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First carrot, then stick: How the adaptive hybridization of incentives promotes cooperation

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***Title Page**

Title:

First carrot, then stick: How the adaptive hybridization of incentives promotes cooperation

Running headline:

'First carrot, then stick' promotes cooperation

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Abstract

Social institutions often use rewards and penalties to promote cooperation. Providing incentives tends to be costly, so it is important to find efficient policies for the combined use and synthesis of rewards and penalties. Most studies of cooperation have, however, addressed rewarding and punishing in isolation and have focused on peer-to-peer sanctioning as opposed to institutional sanctioning. Here, we demonstrate that an institutional sanctioning policy we call 'first carrot, then stick' is unexpectedly successful in promoting cooperation. The policy switches the incentive from rewarding to punishing when the frequency of cooperators exceeds a threshold. We find that this policy establishes and recovers full cooperation at lower cost and under a wider range of conditions than either rewards or penalties alone, in both well-mixed and spatial populations. In particular, the spatial dynamics of cooperation make it evident how punishment acts as a 'booster stage' that capitalizes on and amplifies the pro-social effects of rewarding. Together, our results show that the adaptive hybridization of incentives offers the 'best of both worlds' by combining the effectiveness of rewarding in establishing cooperation with that of punishing in recovering it, and thus provides a surprisingly inexpensive and widely applicable method of promoting cooperation.

Keywords: punishment; rewards; public goods; evolutionary games; social design

1. Introduction

Cooperation is desirable whenever groups of cooperating individuals can reap higher benefits than groups of individuals acting for individual self-interest. Promoting cooperation can be difficult, however, because a single non-cooperating individual (‘defector’) in a group of cooperators often achieves a higher net benefit by free-riding on the others’ contributions. An efficient policy for promoting cooperation needs to overcome two fundamental challenges: to ensure that cooperators can gain a foothold in a community of defectors, and to protect a community of cooperators from exploitation by defectors once cooperation has been established.

Incentives can help overcome these challenges (Balliet et al., 2011; Ostrom, 1990; Sigmund, 2007). The promise of reward or the threat of punishment can induce cooperation among self-interested individuals who would otherwise prefer actions that undermine the public good. At first glance, there might seem to be little difference between a reward and a penalty: After all, cooperation is induced whenever the size of the incentive exceeds the payoff difference between a cooperator and a defector, irrespective of whether the incentive is positive or negative (Sasaki et al., 2012). This equivalence ceases to hold, however, when one considers the challenge of implementing an institutional incentive scheme. Rewarding a large number of cooperators, or penalizing a large numbers of defectors, are either very costly or become ineffective when a limited budget for incentives is stretched out too far. Pamela Oliver exemplifies this with the problem of fund-raising (Oliver 1984): ‘If only 5% of the population needs to contribute to an Arts Fund for it to be successful, they can be rewarded by having their names printed in a program: It would be silly and wasteful to try to punish the 95% who did not contribute.’ While the challenges of implementing positive and negative incentives are separately well known (Balliet et al., 2011; Sigmund, 2007), no study to date has established how such incentives should best be combined at an institutional level to promote cooperation.

Here, we demonstrate how an institution implementing incentives can effectively establish and recover cooperation at a low cost. Institutional sanctioning is widespread (Casari & Luini, 2009; Chen et al., 2013; Cressman et al., 2012, 2013; Cuesta et al., 2008; Falkinger, 1996; Kanazawa et al., 2009; Kosfeld et al., 2009; Ostrom, 1990; Sasaki 2013; Sasaki et al., 2012; Sigmund et al., 2010; Vasconcelos et al., 2013), but surprisingly few theoretical studies have thus far considered the effects of institutionalized incentives on the evolution of cooperation, and the few studies which exist have considered rewarding and punishing in isolation (Cuesta et al., 2008; Sasaki 2013; Sasaki et al., 2012), or did not consider how optional incentives change with the frequency of cooperators (Cressman et al., 2012, 2013; Kanazawa et al., 2009). Indeed, sanctioning entities such as officers and managers often alter the strengths of reward and punishment dynamically as events unfold. We address this question in an established game-theoretical framework for studying cooperation under institutionalized incentives (Sasaki 2013; Sasaki et al., 2012). By considering the incentives’ strengths as independent variables, we can encompass a range of hybrid incentive policies. In particular, by allowing relative allocation of incentives to rewarding and punishing to vary with the frequency of cooperators, our framework includes hybrid incentive policies controlled by adaptive feedback from the community’s state.

2. Model

Our model is based on the public good game, recognized as the most promising mathematical metaphor for studying cooperation in large groups (Hauert et al., 2006). We posit well-mixed populations of interacting individuals. From time to time, individuals randomly selected from the population form an *n*-player group, with $n \geq 2$. A cooperator invests a fixed amount $c > 0$ into a common pool, whereas a defector invests nothing. The total contribution is thus then multiplied by a public-benefit factor $r > 1$ and distributed equally among all *n* group members. The infamous 'tragedy of the commons' (Hardin 1968) arises when $r < n$ and no incentives are applied, because single individuals can then improve their payoffs by withholding their contributions. The total budget for providing incentives is given by $n\delta$ per group, where $\delta > 0$ is the per capita incentive. This budget $n\delta$ is then divided into two parts based on a relative weight *w* with $0 \leq w \leq 1$: The part $wn\delta$ is shared among the n_C cooperators in the group (see also Chen et al., 2013 for application to the *N*-person volunteer's dilemma), who thus each obtains a reward $awn\delta/n_\mathrm{C}$, while the remainder is used for punishing the $n - n_\mathrm{C}$ defectors, who thus have their payoffs reduced by $b(1-w)n\delta/(n-n_\mathrm{C})$. The factors $a, b > 0$ are the respective leverages of rewarding and punishing, i.e., the factors by which a recipient's payoff is increased or decreased relative to the cost of implementing the incentive. We assume replicator dynamics (Hofbauer & Sigmund, 1998) and account for feedback from the community's state by allowing the weight *w* to depend on the frequency of cooperators *x*, $w = w(x)$. Pure rewarding and pure punishing correspond to $w(x) = 1$ or $w(x) = 0$, respectively Therefore, a cooperator and a defector obtain the payoffs

$$\frac{rcn_\mathrm{C}}{n} - c + \frac{awn\delta}{n_\mathrm{C}} \quad \text{and} \quad \frac{rcn_\mathrm{C}}{n} - \frac{b(1-w)n\delta}{n-n_\mathrm{C}}, \qquad (1)$$

respectively.

We now consider an institutional sanctioning policy we call 'first carrot, then stick', through which incentives are allocated to rewarding when cooperators are rare and to punishing when defectors are rare. This naturally raises the question of whether the transition between rewarding and punishing should be gradual or abrupt, and at which frequency of cooperation it should occur. As the criteria for answering this question, we will consider the sanctioning policy's effectiveness and efficiency in promoting cooperation. By effectiveness, we mean the parameter range for which full cooperation can be established or recovered with certainty, while by efficiency we mean the cumulative cost and total time required for converting a community of defectors to full cooperation or for recovering full cooperation from invasion of a single defector.

3. Results

We find that a sudden switch from rewarding to punishing, when the frequency of cooperators in the community surpasses a threshold, is the most effective and the most efficient policy for promoting cooperation. For well-mixed populations, we can prove that this specific hybridization of the two incentives maximizes the relative payoff of cooperators, a condition which in turn ensures that the sanctioning policy is most effective for converting a community of defectors to cooperation (Fig. 1*a*–*f*; see the electronic supplementary material for the mathematical proof). By combining the strengths of rewarding and punishing, this hybridization of incentives is far more effective than punishing in establishing cooperation (Fig. 1*c*,*e*) and far more effective than rewarding in recovering cooperation (Fig. 1*b*,*f*). Offering the 'best of both worlds', the most effective 'first carrot, then stick' policy of rewarding and punishing will hereafter be called the adaptive hybrid.

Although it is natural to expect that the threshold at which the adaptive hybrid switches from rewarding to punishing could change from one situation to another, it turns out that this is not the case: this threshold remains the same independent of the per capita incentive δ and the public-benefit factor r. When there is no difference in leverage between positive and negative incentives ($a = b$), this threshold corresponds to a frequency of cooperators of exactly 50%. In practice, punishing is often more effective than rewarding (Baron, 2009) ($a < b$), in which case the switching point for hybridization is lower than 50% (the electronic supplementary material, Fig. S1).

The adaptive hybrid policy is also more efficient for establishing and recovering cooperation than either rewarding or punishing alone (Fig. 2*a*–*f*). Once a state of full cooperation has been reached, punishing is cheaper as a means of recovering cooperation, since it needs to be used only occasionally. As the adaptive hybrid policy stipulates punishment once the frequency of cooperators surpasses the threshold, it is similar to pure punishment in this respect. The two policies differ markedly, however, in the cost of converting a community of defectors to a community of cooperators. The adaptive hybrid policy has the lowest cumulative costs of all three policies and hence requires both the lowest establishment cost and the lowest recovery cost for full cooperation. With respect to conversion speed, it generically takes a similar (finite) time for all three policies to establish and recover cooperation (the electronic supplementary material, Fig. S2).

In the real world, social planning tends to be spatially distributed and is often assisted by sanctioning institutions. To see whether the adaptive hybrid policy copes well with the resultant spatio-temporal complexity, we extend our framework to a spatial population inhabiting an

$N \times N$ square lattice with periodic boundaries. Each individual in this lattice joins a public good game with its four nearest neighbours ($n = 5$) and updates its strategy probabilistically based on its resultant payoff. The sanctioning institution receives feedback locally from the five local participants and the implementation of the hybrid incentive policy therefore varies across the lattice, as local conditions require. In equation (1), x denotes the frequency of cooperators within a given neighbourhood.

The adaptive hybrid policy is superior also in spatial populations (Fig. 1*g*–*l*). Unexpectedly, it gives rise to spatial patterns of cooperation and defection that cannot easily be predicted from those of either rewarding or punishing alone. For small and large incentives, emerging patterns from a single cooperator resemble those observed under pure rewarding and punishing, respectively. Cooperators thrive under a policy of pure rewarding (Fig. 3*a*), forming local mixtures with defectors, but ultimately fail to establish a cooperative norm for the incentive strength considered. With pure punishing (Fig. 3*b*), an invasion which begins with a single cooperator always results in a cluster of cooperators that grows and eventually displaces all defectors. The adaptive hybrid policy, in contrast, exhibits an intriguing transition between these two distinct patterns for intermediate incentive strengths. Fragmented islands of cooperators, initially inspired by rewarding, create circumstances under which punishing can act as a ‘booster stage’ that capitalizes on and amplifies the pro-social effects of rewarding, promoting the rapid growth of cooperator clusters (Fig. 3*c*). All three policies are capable of recovering cooperation in much the same way as for well-mixed populations. The only qualitative difference is that an initially single defector can occasionally cause the separation of connected cooperators into sub-clusters. This has been demonstrated for the spatial extension of the well-studied Prisoner’s Dilemma (Fu et al., 2010), but occurs in our model only for vanishing or very small incentives.

In the electronic supplementary material, we demonstrate the robustness of our results with respect to the following model variants. (i) First, we establish that in spatial populations, the adaptive hybrid policy with either local or global feedback establishes and recovers full cooperation at lower cost and under a wider range of conditions than a natural alternative hybridization of incentives in which the reward weight w is proportional to the frequency of cooperators (Fig. S3). Furethmore, information about the local degree of cooperation allows an institution which implements the adaptive hybrid policy to establishing full cooperation more readily that information about the global, population-wide, degree of cooperation (c.f. Vasconcelos et al., 2013). This is in line with expectations, as tailoring a strategy to local conditions should generally achieve better results than a strategy which depends on conditions that are averaged across large spatial scales. We also explore (ii) a variant of the public good game, in which a cooperator does not benefit from its own contribution (Sasaki et al., 2012) (Fig. S4), and (iii) a variant of the incentive scheme, in which we relax the assumption that the received incentive is inversely proportional to the number of cooperators or defectors in an interacting group (Sasaki et al., 2012) (Fig. S5). We also test variants of our spatial model with (iv) interactions encompassing the eight nearest neighbors (Roca et al., 2009; Szabó & Fáth, 2007) (chess-king move, $n = 9$, Fig. S6), (v) smaller population size (Fig. S7), (vi) asynchronous updating (Roca et al., 2009; Szabó & Fáth, 2007) (Fig. S8), (vii) proportional imitation rule (Roca et al., 2009; Szabó & Fáth, 2007) (Fig. S9), (viii) errors in perception and implementation (for individuals (Hilbe & Sigmund, 2010) or institutions (Gächter, 2012), Figs. S10–14), and (ix) varied switching points (Fig. S15). All variants (ii)–(viii) do not qualitatively affect the results regarding the applicability and efficiency of incentives (Figs. S4–14). Exploring (ix) reveals that the optimal switching point for the spatial model is again around 50%, as in a well-mixed population when there is no difference in leverage between positive and negative incentives (Fig. S15). As a final model variant, we assume that individuals share the cost of funding the incentive budget (Sasaki et al., 2012; Sasaki 2013), and find that the resultant dynamics are entirely unaffected.

4. Discussion

We have demonstrated how an institutional sanctioning policy of ‘first carrot, then stick’ can be surprisingly successful in promoting cooperation. The first-carrot-then-stick policy establishes and recovers cooperation at a lower cost and under a wider range of conditions than either rewards or penalties alone. Our findings are based on the public good game, a standard framework for cooperation in groups. They apply to both well-mixed and spatial populations and remain robust under a broad spectrum of model variations and parameter combinations.

Rewards and penalties are frequently used in concert to promote cooperation. Considering how often they are used together, at all levels from parents to teachers and leaders of organizations, it is surprising that no prior study to date has investigated how to optimally use a combination of rewards and penalties in an institutional setting. Unexpectedly, we found that the optimal strategy is not a gradual change in the relative allocation towards rewards and penalties, but a sudden switch once cooperation is sufficiently widespread. When the first-carrot-then-stick policy is used to promote cooperation in spatio temporal populations, it interestingly gives rise to complex spatial patterns of cooperators and defectors that differ qualitatively from the simpler patterns that arise when rewards or penalties are used in isolation. This is because punishment acts as a booster stage that reinforces the pro-social effects of rewarding, thus allowing cooperation to be rapidly established in those parts of a population where the cooperative level has surpassed the critical threshold. Although our analytical methods do not extend to spatial populations, extensive numerical investigations confirm that a sudden switch from rewarding to punishment, not a gradual change in the relative allocation, is the optimal institutional sanctioning policy for promoting and recovering cooperation also in spatial populations.

Our theoretical results can be compared with the handful of experimental studies that have explored the combined use of positive and negative incentives in peer-sanctioning (Andreoni et al., 2003; Kamijo & Takeuchi, 2007; Sefton et al., 2007; Sutter et al., 2010) or by an assigned team leader (Gürerk et al., 2009). Although these studies differ significantly in their experimental design, they share two common characteristics. First, punishment is typically more effective than rewarding at promoting high contributions to the public good. Second, players initially have a propensity for rewarding cooperation, which is soon superseded by a propensity for punishing defectors (Kamijo & Takeuchi, 2007; Sefton et al., 2007; Sutter et al., 2010). While the latter trend might superficially be interpreted as corroborative evidence for the effectiveness of the institutional sanctioning policy developed here, the rationale for shifting from positive to negative incentives is strikingly different. In the experimental studies, this shift typically coincides with declining average contributions and can thus be interpreted as a response to the emergence of defectors (Gürerk et al., 2009). In particular, the study on team leadership concluds that ‘leaders who experience frequent complete free-riding and high variance in contributions in their teams are more likely to switch from positive to negative incentives’ (Gürerk et al., 2009), while other studies find that punishing is more effective than rewarding at staving off complete free-riding (Kamijo & Takeuchi, 2007; Sefton et al., 2007; Sutter et al., 2010). By contrast, we have demonstrated the advantage of shifting from positive to negative incentives as contributions increase, and we predict that rewarding is more effective than punishing in staving off complete free-riding (c.f. Szolnoki & Perc, 2012).

We have determined the optimal sanctioning policy for a social institution charged with overseeing rational agents. Two complementary studies on peer-sanctioning that account, respectively, for reputation effects and the potential of group selection have similarly highlighted the role of positive incentives in promoting incipient cooperation among defectors (Herold, 2012; Hilbe & Sigmund, 2010). These theoretical predictions derived under the assumption of rational behaviour clearly question the wisdom of the human behaviour observed in the aforementioned experimental studies. Understanding whether punishment in the face of rampant defection is a human fallacy or a rational choice under circumstances other than those analyzed here is a key challenge for future research.

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References

Andreoni, J., Harbaugh, W. T., & Vesterlund, L. (2003). The carrot or the stick: rewards, punishments, and cooperation. *The American Economic Review*, 93, 893–902.

Balliet, D., Mulder, L. B., & Van Lange, P. A. M. (2011). Reward, punishment, and cooperation: a meta-analysis. *Psychological Bulletin*, 137, 594–615.

Baron, J. (2009). Weighing reward and punishment. *Science*, 326, 1632.

Casari, M., & Luini, L. (2009). Cooperation under alternative punishment institutions: an experiment. *Journal of Economic Behavior & Organization*, 71, 273–282.

Chen, X., Gross, T., & Dieckmann, U. (2013). Shared rewarding overcomes defection traps in generalized volunteer's dilemmas. *Journal of Theoretical Biology*, 335, 13–21.

Cressman, R., Song, J. -W., Zhang, B. -Y., & Tao, Y. (2012). Cooperation and evolutionary dynamics in the public goods game with institutional incentives. *Journal of Theoretical Biology*, 299, 144–151.

Cressman, R., Wu, J. J., Li, C., & Tao, Y. (2013). Game experiments on cooperation through reward and punishment. *Biological Theory*, 8, 158–166.

Cuesta, J. A., Jiménez, R., Lugo, H., & Sánchez, A. (2008). The shared reward dilemma. *Journal of Theoretical Biology*, 251, 253–263.

Falkinger, J. (1996). Efficient private provision of public goods by rewarding deviations from average. *Journal of Public Economics*, 62, 413–422.

Fu, F., Nowak, M. A., & Hauert, C. (2010). Invasion and expansion of cooperators in lattice populations: prisoner’s dilemma vs. snowdrift games. *Journal of Theoretical Biology*, 266, 358–366.

Gächter, S. (2012). Carrot or stick? *Nature*, 483, 39–40.

Gürerk, O., Irlenbusch, B., & Rockenbach, B. (2009). Motivating teammates: the leader’s choice between positive and negative incentives. *Journal of Economic Psychology*, 30, 591–607.

Hardin, G. (1968). The tragedy of the commons. *Science*, 162, 1243–1248.

Hauert, C., Michor, F., Nowak, M. A., & Doebeli, M. (2006). Synergy and discounting of cooperation in social dilemmas. *Journal of Theoretical Biology*, 239, 195–202.

Herold, F. (2012). Carrot or stick? The evolution of reciprocal preferences in a haystack model. *The American Economic Review*, 102, 914–940.

Hilbe, C., & Sigmund, K. (2010). Incentives and opportunism: from the carrot to the stick. *Proceedings of the Royal Society of London B: Biological Sciences*, 277, 2427–2433.

Hofbauer, J., & Sigmund, K. (1998). *Evolutionary Games and Population Dynamics*. Cambridge, UK: Cambridge University Press.

Kanazawa, T., Fukumoto, Y., Ushio, T., & Misaka, T. (2009). Replicator dynamics with Pigovian subsidy and capitation tax. *Nonlinear Analysis: Theory, Methods & Applications*, 71, e818–e826.

Kamijo, Y., & Takeuchi, A. (2007). Voluntary contribution mechanism game and endogenous institution selection. *The Waseda Journal of Political Science and Economics*, 368, 21–40, in Japanese.

Kosfeld, M., Okada, A., & Riedl, A. (2009). Institution formation in public goods games. *The American Economic Review*, 99, 1335–1355.

Oliver, P. (1984). Rewards and punishment as selective incentives: an apex game. *Journal of Conflict Resolution*, 28, 123–148.

Ostrom, E. (1990). Governing the Commons: The Evolution of Institutions for Collective Action. New York, NY: Cambridge University Press.

Roca, C. P., Cuesta, J. A., & Sánchez, A. (2009). Effect of spatial structure on the evolution of cooperation. *Physical Review E*, 80, 046106.

Sasaki, T. (2013). The evolution of cooperation through institutional incentives and optional participation. *Dynamic Games and Applications*. Published online: 17 Aug 2013. DOI:10.1007/s13235-013-0094-7.

Sasaki, T., Brännström, Å., Dieckmann, U., & Sigmund, K. (2012). The take-it-or-leave-it option allows small penalties to overcome social dilemmas. *Proceedings of the National Academy of Sciences*, 109, 1165–1169.

Sefton, M., Shupp, R., & Walker, J. M. (2007). The effect of rewards and sanctions in provision of public goods. *Economic Inquiry*, 45, 671–690.

Sigmund, K. (2007). Punish or perish? Retaliation and collaboration among humans. *Trends in Ecology & Evolution*, 22, 593–600.

Sigmund, K., De Silva, H., Traulsen, A., & Hauert, C. (2010). Social learning promotes institutions for governing the commons. *Nature*, 466, 861–863.

Sutter, M., Haigner, S., & Kocher, M. G. (2010). Choosing the carrot or the stick? Endogenous institutional choice in social dilemma situations. *The Review of Economic Studies*, 77, 1540–1566.

Szabó, G., & Fáth, G. (2007). Evolutionary games on graphs. *Physical Reports*, 446, 97–216.

Szolnoki, A., & Perc, M. (2012). Evolutionary advantages of adaptive rewarding. *New Journal of Physics*, 14, 093016.

Vasconcelos, V. V., Santos, F. C., & Pacheco, J. M. (2013). A bottom-up institutional approach to cooperative governance of risky commons. *Nature Climate Change*, 3, 797–801.

Figure legends

Fig. 1. Effects of institutional incentive policies on public good games. The adaptive hybrid policy has the broadest domain of applicability for establishing full cooperation (green) from an initially single cooperator (first and third columns from the left), and also for recovering it against an initially single defector (second and fourth columns from the left). With no or very small incentives, full defection (red) is the only evolutionary outcome, and with sufficiently large incentives, so is full cooperation; this applies to all three incentive policies. Intermediate incentives have strikingly different impacts, as follows. **Rewarding:** (*a*, *b*, *g*, *h*) In well-mixed populations, the outcome is independent of the initial condition; (*a*) and (*b*) are identical. In spatial populations, by contrast, full cooperation and full defection are more likely to be maintained when the public-benefit factor r is large and the per capita incentive δ is small [upper

left corners of (*g*) and (*h*), respectively]. **Punishing:** (*c*, *d*, *i*, *j*) When the institution increases δ beyond a threshold value (which depends on *r*), full defection abruptly changes into full cooperation. Differences between (*c*) and (*d*), or (*i*) and (*j*), indicate combinations of *r* and δ for which full cooperation and full defection are both stable, and for which initial conditions therefore affect the outcome. The difference between (*c*) and (*i*) indicates that, interestingly, spatial population structure much reduces the range of combinations of *r* and δ for which a single cooperator can invade, especially for large *r*. In (*i*) [and also in upper parts of (*g*) and (*j*), lower parts of (*k*) and (*l*)], the narrow (yellow) band between no and full cooperation results from the survival probability of the initial cooperator (and therefore does not indicate the coexistence of cooperators and defectors). **Adaptive hybrid:** (*e*, *f*, *k*, *l*) The domain of recovering full cooperation is almost equal to the case of punishing (*f* and *l*), while the domain of establishing full cooperation is much enlarged relative to the case of punishing (*e* and *k*). In particular, as the institution increases δ, the equilibrium frequency of cooperators gradually rises, and when δ crosses a threshold value (again dependent on *r*), which is smaller than in the case of punishing, full cooperation is established abruptly (*e* and *k*). Parameters: $n = 1$, $c = 1$, $a = b = 1$, $k = 10$, and $N = 100$ (population's size 10,000).

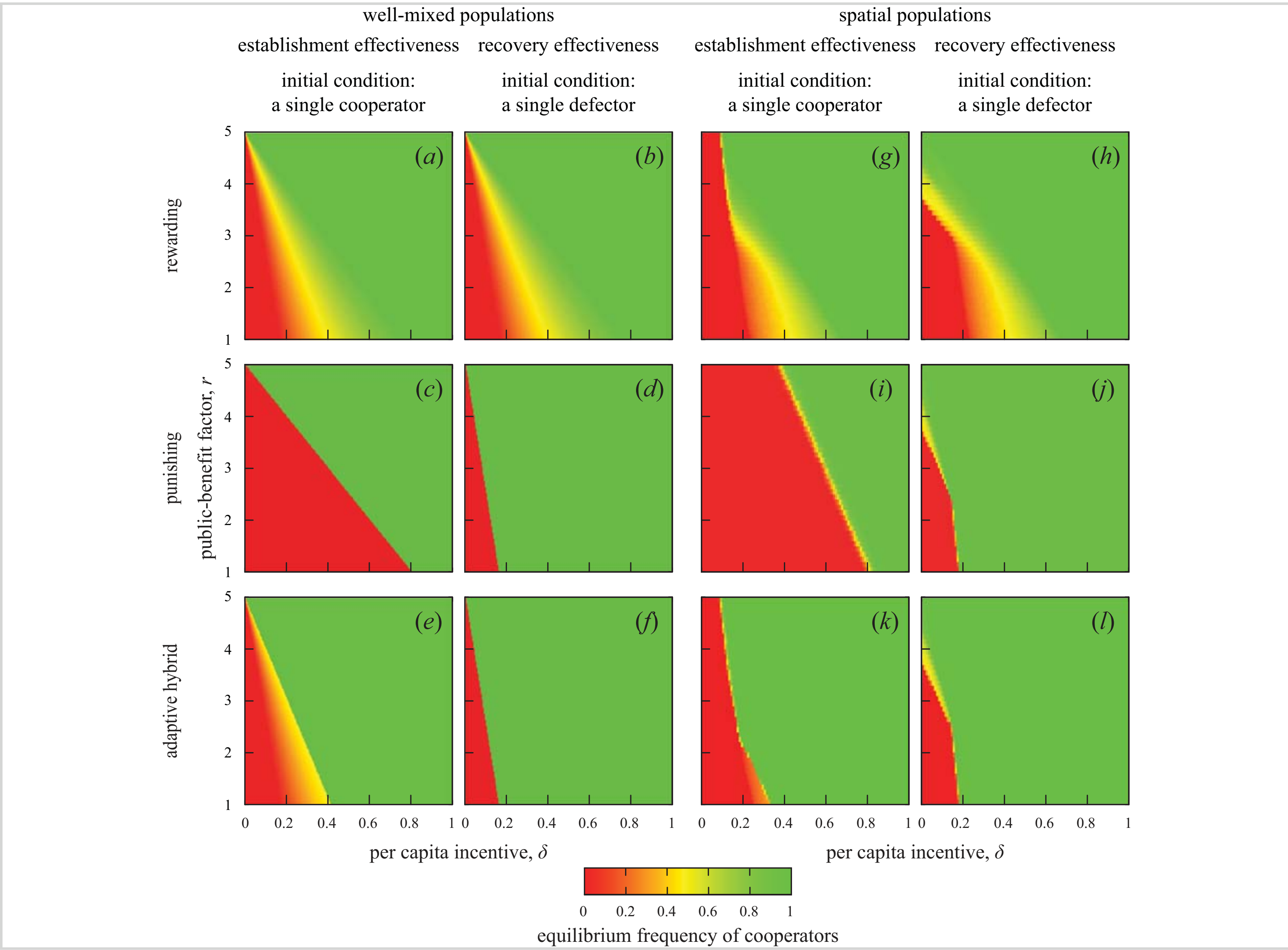
Fig. 2. Costs for establishing and recovering full cooperation. The adaptive hybrid policy is not only most effective (Fig. 1), but also least expensive in establishing full cooperation from an initially single cooperator (first and third columns from the left), and in recovering full cooperation against an initially single defector (second and fourth columns from the left). If no or very small incentives are provided, achieving each of these goals is impossible (white regions),

independent of the institution policy. Otherwise, these policies have strikingly different impacts on the required cumulative costs. **Rewarding:** (*a*, *b*, *g*, *h*) Both in well-mixed and in spatial populations, rewarding is not least expensive; in particular, rewarding requires recovery costs that are 1,000–100,000 times more expensive than either punishing or the adaptive hybrid policy. This relative cost difference furthermore increases in proportion to the population's size. **Punishing:** (*c*, *d*, *i*, *j*) In the case of punishing, recovery costs are much reduced relative to the case of rewarding, while establishment costs remain at a similarly high level as or even slightly larger than in the case of rewarding. **Adaptive hybrid:** (*e*, *f*, *k*, *l*) The adaptive hybrid policy requires recovery costs that are similar to the case of punishing (and thus much lower than in the case of rewarding), but substantially reduces establishment costs relative to either rewarding or punishing. (For understanding the costs right at the border to the white regions, see the electronic supplementary material, Fig. S2.) All parameters are as in Fig. 1.

Fig. 3. Emerging patterns of cooperation. For each incentive policy, the sequence of panels displays the spatio-temporal dynamics of cooperation, starting from a single cooperator located at the population's centre. **Rewarding:** (*a*) A mixed region of cooperators and defectors expands until small cooperator clusters occur across the whole population (electronic supplementary material, movie S1). **Punishing:** (*b*) The initially single cooperator expands into a compact cluster of cooperators, which eventually covers the entire population (electronic supplementary material, movie S2). **Adaptive hybrid:** (*c*) The initial spread of small cooperator clusters closely resembles the case of rewarding. This prepares the ground for local switches from rewarding to punishing, which enables the expansion of compact clusters of cooperators. This 'booster stage'

enables the establishment of full cooperation with much lower incentives δ than is possible in the case of punishing (electronic supplementary material, movie S3). Parameters: r = 2, and δ = 0.22 (*a*), 0.75 (*b*), or 0.22 (*c*). All other parameters are as in Fig. 1.

Figure 1



well-mixed populations
spatial populations
establishment effectiveness
recovery effectiveness
establishment effectiveness
recovery effectiveness
initial condition: a single cooperator
initial condition: a single defector
initial condition: a single cooperator
initial condition: a single defector
rewarding
punishing
adaptive hybrid
public-benefit factor, r
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
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0.4
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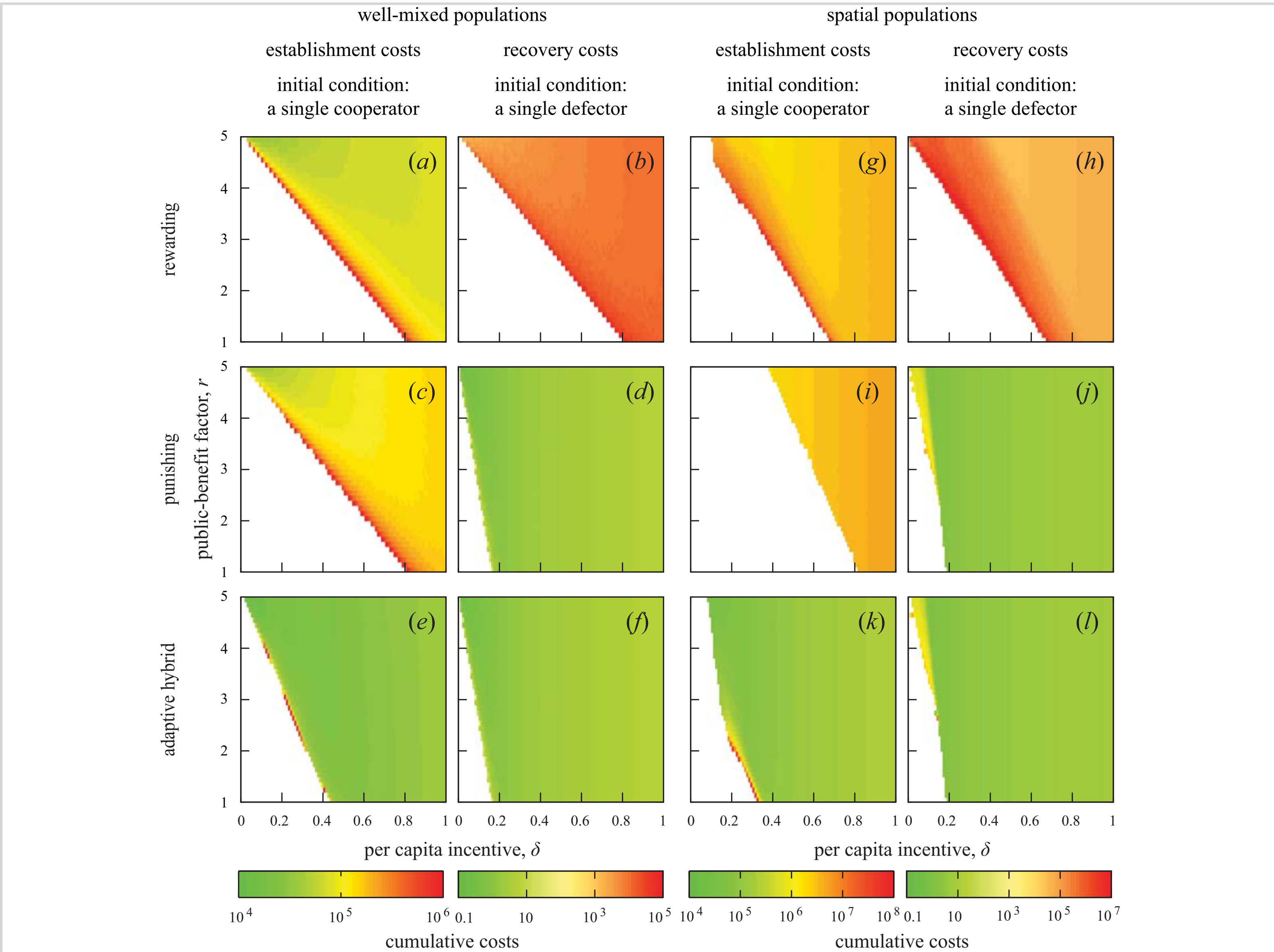
per capita incentive, δ
per capita incentive, δ
equilibrium frequency of cooperators

Figure 2



well-mixed populations
spatial populations
establishment costs
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establishment costs
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initial condition: a single cooperator
initial condition: a single defector
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rewarding
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adaptive hybrid
public-benefit factor, r
(a)
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per capita incentive, δ
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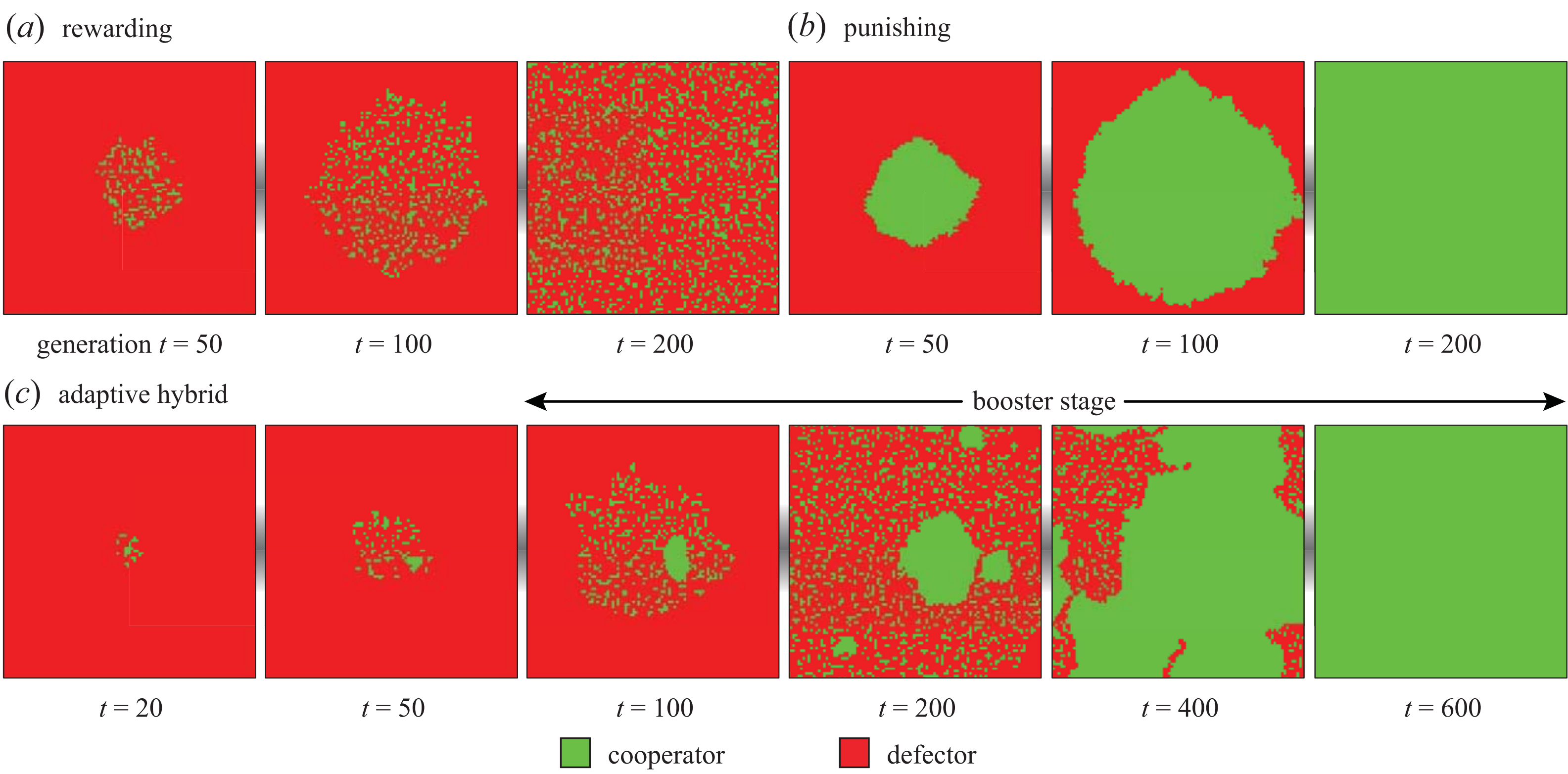
Figure 3


(a) rewarding
(b) punishing
generation t = 50
t = 100
t = 200
t = 50
t = 100
t = 200
(c) adaptive hybrid
booster stage
t = 20
t = 50
t = 100
t = 200
t = 400
t = 600
cooperator
defector

Video Still_movie S1
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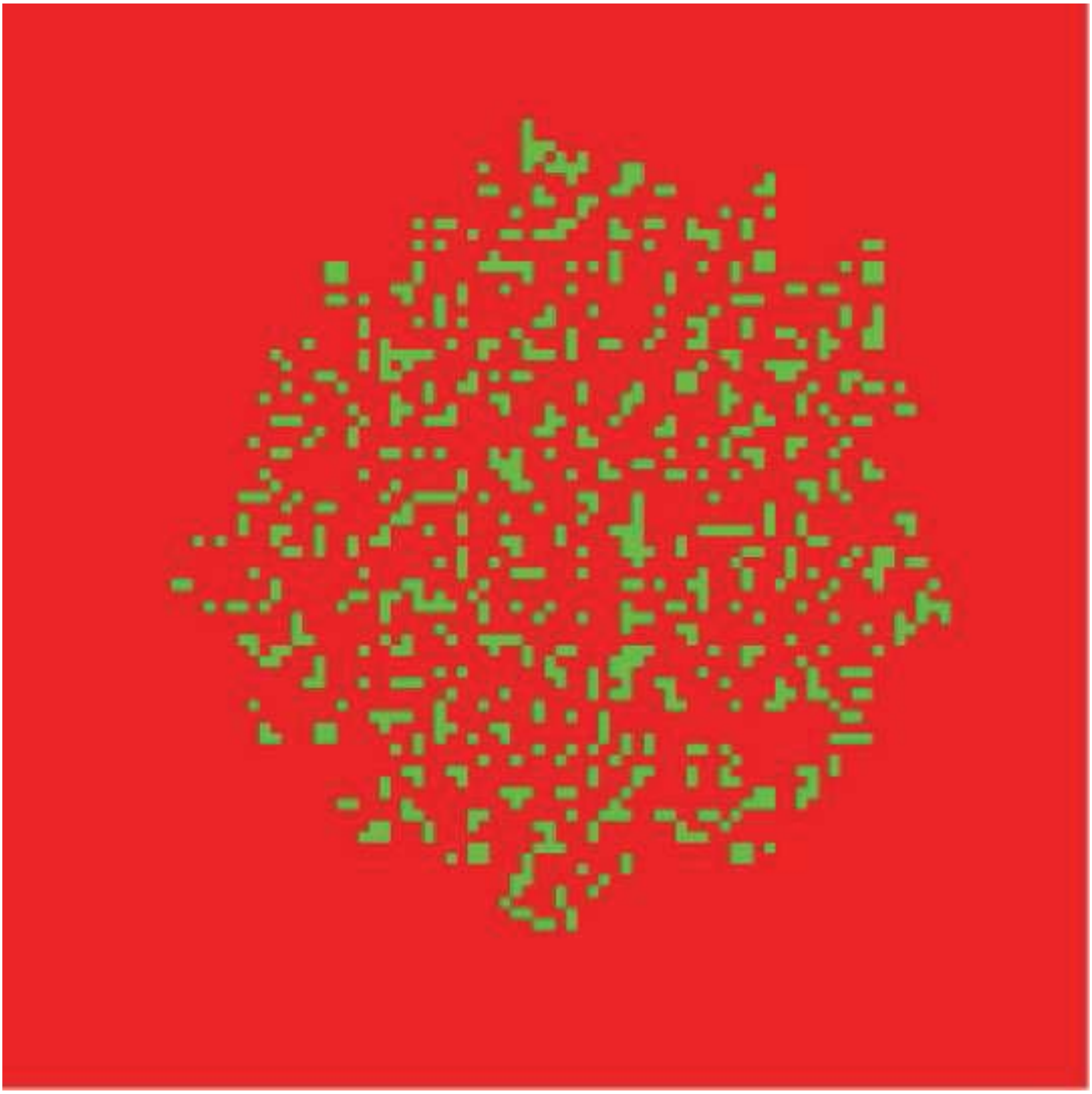

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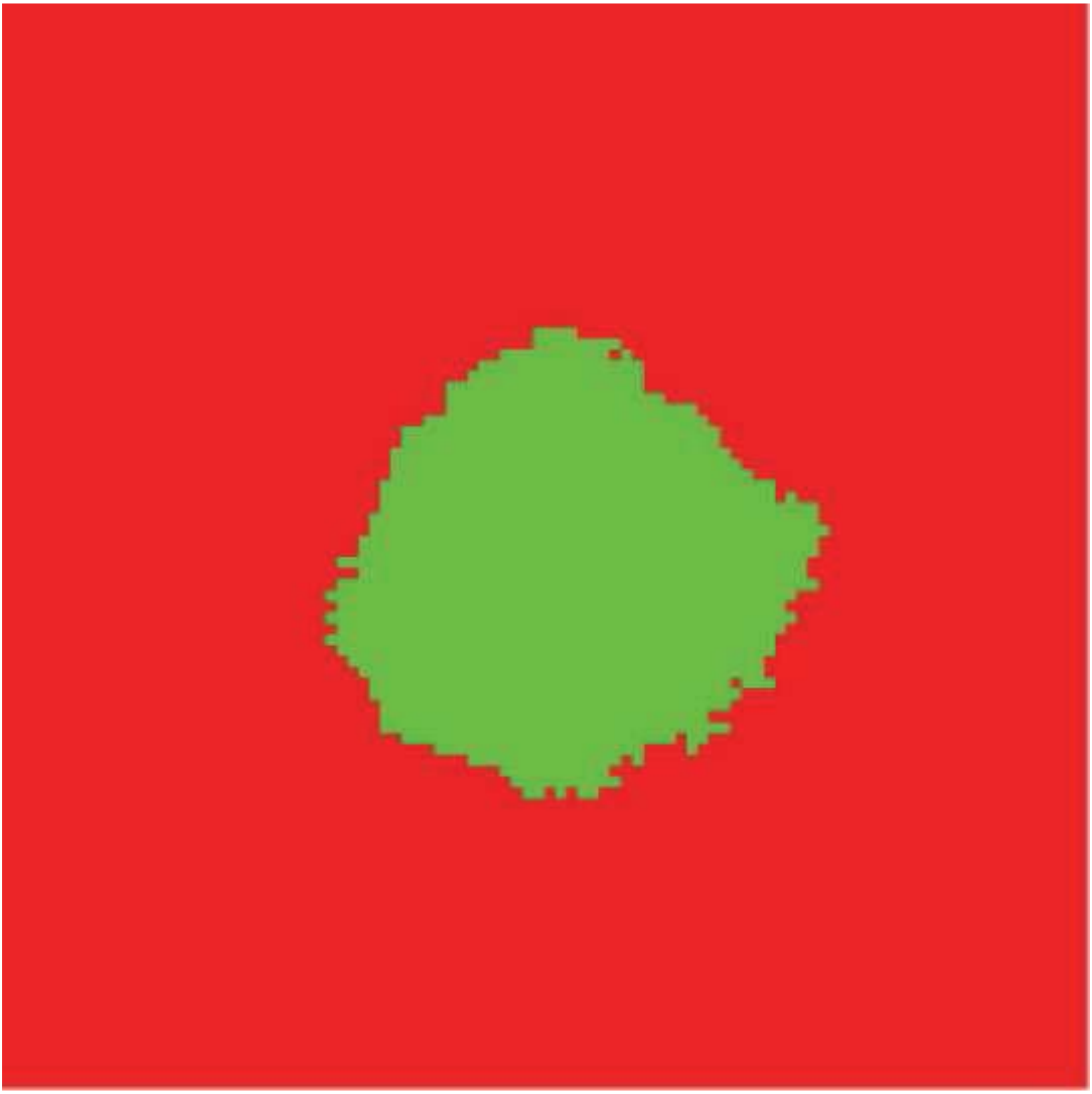

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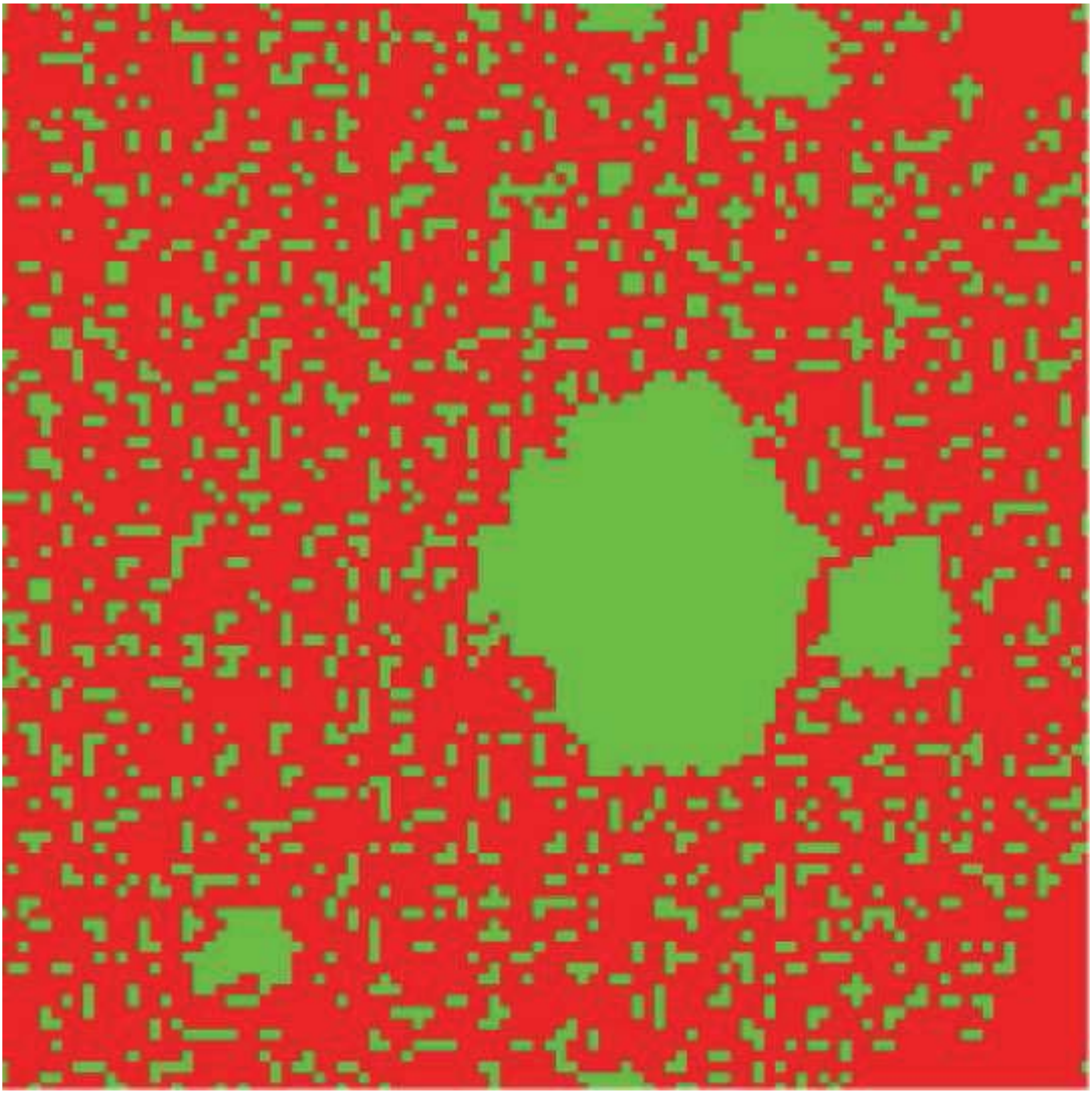

Supplementary Movie S1
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Supplementary Movie S2

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Supplementary Movie Captions

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Supplementary Text and Figures