Can Technological Change Weaken the Robustness of Common-Property Regimes?

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Abstract

We examine the effect of technological change on the incentives to cooperate in the provision of common-pool resources (CPRs). We focus our analysis on CPRs that require investments in improvement and maintenance, such as irrigation systems. We find that major technological improvements, such as replacing a primitive irrigation system with a modern system, risk compromising cooperation as the temptation to freeride on other farmers' investments is increased. By contrast, minor technological improvements within an existing irrigation system, such as strengthening water diversion devices, do not hinder incentives to cooperate. In our analysis, an irrigation system can be well-managed for a long period of time during technological progress when changes are minor. When technology changes are major, cooperation can be maintained if the community is patient and initially their discount factor is well above the critical level for cooperation. However, when the threshold is reached, any further major technological improvement will lead to a breakdown of cooperation and collapse of investments in the irrigation system.

Key words: common-property regime, provision of common-pool resources, cooperation, technological progress, farmer-managed irrigation systems

Introduction

Ostrom challenged Hardin's "tragedy of the commons" argument through numerous field studies of successful common-property regimes, such as irrigation systems in the Philippines and Spain, and common lands in Switzerland and Japan.[1] While many of these common-property regimes have been robust for hundreds of years, a question arises whether such commons can continue to exist in the face of rapid technological progress. This is the question we address in this chapter, focusing on the provision of common-pool resources (CPRs), for which it is hard to exclude users. We find that major technological improvement, such as replacing a primitive irrigation system with modern technologies, risks compromising cooperation because the temptation to freeride on other farmers' maintenance activities is increased. However, a minor technological improvement within an existing irrigation system, such as strengthening water diversion devices, does not harm incentives to cooperate. Our analysis implies that the characteristics of the resource and the technologies used both have an important effect on whether a common-property regime can be successful.

Ostrom referred to the theory of repeated games in explaining how the tragedy of the commons can be avoided. Using insights from repeated games, she argued that cooperation among individuals can be achieved if the benefits of future cooperation outweigh the one-off gain from over-appropriating the resource or under-providing to its maintenance and improvement. Cooperation is more likely if the individuals are patient so that they place a significant value on the benefits of future cooperation.[2] She further argued that this condition is satisfied in a traditional community managing a CPR, as individuals live side by side and expect their children and grandchildren to inherit their land.[3] However, she also criticized the

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[1] Elinor Ostrom, *Governing the Commons: The Evolution of Institutions for Collective Actions* (Cambridge University Press, 1990); Garett Hardin, "Tragedy of the Commons," *Science* 162 (1968): 1243-8.
[2] For more details on how Ostrom utilized game theory in her research see Elinor Ostrom, Roy Gardner and James Walker, *Rules, Games, and Common-Pool Resources* (University of Michigan Press, 1994).
[3] Ostrom, *Governing the Commons,* 88.

theory of repeated games for employing trigger strategies, which punish infractions with a permanent breakdown of cooperation, as she concluded they are rarely observed in actual field studies.[4] Instead, Ostrom found that punishment often took the form of fines that the offender is required to pay to the community. In this chapter, we take the repeated games approach to CPRs, but we include such fines in our analysis.

Our focus is on analyzing the effect of technological change on the incentives to cooperate. In order to address this question, we examine a CPR, such as an irrigation system, owned and managed by a group of farmers. The irrigation system requires maintenance. The farmers can also invest in expanding and improving the irrigation system. If the farmers interacted only once, for example, they would choose investments that maximize their own payoffs, not taking into account that the other farmers also benefit from the improvements. Such behaviour would result in a poorly maintained irrigation system, which, in effect, is a type of "tragedy of the commons". However, in reality, the farmers interact repeatedly, which may enable them to cooperate and manage the irrigation system well. If the farmers are patient enough, the temptation to freeride on others' investments will be deterred by the prospect of a future fine.

Consider then a technological change that makes the farmers' investments more effective in improving the irrigation system. How will it affect their incentives to cooperate? We find that a more effective technology increases the farmers' cooperative investments and, therefore, makes it more tempting to freeride on other farmers' higher investments. At the same time, the value of future cooperation increases making fines more effective in disciplining the farmers. These factors have opposing effects on the incentives to cooperate. We find that the overall effect depends on the type of technological change. A major technological

[4] Ostrom, *Governing the Commons,* 98.

improvement, such as replacing a primitive irrigation system by a modern technology, hinders cooperation because the dominant effect is the increased temptation to freeride. While a minor technological improvement within an existing irrigation system, such as strengthening water diversion devices, increases the temptation and its consequences proportionately, so that there is no effect on overall incentives to cooperate.

These results imply that the technologies used, as well as the characteristics of the resource, play an important role in determining whether a common-property regime can be successful. Our analysis differs from Ostrom's (largely endogenous) design principles which were identified by comparing successful and unsuccessful CPRs. Our results suggest that applying these design principles may not be effective unless the resource *and* the technology used have the characteristics that support cooperation under a common-property regime.

In repeated interaction, the farmers can cooperate if they are patient enough. A major technological improvement increases the patience requirement. Therefore, more effective technology that could potentially improve the farmers' livelihoods may lead to a breakdown of cooperation and worse outcome. However, if the farmers are very patient and initially well above the patience requirement for cooperation, they can continue cooperation even after major technological improvement and benefit from increased payoffs. Alternatively, if the technological improvement is minor, it does not harm cooperation and the farmers' payoffs increase due to better technology. Therefore, it is possible that a CPR can be well-managed for a long period of time during technological change, but when the patience requirement finally increases sufficiently, further technological improvement breaks down cooperation leading to deterioration of the CPR.

There is an extensive literature analyzing appropriation of renewable CPRs, such as fisheries and forests. According to Benhabib and Radner, a CPR can be appropriated sustainably – and the tragedy of the commons can be avoided – if the individuals are patient enough and the stock of the CPR is high enough.[5] Copeland and Taylor show that improvement in the harvesting technology initially leads to a transition from open access to active management of the CPR. However, further technological change undermines sustainable management of the resource.[6] We differ from this literature by focusing on provision rather than appropriation of the CPR. While it is intuitive that more effective appropriation technology can exacerbate the over-appropriation problem, it is less obvious that more effective provision technology might increase the *under*-provision problem.

We build on our earlier work where we also focus on provision, but compare incentives to cooperate under common-property regime to other ownership structures, such as government or private ownership.[7]

The literature has extensively examined the role of group size and heterogeneity in the management of CPRs, while the effect of technology has received less attention.[8] Several empirical studies, however, show that replacing primitive irrigation systems with modern technologies reduces agricultural productivity.[9] In these cases, technological change was accompanied with a move from a farmer-managed regime to a government-run regime. As such, the reduced productivity was attributed to the change in governance arrangement rather

[5] Jess Benhabib and Roy Radner, "Joint Exploitation of a Productive Asset," *Economic Theory* 2, no. 2 (1992): 155-190.
[6] Brian R. Copeland and Scott M. Taylor, "Trade, Tragedy, and the Commons," *American Economic Review* 99, no. 3 (2009): 725-749.
[7] Maija Halonen-Akatwijuka and Evagelos Pafilis, "Common Ownership of Public Goods," Mimeo (2019).
[8] Jeff Dayton-Johnson, "Small-Holders and Water Resources: A Review Essay on the Economics of Locally-Managed Irrigation," *Oxford Development Studies* 31, no. 3 (2003): 315-339; Amy R. Poteete and Elinor Ostrom, "Heterogeneity, Group Size and Collective Action: The Role of Institutions in Forest Management," *Development and Change* 35, no. 3 (2004): 435-461; Lore M. Ruttan, "Economic Heterogeneity and the Commons: Effects on Collective Action and Collective Goods Provisioning," *World Development* 36, no. 5 (2008): 969-985.
[9] Elinor Ostrom and Roy Gardner, "Coping with Asymmetries in the Commons: Self-Governing Irrigation Systems Can Work," *Journal of Economic Perspectives* 7, no. 4 (1993): 93-112; Elinor Ostrom, Wai Fung Lam and Myungsuk Lee, "The Performance of Self-Governing Irrigations Systems in Nepal," *Human Systems Management* 13 (1994):197-207; Wai Fung Lam, "Improving the Performance of Small-Scale Irrigation Systems: The Effects of Technological Investments and Governance Structure on Irrigation Performance in Nepal," *World Development* 24, no. 8 (1996): 1301-1315.

than technology. In our analysis a major technological change alone can reduce productivity by breaking down cooperation.

In related work, Harstad, Lancia and Russo show that technological investments can be geared to improving incentives to cooperate in an environmental treaty.[10] They find that over-investment in green technologies and under-investment in brown technologies can reduce the temptation to defect from agreed emission levels.[11]

Incentives to Cooperate and Technological Change

The Model

Consider a CPR, such as an irrigation system, owned and managed by farmers. For simplicity, let us assume that there are only two farmers. Farmer *h* (high-valuation farmer) has a higher valuation for the irrigation system than farmer *l* (low-valuation farmer) because he has more land to irrigate. The farmers make investments, y_h and y_l, respectively, in improvement, expansion and maintenance of the irrigation system.[12] The value of the irrigation system depends on the investments and is given by $v = [(y_h)^\alpha + (y_l)^\alpha]$, where $\alpha \leq 1$.[13] Parameter α plays a key role is our analysis. It measures how responsive the value of the irrigation system is to farmers' investments. If the farmers increase their investments by one per-cent, the value of the irrigation system increases by α per-cent. A technological improvement can increase α

[10] Bård Harstad, Francesco Lancia and Alessia Russo, "Compliance Technology and Self-Enforcing Agreements," *Journal of the European Economic Association* 17, no. 1 (2017):1-29.
[11] Brown technology is for example a drilling technology that is complementary to fossil fuel consumption, while renewable energy is an example of a green technology.
[12] We focus on provision of CPRs. Therefore, a public good model is appropriate (see Ostrom, *Governing the Commons*, 32). The main issue with provision is that it is difficult to exclude users from improvements to the CPR. This can be captured by a public good model.
[13] Farmer *h*'s valuation for the irrigation system is $\theta_h v$, while farmer *l*'s valuation is $\theta_l v$, where $\theta_h > \theta_l$.

so that the farmers' investments become more effective in increasing the value of the irrigation system.

The investments are costly to the farmers in terms of effort, time and materials. Investment costs for farmer *h* and *l* are given by $c_h = \sigma(y_h)^\beta$ and $c_l = \sigma(y_i)^\beta$, where $\beta \geq 1$.[14] A technological improvement will reduce the investment costs. Figure 1 displays two types of technological changes. A *major technological improvement* changes the shape of the cost function and shifts costs downward from the solid to the broken line. A reduction in β has such effect on the cost function. Replacing a primitive irrigation system by a completely modern system is an example of a major technological improvement.

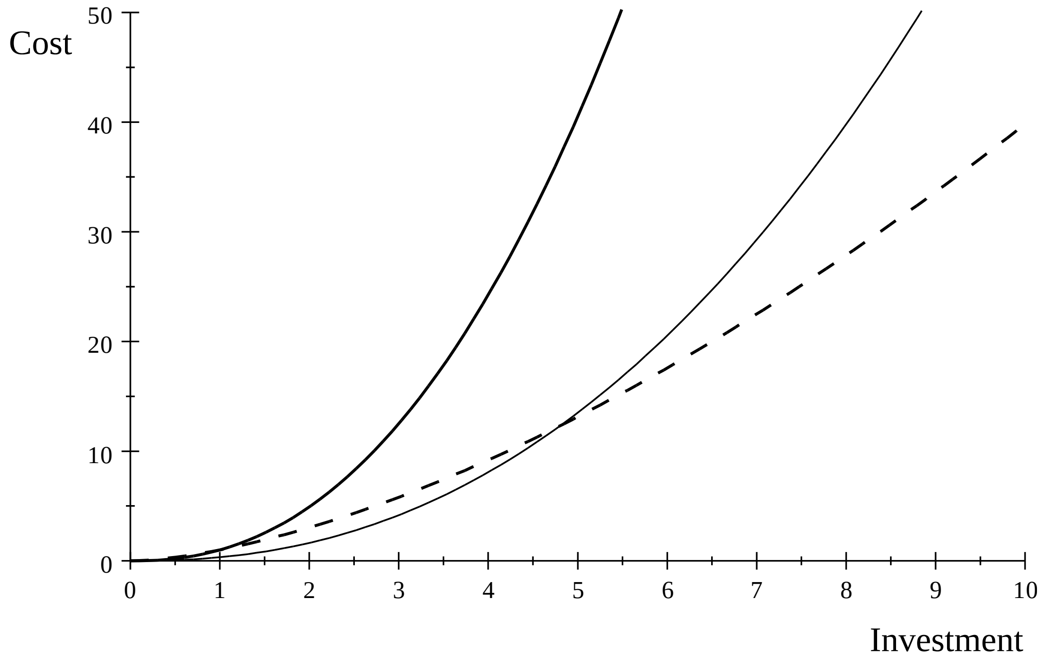

Figure 1. Major and minor technological improvement

A *minor technological improvement* does not change the shape of the cost function but will shift costs downward proportionately. This is displayed in Figure 1 by moving the cost

[14] We assume $\alpha/\beta < 1$.

function from the solid to the thin line. Lower value of σ has such effect on the investment costs. Strengthening water diversion devices within an existing irrigation system and providing simple canal lining are examples of minor technological improvements.

Whether technological change is major or minor affects also how the value of the irrigation system depends on farmers' investments. A major technological improvement can make the value of the irrigation system more responsive to investments (higher α) or the costs less responsive to investments (lower β). It turns out that the results depend on the ratio α/β. A minor technological improvement could have a proportionate effect also on the value of the irrigation system, but for simplicity we examine its effect only on costs.[15]

Our main interest is in how technological improvement affects farmers' incentives to cooperate. Are the farmers able to manage the irrigation system well or will they attempt to freeride on others' investments resulting in deterioration of the irrigation system? The results will depend on the type of technological change.

The Tragedy of the Commons

When farmer *h* invests in the irrigation system, also farmer *l* benefits from the improved system. If farmer *h* were to take into account the benefit to both farmers, he would choose an investment that maximizes the farmers' joint surplus. In determining his investment, farmer *h* would equate the marginal return of his investment to both farmers to its marginal cost. We call this the *cooperative investment*. Farmer *l*'s cooperative investment is determined in a similar manner.

[15] Minor technological improvement could also be measured by a multiplier on the value of the irrigation system. This would not change our results.

Consider then a situation where the farmers interact only once. Farmer *h* chooses an investment level that maximizes his own payoff, not the farmers' joint surplus. Farmer *h* equates the marginal return to his investment, which is now lower than in the cooperative case as he is ignoring the benefit to the other farmer, to his marginal cost. As a result, his investment is lower than the cooperative investment. By the same logic, also farmer *l* underinvests and, accordingly, the irrigation system is not well maintained. The farmers are worse off than if they both made the cooperative investment. "The tragedy of the commons" in improvement of the irrigation system occurs because the farmers do not take into account the benefit of their investment to the other farmers.[16]

Incentives to Cooperate in A Repeated Game

In reality, the farmers are in an ongoing relationship and interact repeatedly. Such repeated interaction may enable the farmers to sustain cooperative investments because there can be a consequence for underinvestment in the future. Cooperation can be sustained if the farmers are patient so that they place sufficient weight on the future consequences of freeriding.

Cooperation can be achieved in a repeated game through the use of a trigger strategy.[17] The trigger strategy implies that a farmer cooperates as long as the other farmer cooperates and any defection is punished by a permanent breakdown in cooperation. Suppose the game (interaction) is infinitely repeated (or ends at a random date). In order to avoid a tragedy of the commons, the farmers want to have a meeting and agree to make cooperative investments. After the meeting, farmer *h* starts by making the cooperative investment in period 1. He then

[16] Hardin referred to the problem of over-appropriation by "the tragedy of the commons" (Hardin, "Tragedy of the Commons"). We use the term to describe under-provision of the CPR arising from a similar incentive problem.
[17] James W. Friedman, "A Non-Cooperative Equilibrium for Supergames," *Review of Economic Studies* 38, no. 1 (1971): 1-12.

observes farmer *l*'s investment. If farmer *l* also made the cooperative investment, *h* continues with the cooperative investment in the next period and so on. However, if in any period farmer *l* underinvests and freerides on *h*'s cooperative investment, then according to the trigger strategy, the punishment starts from the next period: *h* will underinvest in all future periods. Then also farmer *l* will continue underinvesting. Any reneging from their agreement results in a complete breakdown of cooperation with both farmers underinvesting, resulting to a poorly maintained irrigation system reducing both farmers' payoffs.

Employing such trigger strategies can enable the farmers to sustain the higher cooperative investments if they are patient enough. In a repeated game, the farmer faces a trade-off between the immediate temptation to underinvest and freeride on the other farmer's cooperative investment and the future consequence of a breakdown of cooperation. Which effect dominates depends on how patient the farmer is. If he is patient enough, the farmer will place more weight on the future consequences than the immediate temptation, and will make a cooperative investment.

While this reasoning works in theory, Ostrom argued that trigger strategies are not relevant for understanding real life CPRs because they are rarely observed in actual field studies. Instead, Ostrom found that punishment often takes the form of fines that the offender is required to pay to the community. If a farmer is absent when the community gathers to work on the CPR, he will have to pay a fine to the community, unless an acceptable excuse is provided.[18] We take Ostrom's conclusion on board and introduce fines into the repeated game scenario.

[18] For example, in the villages of Japan the only acceptable excuses were illness, family tragedy or the absence of able-bodied adults. Margaret McKean, "The Japanese Experience with Scarcity: Management of Traditional Common Lands," *Environmental Review* 6, no. 2 (1982): 63-91.

When underinvestment can be punished by a fine, cooperation can continue, and the tragedy of the commons can potentially be avoided. Even if farmer *l* underinvests in one period, he can restore cooperation by paying a fine F to the community (or to farmer h in our model) in the next period. Then the farmer faces a trade-off between immediate temptation to freeride and the future consequence of paying the fine. If the farmer is patient enough, the future consequence outweighs the temptation and the farmer is better off by making the cooperative investment.

To enable us to examine the effect of technological change on the incentives for cooperation, we need to add detail to our analysis. Suppose that farmer l's payoff from cooperation is C and his payoff from defecting from the cooperative investment is D. The farmer can increase his payoff by $(D - C)$ if he freerides rather than makes the higher cooperative investment. $(D - C)$ measures the farmer's immediate *temptation* to freeride. The farmer compares the temptation to the consequence of freeriding: the fine he has to pay in the next period. This trade-off depends importantly on how patient the farmer is. Farmer's discount factor δ measures his patience. δ is today's value of $1 in the next period. Therefore, δ is large if the farmer is very patient.[19] If the farmer is very patient – and the fine is large enough – today's value of the fine, δF, outweighs the temptation, $(D - C)$, and farmer l is better off by cooperating. While an impatient farmer is more interested in increasing his immediate payoff: the temptation outweighs its consequences and the farmer is likely to freeride.

We also have to take into account that the farmers' agreement is informal and there is no formal institution to enforce the fine. This means that the defecting farmer has to be willing to pay the fine. What is the consequence of refusing to pay the fine? We assume that after

[19] We assume that $\delta < 1$.

underinvesting, if farmer *l* will not pay the fine, farmer *h* will also underinvest *for one period*, but not indefinitely as with a trigger strategy. This means that in the next period farmer *l* will not get another opportunity to freeride on h's cooperative investment but instead, will earn a punishment payoff. The punishment payoff is what the farmer would earn in a one-shot interaction (that is, the tragedy of the commons). After this punishment, farmer l is given another chance to pay the fine in the following period, after which cooperation can be restored.

We can then choose the level of the fine so that the future consequence of farmer h's underinvestment is enough deterrence to keep farmer *l* from defaulting on the fine. If farmer l pays the fine, cooperation is restored and he starts earning C already in this period. Alternatively, if he does not pay the fine, also farmer *h* will underinvest (for one period) and farmer *l* will earn the punishment payoff P and defer paying the fine until the following period. If the farmer does not pay the fine, his payoff is reduced by $(C - P)$ every period until he pays the fine. The farmer is better off paying the fine as long as it is less costly than such payoff reduction. Therefore, $(C - P)$ measures the value of a cooperative relationship to farmer *l*. The higher is *the value of the relationship*, the higher fine farmer *l* is willing to pay to restore cooperation if he were to freeride. A high fine in turn can deter the farmer from freeriding in the first place. That is why high value of the relationship improves the incentives to cooperate.

In the Appendix, we show that both farmers will make the cooperative investments if

$$\delta \geq \frac{T}{T+V} = \underline{\delta}.$$

T is the farmers' combined temptation to freeride and V is the farmers' combined value of the relationship. Together T and V determine $\underline{\delta}$, which is the minimum patience requirement for cooperation. If the farmers' discount factor δ is greater than the threshold $\underline{\delta}$, the farmers can overcome the potential tragedy of the commons and will make cooperative investments in the irrigation system. The equation shows that higher temptation increases $\underline{\delta}$ and hinders cooperation by making the patience requirement more difficult to satisfy. While higher value of the relationship decreases $\underline{\delta}$ and facilitates cooperation by relaxing the patience requirement.

Technological improvement and the incentives to cooperate

Our main interest is in how technological change affects the threshold $\underline{\delta}$ for cooperation. If technological change increases $\underline{\delta}$, cooperation is hindered because there is an increased patience requirement for the farmers. The threshold $\underline{\delta}$ depends on the ratio of the temptation to the value of the relationship. It is useful to first examine the effect of technological change on the temptation and the value of the relationship separately and then evaluate the overall effect on $\underline{\delta}$.

Let us first examine the effect of a major technological improvement on the value of the relationship (the difference between the cooperative payoffs and the punishment payoffs). Major technological improvement makes the value of the irrigation system more responsive to farmers' investments or the costs less responsive to investments. Therefore, the payoffs from cooperation increase but so do the punishment payoffs. However, since the cooperative investments are higher than the punishment investments, the payoffs from cooperation increase more than the punishment payoffs and the value of the relationship increases. Higher value of the relationship in turn has a positive effect on the incentives to cooperate by relaxing the patience requirement.

However, technological improvement also increases the temptation to freeride. Improved technology gives the farmers incentives to increase their investments. In particular, the cooperative investments increase making it more tempting to freeride on the other farmer's higher investment. Higher temptation has a negative effect on the incentives to cooperate by increasing the patience requirement.

Higher temptation hinders cooperation while higher value of the relationship facilitates cooperation and it is not immediately clear what the overall effect is on the incentives to cooperate. In the Appendix we show how $\underline{\delta}$ depends on the major technological improvement measured by the ratio α/β. Higher α makes the farmers' investments more effective in increasing the value of the irrigation system, while lower β reduces the investment costs. According to simulations presented by the solid line in Figure 2, the effect of increased temptation is dominant and major technological improvement has a negative effect on the incentives to cooperate: patience requirement $\underline{\delta}$ is increased.

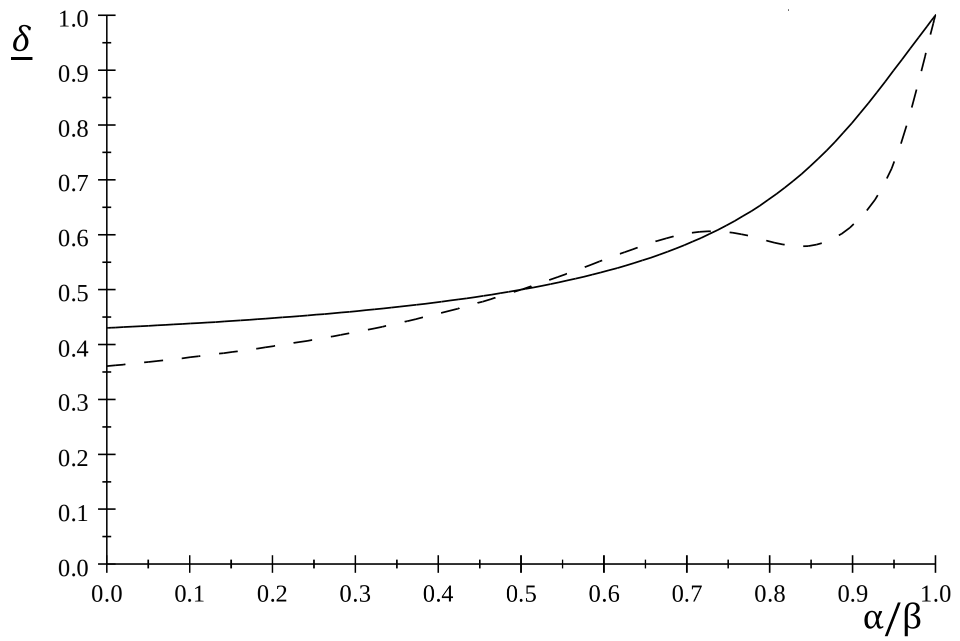

Figure 2. Incentives to cooperate for a major technological improvement

The broken line in Figure 2 presents a situation where the farmers have very different valuations for the irrigation system. In that case $\underline{\delta}$ is not smoothly increasing but even then it is broadly increasing for a major technological improvement.[20]

Result 1. *Major technological improvement hinders cooperation.*

The dominant effect is that the farmers respond to a major technological improvement by increasing their cooperative investments. This makes it more tempting to freeride on the other farmer's cooperative investment. The increased temptation increases the threshold $\underline{\delta}$ and hinders cooperation.

Suppose that the farmers' discount factor is equal to 0.6. Initially α/β is just below 0.7, so that, according to the solid line in Figure 2, $\underline{\delta}$ is just below 0.6 so that the farmers' patience requirement is satisfied. Then technological improvement increases α/β above 0.7. Higher α/β increases the farmers' cooperative payoffs so that the farmers would benefit from technological improvement if they were able to continue cooperation. However, higher α/β also increases $\underline{\delta}$ above 0.6 and cooperation breaks down because temptation to freeride has increased. This is why technological improvement can reduce the farmers' payoffs.

Alternatively, if α/β is initially very low, say 0.2, so that the farmers' discount factor is well above $\underline{\delta}$, the farmers can continue cooperation even after significant technological change occurs. This implies that it is possible that the irrigation system can be well-managed for a long period of time during technological change, but when α/β finally reaches 0.7, further

[20] Furthermore, the range of α/β where higher α/β decreases $\underline{\delta}$ occurs only for $\alpha/\beta > 0.5$. In the next section we show that common-property regime is not the best way to govern the resource when $\alpha/\beta > 0.5$.

technological improvement breaks down cooperation resulting in a collapse in investments in the irrigation system.[21]

We turn our attention now to minor technological improvement, which is measured by lower σ. In the Appendix we show that $\underline{\delta}$ does not depend on σ. This gives our second result.

Result 2. *Minor technological improvement has no effect on the incentives to cooperate.*

Technological improvement that shifts costs downward proportionately increases the farmers' cooperative payoffs. But such technological improvement does not change the farmers' incentives to cooperate. So if the farmers were able to cooperate before the change, they can continue cooperation after the improvement and benefit from the increased cooperative payoffs.

Although minor technological improvement does not affect $\underline{\delta}$, it has an effect on the value of the relationship and the temptation to freeride. In fact, as with a major technological improvement, both the value of the relationship and the temptation increase but because the increase is proportionate their ratio remains constant and so does $\underline{\delta}$.

With this type of technological improvement, the degree of responsiveness of costs to investments (parameter β) remains constant, which explains why the changes are proportionate. Major technological improvement changes the degree of responsiveness (ratio α/β) itself, leading to different results.

[21] Furthermore, the shape of $\underline{\delta}$ in Figure 2 shows that for low values of α/β technological change increases $\underline{\delta}$ marginally but eventually the increase is significant. This strengthens the argument that the irrigation system can be robust for a long time but when the threshold is reached, cooperation breaks down.

Alternative Ownership Structures

In the previous section we found that major technological improvement hinders cooperation under a common-property regime. Therefore, if α/β increases significantly, common-property regimes may cease to be optimal. (Minor technological improvement does not have such effect.) This is indeed what we find in our earlier work where we compare common-property regime to other ownership structures such as joint ownership and single ownership by farmer *h* or *l*.[22] Joint ownership is a shared structure where both farmers have a veto power, while single ownership can be interpreted as private or government ownership.

We find that the value of the relationship (the difference between cooperative payoffs and the punishment payoffs) is large under common-property regime as compared to joint ownership or ownership by farmer *h*.[23] In the previous section we found that high value of the relationship improves the incentives to cooperate. This strength of common-property regime arises from the possibility of the tragedy of the commons. Defecting farmer has strong incentives to pay the required fine to avoid underinvestment by the other farmer at the level of the tragedy of the commons. Ownership by farmer *h* or joint ownership have less punishment power as they provide better incentives for investments *in the one-shot interaction*.

However, the weakness of common-property regime is that the temptation to freeride is large. Temptation is larger under common-property regime because farmer *h* can keep his high benefit from the CPR to himself, while under joint ownership or *h*-ownership the farmers have to bargain how to share the benefits. In the previous section we found that technological progress in terms of higher α/β has a greater effect on the temptation than on the value of the

[22] Halonen-Akatwijuka and Pafilis, "Common Ownership of Public Goods".
[23] Ibid.

relationship under common-property regime. Therefore increasing α/β eventually reduces the incentives to cooperate so much that it is better to switch to an ownership structure that minimizes the temptation to freeride: either ownership by agent h or joint ownership. We find that this switch is optimal when $\alpha/\beta > 0.5$. Higher α/β increases $\underline{\delta}$ even under agent h ownership and joint ownership, but less than under common-property regime. Therefore, the incentives to cooperate can be improved by switching away from common-property regime.

While common-property regime is no longer optimal when technological improvement has increased α/β above 0.5, common-property regime provides the best incentives for cooperation for less effective technologies for which $\alpha/\beta < 0.5$. This condition can be satisfied either because of a low α or a high β. Low α implies that the value of the CPR is not very responsive to investments. This is consistent with a stylized fact of communal grazing lands in the Swiss Alps identified by Netting and discussed by Ostrom: the value of the communal grazing lands cannot be increased much due to altitude, a limited growing season and thin soil.[24] This is in contrast to privately owned arable lands in the mountain valleys, the yield of which can be increased by "irrigation, manuring, erosion control, crop rotation, and careful horticulture."[25]

Alternatively, the rationale for common-property regime ($\alpha/\beta < 0.5$) can arise from high β. High β implies that higher investment increases costs significantly. Then common-property regime can be optimal even when investments increase the value of the CPR significantly, contrary to the above stylized fact. This is the case with respect to the irrigation

[24] Robert McC Netting, "What Alpine Peasants Have in Common: Observations on Communal Tenure in a Swiss Village," *Human Ecology* 4, no. 2 (1976):135-146; Ostrom, *Governing the Commons,* 63.
[25]Netting, "What Alpine Peasants Have in Common," 143. Also in the common lands in Japan maintenance investments, such as the annual burning of the grasslands, have a limited impact on the yield. Margaret McKean, "The Japanese Experience with Scarcity: Management of Traditional Common Lands,"; Ostrom, *Governing the Commons,* 67.

systems in Nepal and the Philippines studied by Ostrom and Yoder.[26] There, the ineffectiveness of the technology is driven by high maintenance costs. For example, in one of the Zanjera irrigation communities in the Philippines, the average annual contribution to maintenance was thirty seven days of work per person.[27] The major cost of maintenance arises from the time and effort taken away from cultivating privately owned fields. When maintenance activities are at such a high level, they can have a significant effect on the productivity of private cultivation. Therefore, the costs in terms of lost productivity of private cultivation are very responsive to increasing maintenance activities. According to our results, this is when common-property regime provides the best incentives for cooperation. Zanjera communities have indeed been successful in routinely mobilizing labor for maintenance of the irrigation system. A compliance rate of 94% was reported.[28]

Ostrom's Design Principles

Our analysis implies that the exogenous characteristics of the particular resource and the technologies used are relevant to determining whether a common-property regime can be successful. Low α/β is favourable to common-property regime, while incentives to cooperate are weak and can be improved by changing the ownership structure when α/β is high.

We will now apply our results to Ostrom's design principles. Ostrom examined numerous field studies of successful and unsuccessful CPRs and identified the key principles that characterize the successful ones.[29] The design principles include well-defined boundaries, graduated sanctions and low-cost conflict-resolution mechanisms, among others, all of which

[26] Ostrom, *Governing the Commons*, 82-88; Robert Yoder, *Organization and Management by Farmers in the Chhatis Mauja Irrigation System, Nepal*, (Colombo, Sri Lanka: IIMI, 1994).
[27] Walter E. Coward and Robert Y. Siy, "Structuring Collective Action: An Irrigation Federation in the Northern Philippines," *Philippine Sociological Review* 31 (1983): 3-17; Ostrom, *Governing the Commons*, 85-86.
[28] Ostrom, *Governing the Commons*, 86.
[29] Ostrom, *Governing the Commons*.

are largely endogenous. According to our results, applying these design principles may not be effective unless the characteristics of the resource and technology are such that common-property regime provides good incentives for cooperation.

However, we show that the classical case studies of successful common-property regimes (where investments play a role) – irrigation systems in Nepal and the Philippines and common lands in Switzerland and Japan – have similar design principles and can also be characterized by ineffective technology.

Ostrom on Irrigation Technologies

Ostrom was critical of the view that irrigation is simply an engineering problem; she focused on the importance of governance as well. Replacing primitive farmer-managed irrigation systems with modern technology and coupling it with management by a government agency is typically associated with a reduction in agricultural productivity.[30] Ostrom's explanation is that government agencies – unlike the farmers themselves – lack incentives to manage the irrigation system well.

However, it is also possible to improve technology without handing over the management to a government agency. Our results speak to this situation. In our analysis of an irrigation system owned and managed by farmers, major technological improvement alone may lead to a breakdown of cooperation among the farmers and, ultimately, the deterioration of the irrigation system itself. This is the case when the farmers' discount factor is initially close to the critical discount factor $\underline{\delta}$. In most of the cases covered by the empirical literature, major

[30] Ostrom and Gardner, "Coping with Asymmetries in the Commons"; Ostrom, Lam and Lee, "The Performance of Self-Governing Irrigations Systems in Nepal"; Lam, "Improving the Performance of Small-Scale Irrigation Systems"; Elinor Ostrom, Joanna Burger, Christopher B. Field, Richard B. Norgaard and David Policansky, "Revisiting the Commons: Local Lessons, Global Challenges," *Science* 284 (5412) (1999): 278-282.

technological improvements have been accompanied by a move to a government-run regime and the change in ownership has been seen to be responsible for the poor performance of these irrigation systems. We argue that the nature of the technological improvement and its impact on the farmers' incentives to cooperate play a role in poor performance.

Alternatively, in our analysis technological change may lead to a genuine improvement without disrupting farmers' incentives to cooperate. This is the case with major technological improvement when the farmers' discount factor is well above $\underline{\delta}$. Furthermore, minor technological improvements within an existing irrigation system – such as strengthening water diversion devices, providing simple canal lining or training programs – can increase productivity without compromising cooperation.[31] Lam and Ostrom find that these minor technological changes improved water adequacy in farmer-managed irrigation systems.[32]

Conclusions

In this chapter we examined the robustness of common-property regimes in the face of technological progress. Our focus has been on their provision. We show that technological change can potentially hinder cooperation. This is the case for major technological changes, such as switching from a primitive to a modern irrigation system. Such a change hinders incentives to cooperate by increasing the temptation to freeride on others' cooperative investments. While minor improvements within an existing irrigation system, such as

[31] Training programs have been offered e.g. in Nepal with the aim to "stimulate the transfer of experience from farmers in well-managed systems to those in poorly managed systems". Naresh Pradhan, *A Farmer to Farmer Exchange Training for Improved Irrigation Management Organized by DIHM's Irrigation Management Center* (Kathmandu, Nepal: Irrigation Management Project Memo, 1987), 1.

[32] Wai Fung Lam and Elinor Ostrom, "Analyzing the Dynamic Complexity of Development Interventions: Lessons from an Irrigation Experiment in Nepal," *Policy Sciences* 43 (2010): 1-25. Lam and Ostrom also show that the positive effect on technical efficiency was only short-term. See also Torsten R. Berg (2008). *Irrigation Management in Nepal's Dhaulagiri Zone: Institutional Responses to Social, Political and Economic Change* (PhD Thesis, Aalborg University, Department of History, International and Social Studies, 2008).

introducing simple canal linings, leave incentives to cooperate unaffected. This is because both the temptation to deviate and its consequences increase proportionately leaving overall incentives for cooperation unchanged.

Our model can be helpful for understanding the long-term success of common-property regimes during times of technological progress. Even when technology changes are major, cooperation can be maintained if the community is patient and initially their discount factor is well above the critical level. However, when the threshold is reached, any further technological change can lead to a breakdown of cooperation and collapse in investments in the CPR.

Our analysis has focused on the provision of CPRs such as irrigation systems and common lands. More work emphasizing provision rather than appropriation of CPRs is needed. Some of the biggest challenges faced by humankind involve global CPRs, such as the earth's shared natural resources and outer space. Such CPRs not only differ in terms of their characteristics but also pose different challenges and opportunities. The impact of technological change on such resources remains an interesting and critical question for future research.

Appendix

We first derive the cooperative investments, y_h^* and y_l^*. The farmers' joint surplus is equal to $S = (\theta_h + \theta_l)[(y_h)^\alpha + (y_l)^\alpha] - \sigma(y_h)^\beta - \sigma(y_i)^\beta$.

Maximizing the joint surplus with respect to investments gives

(A1) $y_i^* = \left(\frac{\alpha(\theta_h+\theta_l)}{\sigma\beta}\right)^{\frac{1}{\beta-\alpha}}$ for $i = h, l$.

In the one-shot game, each farmer maximizes his own payoff $P_i = \theta_i[(y_h)^\alpha + (y_l)^\alpha] - \sigma(y_i)^\beta$ and chooses investment given by

(A2) $y_i^e = \left(\frac{\alpha\theta_i}{\sigma\beta}\right)^{\frac{1}{\beta-\alpha}}$ for $i = h, l$.

In the repeated game, the combined incentive constraint for both farmers to make the cooperative investments is given by[33]

(A3) $\delta(F_h + F_l) \geq (D_h + D_l) - (C_h + C_l)$,

where F_i is the fine, D_i is the defection payoff and C_i is the cooperative payoff of farmer $i = h, l$. The combined incentive constraint for both farmers to be willing to pay the fine is given by

(A4) $(F_h + F_l) \leq \frac{1}{1-\delta}[(C_h + C_l) - (P_h + P_l)]$

where P_i is the punishment payoff of farmer $i = h, l$. Substituting the maximal fines to equation (A3) and simplifying, we obtain

(A5) $\delta \geq \frac{T}{T+V} = \underline{\delta}$.

[33] If the discounted value of the fines outweigh the combined temptation to freeride, the farmers can find a suitable monetary transfer (if necessary) to satisfy each farmer's individual incentive constraint. See Halonen-Akatwijuka and Pafilis, "Common Ownership of Public Goods".

where $T = (D_h + D_l) - (C_h + C_l)$ is the farmers' combined temptation to freeride and $V = (C_h + C_l) - (P_h + P_l)$ is the combined value of the relationship.

The explicit form of T is given by

$$T = \left[\theta_h((y_h^e)^\alpha + (y_l^*)^\alpha) - \sigma(y_h^e)^\beta\right] + \left[\theta_l((y_l^e)^\alpha + (y_h^*)^\alpha) - \sigma(y_l^e)^\beta\right]$$
$$- \left[(\theta_h + \theta_l)((y_h^*)^\alpha + (y_l^*)^\alpha) - \sigma(y_h^*)^\beta - \sigma(y_l^*)^\beta\right].$$

While $T + V$ is given by

$$T + V = (D_h + D_l) - (P_h + P_l)$$

$$= \left[\theta_h((y_h^e)^\alpha + (y_l^*)^\alpha) - \sigma(y_h^e)^\beta\right] + \left[\theta_l((y_h^*)^\alpha + (y_l^e)^\alpha) - \sigma(y_l^e)^\beta\right]$$
$$- \left[\theta_h((y_h^e)^\alpha + (y_l^e)^\alpha) - \sigma(y_h^e)^\beta\right] - \left[\theta_l((y_h^e)^\alpha + (y_l^e)^\alpha) - \sigma(y_l^e)^\beta\right]$$

$$= \theta_h[(y_l^*)^\alpha - (y_l^e)^\alpha] + \theta_l[(y_h^*)^\alpha - (y_h^e)^\alpha].$$

Finally, we solve for the threshold $\underline{\delta} = \frac{T}{T+V}$. We substitute the investments from (A1) and (A2) in T and $T + V$ and simplify, obtaining

$$\underline{\delta} = \frac{\left[1+\left(\frac{\theta_h}{\theta_l}\right)^{\frac{1}{1-\alpha/\beta}}\right]\left(1-\frac{\alpha}{\beta}\right)-\left(\frac{\theta_h}{\theta_l}+1\right)^{\frac{1}{1-\alpha/\beta}}\left(1-\frac{2\alpha}{\beta}\right)}{\frac{\theta_h}{\theta_l}\left[\left(\frac{\theta_h}{\theta_l}+1\right)^{\frac{\alpha/\beta}{1-\alpha/\beta}}-1\right]+\left[\left(\frac{\theta_h}{\theta_l}+1\right)^{\frac{\alpha/\beta}{1-\alpha/\beta}}-\left(\frac{\theta_h}{\theta_l}\right)^{\frac{\alpha/\beta}{1-\alpha/\beta}}\right]}.$$