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Supplemental information

Combination of institutional incentives for cooperative governance of risky commons

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Here we present detailed numerical results about the evolutionary dynamics in finite populations when fixed and flexible incentives are respectively considered under global scheme of sanctioning.

Fixed incentives under global scheme

In Figure S1 we first show the evolutionary dynamics of cooperators, defectors, and executors in the entire population under global scheme when fixed values of incentives are used. We find that when executors choose to reward cooperators ($\alpha = 1$) or punish defectors ($\alpha = 0$) exclusively, then the entire population always spends most time near the full defection state. The direction flow of orange arrows suggests that when the number of executors is larger than a given threshold (see blue dash line), most arrows flow to the *CE*-edge, and then enter the bottom of the blue dashed line along the *CE*-edge, and finally arrive to the vertex *D*. Accordingly, free-riders can dominate the entire population no matter whether pure reward strategy or pure punishment strategy is considered under global scheme. Furthermore, in order to better distinguish the effectiveness of pure reward strategy and pure punishment strategy, we have calculated the group achievement values for $\alpha = 1$ and $\alpha = 0$, and we have obtained that both values are 0.07%. Hence, we find that pure reward strategy does not have a distinct advantage over pure punish-

ment strategy in improving the level of group achievement. Indeed this is because the payoff differences between any two competing strategies are independent of the parameter α for fixed incentives under global scheme, and then we can have the same stationary distribution and the same gradient of selection for different values of α.

Figure S2 summarizes how the group achievement η_G depends on the key pa-

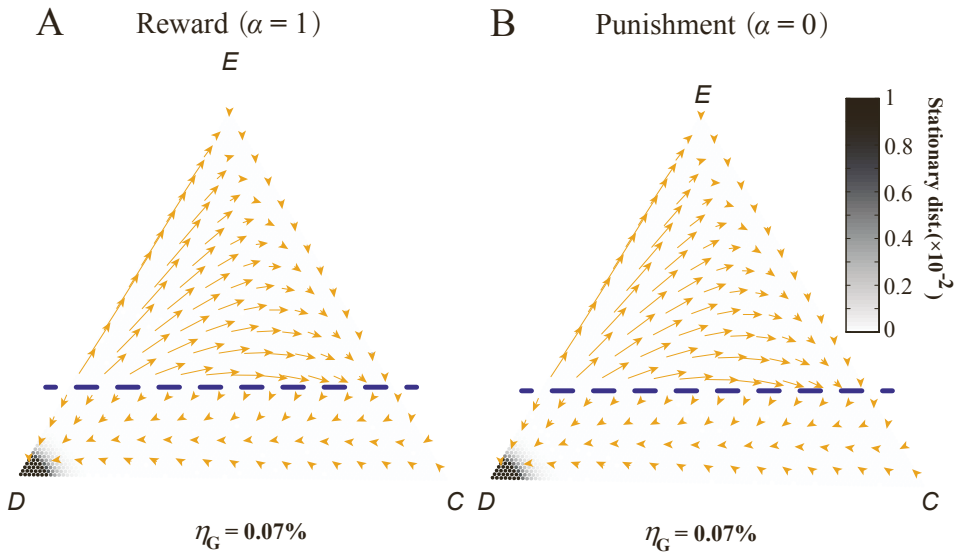

Figure S 1: **Evolutionary dynamics of cooperators, defectors, and executors under global scheme with fixed incentives.** The risk level is $r = 0.2$. In panel A, the $\alpha = 1$ extreme case of pure reward strategy is considered. In panel B, the other $\alpha = 0$ extreme case of pure punishment is considered. Incentives are imposed on global level when the number of executors exceeds 25% of the population. Parameter values are $Z = 100$, $N = 4$, $c = 0.1$, $b = 1$, $\mu = 1/Z$, $\pi_t = 0.03$, and $\pi_e = 0.3$.

rameters of the model. In panel A we show that there is no distinct change in dependence of α. Hence, this suggests that pure reward strategy does not improve the level of group achievement than other combination of incentives for different values of r. Panel B of Figure S2 demonstrates clearly that higher risk level enforces higher group achievement. For comparison, we here also show the two-strategy case when incentive strategy is missing (see black dash line). We can find that the introduction of E strategy improves the results. Last we present the effect of mutation rate μ on the group achievement η_G in panel C of Figure S2. Similarly to local institutions, the value of η_G first increases, then reaches a maximum, and finally saturates for high μ values. However, we still find that for fixed incentives under global scheme pure reward strategy does not have an evident advantage over other incentive strategies when strategy E rewards cooperators exclusively.

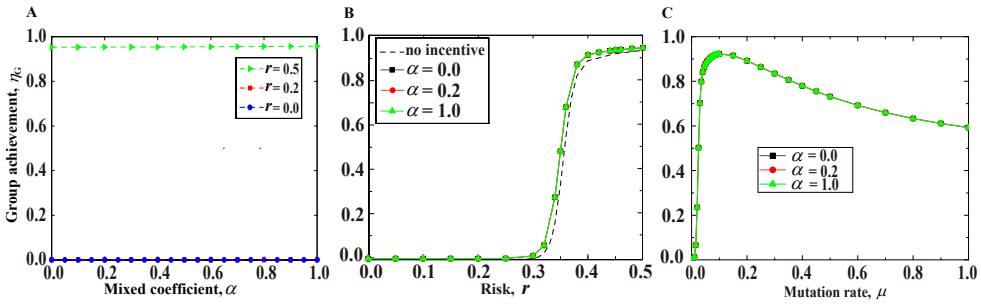

Figure S 2: **The average group achievement η_G under global scheme with fixed incentives.** Parameter values are Z = 100, N = 4, c = 0.1, b = 1, $\mu = 1/Z$, $\pi_t = 0.03$, and $\pi_e = 0.3$ in panels A and B; Z = 100, N = 4, c = 0.1, b = 1, r = 0.3, $\pi_t = 0.03$, and $\pi_e = 0.3$ in panel C.

Flexible incentives under global scheme

We first show the effectiveness of pure reward strategy and pure punishment strategy in improving the level of group achievement, as shown in Figure S3. Importantly, the imposed incentives are not fixed, instead the incentive values depend on the number of executors, whose collective efforts are acknowledged via an enhancement factor δ. The comparison of simplex suggests that there is no qualitative difference between the cases of low and high δ values. Namely, the population not only spends most of the time in the vicinity of vertex *C*, but also spends a reasonable time very close to vertex *D*. This is valid both for pure reward and pure punishment strategies. For a more accurate comparison, we have calculated the group achievement values for both cases and added their values to the simplexes. Accordingly, this value is always higher for $\alpha = 1$, regardless of the enhancement factor values.

To explore the proper consequence of mixed incentives, we present η_G as a function of α for three different values of δ in Figure S4A. Similarly to the local scheme case, we find that when the value of δ is small, the level of group achievement is very low, regardless of the value of α. By increasing δ, however, η_G can be improved significantly for large α. Hence we can conclude that pure reward strategy is always more effective than other combinations of incentives, especially when the value of δ is large. In Figure S4B we present η_G as a function of r for three different values of α. For comparison, we also show the group achievement in the absence of executor strategy. As expected, η_G grows by increasing the risk level of collective failure, but the curves evolve in a very similar way. Strictly speaking, the curve belonging to $\alpha = 1$ case is always higher than other curves,

hence the superiority of pure reward option remains intact. Next we present η_G as a function of δ for three different values of α. Figure S4C suggests that the group achievement level increases by increasing the value of δ. Furthermore, the usage of pure reward strategy can be more effective than any other mixture of incentives especially when the value of δ is large. Finally we show how the mutation rate μ influences the group achievement η_G for three different values of α. Figure S4D shows that the advantage of pure reward against any other combinations is justified when the mutation is less than 0.2 for flexible incentives under global scheme.

Robustness to the intensity of selection

In Figure S5, we show how the group achievement varies when the intensity of selection is changed appropriately for fixed incentives under local scheme, flexible incentives under local scheme, fixed incentives under global scheme, and flexible incentives under global scheme, respectively. We find that our main results remain valid when changing the value of intensity of selection, that is, pure reward strategy outperforms other combinations of incentives for fixed incentives under local scheme, flexible incentives under local scheme, and flexible incentives under global scheme. However, for fixed incentives under global scheme, we find that changing the value of intensity of selection can alter the group achievement for each α value, but there is no distinct change in dependence of α when the value of intensity of selection is fixed.

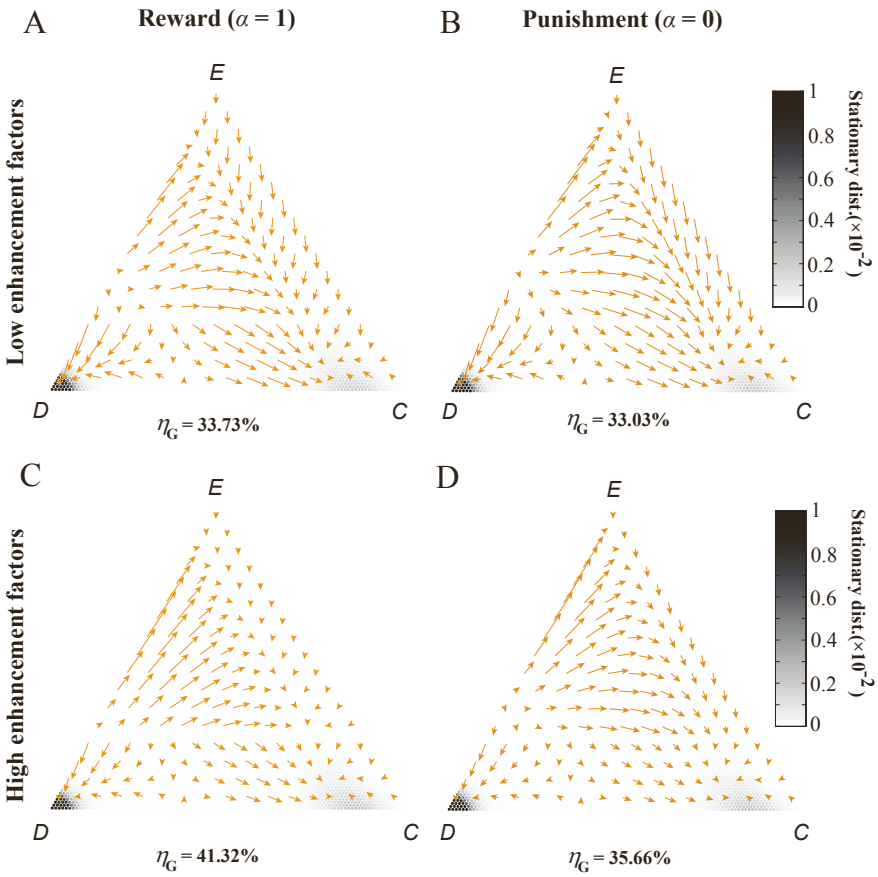

Figure S 3: **Evolutionary dynamics of cooperator, defector, and executor strategy under global scheme with flexible incentives.** The risk level is r = 0.35. Panels A and C show the case of pure reward ($\alpha = 1$). Panels B and D show the case of pure punishment ($\alpha = 0$). Parameter values are Z = 100, N = 4, c = 0.1, b = 1, $\mu = 1/Z$, $\pi_t = 0.03$, and $\delta = 1.4$ in panels A and B; Z = 100, N = 4, c = 0.1, b = 1, $\mu = 1/Z$, $\pi_t = 0.03$, and $\delta = 3$ in panels C and D.

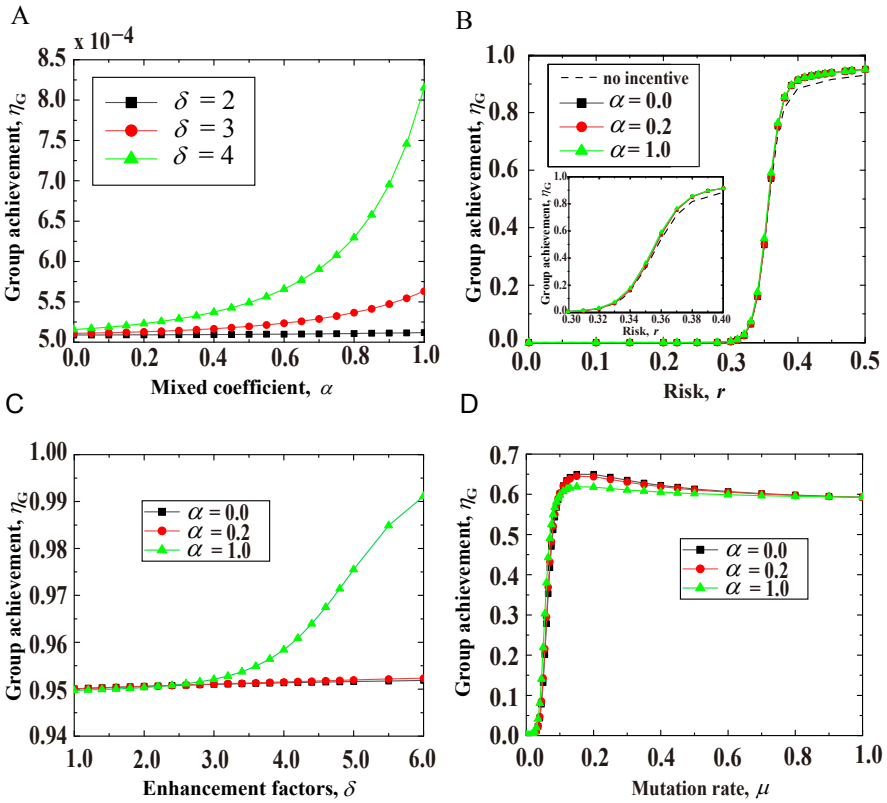

Figure S 4: **The average group achievement η_G under global scheme with flexible incentives.** The applied weight factor values are marked in the legends and panel B also contains the traditional case in the absence of strategy E. Parameter values are Z = 100, N = 4, c = 0.1, b = 1, $\mu = 1/Z$, r = 0.2, and $\pi_t = 0.03$ in panel A; Z = 100, N = 4, c = 0.1, b = 1, $\mu = 1/Z$, $\delta = 2$, and $\pi_t = 0.03$ in panel B; Z = 100, N = 4, c = 0.1, b = 1, $\mu = 1/Z$, $r = 0.5$, and $\pi_t = 0.03$ in panel C; Z = 100, N = 4, c = 0.1, b = 1, $\mu = 1/Z$, r = 0.2, $\delta = 3$, and $\pi_t = 0.03$ in panel D.

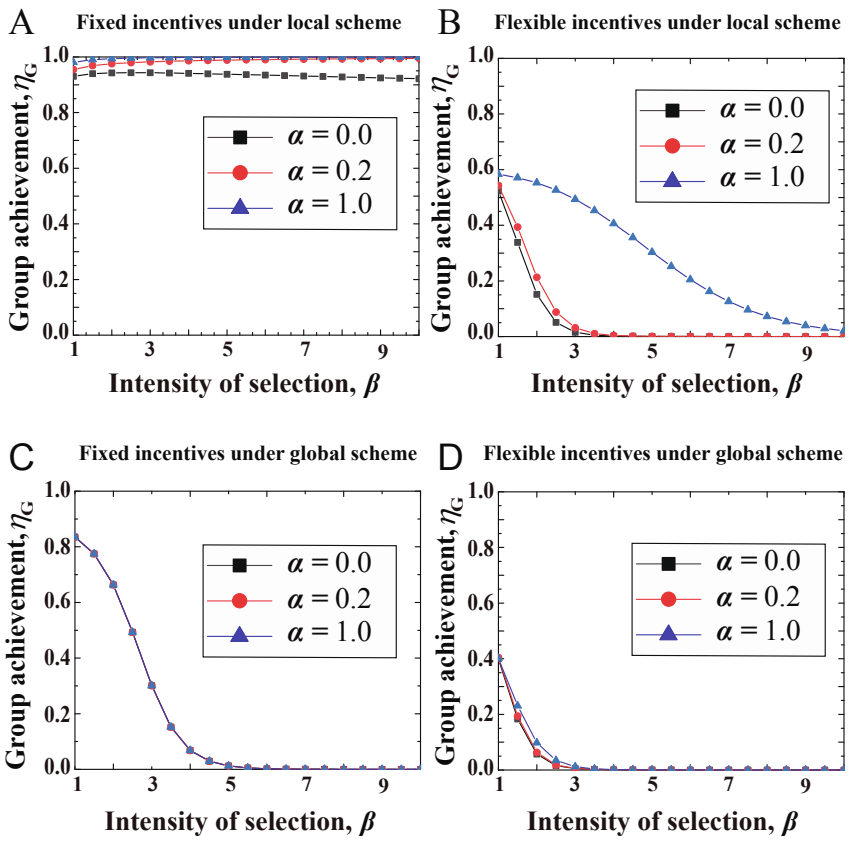

Figure S 5: **Robustness of the average group achievement η_G to the changes of the intensity of selection.** Panel A shows η_G as a function of β for three different values of α under local scheme with fixed incentives. Panel B shows η_G as a function of β for three different values of α under local scheme with flexible incentives. Panel C shows η_G as a function of β for three different values of α under global scheme with fixed incentives. Panel D shows η_G as a function of β for three different values of α under global scheme with flexible incentives. Parameter values are $Z = 100$, $N = 4$, $c = 0.1$, $b = 1$, $r = 0.3$, $\pi_t = 0.03$, and $\pi_e = 0.3$ in panel A; $Z = 100$, $N = 4$, $c = 0.1$, $b = 1$, $r = 0.2$, $\pi_t = 0.03$, and $\delta = 3$ in panel B; $Z = 100$, $N = 4$, $c = 0.1$, $b = 1$, $r = 0.3$, $\pi_t = 0.03$, and $\pi_e = 0.3$ in panel C; $Z = 100$, $N = 4$, $c = 0.1$, $b = 1$, $r = 0.2$, $\pi_t = 0.03$, and $\delta = 3$ in panel D.