**Rescuing ecosystems from extinction cascades through compensatory perturbations**

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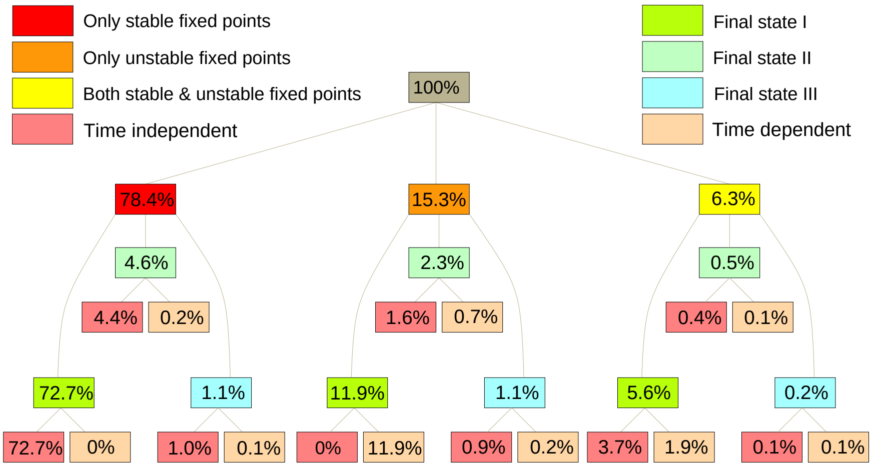
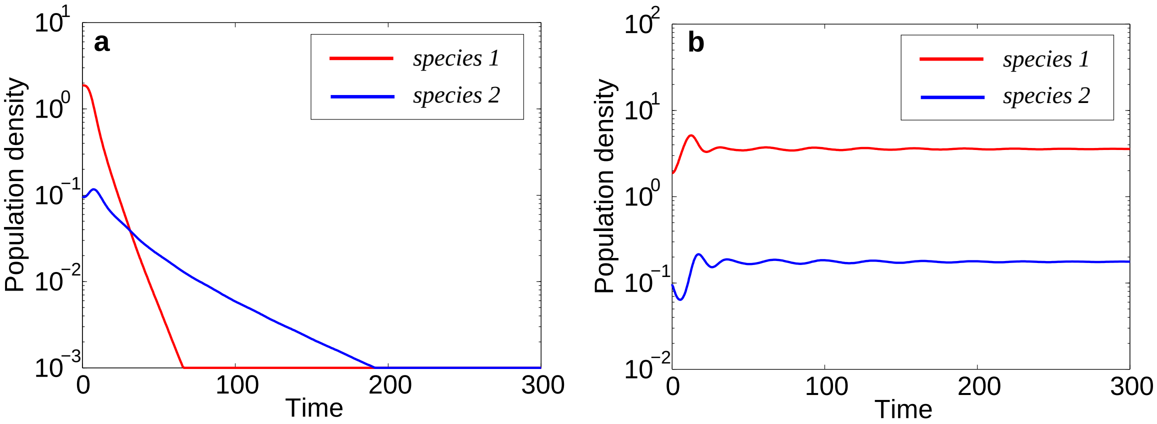
# Supplementary Information

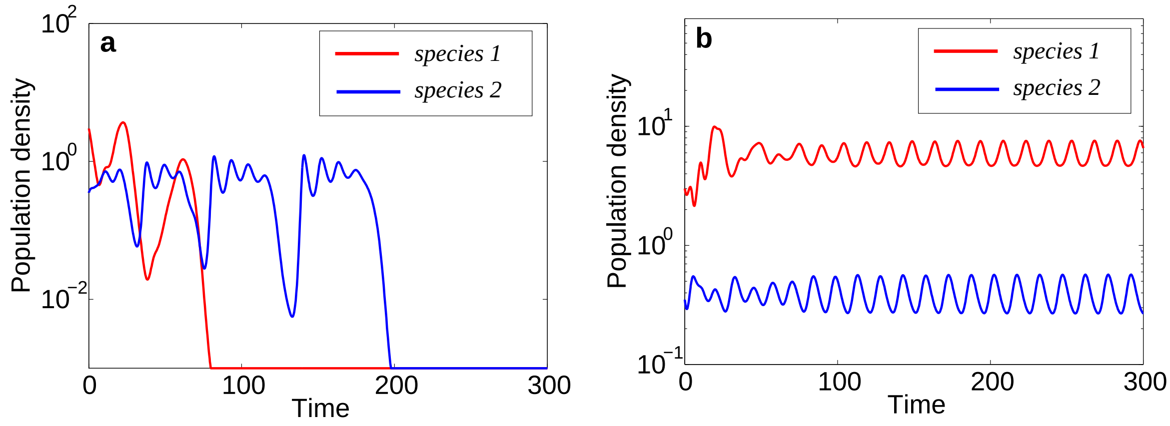
## Contents



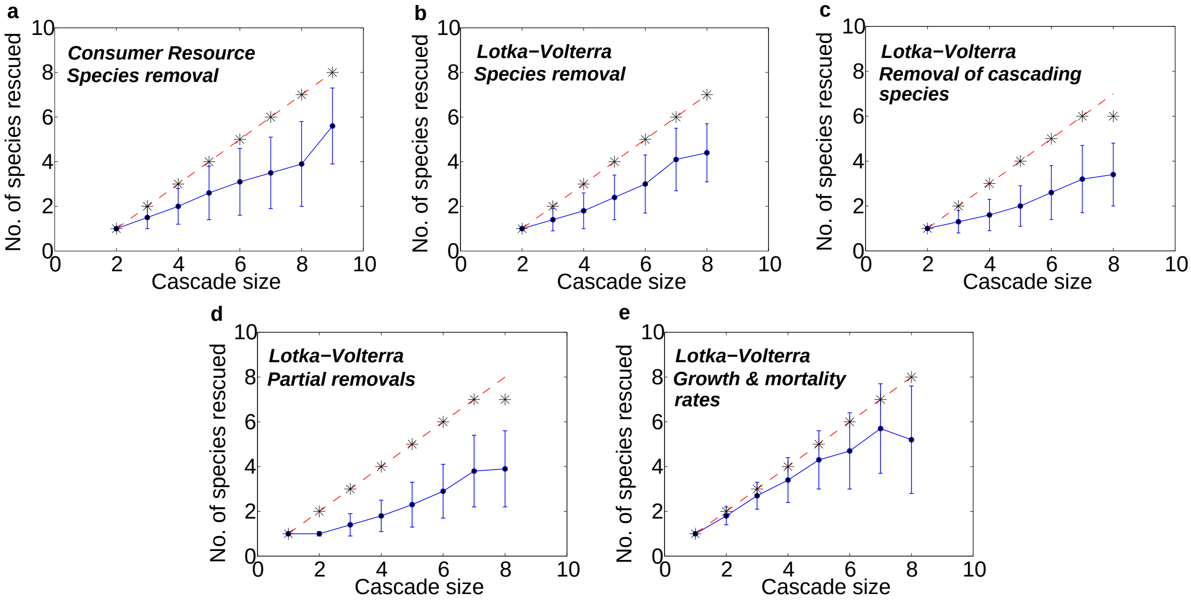
**Supplementary Figure** S1: **Classification of the asymptotic rescue states.** The statistics are for all cascades mitigated by a species removal in Fig. 2b of the paper. The rescue states are classified into cases with $n^*_{new} = n^*$ (final state I), $n^*_{new} = n^* - 1$ (final state II), and $n^*_{new} < n^* - 1$ (final state III), where $n^*$ corresponds to the target states consistent with the given forced removal that have the largest number of nonzero-population species. This set of target states is classified according to whether the fixed points are all stable, all unstable, or some stable and others unstable. For each of these cases, the mitigated cascades are separated into those that reach a time-independent versus a time-dependent final state. In particular, the rescued system is shown to approach one of the corresponding stable target states in most of the cases when all such fixed points are stable ($72.7\%$ out of $78.4\%$).



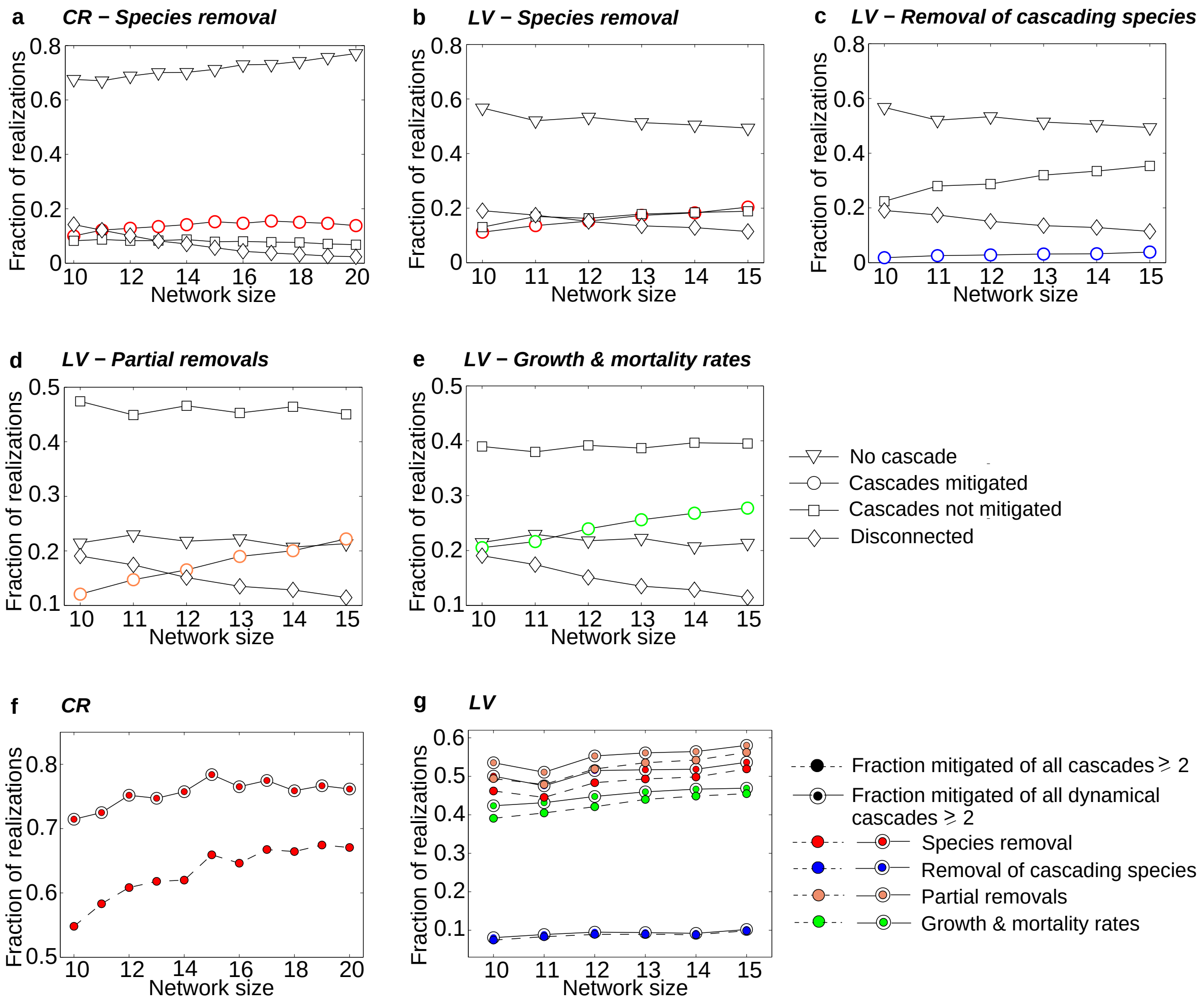
**Supplementary Figure** S2: **Example of a time-independent final state.** (**a**) Cascading extinctions of two species triggered by the primary removal of one species (not shown) at time zero. (**b**) Rescues of the two cascading species determined by the proactive forced removal of a different species (not shown) shortly after the primary removal. The forced removal corresponds to the sole zero-population species at a stable target state (in addition to the primary removal), and this intervention drives the system to that state. The network consists of 15 species, therefore with $n^p = 14$, $n^c = 12$, and $n_{new} = n^* = 13$, and was simulated using the Lotka-Volterra model.



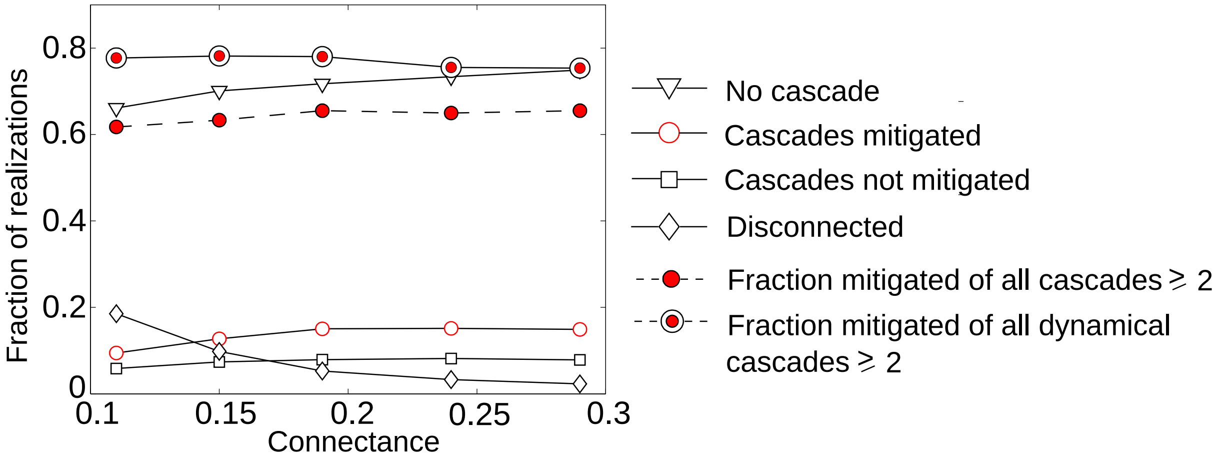
**Supplementary Figure** S3: **Same as in Supplementary Figure S2 for a time-dependent final state.** The forced removal is on a species that corresponds to the sole zero at an unstable target state in addition to the one introduced by the primary removal. This forced removal drives the system to an oscillatory state rather than to the fixed point itself. The network consists of 15 species, therefore with $n^p = 14$, $n^c = 12$, and $n_{new} = n^* = 13$, and was simulated using the Lotka-Volterra model.



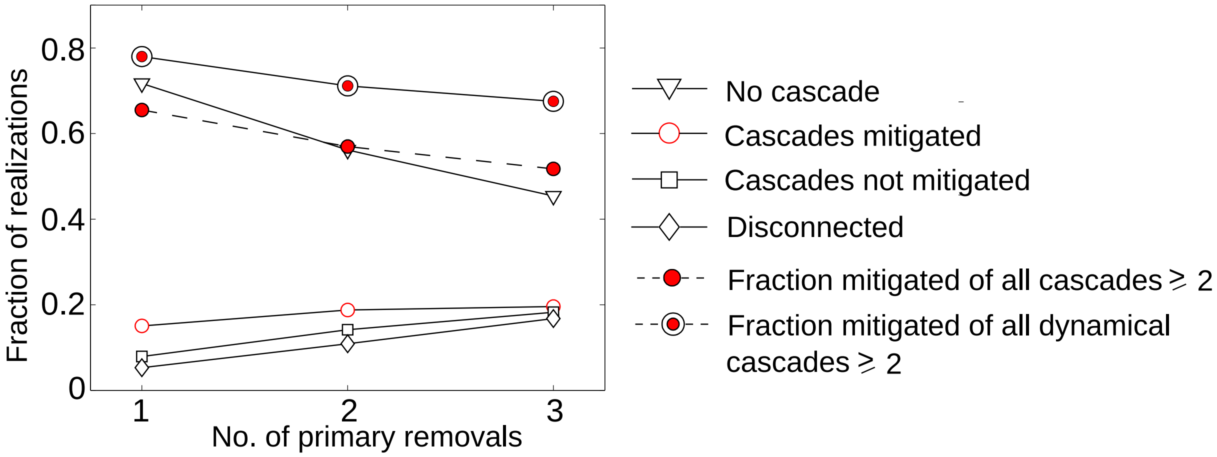
**Supplementary Figure** S4: **Number of species rescued as a function of the size of the cascades.** The statistics correspond to the model networks considered in Supplementary Table S1. (**a**) Rescues based on forced species removals in the case of the consumer-resource dynamics. (**b-e**) Rescues based on forced species removals (**b**), forced removals limited to cascading species (**c**), forced partial removals (**d**), and growth and mortality rate manipulation (**e**), in the case of the Lotka-Volterra dynamics. In each panel, the dots correspond to the average over all realizations, the error bars to the standard deviations, the dashed line to the theoretical maximum number of rescues, and the stars to the maximum number of rescues observed in our numerical experiments. The continuous lines are included to guide the eyes.



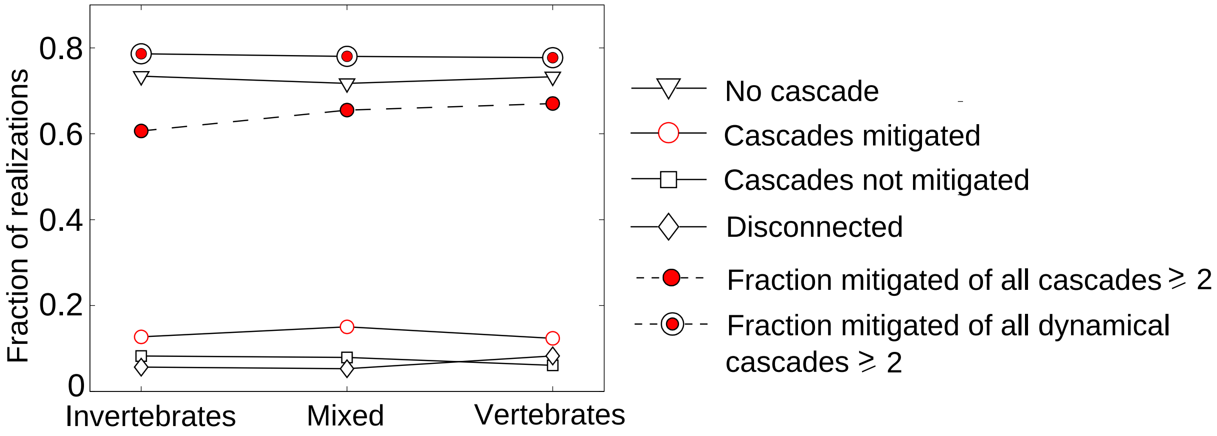
**Supplementary Figure** S5: **Variation with network size.** Both the consumer-resource (CR) and the Lotka-Volterra (LV) dynamics are tested for all single-species primary removals. (**a-e**) Fraction of realizations in which there is no cascade $\geq 2$ (**a-c**) or $\geq 1$ (**d**,**e**) ($\bigtriangledown$), in which such a cascade exists and can be mitigated ($\bigcirc$), in which such a cascade exists and cannot be mitigated ($\square$), and in which the network becomes disconnected by the primary removal ($\Diamond$). (**f**, **g**) Fraction of all cascades $\geq 2$ that can be mitigated ($\bullet$) and fraction of all cascades with 2 or more dynamical extinctions that can be mitigated ($\odot$) for the scenarios shown in (**a**) (**f**, consumer resource) and in (**b-e**) (**g**, Lotka-Volterra). The consumer-resource dynamics was implemented using communities of mixed type. The simulations were implemented using $1,000$ independent networks of each size generated from an initial connectance of $0.20$.



**Supplementary Figure** S6: **Variation with connectance.** The statistics are over all single-species primary removals, for interventions based on the forced removal of one species. The different open symbols indicate the fraction of realizations in which there is no cascade $\geq 2$ (▽), in which such a cascade exists and can be mitigated (○), in which such a cascade exists and cannot be mitigated (□), and in which the network becomes disconnected by the primary removal (◊). The solid and semi-solid symbols indicate respectively the fraction of all such cascades that can be mitigated (●) and the fraction of all cascades with $2$ or more dynamical extinctions that can be mitigated (◉). The simulations were implemented using the consumer-resource dynamics with communities of mixed type and $1,000$ independent networks of 15 species for each parameter choice. The figure shows the resulting connectance for the persistent 15-species networks generated from initial connectance values of $0.10$, $0.15$, $0.20$, $0.25$, and $0.30$ (see also Network Generation, in Supplementary Methods).



**Supplementary Figure** S7: **Variation with the number of primary removals.** The interventions are based on the forced removal of one species. The symbols are defined as in Supplementary Figure S6. The simulations were implemented using the consumer-resource dynamics in $1,000$ independent networks of 15 species generated from an initial connectance of $0.20$.



**Supplementary Figure** S8: **Variation with community type.** The statistics are over all single-species primary removals, for interventions based on the forced removal of one species. The symbols are defined as in Supplementary Figure S6. The simulations were implemented using the consumer-resource dynamics in $1,000$ independent networks of 15 species generated from an initial connectance of $0.20$.

| *Food-web dynamics* | Lotka-Volterra | | | | Consumer Resource | | |
|---|---|---|---|---|---|---|---|
| *Food-web structure* | Model networks | | | | Model networks | Chesapeake Bay | Coachella Valley |
| *Intervention* | RS (%) | RS$^c$(%) | PR (%) | GM (%) | RS (%) | RS (%) | RS (%) |
| *No cascades* | 55.7 | 55.7 | 55.7 (24.1) | 55.7 (24.1) | 75.7 | 72.1 | 82.9 |
| *Cascades mitigated* | 23.0 | 4.4 | 24.8 (25.0) | 20.1 (31.3) | 15.9 | 25.4 | 7.0 |
| *Cascades not mitigated* | 21.3 | 39.9 | 19.5 (50.9) | 24.2 (44.6) | 8.4 | 2.5 | 10.1 |

**Supplementary Table S1**: **Statistics of extinction cascades triggered and extinction cascades mitigated.** The initially persistent networks are perturbed by the removal of one species (model food webs) or three species (Chesapeake Bay and Coachella Valley food web). In columns RS, the control intervention consists of the forced removal of one species. In column RS$^c$, the forced removal is limited to the subset of species that would be extinct by the cascade in the absence of intervention. In column PR, the removals can be partial and include one or more species according to the number of species with reduced population at the target state. In column GM, the intervention consists of reducing the growth rate of basal species and/or increasing the mortality rate of other species. All percentages refer to cascades involving two or more secondary extinctions, except for those in parenthesis, which also include cascades with a single secondary extinction. The data for the model food webs were generated using $1,000$ independent realizations of networks with $15$ species, which were then perturbed by all single-species removals. The total number of realizations on which the statistics are based is $13,284$ (Lotka-Volterra) and $14,206$ (consumer resource), where the difference from $15 \times 1,000$ is due to realizations in which the network becomes disconnected following the primary removal. The corresponding number of realizations for the Chesapeake Bay food web is $3,281$ and for the Coachella Valley food web is $4,059$.

## Supplementary Methods

### Lotka-Volterra Model

In our implementation of the Lotka-Volterra predator-prey model for $n$ species, the dynamics is determined by

$$\frac{dX_i}{dt} = X_i \left( b_i + \sum_j a_{ij} X_j \right), \tag{S1}$$

where $X_i$ is the population of species $i$ per unit of area (population density), $b_i$ is the growth rate and mortality rate for basal and non-basal species, respectively, and $A = (a_{ij})$ is the matrix that accounts for the network of interactions between different species[31]. The growth rate is the difference between reproduction and mortality rate, and the mortality rate refers specifically to natural mortality rate, which is not accounted for by the last term in Eq. (S1). The network itself is generated using the niche model[32].

In our analysis, the initial population density $X_i$ and growth rate $b_i$ are chosen randomly from a uniform distribution in the interval $(0, 1)$. In the case of non-basal species, the value of $b_i$ is negative, since it represents a mortality rate, and is drawn from a uniform distribution in the interval $(-1, 0)$. The nonzero entries of matrix $A$ are selected according to following constraints. If $j$ feeds on $i$, then $a_{ij}$ is randomly selected from a uniform distribution in the interval $(-1, 0)$ and $a_{ji} = -ea_{ij}$, where the efficiency parameter $e > 0$ is a measure of the amount of preys required to produce a predator. If species $i$ and species $j$ do not share any direct link between them, then $a_{ij} = a_{ji} = 0$. In our simulations we assume that $e = 0.1$. To prevent the population of basal species from going to infinity in the absence of predators, we use a self-regulating term for the basal species. This is implemented by assigning $a_{ii} = -0.01$, where $i$ is for basal species only. If species $i$ has a cannibalistic link then $a_{ii} = v - ev$, where $v$ is drawn from a uniform distribution in the interval $(-1, 0)$. Note that the mortality rate (or growth rate) $b_i$ and the interaction strength $a_{ij}$ for $j \neq i$ are assumed to vary across species and pairs of species, respectively.

We assume that there is a threshold $s$ for the population density below which the species go extinct. This threshold reflects the constraints imposed by the minimum viable population size[40]. For the arbitrary units considered above, we select the threshold to be $s = 10^{-3}$. We have verified that our conclusions are not sensitive to the choice of this parameter, as long as the parameter is small. In our simulations, Eq. (S1) is integrated over a sufficiently long time such that in the end all remaining species attain a time-independent nonzero population or exhibit stationary oscillations away from zero. The integration time used in our simulations that meets this criterion is $T = 5 \times 10^3$. We have verified that this choice of $T$ accounts for most secondary extinctions (over 99% of them on average in the networks of $15$ species considered in the paper). The unit of time depends on the particular system under consideration. For example, in an ecosystem in which the mortality rate ranges from $0$ to $3.5\ yr^{-1}$ our unit of time will be $1/3.5$ of a year.

The Lotka-Volterra predator-prey model is well suited for our proof-of-concept study because key aspects of its asymptotic behavior are analytically treatable (see Methods). The potential limitations of the Lotka-Volterra model are: (*i*) the constant interaction matrix $A$ does not account for changes in the strengths of the interactions when there are significant changes in individual prey populations; and (*ii*) in the space of parameters, the number of configurations that result in persistent food webs with a realistic number of trophic levels decreases quickly with the number of species (e.g., for the parameters considered in our numerical experiments, relatively few configurations are persistent with $> 3$ trophic levels and more than $15$ species). However, the results presented in the paper are not sensitive to these limitations; they remain valid for the consumer-resource model, which is more realistic, generally more robust, and incorporates functional responses that account for *adaptive* behavior (i.e., behavior in which the relative consumption of preys per predator depends on the relative density of preys).

**Consumer-Resource Model**

We consider an implementation of the $n$-species consumer-resource model[29,30] in which the dynamics of the basal species follows

$$\frac{dB_i}{dt} = r_i G_i B_i - \sum_{j\in\, co(i)} x_j y B_j F_{ji}/e_{ji}, \tag{S2}$$

while the dynamics of the non-basal species is governed by

$$\frac{dB_i}{dt} = -x_i B_i + \sum_{j\in\, re(i)} x_i y B_i F_{ij} - \sum_{j\in\, co(i)} x_j y B_j F_{ji}/e_{ji}, \tag{S3}$$

where $co(i)$ and $re(i)$ denote the consumers (predators) and resources (preys) of species $i$, respectively. In this model, $B_i$ is the biomass per unit of area (biomass density), $r_i$ is the mass-specific growth rate, $G_i = (1 - B_i/K)$ is the logistic growth rate, $K$ is the carrying capacity, $x_i$ is the mass-specific metabolic rate relative to mass-specific growth rate, $y$ is the mass-specific ingestion rate relative to the mass-specific metabolic rate, $e_{ji}$ is the assimilation efficiency of species $j$ when feeding on $i$, and $F_{ij}$ is the functional response. The functional response $F_{ji}$ describes the amount of prey $i$ consumed per predator $j$ as a function of the prey density. A mass-specific rate is defined as the rate per unit mass.

The functional response is given by

$$F_{ij} = \frac{\Omega_{ij} \times (B_j)^h}{1 + wB_i + \sum_{k\in\, re(i)} \Omega_{ik} \times (B_k)^h}\,, \tag{S4}$$

where $\Omega_{ij}$ is the relative rate of species $j$ in the diet of species $i$ and $w$ accounts for the intraspecies competition. Different types of functional responses can be obtained by selecting different values[54] for the exponent $h$. Type II response, in which the amount of prey captured by a predator increases sublinearly and saturates after the prey density increases beyond a certain value, is obtained by setting $h = 1$. Type III response, which occurs in cases where the amount of prey captured initially increases superlinearly with increasing prey density, is obtained when $h = 2$. Compared to Type II, the predation for Type III response is smaller when prey density is small and larger when prey density is large. Most diverse ecosystems have some pairs of species that interact according to Type II response and others that interact according to Type III response. Hence, to incorporate both responses we set the value of $h$ to lie in between $1$ and $2$. In our simulations we take $\Omega_{ij} = 1/\sum_{k\in re(i)} 1$, meaning that the predators do not have preference over the different prey species.

It is assumed that the average body mass of the species increases with the trophic level as

$$m_i = Z^{\tau-1}, \tag{S5}$$

where $\tau$ denotes the trophic level and $Z$ is a constant. This automatically sets the body mass of the basal species to be unity. Employing the usual assumption[55] that the mass-specific rates scale as $m_i^{-0.25}$, and choosing the time scale of the system in such a way that the mass-specific growth rate of the basal species is unity, we obtain:

$$r_j = 1, \quad x_i = \frac{d_x}{d_r} m_i^{-0.25}, \quad y = \frac{d_y}{d_x}, \tag{S6}$$

where $d_r$, $d_x$, and $d_y$ are allometric constants. Different indices are used for $r$ and $x$ because $r$ exists only for basal species and $x$ is used only for non-basal species in the model (Eqs. (S2)-(S3)).

We follow ref. 56 in setting the parameter values for our numerical experiments. The assimilation efficiency parameter $e_{ij}$ is set to $0.85$ for carnivores and $0.45$ for herbivores. For the ratio $d_x/d_r$ we use $0.314$ for invertebrates and $0.88$ for vertebrates. The mass-specific ingestion rate $y$ is set to $8$ and $4$ for invertebrates and vertebrates, respectively. A small amount of intraspecies interference is allowed by taking $w = 0.05$ and a mixed functional response was used by selecting $h = 1.2$. The carrying capacity $K$ is taken to be $1$. We also set $Z = 10$, which is the average in a global empirical database[57]. Because the Chesapeake Bay and Coachella Valley food webs have both vertebrate and invertebrate species, in the simulations involving these networks we used $y = 6$ and $d_x/d_r = 0.597$, which are averages of the parameter values for vertebrates and invertebrates[56]. The same values are used in our simulations of model food webs with mixed vertebrate-invertebrate communities. To obtain persistent states vulnerable to cascades and in which the population of all species are nonzero, we also changed the parameter $w$ to $15.9$ for the Chesapeake Bay food web and $8.75$ for the Coachella Valley food web. In all cases, the initial biomass densities $B_i$ are generated randomly from a uniform distribution in the interval $(0, 1)$.

### Network Generation

The niche model is used to generate the network structure[32]. Every species is assigned a random value $\eta_i$, the so-called niche value, which is drawn from a uniform distribution in the interval $(0, 1)$. Species $i$ feeds on all the species whose niche value falls in a range $r_i$, where the center of this range, $c_i$, is drawn from a uniform distribution in $(r_i/2,\ \eta_i)$. The value $r_i$ itself is the product between $\eta_i$ and a random number drawn from a beta distribution in the interval $(0, 1)$. The distribution has an expected value $2C$, where $C$ will be the expected directed connectance of the resulting network. Every network has at least one basal species because we assign $r_i = 0$ to the species with lowest niche value. In the end, the network is checked for connectedness, and networks that are not connected are discarded. The strengths of the interactions are determined by the model used to represent the dynamics, and are different for the Lotka-Volterra and the consumer-resource model.

In the Lotka-Volterra model, to obtain a persistent food-web configuration, we start with initial networks of $50$ nodes and $500$ links so that $C = 0.20$. We then evolve the system according to Eq. (S1) over a time interval $T = 5 \times 10^3$ to identify the largest connected set of species that remain above the threshold $s$. We select the number of links to be $500$ because this choice typically leads to a connected component with desirable properties, namely a persistent food web with up to $15$ species, realistic connectance, and maximum trophic level $\approx 3$. Our simulations are based on selecting connected components with number of species ranging from $10$ to $15$, which represents a good compromise between complexity and computational feasibility. These persistent networks retain the properties of the niche model, including cannibalism and looping, and form the starting point of our analysis. A persistent network here means that all species have nonzero populations in the resulting food web.

In the consumer-resource model, the network structure is generated using the same procedure except that, because the consumer-resource dynamics is more robust, in this case we implement the niche model starting with networks of $25$ nodes and $125$ links. This choice is made so that $C = 0.20$. We select connected networks with number of species ranging from $10$ to $20$ and use the same values for the threshold $s$, now applied to the biomass density, and for the integration time $T$ as in the Lotka-Volterra model. We have also considered the impact of the connectance by generating persistent networks with initial connectance varying from $0.10$ to $0.30$ (see details below).

Thus, in our simulations, each food web corresponds to an independent realization of the network structure and an independent assignment of the initial populations ($X_i$ in the Lotka-Volterra model and $B_i$ in the consumer-resource model)[†], with all other parameters kept fixed. The food

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[†] In the case of the Lotka-Volterra model, this also includes an independent assignment of the corresponding growth

webs are then perturbed by every single-species removal by removing one species at a time (the effect of multiple removals is considered in connection with Supplementary Figure S7). This corresponds to $n$ simulations of a primary removal for a network of $n$ species. We discard realizations that become disconnected due to the primary perturbation. The discarded realizations are not counted towards the statistics represented in Figs. 2 and 4 and in Supplementary Table S1. The rationale for this choice is that the fragmentation of a food web may be an artifact of the non-inclusion of other species likely to be present in realistic situations, which could have significant influence on the dynamics of the network at the edge of fragmentation.

### Stability Analysis

Supplementary Figure S1 shows the properties of the asymptotic states as compared to those of target states for cascades mitigated by forced species removals. For a given forced removal, the corresponding set of target states with largest $n^*$ can consist of only stable fixed points, only unstable fixed points, or both. For each of these cases, the figure shows the break down according to whether the final state has $n^*_{new} = n^*$, $n^*_{new} = n^* - 1$, or $n^*_{new} < n^* - 1$. It also shows a further break down according to whether the final state is time independent (i.e., a stable fixed point) or time dependent. With the exception of the case $n^*_{new} = n^*$ for unstable fixed points and the negligible case $n^*_{new} < n^* - 1$ for coexisting stable and unstable fixed points, all cases tend to converge more often to time-independent states.

Supplementary Figure S2 shows an example of the control of a cascade of extinctions through the forced removal of one species when the target state is stable. As the system approaches the stable fixed point, all populations approach a steady-state asymptotic configuration. Supplementary Figure S3 shows a similar example for the case of an unstable target state. In this case all populations exhibit persistent oscillations in time, which are consistent with the existence of a stable limit cycle around the corresponding unstable fixed point[58]. In Lotka-Volterra systems, solutions not approaching stable fixed points may also exhibit chaotic behavior[59], but previous studies have shown that the prevalence of chaotic dynamics decreases both with the increase in network size and the reduction in the number of trophic levels[60]. In agreement with this prediction, we do not find chaos to be prevalent in the (relatively large) food webs with moderate number of trophic levels considered in our numerical experiments.

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and mortality rates $b_i$.

### Comparison between Models

It is instructive to write the Lotka-Volterra model in a form that is similar to the consumer-resource model. Employing the definition of $co(i)$ and $re(i)$ introduced in connection with Eqs. (S2)-(S3), the Lotka-Volterra equations for basal and non-basal species take the form

$$\dot{X}_i = X_i \left(b_i - |a_{ii}| X_i\right) - \sum_{j \in co(i)} H_{ji} X_j / e, \tag{S7}$$

$$\dot{X}_i = -X_i |b_i| + \sum_{j \in re(i)} H_{ij} X_i - \sum_{j \in co(i)} H_{ji} X_j / e, \tag{S8}$$

respectively, where $H_{ji} = a_{ji} X_i$ is a Type I functional response. That is, in contrast with the consumer-resource model, in the Lotka-Volterra model the amount of a prey species consumed per predator grows linearly with the population density of that species.

Accordingly, the structure of the resulting persistent food webs is different for the two models. For the model food webs considered in Fig. 2 of the paper, which have size $15$, the average maximum trophic level[‡] is found to be $2.9 \pm 0.2$ and $3.4 \pm 0.5$ for the Lotka-Volterra model and consumer-resource model, respectively. The resulting connectance is $0.16 \pm 0.03$ and $0.19 \pm 0.05$, respectively, where the connectance is defined as $\ell / n^2$ for $\ell$ directed links and $n$ species. Basal species consist of $48.5 \pm 5.2\%$ of all species for the Lotka-Volterra model and $32.0 \pm 8.0\%$ for the consumer-resource model.

### Fraction of Cascades Mitigated

Supplementary Table S1 shows the fraction of cascades mitigated in model food webs of 15 species, in the Chesapeake Bay food web, which has 33 species, and in the Coachella Valley food web, which has 30 species. The absolute number of mitigated cascades is comparatively smaller for the consumer-resource model than for the Lotka-Volterra model, but that is because the consumer-resource dynamics is less prone to extinction cascades in the first place[30]. Forty percent or more of the cascades of minimum size $2$ are mitigated in all cases, except for intentional removals limited to cascading extinctions, which are expected to produce a lower yield. In the case of partial removals and manipulation of mortality rates, cascades of size $1$ can also be rescued, although such rescues are less frequent because target states in which all populations are positive are relatively rare (cascades of size $1$ constitute $31.6\%$ of all the realizations for Lotka-Volterra dynamics, but rescued cascades of size $1$ constitute only $0.2\%$ for partial removals and $11.2\%$ for growth and mortality rate control). Cascades with structural extinctions and only one dynamical

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[‡] The trophic levels were estimated using the prey-averaged trophic level algorithm[35].

extinction are similarly difficult to mitigate, but they can in some cases be mitigated by the forced removal of one of the species that would vanish as a structural extinction. While we have found no such rescues in the $1.4\%$ of all realizations that correspond to such cascades in the Lotka-Volterra dynamics, in the consumer-resource dynamics approximately $0.2\%$ of all realizations can be rescue through this mechanism (out of a total of $4.0\%$ corresponding to such cascades). Realizations that lead to a disconnected network after the primary removal are not included in the calculations of these percentages.

### Number of Species Rescued

Supplementary Figure S4 shows the number of species rescued as a function of the size of the cascades for the model networks considered in Supplementary Table S1. In all cases, a significant fraction of secondary extinctions is prevented. In many cases the number of species rescued corresponds to the theoretical maximum, namely, $n^*_{new} = n^p - 1$ for the forced removal of one species and $n^*_{new} = n^p$ for partial removals and for the manipulation of growth and mortality rates. The forced removal of one species is comparably effective for the consumer-resource and Lotka-Volterra dynamics (Supplementary Fig. S4a,b). Among the interventions considered for the Lotka-Volterra dynamics (Supplementary Fig. S4b-e), the manipulation of growth and mortality rates is the most effective one. In the case of forced removals, it is interesting to observe that the interventions remain nearly as effective when they are limited to the set of cascading species (Supplementary Fig. S4c). Note that this refers to the number of rescues in cascades that are mitigated. The fraction of cascades mitigated provides a different measure of the effectiveness of the interventions (previous Section).

### Variation with Network Size, Connectance, Perturbation Size, and Community Type

Supplementary Figure S5 shows the statistics of perturbations and rescues as a function of the network size for forced removals in the consumer-resource systems and various rescue interventions in the Lotka-Volterra systems. An important aspect of these results is that each control strategy exhibits a monotonic increase in the percentage of cascades mitigated as the network size is increased (Supplementary Fig. S5f,g). A relatively large fraction of cascades cannot be mitigated when cascades consisting of a single secondary extinction are included, such as in the cases of partial removals and manipulations of growth and mortality rates (Supplementary Fig. S5d,e; solid symbols), but this is mainly because cascades of size one are more difficult to mitigate. The rescue rates are substantially higher among cascades of size larger than one and even higher for cascades with at least two dynamical extinctions, i.e., extinctions not directly determined by the lack of connectivity in the network (Supplementary Fig. S5f,g).

Extinctions that are not dynamical are said to be structural and occur when a non-basal species is left without any directed path connecting it to basal species of the food web. Structural extinctions are less common for the Lotka-Volterra than for the consumer-resource model and this is so because persistent Lotka-Volterra food webs have a smaller number of trophic levels and a larger number of basal species. In contrast with structural extinctions, dynamical extinctions can in principle be prevented by the interventions considered in the paper.

Supplementary Figure S6 shows the corresponding statistics as the connectance is varied from $0.10\%$ to $0.30\%$. The fraction mitigated of all cascades increases slowly and reaches a saturation with increasing connectance (solid symbols). This change is in fact overcompensated by the concurrent decrease observed in the fraction of structural extinctions (semi-solid symbols). For all connectances, approximately $2/3$ of the cascades can be mitigated. These results refer to forced removals in networks of 15 species simulated using the consumer-resource dynamics with communities of mixed type, but represent a more general trend.

Supplementary Figure S7 shows similar statistics as a function of the size of the primary perturbation. The perturbations consist of single, double and triple removals in networks of 15 species generated from an initial connectance of $0.20$ and simulated using the consumer-resource dynamics with communities of mixed type. As above, varying a single parameter (in this case the size of the perturbation) is necessary for numerical feasibility. The fraction mitigated of all cascades decreases as the size of the perturbation increases (solid symbols), and similar behavior is observed when structural extinctions are factored out (semi-solid symbols). This dependence is expected because increasing the perturbation size increases the damage in the network, making it more difficult to be rescued. Increasing the perturbation size also reduces the size of the network and, as predicted above, extinction cascades are generally more difficult to mitigate in smaller networks.

Supplementary Figure S8 shows the statistics of perturbations and rescues for different types of communities. We observe a slow increase in the fraction of cascades mitigated as we go from invertebrate communities, to mixed communities, to vertebrate communities (solid symbols), and this change matches the change in the frequency of structural extinctions (semi-solid symbols). The latter suggests that the theoretical limit on the fraction of cascades that can be mitigated will be larger in communities with more vertebrates.

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