Inequality and Rule Performance in the Governance of Water Resources*

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Abstract

This paper focuses on collective action problems in the governance of water resources. Within this context, it investigates the interaction between inequality in land-holding and water allocation rules through the *joint* incentives-to-cooperate that those generate. The proposed model involves two types of farmers who differ in terms of their initial endowment of land and can voluntarily contribute to the construction/maintenance of an irrigation network. The total amount of irrigation water is distributed according to some allocation rule and used by each farmer as an input of production in combination with land. The analysis identifies two key forces: an 'efficiency-based' and an 'incentive-based' force, which affect the distribution of water in opposite directions. The trade-off between those two forces determines the nature of the relationship between inequality and optimal allocation rules. This trade-off, in turn, critically depends on the degree of complementarity between agents' efforts. The predictions of the model offer a theoretical explanation for the apparently contradicting results of the theoretical and empirical literature in this field.

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1 Introduction

The collective management of natural resource systems is critically important in the rural sector of developing economies. People living in rural areas typically rely upon natural resources for their livelihood and engage in collective action on a daily basis; for example, when they plant and harvest together, use a common facility or technology of production, construct and maintain an irrigation network, decide the rules to access a common resource (Platteau, 1991; Bardhan et al., 2006; Ostrom, 2003).

The ability to cooperate in collective activities such as those mentioned above is, therefore, a key determinant of economic performance (Bandiera et al., 2005).

In the past decades, many researchers from different disciplines have tried to explain which factors may favour or discourage cooperation in collective action. One of the most significant conclusions emerging from the literature concerns the role of group size: the smaller the group, the stronger its ability to perform collectively (Hardin, 1982; Sandler, 1992; Baland and Platteau, 1996; Agrawal and Goyal, 2001).

A more controversial issue surrounds the role of inequality: how does inequality among the members of a community affect the ability and the incentives to cooperate in collective action problems? The goal of the present paper is to explain some of the complex mechanisms linking inequality and collective outcomes, with particular reference to the context of water resource management.

Despite the impressive advances of economic research in this field, many aspects still remain to be understood and clarified. In particular, the theoretical literature has mainly concentrated on the relationship between inequality in initial conditions (such as wealth or land distribution) and individuals' incentives.

The basic notion is that agents with different initial endowments may have different *intrinsic* interests in the collective good. Therefore, inequality affects system performance by creating differential incentives to cooperate.

This aspect is crucial, but not exhaustive. The last ten years of empirical research have indeed demonstrated that inequality also has important effects on the institutions adopted by a community. Institutions, in turn, influence the success with which a community undertakes collective action by shaping agents' returns from cooperation. In the context of water resource management, for example, a relationship seems to exist between the degree of land inequality and the water allocation schemes observed in rural irrigation communities. The nature of this relationship, however, is not straightforward: some studies (see, for example, Dayton-Johnson 1999, 2000) show that communities characterized by relatively high degrees of inequality in land-holding tend to choose allocation rules that favour the rich. By contrast, other studies (Bardhan, 2000, and Khwaja 2001) find that more unequal communities choose relatively fairer rules.

At the theoretical level, a satisfactory explanation for these apparently contradicting results has not been provided yet. The present paper seeks to approach the problem in a more comprehensive way by investigating the interaction between inequality and water allocation rules through the *joint* incentives to cooperate that those generate. The proposed model involves two types of farmers who differ in terms of their initial endowment of land and can voluntarily contribute to the construction and maintenance of an irrigation network. The total amount of irrigation water is distributed according to some allocation rule and used by each farmer as an input of production in combination with land. The analysis identifies two key forces - an 'efficiency-based' and an 'incentive-based' force - which affect the distribution of water in opposite directions. The trade-off between those two forces determines the nature of the relationship between inequality and optimal allocation rules. This trade-off, in turn, critically depends on the strategic importance of agents' contributions in the realization of the collective good. The predictions of the model offer a theoretical explanation for the somewhat mixed evidence stemming from the empirical literature and may have important implications in terms of incentives design.

The structure of the paper is as follows. In section 2, I discuss those contributions which are most closely related to the present work. Section 3 describes the setup of the model. Section 4 is devoted to the resolution of the model. More precisely, in 4.1 I characterize the optimal individual contributions and the collective output produced in equilibrium for a given distribution of land and a given allocation rule; in 4.2, I derive the 'optimal' allocation rule, and in 4.3 I investigate the relationship between the optimal rule and the degree of inequality characterizing the economy. In section 5, I discuss three special cases for the production technology of the collective good; that is: linear, Leontief and Cobb-Douglas production technology. Finally, section 6 summarizes the main findings of the paper and its policy implications.

2 Related literature

The existing literature on the role of inequality in collective action problems tends to divide into two main camps: those studies that find a positive role for inequality and those that point out a negative role.[1] The debate dates back to

[1] Starting from Olson (1965)'s seminal paper, several authors have enphasized the positive role of inequality in a variety of fields of economics: from oligopolistic collusion and military alliances, to regional schemes for economic integration and farmers' participation in rural cooperatives (see, for example, Sandler and Forbes, 1980; Olson, 1982; Sandler 1992; Datta and Kapoor, 1996). At the same time, numerous examples of the harmful effects of inequality can be found in the case-study literature. In the context of water resources see, for example,

the mid-1960s when Olson contended that inequality may favour the provision of collective goods. The idea behind Olson's argument is that richer users may have an inherently higher interest in the collective good and, therefore, gain from seeing that the good is provided, even if they have to pay the whole cost (Olson, 1965).

In fact, this result is particularly dependent on the assumptions that one makes on the technology of production of the collective good. In particular, it has been shown that the Olson effect is likely to arise when individual contributions in the collective project are *perfect substitutes* (Hirshleifer, 1983).

Many real-life situations display intermediate degrees of substitution or complementarity across individual effort. This is especially true for the management of irrigation or watershed infrastructures in which the proper maintenance of the scheme requires the stabilization of the rims or the desalting of minor channels across the land of participating farmers. In this case, the maintenance effort of one farmer needs to be complemented by similar efforts elsewhere in the network for the entire system to function effectively. Baland et al. (2007) provide an interesting analysis of the relationship between allocation rules and the generated surplus in these 'intermediate' situations. The main result in that paper is that perfect equality of shares is the most efficient division rule 'long before' the point of perfect complementarity of efforts is reached: that is, even for fairly low levels of complementarity between individual contributions.

However, in Baland et al.(2007), agents are ex-ante identical except for their share in the collective good. In other words, the authors do not explicitly model inequality in initial conditions such as the distribution of wealth or land. This does not allow one to capture how the performance of different allocation rules

Jayaraman (1981), Easter and Palanisami (1986), Varughese and Ostrom (2001).

(and eventually the type of rules chosen) may vary as initial conditions change.

As previously mentioned, the empirical literature has shown that inequality in initial conditions may have important effects on the choice of distributive rules. Dayton-Johnson (2000) develops a simple model to assess the allocation rules observed in a number of rural irrigation communities in Central Mexico. The author focuses on two types of distributive rules: rules with congruence between the sharing of collective costs and benefits and rules that allocate water proportionally to land. The analysis shows that, although less efficient than congruent rules, proportional allocation rules are more likely to be observed in systems characterized by higher inequality in land distribution. This study then raises the question of why, in many contexts, *apparently* 'dominated' rules are adopted.

In a recent contribution, Bardhan et al. (2006) propose a valuable framework to analyze the relationship between initial inequality and efficiency across a range of collective action problems. In particular, they assume that there is inequality in the distribution of the endowment of a private input (such as wealth or land) and that agents use this private input in combination with a collective input to produce a final good. The authors focus on the effects of inequality in the distribution of the private input on agents' incentives to contribute towards the collective good. They show, for instance, that when the collective action problem involves an impure public good, efficiency tends to increase with greater equality in the distribution of the private input. However, if inequality is sufficiently high such that some players stop contributing then any further increase in wealth inequality increases the equilibrium level of the collective input.

As in Bardhan et al. (2006), I adopt the idea that the private input (land) − which can be more or less equally distributed among agents − is complementary in production with the collective input (water). The focus of the present paper, however, is different. The model proposed here looks at the relevance of initial inequality not only in terms of the differential incentives to cooperate that it creates, but also in terms of its effects on the institutions adopted by local communities. As previously explained, this additional channel is taken into account by modelling the interaction between land inequality and rule performance in the governance of water resources. This aspect is not considered in Bardhan et al. (2006) because the choice of distributive rules is not explicitly modelled. Another point of departure is that the model introduced in this paper allows for players' contributions to have different degrees of *complementarity* while both Bardhan et al. (2006) and Dayton-Johnson (2000) assume that efforts are perfect substitute in the production technology of the collective good.

3 Setup of the model

Consider two types of farmers: 1 and 2. Each type is endowed with an amount of irrigable land l_i, with $l_i > 0$ and $i = \{1, 2\}$. Let $l \equiv l_1 + l_2$ denote the total amount of land in the economy. Farmers' endowments can then be defined as: $l_1 = \lambda \times l$ and $l_2 = (1 - \lambda) \times l$, with $\lambda \in (0, 1)$. In the remainder of the paper, I normalize l to one and assume $\lambda > 0.5$. The two types can, therefore, be interpreted as the representatives of two different groups of farmers: large landowners (type 1), and small landowner (type 2).

Farmers can voluntarily engage in a joint project for the maintenance of a network of irrigation channels. Collective-maintenance activity increases the supply of water available for irrigation. Better maintenance, for example, leads to lower losses from filtration, leakage and sedimentation. The output of the project, Z, is represented by the average water flow delivered through the system and is a function of farmers' efforts: e_1, e_2. More precisely, I parametrize the production technology for Z by using a CES production function:

$$Z = F(e_1, e_2) = [e_1^\sigma + e_2^\sigma]^{\frac{1}{\sigma}} \tag{1}$$

where $\sigma < 1$ measures the degree of complementarity between individual efforts.[2]

Agents' efforts are assumed to be unobservable (or not enforceable).

The collective output, Z, is divided among farmers according to an allocation rule $\Gamma = (\boldsymbol{\gamma}_1, \boldsymbol{\gamma}_2)$, where $\boldsymbol{\gamma}_1$ and $\boldsymbol{\gamma}_2$ are farmers' shares in Z, with $\boldsymbol{\gamma}_1, \boldsymbol{\gamma}_2 \geq 0$ and $\boldsymbol{\gamma}_1 + \boldsymbol{\gamma}_2 = 1$. When convenient, I will simplify the notation as follows: $\boldsymbol{\gamma}_1 = \gamma$, $\boldsymbol{\gamma}_2 = 1 - \gamma$.

The amount of water allocated to a farmer according to the allocation rule Γ is given by $z_i = \gamma_i Z$ with $i = \{1, 2\}$. Each agent uses two inputs, land and water, to produce a final good. Agent i's payoff is defined as:

$$\Pi_i = f(l_i, z_i) - e_i$$

where, $f(l_i, z_i)$ is the individual production function for the final good and e_i is i's contribution for the maintenance of the irrigation network.

I assume that the cost of e_i units of effort is simply e_i and that the production technology for the final good is well represented by a Cobb-Douglas production function with constant returns to scale. Formally:

[2]It is well known that the CES production function takes on a variety of shapes depending on the value of the parameter σ. For example, for $\sigma \rightarrow 1$ the production technology for Z approximates a linear production function. As σ approaches zero, the isoquants of the CES function look like the isoquants of the Cobb-Douglas production function. In the limit case for $\sigma \rightarrow -\infty$, the CES function approximates a Leontief technology, where efforts are perfect complements.

$$f(l_i, z_i) = (z_i)^{\alpha} (l_i)^{1-\alpha}, \text{ with } \alpha \in (0,1) \tag{2}$$

From the complementarity between l_i and z_i in (2), it follows that the marginal return on water is an increasing function of land. Therefore, a farmer endowed with a larger amount of land has a higher marginal return on water than a small land-owner.

The implied game is simple: each agent chooses the level of effort that maximizes his own payoff, given the contribution made by the other. Formally:

$$\max_{e_i \geq 0} \Pi_i = f(l_i, z_i(e_i, \overline{e}_j) - e_i$$

where i, $j = \{1, 2\}$, and $i \neq j$.

In section 4.1, I solve the above optimization problem for each agent and derive the collective output produced in equilibrium for a given distribution of land and a given allocation rule. In sections 4.2 and 4.3, I identify the allocation rule that maximizes the supply of irrigation water and analyze how this depends on the degree of initial inequality.

4 Resolution of the model

4.1 Individual optimization problem

Consider type 1's optimization problem. Given the contribution made by the other farmer, type 1 chooses e_1 to maximize his own payoff:

$$\max_{e_1 \geq 0} \Pi_1 = f(l_1, z_1(e_1, \overline{e}_2)) - e_1$$

Type 1's payoff can be written, more explicitly, as:

$$\Pi_1 = (\gamma Z)^{\alpha} (\lambda)^{1-\alpha} - e_1$$

with $Z = [e_1^{\sigma} + e_2^{\sigma}]^{\frac{1}{\sigma}}$.

The first-order conditions for type 1's optimization problem are as follows:

$$\frac{\partial \Pi_1}{\partial e_1} = 0 \Rightarrow \alpha \times \left[(\gamma)^{\alpha}(\lambda)^{1-\alpha}\right] \times (Z)^{\alpha-1} \times \frac{\partial Z}{\partial e_1} - 1 = 0 \tag{3}$$

From (1), the derivative of Z with respect to e_1 can be written as:

$$\frac{\partial Z}{\partial e_1} = (Z)^{1-\sigma}(e_1)^{\sigma-1} \tag{4}$$

By substituting (4) into (3), the following expression can be obtained:

$$(e_1)^{\sigma} = (\alpha)^{\frac{\sigma}{1-\sigma}} \times \left[(\gamma)^{\alpha}(\lambda)^{1-\alpha}\right]^{\frac{\sigma}{1-\sigma}} \times (Z)^{\frac{\sigma(\alpha-\sigma)}{1-\sigma}} \tag{5}$$

Similarly, from type 2's optimization problem we have:

$$(e_2)^{\sigma} = (\alpha)^{\frac{\sigma}{1-\sigma}} \times \left[(1-\gamma)^{\alpha}(1-\lambda)^{1-\alpha}\right]^{\frac{\sigma}{1-\sigma}} \times (Z)^{\frac{\sigma(\alpha-\sigma)}{1-\sigma}} \tag{6}$$

By substituting (5) and (6) into equation (1) and rearranging the terms, the following expression for Z can be derived:

$$Z^{*} = \phi \times \left\{\left[(\gamma)^{\alpha}(\lambda)^{1-\alpha}\right]^{\beta} + \left[(1-\gamma)^{\alpha}(1-\lambda)^{1-\alpha}\right]^{\beta}\right\}^{\mu} \tag{7}$$

where $\phi \equiv (\alpha)^{\frac{1}{1-\alpha}}$, $\beta \equiv \frac{\sigma}{1-\sigma}$ and $\mu \equiv \frac{1-\sigma}{\sigma(1-\alpha)}$.[3]

[3] Notice that ϕ, β and μ are only well defined if $\alpha \neq 1$ and $\sigma \neq 1$, which will be assumed in the reminder of the paper. From equation (1), $\sigma = 1$ corresponds to the case in which agents' efforts are perfect substitutes in the production technology of Z. This special case will be discussed in section 5.1.

Equation (7) represents the amount of collective output produced in equilibrium for a given distribution of land and a given allocation rule.[4]

4.2 The optimal water allocation rule

In the context of the present analysis, the 'optimal' allocation rule is defined as the rule γ that maximizes the collective output produced in equilibrium (Z^*). Formally, the problem can be expressed as follows:

$$\max_{0\leq\gamma\leq1} Z^* = \phi \times \left\{ \left[(\gamma)^\alpha(\lambda)^{1-\alpha}\right]^\beta + \left[(1-\gamma)^\alpha(1-\lambda)^{1-\alpha}\right]^\beta \right\}^\mu \tag{8}$$

If a solution interior to the interval [0,1] exists, then the following FOC must hold:

$$\begin{aligned} \frac{\partial Z^*}{\partial \gamma} &= \frac{\alpha}{1-\alpha} \times \left\{ \left[(\gamma)^\alpha(\lambda)^{1-\alpha}\right]^\beta + \left[(1-\gamma)^\alpha(1-\lambda)^{1-\alpha}\right]^\beta \right\}^{\mu-1} \times \\ &\quad \times \left\{ \left[(\gamma)^{(\alpha\beta-1)}(\lambda)^{(1-\alpha)\beta}\right] - \left[(1-\gamma)^{(\alpha\beta-1)}(1-\lambda)^{(1-\alpha)\beta}\right] \right\} \\ &= 0 \end{aligned} \tag{9}$$

Notice that, for $\alpha \in (0,1)$ and $\lambda \in (0,1)$ the first two terms in (9) are strictly positive.

Condition (9) can, therefore, be simplified as follows:

$$\left[(\gamma)^{(\alpha\beta-1)}(\lambda)^{(1-\alpha)\beta}\right] - \left[(1-\gamma)^{(\alpha\beta-1)}(1-\lambda)^{(1-\alpha)\beta}\right] = 0 \tag{10}$$

By substituting for $\beta = \frac{\sigma}{1-\sigma}$ and solving with respect to γ, the following result

[4] It can be shown that there exists another equilibrium which involves $e_i = 0$ for all i and, consequently, $Z^* = 0$. This, however, will be ignored. The analysis will focus, instead, on the Pareto-efficient equilibrium, i.e. on the solution in which farmers choose a positive level of effort.

can be obtained:

$$\gamma^* = \frac{\lambda^\theta}{\lambda^\theta + (1-\lambda)^\theta} \tag{11}$$

where: $\theta \equiv \frac{(1-\alpha)\sigma}{(1-\sigma-\alpha\sigma)}$.

It can be shown – see appendix – that for $\sigma < \frac{1}{1+\alpha}$ the maximization problem in (8) admits an *interior* solution and such solution is given by (11). For $\sigma > \frac{1}{1+\alpha}$, Z^* is still increasing in γ at the value $\gamma = 1$. In such a case, the supply of irrigation water is thus maximized by allocating all the water available to the large landowner; that is by setting $\gamma^* = 1$.[5]

4.3 Inequality and rule performance

How does inequality in initial conditions (as represented by $\lambda > 0.5$) affect the optimal water allocation scheme?

As shown in the appendix, for $\sigma \in \left(\frac{1}{1+\alpha}, 1\right)$ the optimal allocation rule is $\gamma^* = 1$. That is, the supply of irrigation water is maximized by allocating all the water available to the large landowner for any $\lambda > 0.5$.

For $\sigma < \frac{1}{1+\alpha}$, the optimal rule is given by (11). Equation (11) can be interpreted as a 'weighted' index of the degree of inequality characterizing the economy. More precisely, inequality in land distribution is weighted by the parameter θ, which is a function of two elements: (i) the strategic importance of agents' efforts in the realization of the collective good – as measured by σ; and (ii) the relative importance of water compared to land in the production of the final good – as measured by α.

From (11), the derivative of γ^* with respect to λ is given by:

[5] The appendix also shows that the other possible corner solution, $\gamma = 0$, can never be a global maximum for any $\lambda \geq 0.5$.

$$\frac{\partial\gamma^*}{\partial\lambda} = \frac{\theta \times [\lambda(1-\lambda)]^{\theta-1}}{\left[\lambda^\theta + (1-\lambda)^\theta\right]^2} \tag{12}$$

with $\theta \equiv \frac{(1-\alpha)\sigma}{(1-\sigma-\alpha\sigma)}$.

It can be easily shown that, for $\lambda \in (0,1)$, the sign of $\frac{\partial\gamma^*}{\partial\lambda}$ solely depends on θ. Moreover, within the range of parameter values $\sigma < \frac{1}{1+\alpha}$, the sign of θ varies as follows: $\theta < 0$ for $\sigma < 0$; and $\theta > 0$ for $\sigma \in \left(0, \frac{1}{1+\alpha}\right)$.

The relationship between the optimal water allocation rule and the degree of inequality in landholding can, therefore, be summarized as follows:

- For $\sigma < 0 \Rightarrow \frac{\partial\gamma^*}{\partial\lambda} < 0$;
- For $\sigma \in \left(0, \frac{1}{1+\alpha}\right) \Rightarrow \frac{\partial\gamma^*}{\partial\lambda} < 0$;
- For $\sigma \in \left(\frac{1}{1+\alpha}, 1\right) \Rightarrow \gamma^* = 1, \forall\lambda > 0.5$

For $\sigma < 0$ – that is, as one moves towards relatively high degree of complementarity between agents' efforts – the collective output is maximized by allocating a larger share of water to the small landowner. Moreover, the optimal allocation scheme is such that the share of the small landowner must increase as inequality in land holding becomes more pronounced. The opposite holds within the interval $\sigma \in \left(0, \frac{1}{1+\alpha}\right)$ – that is, for lower degrees of complementarity. In such a case, assigning more water to the large landowner favours the provision of the collective good and the share of the large landowner must increase with the degree of initial inequality. Finally, when agents' contributions display relatively high degrees of substitutability – that is for $\sigma \in \left(\frac{1}{1+\alpha}, 1\right)$ – the supply of irrigation water is maximized by allocating all the water available to the large landowner, independently of the degree of inequality in landholding (i.e., *for any* $\lambda > 0.5$).

How can the above results be interpreted? In the context of the present analysis, it is possible to identify two types of forces which affect the distribution of the collective good (water) in opposite directions. I will refer to the first force as an 'efficiency-based force'. Productive-efficiency pushes the distribution of water in favour to the agent with the higher marginal productivity on water (MPW). From the complementarity between land and water in the production of the final good (equation 2), the MPW is increasing in land. Following the logic behind the 'efficiency-based force', more water should therefore be allocated to the large landowner.

The second force is an 'incentive-based force'. As above, the starting point is the observation that the MPW typically increases with land. This fact implies that the *intrinsic* incentive to exert maintenance effort is lower for a small landowner. The idea behind the incentive-based force is that the distribution of water could be used to 'correct' for the lack of incentives created by the unequal distribution of land. As a result, more water should be allocated to the agent with the lower intrinsic incentive; that is, the small landowner.

The use of water as an incentive mechanism might seem at first glance inefficient since it implies (in some cases) giving more water to the agent whose marginal value of water is lower. This, however, may still represent the 'constrained' optimum when other contracting possibilities are not available, as in the context considered in the present analysis. When, for example, effort is unobservable contracting over effort is not a feasible option. Furthermore, in some institutional settings contracting over output may also be difficult due to lack of commitment on the part of the producers or to limited enforcement capacity on the part of governmental authorities.[6]

[6]For simplicity, the model proposed in this paper assumes that output is deterministic. In the rural sector of developing economies, however, output tends to be highly sensitive to

Within the proposed framework, the relationship between inequality in landholding and water allocation schemes is therefore determined by the trade-off between the two forces previously described. How does this trade-off resolve crucially depends on the strategic importance of agents' contributions in the realization of the collective good. If, for example, the technology of production for the collective good displays high degrees of substitutability between agents' efforts (i.e., the parameter σ is realitively high), the efficiency-based force will prevail. In such a case, 'creating more inequality' by assigning a larger share of water to the big landowner will favour the provision of the collective good. This prediction is in line with Olson's argument and provides a theoretical support for the empirical findings obtained by Dayton-Johnson (1999), who shows that communities where the distribution of landholdings is unequal tend to choose water allocation rules that favour the rich. By contrast, when there exists sufficient complementarity between agents' efforts, the participation of both types is important for the realization of the collective good. In such a case, the incentive-based effect will prevail. This would explain the apparently contradicting result obtained by Bardhan (2000) in his large-scale analysis of small irrigation communities in South India, where a tendency was found for fairer rules in more unequal communities.

idiosincratic shocks. This, in turn, gives room to opportunistic behaviour by the parties - who might have an incentive to cheat about the amount of output being produced - and adds further difficulties to the possibility of contracting over output.

5 Technology of production of the collective good: Special cases

In this section, I formally analyze three special cases for the production technology of the collective good; that is: linear, Leontief and Cobb-Douglas production technology. Those correspond to the limit cases in which the parameter σ in equation (1) tends to: one, $(-\infty)$ and zero, respectively.

5.1 Perfect substitution

Consider the following production technology for Z:

$$Z = F(e_1, e_2) = e_1 + e_2 \tag{13}$$

As described in section 4.1, the individual optimization problem is as follows:

$$\max_{e_i \geq 0} \Pi_i = f(l_i, z_i(e_i, \overline{e}_j) - e_i$$

where $f(l_i, z_i) = (z_i)^{\alpha} (l_i)^{1-\alpha}$, and $z_i = \gamma_i Z$.

The FOC$_\text{s}$ for the above problem are given by:

$$\frac{\partial \Pi_i}{\partial e_i} = 0 \Rightarrow \frac{\partial f(\cdot)}{\partial z_i} \times \frac{\partial z_i}{\partial e_i} = 1 \qquad i = 1, 2$$

Agents' reaction functions can then be written as:

$$e_1(e_2) = \vartheta_1 - e_2$$

$$e_2(e_1) = \vartheta_2 - e_1$$

where: $\vartheta_1 \equiv \left[\alpha\gamma^{\alpha}\lambda^{(1-\alpha)}\right]^{1/(1-\alpha)}$ and $\vartheta_2 \equiv \left[\alpha(1-\gamma)^{\alpha}(1-\lambda)^{(1-\alpha)}\right]^{1/(1-\alpha)}$.

From the above expressions, it follows that – unless $(\vartheta_1 = \vartheta_2)$ – the Nash equilibrium of the simultaneous moves game in which farmers decide their optimal level of effort is such that only one farmer provides all the effort. This will be the farmer whose reaction function is associated with the highest ϑ_i. By comparing ϑ_1 and ϑ_2, the following condition can be obtained:

$$\vartheta_1 > \vartheta_2 \Leftrightarrow \gamma > \frac{\psi}{1+\psi} \tag{14}$$

where $\psi \equiv \left[\frac{1-\lambda}{\lambda}\right]^{(1-\alpha)/\alpha}$.

It can be easily observed that, for low degree of land inequality (i.e., $\lambda \to 0.5$) the threshold $\frac{\psi}{1+\psi}$ approaches 0.5; while for high degree of land inequality (i.e., $\lambda \to 1$), $\frac{\psi}{1+\psi}$ tends to zero. In the latter case (14) holds for any $\gamma > 0$.

Under condition (14), the large landowner (type 1) is the only one contributing a positive amount of maintanance effort. Formally, the individual optimal contributions are given by $(e_1^* = \vartheta_1; e_2^* = 0)$, and the total collective output produced in equilibrium is simply $Z^* = e_1^* = \vartheta_1$. In such a case, the optimal allocation rule is given by $\gamma = 1$.

This result is in line with Olson's argument that more inequality may favour the provision of collective goods. Olson's result, however, is implicitly based on the assumption that the richest agent is the one benefiting more from the collective good produced. In the proposed framework, this aspect is endogenous to the model and is formally represented by condition (14).

5.2 Perfect complementarity

Consider now the case in which agents' efforts are perfect complements in the production of Z. Formally:

$$Z = F(e_1, e_2) = \min\{e_1, e_2\} \tag{15}$$

As before, taking the contribution of the other agent as given, i maximizes his payoff with respect to e_i:

$$\max_{e_i \geq 0} \Pi_i = f(l_i, z_i(e_i, \overline{e}_j) - e_i$$

In order to determine the equilibrium solutions of the simultaneous-moves game in which agents decide their levels of maintenance effort, I will start from the following lemma:

Lemma 1 *It is never optimal for agent i to choose a level of effort $e_i > \overline{e}_j$.*

Proof. *Assume that $e_i > \overline{e}_j$ is optimal. Then, it must be: $\Pi_i(e_i, \overline{e}_j) > \Pi_i(\overline{e}_j, \overline{e}_j)$, where $\Pi_i(e_i, \overline{e}_j) = f(l_i, z_i(e_i, \overline{e}_j)) - e_i$, and $\Pi_i(\overline{e}_j, \overline{e}_j) = f(l_i, z_i(\overline{e}_j, \overline{e}_j)) - \overline{e}_j$. From the definition of $z_i = \gamma_i \times \min\{e_i, e_j\}$, we have: $z_i(e_i, \overline{e}_j) = z_i(\overline{e}_j, \overline{e}_j) = \gamma_i \times \overline{e}_j$, which implies $f(l_i, z_i(e_i, \overline{e}_j)) = f(l_i, z_i(\overline{e}_j, \overline{e}_j))$. Therefore for $e_i > \overline{e}_j$, $\Pi_i(e_i, \overline{e}_j)$ is always smaller than $\Pi_i(\overline{e}_j, \overline{e}_j)$. This contradicts the initial assumption that $e_i > \overline{e}_j$ is optimal.* ■

Similarly, it can be shown that $e_j > \overline{e}_i$ is never optimal for j. Therefore, both agents have no incentive to set their own contribution higher than their opponent's. Intuitively, this implies that, if an equilibrium exists, it will be such that both agents choose the same level of effort: $e_i = e_j = e$.

What is the (common) level of effort, e, that emerges in equilibrium? Consider the following 'unconstrained' maximization problem:

$$\max_{e} \Pi_i = f(l_i, z_i(e, e)) - e$$

where $z_i = \gamma_i Z$, and $Z = \min\{e_i, e_j\} = e$.

The FOC is given by:

$$\frac{\partial \Pi_i}{\partial e} = 0 \Rightarrow \frac{\partial f(\cdot)}{\partial z_i} \times \frac{\partial z_i}{\partial e} = 1$$

From the above condition the following result can be derived:

$$\widehat{e} = \left[\alpha \gamma_i^{\alpha} l_i^{(1-\alpha)}\right]^{1/(1-\alpha)} \tag{16}$$

(16) represents the maximum level of effort that an agent would choose if he were not constrained by the other agent's decision. By substituting for l_i and γ_i, the unconstrained optimal contributions for the two farmer types can be written respectively as follows:

$$\widehat{e}_1 = \left[\alpha \gamma^{\alpha} \lambda^{(1-\alpha)}\right]^{1/(1-\alpha)} = \vartheta_1$$

$$\widehat{e}_2 = \left[\alpha (1-\gamma)^{\alpha} (1-\lambda)^{(1-\alpha)}\right]^{1/(1-\alpha)} = \vartheta_2$$

I will now prove that any pair (e_1^*, e_2^*), with $e_1^* = e_2^* = e$, and $e \in [0, \min\{\vartheta_1, \vartheta_2\}]$ is a Nash equilibrium of the simultaneous-moves game in which agents independently decide their levels of effort.

To begin, note that both agents setting their levels of effort equal to $e = \min\{\vartheta_1, \vartheta_2\}$ is indeed a Nash equilibrium. On the one hand, from lemma 1, neither agent has an incentive to raise her investment because she will then produce the same amount of output at a higher cost. On the other hand, agents do not gain by lowering their effort. Both agents' profit functions are, indeed, strictly increasing in e within the interval $[0, \min\{\vartheta_1, \vartheta_2\}]$. The solution $e_1^* = e_2^* = \min\{\vartheta_1, \vartheta_2\}$ is not, however, the unique equilibrium of the game. Using similar arguments, it can be shown that any other pair $e_1^* = e_2^* = e$, with $0 \leq e < \min\{\vartheta_1, \vartheta_2\}$ is a Nash equilibrium. All that remains is to prove that in equilibrium agents will never set their investments at a level $e > \min\{\vartheta_1, \vartheta_2\}$. Suppose that $e_1 = e_2 = \overline{e}$, with $\overline{e} > \min\{\vartheta_1, \vartheta_2\}$. In this case, the agent with the lower ϑ has an incentive to deviate. Assume, for example, that $\vartheta_1 > \vartheta_2$ so that $\min\{\vartheta_1, \vartheta_2\} = \vartheta_2$. Then, by choosing $e_2 = \vartheta_2$, agent 2 can determine the size of the collective good $Z = \min\{e_1, e_2\}$ and maximize his own payoff. Moreover, according to lemma 1, it is never optimal for agent 1 to invest more than his opponent. Thus, $e_1 = e_2 = \overline{e}$, with $\overline{e} > \min\{\vartheta_1, \vartheta_2\}$ is not an equilibrium.

Finally, notice that among the set of equilibria identified above, $e_1^* = e_2^* = \min\{\vartheta_1, \vartheta_2\}$ is the Pareto-efficient equilibrium. Again, consider as an example the case in which $\vartheta_1 > \vartheta_2$ so that $\min\{\vartheta_1, \vartheta_2\} = \vartheta_2$. In such a case, the level of effort ϑ_2 represents the solution to agent 2's 'unconstrained' maximization problem. Moreover, $\Pi_1(e_1^* = e_2^* = \vartheta_2)$ is the highest payoff that agent 1 (the large land-owner) can obtain given that agent 2 (the small land-owner) will never invest more than $e_2 = \vartheta_2$.

From the above analysis, it follows that the total amount of the collective good produced in equilibrium varies within the following range:

$$Z^* = \min\{e_1^*, e_2^*\} = e^* \quad , \text{with } e^* \in [0, \min\{\vartheta_1, \vartheta_2\}]$$

As before, I will now focus on the Pareto-efficient equilibrium: $e_1^* = e_2^* = \min\{\vartheta_1, \vartheta_2\}$. From the definition of ϑ_1 and ϑ_2, it is straightforward to show that $Z^* = \min\{\vartheta_1, \vartheta_2\}$ is maximized when $\vartheta_1 = \vartheta_2$; that is, when $\gamma^* = \frac{\psi}{1+\psi}$, with $\psi \equiv \left[\frac{1-\lambda}{\lambda}\right]^{(1-\alpha)/\alpha}$. For $\lambda > 0.5$, as it was assumed in section 3, $\frac{\psi}{1+\psi} < 0.5$; that is, the optimal allocation scheme requires that more water is allocated to the small landowner. Perfect complementarity represents the limit case in which the only force at work is the 'incentive-based force' previously described.

5.3 Cobb-Douglas production technology

Finally, assume that the production technology for Z is well represented by a Cobb-Douglas production function with constant returns to scale. Formally:

$$Z = F(e_1, e_2) = e_1^{\sigma} e_2^{(1-\sigma)} \tag{17}$$

with $\sigma \in (0, 1)$.

Type 1's maximization problem can be written as follows:

$$\max_{e_1 \geq 0} \Pi_1 = (\gamma Z)^{\alpha} (\lambda)^{1-\alpha} - e_1$$

The FOC for the above problem is given by:

$$\frac{\partial \Pi_1}{\partial e_1} = 0 \Rightarrow \alpha \times \left[(\gamma)^{\alpha}(\lambda)^{1-\alpha}\right] \times (Z)^{\alpha-1} \times \frac{\partial Z}{\partial e_1} - 1 = 0 \tag{18}$$

From (17), the derivative of Z with respect to e_1 is:

$$\frac{\partial Z}{\partial e_1} = \sigma {e_1}^{(\sigma-1)} {e_2}^{(1-\sigma)} \tag{19}$$

By substituting (19) into (18) and solving with respect to e_1, the following reaction function for farmer type 1 can be derived:

$$e_1(e_2) = \left[\alpha\sigma\gamma^{\alpha}\lambda^{(1-\alpha)}e_2^{\alpha(1-\sigma)}\right]^{1/(1-\alpha\sigma)}$$

Similarly, from type 2's maximization problem we have:

$$e_2(e_1) = \left[\alpha(1-\sigma)(1-\gamma)^{\alpha}(1-\lambda)^{(1-\alpha)}e_1^{\alpha\sigma}\right]^{1/[1-\alpha(1-\sigma)]}$$

Solving the system of farmers' reaction functions, the following equilibrium levels of effort can be obtained:[7]

$$\left(e_1^* = g_1^{\left(\frac{1-\alpha(1-\sigma)}{1-\alpha}\right)} \times g_2^{\left(\frac{\alpha(1-\sigma)}{1-\alpha}\right)};\ e_2^* = g_1^{\left(\frac{\alpha\sigma}{1-\alpha}\right)} \times g_2^{\left(\frac{1-\alpha\sigma}{1-\alpha}\right)}\right) \tag{20}$$

where: $g_1 \equiv \alpha\sigma\gamma^{\alpha}\lambda^{(1-\alpha)}$, and $g_1 \equiv \alpha(1-\sigma)(1-\gamma)^{\alpha}(1-\lambda)^{(1-\alpha)}$.

The collective output produced in equilibrium is:

$$Z^* = (e_1^*)^{\sigma}(e_2^*)^{(1-\sigma)} = g_1^{\left(\frac{\sigma}{1-\alpha}\right)} \times g_2^{\left(\frac{1-\sigma}{1-\alpha}\right)} \tag{21}$$

The allocation scheme that maximizes the provision of the collective good is given by the rule γ that solves the following equation:

$$\frac{\partial Z^*}{\partial \gamma} = 0 \Rightarrow \left(\frac{1}{1-\alpha}\right) \times \left[g_1^{\left(\frac{\sigma}{1-\alpha}\right)} \times g_2^{\left(\frac{1-\sigma}{1-\alpha}\right)}\right] \times \left[\frac{\sigma}{\gamma} - \frac{(1-\sigma)}{1-\gamma}\right] = 0 \tag{22}$$

Notice that (22) is not well defined for $\gamma = 0$ and $\gamma = 1$. In what follows, I assume $\gamma \in (0,1)$. Under this assumption, the firt term in (22) is strictly positive since the parameters α, σ and λ vary within the interval $(0,1)$. Condition (22)

[7]It can be shown that there exists another equilibrium which involves $e_1 = e_2 = 0$ and, consequently, $Z^* = 0$. As in section 4.1, this will be ignored. The analysis will focus, instead, on the Pareto-efficient equilibrium, which is given by (20).

can, therefore, be simplified as follows:

$$\frac{\sigma}{\gamma} - \frac{(1-\sigma)}{1-\gamma} = 0 \tag{23}$$

By solving (23) with respect to γ, we have: $\gamma^* = \sigma$; that is, the optimal allocation rule depends only on the marginal productivity of agents' effort in the production of the collective good. The Cobb-Douglas case is a very special case. With that production technology, the two forces identified in section 4.3 – efficiency-based and incentive-based force – perfectly offset each other. As a result, γ^* turns out to be *independent* of the degree of inequality in land-holding.

6 Conclusions

This paper focused on collective action problems associated with the management of water resources at the local level. Within this context, it investigated the interaction between economic inequality and water allocation rules through the joint incentives-to-cooperate that those generate.

From the analysis, two types of forces have emerged which affect the distribution of the collective good (water) in opposite directions. The first force is an 'efficiency-based force' and pushes in favour to the agent whose marginal value of water is higher. From the complementarity between land and water in production, this is represented by the large landowner. The second force is an 'incentive-based force'. The underlying idea in this case is to use water as an incentive mechanism to 'correct' potential distortions created by the unequal distribution of land. The previously mentioned complementarity between land and water implies that the *intrinsic* incentives to exert maintenance effort are lower for the agent endowed with a smaller amount of land. Following the logic behind the incentive-based force, this agent should therefore be allocated a relatively larger amount of water.

The trade-off between those two forces determines the nature of the relationship between inequality in land holding and optimal water allocation rule. The way in which such trade-off resolves depends, in turn, on the strategic importance of agents' contributions in the realization of the collective good.

The framework proposed in this paper then offers a theoretical explanation for the somewhat mixed evidence from the theoretical and empirical literature. For sufficiently high degrees of substitutability between agents' efforts, the model predicts that the efficiency-based force tends to prevail. As a result, the optimal allocation rule is such that a larger share of water is assigned to the big landowner and the share of the big landowner increases with the degree of inequality in land holding. Such prediction is in line with Olson's argument − namely, higher inequality by enhancing the interest of the richest agent has the effect of increasing the amount of the collective good provided − and offers a theoretical support for those studies which found a positive correlation between the degree of inequality in landholding and the choice of water allocation rules that favour the rich. By contrast, when there exists sufficient complementarity between agents' efforts, the incentive-based effect will prevail. This would explain the apparently contradicting result obtained by Bardhan (2000) and Khwaja (2001), who find that more unequal communities tend to choose 'fairer' rules.

Appendix

In the context of the present analysis, the 'optimal' allocation rule (γ^*) is defined as the rule that maximizes the provision of the collective output in equilibrium (Z^*). Formally, γ^* is the solution to the following maximization problem:

$$\max_{0\leq\gamma\leq 1} Z^* = \phi \times \left\{ \left[(\gamma)^{\alpha}(\lambda)^{1-\alpha}\right]^{\beta} + \left[(1-\gamma)^{\alpha}(1-\lambda)^{1-\alpha}\right]^{\beta} \right\}^{\mu} \qquad (a.1)$$

where $\phi \equiv (\alpha)^{\frac{1}{1-\alpha}}$, $\beta \equiv \frac{\sigma}{1-\sigma}$ and $\mu \equiv \frac{1-\sigma}{\sigma(1-\alpha)}$.

By substituting for $\beta = \frac{\sigma}{1-\sigma}$, the FOC for the above problem can be expressed as follows:

$$(\gamma)^{\left(\frac{\alpha\sigma}{1-\sigma}-1\right)} \times (\lambda)^{\frac{(1-\alpha)\sigma}{1-\sigma}} - (1-\gamma)^{\left(\frac{\alpha\sigma}{1-\sigma}-1\right)} \times (1-\lambda)^{\frac{(1-\alpha)\sigma}{1-\sigma}} = 0 \qquad (a.2)$$

Condition $(a.2)$ is implicitly *assuming* that the solution to $(a.1)$ is *interior* to the interval [0,1]. However, the optimum may well be a corner solution. In other words, it may well be: $\gamma^* = 1$ and/or $\gamma^* = 0$. In this appendix, I will analyze whether and under what conditions those limit values for γ could represent a solution to $(a.1)$.

Consider first $\gamma = 1$. This will be an optimum if $\frac{\partial Z^*}{\partial \gamma} > 0$ when γ approaches one. In that case, Z^* would still be increasing in γ at the value $\gamma = 1$.

Notice that, when the exponent of $(1-\gamma)$ in equation $(a.2)$ is negative, it cannot be true that $\gamma^* = 1$, because:

$$\frac{\alpha\sigma}{1-\sigma} - 1 < 0 \Rightarrow \lim_{\gamma\to 1}(1-\gamma)^{\left(\frac{\alpha\sigma}{1-\sigma}-1\right)} = \lim_{\gamma\to 1}\frac{1}{(1-\gamma)^{\left(1-\frac{\alpha\sigma}{1-\sigma}\right)}} = \infty$$

Hence,

$$\lim_{\gamma\to 1}\left[\frac{1}{(\gamma)^{\left(1-\frac{\alpha\sigma}{1-\sigma}\right)}}\times(\lambda)^{\frac{(1-\alpha)\sigma}{1-\sigma}}-\frac{1}{(1-\gamma)^{\left(1-\frac{\alpha\sigma}{1-\sigma}\right)}}\times(1-\lambda)^{\frac{(1-\alpha)\sigma}{1-\sigma}}\right]=-\infty$$

violating the FOC.

It can be easily shown that $\left(\frac{\alpha\sigma}{1-\sigma}-1\right)$ is negative for $\sigma<\frac{1}{1+\alpha}$.[8] Within this range of parameter values the solution to $(a.1)$ is, therefore, given by equation (11).

When $\sigma>\frac{1}{1+\alpha}$, then:

$$\frac{\alpha\sigma}{1-\sigma}-1>0\Rightarrow\lim_{\gamma\to 1}(1-\gamma)^{\left(\frac{\alpha\sigma}{1-\sigma}-1\right)}=0$$

Therefore:

$$\lim_{\gamma\to 1}\left[(\gamma)^{\left(1-\frac{\alpha\sigma}{1-\sigma}\right)}\times(\lambda)^{\frac{(1-\alpha)\sigma}{1-\sigma}}-(1-\gamma)^{\left(1-\frac{\alpha\sigma}{1-\sigma}\right)}\times(1-\lambda)^{\frac{(1-\alpha)\sigma}{1-\sigma}}\right]=(\lambda)^{\frac{(1-\alpha)\sigma}{1-\sigma}}>0$$

which, in turn, implies that for any $\sigma>\frac{1}{1+\alpha}$, the optimal allocation rule is $\gamma^*=1$.

Consider now the limit case $\gamma=0$. It is easy to prove that this can never be a global maximum within the compact set [0,1]. Let:

$$Z_0\equiv Z^*(\gamma=0)=(\alpha)^{\frac{1}{1-\alpha}}\times\left[(1-\lambda)^{\frac{(1-\alpha)\sigma}{1-\sigma}}\right]^{\frac{1-\sigma}{\sigma(1-\alpha)}}=(\alpha)^{\frac{1}{1-\alpha}}\times(1-\lambda)$$

and

$$Z_1\equiv Z^*(\gamma=1)=(\alpha)^{\frac{1}{1-\alpha}}\times\left[(\lambda)^{\frac{(1-\alpha)\sigma}{1-\sigma}}\right]^{\frac{1-\sigma}{\sigma(1-\alpha)}}=(\alpha)^{\frac{1}{1-\alpha}}\times\lambda$$

[8] Remember that the parameter σ varies within the interval $(-\infty,1)$.

For $\lambda > 0.5$ – as it was assumed in section 3 – it is straightforward to observe that $Z_0 < Z_1$. Then, $\gamma = 0$ cannot be a global maximum for $\gamma \in [0, 1]$, since there exists at least one value of $\gamma \in [0, 1]$ such that $Z^*(\gamma) > Z_0$.

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