

Supporting Information

SI 1 Derivation of the evolutionarily stable strategy

An evolutionarily stable strategy (ESS) is a strategy that is not invaded by any other strategies when it is dominant in the population. This section derives the conditions under which each of the four strategies, the cooperative believers (CB), selfish believers (SB), cooperative non-believers (CN), and selfish non-believers (SN), is evolutionarily stable in our general model in the main text. When cooperative or selfish strategies are fixed, the amount of the natural resources is $R_a^* = K(1 - a/\mu)$ or $R_b^* = K(1 - b/\mu)$, respectively. Note that $R_a^* > R_b^*$ because $b > a > 0$.

SI 1.1 CB can be an ESS

SB cannot invade the population of CB if and only if the fear of the supernatural punishment is larger than the temptation to selfishness:

$$P(R_a^*) > \Delta(R_a^*). \quad (\text{S1})$$

CN cannot invade the population of the CB if the positive missionary rate is larger than the negative missionary rate because their payoffs are identical for any R :

$$v_+ > v_-. \quad (\text{S2})$$

SN cannot invade the population of CB if the positive missionary rate is larger than the temptation:

$$v_+ > \Delta(R_a^*). \quad (\text{S3})$$

Combining the above three inequalities results in the necessary and sufficient conditions for CB to be an ESS.

When the amount of natural resources is constant over time, the temptation to selfishness and the fear of supernatural punishment become constant Δ and P , respectively. If the negative missionary events do not occur ($v_- = 0$), CB is evolutionarily stable if and only if

$$\begin{cases} P > \Delta \\ v_+ > \Delta. \end{cases} \quad (\text{S4})$$

Figs. 2a and c are examples that satisfy the above conditions.

SI 1.2 SB can be an ESS

CB cannot invade the population of SB if the temptation to selfishness is larger than the fearness of the supernatural punishment:

$$\Delta(R_b^*) > P(R_b^*). \quad (\text{S5})$$

CN cannot invade the population of SB if the temptation to selfishness plus the positive missionary rate is larger than the fearness of the supernatural punishment:

$$\Delta(R_b^*) + v_+ > P(R_b^*). \quad (\text{S6})$$

SN cannot invade the population of SB if the difference between the positive missionary and negative missionary rates is larger than the fear of supernatural punishment:

$$v_+ - v_- > P(R_b^*). \quad (\text{S7})$$

Because the CN cannot invade SB when CB cannot invade SB, SB is evolutionarily stable if and only if

$$\begin{cases} \Delta(R_b^*) > P(R_b^*) \\ v_+ - v_- > P(R_b^*). \end{cases} \quad (\text{S8})$$

Assuming a constant amount of natural resources and no negative missionary events simplifies the conditions as follows:

$$\begin{cases} \Delta > P \\ v_+ > P. \end{cases} \quad (\text{S9})$$

See Fig. 2e as an example.

SI 1.3 CN cannot be an ESS

CN cannot be evolutionarily stable because SN always invades the population of CN. However, CB cannot invade the population of CN if and only if

$$v_+ < v_-. \quad (\text{S10})$$

In addition, SB cannot invade the population of CN if and only if

$$\Delta(R_a^*) < P(R_a^*) + v_+ \quad (\text{S11})$$

SI 1.4 SN can be an ESS

CB and CN cannot invade the SN population because SN always has a larger payoff than them. The SN is evolutionarily stable if and only if SB cannot invade the population of SN:

$$v_+ - v_- < P(R_b^*) \quad (\text{S12})$$

In other words, SN is evolutionarily stable if the fear of supernatural punishment is greater than the difference between positive and negative missionary rates.

These analyses also clarify that $v_+ - v_- > 0$ is a necessary condition for CB to be evolutionarily stable. If $v_+ - v_- < 0$ SN is a unique ESS (e.g., Section 3.1 in the main text).

SI 2 Local stability analysis of the coexistence of multiple strategies without negative missionary

This section shows the local stability analysis when two or all of CB, SB, and SN coexist without negative missionary events. Here, we assume $x_{\text{CN}} = 0$ because CN obtains a lower payoff than SN, and CN changes into CB due to the positive missionary events. Then, because $x_{\text{SN}} = 1 - x_{\text{CB}} - x_{\text{SB}}$, the system becomes simplified as follows.

$$\dot{R} = \mu R \left(1 - \frac{R}{K} \right) - R \{ a x_{\text{CB}} + b(1 - x_{\text{CB}}) \} \quad (\text{S13a})$$

$$\epsilon \dot{x}_{\text{CB}} = x_{\text{CB}} \{ f_1(R) - \bar{f}(R) \} \quad (\text{S13b})$$

$$\epsilon \dot{x}_{\text{SB}} = x_{\text{SB}} \{ f_{\text{SB}}(R) - \bar{f}(R) \} + v_+(x_{\text{CB}} + x_{\text{SB}})(1 - x_{\text{CB}} - x_{\text{SB}}) \quad (\text{S13c})$$

The Jacobian matrix J is then written as follows:

$$J = (J_1, J_2, J_3) \quad (\text{S14})$$

where

$$J_1 = \begin{pmatrix} \mu(1 - \frac{2R}{K}) - ax_{CB} - b(1 - x_{CB}) \\ \frac{x_{CB}}{\epsilon} \left(\frac{df_{CB}}{dR} - \frac{\bar{f}}{dR} \right) \\ \frac{x_{SB}}{\epsilon} \left(\frac{df_{SB}}{dR} - \frac{d\bar{f}}{dR} \right) \end{pmatrix}, \quad (S15)$$

$$J_2 = \begin{pmatrix} R(b - a) \\ \{(1 - 2x_{CB})f_{CB} - x_{SB}f_{SB} - (1 - 2x_{CB} - x_{SB})f_{SN}\} / \epsilon \\ [-x_{SB}(f_{CB} - f_{SN}) + v_+\{1 - 2(x_{CB} + x_{SB})\}] / \epsilon \end{pmatrix}, \quad (S16)$$

$$J_3 = \begin{pmatrix} 0 \\ -x_{CB}(f_{SB} - f_{SN}) / \epsilon \\ [-x_{CB}f_{CB} + (1 - 2x_{SB})f_{SB} - (1 - x_{CB} - 2x_{SB})f_{SN} + v_+\{1 - 2(x_{CB} + x_{SB})\}] / \epsilon \end{pmatrix}. \quad (S17)$$

According to the Routh-Hurwitz criteria, the coexistence of multiple strategies is locally stable if and only if

$$\begin{cases} \text{tr}J < 0 \\ \det J > 0 \\ \sum_{i=1}^3 M_{ii} > 0. \end{cases} \quad (S18)$$

where M_{ii} represents the (i, i) minor of the Jacobian matrix.

SI 2.1 Coexistence of CB with SB

When CB coexists with SB, no positive missionary events occur. The amount of the natural resources at the equilibrium is, therefore, given by a root of

$$\Delta(R^*) = P(R^*). \quad (S19)$$

In other words, the temptation to selfishness and the fear of supernatural punishment are balanced at equilibrium. Once the root R^* is obtained, the fractions of CB and SB are written as follows, respectively:

$$x_{CB}^* = \frac{b - \mu(1 - R^*/K)}{b - a} \quad (S20)$$

$$x_{SB}^* = 1 - x_{CB}^* \quad (S21)$$

Before analysing the Routh-Hurwitz criteria, it should be noted that

$$f_1(R^*) = f_2(R^*) = \bar{f}(R^*) \equiv f^* \quad (S22)$$

for the convenience of further calculation. The Jacobian matrix at this equilibrium is written as follows:

$$J = \begin{pmatrix} -\mu R^* & R(b-a) & 0 \\ J_{21} & J_{22} & J_{22} \\ -J_{21} & J_{32} & J_{32} \end{pmatrix} \quad (\text{S23})$$

where

$$J_{21} = \frac{x_{\text{CB}}^*}{\epsilon} (1 - x_{\text{CB}}^*) \left(\frac{df_{\text{CB}}}{dR} - \frac{df_{\text{SB}}}{dR} \right) \quad (\text{S24a})$$

$$J_{22} = \frac{x_{\text{CB}}^* (f_{\text{SN}} - f^*)}{\epsilon} \quad (\text{S24b})$$

$$J_{32} = \frac{(1 - x_{\text{CB}}^*) (f_{\text{SN}} - f^*) - v_+}{\epsilon} \quad (\text{S24c})$$

The Routh-Hurwitz criteria (S18) reduce to

$$\begin{cases} \text{tr}J < 0 \\ \det J < 0 \\ \sum_i^3 M_{ii} > 0 \end{cases} \Leftrightarrow \begin{cases} -\mu R^* + J_{22} + J_{32} < 0 \\ J_{21}(J_{22} + J_{32}) > 0 \\ -\mu R(J_{22} + J_{32}) - R(b-a)J_{21} > 0 \end{cases} \quad (\text{S25})$$

$$\Leftrightarrow \begin{cases} J_{21} < 0 \\ J_{22} + J_{32} < 0 \end{cases} \quad (\text{S26})$$

$$\Leftrightarrow \begin{cases} \frac{df_{\text{CB}}}{dR} \Big|_{R=R^*} < \frac{df_{\text{SB}}}{dR} \Big|_{R=R^*} \\ P(R^*) < v_+ \end{cases} \quad (\text{S27})$$

The first inequality argues that the fitness gradient of SB is larger than that of CB, and the second one argues that SN cannot take the place of SB.

SI 2.2 CB cannot coexist with SN

Next, we consider the coexistence of CB with SN $(R, x_1, x_2) = (R^*, x_1^*, 0)$ where

$$0 < x_{\text{CB}}^* < 1 \quad (\text{S28a})$$

$$0 < R^* \quad (\text{S28b})$$

At this equilibrium, the following equation should be satisfied:

$$\begin{aligned} \epsilon \dot{x}_{\text{CB}} &= 0 \\ \Leftrightarrow (1 - x_{\text{CB}}^*) \{f_{\text{CB}}(R) - f_{\text{SN}}(R^*)\} &= 0 \\ \Leftrightarrow (1 - x_{\text{CB}}^*) \Delta(R^*) &= 0 \end{aligned} \quad (\text{S29})$$

$$\Leftrightarrow x_{\text{CB}}^* = 1 \quad \text{or} \quad R^* = 0. \quad (\text{S30})$$

This contradict with inequalitiws (S28a) and (S28b). Therefore, CB cannot coexist with SN.

SI 2.3 SB cannot coexist with SN

This subsection shows that SB and SN cannot coexist $(R_2, 0, x_2^*$ where $0 < x_2^* < 1)$. In this case,

$$\dot{x}_{\text{SB}} = 0 \Leftrightarrow \{f_{\text{SB}}(R^*) - f_{\text{SN}}(R^*) + v_+\} = 0 \quad (\text{S31})$$

Then, the Routh-Hurwitz criteria cannot be satisfied because

$$\det J = 0. \quad (\text{S32})$$

This is because $J_3 = \vec{0}$. SB cannot, therefore, stably coexist with SN.

SI 2.4 Coexistence of CB, SB, and SN

The three strategies, CB, SB, and SN, can stably coexist. At a such equilibrium, $(R, x_1, x_2) = (R^*, x_1^*, x_2^*)$ satisfied the following inequalities.

$$0 < R^* < K \quad (\text{S33})$$

$$0 < x_{\text{CB}}^* < 1 \quad (\text{S34})$$

$$0 < x_{\text{SB}}^* < 1 \quad (\text{S35})$$

$$0 < x_{\text{CB}}^* + x_{\text{SB}}^* < 1 \quad (\text{S36})$$

The equilibrium should satisfy the following equations:

$$x_1^* = \frac{\Delta^*(1 - P^*/v_+)}{\Delta^* - P^*} \quad (\text{S37a})$$

$$x_2^* = \frac{\Delta^*(\Delta^*/v_* - 1)}{\Delta^* - P^*} \quad (\text{S37b})$$

$$x_1^* + x_2^* = \frac{\Delta^*}{v_*} \quad (\text{S37c})$$

$$R^* = K \left(1 - \frac{ax_1^* + b(1 - x_1^*)}{\mu} \right) \Leftrightarrow x_1^* = \frac{b - \mu(1 - R^*/K)}{b - a} \quad (\text{S37d})$$

where $\Delta^* = \Delta(R^*)$ and $P^* = P(R^*)$, respectively. Eq (S37a) = Eq (S37d) derives the equilibrium, but it is challenging to solve this equation due to the nonlinearity of $\Delta(R)$ and $P(R)$.

Below, we continue the local stability analysis. Here we aim to show that the time scale parameter ϵ affects the stability without changing the equilibrium. For the rest of the types of equilibria, we have already shown

that ϵ does not affect the stability. Notice that

$$\left\{ \begin{array}{l} 1 > x_{\text{CB}}^* > 0 \\ 1 > x_{\text{SB}}^* > 0 \\ 1 > x_{\text{CB}}^* + x_{\text{SB}}^* > 0 \\ K > R^* > 0 \end{array} \right. \Leftrightarrow P^* > v_+ > \Delta^* \quad (\text{S38a})$$

because $\Delta^* x_{\text{CB}} + P^* x_{\text{SB}} = \Delta^*$. The Jacobian matrix at this equilibrium is written as follows:

$$J = \begin{pmatrix} -\frac{\mu R^*}{K} & R^*(b-a) & 0 \\ J_{21}^* & \Delta^* x_{\text{CB}}/\epsilon & P^* x_{\text{CB}}/\epsilon \\ J_{31}^* & (\Delta^* x_{\text{SB}} + v_+ - 2\Delta^*)/\epsilon & (P^* x_{\text{SB}} - (P^* + \Delta^* - v_+)/\epsilon) \end{pmatrix}. \quad (\text{S39})$$

where

$$J_{21}^* = \frac{x_1^*}{\epsilon} \left\{ -(1-x_1^*) \frac{d\Delta}{dR} \Big|_{R=R^*} + x_2^* \frac{dP}{dR} \Big|_{R=R^*} \right\} \quad (\text{S40a})$$

$$J_{31}^* = \frac{x_2^*}{\epsilon} \left\{ -(1-x_2^*) \frac{dP}{dR} \Big|_{R=R^*} + x_1^* \frac{d\Delta}{dR} \Big|_{R=R^*} \right\} \quad (\text{S40b})$$

Note that $J_{22}, J_{23}, J_{33} > 0$ because $x_1^*, x_2^* > 0$. Now, we consider the Routh-Hurwitz criteria. The trace of the Jacobian matrix at the equilibrium is always negative because $v_+ < P^*$:

$$\text{tr}J < 0 \Leftrightarrow \frac{\mu R^*}{K} > \underbrace{\frac{v_+ - P^*}{\epsilon}}_{< 0}. \quad (\text{S41})$$

To investigate whether the equilibrium is stable or not, we need to evaluate the other two Routh-Hurwitz criteria:

$$\det J < 0 \Leftrightarrow J_{11}M_{11} + J_{12}(J_{31}J_{23} - J_{21}J_{33}) < 0 \quad (\text{S42})$$

$$\begin{aligned} \sum_i M_{ii} > 0 &\Leftrightarrow \underbrace{M_{11}}_{\mathcal{O}(\epsilon^{-2})} + \underbrace{M_{22}}_{\mathcal{O}(\epsilon^{-1})} + \underbrace{M_{33}}_{\mathcal{O}(\epsilon^{-1})} > 0 \\ &\Leftrightarrow M_{11} + \frac{\mu R^*(P^* - v_+)}{K\epsilon} - J_{12}J_{21} > 0 \end{aligned} \quad (\text{S43})$$

Although it is difficult to continue the further analysis, the above equations clarify that the time scale parameter ϵ affects the stability of the equilibrium. Below, we illustrate an example when $\Delta(R)$ and $P(R)$ are linear functions of R .

SI 2.4.1 Simple example: linear temptation and fearness

For illustration, we consider the case when both the temptation to the selfishness $\Delta(R)$ and the fearness of the supernatural punishment $P(R)$ are linear functions (i.e., $w = u = 1$). In this case, the equilibrium where

CB, SB, and SN coexist is unique because Eq (S37a) = Eq (S37d) results in a linear equation of R^* . Once the equilibrium is derived, its stability is analyzed as follows: Because $\Delta x_1^* + Px_2^* = \Delta$ at this equilibrium,

$$(b-a)x_{\text{CB}}^* + px_{\text{SB}}^* = b-a \Leftrightarrow x_{\text{CB}}^* \frac{d\Delta}{dR} + x_{\text{SB}}^* \frac{dP}{dR} = \frac{d\Delta}{dR} \quad (\text{S44})$$

$$\Leftrightarrow J_{21} = 0 \quad (\text{S45})$$

Similarly,

$$J_{31} = x_{\text{SB}}(b-a-p)/\epsilon < 0 \quad (\text{S46})$$

Then,

$$M_{11} = -\frac{x_{\text{CB}}^*(v_+ - \Delta^*)(P^* - \Delta^*)}{\epsilon^2} < 0. \quad (\text{S47})$$

Now, the Routh-Hurwitz conditions are written as follows:

$$\text{tr}J < 0 \Leftrightarrow \frac{\mu R^*}{K} > \frac{v_+ - P^*}{\epsilon} \quad (\text{S48})$$

$$\text{det}J < 0 \Leftrightarrow \frac{(b-a)x_{\text{SB}}^*}{R^*} > \frac{\mu}{K}(v_+ - \Delta^*) \quad (\text{S49})$$

$$\sum_{i=1}^3 M_{ii} > 0 \Leftrightarrow \underbrace{-\frac{x_{\text{CB}}(v_+ - \Delta^*)(P^* - \Delta^*)}{\epsilon^2}}_{<0} + \underbrace{\frac{\mu R^*(P^* - v_*)}{K\epsilon}}_{>0} > 0 \quad (\text{S50})$$

The first inequality always holds because $P^* > v_+ > \Delta^*$ should be satisfied if this equilibrium exists. One can easily evaluate the second inequality once the equilibrium is obtained. The third inequality argues that the stability changes over ϵ even when the other parameter values are fixed. When $\epsilon \gg 1$ (i.e., the evolution of human behavior is small compared to the dynamics of natural resources), $\sum_{i=1}^3 M_{ii} > 0$ because the first term in the equality can be omitted. In this case, the coexistence of the three strategies is stable if $\text{det}J$ is positive. When $\epsilon \ll 1$ (i.e., the rapid evolution of human behavior), the equilibrium is unstable because $\sum_{i=1}^3 M_{ii} \approx M_{11} < 0$.

Note that $w = u = 1$ indicates that CB cannot stably coexist with SB. When the two strategies coexist, the following equation should be satisfied.

$$\Delta(R) = P(R) \Leftrightarrow b - a = p. \quad (\text{S51})$$

Recall that this equilibrium is stable if and only if

$$\left. \frac{df_{\text{CB}}}{dR} \right|_{R=R^*} < \left. \frac{df_{\text{SB}}}{dR} \right|_{R=R^*} \Leftrightarrow p < b - a. \quad (\text{S52})$$

Therefore, the case of $w = u = 1$ has at most four equilibria: fixation of CB, fixation of SB, fixation of SN, or

coexistence of the three strategies.

SI 3 CN cannot stably coexist with the other strategies

This section proves that CN cannot stably coexist with the other strategies without the negative missionary events ($v_- = 0$). We begin the analysis by examining whether CN coexists with one of the three states. First, CN cannot stably coexist with CB because their payoffs are identical for any R (i.e., $f_{CB}(R) = f_{CN}(R)$) but the positive missionary events alter CN to CB. Second, CN cannot coexist with SB stably. Suppose SB and CN coexist. CB can, however, invade this coexistence due to the positive missionary events. CN cannot coexist with SN because the temptation to the selfishness $\Delta(R)$ alters CN to SN.

Next, we consider the coexistence of three strategies. Suppose CN coexist with CB and SB. At an equilibrium point, the fractions of CB and CN should satisfy the following equations:

$$\begin{cases} x_{CB}^* (f_{CB}(R^*) - \bar{f}(R^*)) + v_+ (x_{CB}^* + x_{SB}^*) x_{CN}^* = 0 \\ x_{CN}^* \underbrace{(f_{CN}(R^*) - \bar{f}(R^*))}_{=f_{CB}(R^*) - \bar{f}(R^*)} - v_+ (x_{CB}^* + x_{SB}^*) x_{CN}^* = 0 \end{cases} \quad (S53)$$

$$\Leftrightarrow x_{CB}^* = -\frac{v_+ (x_{CB}^* + x_{SB}^*) x_{CN}^*}{(f_{CB}(R^*) - \bar{f}(R^*))} = -x_{CN} \quad (S54)$$

where the asterisks represent the values at the equilibrium point. Because x_{CB}^* and x_{CN}^* should be positive, the coexistence of CB, CN, and SB is not feasible. The coexistence of all four strategies is not feasible for the same reason.

When CN coexists with SB and SN, this coexistence is not stable because CB can invade:

$$\dot{x}_{CN} = x_{CN}^* \underbrace{(f_{CN}(R^*) - \bar{f}(R^*))}_{=f_{CB}(R^*) - \bar{f}(R^*)} - v_+ x_{SB}^* x_{CN}^* = 0 \quad (S55)$$

$$\Rightarrow \dot{x}_{CB} = v_+ x_{SB}^* x_{CN}^* > 0. \quad (S56)$$

Therefore, CN cannot coexist with any of the other three strategies without the negative missionary.

SI 4 SB cannot stably coexist with SN in the full model

SB can coexist with the SN in the presence of the negative missionary (c.f., [SI 2.3](#)). At the equilibrium,

$$\begin{aligned} \dot{x}_{SB} &= 0 \\ \Leftrightarrow P(R_b^*) &= v_- - v_+. \end{aligned} \quad (S57)$$

This equilibrium is feasible only if the negative missionary rate v_- is equal to or higher than the positive missionary rate v_+ because the fearness of the supernatural punishment is non-negative. However, this equilibrium

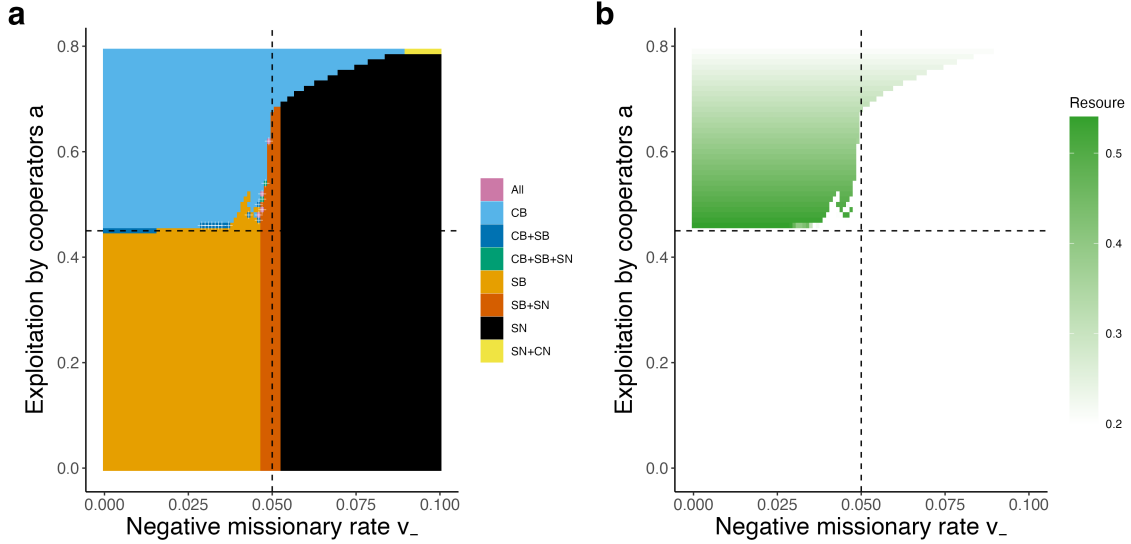


Figure S1: Parameter space when the temptation is a concave function

Similar to Fig. 5 in the main text, but the temptation to selfishness was a concave function in this figure ($w = 0.5$). The remaining parameter values were identical to Fig. 5.

is not stable because

$$\frac{\partial}{\partial x_{\text{SB}}} \dot{x}_{\text{SB}} = \{P(R_b^*) - v_- + v_+\} (1 - 2x_{\text{SB}}) = 0. \quad (\text{S58})$$

In other words, when the fraction of SB changes from the equilibrium due to a small perturbation, the fraction cannot return to its original. The coexistence of SB with SN is, therefore, unstable.

SI 5 Parameter space when the temptation and the fearness are nonlinear functions of the natural resource

In the main text, we investigated how the negative missionary rate v_- and the exploitation rate by the cooperators a affect the evolutionary fate of the human behaviors and the average natural resource availability at the end when the temptation to selfishness $\Delta(R)$ and the fearness of the supernatural punishment $P(R)$ are linear functions of R (i.e., $w = u - 1$). In this section, we analyzed the cases when either of the two functions was nonlinear. Remarkably, we investigated the instances where the temptation was a concave ($w = 0.5$) or convex ($w = 2$) function while the fearness remained the linear function ($u = 1$). We also investigated cases where the fearness was a concave ($u = 0.5$) or convex ($u = 2$) function while the temptation was linear ($w = 1$).

The nonlinearity of the temptation w changed the threshold of $P(R_b^*) = \Delta(R_b^*)$. When the temptation was a concave function of R (Fig. S1), the areas where the cooperative believers coexisted with other strategies disappeared, and SB was fixed instead. The concave function shrunk the parameter spaces in which the R was larger than R_b^* at the end of the simulations. When the temptation was a convex function of R (Fig. S2), SB

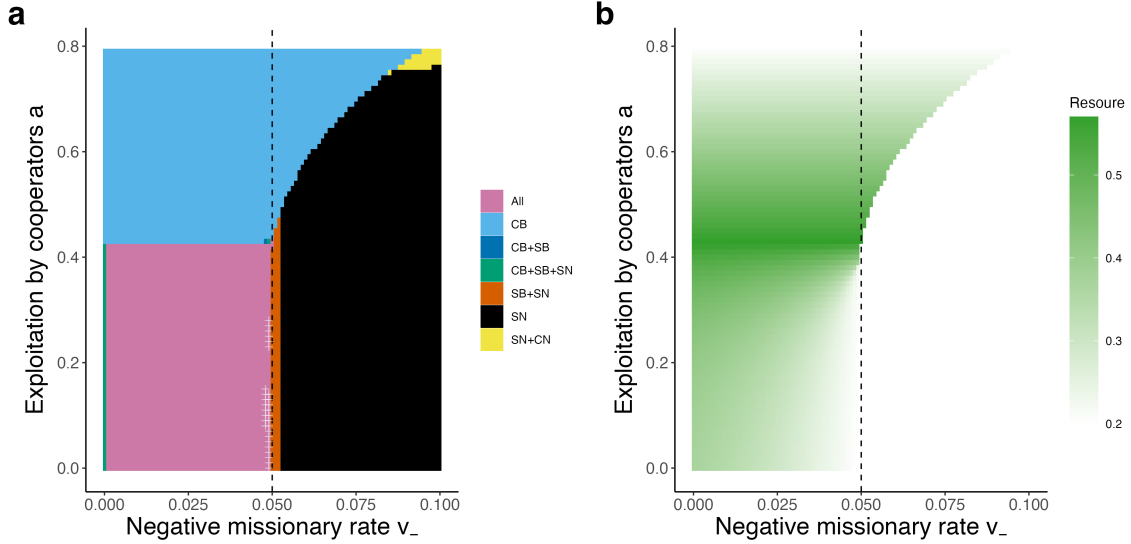


Figure S2: Parameter space when the temptation is a convex function

Similar to Fig. 5 in the main text, but the temptation to selfishness was a convex function in this figure ($w = 2$). The remaining values were identical to Fig. 5. The selfish believer cannot be evolutionarily stable in this case because no real a satisfies $P(R_b^*) = \Delta(R_b^*)$. The horizontal dashed line vanished for this reason.

was not fixed because no real a satisfied $P(R_b^*) = \Delta(R_b^*)$. CB persisted in broader parameter ranges, typically coexisting with the three other strategies.

The nonlinearity of the fearness u , on the other hand, changed the two thresholds $P(R_b^*) = \Delta(R_b^*)$ and $v_- = v_+ - P(R_b^*)$. The nonlinearity resulted in a decrease in the parameter space where CB persisted. When the fear of supernatural punishment was a concave function (Fig. S3), the two thresholds became negative, leading to the fixation of SN in most cases. CB fixated only when the exploitation rates by the cooperatives and the selfish strategies were close. When the fearness of the supernatural punishment was a convex function (Fig. S4), the two thresholds became larger than in the linear case (Fig. 5). As a result, SB fixated in the population unless the exploitation rate by the cooperators was close to that of the selfish strategies. These two cases show limited areas where the resource availability remained higher than the minimum value R_b^* .

In short, while the nonlinearity in the fear of the supernatural punishment decreased the parameter space where CB can persist, a convex function of the temptation increased such parameter space.

SI 6 Cases of negative correlation between the fear of supernatural punishment and the amount of natural resources

In the main text, we assumed that the fear of supernatural punishment increased with the amount of natural resources. In this section, we analyzed our model under the opposite assumption: the fear of supernatural punishment decreased with the amount of natural resources because individuals may regard depleting them as

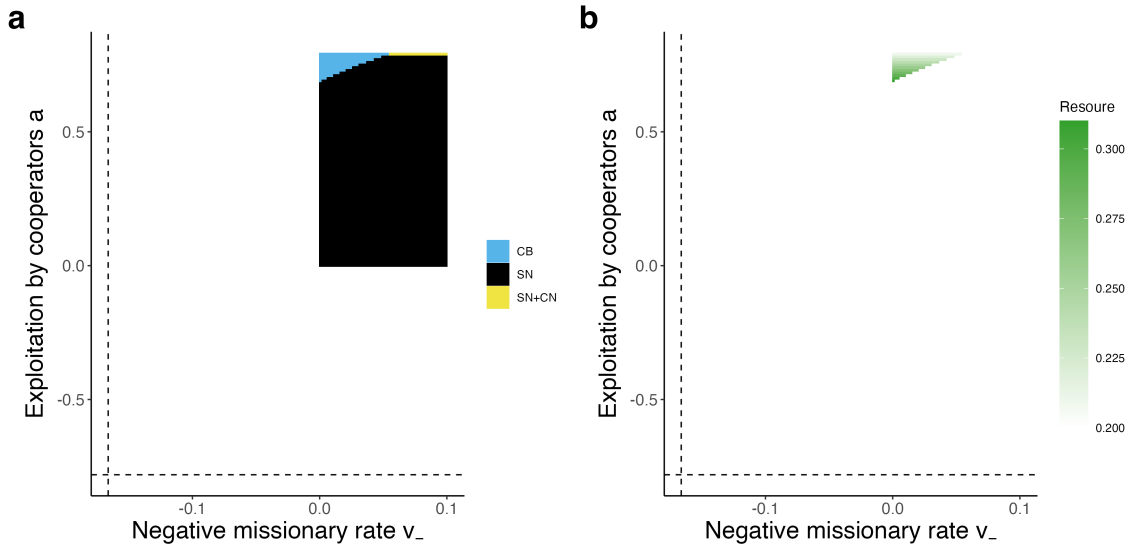


Figure S3: Parameter space when the fearness is a concave function

Similar to Fig. 5 in the main text, but the fearness of the supernatural punishment was a concave function in this figure ($u = 0.5$). The remaining parameter values were identical to Fig. 5. As in the main text, we analyzed the parameter ranges $0 \leq v_- \leq 0.1$ and $a \leq a \leq 0.79$.

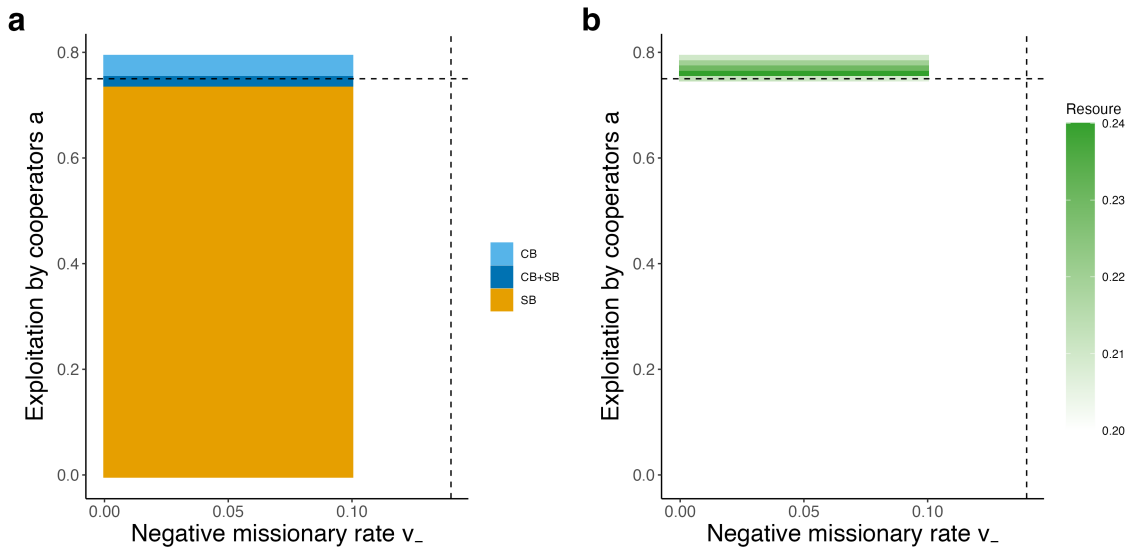


Figure S4: Parameter space when the fearness was a convex function

Similar to Fig. 5 in the main text, but the fearness of the supernatural punishment was a convex function in this figure ($u = 2$). The rest of the parameter values were identical to Fig. 5. As in the main text, we analyzed the parameter ranges $0 \leq v_- \leq 0.1$ and $a \leq a \leq 0.79$.

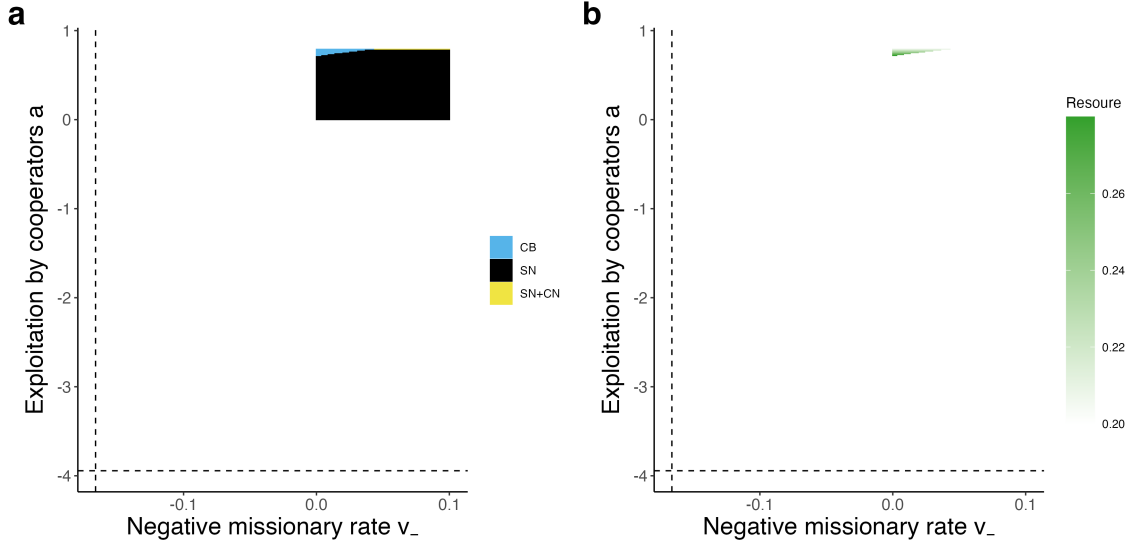


Figure S5: Parameter space when the fearness decreased over the resource

Similar to Fig. 5 in the main text, but the fearness of the supernatural punishment was $P(R) = 1 - (pR)$ in this figure. The rest of the parameter values were identical to Fig. 5. As in the main text, we analyzed the parameter ranges $0 \leq v_- \leq 0.1$ and $a \leq a \leq 0.79$.

more “sinful.” Mathematically, we assume the following function of $P(R)$ in this section:

$$P(R) = 1 - (pR)^u. \quad (\text{S59})$$

In this case, dP/dR becomes negative. Nevertheless, our analyses in the main text and Supporting Information hold (except for the example in SI 2.4.1) because our conclusion does not depend on the sign of dP/dR .

Fig. S5 shows the evolutionary fate when $P(R) = 1 - (pR)$ (i.e., $u = 1$) over two parameter values a and v_- while the rest of the parameter values were identical to Fig. 5. Because $P(R_b^*)$ in this case was larger than in the main text, inequality (5) cannot hold in our parameter ranges. As a result, SN were evolutionarily stable in most cases. Although we found small areas where CB was fixed, both CB and SN were evolutionarily stable there. Fig. S6 shows that the initial conditions altered the evolutionary fate at such parameter values.

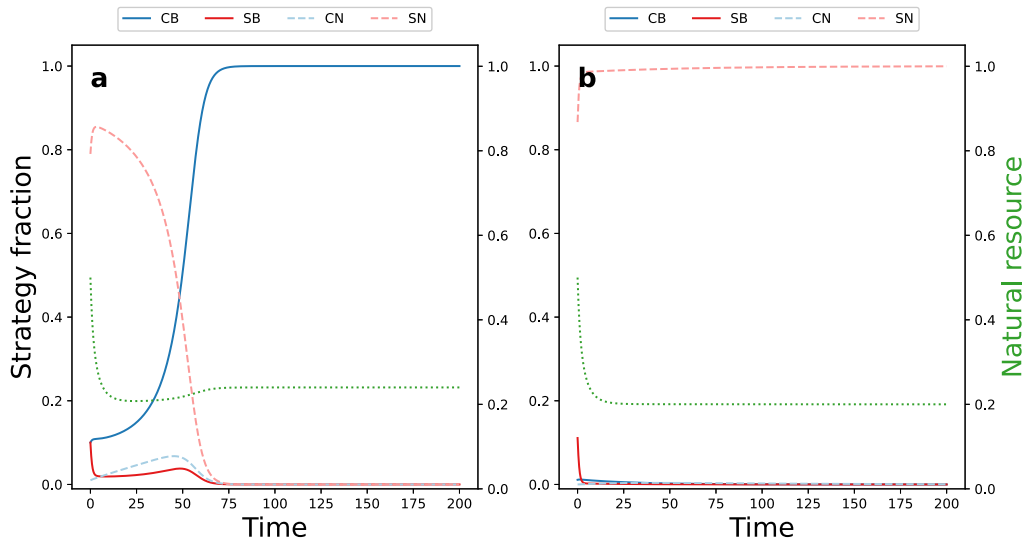


Figure S6: Example of dynamics when the fearness decreased over the resource

Examples of the dynamics in Fig. S5. Panel a started from $(R, x_{CB}, x_{SB}, x_{CN}, x_{SN}) = (0.5, 0.1, 0.1, 0.01, 0.79)$ while b started from $(R, x_{CB}, x_{SB}, x_{CN}, x_{SN}) = (0.5, 0.01, 0.1, 0.1, 0.79)$. Parameters are identical to Fig. 5 except that $v_- = 0.01$ and $a = 0.76$ in this figure.