Climate Change and Incentives to Cooperate*

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June 10, 2022

Abstract

We analyze incentives to cooperate in maintenance and improvement of local commons, such as irrigation systems. We show that climate change modelled as a reduction in agricultural productivity reduces the value of the relationship but also reduces the temptation to freeride in maintenance. The overall incentives to cooperate are improved because lower temptation to freeride is the dominant effect. Therefore, the negative effect of climate change is mitigated by higher degree of cooperation – but only if agricultural productivity was initially so high that full cooperation was not possible. While climate change results in full reduction of surplus if agricultural productivity was initially relatively low and cooperation at the first best level was already sustainable.

*I would like to thank Yusuke Mori, Larry Samuelson and seminar audience in Bristol for helpful comments.

1 Introduction

Many local commons, including grazing grounds, forests and irrigation systems, have been managed sustainably and successfully for hundreds of years (Ostrom 1990). How does climate change affect the robustness of these local commons? Are there any lessons we can learn from these local commons to tackle climate change in global context? In this paper we analyze the first of these questions, aiming to take a step toward examining the second.

One stylized fact is that 'difficult' commons tend to be successful. Examples of such commons are grazing grounds in high altitudes, where it is difficult to increase the value of the land, and traditional irrigation systems in monsoon climate, which are very costly to maintain. Consistent with this stylized fact, we show that in a repeated game less effective technology improves incentives to cooperate in maintenance of a shared resource. Although less effective technology reduces the value of the relationship – weakening the incentives to cooperate – the dominant effect is the reduced temptation to deviate. This offers hope for tackling climate change as more difficult conditions may improve the incentives to cooperate.

Our main application is in irrigation systems. This is an important context as according to IPCC (2022) water security has a central role in adapting to climate change and agriculture and irrigation account for 60 – 70 per cent of water withdrawals. We focus on cooperation in the maintenance and improvement of irrigation systems. Traditional irrigation systems require considerable maintenance. For example in Zanjera irrigation communities in Philippines average annual contribution was 37 days of work per person (Coward and Siy, 1983; Ostrom, 1990). Yet they achieved 94 per cent compliance rate in maintenance activities.

We analyze a model where two agents invest in a public good, such as maintenance of an irrigation system. In a one-shot game the agents underinvest relative to the first best as they do not take into account that their investment increases the value of the public good also for the other agent. In a repeated game higher cooperative investments can be supported. We show that less effective technology improves the incentives to cooperate. Less effective technology reduces the value of the relationship which ceteris paribus weakens the incentives to cooperate. However, also the temptation to deviate is reduced and that is the dominant effect. Less effective technology reduces the cooperative investment making it less tempting to freeride in maintenance.

As long as the agents are at least moderately patient, first-best investments can be supported for relatively ineffective technology. While for sufficiently effective technology the degree of cooperation has to be reduced to lower the temptation to deviate so that the incentive compatibility constraint can be satisfied. Therefore, the negative effect of lower agricultural productivity due to climate change is mitigated by improved incentives to cooperate, but only if productivity was initially so high that full cooperation was not possible. While climate change results in full reduction of surplus if agricultural productivity was initially relatively low and cooperation at the first best level was already sustainable.

The rest of the paper is organized as follows. Section 2 presents the model. Section 3 analyzes the repeated game. Section 4 examines the effect of reduced agricultural productivity due to climate change on the incentives to cooperate. Section 5 extends the analysis to impatient agents.

1.1 Related literature

Within the theoretical relational contracts literature, there is little work on the interaction of technology and incentives to cooperate. Harstad et al. (2019) and (2021) come closest with their work on environmental treaties. In Harstad et al. (2019) countries make repeated technological investments and binary emission decisions. They find that overinvestment in green technology improves the incentives to comply with low emissions by reducing the temptation to increase emissions. Harstad et al. (2021) allow emission levels to be continuous and find that good incentives to comply may be achieved by underinvestment in green technology. Although underinvestment increases the temptation to emit more, it also strengthens the ability to punish others by higher emissions. In this paper we examine the incentives to comply in maintenance investments and how those incentives depend on the effectiveness of technology exogenously affected by climate change.

The setup of our model is similar to Halonen-Akatwijuka and Pafilis (2020) and (2022) who also analyze incentives to cooperate in maintenance of a public good. Halonen-Akatwijuka and Pafilis (2020) examine the optimal ownership structure and show that common ownership is optimal for relatively ineffective technology. Ownership plays a role via its effect on bargaining between agents who have different valuations for the public good. In this paper the agents have the same valuation for the public good, which is why we can abstract from ownership. Halonen-Akatwijuka and Pafilis (2022) show that a minor technological change (proportional reduction in investment costs) does not affect incentives to cooperate because both the value of the relationship and the temptation increase proportionally and the effects cancel out in the incentive compatibility constraint. They also present some simulation results regarding a major technological change (that changes the shape of the value or cost function). Climate change is a major technological change and in this paper we analyze that in detail, including varying levels of cooperation and different rates of punishment.

Ramey and Watson (1997) and Halac (2015) examine the effect of one-off specific investment on the incentives to cooperate in an employment relationship. They find that the one-off investment – which would lose its value if the parties separate – improves incentives to cooperate by increasing the value of the relationship. In this paper we analyze repeated investments. Gjertsen et al. (2021) analyze relational conservation agreements where an NGO pays the local community for protecting environmental resources. NGO's technology choice is whether to monitor the community, allowing it to punish the community for exploitation of the resource by withdrawing the payment.

Moving to dynamic games, an extensive literature starting from Benhabib and Radner (1992) examines renewable common pool resources (CPRs), such as fisheries and forests, focusing on sustainable appropriation of the CPR. Copeland and Taylor (2009) analyze the effect of improvement in harvesting technology. They show that sustainable appropriation requires initially a transition from open access to active management of the CPR, but further improvement in harvesting technology leads to overappropriation of the CPR. Our focus is on provision rather than appropriation of the CPR. In our setup it is a priori less clear cut why improvement in provision technology might lead to under-provision problem.

Finally, in empirical work Ostrom and Gardner (1993), Ostrom et al. (1994) and Lam (1996) compare traditional farmer-managed irrigation systems to modern government-run technologies and find that the traditional irrigation systems resulted in greater agricultural productivity in Nepal. The productivity difference was attributed to governance rather than technology. In this paper technological improvement alone can reduce the degree of cooperation.

2 The model

Two agents $i = 1, 2$ make an investment y_i in a public good. Our main application is an irrigation system where the investment takes the form of maintenance and improvement.[1] The investment is observable but not verifiable.[2] The agents rely on relational contracts to provide incentives for investments.[3]

The value of the public good to each agent is $\theta[v(y_1) + v(y_2)]$, where $\theta > 0$, $v(y_i) = (y_i)^\alpha$ and $\alpha \in (0, 1)$. Investment costs are given by $c(y_i) = (y_i)^\beta$, where $\beta > 1$. We model climate change as technological change. Agricultural productivity is reduced due to the impact of higher temperature on the land, the farmers and the availability of water (IPCC, 2022). We assume that the effect of higher temperature can be approximated by changes in elasticities.[4] The value becomes less responsive to investment (lower α) or the costs become more responsive to investment (higher β). The results will depend on their ratio, $\frac{\alpha}{\beta}$.

[1] Public good model is relevant for irrigation system as our focus is on provision, i.e. maintenance and improvement (Ostrom, 1990, p.32). No user can be excluded from the improvement to the irrigation system.

[2] Observability is a reasonable assumption as the community gathers on specific days to maintain the irrigation system and attendance is observable.

[3] E.g. weak institutions can lead to reliance on relational contracts.

[4] It is reasonable to assume that climate change affects the shape of the agricultural production function rather than results in a simple proportional reduction in productivity.

Joint surplus, S, equals

$$S = 2\theta[v(y_1) + v(y_2)] - c(y_1) - c(y_2). \tag{1}$$

The first-best investment, y^*, takes into account the benefit to both parties.

$$2\theta v'(y^*) - c'(y^*) = 0 \tag{2}$$

Given the functional forms, we can solve for y^* explicitly.

$$y^* = \left(\frac{2\theta\alpha}{\beta}\right)^{\frac{1}{\beta-\alpha}} \tag{3}$$

In a one-shot game each agent chooses investment to maximize his utility. Agent i's utility is

$$u_i(y_i, y_j) = \theta[v(y_1) + v(y_2)] - c(y_i). \tag{4}$$

The optimal investment, y^N, is given by

$$\theta v'(y^N) - c'(y^N) = 0, \tag{5}$$

and in the explicit form

$$y^N = \left(\frac{\theta\alpha}{\beta}\right)^{\frac{1}{\beta-\alpha}} < y^*. \tag{6}$$

The agents underinvest relative to the first best because they ignore the value of the public good to the other agent. In essence, this is the tragedy of the commons in terms of maintenance.

In a repeated game the agents may be able to sustain investments higher than y^N. Denote *cooperative investment* by $y^c \in (y^N, y^*]$. Cooperative investment is the highest incentive compatible investment in a subgame perfect equilibrium (SPE) of the repeated game. Specifically, we define

$$y^c = \left(\frac{\eta\theta\alpha}{\beta}\right)^{\frac{1}{\beta-\alpha}}, \tag{7}$$

where $\eta \in (1, 2]$ is the endogenous degree of cooperation. We focus on the Pareto optimal SPE where the agents invest y^c.[5]

The agents invest in each period of the infinitely repeated game and have a common discount factor of $\delta \in (0, 1)$. We assume that the value of the maintenance investment depreciates by the beginning of the next period.

3 Repeated game

In the repeated game the agents agree to make the cooperative investment, y^c. If agent i were to deviate from y^c, he would choose y^N to maximize his current period payoff – and freeride on agent j's cooperative investment. Consistent with many local commons, we assume that deviation is punished by a fine, F, paid to the community (the other agent). The fine is paid at the beginning of the following period, before investments are made. If the deviating agent pays the fine, cooperation in investment resumes in the same period. Therefore, the incentive compatibility constraint (IC) for making the cooperative investment is

$$u_i^c \geq (1 - \delta)u_i^d + \delta[u_i^c - (1 - \delta)F], \tag{8}$$

where agent i's cooperative payoff is $u_i^c = u_i(y^c, y^c)$ and the deviation payoff is given by $u_i^d = u_i(y^N, y^c)$. We have multiplied the payoffs by $(1 - \delta)$ to express them as per-period averages. Equation (8) simplifies to

$$\delta F \geq u_i^d - u_i^c \equiv T, \tag{9}$$

where T is the *temptation* to deviate. If the discounted value of the fine exceeds the temptation to deviate from the cooperative investment, the cooperative investments can be supported in SPE.

There is no formal institution to enforce the fine. Therefore, also F has to be incentive compatible. If agent i defaults on F at the beginning of the period,

[5] In a community meeting the agents can agree to make the highest incentive compatible investment y^c.

agent j makes a punishment investment $y^p \in [0, y^N]$ in that period. We define the punishment investment as

$$y^p = \left(\frac{\rho\theta\alpha}{\beta}\right)^{\frac{1}{\beta-\alpha}}, \tag{10}$$

where $\rho \in [0, 1]$ is the endogenous rate of punishment.

The IC for paying the fine is

$$u_i^c - (1-\delta)F \geq (1-\delta)u_i^p + \delta[u_i^c - (1-\delta)F]. \tag{11}$$

If agent i pays the fine, cooperation is restored in the same period. If agent i does not pay the fine, his payoff in that period is $u_i^p = u_i(y^N, y^p)$ due to agent j's punishment investment. By the one-shot deviation principle, agent i pays the fine at the beginning of the next period and cooperation resumes. (11) simplifies to

$$F \leq \frac{u_i^c - u_i^p}{1-\delta} = \frac{V}{1-\delta}, \tag{12}$$

where $V \equiv u_i^c - u_i^p$ is the *value of the relationship*. Since higher fine relaxes the IC for the cooperative investment (9), it is optimal to choose the maximal fine, $F = \frac{V}{1-\delta}$. Substituting the maximal fine in (9), the IC for the cooperative investment simplifies to

$$\delta \geq \frac{T}{T+V} \equiv \underline{\delta}. \tag{13}$$

Our interest is in how technological change affects $\underline{\delta}$.

The final IC is for the punishment investment. Agent j has to sacrifice current payoff by reducing his investment to punishment level. However, if agent j does not engage in punishment, he himself has to pay a fine in the following period. Therefore, the IC for punishment investment is given by

$$(1-\delta)\hat{u}_j^p + \delta[(1-\delta)F + u_j^c] \geq (1-\delta)\hat{u}_j^d + \delta[u_j^c - (1-\delta)F], \tag{14}$$

where $\hat{u}_j^p = u_j(y^p, y^N)$ is the punisher's payoff and $\hat{u}_j^d = u_j(y^N, y^N)$ is what j can obtain by deviating from punishment. If agent j makes the punishment investment, then by the one-shot deviation principle agent i pays the fine to agent j in the following period, restoring cooperation. If j deviates from punishment and chooses y^N to maximize his current period payoff instead, it is agent j to pay F to agent i in the following period. (14) simplifies to

$$2F\delta \geq (\hat{u}_i^d - \hat{u}_i^p) \equiv T^p, \tag{15}$$

where T^p is the temptation to deviate from the punishment investment. There is $2F$ in the left-hand-side of (15) because deviation from punishment results not only in agent j paying the fine in the following period, but also forfeiting the fine i would have paid to j.

Substituting the maximal F from (12) in (15), we obtain

$$\delta \geq \frac{T^p}{T^p + 2V} \equiv \underline{\delta}^p. \tag{16}$$

Thus, the cooperative investment is sustainable in SPE if and only if the IC for both the cooperative investment and the punishment investment are satisfied, that is, $\delta \geq max\{\underline{\delta}, \underline{\delta}^p\}$.

4 Incentives to cooperate

In this Section we examine how technology affects the critical discount factors, $\underline{\delta}$ and $\underline{\delta}^p$. First, we solve for $\underline{\delta}$ explicitly. According to (9) and (12),

$$T = u_i(y^N, y^c) - u_i(y^c, y^c) = [\theta v(y^N) - c(y^N)] - [\theta v(y^c) - c(y^c)], \tag{17}$$

$$T + V = u_i(y^N, y^c) - u_i(y^N, y^p) = \theta[v(y^c) - v(y^p)]. \tag{18}$$

In the Appendix we show that

$$\frac{T}{T+V} = \frac{\theta\left(\frac{\theta\alpha}{\beta}\right)^{\frac{\alpha}{\beta-\alpha}}\left[\left(1-\frac{\alpha}{\beta}\right) - \eta^{\frac{\alpha}{\beta-\alpha}}\left(1-\eta\frac{\alpha}{\beta}\right)\right]}{\theta\left(\frac{\theta\alpha}{\beta}\right)^{\frac{\alpha}{\beta-\alpha}}\left(\eta^{\frac{\alpha}{\beta-\alpha}} - \rho^{\frac{\alpha}{\beta-\alpha}}\right)},$$

and therefore

$$\underline{\delta}(x,\eta,\rho) = \frac{(1-x) - \eta^{\frac{x}{1-x}}(1-\eta x)}{\eta^{\frac{x}{1-x}} - \rho^{\frac{x}{1-x}}}. \tag{19}$$

We have adopted notation $x \equiv \frac{\alpha}{\beta} \in (0,1)$.[6] x measures the effectiveness of the technology, e.g. agricultural productivity. We model climate change as a reduction in x and are interested in how it affects the incentives to cooperate. Lemma 1 examines some useful properties of $\underline{\delta}(x,\eta,\rho)$.

Lemma 1 *(i)* $lim_{x\to 1}\underline{\delta}(x,\eta,\rho) = \eta - 1$.
(ii) $lim_{x\to 0}\underline{\delta}(x,\eta,\rho) = \frac{\eta-1-\ln(\eta)}{\ln(\eta)-\ln(\rho)} \geq 0$. $lim_{x\to 0}\underline{\delta}(x,\eta,0) = 0$.
(iii) $\frac{\partial\underline{\delta}(x,\eta,\rho)}{\partial\rho} > 0$.

According to Lemma 1, cooperation at the first-best level, $\eta = 2$, is not possible for the most effective technologies since $lim_{x\to 1}\underline{\delta}(x,2,\rho) = 1$. This is unaffected by the rate of punishment. While for values of x strictly less than 1, tougher punishment relaxes the IC for the cooperative investment and thus zero punishment investment minimizes $\underline{\delta}(x,\eta,\rho)$. With the toughest punishment $\rho = 0$, the IC is satisfied for the most ineffective technologies since $lim_{x\to 0}\underline{\delta}(x,\eta,0) = 0$.

Lemma 2 *Suppose* $\rho = 0$.
(i) $\frac{\partial\underline{\delta}(x,\eta,0)}{\partial x} > 0$.
(ii) $\frac{\partial\underline{\delta}(x,\eta,0)}{\partial\eta} > 0$.

Lemma 2 shows that for $\rho = 0$ more effective technology weakens the incentives to cooperate. Inversely, lower agricultural productivity due to climate change relaxes the IC for the cooperative investment. Lemma 2 furthermore establishes that the IC can be relaxed by a lower degree of cooperation.

[6] Since $\alpha \in (0,1)$ and $\beta > 1$, $x \in (0,1)$.

To understand why more effective technology tightens the IC, we examine its effect on the value of the relationship and the temptation to deviate separately. From (12)

$$V = u_i(y^c, y^c) - u_i(y^N, 0) = [2\theta v(y^c) - c(y^c)] - [\theta v(y^N) - c(y^N)]. \tag{20}$$

Consider the effect of higher α. Total differentiation of (20) gives

$$\frac{dV}{d\alpha} = \theta\Big[2\frac{\partial v(y^c)}{\partial\alpha} - \frac{\partial v(y^N)}{\partial\alpha}\Big] + [2\theta v'(y^c) - c'(y^c)]\frac{\partial y^c}{\partial\alpha} - [\theta v'(y^N) - c'(y^N)]\frac{\partial y^N}{\partial\alpha}. \tag{21}$$

Note that by (5) the third term in square brackets equals zero, and by definition $\eta\theta v'(y^c) = c'(y^c)$. Thus, (21) simplifies to

$$\frac{dV}{d\alpha} = \theta\Big[2\frac{\partial v(y^c)}{\partial\alpha} - \frac{\partial v(y^N)}{\partial\alpha}\Big] + (2-\eta)\theta v'(y^c)\frac{\partial y^c}{\partial\alpha} > 0. \tag{22}$$

The term in the square brackets is positive because higher α increases the value of the larger cooperative investment more than the value of Nash investment.[7] In addition to this direct effect, there is an investment effect. The cooperative investment increases, which further increases the value of the relationship. Therefore, more effective technology increases the value of the relationship, which ceteris paribus *improves* the incentives to cooperate.

Accordingly, weaker incentives to cooperate must be driven by greater temptation to deviate. Total differentiation of (17) gives

$$\begin{aligned}\frac{dT}{d\alpha} &= \theta\Big[\frac{\partial v(y^N)}{\partial\alpha} - \frac{\partial v(y^c)}{\partial\alpha}\Big] + [\theta v'(y^N) - c'(y^N)]\frac{\partial y^N}{\partial\alpha} - [\theta v'(y^c) - c'(y^c)]\frac{\partial y^c}{\partial\alpha} \\ &= \theta(\eta-1)v'(y^c)\frac{\partial y^c}{\partial\alpha} - \theta\Big[\frac{\partial v(y^c)}{\partial\alpha} - \frac{\partial v(y^N)}{\partial\alpha}\Big] > 0. \end{aligned} \tag{23}$$

Since the second term in (23) is negative, weaker incentives must be driven by the positive first term: more effective technology increases the cooperative investment

[7]Note that $\frac{\partial v(y)}{\partial\alpha} = y^\alpha \ln y$. Therefore, $\frac{\partial v(y^c)}{\partial\alpha} > \frac{\partial v(y^N)}{\partial\alpha}$ since $y^c > y^N$, assuming $y^N > 1$.

and makes deviation more tempting. This can be understood as follows. Agent i's payoff from his own investment is $\theta v(y_i) - c(y_i)$. It is maximal at $y_i = y^N$ and gives lower payoff at $y_i = y^c$. Temptation is the difference between the two payoffs. Higher α has a negligible effect on the payoff at the local maximum, $y_i = y^N$, but pushes y^c further away from y^N, reducing the payoff at $y_i = y^c$ and increasing the temptation to deviate from y^c.

Finally, we examine the IC for the punishment investment. In the Appendix we show that for $\rho = 0$

$$\underline{\delta}^p(x, \eta, 0) = \frac{T^p}{T^p + 2V} = \frac{(1-x)}{2\eta^{\frac{x}{1-x}}(2-\eta x) - (1-x)}. \tag{24}$$

Lemma 3 explores the properties of $\underline{\delta}^p(x, \eta, 0)$.

Lemma 3 *Suppose* $\rho = 0$.

(i) $lim_{x\to 0}\underline{\delta}^p(x, \eta, 0) = \frac{1}{3}$.

(ii) $lim_{x\to 1}\underline{\delta}^p(x, \eta, 0) = 0$.

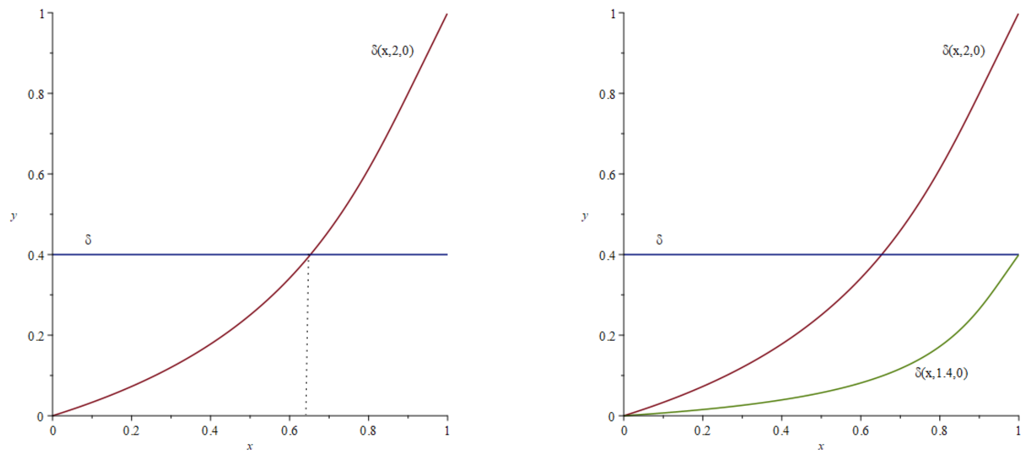
(iii) $\frac{\partial \underline{\delta}^p(x,\eta,0)}{\partial x} < 0$.

V has a multiplier 2 in the denominator of $\underline{\delta}^p$ because deviation from punishment investment results not only in paying the fine in the following period but also in forfeiting the fine that the other agent would have paid. Due to the multiplier, $\underline{\delta}^p$ is relatively low – its maximum value is $\frac{1}{3}$. For the same reason, the comparative statics with respect to x is driven by V and, thus, $\underline{\delta}^p$ is decreasing in x.[8]

For the rest of this Section we assume $\delta \in [\frac{1}{3}, 1)$ guaranteeing that the IC for zero punishment investment is satisfied for all x. In Section 5 we will examine $\delta \in (0, \frac{1}{3})$.

Figure 1(a) shows the critical discount factor for the first-best investment, $\underline{\delta}(x, 2, 0)$. By Lemma 1 $\underline{\delta}(x, 2, 0)$ ranges from 0 to 1 and by Lemma 2 $\underline{\delta}(x, \eta, 0)$ is monotonically increasing in x. Therefore, there exists a unique $\hat{x} \in (0, 1)$ such that $\delta = \underline{\delta}(\hat{x}, 2, 0)$. Accordingly, the first-best investment is sustainable in SPE for any technology more ineffective than $\hat{x}$. While for a technology more effective than $\hat{x}$, first best is not sus-

[8]Note that $T^p = [\theta v(y^N) - c(y^N)]$ for zero punishment investment. Therefore, $\frac{dT^p}{d\alpha} = \theta\frac{\partial v(y^N)}{\partial \alpha} > 0$.



(a) (b)

Figure 1: Incentive compatibility constraint

tainable but the degree of cooperation has to be reduced so that the IC just binds. Theorem 4 presents our main result.

Theorem 4 *Suppose* $\delta \in [\frac{1}{3}, 1)$.

(i) y^* *is supported in SPE if and only if* $x \in (0, \hat{x}]$*, where* $\hat{x} \in (0, 1)$.

(ii) For $x \in (\hat{x}, 1)$ *the highest incentive compatible degree of cooperation,* $\hat{\eta}$*, is given by*

$$(1-x)\hat{\eta}^{\frac{-x}{1-x}} - (1 - \hat{\eta}x) = \delta,$$

where $\frac{\partial \hat{\eta}}{\partial x} < 0$*,* $\frac{\delta \hat{\eta}}{\partial \delta} > 0$ *and* $\hat{\eta} \in (1 + \delta, 2)$.

From Theorem 4 we obtain our main result. Since $\frac{\partial \hat{\eta}}{\partial x} < 0$, the effect of lower agricultural productivity due to climate change – reduction in x – is mitigated by higher degree of cooperation, but only if technology was initially so effective that full cooperation was not possible, $x \in (\hat{x}, 1)$. While lower productivity results in full reduction of surplus if technology was initially relatively ineffective, $x \in (0, \hat{x}]$, and cooperation at the first best level was already sustainable.[9]

[9]Note that we do not examine the process of change to obtain this comparative statics. Rather, we compare the world that did not expect climate change to the one where global temperature has risen and agricultural productivity has been reduced.

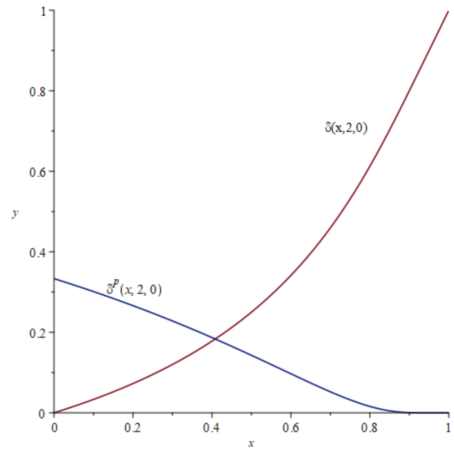


Figure 2: IC for punishment investment and cooperative investment

Note that the minimum degree of cooperation, $\underline{\eta}$, is given by $lim_{x\to 1}\underline{\delta}(x, \underline{\eta}, 0) = \underline{\eta} - 1 = \delta$, see Figure 1(b). Accordingly, $\underline{\eta} = 1 + \delta$. Therefore, some cooperation is always possible – as long as $\delta \in [\frac{1}{3}, 1)$ – and more patient agents can achieve higher degree of cooperation, $\frac{\delta\hat{\eta}}{\partial\delta} > 0$.

5 Impatient agents

In this Section we examine impatient agents for whom $\delta \in (0, \frac{1}{3})$ and the IC for zero punishment investment is not satisfied for all x. Figure 2 shows both $\underline{\delta}(x, 2, 0)$ and $\underline{\delta}^p(x, 2, 0)$ and demonstrates that for relatively ineffective technologies the IC for the first-best investment is satisfied but the IC for zero punishment investment is not. However, a softer punishment may support y^*.

Consider small x and δ just below $\underline{\delta}^p$. Softer punishment (higher ρ) relaxes the IC for the punishment investment as the sacrifice in current payoff is reduced. $\underline{\delta}^p$ shifts downwards so that the IC for y^p is satisfied. Softer punishment also tightens the IC for y^* because softer punishment supports a smaller fine and smaller fine is less effective in disciplining cooperative investment. Therefore, $\underline{\delta}$ shifts upwards – but since there is considerable slack in this IC, it is still satisfied. This is why softer punishment can expand the area where the first-best investment is supported in SPE.

6 Conclusions

In this paper we have analyzed incentives to cooperate in maintenance of a public good. We find that, consistent with a stylized fact from local commons, more difficult conditions improve incentives to cooperate. Applying this result to climate change implies that the negative effect of climate change may be mitigated by higher degree of cooperation.

We have focused on the provision of the public good. Appropriation – e.g. allocation of water in an irrigation system – and its interaction with provision remains an interesting question for future research.

Appendix

First, we derive $\underline{\delta} = \frac{T}{T+V}$. From (17),

$$T = [\theta(y^N)^\alpha - (y^N)^\beta] - [\theta(y^c)^\alpha - (y^c)^\beta]$$

$$= \theta\Big(\frac{\theta\alpha}{\beta}\Big)^{\frac{\alpha}{\beta-\alpha}}\Big[\Big(1 - \frac{\alpha}{\beta}\Big) - \eta^{\frac{\alpha}{\beta-\alpha}}\Big(1 - \eta\frac{\alpha}{\beta}\Big)\Big]. \tag{25}$$

From (18),

$$T + V = \theta[(y^c)^\alpha - (y^p)^\alpha] = \theta\Big(\frac{\theta\alpha}{\beta}\Big)^{\frac{\alpha}{\beta-\alpha}}(\eta^{\frac{\alpha}{\beta-\alpha}} - \rho^{\frac{\alpha}{\beta-\alpha}}). \tag{26}$$

Therefore,

$$\underline{\delta} = \frac{(1 - \frac{\alpha}{\beta}) - \eta^{\frac{\alpha}{\beta-\alpha}}(1 - \eta\frac{\alpha}{\beta})}{\eta^{\frac{\alpha}{\beta-\alpha}} - \rho^{\frac{\alpha}{\beta-\alpha}}}. \tag{27}$$

Defining $x \equiv \frac{\alpha}{\beta}$ and substituting in (27), we obtain

$$\underline{\delta}(x, \eta, \rho) = \frac{(1 - x) - \eta^{\frac{x}{1-x}}(1 - \eta x)}{\eta^{\frac{x}{1-x}} - \rho^{\frac{x}{1-x}}}. \tag{28}$$

<u>Proof of Lemma 1.</u>

(i) Dividing the numerator and the denominator of (28) by $\eta^{\frac{x}{1-x}}$ we obtain

$$\underline{\delta}(x, \eta, \rho) = \frac{(1 - x)\eta^{\frac{-x}{1-x}} - (1 - \eta x)}{1 - \big(\frac{\rho}{\eta}\big)^{\frac{x}{1-x}}}. \tag{29}$$

From (29) we obtain $lim_{x\to 1}\underline{\delta}(x, \eta, \rho) = \eta - 1$ given $lim_{x\to 1}\eta^{\frac{-x}{1-x}} = 0$.

(ii) For $x \to 0$, both the numerator and the denominator of (29) equal zero. Therefore, we apply L'Hôpital's rule and take into account that $lim_{x\to 0}\eta^{\frac{-x}{1-x}} = 1$.

$$lim_{x\to 0}\frac{(1 - x)\eta^{\frac{-x}{1-x}} - (1 - \eta x)}{1 - \big(\frac{\rho}{\eta}\big)^{\frac{x}{1-x}}} = lim_{x\to 0}\frac{\eta - \eta^{\frac{-x}{1-x}}[1 + \frac{\ln\eta}{(1-x)}]}{\big(\frac{\rho}{\eta}\big)^{\frac{x}{1-x}}[\ln\eta - \ln\rho]\frac{1}{(1-x)^2}}$$

$$= \frac{\eta - 1 - \ln\eta}{\ln\eta - \ln\rho} \tag{30}$$

Note that the numerator of (30) is positive because $\eta - 1 > \ln\eta$ for any $\eta \neq 1$. Also the denominator is positive because $\ln\eta > 0$ and $\ln\rho \leq 0$. Furthermore, if $\rho = 0$ $lim_{x\to 0}\underline{\delta}(x, \eta, 0) = 0$ by (30).

(iii) It is obvious from (28) that $\frac{\partial\underline{\delta}(x,\eta,\rho)}{\partial\rho} > 0$.

Q.E.D.

Proof of Lemma 2.

Substitute $\rho = 0$ in (29).

$$\underline{\delta}(x, \eta, 0) = (1 - x)\eta^{\frac{-x}{1-x}} - (1 - \eta x) \tag{31}$$

(i) First, we prove that $\underline{\delta}(x, \eta, 0)$ is increasing in x.

$$\frac{\partial\underline{\delta}(x, \eta, 0)}{\partial x} = \eta - \eta^{\frac{-x}{1-x}}\left[1 + \frac{\ln\eta}{(1 - x)}\right] \tag{32}$$

$$\begin{aligned} \frac{\partial^2\underline{\delta}(x, \eta, 0)}{\partial x^2} &= \eta^{\frac{-x}{1-x}}\frac{\ln\eta}{(1 - x)^2}\left[1 + \frac{\ln\eta}{(1 - x)}\right] - \eta^{\frac{-x}{1-x}}\frac{\ln\eta}{(1 - x)^2} \\ &= \eta^{\frac{-x}{1-x}}\frac{(\ln\eta)^2}{(1 - x)^3} > 0 \end{aligned} \tag{33}$$

From (32) $\frac{\partial\underline{\delta}}{\partial x}|_{x=0} = \eta - (1 + \ln\eta) > 0$ since $\eta - 1 > \ln\eta$ for any $\eta \neq 1$. By (33) $\underline{\delta}(x, \eta, 0)$ is convex in x and, accordingly, $\underline{\delta}(x, \eta, 0)$ is increasing in x for all $x \in (0, 1)$.

(ii)

$$\frac{\partial\underline{\delta}(x, \eta, 0)}{\partial\eta} = x(1 - \eta^{\frac{-1}{1-x}}) > 0 \tag{34}$$

since $-\frac{1}{1-x}\ln\eta < 0$.

Q.E.D.

Proof of Lemma 3.

First, we derive $\underline{\delta}^p(x,\eta,\rho) = \frac{T^p}{T^p+2V}$. From (6), (10) and (15),

$$T^p = \Big[\theta\Big(\frac{\theta\alpha}{\beta}\Big)^{\frac{\alpha}{\beta-\alpha}} - \Big(\frac{\theta\alpha}{\beta}\Big)^{\frac{\beta}{\beta-\alpha}}\Big] - \Big[\theta\Big(\frac{\rho\theta\alpha}{\beta}\Big)^{\frac{\alpha}{\beta-\alpha}} - \Big(\frac{\rho\theta\alpha}{\beta}\Big)^{\frac{\beta}{\beta-\alpha}}\Big]$$

$$= \theta\Big(\frac{\theta\alpha}{\beta}\Big)^{\frac{\alpha}{\beta-\alpha}}\Big[\Big(1-\frac{\alpha}{\beta}\Big) - \rho^{\frac{\alpha}{\beta-\alpha}}\Big(1-\rho\frac{\alpha}{\beta}\Big)\Big]. \tag{35}$$

From (6), (7), (10) and (12),

$$V = \Big[2\theta\Big(\frac{\eta\theta\alpha}{\beta}\Big)^{\frac{\alpha}{\beta-\alpha}} - \theta\Big(\frac{\eta\theta\alpha}{\beta}\Big)^{\frac{\beta}{\beta-\alpha}}\Big] - \Big[\theta\Big(\frac{\theta\alpha}{\beta}\Big)^{\frac{\alpha}{\beta-\alpha}} + \theta\Big(\frac{\rho\theta\alpha}{\beta}\Big)^{\frac{\alpha}{\beta-\alpha}} - \theta\Big(\frac{\theta\alpha}{\beta}\Big)^{\frac{\beta}{\beta-\alpha}}\Big]$$

$$= \theta\Big(\frac{\theta\alpha}{\beta}\Big)^{\frac{\alpha}{\beta-\alpha}}\Big[\eta^{\frac{\alpha}{\beta-\alpha}}\Big(2-\frac{\eta\alpha}{\beta}\Big) - \Big(1+\rho^{\frac{\alpha}{\beta-\alpha}} - \frac{\alpha}{\beta}\Big)\Big] \tag{36}$$

Accordingly,

$$\underline{\delta}^p(x,\eta,\rho) = \frac{(1-x)-\rho^{\frac{x}{1-x}}(1-\rho x)}{(1-x)-\rho^{\frac{x}{1-x}}(1-\rho x)+2\eta^{\frac{x}{1-x}}(2-\eta x)-2(1+\rho^{\frac{x}{1-x}}-x)}$$

$$= \frac{(1-x)-\rho^{\frac{x}{1-x}}(1-\rho x)}{2\eta^{\frac{x}{1-x}}(2-\eta x)-\rho^{\frac{x}{1-x}}(3-\rho x)-(1-x)}. \tag{37}$$

Substitute $\rho = 0$ in (37).

$$\underline{\delta}^p(x,\eta,0) = \frac{(1-x)\eta^{\frac{-x}{1-x}}}{2(2-\eta x)-(1-x)\eta^{\frac{-x}{1-x}}}. \tag{38}$$

(i) From (38) $lim_{x\to 0}\underline{\delta}^p(x,\eta,0) = \frac{1}{3}$ since $lim_{x\to 0}\eta^{\frac{-x}{1-x}} = 1$.

(ii) From (38) $lim_{x\to 1}\underline{\delta}^p(x,\eta,0) = \frac{0}{2(2-\eta)}$, which is equal to 0 for any $\eta < 2$. Substituting $\eta = 2$ in (38), we obtain

$$\underline{\delta}^p(x,\eta,0) = \frac{2^{\frac{-x}{1-x}}}{4-2^{\frac{-x}{1-x}}}. \tag{39}$$

$lim_{x\to 1}\underline{\delta}^p(x,\eta,0) = 0$ also for $\eta = 2$ since $lim_{x\to 1} 2^{\frac{-x}{1-x}} = 0$.

(*iii*) From (38) $\frac{\partial \underline{\delta}^p(x,\eta,0)}{\partial x}$ has the same sign as

$$-\eta^{\frac{-x}{1-x}}\Big[1+\frac{\ln\eta}{(1-x)}\Big]\Big[2(2-\eta x)-(1-x)\eta^{\frac{-x}{1-x}}\Big]-(1-x)\eta^{\frac{-x}{1-x}}\Big[-2\eta+\eta^{\frac{-x}{1-x}}\Big(1+\frac{\ln\eta}{(1-x)}\Big)\Big]$$

$$= 2\eta^{\frac{-x}{1-x}}\Big[\eta(1-x)-(2-\eta x)\Big(1+\frac{\ln\eta}{(1-x)}\Big)\Big] \tag{40}$$

(40) has the same sign as

$$z(x) = \eta(1-x)^2 - (2-\eta x)[(1-x)+\ln\eta]. \tag{41}$$

Since

$$z'(x) = (2-\eta) + \eta\ln\eta > 0, \tag{42}$$

$$z(1) = (\eta-2)\ln\eta \leq 0, \tag{43}$$

$z(x) < 0$ for all $x \in (0,1)$. Accordingly, $\frac{\partial \underline{\delta}^p(x,\eta,0)}{\partial x} < 0$.

Q.E.D.

Proof of Theorem 4.

By Lemma 3 the IC for $y^p = 0$ is satisfied for all x when $\delta \geq \frac{1}{3}$. Accordingly, y^c is supported in SPE if and only if $\delta \geq \underline{\delta}(x,\eta,0)$. By Lemma 1 $\underline{\delta}(x,2,0)$ ranges from 0 to 1 and by Lemma 2 $\frac{\partial \underline{\delta}(x,\eta,0)}{\partial x} > 0$. Thus, there exists $\hat{x} \in (0,1)$ such that $\delta = \underline{\delta}(\hat{x},2,0)$. Therefore, y^* is supported in SPE if and only if $x \in (0,\hat{x}]$. The highest incentive compatible degree of cooperation for $x \in (\hat{x},1)$ is given by

$$(1-x)\hat{\eta}^{\frac{-x}{1-x}} - (1-\hat{\eta}x) - \delta = 0. \tag{44}$$

From (44) we can obtain

$$\frac{d\hat{\eta}}{dx} = -\frac{\eta - \eta^{\frac{-x}{1-x}}[1+\ln\eta\frac{1}{(1-x)}]}{x(1-\eta^{\frac{-1}{1-x}})} < 0 \tag{45}$$

The numerator of (45) is equivalent to (32) and therefore positive, implying that $\frac{d\hat{\eta}}{dx} < 0$. Since by Lemma 1 $lim_{x \to 1} \underline{\delta}(x, \eta, 0) = \eta - 1$, the minimum degree of cooperation is given by $\underline{\eta} = 1 + \delta$. Therefore, for $x \in (\hat{x}, 1)$ we have $\hat{\eta} \in (1 + \delta, 2)$. Finally, from (44) we obtain

$$\frac{d\hat{\eta}}{d\delta} = \eta - \eta^{\frac{-x}{1-x}} [1 + \ln \eta \frac{1}{(1-x)}] > 0 \tag{46}$$

(46) is equivalent to (32) and thus positive.

Q.E.D.

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