

## Appendix A: Ecological model assumptions.

In this section we discuss the assumptions of the ecological model in detail. First, we assumed that communities initially contained the same set of species and differed only in environmental variation as defined by the phase parameter,  $x_j$  (Figure 1a). Second, we assumed that species differed only in their consumption rates, which varied by community as a function of  $H_i$  and  $x_j$  (Figure 1b). This implies that species are similar in their ecological function and exist within a single trophic level. Consumption rates are also deterministic. Stochastically varying consumption rates changes the source-sink effects of dispersal but does not alter non-monotonic relationship between biodiversity and dispersal (Urban, 2006). Third, we assumed that species competed for a single limiting resource whose natural influx and loss rates are constant and independent across time and space. Between-patch heterogeneity in resource influx rates changes the capacity for patches to maintain species stocks and subsequently the flows of species between them. Shanafelt et al. (2015) showed that stochastically varying resource influx rates across space and time did not affect the biodiversity-dispersal relationship. Fourth, we assumed that species competition arose solely from resource consumption. The system is equivalent to a Holling type I predator response where species have the same conversion efficiency but different consumption (predation) rates. There is no direct interaction between individuals within and across patches (e.g. local competition for light or nutrients in plant systems).

Finally, we assumed that dispersal was density-independent and occurred at a constant rate. This implicitly assumes a spatially homogeneous environment where all patches are equally connected. When dispersal rates are low, each community functions as a separate closed subsystem. When dispersal rates are high, the metacommunity functions as a single integrated system.

Ecologically speaking, we would not expect other types of dispersal to alter the general conclusions of our model (though it will change the source-sink effect of dispersal). In a similar ecological framework Shanafelt et al. (2015) showed that making certain patches (species) easier/harder to reach (better/worse dispersers) decreased overall levels of biodiversity but did not alter the relationship between biodiversity and dispersal. Hauzy et al. (2010) demonstrated analytically that moving from a constant to density-dependent dispersal did not alter the long-term equilibria of a two-species predator-prey model.

The effect of the interaction between dispersal and harvest is less clear. We discuss two scenarios of non-constant dispersal. Recall that dispersal directly affects harvest via the movement of species out of a patch. It indirectly affects harvest by the movement of species into a patch. For species exhibiting direction or conditional dispersal, species disperse according to fitness gradients between patches which are functions of ecological parameters and species abundances (Armsworth and Roughgarden, 2005). In this case a species considers its abundance and the relative strength of competition with other species. This means that a species will disperse into a patch if the species has a competitive advantage over other species or a low abundance in the destination - likely patches where the species is suppressed or harvested.

For species exhibiting density-dependent dispersal, species disperse out of high-abundant patches into less abundant ones (Edelstein-Keshet, 2005) - likely those where the species is less competitive, suppressed, or harvested. Much depends on the distribution of relative prices of harvest. Immigration can act as a stressor on local species abundances. In our model harvest increases with dispersal, all else constant (Equation 9). The combination of the relative prices and immigration can destabilize source patches. If most species disperse into heavily suppressed

or harvest patches, then it is likely that directed or density-dependent dispersal will lower abundances compared to a case where the pool of dispersers are equally distributed across the metacommunity. The same conclusions hold for heterogeneous dispersal rates between species and/or patches.

While restrictive, these assumptions simplify the analysis while providing a structure for analyzing competition over a range of environmental conditions, and the effect of harvest on species composition and resource availability. Loreau et al. (2003), Gonzalez et al. (2009), Urban (2006), Shanafelt et al. (2015) and Thompson et al. (2014) provide detailed analyses and extensions of the Loreau spatial insurance hypothesis model.

## Appendix B: Derivation of optimal harvest.

Optimal levels of harvest effort were solved by the maximum principle (Clark, 2010). We defined the current-value Hamiltonian, hereafter the Hamiltonian. Suppressing time arguments the Hamiltonian is:

$$(S1) \quad \tilde{H} = \sum_{i=1}^s (p_{ij}qE_{ij}N_{ij} - wqE_{ij} + \alpha_{ij}N_{ij}) + \beta_j \left( 1 - \sum_{i=1}^s \left( \frac{N_{ij}}{N_j} \right)^2 \right) + \sum_{i=1}^s \lambda_{ij}\dot{N}_{ij} + \mu_j\dot{R}_j$$

where  $\lambda_{ij}$  and  $\mu_j$  represent the shadow value of species and resource biomass respectively. By converting the units of the equations of motion (biomass\*time<sup>-1</sup>) into the units of the objective function, they define the social value of a marginal change in species or resource biomass.

The Hamiltonian is linear in harvest effort, therefore the optimal control rule must include a most rapid approach path (Conrad and Clark, 1987). From (S1) the marginal impact of harvest effort on the  $i^{\text{th}}$  species depends on the size of the stock of species  $i$ :

$$(S2) \quad \frac{\partial \tilde{H}}{\partial E_{ij}} = p_{ij}qN_{ij} - wq - \lambda_{ij}qN_{ij}$$

The associated adjoint equations describe the evolution of shadow prices along any arbitrary trajectory (Clark, 2010; Fenichel and Abbott, 2014):

(S3)

$$\dot{\lambda}_{ij} - \delta\lambda_{ij} = -\frac{\partial H}{\partial N_{ij}} = \mu_j R_j c_{ij} + \lambda_{ij} (m - ec_{ij}R_j + qE_{ij} + a) - p_{ij}qE_{ij} - \alpha_{ij} - \frac{2\beta_j \left( \sum_{k \neq i} N_{kj}^2 - N_{ij} \sum_{k \neq i} N_{kj} \right)}{\left( \sum_{k=1}^s N_{kj} \right)^3}$$

$$(S4) \quad \dot{\mu}_j - \delta\mu_j = -\frac{\partial H}{\partial R_j} = \mu_j \left( l + \sum_{i=1}^s c_{ij}N_{ij} \right) - \sum_{i=1}^s \lambda_{ij}N_{ij}ec_{ij}$$

where species consumption rates,  $c_{ij}$ , are taken as exogenous following exogenous changes in  $F_j(t)$ . From (S2), assuming the optimality of the singular solution, the shadow value of an extra unit of species biomass is increasing in the social marginal net benefit of harvest effort - the difference between the marginal revenue and marginal cost per unit of harvested species.

$$(S5) \quad \lambda_{ij} = p_{ij} - \frac{w}{N_{ij}}$$

The ecological models of the spatial insurance hypothesis are concerned with the behavior of the system at equilibrium, and specifically with the effect of species dispersal on long run equilibrium productivity, stability, and diversity (Gonzalez et al., 2009; Loreau et al.,

2003; Mouquet and Loreau, 2003; Shanafelt et al., 2015). To address the long-run equilibrium properties of the social-ecological system we solved for the optimal harvest at equilibrium. In our model, equilibria are characterized by non-constant, cyclical fluctuations in species and resource biomass caused by variation in environmental conditions. This is the equivalent to a stable limit cycle in ecological models.

Evaluating (S3) and (S4) at equilibrium we can see that:

$$(S6) \quad \mu_j = \frac{\sum_{i=1}^S \lambda_{ij} N_{ij} e c_{ij}}{l + \sum_{i=1}^S c_{ij} N_{ij} + \delta}$$

That is, the value of an extra unit of resource at the steady state is the ratio of the marginal value of the biomass of all species it induces to the marginal opportunity cost of the resource. By substituting  $\lambda_{ij}$  and  $\mu_j$  into (S3), we may solve for the singular harvest effort directed at species  $i$  in terms of the model parameters:

$$(S7) \quad E_{ij}^* = \frac{N_{ij}}{wq} \left[ \begin{aligned} & \frac{e c_{ij} R_j \sum_{k=1}^S (p_{kj} N_{kj} c_{kj} - w c_{kj})}{l + \sum_{k=1}^S (c_{kj} N_{kj}) + \delta} + \left( p_{ij} - \frac{w}{N_{ij}} \right) (m + a - e c_{ij} R_j + \delta) \\ & - \alpha_{ij} - \beta_j \left( \frac{2 \left( \sum_{k \neq i} N_{kj}^2 - N_{ij} \sum_{k \neq i} N_{kj} \right)}{\left( \sum_{k=1}^S N_{kj} \right)^3} \right) \end{aligned} \right]$$

Assuming equilibrium in harvest assumes that the system reaches its equilibrium relatively quickly and the trajectories to the equilibrium are less important. In order to check the validity of this assumption, we derive an alternative full analytical solution for optimal harvest without assuming equilibrium in SI Text S3. We then verified that our results matched those obtained from the full analytical solution at equilibrium in SI Text S4.

Also note that while species abundance is impacted directly via harvest, it is also affected by ecological interactions (intraspecific competition between species in the system for the limiting resource). The resource itself is not controlled. This implies that harvest is an "imperfect control" and the singular solution (now "singular arc") is one of an infinite number of possible solutions. This has been shown to lead to complex linear feedback rules for efficient management (Fenichel et al. 2010; Horan and Fenichel 2007; Horan and Wolf 2005). Traditional linear control problems in economics rely on the existence of control variables for each state variable and that each control variable perfectly controls a different state variable at every moment in time (Conrad and Clark 1987). When this is violated, there is the possibility that the singular solution is not optimal.

While the adjustment of the state variables with imperfect control will be slower than if the control perfectly targets the states of the systems, the difference between the two may be

negligible if the indirectly-controlled state variable responds quickly to the directly-controlled ones. Therefore, we evaluated the stability of the social-ecological system (Table S1, SI Text S4). While stability is not the same as optimality, we show that the eigenvalues associated with the resource are large, which implies that the resource quickly approaches an attractor.

## Appendix C: Full-analytical derivation of optimal harvest.

The full analytical derivation of optimal harvest follows that of Fenichel et al. (2010), Fenichel et al. (2015), Horan and Fenichel (2007), and Horan et al. (2011).

First, it is useful to focus on the case with zero dispersal. Differentiating the single-patch equivalent of (S5) with respect to time yields:

$$(S8) \quad \dot{\lambda}_i = \frac{w}{N_i} (ec_i R - m - qE_i)$$

Then, by substituting (S5) and (S8) into (S4), one can solve for:

$$(S9) \quad \mu = \frac{1}{Rc_i} \left( \frac{w\delta}{N_i} - p_i (m - ec_i R + \delta) + \alpha_i + 2\beta \left[ \frac{\sum_{k \neq i} N_k^2 - N_i \sum_{k \neq i} N_k}{\left( \sum_{i=1}^S N_i \right)^3} \right] \right)$$

For simplicity, define the Simpson's index ( $B$ ) and its associated first and second derivatives as:

$$(S10) \quad B = \beta \left( 1 - \sum_{i=1}^S \frac{N_i}{N} \right)$$

$$(S11) \quad \partial B / \partial N_i = \frac{2\beta \left( \sum_{k \neq i} N_k^2 - N_i \sum_{k \neq i} N_k \right)}{\left( \sum_{i=1}^S N_i \right)^3}$$

$$(S12) \quad \partial^2 B / \partial N_i \partial t = 2\beta \left[ \frac{2 \left( \sum_{k \neq i} N_k \dot{N}_k - N_i \sum_{k \neq i} \dot{N}_k - \dot{N}_i \sum_{k \neq i} N_k \right)}{\left( \sum_{i=1}^S N_i \right)^3} + \frac{3 \left( N_i \sum_{k \neq i} N_k - \sum_{k \neq i} N_k^2 \right) \sum_{i=1}^S \dot{N}_i}{\left( \sum_{i=1}^S N_i \right)^4} \right]$$

Taking the derivative of (S9) with respect to time allows us to solve for the equation describing how the resource shadow value changes over time:

$$(S13) \quad \begin{aligned} \dot{\mu} &= \frac{-\dot{R}}{c_i R^2} \left( \frac{w\delta}{N_i} - p_i (m - ec_i R + \delta) + \alpha_i + \partial B / \partial N_i \right) + \frac{1}{c_i R} \left( -\frac{w\delta}{N_i^2} \dot{N}_i + p_i ec_i R + \partial^2 B / \partial B \partial t \right) \\ &= \frac{-\dot{R}}{R} \mu + \frac{1}{c_i R} \left( -\frac{w\delta}{N_i^2} \dot{N}_i + p_i ec_i R + \partial^2 B / \partial B \partial t \right) \end{aligned}$$

Substituting, (S5), (S9) and (S13) into (S4) allows one to solve for the optimal path of harvest per species:

$$\begin{aligned}
& Rc_i \left( \mu \left( l + \sum_{i=1}^S c_i N_i + \delta + \frac{\dot{R}}{R} \right) + \sum_{i=1}^S \lambda_i N_i e c_i \right) - p_i e c_i \dot{R} + \frac{w \delta e c_i R}{N_i} - \frac{w \delta m}{N_i} \\
& + 2\beta \left( \frac{N_i \sum_{k \neq i} \dot{N}_k - 2 \sum_{k \neq i} N_k \dot{N}_k + (N_i e c_i R - N_i m) \sum_{k \neq i} N_k}{\left( \sum_{i=1}^S N_i \right)^3} \right) \\
& + \frac{6\beta \left( N_i \sum_{k \neq i} N_k - \sum_{k \neq i} N_k^2 \right) \left( N_i m - N_i e c_i R - \sum_{k \neq i} \dot{N}_k \right)}{\left( \sum_{i=1}^S N_i \right)^4} \\
\text{(S14) } E_i^* &= \frac{\frac{w \delta q}{N_i} - \frac{6\beta \left( N_i \sum_{k \neq i} N_k - \sum_{k \neq i} N_k^2 \right) q N_i}{\left( \sum_{i=1}^S N_i \right)^4} + \frac{2\beta N_i \sum_{k \neq i} N_k}{\left( \sum_{i=1}^S N_i \right)^3}}{\dots}
\end{aligned}$$

Note that (S14) is a function of the harvest efforts of the other species in the patch. In order to solve for the full solution, one must solve (S14) for each species simultaneously - a system of three equations and three unknowns. Also note that because  $N_i^*$  is a non-autonomous function of time,  $E_i^*$  will fluctuate as a limit cycle.

To solve the full system with dispersal, note that equations (S8) and (S9) become:

$$\text{(S15) } \dot{\lambda}_{ij} = \frac{w}{N_{ij}} (e c_{ij} R_j - m - q E_{ij} - a) + a \frac{w}{N_{ij}^2} \sum_{k \neq j} N_{ik}$$

$$\text{(S16) } \mu_j = \frac{1}{R_j c_{ij}} \left( p_{ij} (e c_{ij} R_j - m - a - \delta) + \frac{w}{N_{ij}} \left( \delta + \frac{1}{N_{ij}} \frac{a}{2} \sum_{k \neq j} N_{ik} \right) + \alpha_{ij} + 2\beta \left[ \frac{\sum_{k \neq i} N_{kj}^2 - N_{ij} \sum_{k \neq i} N_{kj}}{\left( \sum_{i=1}^S N_{ij} \right)^3} \right] \right)$$

where subscripts  $i$  and  $j$  denote species and patch respectively. Following the procedure above it can be shown that  $E_{ij}^*$  is an equation that is a function of the harvest efforts of all species within patch  $j$  and the harvest effort of all species  $i$  on patch  $k$  where  $k \neq j$ . The harvest efforts of all species in the system must be solved simultaneously - a system of  $i^* j$  equations with  $i^* j$  unknowns.

## Appendix D: Comparison of equilibrium and full-analytical derivations of harvest.

Define optimal harvest assuming equilibrium (SI Text S2) and the full analytical solution (SI Text S3) as  $E_{EQ}^*$  and  $E_{FA}^*$  respectively. In order to calculate the trajectories of the biological system to equilibrium, optimal harvest rates are substituted into the equations of motion for species and resource biomass and the resulting system of differential equations solved (Fenichel et al. 2010; Horan and Fenichel 2007; Horan et al. 2011). However, even under constant species consumption rates, benefits only from harvest, and zero dispersal the system is highly nonlinear. Evaluating of the trajectories is mathematically intractable.<sup>1</sup>

Instead we calculated the steady states of the system and their stability under  $E_{EQ}^*$  and  $E_{FA}^*$ . We held species consumption rates constant, assumed benefits only from harvest and zero dispersal, and held harvest at the singular solution ( $E_{EQ}^*$  and  $E_{FA}^*$  separately). We found the same steady state values under  $E_{EQ}^*$  and  $E_{FA}^*$  though the stability of the fixed points differed between the two harvest solutions (Table S1). Under  $E_{FA}^*$  it is likely that harvest will shift the equilibrium away from the stable resource-only fixed point to a saddle that includes one or more species and the resource. Given the assumption that all species are positively valued for harvest, the full coexistence saddle point is a feasible long-run equilibrium point.

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<sup>1</sup> Analysis was conducted in Mathematica 10.4 using analytical and numerical differential equation solvers. We explored multiple methods for solving nonlinear systems of equations.



Table S1. Steady states and stability under  $E_{EQ}^*$  and  $E_{FA}^*$ .

*Equilibrium assumption,  $E_{EQ}^*$*

steady states ( $N_1^*[t], N_2^*[t], N_3^*[t], R^*[t]$ )				eigenvalues ( $N_1^*[t], N_2^*[t], N_3^*[t], R^*[t]$ )				stability of fixed point
0.000	0.000	0.000	16.500	-10.000	0.010	0.010	0.010	saddle
39.785	0.000	0.000	10.333	-14.533	-2.641	0.010	0.010	saddle
0.000	48.744	0.000	11.093	-14.610	-0.529	0.010	0.010	saddle
0.000	0.000	108.866	10.684	-15.321	-0.253	0.010	0.010	saddle
39.681	0.385	0.000	10.319	-14.568	-2.621	-0.010	0.010	saddle
39.719	0.000	0.690	10.317	-14.567	-2.626	-0.010	0.010	saddle
0.000	47.364	4.910	11.013	-14.735	-0.496	-0.010	0.010	saddle
39.614	0.386	0.693	10.303	-14.602	-2.606	-0.010	-0.010	stable node

*Full analytical solution,  $E_{FA}^*$*

steady states ( $N_1^*[t], N_2^*[t], N_3^*[t], R^*[t]$ )				eigenvalues ( $N_1^*[t], N_2^*[t], N_3^*[t], R^*[t]$ )				stability of fixed point
0.000	0.000	0.000	16.500	-10.010	-10.010	-10.009	-10.000	stable node
39.785	0.000	0.000	10.333	-247.637	-15.978	-15.978	247.647	saddle
0.000	48.744	0.000	11.093	-107.225	-14.884	-14.884	107.235	saddle
0.000	0.000	108.866	10.684	-77.362	-15.453	-15.453	77.372	saddle
39.681	0.385	0.000	10.319	-246.737	-16.001	16.001	246.747	saddle
39.719	0.000	0.690	10.317	-246.917	-16.002	16.002	246.927	saddle
0.000	47.364	4.910	11.013	-103.440	-14.992	14.992	103.450	saddle
39.614	0.386	0.693	10.303	-246.009	16.025	16.025	246.019	saddle

Steady states and stability were evaluated assuming that species consumption rates were constant such that  $c_1(t) = 0.15$ ,  $c_2(t) = 0.10$ , and  $c_3(t) = 0.05$ . Benefits were obtained solely through harvest such that  $p_1 = 25$ ,  $p_2 = 5$ ,  $p_3 = 1$ , and  $w = 65$ . All other parameters are reported in Table 1.

## **Appendix E: Effect of alternative competition parameters and environmental conditions.**

In this section, we test the sensitivity of the model to different species competition parameters and environmental conditions. Specifically we tested the boundary species competition parameters of Loreau et al. (2003) and Gonzalez et al. (2009) ( $H_i = 1$  and  $H_i = 0$ ). Compared to  $H_i = 1/2$ , the corresponding consumption rate curves were lower on average and reached a maximum only once (Figure 1b). With these competition parameters we did not observe the suppression of the least valuable species. We found similar, but asynchronous, harvest regimes for each species (Figures S1-S3). Effort was staggered such that the most valuable species was most abundant.

Environmental variation did not qualitatively affect our results. The phase parameter  $x_j$  shifts species consumption rate curves forwards or backwards in time. It affects where in the phase we end our simulations but not the behavior of the bioeconomic model.

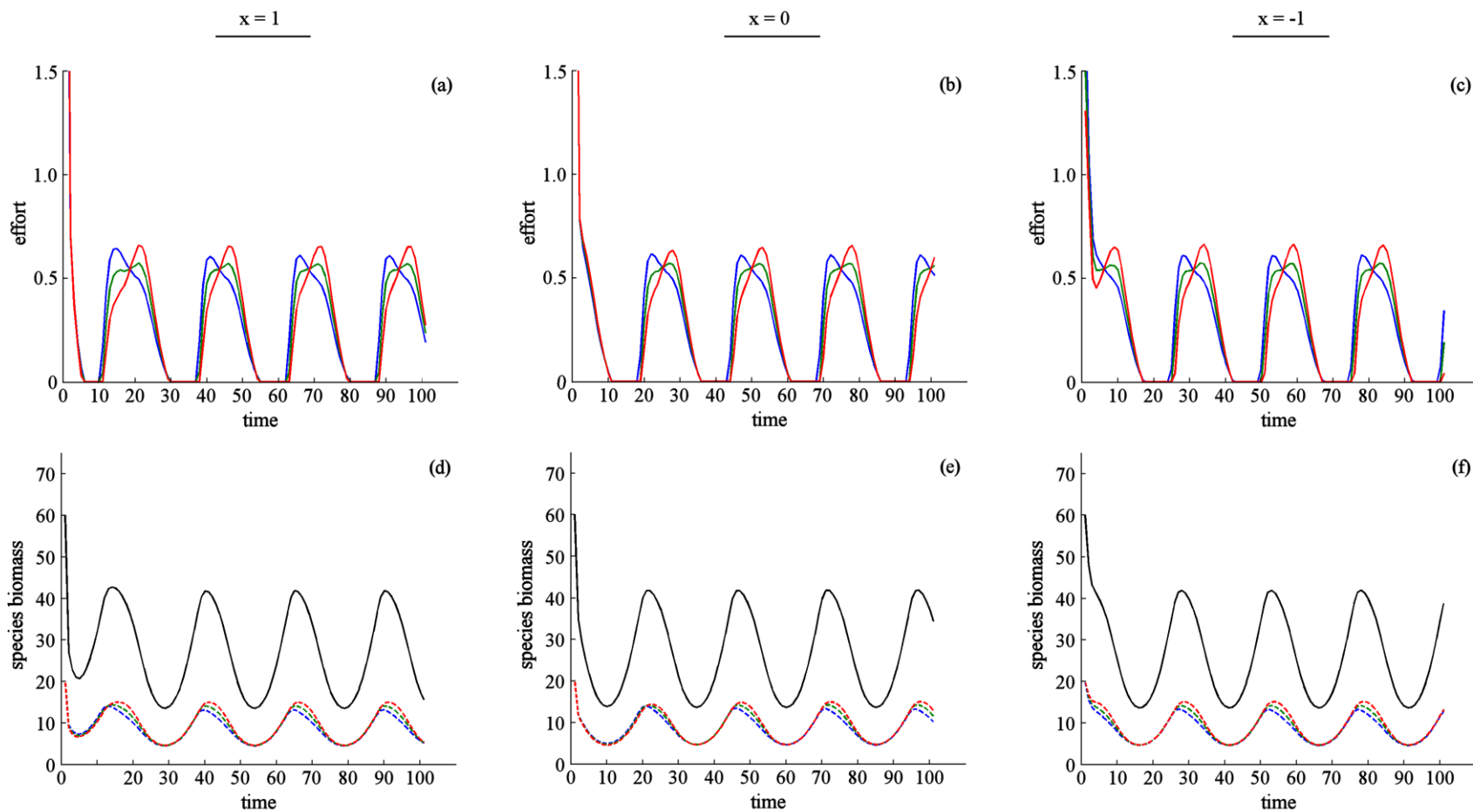


Figure S1. Effect of species competition parameter  $H_i = 0$  on harvest effort (a-c) and species biomass (d-f) in different environmental conditions. The column indicates the value of the environmental phase parameter:  $x_j = 1$  (a, d),  $x_j = 0$  (b, e), and  $x_j = -1$  (c, f). Color indicates species: species 1 (red, highest harvest price), species 2 (green), species 3 (blue, lowest harvest price). In (d-f), the solid black line is the aggregate level of biomass across all species.

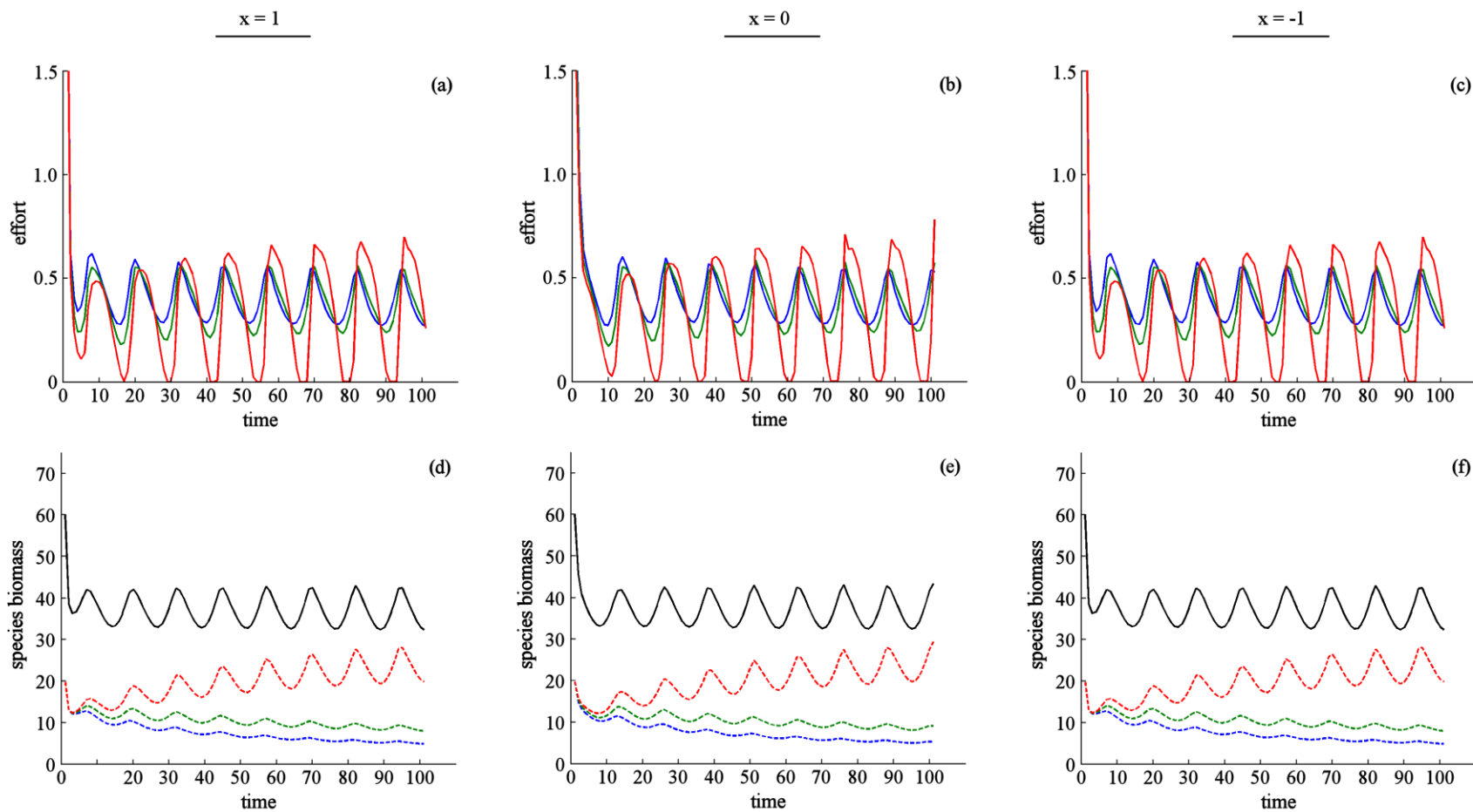


Figure S2. Effect of species competition parameter  $H_i = 1/2$  on harvest effort (a-c) and species biomass (d-f) in different environmental conditions. The column indicates the value of the environmental phase parameter:  $x_j = 1$  (a, d),  $x_j = 0$  (b, e), and  $x_j = -1$  (c, f). Color indicates species: species 1 (red, highest harvest price), species 2 (green), species 3 (blue, lowest harvest price). In (d-f), the solid black line is the aggregate level of biomass across all species.

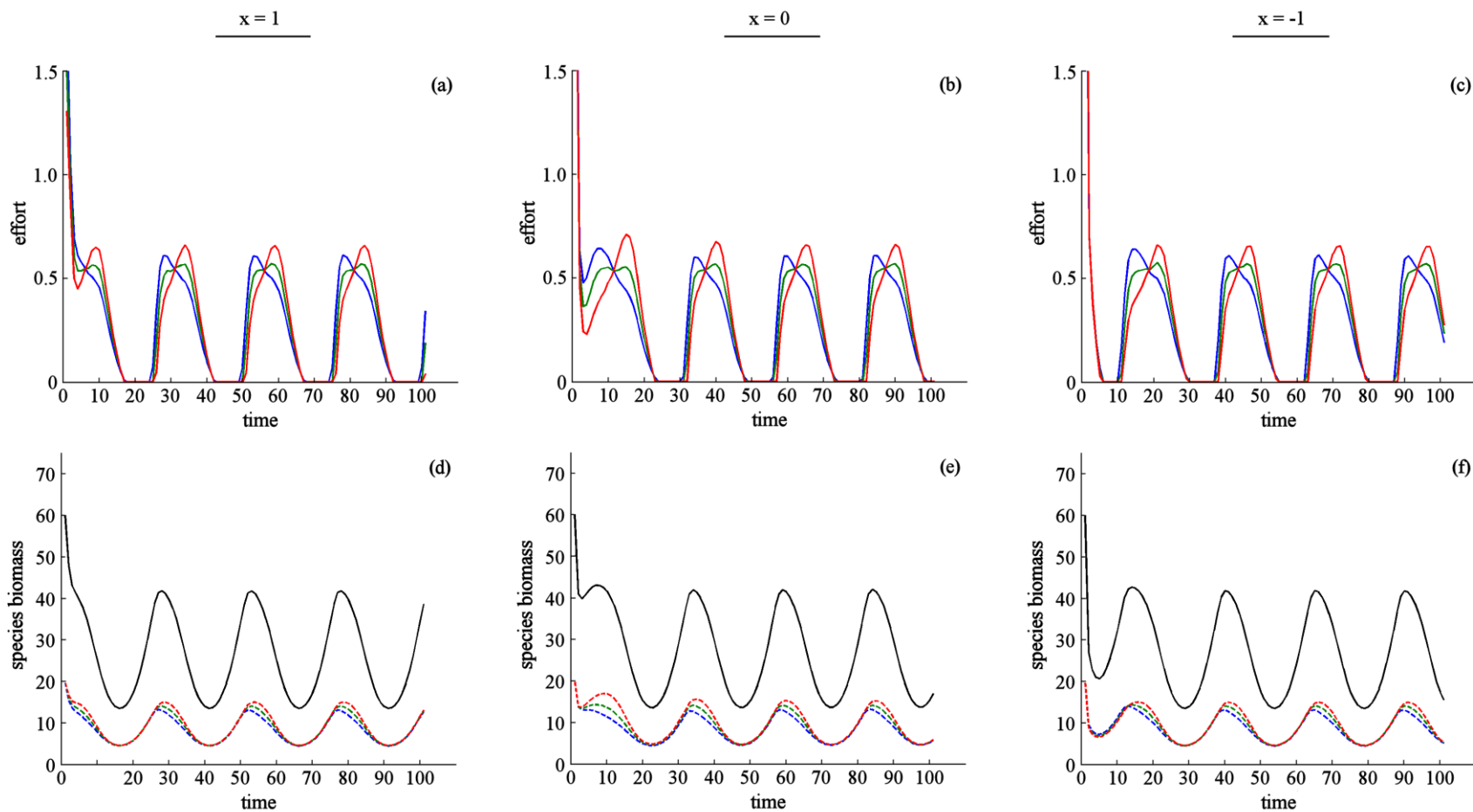


Figure S3. Effect of species competition parameter  $H_i = 1$  on harvest effort (a-c) and species biomass (d-f) in different environmental conditions. The column indicates the value of the environmental phase parameter:  $x_j = 1$  (a, d),  $x_j = 0$  (b, e), and  $x_j = -1$  (c, f). Color indicates species: species 1 (red, highest harvest price), species 2 (green), species 3 (blue, lowest harvest price). In (d-f), the solid black line is the aggregate level of biomass across all species.

## **Appendix F: Effect of negative harvest price on harvest effort.**

We assumed that species were functionally identical, managers obtained benefits solely from harvest, there was no dispersal, and that harvest price was initially positive for all species. In order to test the sensitivity of the economic model to changes in model price, we varied the price of the most valued species (holding all others constant). We found that the suppression of the least valued species varied inversely with harvest price (Figure S4). As price decreased the level of initial suppression increased. This held for negative prices (e.g. pest species).

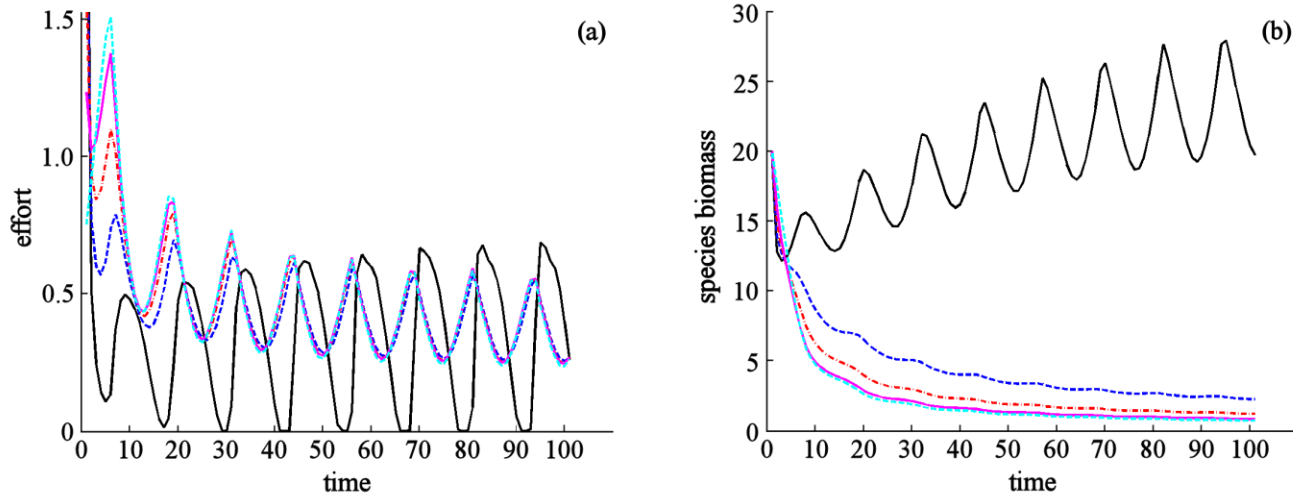


Figure S4. Effect of harvest price on harvest effort (a) and species biomass (b) when benefits are obtained through harvest only. Color indicates the price per unit species harvested for species 1 (prices for other species are held constant at  $p_2 = 14$  and  $p_3 = 15$ ): black ( $p_1 = 16$ ); blue ( $p_1 = 10$ ); red ( $p_1 = 5$ ); magenta ( $p_1 = 0$ ); cyan ( $p_1 = -5$ ).

## Appendix G: Additional figures.

Figure	Description
S5	Visual representation of the distribution of preferences over species across the metacommunity.
	<i>No dispersal - Benefits from abundance and biodiversity</i>
S6	Full trajectory of harvest effort, species abundance, and biodiversity when benefits are obtained through harvest only, harvest and abundance, and harvest and the mix of species.
S7	Effect of harvest price when benefits are obtained through harvest and species abundance.
S8	Effect of harvest price when benefits are obtained through harvest and species biodiversity.
	<i>Dispersal - Harvest of functionally identical species for consumptive benefits</i>
S9	Effect of dispersal when all species possess <i>identical</i> ecological competition parameters, benefits are obtained through the direct consumption of species, and preferences for species are <i>identical</i> between patches. Environmental conditions are the <i>same</i> across patches.
S10	Effect of dispersal when all species possess <i>identical</i> ecological competition parameters, benefits are obtained through the direct consumption of species, and preferences for species <i>differ</i> between patches. Environmental conditions are the <i>same</i> across patches.
	<i>Dispersal - Harvest of functionally different species for consumptive benefits</i>
S11	Full trajectory of the effect of dispersal when species possess <i>different</i> ecological parameters, benefits are obtained through the direct consumption of species, and preferences for species are <i>identical</i> between patches. Environmental conditions are the <i>same</i> across patches.
S12	Effect of dispersal when species possess <i>different</i> ecological competition parameters, benefits are obtained through the direct consumption of species, and preferences for species are <i>identical</i> between patches. Environmental conditions <i>differ</i> across patches.
S13	Effect of dispersal when species possess <i>different</i> ecological competition parameters, benefits are obtained through the direct consumption of species, and preferences for species <i>differ</i> between patches. Environmental conditions are the <i>same</i> across patches.
S14	Full trajectory of the effect of dispersal when species possess <i>different</i> ecological parameters, benefits are obtained through the direct consumption of species, and preferences for species <i>differ</i> between patches. Environmental conditions <i>differ</i> across patches.



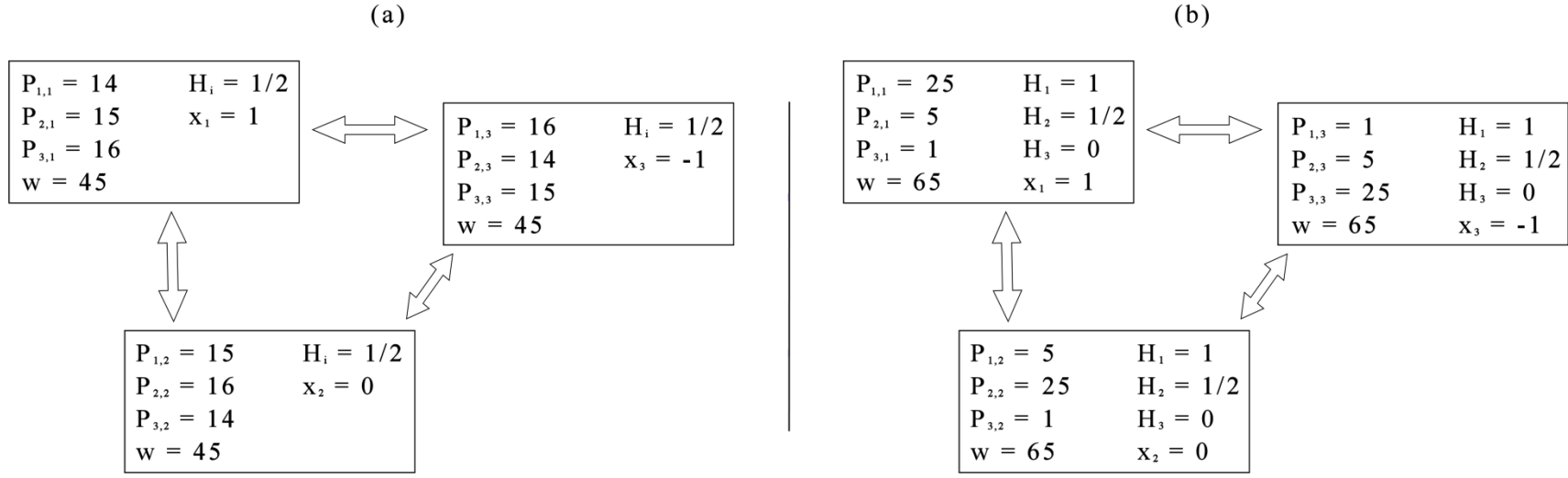


Figure S5. Visual representation of the distribution of preferences over species across the metacommunity. Squares indicate communities; arrows a connection between them. Harvest price and cost for species  $i$  in patch  $j$  are given by  $p_{i,j}$  and  $w$  respectively. Species competition and environmental phase parameters are indicated by  $H_i$  and  $x_j$ .

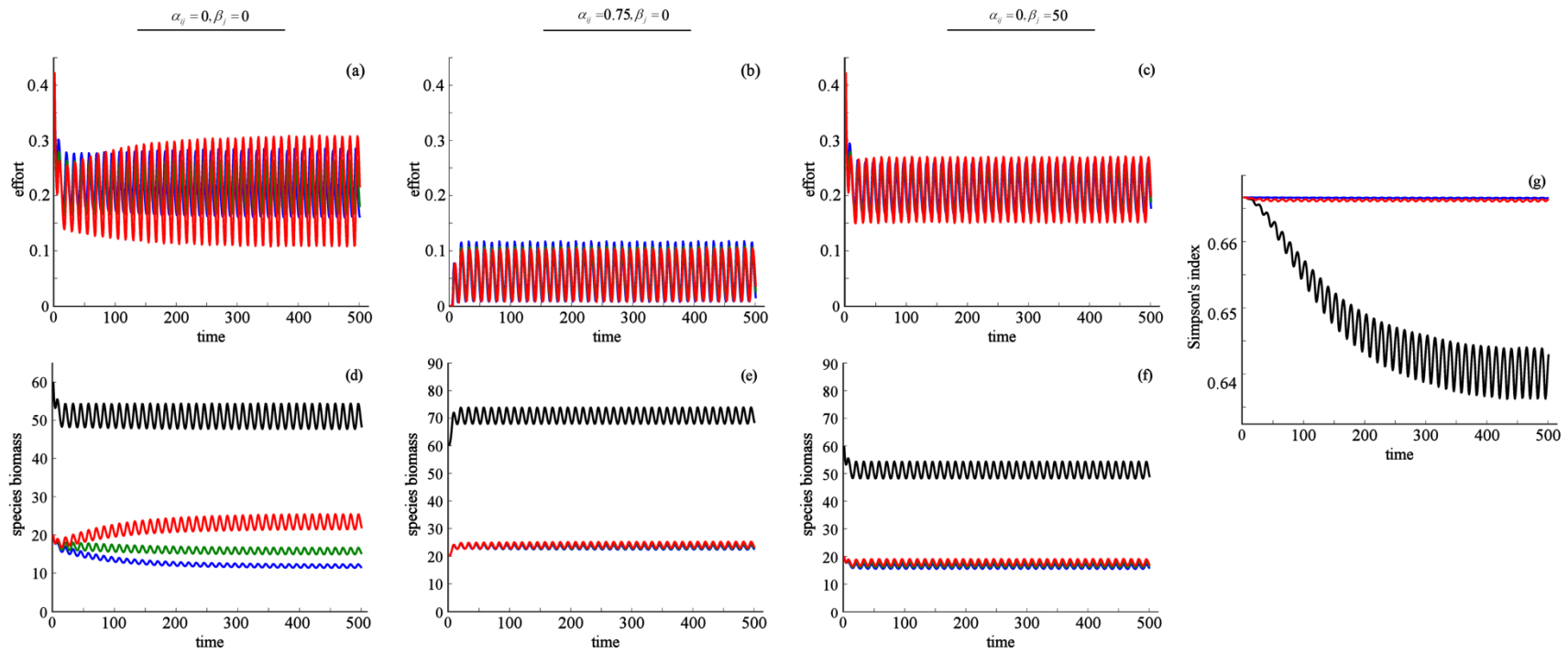


Figure S6. Full trajectory of harvest effort (a-c), species abundance (d-f), and biodiversity (g) when benefits are obtained through harvest only (a, d), harvest and abundance (b, e), and harvest and the mix of species (c, f). In (a-f) color indicates harvest effort and species biomass: species 1 (red, highest harvest price), species 2 (green), species 3 (blue, lowest harvest price). In (d-f) the black line is the aggregate level of biomass across all species. In (g) color indicates the type of benefits: harvest only (black), harvest and species abundances (blue), and harvest and the mix of species (red). To aid in model convergence, costs per unit of harvest effort for all species were set to 150.

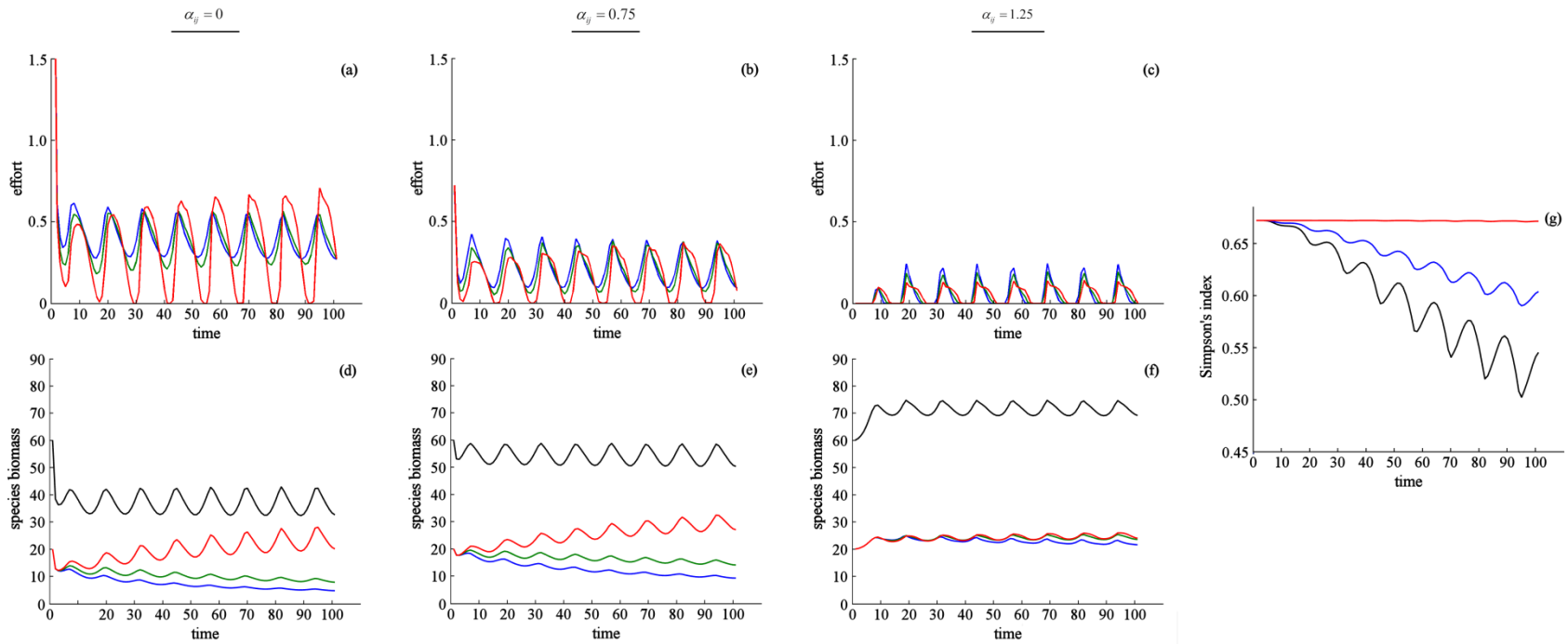


Figure S7. Effect of harvest price when benefits are obtained through harvest and species abundance. The non-consumptive benefits,  $\alpha_{ij}$ , are the same for all species:  $\alpha_{ij} = 0$  (a, d),  $\alpha_{ij} = 0.75$  (b, e), and  $\alpha_{ij} = 1.25$  (c, f). Harvest effort (a-c); species biomass (d-f); and biodiversity (g). In (a-f) color indicates harvest and species biomass: species 1 (red, highest harvest price), species 2 (green), species 3 (blue, lowest harvest price). The black line is the aggregate level of biomass across all species. In (g) color indicates the level of non-consumptive benefits:  $\alpha_{ij} = 0$  (black),  $\alpha_{ij} = 0.75$  (blue), and  $\alpha_{ij} = 1.25$  (red). Values of  $\alpha_{ij}$  were chosen to illustrate the qualitative shift in the harvest regiment.

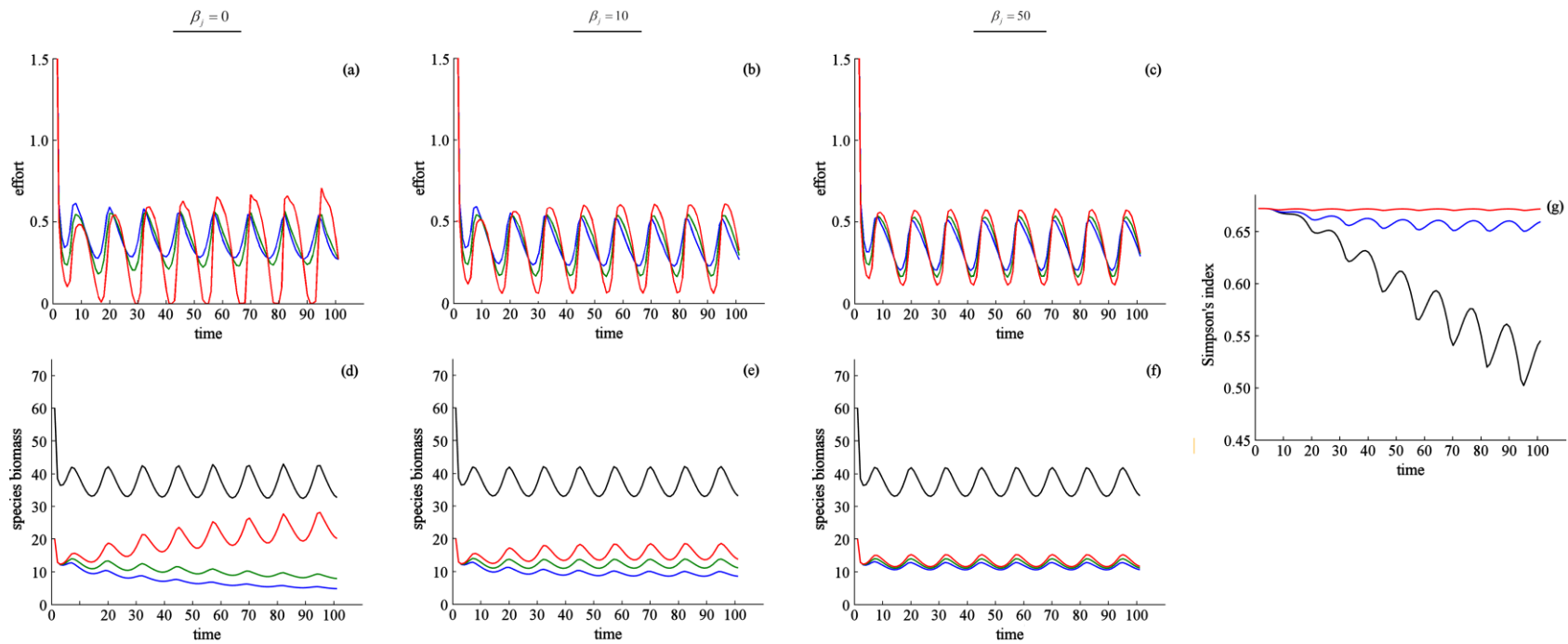


Figure S8. Effect of harvest price when benefits are obtained through harvest and species biodiversity:  $\beta_j = 0$  (a, d);  $\beta_j = 10$  (b, e);  $\beta_j = 50$  (c, f). Harvest effort (a-c); species biomass (d-f); and biodiversity (g). In (a-f) color indicates harvest and species biomass: species 1 (red, highest harvest price), species 2 (green), species 3 (blue, lowest harvest price). The black line is the aggregate level of biomass across all species. In (g) color indicates the level of benefits of biodiversity:  $\beta_j = 0$  (black);  $\beta_j = 10$  (blue);  $\beta_j = 50$  (red). Values of  $\beta_j$  were selected to illustrate the qualitative changes in the distribution of harvest as  $\beta_j$  increases.

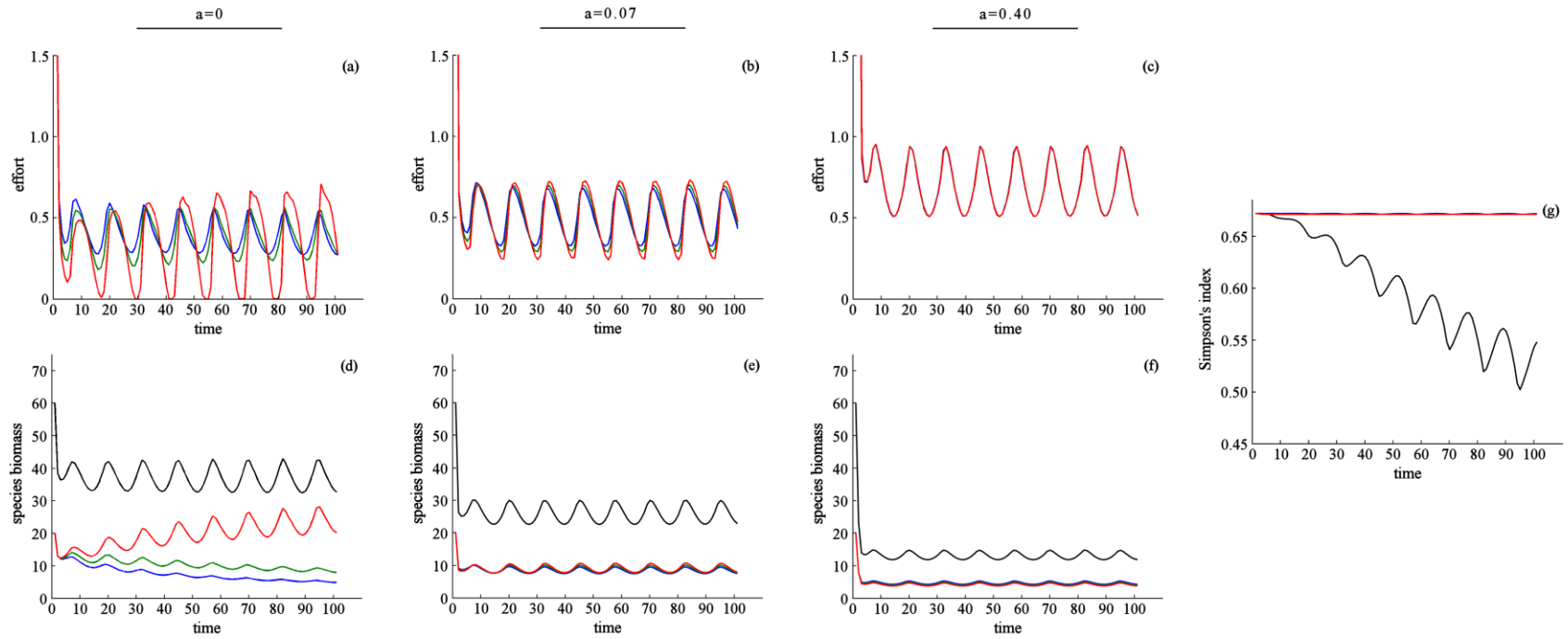


Figure S9. Effect of dispersal when all species possess *identical* ecological competition parameters, benefits are obtained through the direct consumption of species, and preferences for species are *identical* between patches. Environmental conditions are the *same* across patches. Harvest effort (a-c); species biomass (d-f); utility (g); productivity (h); biodiversity (i). In (a-f) column indicates dispersal rate:  $a = 0$  (a, d),  $a = 0.07$  (b, e), and  $a = 0.40$  (c, f). Color indicates harvest effort and species biomass for species 1 (red, highest harvest price), species 2 (green), and species 3 (blue, lowest harvest price). Black shows aggregate species biomass. In (g-i) color indicates dispersal rate:  $a = 0$  (black),  $a = 0.07$  (blue), and  $a = 0.40$  (red).

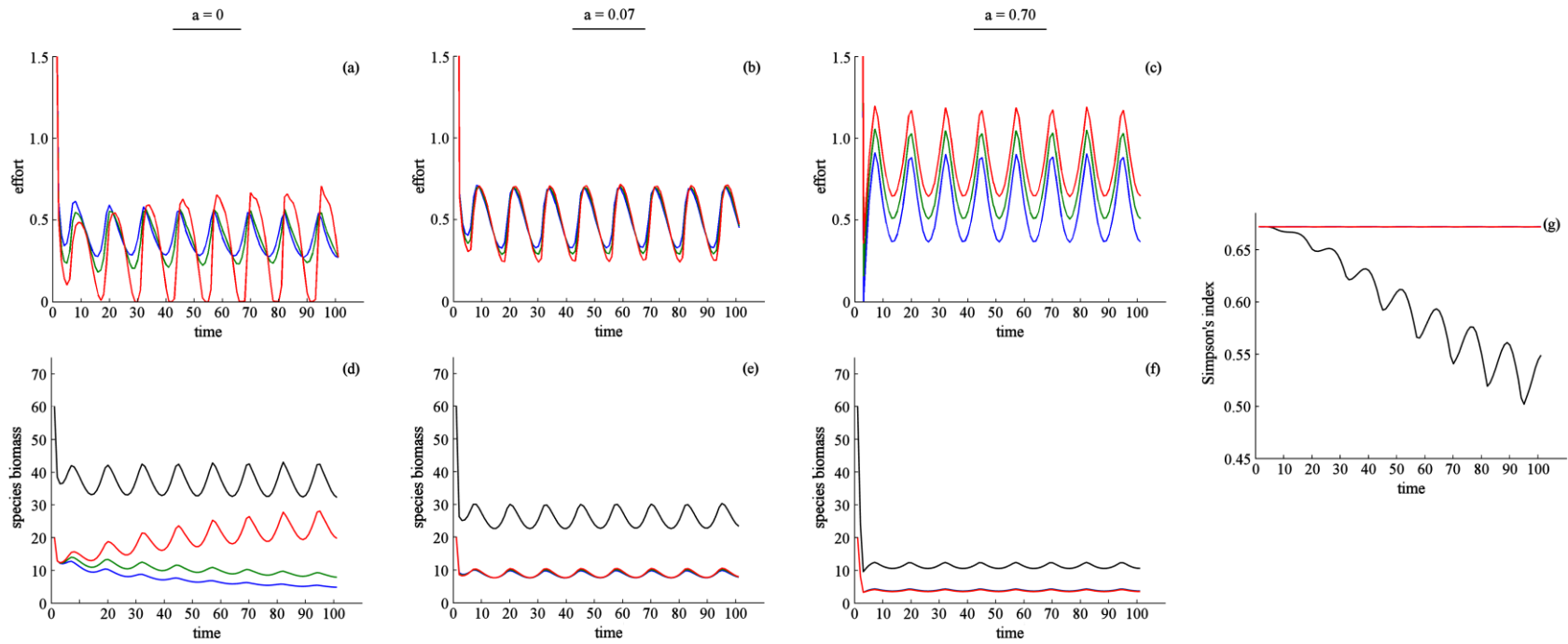


Figure S10. Effect of dispersal when all species possess *identical* ecological competition parameters, benefits are obtained through the direct consumption of species, and preferences for species *differ* between patches. Environmental conditions are the *same* across patches. Harvest effort (a-c); species biomass (d-f); and biodiversity (g). In (a-f) column indicates dispersal rate:  $a = 0$  (a, d),  $a = 0.07$  (b, e), and  $a = 0.70$  (c, f). Color indicates harvest effort and species biomass for species 1 (red, highest harvest price), species 2 (green), and species 3 (blue, lowest harvest price). Black shows aggregate species biomass. In (g) color indicates dispersal rate: low (black), intermediate (blue), and high (red).

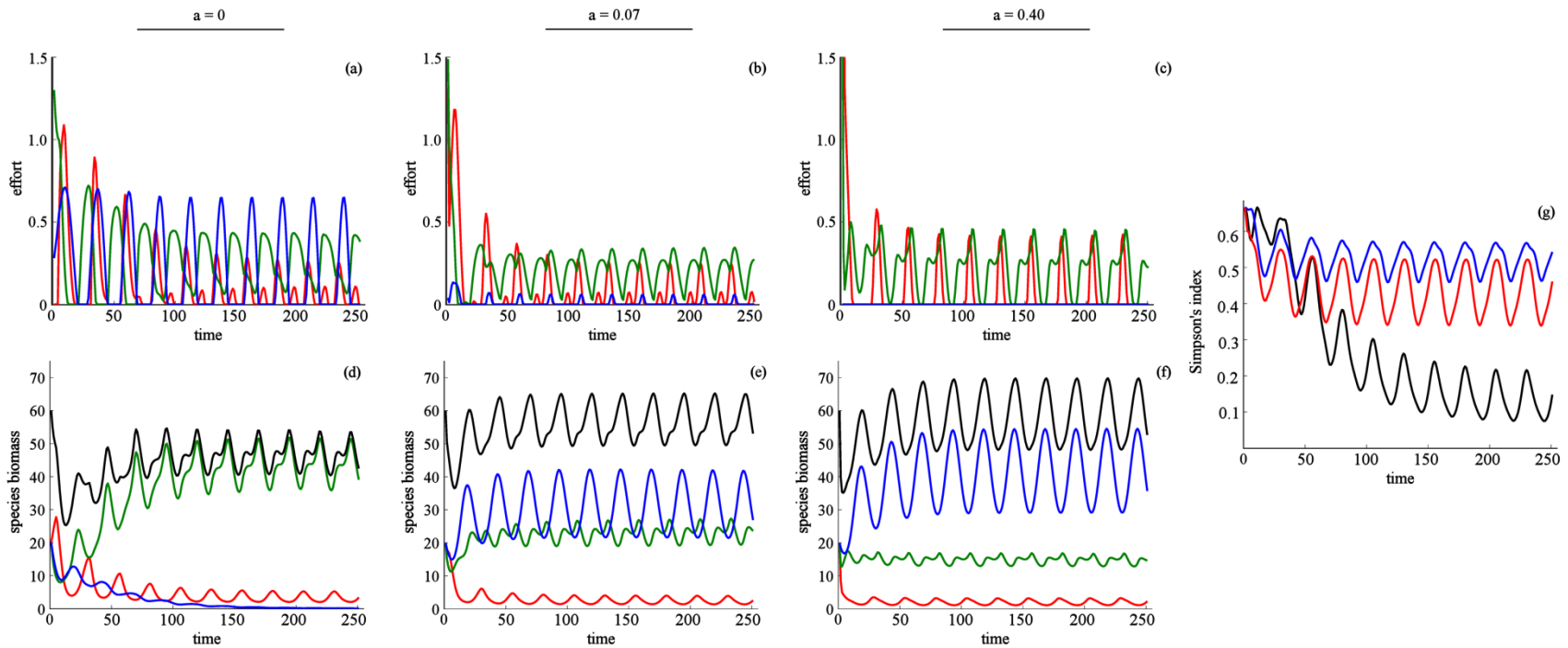


Figure S11. Full trajectory of the effect of dispersal when species have *different* ecological parameters, benefits are obtained through the direct consumption of species, and preferences for species are *identical* between patches. Environmental conditions are the *same* across patches. Harvest effort (a-c), species biomass (d-f), and biodiversity (g). In (a-f) dispersal rate is indicated by column:  $a = 0$  (a, d),  $a = 0.07$  (b, e), and  $a = 0.40$  (c, f). In (a-f), color indicates harvest effort and species biomass for species 1 (red, highest harvest price), species 2 (green), and species 3 (blue, lowest harvest price). Black shows aggregate species biomass. In (g) color indicates the dispersal rate: low (black,  $a = 0$ ), intermediate (blue,  $a = 0.07$ ), high (red,  $a = 0.40$ ).

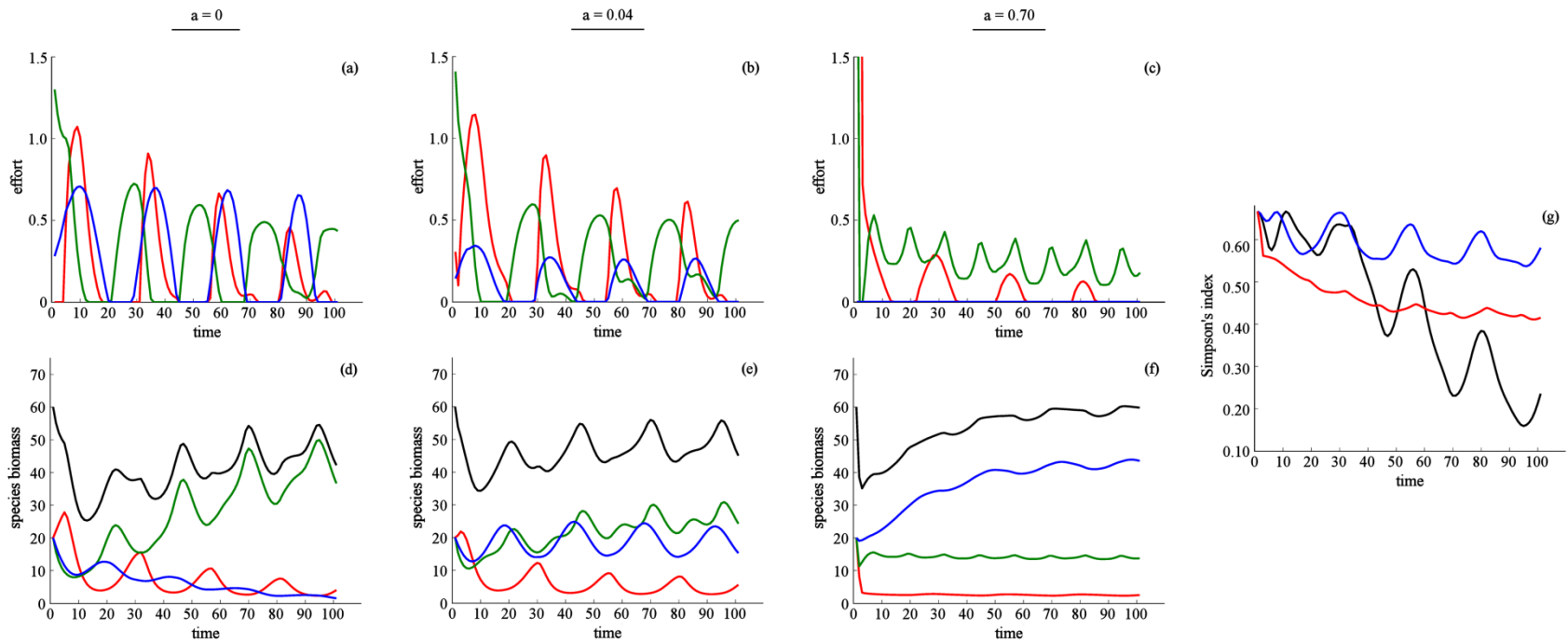


Figure S12. Effect of dispersal when species possess *different* ecological competition parameters, benefits are obtained through the direct consumption of species, and preferences for species are *identical* between patches. Environmental conditions *differ* across patches. Harvest effort (a-c); species biomass (d-f); and biodiversity (g). In (a-f) dispersal rate is indicated by column:  $a = 0$  (a, d),  $a = 0.04$  (b, e), and  $a = 0.70$  (c, f). Color indicates harvest effort and species biomass for species 1 (red, lowest harvest price), species 2 (green), and species 3 (blue, highest harvest price). Black shows aggregate species biomass. In (g) color indicates dispersal rate:  $a = 0$  (black),  $a = 0.04$  (blue), and  $a = 0.70$  (red).



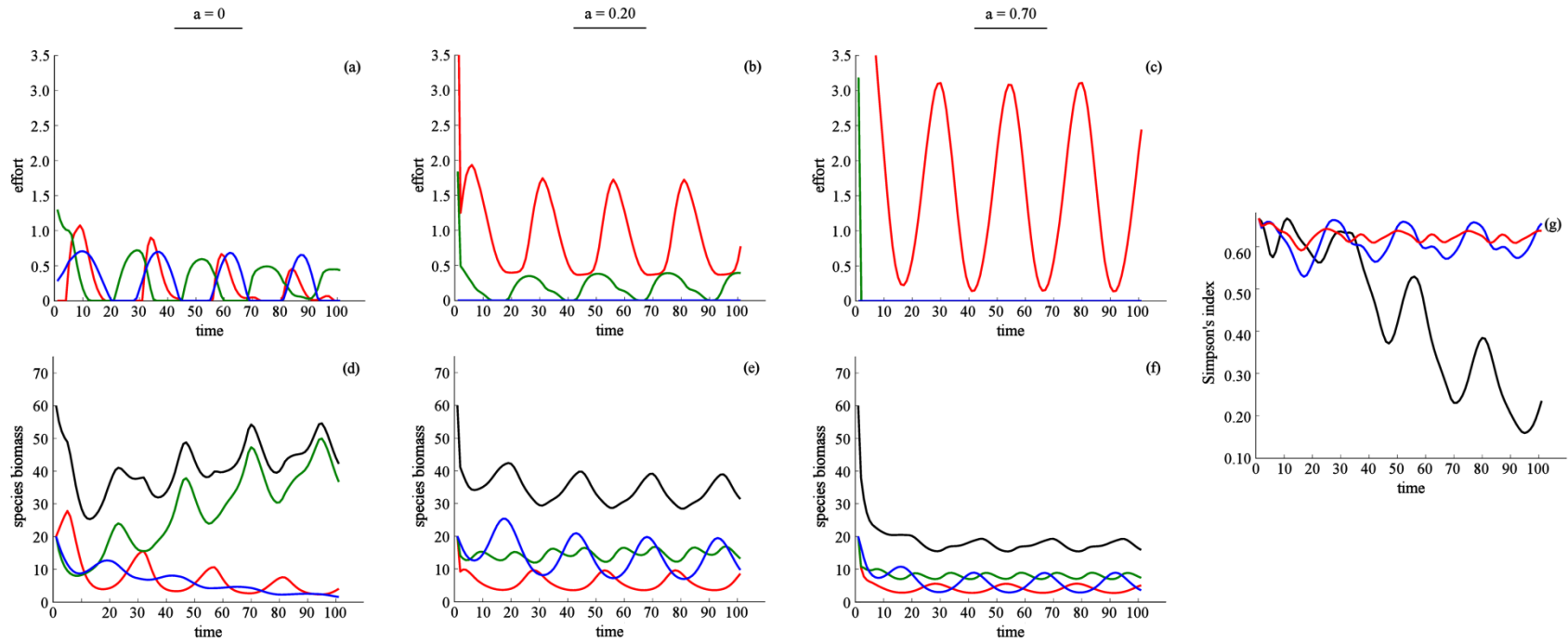


Figure S13. Effect of dispersal when species possess *different* ecological competition parameters, benefits are obtained through the direct consumption of species, and preferences for species *differ* between patches. Environmental conditions are the *same* across patches. Harvest effort (a-c); species biomass (d-f); and biodiversity (g). In (a-f) column indicates dispersal rate:  $a = 0$  (a, d),  $a = 0.20$  (b, e), and  $a = 0.70$  (c, f). Color indicates harvest effort and species biomass for species 1 (red, lowest harvest price), species 2 (green), and species 3 (blue, highest harvest price). Black shows aggregate species biomass. In (g) color indicates dispersal rate:  $a = 0$  (black),  $a = 0.20$  (blue), and  $a = 0.70$  (red).

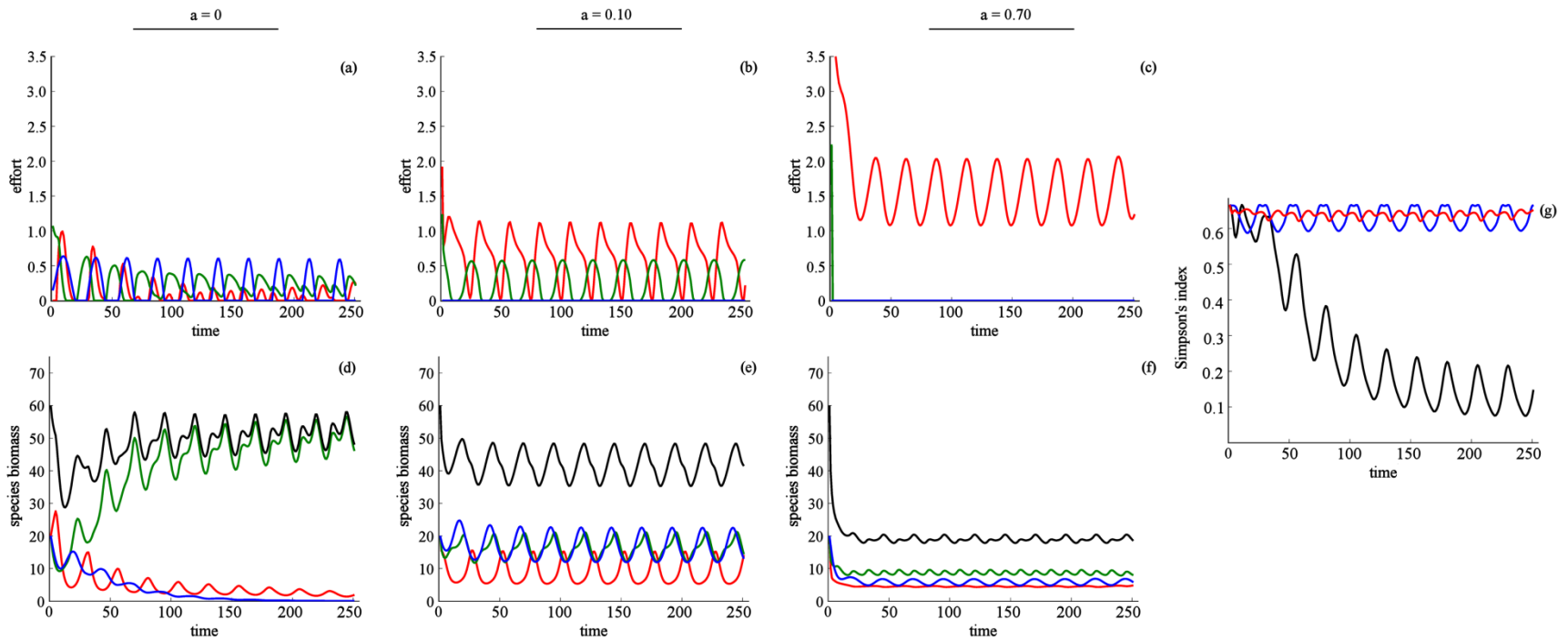


Figure S14. Full trajectory of the effect of dispersal when species have *different* ecological parameters, benefits are obtained through the direct consumption of species, and preferences for species *differ* between patches. Environmental conditions *differ* across patches. Harvest effort (a-c), species biomass (d-f), and biodiversity (g). In (a-f) dispersal rate is indicated by column:  $a = 0$  (a, d),  $a = 0.10$  (b, e), and  $a = 0.70$  (c, f). In (a-f), color indicates harvest effort and species biomass for species 1 (red, highest harvest price), species 2 (green), and species 3 (blue, lowest harvest price). Black shows aggregate species biomass. In (g) color indicates the dispersal rate: low (black,  $a = 0$ ), intermediate (blue,  $a = 0.10$ ), high (red,  $a = 0.70$ ).

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