes	No	No	Yes	10	-1150.99
5. I/C	BiSSE	No	No	Yes	No	5	-1194.80
6. I/C-A/B	HiSSE	No	No	Yes	Yes	10	-1155.37
7. ID/P/CD	MuSSE	Yes	Yes	Yes	No	10	-1344.50
8. ID/P/CD no δ	MuSSE	Yes	No	Yes	No	9	-1345.87
9. ID/P/CD-A/B	MuHiSSE	Yes	Yes	Yes	Yes	16	-1300.35
10.ID/P/CD no δ -A/B	MuHiSSE	Yes	No	Yes	Yes	15	-1303.55

Table 1: Marginal likelihoods for the ten diversification models proposed.

Polyploidy Models					Breeding System Models		Polyploidy 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/P/CD	·	1.36	-44.15	-40.95
2. D/P no δ	·	·	-47.97	-42.66	6. I/C-A/B	·	·	8. ID/P/CD no δ	·	·	-45.51	-42.31
3. D/P- A/B	·	·	·	5.30				9. ID/P/CD-A/B	·	·	·	3.2
4. D/P no δ -A/B	·	·	·	·				10. ID/P/CD no δ -A/B	·	·	·	·

Table 2: Bayes factors in log scale. We compare every possible pair. Number models as indicated in Table 1.