

# How Fluctuation-Dependent Coexistence Mechanisms Affect the Temporal Stability of Ecosystem Function

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ABSTRACT: For biodiversity to increase the temporal stability of ecosystem function in the long-term, coexistence must be stable. Species-specific responses to environmental variation through time is key to understanding fluctuation-dependent coexistence mechanisms and how asynchrony in species dynamics can arise to stabilize ecosystem function. Despite the shared dependence on environmental fluctuations, theory on species coexistence and the relationship between species richness and ecosystem stability have developed independently. To formally link the two bodies of theory, we use consumer-resource models where coexistence between two species utilizing a single resource is maintained by two fluctuation-dependent mechanisms: the storage effect and relative nonlinearity. We examine how the strength of species coexistence relates to the temporal stability of aggregate ecosystem function and how the effect of environmental variability on stability is mediated by the mechanism of coexistence. Blah, blah, blah...

**Keywords:** coexistence, storage effect, relative nonlinearity, diversity-stability hypothesis, pulsed differential equation, consumer-resource dynamics, synchrony

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## 22 Introduction

23 Species-specific responses to non-constant environmental conditions can stabilize species coex-  
24 istence (Chesson 2000) and ecosystem function (Loreau 2010). This means that fluctuation-  
25 dependent mechanisms of species coexistence are the very same mechanisms that link biodi-  
26 versity and ecosystem function. Yet, the theory that has developed over the past 20 years to  
27 explain the, generally, positive relationship between species richness and stability of ecosys-  
28 tem function has implicitly assumed species coexistence (Loreau 2010), or, when explicitly  
29 considered, coexistence is maintained by fluctuation-independent mechanisms (Turnbull et  
30 al. 2013). Despite rapid theoretical developments in the fields of species coexistence and  
31 biodiversity-ecosystem function, a gulf remains between the two lines of inquiry (Carroll et  
32 al. 2011, Turnbull et al. 2013). This is especially surprising since stable coexistence, however  
33 maintained, is a prerequisite for biodiversity to confer stability of ecosystem function in the  
34 long term.

35 Among the dizzying array of mechanisms that can maintain diversity, Chesson (2000)  
36 formalized two broad classes: fluctuation-independent and fluctuation-dependent mechanisms.  
37 Both classes of mechanisms rely on niche differences being greater than relative fitness  
38 differences for all species pairs in a community (Chesson 2000, Adler et al. 2007). In a  
39 fluctuation-independent case, species coexistence can be maintained by resource partitioning  
40 so long as each species is limited by a different resource (Tilman 1982). Much of the theoretical  
41 literature aimed at deciphering the mechanisms behind the diversity-stability relationship  
42 implicitly assumes fluctuation-independent coexistence. For example, Lotka-Volterra models  
43 have been widely used and include coexistence by keeping competition coefficients less than  
44 one (e.g., Loreau and de Mazancourt 2013). Our focus, on the other hand, is on the interaction  
45 between species coexistence and ecosystem stability in communities where coexistence is  
46 dependent on environmental fluctuations.

47 There are two ways that species coexist in temporally fluctuating environments. First,

there is the storage effect, where species coexistence is stable if the following three conditions are met: (i) have unique responses to environmental conditions, (ii) have some way to persist in unfavorable years, and (iii) the effects of competition must be greater in ‘good’ years relative to ‘bad’ years (Chesson 2000). Second, there is relative nonlinearity, where species have unique, nonlinear responses to a shared resource that fluctuates through time (Chesson 2000).

Both the storage effect and relative nonlinearity require that species have unique responses to environmental conditions. Not only do such species-specific responses stabilize coexistence, they can also stabilize ecosystem function by creating compensatory dynamics. All else being equal, ecosystem stability is highest when species responses to the environment are perfectly uncorrelated. Under the storage effect, uncorrelated species responses to the environment also results in the most stable conditions for coexistence. It stands to reason, then, that the strength of the storage effect should predict the degree to which species asynchrony stabilizes ecosystem function. However, the exact relationship between storage effect strength and ecosystem stability could take many, unknown, forms.

Unlike the potential interaction between the storage effect and ecosystem stability, how relative nonlinearity might interact with ecosystem stability is less clear.

## Model and Analysis

### A General Consumer-Resource Model

We start with a general consumer-resource model where the consumer can be in one of two-states: a dormant state  $D$  and a live state  $N$  (Fig. 1). Transitions between  $N$  and  $D$  occur at discrete intervals  $T$ , so our model is formulated as “pulsed differential equations” (Pachepsky et al. 2008, Mailleret and Lemesle 2009). For clarity we refer to  $T$  as years and the growing time between years as seasons with daily ( $\tau$ ) time steps. Seasonal (within-year) dynamics are modeled as three differential equations:

$$\frac{dD_i}{d\tau} = N_i a_i - (m_{D,i} D_i) \quad (1)$$

$$\frac{dN_i}{d\tau} = N_i [f_i(R) - m_{N,i} - a_i] \quad (2)$$

$$\frac{dR}{d\tau} = r_\tau - \sum_{i=1,2} f_i(R) N_i \quad (3)$$

73 where  $i$  denotes species,  $D$  is the dormant (long-lived) biomass state,  $N$  is the living biomass  
74 (fast-growing, shorter-lived) state,  $a$  is fraction of life biomass allocated to seed production,  
75 and  $m$  is the biomass loss rate. The growth rate of living biomass is a resource-dependent  
76 Hill function,  $f_i(R) = b_i R^{\alpha_i} / (\beta_i^{\alpha_i} + R^{\alpha_i})$ , where  $b$  is a species' intrinsic growth rate and  $\alpha$  and  
77  $\beta$  define the curvature of the function. The single resource  $R$  is replenished with daily pulse,  
78  $r_\tau$ , randomly drawn from a log normal distribution:  $r_\tau = \text{LogNormal}(R_\mu, R_\sigma)$ . Resource  
79 depletion is equal to the sum of each species' consumption,  $\sum_{i=1,2} f_i(R) N_i$ .

80 At the beginning of each season we start with initial conditions defined as  $V_t$ ,  $W_t$ , and  
81  $Z_t$  for the dormant state, the live state, and the resource, respectively. So for each season,  
82 eqs. 1-3 are solved given the initial conditions:

$$D_i(0) = V_{i,t} \quad (4)$$

$$N_i(0) = W_{i,t} \quad (5)$$

$$R(0) = Z_t \quad (6)$$

83 The consumers transition between  $N$  and  $D$  instantaneously between years. So, at the yearly  
84 transition:

Table 1: Definition of model states and parameters. ‘Constant’ parameters do not fluctuate during a simulation, while ‘variable’ parameters do fluctuate through time in a given simulation.

Parameter	Definition
$N$	live biomass
$D$	dormant biomass
$R$	resource supply
$m_D$	dormant state mortality rate (constant)
$b$	live state maximum resource uptake rate (constant)
$m_N$	live state mortality rate (constant)
$a$	allocation fraction of live biomass to seed bank (constant)
$g$	dormant-to-live biomass transition fraction (variable)
$\rho$	correlation of species’ responses transition cue (constant)
$\sigma_E^2$	variance of transition cue (constant)
$r$	daily resource supply pulse (variable)
$R_\mu$	mean resource pulse, on log scale (constant)
$R_{\sigma^2}$	variance of daily resource supply, on log scale (constant)

$$V_{i,t+1} = [N_i(T^-) + D_i(T^-)](1 - g_t) \quad (7)$$

$$W_{i,t+1} = [N_i(T^-) + D_i(T^-)]g_t \quad (8)$$

$$Z_{t+1} = R(T^-) + R(T^+) \quad (9)$$

where  $D(T^-)$ ,  $N(T^-)$ , and  $R(T^-)$  are the densities of each state at the end of the year and  $g$  is a time-fluctuating activation rate that regulates how much dormant biomass is converted to growing-season live biomass each year.  $R(T^+)$  is a randomly generated resource pulse from a log-normal distribution with mean  $R_\mu$  and variance  $R_{\sigma^2}$  (same mean and variance used to generate daily pulses). Our formulation assumes that at the end of each season all accumulated living biomass  $[N(T^-)]$  is converted to dormant biomass. Parameter notations and definitions are in table 1.

## Implementing the Storage Effect

To make this a “storage-effect” model, we need to satisfy three conditions: (1) the organisms must have a mechanism for persistence under unfavorable conditions, (2) species must respond differently to environmental conditions, and (3) the effects of competition on a species must be more strongly negative in good years relative to unfavorable years. Our model meets condition 1 because we include a dormant stage with very low death rates. We satisfy condition 2 with our model whenever  $g$  is not perfectly correlated between species. Lastly, our model meets condition 3 because condition 2 partitions intraspecific and interspecific competition into different years. Thus, during a high  $g$  year for one species, resource uptake is also inherently high for that species, which increases intraspecific competition relative to interspecific competition. So, given adequate variability in  $g$ , the inferior competitor (species with lower  $r$ ) can persist.

Following Adler and Drake (2008), we generated sequences of (un)correlated dormant-to-live state transition rates ( $g$ ) for each species by drawing from multivariate normal distributions with mean 0 and a variance-covariance matrix ( $\Sigma_g$ ) of

$$\Sigma_g = \begin{bmatrix} \sigma_E^2 & \rho\sigma_E^2 \\ \rho\sigma_E^2 & \sigma_E^2 \end{bmatrix} \quad (10)$$

where  $\sigma_E^2$  is the variance and  $\rho$  is the correlation between the two species’ transition rates. For environmental variability, here induced as variability in  $g$ , to promote coexistence via the storage effect,  $\rho$  must be less than 1. The inferior competitor has the strongest potential to persist when  $\rho = -1$  (perfectly uncorrelated transition rates).

## Implementing Relative Nonlinearity

When considering consumer-resource dynamics, species coexistence by relative nonlinearity requires that each species has different nonlinear responses to resource availability, and resource availability must fluctuate through time. In a constant resource environment, the species with the lowest  $R^*$  will always exclude the other species. So we can compare this model to the storage effect model, we still allow the germination rate  $g$  to vary, but both species are perfectly correlated – that is,  $\rho = 1$ .

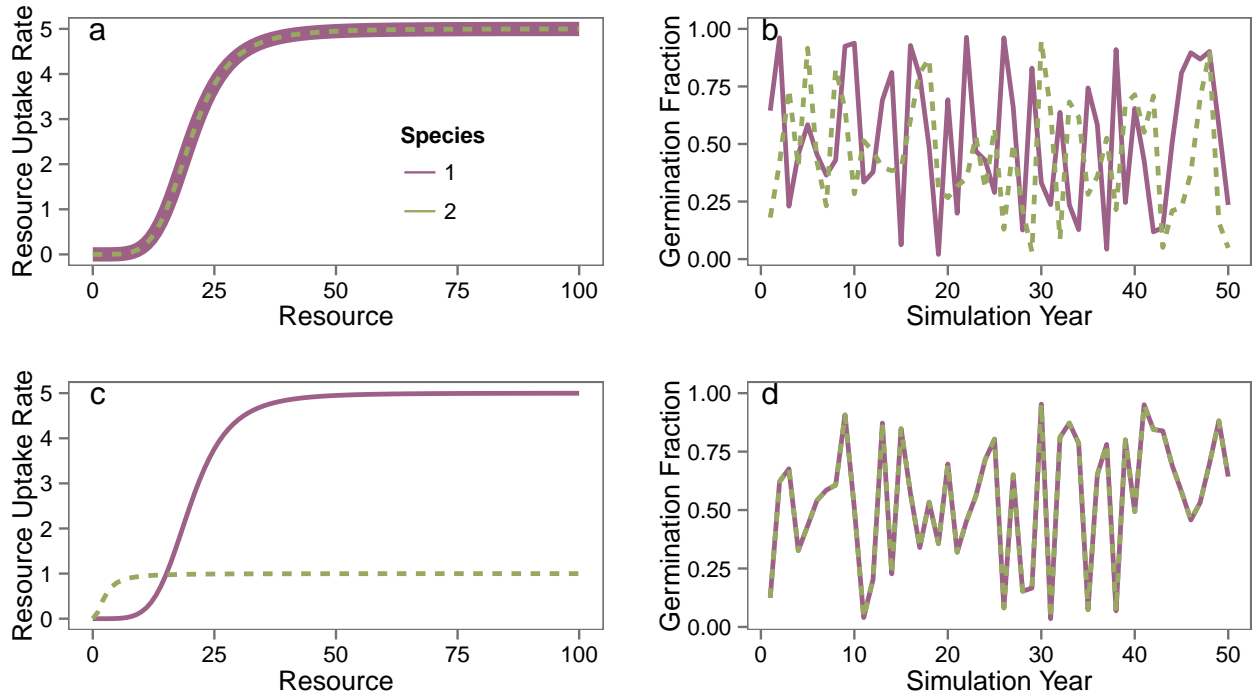


Figure 1: Resource uptake functions and example time series of (un)correlated germination fractions for the storage effect (*a,b*) and relative nonlinearity (*c,d*) formulations of the consumer-resource model. The resource uptake functions for both species are equivalent for the storage effect, but their germination fractions are uncorrelated in time. The opposite is true for relative nonlinearity: the two species have unique resource uptake functions, but their germination fractions are perfectly correlated in time.

## Model Simulations

For each coexistence mechanism (storage effect, relative nonlinearity), we ran model simulations at different levels of resource variance ( $R_{\sigma^2}$ ), environmental cue variance ( $\sigma_E$ ), and

correlation of species responses to the environmental cue ( $\rho$ ). We ran simulations for 2,000 ‘years’ with 60 day growing seasons. After discarding an initial 100 years to reduce transient effects on our results, we calculated the stability of summed species biomass through time and species synchrony through time. For storage effect simulations, species were equivalent in their ability to capture and assimilate the resource ( $R$ ) but had different, depending on  $\rho$ , germination rates. For relative nonlinearity simulations, species had equivalent germination rates ( $\rho = 1$ ) but different resource acquisition functions (fig. 1). We explored a limited set of parameter space where the storage effect and relative nonlinearity were operating simultaneously. Within-season dynamics were solved given initial conditions using the package ‘deSolve’ (Soetaert et al. 2010) in R (Team 2013).

## Results

## Discussion



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