**An empiricist’s guide to modern coexistence theory for competitive communities**

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**Abstract**

Prior to 2000, nearly all ecological theory argued that the coexistence of species in competitive communities was controlled by the magnitude of niche differences among species in space or time. In 2000, Chesson published a more general theory of coexistence in competitive communities, showing that species coexistence in most models of competition is controlled by the balance of two opposing forces: Relative fitness differences (RFD) establish competitive hierarchies among species that hasten competitive exclusion, whereas niche differentiation (ND) helps offset the effects of RFD by giving species a growth advantage when rare, which helps to stabilize negative interactions. Even since Chesson’s general framework of coexistence was established, an increasing number of empirical studies have attempted to quantify the magnitude of ND and RFD for real assemblages of plants and animals. However, because the various methods used to measure ND and RFD to date have been derived from different theoretical origins and make differing assumptions, they are not directly comparable in terms of the quantities and predictions they produce. In this review, we compare five of the most common methods that have been used to measure ND and RFD: (1) negative frequency dependence, (2) sensitivity to mutual invasibility, (3) parameterization of Lotka-Volterra competition models, (4) MacArthur’s consumer resource model, and (5) Tilman’s consumer resource model. We show that ND and RFD can be measured using all of five methods, and that the measures correctly predict species coexistence under the specific limiting assumptions of those methods. However, the methods are not comparable to one other, which means that measures of ND and RFD estimates from different studies may not be comparable. Furthermore, several of the methods have important assumptions or limitations that empiricists need to be aware of before using them to measure ND and RFD in any real system. After reviewing the methods, we offer guidance for empiricists to determine which method(s) are most appropriate for measuring ND and RFD in their study system.

**Introduction**

Throughout most of the history of community ecology, it has been assumed that niche differentiation among species is the sole biological mechanism that can offset the negative impacts of interspecific competition and prevent competitive exclusion (Volterra 1926, Gause 1934, May and Macarthur 1972, Abrams 1990, Chesson 1991, Leibold 1995, Chase and Leibold 2003, Tilman 2004). This idea dates at least to 1928 when Volterra (Volterra 1926) introduced a dynamic model of competition that became the foundation for the competitive exclusion principle (Gause 1934). The competitive exclusion principle led to the conclusion that ecosystems should only contain as many species as there are limiting resources (or consumers); thus, species only coexist if they are limited by different resources (or consumers) at the same location and time, or if they partition resources (or consumers) in space or time (Rescigno and Richards 1965, Macarthur and Levins 1967, Macarthur 1970, Abrams 1986, Leibold 1995). Nearly all subsequent hypotheses to explain coexistence have argued that biodiversity exists because of such niche differences among species.

While niche partitioning has been the foundation for most explanations of the world's biodiversity, theories of species coexistence have recently undergone a major revision. In 2001, Hubbell published The Unified Neutral Theory of Biodiversity (Hubbell 2001), which argued that patterns of biodiversity in nature can be explained by a relatively simple model that does not invoke niche differences among species. According to Hubbell’s theory, species coexist not because they are different, but because their demographic parameters are identical, or nearly so, such that the consequences of their interactions are 'neutral' (i.e. essentially equal among all species). As such, Hubbell argued that the biodiversity we observe in nature can be explained by a series of stochastic events that give some populations the chance opportunity to rise to dominance while others exhibit random walks to extinction.

Even as Hubbell was developing his neutral theory, Chesson (Chesson 2000) was completing a ground-breaking synthesis of coexistence framework that would ultimately provide a road map for how to integrate the niche and neutral perspectives on biodiversity. Chesson’s coexistence framework was built on his insight to the invisibility criterion, i.e. whether a species can have positive growth rate when invading resident species from rare (Chesson 1994, 2000). If both species have positive growth rates as the invader, the two species will coexist. Chesson argued that, theoretically, species’ invasion growth rate can be decomposed into two general terms representing fluctuation independent and fluctuation dependent mechanisms (Chesson 2000, 2003). Fluctuation independent mechanisms are those that do not require fluctuations in population densities or environmental factors in order to facilitate coexistence. On the other hand, fluctuation dependent mechanisms occur through species’ differential responses to the variance of environmental factors, i.e. relative nonlinearities (e.g. Letten et al. 2018), or operate through the covariance between environment and species’ interactions, i.e. storage effects (Miller and Klausmeier 2017).

The fluctuation independent mechanisms in Chesson’s coexistence framework include two forces, which he called stabilizing and equalizing. Stabilizing forces represent various forms of niche difference (ND) among a pair of species, all of which cause species to limit their own growth more strongly than they limit the growth of other species (intra > interspecific competition). This can occur when species partition limiting resources in space or time, or when they experience differential consumption by shared consumers. In contrast, equalizing forces minimize what Chesson and others now refer to as relative fitness differences (RFD) among species (Adler et al. 2007, Levine andHilleRisLambers 2009, Hillerislambers et al. 2012, Turnbull et al. 2013). Chesson's definition of a ‘fitness difference’ is not the same as that used by evolutionary biologists, as he was referring to differences in competitive abilities among species, not differences in reproduction among individuals. RFDs set up competitive hierarchies among species when ND is absent, and are the result of inherent variation in biological traits such as minimum resource or consumer requirements (e.g. R\*/P\*’s; Tilman 1982), differential resistance to consumers, or differences in potential growth rates (Adler et al. 2007, Levine andHilleRisLambers 2009, Hillerislambers et al. 2012). RFDs represent differences in competitive abilities that persist irrespective of how much ND there is among species. For all fluctuation independent mechanisms of coexistence, Chesson showed it is the balance of these two forces – RFDs that establish competitive hierarchies, and NDs that prevent competitive exclusion – that ultimately determine whether species maintain non-negative long-term growth rates in competitive communities (Chesson 2000). To coexist, ND must be sufficiently large to offset and stabilize the competitive hierarchies generated by RFD’s. It has subsequently been shown that Hubbell's neutral theory represents a specific, limiting case of Chesson's coexistence theory where NDs and RFDs are both zero, causing the outcome of competition to be approximated by a random walk to extinction (Adler 2007). Thus, Chesson’s inequality provides a general framework for predicting species coexistence.

Much attention in ecology has recently turned towards the empirical measurement of niche and relative fitness differences to determine how these two forces contribute to coexistence in real communities. As a growing number of empiricists have tried to quantify ND and RFD in their individual study system, the number of different empirical approaches proposed for doing so has also grown. For example, based on empirical measurements of population dynamics, niche difference can be quantified and demonstrated to be important to maintain biodiversity in annual plant communities (Levine andHilleRisLambers 2009). Moreover, by comparing species’ population dynamics with versus without a competitor, one can quantify ND and RFD between species pairs and to predict coexistence in green algae communities (Narwani et al. 2013). However, these methods stem from very different models of species coexistence, make different assumptions, and use different experimental designs. Therefore, it is important to compare these methods and how they would be implemented in order to determine whether these methods give comparable values of ND and RFD as well as offer the same predictions regarding coexistence.

Here we provide a summary and comparison of five common methods that have been used to measure ND and RFD empirically in real communities. In part 1 of our paper, we describe the theoretical background of each method and how it could be implemented empirically, compare the methods in terms of how they relate to ND and RFD, and use simulations to ask whether they give the same estimates and predictions regarding coexistence. In Part 2 of the paper we provide a list of decision steps to help empiricists select the most appropriate method for their study system and contrast the methods in terms of the amount of empirical information (e.g. experimental treatments) required to use them. In part 3, we discuss the main advantages and disadvantages of the approaches and make some suggestions for future empirical work on coexistence theory.

**Part 1. Theoretical background for five empirical methods**

1. *Theoretical background for five empirical methods*

In Chesson’s coexistence framework, niche difference (ND) and relative fitness difference (RFD) are being used in the following inequality to assess the mutual invasibility criterion (Chesson 1990).

(1)

In this inequality, *ρ* is the niche difference (ND) and is the relative fitness difference (RFD). The (ND), (RFD) and the inequality are first derived by using the classic Lotka-Volterra competition model to approximate MacArthur’s consumer resource model (Chesson 1990). Since ND, RFD and the inequality for mutual invasibility are based on the Lotka-Volterra competition model, we first describe how each method can be used to approximate the interaction coefficients in the Lotka-Volterra competition model in order to measure ND and RFD for assessing the inequality (equation 1). We then explain the empirical approach required for each method and end each method section with some of the known limitations of each method. In the end of this part, we conclude by comparing these methods in terms of whether these methods yield the same prediction for coexistence based on the mutual invasibility criteria and whether they give the same estimates of ND and RFD.

* 1. *Negative frequency dependence (NFD)*
     1. *Theoretical background*

The negative frequency dependence method quantifies the relationship between a species’ frequency in a community (individuals of species 1 / total individuals of all species) and its per capita growth rate (Adler et al. 2007, Levine and HilleRisLambers 2009). The relationship between a species’ growth rate and its relative frequency has been used to assess the mutual invasibility criterion because the magnitude of the frequency dependency should reflect the difference between intra- versus inter-specific competition. The magnitude of the frequency dependency can be used to reflect the difference between intra- versus inter-specific competition relies on a key assumption that the community is saturated with respect to density or biomass (Adler et al. 2007). Under this assumption, all resources or niches are occupied by either the focal species *i* or its competitor *j*, so that increasing the frequency of individuals for focal species *i*, means individuals of species *i* will compete with more individuals of its own kind, and thus experience more intra- than inter-specific competition. Therefore, if intra-specific competition is greater than inter-specific competition, the dependency of species’ growth rate on its relative frequency should be negative, i.e. the NFD slope should be negative. More negative NFD slope thus represents a stronger stabilizing forces, i.e. niche difference (ND; Adler et al. 2007). In addition, Adler et al. 2007 argue that the difference between species’ growth rate in the absence of stabilizing forces is the relative fitness difference (RFD; Figure 1 in Adler et al. 2007) and the RFD is proportional to the NFD intercept. As long as the relationship between a species’ frequency and its growth rate is linear, the balance between the slope of frequency dependence and the difference in growth rates in the absence of stabilizing forces can be used to predict whether both species will have positive growth rates when rare, thus meeting the mutual invasibility criterion.

* + 1. *Empirical approaches*

It is important to note that the slope of ND has not been used literally as a measure of ND, nor has the difference in competition-free growth rate been used as a literal measure of RFD. Instead, papers have used estimates of inter and intraspecific competition coefficients from the Lotka Volterra-like model to quantify niche differences and then experimentally remove ND through manipulation to illustrate its effect as a stabilizing force (Levine andHilleRisLambers 2009). Other studies have measured NFD as evidence for the importance of stabilizing forces, but do not directly interpret the slope as ND or the intercepts as RFD (Yenni et al. 2017a). Nonetheless, the NFD method could be applied empirically to predict coexistence based on the mutual invasibility principle.

The NFD method is attractive for empirical work because it does not require any underlying population growth model or mechanism of species interactions. Frequency dependency of a species can be quantified by experimentally manipulating the relative frequency of species in a community, and then plotting the per capita growth rate versus the corresponding relative frequency (Fig. 1) For example, one experimental approach that is particular to annual plants is to seed a plot with varying densities of the two species and then use seed production and survival as a surrogate for per capita growth rates between years. The density of seeding can be manipulated to remove the effect of interspecific competition so that competitive interaction is determined only by RFD. Additionally, frequency dependency could, in principle, also be constructed using observational data from natural ecosystems. Doing this approach allows an empiricist to construct frequency dependency on species that are not easy to manipulate their growth rate. As long as the per capita growth rate and the relative frequency of the species can be estimated, and the community is assumed to be saturated with respect to density or biomass, it would be possible to parameterize the relationship between growth rate and frequency. Although this approach has not been applied empirically to make predictions regarding coexistence (but see Yenni et al. 2012, 2017) it is one of only two methods reviewed here that do not require manipulative experiments.

* + 1. *Limitations*

Despite some of the desirable aspects of the NFD method, there is a major caveat of this method. Namely, this method requires that the relationship between growth rate and frequency is linear, or that an empiricist can adequately describe the relationship to account for the non-linearity in predict growth rates when invading. From numerical simulations that mimic invasion experiments, we show that the species’ per capita growth rate is non-linearly dependent on its frequency, i.e. the NFD slope is not constant across frequencies even when the total community biomass is saturated (Fig. 1). The NFD slope is only constant when the community density is not only saturated but is always fixed regardless of the species’ frequency (appendix A). According to Appendix A, even though the NFD slope is constant, the NFD slope and intercept cannot be used to calculate ND and RFD. We also show that the non-linear frequency dependence can lead to incorrect predictions about species coexistence when applied to systems with non-linear relationships between species’ growth rates and densities (Supplement 1). When the NFD slope is not constant, the NFD method can only have correct predictions when evaluated at frequency approaching zero for each species. This finding means that for an empiricist to use the NFD method, they would need to either 1) measure the growth rate of each species across the full range of frequencies to establish that the growth rate of each species is linearly related to its frequency or 2) evaluate the growth rate of each species when rare (i.e. directly demonstrate mutual invasibility). Both of these options would dramatically increase the effort required but may be necessary in systems where only observational studies are possible.

* 1. *Parameterizing the Lotka-Volterra competition model*
     1. *Theoretical background*

The second empirical method to measure ND and RFD is based on parameterizing the Lotka-Volterra model empirical data from experiments or time series of species in natural ecosystems. In the classic Lotka-Volterra model, the *per capita* growth rate of species *i* can be described by equation 2:

(2)

In equation 2, *αii* is the *per capita* intra-specific competition coefficient, which describes the *per capita* effect of species *i* on the *per capita* growth rate of species *i*. *Ni*, is the density of species *i* scaled to its carrying capacity, and *ri* is the intrinsic per capita growth rate.

To meet the mutual invasibility criteria for any two species (e.g. *i* and *j*), both intra-specific competition coefficients must be greater than the inter-specific competition coefficients, i.e. *αii* > *αij* and *αjj* > *αji*. After obtaining the intra- and inter-specific competition coefficients, ND and RFD can be calculated following Chesson’s definition, i.e. and ,.

* + 1. *Empirical approaches*

To use the Lotka-Volterra model to empirically predict coexistence for species *i* and *j*, one must first estimate six different parameters that are used in the Lotka-Volterra model: intrinsic per capita growth rate of each species (*ri* and *rj*), per capita intra-specific competition coefficients (*αii* and *αjj*), and per capita inter-specific competition coefficients (*αij* and *αji*). In principle, this could be accomplished using maximum likelihood method from a single co-culture time-series dataset, where both species are introduced at low density and allowed to grow to steady-state. However, in practice, it is difficult to parameterize all eight variables from a single time-series. So, the simplest way to parameterize the model would be to use three datasets for each species pair: a time-series of each species grown alone as a monoculture to obtain intrinsic per capita growth rate of each species as well as per capita intra-specific competition coefficients, and one time-series representing a co-culture of the two species to obtain per capita inter-specific competition coefficients (Fig. 2).

* + 1. *Limitations*

An inherent limitation associated with the Lotka-Volterra method is that it assumes that the intra- and inter-specific competition coefficients are constant with respect to population sizes of either species. In other words, the species’ first individual and the last individual have the same per capita effect on the growth rates of its own kind or its competitor. However, intra- and inter-specific competition coefficients are easily subject to species’ density (e.g. Smith-Gill and Gill 1978), so that constant intra- and inter-specific competition coefficients might be unlikely occur in practice (Abrams 1980). Errors in estimating intra- and inter-specific competition coefficients can lead to incorrect calculation of ND and RFD. One solution is to make the assumption that intraspecific competition coefficients (*αii*) is fixed at 1/*Ni\**, where *Ni\** is the equilibrium density of the focal species. Supplement figure S2 shows that when applied to the numerical simulations based on Tilman’s CRM, the method using assumed intraspecific competition coefficients accurately predicts coexistence whereas intraspecific coefficients measured in monoculture near equilibrium lead to inaccurate predictions regarding coexistence.

* 1. *Sensitivity measurement in mutual invasibility experiments*
     1. *Theoretical background*

A third empirical method for measuring ND and RFD is to conduct mutual invasibility experiments that evaluate whether each species can invade a steady-state population of the other from rarity (Fig. 3). In the mutual invasibility experiment, a species’ sensitivity (*Si*) to competition is defined as the amount by which its per capita growth rate is reduced when invading a steady-state population of a competitor (*μij*) relative to the growth rate achieved during exponential growth in monoculture (*μi*):

(3)

A species’ sensitivity to competition is jointly determined by ND and RFD (Carroll et al. 2011, Narwani et al. 2013) Specifically, greater ND between the two species reduces the sensitivity of both species’ to competition, so that *Si* will approach zero. Greater RFD, on the other hand, causes species to be asymmetrically affected by competition such that one species’ sensitivity increases while the other’s decreases. Further, Carroll et al. (2011) verbally argue that ND can be calculated as and RFD as , where *Si* is the sensitivity of the species with the greater sensitivity. In appendix B, we show that such argument is valid and derive an inequality for coexistence expressed with sensitivity metrics, , which is in the same form as in Chesson’s coexistence framework (appendix B).

* + 1. *Empirical approaches*

Like the NFD method, the sensitivity method does not require an empiricist to assume a specific model of species interactions or define the resources that species compete for. To do the mutual invasibility experiments, one would need to measure the maximum growth rate of each species as a monoculture (*μi*) and, subsequently grow each species in monoculture to its carrying capacity (i.e. no significant change in density over time). Then, each species is introduced at low density (e.g. 0.01% of the resident species) to the steady-state monoculture of its competitor. The initial growth rate of each species as an invader is measured at low density (*μij*), long-term invasion growth rates are unnecessary. The growth rate of each species as an invader and resident can be used to calculate the sensitivity to invasion (*Si*) using equation 3. Finally, following the deduction in appendix B, ND and RFD can also be calculated and Chesson’s inequality (equation 1) can be assessed from the sensitivity metric (*Si*).

* + 1. *Limitations*

Using the sensitivity metric (*Si*) to quantify the impact of one species on another species requires one to perform mutual invasibility experiments, which is only practical for organisms whose population growth rates can be measured over tractable periods of time (i.e. days for fast-growing organisms like bacteria, algae, invertebrates, etc.). Mutual invasibility experiments are harder to apply to organisms that grow slowly since measuring their per capita growth rates would take a long time (e.g. trees).

* 1. *Parameterizing MacArthur’s consumer resource model*
     1. *Theoretical background*

A different approach to predicting coexistence among species is to determine the mechanisms by which species interact, then use models of those mechanisms, such as consumer-resource models, to approximate ND and RFD under different conditions. MacArthur’s consumer resource model describes how species consume resources (MacArthur 1969, 1970). MacArthur’s consumer resource model can be reorganized into a Lotka-Volterra form in order to yield estimates of inter and intraspecific interaction coefficients for calculating ND and RFD in Chesson’s inequality (Chesson 1990, 2000). Chesson 1990 showed how the empirically measured parameters in MacArthur’s consumer resource model (each species per capita consumption and yield on shared prey resources, population dynamics of the prey species) can be translated into parameters in Lotka-Volterra model, and thus be used to calculate niche difference (ND) and relative fitness difference (RFD). ND is determined by how similar two species are in terms of using resources (Fig. 4) and the RFD is proportional to the potential growth of each competitor on the resources.

* + 1. *Empirical approaches*

Parameterizing MacArthur’s consumer resource model requires feeding experiments in which each consumer species is grown across a gradient of resource species density (inset figure of Fig. 4). From the feeding experiments, the empiricist measures (1) the per capita consumption of the focal species on all the required resource species and (2) conversion efficiency from each resource species to the focal consumer species. Finally, the per capita growth rate and carrying capacity of each resource also need to be measured in the absence of consumer species.

* + 1. *Limitations*

Parameterizing MacArthur’s consumer resource model not only gives a more mechanistic understanding of species’ competition but also allows one to predict coexistence for other new pairs of species. However, these desirable aspects come with greater experimental effort compared to other methods. In particular, this method requires as many feeding experiments as there are resources, each of which involves measuring consumption rates at a range of resource species densities (Figure 4 inset). While this constraint does not impact the ability of the method to predict coexistence under defined conditions, it does limit the extent to which those predictions can be applied to different environmental circumstances.

* 1. *Parameterizing Tilman’s consumer resource model*
     1. *Theoretical background*

Similar to parameterizing MacArthur’s consumer resource model, Tilman’s consumer resource model (Tilman 1977) can also be empirically parameterized and reorganized to a Lotka-Volterra form (Letten et al. 2017). Using the Tilman consumer-resource model and the R\* concept for essential or substitutable resource, it is possible to determine which resource limits each species under a given set of resource supply conditions. When both species are limited by the same resource, niche overlap is 100% and the relative fitness difference determines which species becomes dominant and which species goes extinct. When the two species are limited by two different resources, however, niche overlap is a function of the species yields on the two resources. Letten et al. 2017 reorganize the Tilman’s two-species consumer resource model to a Lotka-Volterra form which can be used to estimate the intra- and inter-specific competition coefficients, which are consistent with Chesson’s equations for ND and RFD as well as the inequality for species coexistence (equation 1).

* + 1. *Empirical approaches*

There are few empirical attempts to parameterize Tilman’s consumer resource model. For example, in the paper where Tilman first proposed the model, Tilman had measured the parameters describing how two algae species (*Asterionella formosa* and *Cyclotella meneghiniana*) compete for two essential resources (silicate and phosphate) that are delivered to the ecosystem at a constant supply rate that matches the death rate. In general, measuring parameters in Tilman’s consumer resource model can be more easily done with phytoplankton (e.g. Tilman 1980, 1981), though other types of organisms are applicable as well (Miller et al. 2005). Figure 5 shows the hypothetical results from experiments to parameterize Tilman’s two-species consumer resource model for two essential and non-substitutable resources.

* + 1. *Limitations*

Reorganizing Tilman’s consumer resource model requires an empiricist to know which resources are relevant for competition and species’ yield on resources, which could raise substantial efforts. Additionally, the resource supply must be constant and equal to the density-independent loss rate, which could be achieved by some experimental settings like chemostat experiment.

1. *Do the methods give the same prediction regarding coexistence? Do the methods yield the same values of ND and RFD?*

Although each of the five methods can be used to predict coexistence based on mutual invasibility, the experimental approaches to parameterizing those method are different, and it is not clear that these methods would yield the same predictions (or values of ND and RFD) if applied to a given study system. Here we use numerical simulations to investigate whether four of those methods, when implemented as shown in Figures 1-4, lead to the same prediction regarding coexistence and give the same estimates of ND and RFD. We chose to use numerical simulation for this demonstration since we are unaware of any experimental dataset that has been, or could be, analyzed using more than two of the methods. The numerical simulations were based on Tilman’s consumer-resource model [Tilman 1977] with two species of phytoplankton competing for two essential resources (phosphate and silicate), which were the only parameters varied among simulations (See Supplement). For each set of resource conditions, we performed numerical simulations that represent four methods: fitting the Lokta-Volterra model to monocultures and a co-culture, the sensitivity method applied to an invasion experiment, the method using Tilmans’s CRM, and the NFD method.

Figure 6 shows that all four methods made the same prediction about coexistence and that these predictions match the outcome based on the equilibrium condition from simulation. Across the different resource conditions that we explored, the two species were predicted to coexist when the resource supply conditions caused each species to be limited by a different resource [Tilman 1977]. This agreement among the methods was conditional on how the Lotka Volterra and NFD methods were parameterized. The Lotka Volterra method only matched the predictions from the other methods when we assumed that intraspecific competition coefficients were equal to the inverse of the carrying capacity (Figure S2). When we estimated the intraspecific coefficients from the time series as the monocultures approached their carrying capacity, the method overestimated the range of parameter space allowing for coexistence. The NFD method only matched the other methods when we evaluated the slope when species densities were approaching zero and by using both the slope and the intercept to predict the growth rate when invading. Unless these conditions were met, the NFD method tended to over- or under-estimate the region of resource conditions that allow for coexistence.

Although the methods gave the same predictions regarding coexistence, Figure 6 (f and g) shows that the methods do not consistently yield the same values of ND and RFD when applied to the same study system. The Lotka Volterra method (using *αii* = 1/Ni\*) and the sensitivity method gave identical estimates of ND and RFD across the range of resource conditions used, but these estimates differed from the method based on Tilman’s consumer resource model. This disparity is explained by the fact that the Lotka Volterra and sensitivity methods assume that per capita inter- and intraspecific interaction coefficients are independent of species densities. Although this assumption is likely to be violated when species population dynamics are affected by mechanisms that produce non-linearity between population densities and growth rates, using the assumption that *αii* = 1/Ni\* allows for accurate predictions regarding coexistence. In contrast, the method based on Tilman’s consumer resource model does not assume that interaction coefficients are independent of species densities, but instead quantifies both inter- and intraspecific interaction coefficients only at the steady-state density for monocultures. This means that the interaction coefficients, and thus ND and RFD, measured according to either of the phenomenological methods (Figures 2 and 3) are unlikely to match the values predicted from a mechanistic method.

This comparison of the methods highlights an important caution for the field of modern coexistence theory, namely that estimates of ND and RFD obtained by different methods are not always comparable. For example, future syntheses or meta-analyses cannot include studies that measured ND and RFD by different methods. Even within a single method (e.g. the Lotka Volterra method) there can be substantial differences in the estimates of ND and RFD depending on the experimental design and how the interaction coefficients were parameterized. Nonetheless, it appears that each of these methods is capable of correctly predicting coexistence based on the criterion of mutual invasibility.

**Part 2. An empiricist’s guide to when, why, and how each method should be used to predict coexistence and estimate ND and RFD**

Having described and compared the foundation of each empirical method, here in Part II of the paper we now to help empiricists determine 1) which method(s) are most appropriate for their study system, 2) how much experimental effort is required for a given method, and 3) what types of predictions the method can deliver. To aid our discussion, we have summarized the methods in Table 1, which is organized into three sections. The section ‘Decision Steps’ is a decision tree that allows an empiricist to identify the most appropriate method for their study system. The ‘Method’ section directs the empiricist to the key literature for each method. The section ‘Experimental Requirements’ outlines key aspects of the experiments that are required to use the method.

* 1. *Decision Steps - deciding which method to use*

The first section of Table 1 (Decision Steps) uses a sequence of questions about the study system that help an empiricist identify the most appropriate method for their work. The first question asks whether the method must yield estimates of ND and RFD that can be directly related back to Chesson’s inequality (eq. X). This distinction is important since the outputs from this method should not be compared to the other four methods. Thus, Question 1 isolates the negative frequency dependence method from all others. However, the negative frequency dependence method can accurately predict coexistence based on mutual invasibility and, depending on the answers to the remaining questions, it could be the most appropriate method for some study systems. In particular, the NFD method is the only option that does not require that the empiricist grow each species alone as a monoculture (Question 2). This could be an advantage for study systems where experimental manipulations are not feasible (e.g. long-lived species, protected habitats). Several empirical studies have implemented the NFD method in experiments [Levine and HilleRisLambers 2009; Chung and Rudgers 2016] and other similar studies have used NFD in observational studies [Adler et al 2010].

The next question in the decision sequence is whether the empiricist knows which specific resources the species are competing for and can quantify the dependence of each species’ population dynamics on those resources (Question 3). This question separates the four methods for estimating ND and RFD into two separate groups. The phenomenological methods (Lotka-Volterra and Sensitivity) are those that are informed by quantifying species interactions, but which make no assumptions about the resources that species are competing for (highlighted in green). The mechanistic methods (MacArthur’s CRM and Tilman’s CEM) are based on consumer resource models in which species are assumed to interact only by competing for shared resources (highlighted in blue). To use either of the mechanistic methods, an empiricist needs to know which resources determine niche differences. In certain cases, it will not be possible for an empiricist to answer ‘yes’ to Question 3, because the resources required for species to grow are not known or cannot be readily quantified. When one cannot answer yes to Question 3, then the Lotka-Volterra and Sensitivity methods are appropriate because they can still quantify ND and RFD even if the empiricist does not have a good understanding of which resource(s) species are competing for, and thus, which resources define their niche axes. Because this decision step is so influential, the remaining steps are particular to either the phenomenological or mechanistic methods.

Deciding between the Lotka-Volterra method and the Sensitvity method (phenomenological methods, highlighted in green), depends on the answers to whether the method must work for observational datasets (Question 4), whether it is necessary to experimentally grow each species as at steady-state near its carrying capacity (Question 5), and whether the method can be used to predict coexistence among 3 or more species simultaneously (Question 7). An empiricist working with long-lived species or in protected habitats would likely answer ‘yes’ to Question 4, eliminating the sensitivity method. In this case, the empiricist would need to decide whether it is essential to obtain values of ND and RFD compatible with the other four methods (requiring the Lotka Voltera Method) or whether the negative frequency method could be employed to predict mutual invasibility and thus coexistence. Similarly, if an empiricist is unable to answer ‘yes’ to Question 5, she/he would be forced to use either the Lotka Volterra Method or the negative frequency dependence method. The distinction in Question 5 could be particularly important for slowly-growing species where it is possible to parameterize the carrying capacity term from a time series of species densities, but it would take too long for the species to approach the carrying capacity to justify beginning an invasion by the other species. Lastly, the two phenomenological methods differ in terms of whether they can predict species coexistence among three or more species simultaneously (Question 7). While the Lotka-Volterra model can be parameterized to obtain all pairwise competition coefficients for a pool of species, it has not been applied to predicting coexistence of more than two species simultaneously. The sensitivity method can be used beyond pairwise species interactions, however this is limited to situations where all non-focal species can be considered in aggregate (e.g. species *i* invading a community of *j+k+l*).

Deciding between the MacArthur and Tilman CRM methods (mechanistic methods, highlighted in blue), is straightforward and depends on whether the resources that the species compete for are abiotic and governed by a constant rate of supply (e.g. inorganic nutrients consumed by plants) or biotic with their own population dynamics (Question 6). It is worth noting that Tilman’s R\* concept has been extended to include competition mediated by predators (e.g. P\*, Tilman 1982). However, to date, models including predation have not been related to Chesson’s ND and RFD. Additionally, use of MacArthur’s consumer model can theoretically work for more than two species at a time, but this has not been demonstrated for the method based on Tilman’s consumer-resource model (Question 7).

Using this decision tree, an empiricist can determine which method(s) are appropriate for their study system. Due to the study system or experimental constraints, an empiricist may have multiple options for which method to use. In these cases it can be useful to consider the experimental requirements of each method (Table 1, *Experimental Requirements*) and the tradeoffs among the methods in terms of their utility as discussed in Part 3.

* 1. *Experimental Requirements*

In addition to the decision steps outlined in Table 1, there are important practical differences for the experimental or observational studies required to quantify ND and RFD for each method. The most important difference in study design among these methods is whether or not they require species to be grown together in order to make a prediction about coexistence. The negative frequency dependence method and the two phenomenological methods require each pair of species to be grown together in at least one co-culture, but the mechanistic methods do not require the species to be grown together as co-cultures. This distinction means that only the mechanistic methods can yield predictions about coexistence of species without the need for pairwise competition experiments. For example, consider a typical competition experiment involving a pool of three species (A, B, and C). The mechanistic methods can make predictions about all pairwise combinations of the species (A+B, A+C, and B+C) based solely on information about each species when grown individually. The phenomenological methods, however, require at least one co-culture for each pairwise combination of species, which means that information from pairs A+B and A+C cannot be used to make a prediction about coexistence for the pair B+C. The need for species to be grown together in co-culture has important implications for the total number of experimental treatments that would be required to quantify ND and RFD.

Experiments using the phenomenological methods can require more experimental treatments to predict pairwise coexistence among a pool of species than the mechanistic methods do. For the phenomenological methods, the number of experimental treatments required for all pairwise combinations of species increases exponentially with each additional species being considered. In contrast, for the mechanistic methods the total number of experimental treatments required increases linearly with the number of species being considered. This is because the methods based on consumer-resource models do not require any direct competition experiments in order to estimate competition coefficients (*αii* or *αjj*), while all of the phenomenological methods require at least one co-culture of each species pair in order to quantify the competition coefficients. As a result, the relative efficiency of the phenomenological versus mechanistic methods depends upon both the number of species being considered and also the number of resources. When the number of species being considered is small and the number of limiting resources is few, the difference in experimental effort can be modest. For example, to predict pairwise coexistence among a pool of four species, using the Sensitivity Method requires 16 experimental treatments (time series): 4 monocultures to parameterize both maximum growth rate and carrying capacity and 12 invasions to parameterize sensitivity (A invading B, B invading A, etc.). In contrast, using either of the consumer resource models (two limiting resources) would require two experiments per species for a total of 8 experiments. If the mechanistic methods require parameterizing four or more limiting resources, then the phenomenological methods may be more efficient for a pool of four species.

However, for larger pools of species the difference can be substantial. Obtaining pairwise estimates of ND and RFD for a pool of 10 species requires between 55 and 180 treatments for the phenomenological methods but as few as 20 treatments for mechanistic methods.

In addition to the number of experimental treatments required for each method, it is important to consider the amount of effort and time required for each treatment. Specifically, the negative frequency dependence, Lotka Volterra, and sensitivity methods require time series of species densities in the experimental or observation study. In the case of the negative frequency dependence method and the sensitivity method, these time series may be short in duration (i.e. at least one generation) and focused only on population dynamics when species densities are very low or near the steady-state density of monocultures. However, the Lotka Volterra method requires longer time series in order to parameterize both the interaction coefficients and carrying capacities. Longer time series in monoculture and co-culture are more easily attainable for quickly-growing species like microbes and invertebrates, but even short time series could be prohibitively arduous for slowly growing species like trees.

Ultimately, the total effort and resources required for a study is jointly determined by the method, number of species, number of limiting resources (if applicable), length of time series, level of replication, and any other design elements. Using Table 1 as a guide, an empiricist should be able to select a method and begin to design a study that satisfies their aims.

**Part 3. ~~Cautions and future directions~~**

In Part 1 we explained how each of the five methods should be used to predict coexistence among pairs of species and showed that while the methods are not mathematically identical and do not always give comparable values of ND and RFD, they can all be used to accurately predict coexistence. In Part 2 we offer a decision framework for empiricists to select the most appropriate method given their study system, aims, and experimental capabilities. Here in Part 3, we offer advice for empiricists on navigating the tradeoffs among the methods, caution against synthesizing measurements of ND and RFD from different methods, and highlight future directions for implementing modern coexistence theory empirically.

3.1 Tradeoffs Between Phenomenological and Mechanistic Methods

Given the substantial differences in experimental design requirements and effort among the five methods, it is likely that empiricists will encounter tradeoffs in selecting a method for their study system. The most obvious tradeoff is between the phenomenological methods and the mechanistic methods, which differ in three key areas.

First, the phenomenological methods make no assumptions about the resources that the species compete for, which could be an advantage if an empiricist lacks a detailed understanding of the interactions among their species pool. Except for highly controlled experiments where the empiricist can define the relevant niche axes or contexts where the number of niche axes is limited, it might be difficult to parameterize either of the mechanistic methods in practice. For example, an empiricist would be unable to answer ‘yes’ to Question 3 when studying consumer species that are capable of eating numerous different types of plants. It is unlikely that an empiricist could measure the substitutivity of the different plant species in a consumer’s diet, let alone the population dynamics of each plant species available to the consumer.

If however, an empiricist is able to answer ‘yes’ to Question 3, using the methods based on mechanistic models would mean that she/he could predict the coexistence (or not) of any species pair based solely on experiments that take measurements from each species grown alone in monoculture. Another aspect of the mechanistic models is that, in some cases, they might not adequately describe the biology that affects species interactions. For example, flexible elemental quotas (i.e. 1/yield) in phytoplankton is both widespread [Goldman 1979 Nature] and known to affect the outcome of coexistence [Grover 1991 Am Nat 134:4 p.811-835], but this mechanism has not been related to the calculations for ND and RFD.

Second, the mechanistic methods can be far more efficient for considering coexistence among a large species pool. A key disadvantage of all three phenomenological methods is that they require each pair of species to be grown together in competition, which causes the total effort to increase exponentially as more species are considered. The mechanistic methods offer the ability to make predictions about combinations of species without the need to perform all pairwise competition experiments, which has been used as an argument against phenomenological approaches to study niche theory [Tilman 1982]. Moreover, the ability to predict coexistence among pairs of species without the need to grow them together could be useful for addressing certain ecological questions (e.g. invasions by introduced species) that would be impractical using the phenomenological methods.

Third, the mechanistic methods offer the ability to make predictions about species coexistence under different resource supply environments. Letten et al. showed that the Tilman consumer resource model can be used to predict the ND and RFD at different nutrient supply rates or dilution rates (Letten et al. 2017). In contrast, the phenomenological methods cannot be used to predict coexistence when any environmental conditions are changed unless a new set of experiments is performed under those conditions. The ability of the mechanistic methods to handle some changes to environmental context, while limited, could be useful for predicting how anthropogenic stressors (e.g. nutrient pollution) are likely to affect species coexistence. However, aside from limiting resources, neither of the mechanistic methods could be applied to other environmental changes that are known to affect species and their interactions (e.g. temperature).

*Caution 1: Using only ND and RFD to assess mutual invasibility assumes negligible environmental fluctuations*

The five methods reviewed here only apply to fluctuation independent mechanisms of coexistence so that environmental dependent mechanisms, i.e. relative nonlinearity and storage effects, are assumed to be negligible. Empiricists should be able to neglect fluctuation dependent mechanisms and still correctly predict species coexistence, when conducting well-controlled experiments. However, it has been shown that environmental fluctuation can be important to mediate species coexistence in some empirical systems where environmental fluctuations cannot be negligible (Jiang andMorin 2007, Angert et al. 2009). When applying these five methods to predict coexistence, one should justify that environmental fluctuations can be negligible.

*Caution 2: Be aware to the limitation of each method*

Although we have shown that the empirical approaches for predicting coexistence among species can give the same qualitative outcome, each method has its own assumptions or limitations. For instance, the Lotka-Volterra method assumes that the per capita effect of species *i* on species *j* is independent of the density of either species *i* or species *j*. However, there are cases where this assumption is clearly not met (Schoener 1974, Abrams 1980). A hypothetical situation is that, if species were limited by resources (e.g. nutrients), a positive saturating relationship between the availability of resources and per-capita growth rate would mean that density-dependence is weak at low population sizes and stronger at higher population densities. Thus, both the inter and intraspecific competition coefficients would appear to be very small if measured at low population densities and very high if measured at population densities approaching the steady-state biomass. In designing and interpreting experiments, it would be unclear which value to select for the interaction coefficients. Consequently, it is important to apply the empirical method at the conditions that follow the assumptions. When those assumptions are not recognized and justified, any of these five methods can give misleading predictions.

*Caution 3: Limits to the applicability of CRM.*

As shown in table 1, using either of the methods based on consumer-resource models requires that the empiricist knows what the resources that species are competing for. This is more easily achieved for certain experimental systems (e.g. microbes grown under laboratory conditions) than others (e.g. mammals). However, in reality, it is hard to know for sure which resources or factors govern population dynamics. While these experiments are useful for isolating the *mechanism* of competition, they require detailed knowledge about natural history of the organisms, which in many cases is unknown.

*Future directions*

We have shown that five methods for empirically evaluating niche difference (ND) and relative fitness difference (RFD) are all capable of predicting coexistence, but there are important distinctions among these methods that make each empirical method suitable for different conditions. We offer future directions that could benefit the development of modern coexistence theory. First, the modern coexistence theory is under-developed for multi-species systems (but see Carroll et al 2011). In theory, competitive hierarchy between species *i* versus *j* and *j* versus *k* might not directly translate to species *i* and *k*, when these species are engaged in intransitive competition or higher-order interaction (Levine et al. 2017). In fact, none of these three phenomenological methods (NFD, LV, and Sensitivity) can deal with intransitive competition or higher-order interactions. Importantly, the emphasis to date on pairwise interactions and experimentation means that intransitive competitive interactions and higher-order interactions, if present, are unaccounted for. Chesson’s coexistence framework is an informative synthesis so far, and how to expand this framework to multi-species system is a direction worth pursuing.

Second, we need to empirically demonstrate equivalence of these methods. To date, we are unaware of any empirical studies that have applied more than one of these methods to the same study system. According to what we have mathematically shown in part 1, all methods except the negative frequency dependency method can be reduced to the same algebra to calculate ND and RFD, and to assess Chesson’s inequality. We argue that ND and RFD derived from the NFD method should not be comparable to the other methods. However, as we show here, a few papers have applied empirically-derived parameter values obtained from one method to show that two methods are comparable (Levine andHilleRisLambers 2009, Letten et al. 2017), but these ad hoc tests do not reflect the differences in experimental design, assumptions, and calculations that are outlined in Table 2. Without knowing whether these methods are empirically equivalent, we cannot make any synthesis and make inference on the coexistence mechanisms from empirical perspective. We thus advocate studies to empirically demonstrate the equivalence of these methods. As the number of empirical studies using these methods grows, it is critical that differences among these methods are acknowledged.

**Appendix A**

In this appendix, we show that for the NFD slope to be constant, the community density must be not only saturated but also fixed. To do so, we attempt to derive the NFD slope and intercept from a two species Lotka-Volterra competition model (), where *Ni* is scaled on its carrying capacity but does not mean two species have the same carrying capacity. In a Lotka-Volterra model, there is no variable representing species’ frequency, so that we have to assume a fixed community density, *B*. This assumption also satisfies the assumption of the NFD method that the community density is always saturated. Fixing the community density makes the density dependency, *αij*, equivalent to frequency dependency (Adler et al. 2007), and allows species’ frequency to be calculated by *Ni*/*B*. The two-species Lotka-Volterra competition model can then be rewritten as follows

(A1)

, where *B* is the fixed community density and one unit decrease of *Ni* will lead to one unit increase of *Nj*. Note that *B* is an arbitrarily defined constant describing the equilibrium community density at any given density of *Ni*. From equation A1, we derive the NFD slope and intercept in the following equations.

(A2)

(A3)

From equation A2, after we fix the community density at *B*, the NFD slope becomes constant, which means the species’ per capita growth rate linearly depends on its frequency. In addition, from equation A2 and A3, we argue that both NFD intercept and slope should be used with caution in evaluating Chesson’s inequality. First, the NFD intercept represents whether species can invade the carrying capacity of its competitor from rare, so it can be used to accurately assess mutual invasibility. However, neither do the difference nor the ratio of two species’ NFD intercept (equation A2) yield the same calculation of relative fitness difference by Chesson (). NFD slope (equation A3) is also not equivalent to the equation calculating niche difference (), although the slope of NFD has been used to represent ND for annual plant communities (Yenni et al. 2012b, 2017b). Thus, while the negative frequency dependency method can correctly predict mutual invasibility, the NFD intercept and slope should not be interpreted as RFD and ND in order to evaluate Chesson’s inequality.

**Appendix B**

In this appendix, we show that sensitivity measure actually describes the impact of the entire competitor population level, not of the *per capita* level, on the per capita growth rate of focal species. We derive the sensitivity metric (*Si*) from the Lotka-Volterra competition model (equation 3). The *μi* in equation 3 is the maximum growth rate in monoculture, so it is *ri* in equation 2. The *μij* is the invasion growth rate, so that we can replace with species *j*’s carrying capacity, , and replace with 0, so that . Therefore,

(B1)

From equation B1, we see that sensitivity (*Si*) is the equilibrium density of species *j* () times the *per capita* competition coefficient (*αij*). The sensitivity thus is a measurement of the overall population effect of species *j* on focal species i but not the “*per capita*” effect of species *j*. This correction allows for measured sensitivity (*Si*) to be converted to inter-specific competition coefficients (*αij*). In addition, species’ density at the equilibrium (*N\**) is actually , so . The niche difference (ND) and relative fitness difference (RFD) can be calculated from the sensitivity metric (*Si*) because  and RFD of species *j* over species *i* is .

With the above derivation, we can derive Chesson’s inequality for coexistence (equation 1) using the sensitivity metric. From the Lotka-Volterra model, intra-specific competition (*αii*) must be greater than the inter-specific competition (*αij*) to guarantee stable coexistence. Therefore, we can have the following deduction.

, so (B2)

, so (B3)

Combining equation B2 and B3, we have an inequality for coexistence expressed with sensitivity metrics, , which is in the same form as in Chesson’s coexistence framework. As a results, we show that the sensitivity measurement (*Si*) is not directly equal to the per capita competition coefficient (*αij* in the Lotka-Volterra model), but due to its mathematic attributes, it can be used to calculate ND and RFD and correctly predict coexistence. However, as

**Table**



Table 1. The table showing the equivalent of a decision tree that helps empiricists determining when, why, and how each method should be used (Section “Decision steps”). Experimental requirements and outputs of each empirical experiment are also listed.

**Figures**

Figure 1

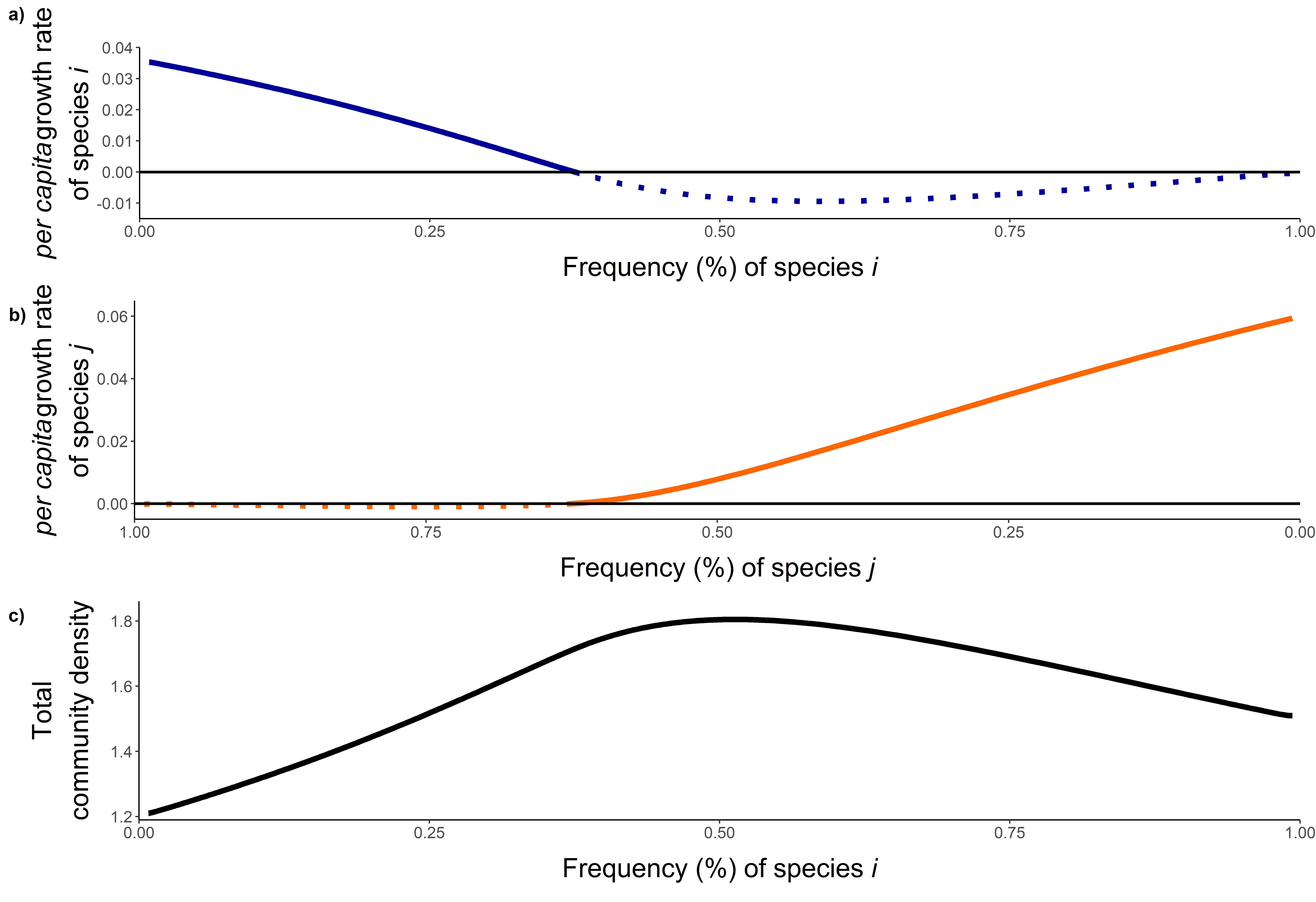


Figure 1. Simulation results of species’ per capita growth rate versus its frequency (panel a, b) from two-species Lotka-Volterra model ( and how the community density change with species’ frequency (panel c). The numerical simulations are performed with arbitrarily defined parameter values that allows species to coexist (, , , , , , ). The simulations are to mimic invasion experiment so that we set species *i* at its equilibrium density with species *j* invading from rare and set species *j* at its equilibrium density with species *i* invading from rare. From these two simulations we calculate pairs of each species’ frequency from the time series of population density. We also plugged in species’ density to the model to calculate the corresponding per capita growth rate at a given species’ frequency. In panel a and b, the species’ frequency and their corresponding per capita growth rates were used to construct frequency dependency plots. The solid parts of the line indicate where species’ density is below the bi-culture equilibrium, so that per capita growth rate is positive; otherwise species’ per capita growth rate is negative (dotted parts). In panel c, we show that community density is not fixed across species *i*’s frequency. From these simulations we see that either non-fixed community density will lead to non-liner frequency dependency.

Figure 2.

A close up of a map

Description automatically generated

Figure 2. An example plot showing the estimation of αij from fitting Lotka-Volterra model to time series. The points represent the density of species i (open circles) and j (solid dots) respectively. The dashed lines are the two fitted growth curves. The species densities were generated by a Lotka- Volterra model and added some random noise.

Figure 3



Figure 3. An example plot showing the estimation of sensitivity (*Sij*) of species *i* invading species *j* (panel a.) or the reverse (panel b.). In both panels, solid dots are the growth curve species when growing alone and the open circles are the growth curve of species when invading the carrying capacity of the other species. To estimate the sensitivity of the focal species (e.g. species *i*), the competing species (species *j*) is fixed at the equilibrium and invade the focus species to estimate the invading growth rate of the focal species.

Figure 4



Figure 4. An example plot demonstrating the idea of niche difference (ND; *ρ*) in MacArthur’s con- sumer resource model. Consumption of species *j* on resource *l* (*cjl*) are plotted against consumption of species *i* on resource *l* (*cil*). The closeness between *cjl* and *cjl* are the closeness between these points to the 1:1 line and is expressed as *ρ*. For example, if all *cjl* are equal to *cil*, which means all points are on the 1:1 line, *ρ* is 1 and ND between species *i* and species *j* is 1−*ρ* = 0. The inset plot is an example plot showing the data required to measure consumption of species *j* on resource *l* (*cjl*).

Figure 5



Figure 5. Example plots showing the empirical data required to estimate *R\** in Tilman’s consumer resource model for species *i* and *j* on resource *i* and *j*. To obtain data one would need to grow the focal species (*i* and *j*) under different resource level and measure the corresponding *per capita* growth rate, which is indicated by the blue and yellow curves in each panel. *ri* (*ri*) is the per capita maximum growth rate of species *i* (*j*), *kij* is the half saturation constant for species *i* limited by resource *j*. means the minimum level of resource *j* that allows species *i* to have positive per capita growth rate equals to the dilution rate of the experiments. The *R\**s can be used to calculate *αii* and *αij* (*αjj* and *αji*) because they determine how sensitivity species *i* will be affected by the resource (resource *j*) that limits the growth rate of species *i*.

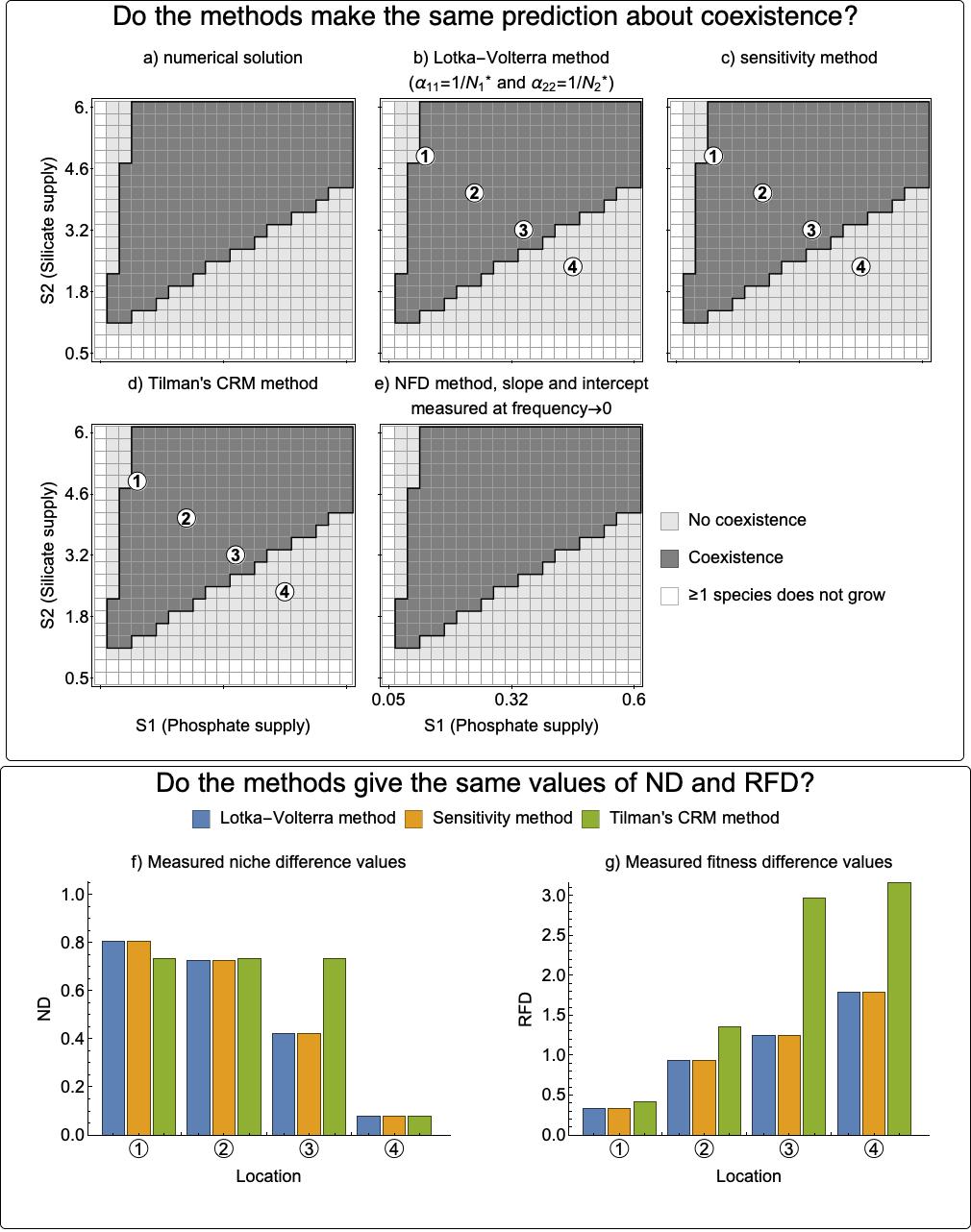


Figure 6. Predictions from the methods for coexistence under different resource supply conditions (a-e). In each panel, the predictions for coexistence are compared against the coexistence outcome based on numerical equilibrium. Three of the methods give the correct predictions regarding coexistence across this region (Lotka-Volterra, sensitivity, Tilman’s CRM) and the NFD method can give the correct prediction depending upon how it is parameterized and used. The methods did not give the same values for niche differences and relative fitness differences (f and g). The labeled locations in panels f and g correspond to marked locations in panels b-d and show that the disagreement among the methods is smaller toward the center of the parameter space that allows for coexistence. The raw RFD values from the sensitivity method were converted to the same ordering as used in the other methods (species in the denominator rather than the species with the greater sensitivity). Because the NFD method cannot be used to produce values of ND and RFD that are comparable with the other four methods, only the predictions regarding coexistence are plotted.

**Supplement 1**

In this supplement, we perform numerical simulation to show that that per capita growth rate does not linearly depend on species’ frequency, i.e. the NFD slope is not constant, under the assumptions that the community biomass is saturated and that the two species are capable of mutual invasion. We then show that depending on the frequency at which the NFD slope is evaluated, predictions of species coexistence is different and can be misleading. To show again that the NFD slope can be not constant, we performed numerical simulation using Tilman’s consumer-resource model with two species of phytoplankton. The equations and parameter values are taken exactly from Tilman 1977. Annotated code for the simulations is provided in a supplemental file. Simulations were performed using the function NDSolve in Mathematica 11.2 (Wolfram Research), employing a variable step size. For each set of resource supply concentrations, we performed four simulations: (1) species 1 as a monoculture growing from rare to near its equilibrium density; (2) species 2 as a monoculture growing from rare to near its equilibrium density; (3) species 1 at its equilibrium density with species 2 invading from rare; (4) and species 2 at its equilibrium density with species 1 invading from rare. From simulations 3 and 4, we used the time series to obtain pairs of each species frequency and its growth rate. These values were used to construct the relationships depicted in panel a and b. From panel a and b of Figure S1, we see that the frequency dependency is nonlinear for both species, i.e. the NFD slope is non-constant. The non-constant slope can lead to incorrect prediction of species coexistence. For example, under the supply ratio of panel a and b of Figure S1, two species can coexist. However, when evaluating the NFD slope at the frequency in the red regions, species are not predicted to coexist.

We subsequently show that when the NFD slope is not constant, using NFD slope can be problematic in practice. To further show that non-constant NFD slope is problematic in predicting species coexistence, we again perform simulations using Tilman’s consumer-resource model with two species of phytoplankton. We the show whether different methods, including the sensitivity method, Letten’s method, fitting Lokta-Volterra method and the NFD method, give the same prediction under a limited range of resource supply concentrations. We perform an additional numerical simulation (“competition experiment”, panel a of Figure S2) to determine whether the species can coexist when both are introduced at low densities and allowed to reach equilibrium biomass. For each simulation, the parameter values were taken directly from Tilman 1977 and only the supply concentration of phosphate and silicate were varied. For each set of resource conditions, we performed four different numerical simulations: (1) species 1 as a monoculture growing from rare to near its equilibrium density; (2) species 2 as a monoculture growing from rare to near its equilibrium density; (3) species 1 at its equilibrium density with species 2 invading from rare; (4) and species 2 at its equilibrium density with species 1 invading from rare. Note that for the NFD method (panel e-j of Figure S2), because the NFD slope depends on species’ frequency, we used the NFD slope evaluated at three frequencies, including near 0% (panel e and h of Figure S2), 50% (panel f and i of Figure S2) and near 100% (panel g and j of Figure S2), and each complimented with (panel e-g of Figure S2) or without (panel h-j of Figure S2) extrapolated vertical intercept that represent the expected growth rate when at rare. For the NFD methods, we see that only when using the NFD slope evaluated at near 0% frequency and complimented with extrapolated vertical intercept, the predictions of species coexistence based on NFD method match the those of the other methods. While certain intermediate frequencies of the two species can be used to make accurate predictions (Figure S2), an empiricist would not know these frequencies without performing the competition experiments or examining frequency dependence across the entire range of frequencies.

Figure S1

A close up of a map

Description generated with very high confidence

Figure S1. Figures showing the simulation results of per capita growth rate versus frequency of species 1 and 2 (panel a and b) and the growth rate dependency across different resource ratio (panel c) At any frequency of the two species, the NFD method requires that we use the slope to extrapolate and estimate the growth rate when a frequency approaching zero (the extrapolated vertical intercept). For frequencies where this method predicts mutual invasibility for both species, i.e. species can coexist, the lines are blue. For frequencies of the two species where the method leads to the incorrect prediction, the lines are red. Both species have positive growth rates when their frequency approaches zero, indicating that they are mutually invasible. The coexistence equilibrium occurs at a frequency of 0.88 for species 1 and 0.12 for species 2. At point A, corresponding to frequency of 0.5 for each species, this method does not predict coexistence because while species 1 would be expected to have a positive growth rate when rare (also has negative NFD slope), species 2 is predicted to have a negative growth rate when rare (positive slope of NFD). If an empiricist did their work between species 1 frequency of ~0.05 to ~0.85, and used the slope of NFD, they would incorrectly predict that the species will not coexist. At point B, which is close to their equilibrium frequencies, both species have negative NFD slope and should have positive growth rates when rare based on this method. Panel c shows the fidelity of prediction from the NFD method as a function of Si:P ratio and the frequency of the two species. The vertical dashed line represents the slice depicted in panels a and b. For all of the Si:P ratios shown in panel c, the species are mutually invasible and will coexist. This plot indicates that using NFD will often predict that the species will not coexist, when in fact they do coexist. This is important because without doing the full range of species frequencies in an experiment, one would not know whether and where the relationship between frequency and growth rate is non-linear.

Figure S2.

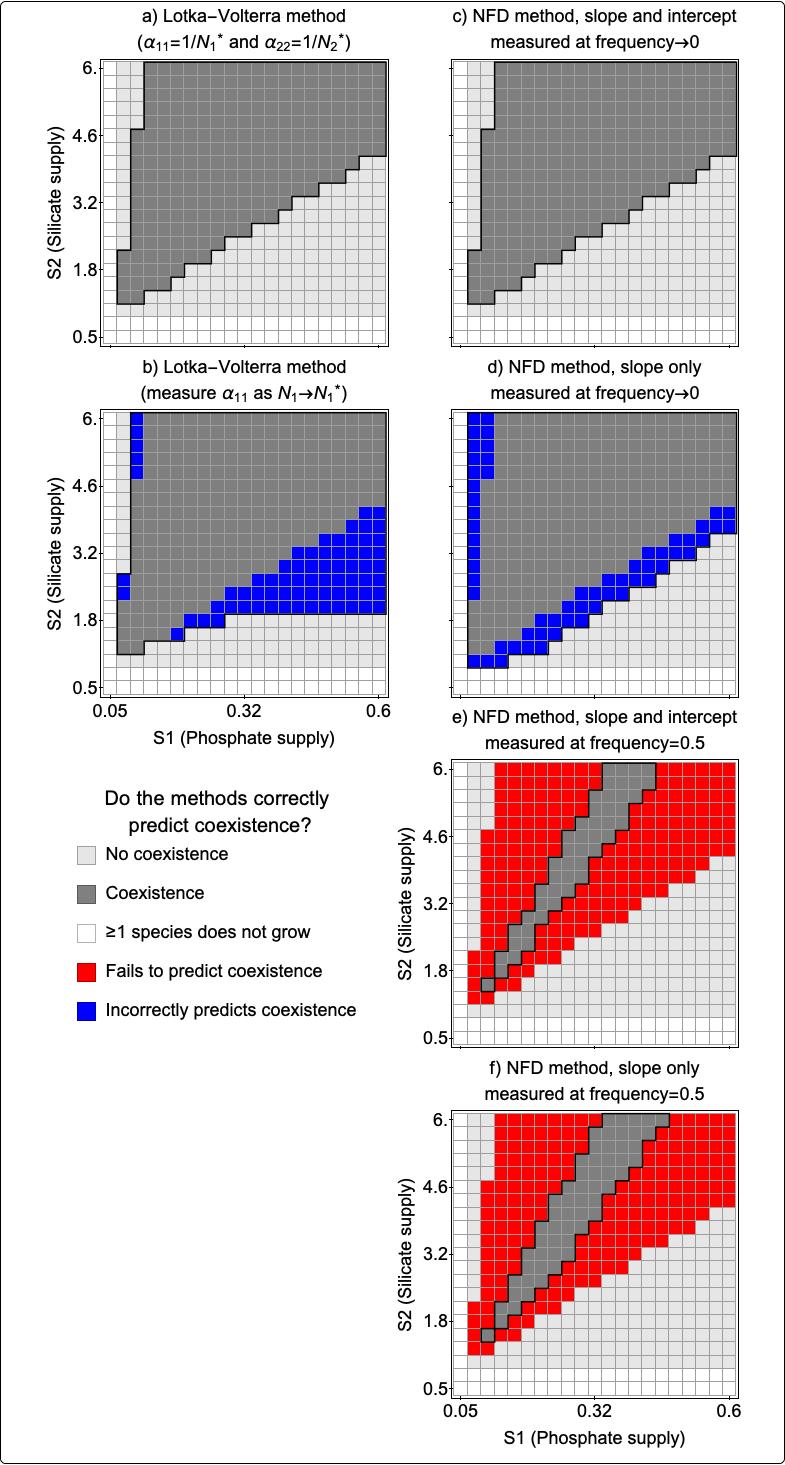


Figure S2. Simulation results showing the parameter space in which two species are predicted to stably coexist using different methods. In each panel, the outcome is compared against the equilibrium from numerical simulation.

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