Cooperative Institutions for Sustainable Management of Common Pool Resources

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Abstract

Beneficiaries of common pool resources (CPRs) may select available non-cooperative and regulatory exogenous institutions for managing the resource, as well as cooperative management institutions. All these institutions may increase the long-term gains, prolong the life of the resource, and help to escape the tragedy of the commons’ trap. Cooperative game theory approaches can serve as the backbone of cooperative CPR management institutions. This paper formulates and applies several commonly used cooperative game theoretic solution concepts, namely the Core, Nash-Harsanyi, Shapley, and Nucleolus. Through a numerical groundwater example, we show how CPR users can share the gains obtained from cooperation in a fair and efficient manner, based on these cooperative solution concepts (management institutions). Although based on their fairness rationales, various cooperative management institutions may suggest different allocations that are potentially acceptable by the users, these allocation solutions may not be stable as some users may find them unfair. This paper discusses how different methods, such as application of the plurality rule and power index, stability index, and propensity to disrupt concepts, can help identify the most stable and likely solutions for enforcing cooperation among the CPR beneficiaries.

Keywords: Common pool resources (CPR), management, exploitation, groundwater, cooperation, game theory, policy, institutions, sustainable development, modeling, optimization, Core, Nash-Harsanyi, Shapley, Nucleolus, power, stability, propensity to disrupt, plurality rule.

1. Introduction

It is not uncommon in practice to face situations in which beneficiaries are required to reduce uses of a scarce resource, e.g., fishery (Munro Gordon 2009) and water during a drought (Zilberman et al. 1998), or reducing production levels of a public bad. e.g., greenhouse gas emissions (Cazorla and Toman 2000), in order to increase their long-term benefits. The overarching commonality across such situations is the fact that the loss of immediate benefits and the gain of long-term benefits should be shared among the beneficiaries. In this paper, various cooperative institutions for management and sharing long-term benefits of Common Pool Resources (CPRs) are introduced and the effectiveness of each institution is explored.

A CPR is defined as a resource system whose yield is subtractable and its characteristics make the exclusion of potential appropriators or limitation of the existing beneficiaries’ rights nontrivial, but not necessarily impossible (Ostrom et al. 1994). Not only do CPRs include the natural resources such as water, forests, pastures, oil, gas, fish, land, air, etc., but also the human-

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made resources that provide service and benefits (e.g., radio frequency spectra, reservoirs, irrigation infrastructure, wastewater treatment facilities, parks, roads, and other public infrastructures).

Early works argued that in a joint usage of CPRs, parties are always driven by immutable logic of more withdrawal from (or less investment in) the CPR than what is optimal to sustain the system (Gardner et al. 1990). Scholars with such a belief expected all CPR users to show non-cooperative and competitive behaviors that make the tragedy of the commons (Gordon 1954, Hardin 1968) inevitable. The argument was that within a CPR dilemma, parties always base their actions on individual rationality (as opposed to rational group choices), which negatively affect all users eventually (Ostrom 2010). Within this school of thought, non-cooperative game theory – the Prisoner’s Dilemma game, and the well-known Nash non-cooperative stability definition (solution concept) (Nash 1951) – provided a reasonable framework for illustrating the individualistic behavior of the parties to a CPR and exploring the resulting tragic outcomes (Madani 2010). To overcome the tragedy of the commons and avoid the inferior outcomes, two basic solutions have been suggested based on the complete rational decision-maker paradigm: external regulations of extraction and appropriation of ownership rights (Castillo and Saysel 2005).

Elinor Ostrom (1990) challenged Hardin’s pessimistic tragedy of the commons hypothesis, suggesting the possibility of existence of cooperative optimal outcomes for CPR problems, based on extensive field studies, real-world evidences, and lab experiments. Ostrom argued that the tragic outcomes are not necessarily inevitable for CPR problems, as CPR users do not always follow Nash strategies (Ostrom et al. 1994, Fehr and Fischbacher 2002), which are merely based on individual rationality (Ostrom 1998). Finding the results of simple one-shot Nash solution-based CPR models and CPR games with finite repetitions solved by backward induction unreliable, Ostrom (1998) recognized the need for expanding the range of rational choice models to be used as a foundation for studying social dilemmas and collective actions. In her view, most previous models had failed to capture the reality of a decision-making process, which might be affected by different factors such as communication, trust, learning, and norms. As discussed by others (Selbirak 1994, Madani and Hipel in press) the Nash non-cooperative solution concept reflects the behavior of a risk-averse myopic player and fails to predict the accurate outcomes of real conflict situations, due to restricted assumptions underlying models of players’ rationality. Thus, to improve the reliability of non-cooperative CPR models, different modifications to the conventional non-cooperative game theory analyses have been suggested, including: developing structures other than Prisoner’s Dilemma for illustrating non-cooperative CPR games (Taylor 1987, Gardner et al. 1990, Sandler 1992, Madani 2010, Madani and Lund 2010), introducing uncertainties or incomplete information in the game (Ostrom 1998), studying CPR games as infinite repeated games in which players take mixed strategies (Ostrom et al. 1994); defining CPR problems in a dynamic game context (Negri 1989); and analyzing games using solution concepts (stability definitions) other than the Nash solution concept, which better reflect the decision makers’ characteristics and behavior during the decision-making process (Madani and Hipel in press, Madani and Lund in press). The results of the improved game models are consistent with the findings of Ostrom (1990) and Ostrom et al. (1994), which were based on both real cases and lab experiments. The results suggest that besides external solutions and appropriating exploitation rights to avoid tragic outcomes, the CPR users have the potential of escaping the resource depletion trap (Castillo and Saysel 2005) through developing cooperative
institutions and collective actions that can enforce sustainable exploitation and development of
the resource.

Madani and Dinar (2010) classified the available institutions for managing CPRs into three
categories, namely the non-cooperative, exogenous regulatory, and cooperative institutions.
Under the non-cooperative institutions, beneficiaries may either adopt myopic ignorant plans in
which the long-term effects of exploitation plans and the externalities are ignored, or develop
plans that are not myopic and/or ignorant. Madani and Dinar (2010) show that non-cooperative
institutions do not necessarily result in tragic outcomes. Rather, sustainable CPRs may be
achieved even under these institutions. Exogenous institutions include interventions by
regulators (e.g., exploitation regulation, ownership rights assignment, and enforcement of
different CPR governing rules) to overcome overexploitation of the resources and achieve
sustainable CPRs (Madani and Dinar 2011). Under cooperative institutions, beneficiaries can
base actions on group rationality and develop exploitation plans that increase the long-term gains
for all users and provide them with sustainable benefits.

Due to complexity of CPR problems and variability of their conditions, selection of an optimal
management institution that provides maximum benefits and enforces sustainability is nearly
impossible (Madani and Dinar 2010). Instead, the optimum CPR management institution should
be selected considering the specific conditions of the problem. For instance, even though
cooperative institutions may provide the highest benefits to the users, the complexity of the
arrangements (Faysse 2005) (e.g., transaction costs) may discourage parties from applying them
in an actual CPR management framework. Nevertheless, an in-depth study of all classes of CPR
management institutions is essential to enable adoption of the most appropriate type of
institution, given the conditions of the problem. Our previous works provide comprehensive
studies of non-cooperative CPR management institutions (Madani and Dinar 2010) as well as
exogenous CPR management institutions (Madani and Dinar 2011). Thus, this paper focuses on
the third category of CPR management institutions – cooperative institutions – to clarify how
they can provide a framework for achieving sustainable CPRs.

In fact, cooperative CPR management institutions provide acceptable solutions, by not only
prolonging the CPR’s lifetime through sustainable and efficient exploitation, but also by
satisfying the beneficiaries’ equity concerns. CPRs can remain sustainable or may be brought
back to a sustainable stage through contributions of stakeholders. It is possible to estimate the
total required contribution of all parties to keep the CPR at a sustainable level. However,
developing a fair and efficient scheme for allocating the achieved benefits among the parties is
challenging, as often the CPR benefits are not equally distributed among the users.

In this paper, various cooperative game theoretic solution methods are introduced, which can be
adopted as cooperative CPR management institutions to estimate the fair shares of the
beneficiaries when CPR is exploited in a sustainable cooperative fashion. These solution
methods are appropriate for problems in which parties have higher levels of foresight and
consider the long-term benefits of cooperation as application of these methods, because long-
term CPR planning and management requires reliable information about the future.

In the next section, various cooperative CPR management institutions are introduced and
formulated. In section 3, a groundwater exploitation problem is introduced and modeled. In
section 4, the problem is solved through a social planning approach and the Core of the problem
is calculated. Cooperative management institutions are applied to the groundwater exploitation
problem in section 5, and the results are compared and discussed. In section 6, different methods for evaluating the acceptability of the proposed solutions are introduced, and the stability of the solutions are examined. The paper concludes in section 7, with policy implications for sustainable management of CPRs in cooperative frameworks.

2. Cooperative CPR management institutions

A CPR exploitation problem has been defined by Madani and Dinar (2010) as a pair \((e, R)\) where \(e\) represents the vector of beneficiaries’ actual exploitations and \(R\) is the total available (remaining) amount of CPR to be exploited such that for beneficiaries \(i=1, 2, ..., n\): \(e= (e_1, e_2, ..., e_n) \geq 0\) and \(\sum_{i=1}^{n} e_i \leq R\). In this problem the beneficiaries’ actual utility is defined as an \(n\)-tuple \(u= (u_1(e_1), u_2(e_2), ..., u_n(e_n))\) where \(u_i(e_i)\) is the utility of CPR beneficiary \(i\) from \(e_i\).

Beneficiaries’ expected utility is defined as an \(n\)-tuple \(E_u= (E_{uu_1(e_1)}, E_{uu_2(e_2)}, ..., E_{uu_n(e_n)})\) where \(E_{uu_i}\) is the expected amount of exploitation from \(R\) and \(E_{uu_i(e_i)}\) is the expected utility of beneficiary \(i\) from \(ee_i\), such that \(\sum_{i=1}^{n} ee_i\) is greater or smaller than \(R\) and \(e_i \leq ee_i\) and \(u_i(e_i) \leq E_{uu_i(e_i)}\) due to the exploitation externalities which lower the availability of the resource to the beneficiaries.

An important characteristic of cooperative CPR management is the perfect information on the part of each beneficiary about the decisions and plans of other beneficiaries. In cooperative environments, CPR users may benefit from adoption of various cooperative game theoretic solutions, which result in higher gains for all beneficiaries (\(u_i^* \geq u_i\), where \(u_i^*\) and \(u_i\) are the utility of CPR beneficiary \(i\) under cooperation and under the status quo, respectively). When additional benefit is achievable through cooperation, the main challenge is to fairly and efficiently allocate it among the cooperating parties. Such a challenge can be addressed through allocating the gains from cooperation using cooperative game theory concepts. An appropriate allocation under cooperation should satisfy the following constraints:

\[
\begin{align*}
&u_i^* \geq u_i \quad \forall i \in N & \text{(individual rationality condition)} \\
&\sum_{i \in S} u_i^* \geq v(s) \quad \forall s \in S, S \subseteq N & \text{(group rationality condition)} \\
&\sum_{i \in N} u_i^* = v(N) & \text{(efficiency condition)}
\end{align*}
\]

where for \(N=\{1, 2, ..., n\}\): \(s\) is a feasible coalition (group of collaborating beneficiaries) in the game, such that \(\{i\} (i= 1, 2, ..., n)\) are the non-cooperative coalitions with single beneficiaries and \(N\) is the grand coalition which includes all beneficiaries; \(S\) is the set of all feasible coalitions (all possible groups of beneficiaries) in the game; \(v(s)\) is the value of coalition \(s\) or the total obtainable benefits by the members of coalition \(s\); and \(v(N)\) is the value of the grand coalition.

Each of the above equations reflects one important condition, which should be satisfied by the final cooperative allocation solution. Equation 1 enforces the individual rationality condition, requiring an allocation under cooperation to each beneficiary to be greater than what can be gained individually under no cooperation. Equation 2 fulfills the group rationality condition, requiring the sum of cooperative allocations to any group of beneficiaries to be greater that the total obtainable benefits under any coalition that includes the same beneficiaries. Equation 3 enforces the joint efficiency condition, requiring that the total obtainable benefits under the grand
coalition to be fully allocated to the members of that coalition. The system of Equations 1 to 3 establishes what is known as the Core of the cooperative game (Gillies 1959) – a set of game allocation gains that is not dominated by any other allocation set. The Core of a cooperative CPR management problem provides valuable insights by suggesting the range of acceptable solutions for each CPR beneficiary. The Core includes an infinite number of cooperative solutions and provides a bound for the maximum benefit allocation that each beneficiary may request under cooperation. The Core is a set that can contain more than one benefit allocation solution. Satisfying the Core conditions (Equations 1 to 3) for an allocation solution is a necessary condition for its acceptability by the players. Therefore, solutions not included in the Core are also not acceptable and not stable (Shapley 1971). However, they may not be stable, as some users may find them unfair. Therefore, different methods are suggested to find the most stable and likely cooperative outcomes.

Below, we formulate cooperative CPR management institutions, based on three cooperative game theory concepts that provide solutions in the Core and are potentially acceptable by the beneficiaries if the Core is not empty.

2.1 Nash-Harsanyi institution. When obtaining extra benefits is possible through cooperation, CPR beneficiaries can apply the Nash-Harsanyi cooperative solution (Harsanyi 1959, 1963) – an extension of Nash bargaining solution for a two-player bargaining game (Nash 1953). To find the Pareto-optimal benefit allocation, use the following mathematical model:

\[
\Omega = \max \prod_{i=1}^{n} (u_i^* - u_i) \tag{4}
\]

subject to the core conditions (Equations 1 to 3), where \( u_i^* - u_i \) is the gain of beneficiary \( i \) from cooperation and \( \sum_{i=1}^{n} (u_i^* - u_i) \) is the total benefits obtained through cooperation by the group of players. The Nash-Harsanyi institution provides a unique allocation solution that is included in the Core (if it is not empty) by maximizing the product of the grand coalition members’ obtained benefits from cooperation. This is subject to the Core conditions (Equations 1-3), with respect to the Nash axioms (Nash 1953). Example applications of the Nash-Harsanyi bargaining solution in the water resources context include Dinar et al. (1986), Dinar and Howitt (1997), Dinar (2001), and Madani (2011) among others.

2.2 Shapley institution. Allocation based on the Shapley solution (Shapley 1953) is another method for fair and efficient sharing of the obtained benefits under cooperation. Under this institution, allocations are determined based on the weighted average of the beneficiaries’ contributions to all possible coalitions and sequences (Shapley 1953), based on the following equation:

\[
u^* = \sum_{S \subseteq N \atop i \in S} \frac{(n-|S|)!(|S|-1)!}{n!} (v(s) - v(s-\{i\})) \tag{5}\]

where for \( \forall i \in N : |S| \) is the number of members of coalition \( S \), and \( n \) is the total number of beneficiaries in the allocation game. The Shapley solution is a unique solution that is in the Core of convex games. Example applications of the Shapley concept in the water resources literature include Young et al. (1982), Dinar et al. (1992), Lejano and Davos (1995), Loehman (1995), and Dinar and Howitt (1997) among others.
2.3 Nucleolus institution: The CPR beneficiaries can allocate the obtained benefits through cooperation based on the Nucleolus solution (Schmeidler 1969), which minimizes the worst inequity or dissatisfaction of the most dissatisfied coalition. The Nucleolus of the benefit allocation game can be determined by finding \( \varepsilon \) through the following optimization model:

\[
\text{max } \varepsilon \tag{6}
\]

subject to

\[
\varepsilon \leq \sum_{i \in s} u_i - u(s) \quad \forall s \in S, S \subseteq N \tag{7}
\]

Equation 3

where \( \varepsilon \) is the maximum tax imposed on all coalitions to keep them in the core. Solving the above mathematical model provides a fair and efficient allocation of benefits to the CPR, based on the Nucleolus fairness principle (Schmeidler 1969). The Nucleolus allocation is a single solution that is always in the Core, if the Core is non-empty. Example applications of the Nucleolus solution in water resources management include Suzuki and Nakayama (1976), Kilgour et al. (1988), Lejano and Davos (1995), Lehmam (1995), and Dinar and Howitt (1997) among others.

We explain how the introduced cooperative management institutions\(^2\) can be applied in practice to CPR management problems by presenting a groundwater problem in the next section.

3. Groundwater exploitation problem

Constituting 98% of total liquid freshwater of the earth, providing 50% of potable water supplies, satisfying 40% of the demand of self-supplied industry, and supplying 20% of water use in irrigation (UN/WWAP 2003), make groundwater one of the most precious natural CPRs. The current rate of global groundwater withdrawals — about 750-800 km\(^3\) per year (Shah et al. 2000) or about a quarter of total global water withdrawals (Shah et al. 2004) — which is in excess of natural groundwater recharge rate, have depleted groundwater resources. This has resulted in declining water tables, decreasing yields of wells, increasing pumping costs, competitive deepening of wells, land subsidence, loss of wetlands and flowing springs and rivers, salt water intrusion and other salinity problems, water quality degradation, and damaging aquatic ecosystems (Konikow and Kendy 2005, Villholth 2006). Such negative effects are common in major regions of North Africa, the Middle East, South and Central Asia, North China, North America, and Australia (Konikow and Kendy 2005). While the value of this resource and the dramatic economic benefits are known, the complexity in regulating and monitoring groundwater withdrawals have made sustainable management of this resource very challenging, making groundwater one of the most studied CPRs in the literature (Gisser 1980, Worthington et al. 1985, Blomquist 1992, Provencher and Burt 1993, Gardner et al. 1997, Burke et al. 1999, Chebaane et al. 2004, Kountouri 2004, Loaiciga 2004, Wegerich 2006, Ross and Martinez-Santos 2009). The groundwater exploitation problem introduced by Madani and Dinar (2010) is presented briefly for application of cooperative CPR management institutions and comparison of the obtained results under the cooperative management institutions with those obtained under the

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\(^2\) The cooperative solution concepts that can be used for CPR management are not limited to the three methods introduced here. There are other methods available in the game theory literature, e.g., \( \tau \)-value (Tijs 1981), Kalai–Smorodinski solution (Kalai and Smorodinsky 1975), Kernel (Davis and Maschler 1965) among others, which can be applied in a similar manner to develop cooperative solutions for CPR problems.
non-cooperative and exogenous groundwater management institutions by Madani and Dinar (2010) and (2011), respectively. The groundwater exploitation problem is mathematically formulated as (more details about the model can be found in Madani and Dinar (2010)):

\[ C_r = (us + v + d_{w, \ldots})Q \quad (8) \]
\[ C = C_r + C_{tech} + C_{other, x} \quad (9) \]
\[ C_{other, x} = i.l^2 + j.l + k_x \quad (10) \]
\[ Y_x = (p.l^2 + q.l)Q_x \quad (11) \]
\[ R = \sum_x z_Y \quad (12) \]
\[ P = R - C \quad (13) \]
\[ Z = \int_0^H Pe^{-\beta t} dh \quad (14) \]

where \( C_r \) is the groundwater pumping cost; \( Q \) is the total well discharge; \( s \) is the groundwater drawdown, resulting from \( Q \); \( h \) is time step; \( d_{w,1} \) is the well water depth in the at the end of previous time step (\( h-1 \)); \( u \) and \( v \) are cost parameters; \( C_{tech} \) is a one-time initial investment for irrigation technologies, represented by the annual-equivalent cost; \( C_{other, x} \) is the cost of seeds, fertilizer, planting, harvesting, etc.; \( C \) is the total cost; \( l_x \) is the area under irrigation for growing crop \( x \); \( i_x, j_x, \) and \( k_x \) are cost parameters which depend on the crop type \( (x) \); \( Q_x \) is the amount of water used for irrigation of crop \( x \); \( Y_x \) is the total yield of crop \( x \); \( p_x \) is a yield parameter which depends on the crop type \( (x) \); \( q_x \) is a yield parameter which depends on the crop type \( (x) \); \( R \) is the revenue gained through selling crops at the end of the growing season; \( z_x \) is the price per weight unit of the crop \( x \); \( \beta \) is time-step dependent discount rate; \( P \) is farmer’s profit in a given time step; \( Z \) is the total present value of farmer’s profit; and \( H \) is the length of the planning horizon.

The groundwater drawdown in a single well with discharge of \( Q \) during time \( t \) at distance \( \lambda \) from the center of a well can be approximated, using Equation 15 (Loaiciga 2004). Equation 15 varies by \( \lambda \) and given \( \lambda \), aquifer transmissivity \( (T) \), and storativity, coefficients \( a \) and \( b \) can be estimated by regression of this equation against the predicted drawdown through the Theis equation for groundwater drawdown (Theis 1935):

\[ s = \frac{Q}{4\pi T} (a \cdot \ln t + b) \quad \forall \lambda \quad (15) \]

When multiple \( (n) \) wells are present, Equation 15 fails to capture the mutual effects of extracted groundwater from the neighboring wells (externalities). In that case the actual drawdown can be estimated using Equation 16 (Loaiciga 2004). This equation also varies by \( \lambda_{ij} \) and coefficients \( a_{ii}, b_{ii}, a_{ij}, \) and \( b_{ij} \) depend on the relative locations of other wells with respect to well \( i \).

\[ s_i = \frac{Q}{4\pi T} (a_i \ln t + b_i) + \sum_{j \neq i} \frac{Q}{4\pi T} (a_j \ln t + b_j) \quad \forall \lambda_{ij} \quad (16) \]

In estimating the drawdown, using Equation 15 or 16, the net well discharges should be used which can be calculated using the following equation:

\[ Q_{c, net} = Q_c - (Q_{c, r} + \Theta Q_c + \sum_{j \neq i} \omega_{ij} Q_j) + Qe. \quad (17) \]
where $Q_i$ is the pumped discharge of well $i$; $Q_{i,r}$ is the natural recharge of well $i$; $\theta_i$ is the ratio of return flow from water use on farm $i$ to well $i$; $\omega_{i,j}$ is the ratio of return flow from water use on a farm $j$ to well $i$; and $Q_{e_i}$ is the evaporative losses of well $i$.

Madani and Dinar (2010) developed a numerical example to use the presented model under non-cooperative CPR management institutions. The same numerical example was used by Madani and Dinar (2011) to examine the performance of regulatory exogenous CPR management institution. Here, we use the same numerical example as a benchmark for comparing the performance of different cooperative institutions for managing CPRs. The problem includes three farmers, located on neighboring farms with different areas, with lot A being the largest and lot C being the smallest. Each farmer operates one well ($i=A, B, C$). The wells have different initial water depths (or pumping costs) due to the slope of the farms, with well A having the maximum water depth and well C having the minimum water depth. Each farmer can choose from two crop options. Tables 1, 2, and 3, respectively, present the values of farmer-dependent, crop-dependent, and independent parameters of the numerical example.

To underline the value of the introduced cooperative CPR management institutions, these institutions are applied next to the numerical example.

4. The social planner solution

Before estimating the fair and efficient shares of the gains to the beneficiaries under cooperative management of a CPR, there is a need to determine the total obtainable benefit from cooperative management of the CPR during the planning horizon. That can be done based on the social planner solution which maximizes the total benefit received by the beneficiaries from the CPR without a concern about how to distribute the obtained benefits among the beneficiaries. The social planner solution for the numerical groundwater example can be found based on the following mathematical model:

$$\text{Max} \sum_{i=A,B,C} Z_{i} \quad (18)$$

subject to

Equations 8-14
Equations 16-17

The maximum obtainable benefit for the entire group of users, determined by the above problem, needs to be allocated among the individual members of the group, based on the introduced cooperative game theory solution concepts. Cooperative Game Theory solutions are expected to meet the fairness and efficiency conditions (equations 1-3). Table 4 presents the shares of each beneficiary and the total obtainable benefit from the CPR during the 50-year planning horizon of the example, calculated based on the social planner model (Equation 18 and 8-14). The results under the social planner solution suggest that the maximum benefit for the three farmers is obtained when only Farmer A farms on his land. In fact, the model suggests that Farmers B and C do not farm and do not extract water from their wells, so the externalities’ effects are minimized. Therefore, the water level in Well A is only affected by the amount of water exploitation from this well alone. Although Farmer A is dealing with the highest vertical pumping depth (or the highest pumping costs), having the largest land and economies of scale

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3 We assume that the users share the net present value of the benefits from the entire planning horizon and not annually.
allows him to offset the pumping costs and gain the highest possible benefit for the system.

Under the transferrable utility assumption (side payments), the only challenge is to suggest how the three farmers can share the maximum obtainable benefits in a fair and efficient manner. To be fair and efficient, the suggested allocation of the joint benefits should be in the computed Core. The boundaries of the Core can be calculated based on Equations 1-3. To do that, we apply the social planner solution to all possible coalitions. Table 5 presents the value of possible coalitions with at least two members. To calculate the value of coalitions with two members, based on the social planner solution, two social planner models were developed. One model includes the two farmers participating in the coalition and the other includes the one that is not cooperating. The two models are then solved simultaneously to estimate the gains\(^4\). By doing this, it is explicitly assumed that the non-cooperating farmer develops his exploitation plan for the whole planning horizon at the beginning, based on Equation 18 as done in Loaiciga (2004). This type of planning matches the characteristics of the “variable ignorant non-myopic management”\(^5\), used in non-cooperative environments (Madani and Dinar 2010).

Since non-cooperating farmers may adopt different management institutions for planning their exploitation plans, it is assumed that coalitions with one member can have different values, based on the non-cooperative management institution used by the only member of the coalition. The values of one-member coalitions are given in Table 6, based on the work of Madani and Dinar (2010). Comparing the values in the last row of this table with the social planner solution of the problem (Table 4) shows that depending on the non-cooperative management institution used by the farmers, cooperation of three farmers can result in an extra benefit of $898,594 to $2,990,698, which should be allocated to the three farmers, based on the introduced cooperative management institutions.

The values given in Tables 5 and 6 allow calculating the boundaries of the Core, based on Equations 1-3, to find the farmers’ preference orders over the possible cooperative solutions. Using an example, the procedure for finding the boundaries of the Core and calculating the extreme points of the Core are illustrated in Appendix A. Table 7 indicates the minimum and maximum expected benefits of the three farmers when they use various types of non-cooperative management institutions in the status quo (under non-cooperation). The results in Table 7 indicate that as farmers become less myopic by replacing their short-term plans with long-term ones, and less ignorant by developing exploitation plans that consider the externalities, the solution space (Core) becomes smaller. This can be explained by the fact that the incremental benefit of cooperation decreases as farmers get smarter and more considerate.

5. Cooperative groundwater management results

The results based on the social planner solution suggest that cooperative groundwater

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\(^4\) Simultaneous solving of the two models allows capturing the externalities through Equations 16 and 17, which estimate the actual drawdowns in the wells of the cooperating and non-cooperating farmers.

\(^5\) Here, we are explicitly assuming that there is a public choice mechanism leading to agreement over development of the exploitation management plan using the same method. Since for the grand coalition (three farmers as a group) the social planner solution is developed based on the characteristics of the “variable ignorant non-myopic management,” the same principles are used to estimate the values of smaller coalitions. Nevertheless, when no party is willing to cooperate, they are allowed to adopt different non-cooperative management institutions. Perhaps future studies should consider the cases in which coalitions smaller than the grand coalition may adopt different management institutions for planning their exploitations.
management institution can provide the highest benefit to the farmers in comparison with non-cooperative and exogenous groundwater management institutions. Results of Madani and Dinar (2010) indicate that within a non-cooperative management framework, farmers can increase their total gain up to 149% by replacing myopic ignorant exploitation plans with non-myopic smart exploitation plans. Madani and Dinar (2011) found that by interference of a regulator through exogenous groundwater management institutions, the total gain of the myopic ignorant farmers may rise by up to 138%. This indicates that long-term planning and consideration of the externalities by the farmers may be more efficient than interference of the regulators. Here, the results based on the social planner solution show that through cooperation the total gain of the non-cooperating farmers may increase by 213%. This suggests that cooperative management institutions are the most efficient institutions in increasing the gain to the CPR beneficiaries and prolonging the CPR’s life in comparison with non-cooperative and exogenous CPR management institutions. Nevertheless, the given number (213%) may be too optimistic, as the transaction costs of establishing cooperative management institutions have not been considered here.

Given the values of Tables 5 and 6, we can calculate the gain to each farmer, based on different cooperative allocation institutions introduced earlier:

5.1 Nash-Harsanyi institution. Table 8 shows the allocated benefits to the three cooperating farmers, based on the Nash-Harsanyi cooperative institution. The cooperative shares of the farmers vary, based on the non-cooperative institution they choose in case of non-cooperation (status quo). All solutions satisfy the Core requirements (Equations A.1 to A.7). Therefore, they are in the Core and are acceptable by the users. However, the level of acceptability and stability of the allocated benefits may vary among the users, as will be discussed in the next section.

According to this table, Farmer C – the poorest farmer – is the one who benefits the most from cooperation with respect to what he could gain non-cooperatively. The opposite is true for Farmer A – the richest farmer. Generally, as users become less myopic by developing long-term plans and less ignorant by considering the externalities, their relative benefit from cooperation decreases. Therefore, the ignorant myopic farmers benefit the most and smart non-myopic farmers benefit the least from cooperation with respect to the status quo. That may suggest that ignorant myopic farmers have higher desire to cooperate than farmers who plan long-term and/or consider the externalities in the exploitation plans. Yet, in practice, the ignorant myopic farmers may be reluctant to cooperate, as they cannot perceive the long-term benefits. Therefore, enforcing cooperation may be more convenient when parties are considerate of the externalities and long-term benefits.

5.2 Shapley institution. Table 9 shows the allocated benefits to the three cooperating farmers, based on the Shapley allocation institution. Shapley’s cooperative allocations satisfy the Core conditions and are acceptable to the three farmers.

Similar to the solutions under the Nash-Harsanyi Institutions, under the Shapley institution farmers’ gains with respect to the status-quo decrease as they become less myopic and less ignorant. Comparison of Tables 9 and 10 suggests that in most cases Farmer C – the poorest farmer – gains less under the Shapley institution than under the Nash-Harsanyi institution. The

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6 Considering the computational limitation only cases in which all farmers apply the same management institution have been examined here (public choice mechanism as explained in footnote 4).
opposite is true for Farmer B, who is not as rich as Farmer A and not as poor as Farmer C. Gains of the Farmer A do not differ significantly under the Nash-Harsanyi and Shapley institutions.

5.3 Nucleolus institution. Table 10 shows the allocated benefits to the three cooperating farmers, based on the Nucleolus allocation institution. All solutions are in the Core and, thus, are acceptable by the farmers.

Similar to the previous two institutions, relative gains of the farmers with respect to the non-cooperative case, decreases when they become less myopic and less ignorant. When comparing the gain of the poorest farmer – Farmer C – under different cooperative management institutions, one can find that this farmer gains the least under the Nucleolus institution. On the other hand, Farmer B, with the middle wealth level, gains the most under this institution in comparison with what he gains under the other two institutions. Gain of the richest farmer – Farmer A – under the Nucleolus institution does not have a significant difference with his gains under the other two institutions.

The results under the three cooperative management institutions rely on an important assumption. Here, it is assumed that utility is transferrable and side-payments are allowed. Therefore, in case of cooperation, it is suggested that only Farmer A, with the lower production cost per unit, farms on his land and shares the benefits with the other two farmers. In this case, the three farmers can enjoy a lower groundwater depth (a longer CPR life) due to minimization of the externalities caused by simultaneous pumping in all the wells. Nevertheless, the solution may be associated with some transaction costs. When utility is not transferrable and side-payments are not allowed, the problem finds a different structure. While cooperation may still result in higher benefits and prolong the CPR’s life, the maximum total benefits obtained will be lower than a case with side payments. In that case, farmers would cooperate by lowering their pumping rates to prolong the groundwater resource’s life and keeping pumping costs lower than the benefits obtained from crop production. Therefore, all farmers will farm on their lands while they are enjoying lower groundwater depths; however, some transactions costs associated with monitoring and enforcement may be experienced. This case is not studied here. Nonetheless, the gains of the farmers under the cooperation can be calculated using the same concepts.

6. Acceptability and stability of the cooperative institutions

To ensure that a cooperative solution works properly in practice, not only should it be in the Core, but also it has to be stable. While being in the Core is a necessary condition for

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7 The reason for that result lays in the calculation of the Shapley and Nash-Harsanyi institutions. In the case of Nash-Harsanyi, each farmer gets an equal incremental gain based on its original benefit at the status quo; however, the Shapley institution allocates incremental gains to each farmer based on their average contribution to the coalition when they enter that coalition. In this case, when entering the coalition, Farmer B has more contribution than Farmer C. Thus, Farmer B’s coalitional gains are higher.

8 The Nucleolus calculation procedure suggests that it would take the lowest ε to keep a coalition with C in the core and a higher ε to keep a coalition with B in the core.

9 For instance, the farmers’ gains from cooperation based on the Nash-Harsanyi institution can be calculated using the Nash-Harsanyi bargaining solution for linked games (Madani 2011). In that case, farmers see the game as interconnection of H (here H=50) games linked to each other. Therefore, the “strategic loss” becomes possible and farmers are willing to strategically lose in some years (in some sub-games) to increase their gain (win) in the overall interconnected game. By benefiting from strategic loss, the feasible solution space is expanded and parties can develop cooperative solutions that increase the gains to all parties.
acceptability of a cooperative solution by the beneficiaries, not all solutions contained in the Core are acceptable. Some solutions that fulfill the Core requirements are found unfair by some beneficiaries, making them unacceptable and unstable. When beneficiaries find a solution unfair, they may threaten to leave the grand coalition to form sub-coalitions or to act on their own, due to their critical role in the coalition. (Dinar and Howitt 1997)

When multiple cooperative solutions are available, one simple method to find which solution is superior to others is using the plurality rule\(^{10}\) finding which method is the most preferred option by the most number of users. Table 11 indicates how the various cooperative management institutions in the numerical example are ranked from 1 (worst option) to 3 (best option) by the farmers using the plurality rule. As indicated in the table, the ranking orders of the farmers over the possible alternatives vary, depending on the non-cooperative management institution they will adopt in the status quo. The plurality rule selects the option considered best by the highest number of users as the socially optimum alternative. The last row of the table indicates which cooperative management institution is selected, based on the plurality rule, depending on the users’ behavioral characteristics in the non-cooperative case. Results indicate that the Shapley institution is never selected. Therefore, this institution cannot provide stable solutions to enforce cooperation among the three farmers. Based on Table 11, the Nucleolus institution is most preferred by the majority of the farmers when they are myopic. When they consider their long-term benefits under non-cooperation, the Nash-Haryanvi institution is preferred by the majority. Since the selected alternative, based on the plurality rule, always complies with the best choice of Farmer A, who has the highest level of power due to his highest wealth level, it is reasonable to expect the plurality rule’s selected option to be stable in practice.

The choice of cooperative institutions can vary based on the conditions of the problem. The Nash-Harsanyi cooperative institution may not be appropriate for all problems as it sometimes may provide unfair allocations, especially if there are big utility differences between the users (e.g., very rich and very poor beneficiaries) (Dinar and Howitt 1997).

While plurality rule is a simple method for determining the most stable cooperative solution, due to its qualitative nature, it fails to provide some useful quantitative information about the stability of the solutions available through application of other stability measurement methods. Propensity to disrupt player \(i\) (PTD\(_i\)) – the ratio of how much the other beneficiaries would lose if player \(i\) leaves the grand coalition and refuses to cooperate, to how much he would lose if he refuses to cooperate – has been suggested as an indicator of players’ powers in a cooperative framework (Gately 1974, Straffin and Heaney 1981):

\[
PTD_i = \frac{\sum_{j \neq i} u^*(N-j) - v(N)}{u^* - v(i)}
\]  

The lower the ratio for a given player, the higher his enthusiasm for cooperating and staying in the grand coalition. The user who has a high enthusiasm for cooperation has a low power in the

\(^{10}\) The plurality rule is perhaps the most common method for finding the socially optimal solution. Other socially optimal rules (e.g., Condorcet Choice, Borda Scoring, Median Voting Rule, Majoritarian Compromise, and Condorcet’s Practical Method) can be used in similar situations when multiple users have a chance to select a best alternative. Fall-back bargaining methods (Brams and Kilgour 2001) can be also used to find the optimal alternative in these situations. See Sheikhmohammady and Madani (2008) for explanation and example applications of various social rules and fall-back bargaining methods.
grand coalition. On the other hand, a player with a high propensity to disrupt has a high power in the grand coalition, using his high contribution to the grand coalition as a basis for a credible threat to the other members of the grand coalition. This player threatens to leave the grand coalition to create sub-coalitions or act on his own, asking for more benefits out of cooperation.

Table 12 presents the calculated propensity to disrupt of the farmers for different cooperative solutions, which vary based on their choice of non-cooperative management institution in status quo. The values in the table suggest that the propensity to disrupt under a given cooperative management institution increases as they become less myopic and less ignorant. This is due to the fact that by long-term planning and consideration of the externalities farmers can increase their gains even without cooperation. That also underlines the value of information. Parties who are aware of the externalities’ effects and are concerned about the CPR’s conditions in the long run have more power when it comes to cooperation.

The value of 0 propensity to disrupt for a myopic Farmer C under the Nash-Harsanyi cooperative institution (Table 12) suggests that this farmer has a very high enthusiasm to stay in the grand coalition as the other players will not lose without him. In such a situation, this farmer may be willing to bribe the other farmers by increasing their gains and asking for less benefit out of the joint cooperative gains. Although by doing this Farmer C ends up with lower cooperative gains, he can create an incentive for the other players to stay in the grand coalition. Therefore, when the players act myopically in status quo, a cooperative solution close to what was suggested by the Nash-Harsanyi institution may be stable. However, given the high propensity to disrupt Farmer B under this institution, it may be concluded that when farmers become non-myopic the Nash-Harsanyi cooperative solution cannot be stable anymore. For myopic farmers, the Shapley institution seems a fair scheme for allocating gains with the lowest maximum propensity to disrupt. However, this institution cannot provide stable solutions for smart non-myopic farmers, as was discussed earlier. Given that Farmers A and B are wealthier and more valuable to the grand coalition than Farmer C, it is reasonable to conclude that cooperative solutions in which Farmers A and B have lower propensity to disrupt are more stable. In that case, the Nucleolus seems to be the best institution for allocating the cooperation benefits.

Calculating the power index of player \( i \) (\( \alpha_i \)) in the cooperative game is another method for evaluating the stability of the cooperative solution (Shapley and Shubik 1954, Loehman et al. 1979):

\[
\alpha_i = \frac{u_i - v(i)}{\sum_{j=1}^{n} (u_j - v(j))}, \quad \sum_{i=1}^{n} \alpha_i = 1 \tag{20}
\]

Based on this concept, to determine if a solution is stable, the power index of each player is calculated based on the given cooperative solution. The higher the power index of a player, the higher his enthusiasm for cooperating and staying in the grand coalition. This method suggests that if the power is distributed more or less equally among the players, then the solution is more likely to be stable (Dinar and Howitt 1997). Looking at the coefficient of variations of power indices, known as stability index (\( \bar{\alpha} \)), one can find if the power distribution is equally distributed among the users. The lower the stability index, the more stable the cooperative solution.

Table 13 shows the calculated power indices of the farmers and stability index of each
cooperative solution for different cooperative solutions, which vary based on their choice of non-cooperative management institution in status quo. Based on the results, Nash-Harsanyi cooperative institution seems to have the best performance in distributing the powers equally among the farmers of the numerical example. Although, the Nucleolus institution fails to distribute the powers equally among the farmers, given the conditions of the problem, it may provide a stable solution as it gives higher powers to the wealthier farmers, so it allows them to remain in the coalition and influence the poorer ones.

Figure 1 indicates the stability index of each cooperative solution for different cooperative solutions, which vary based on their choice of non-cooperative management institution in status quo. Based on the results, Nash-Harsanyi institution shows the best performance (lower stability indices) for all status quo’s non-cooperative behavior types. The opposite is true for the Nucleolus institution. The performance of the Shapley institution is almost insensitive to the non-cooperative behaviors of the farmers in status quo. As the users become less myopic and smarter, stability index gets smaller under Nash-Harsanyi institution, indicating the possibility of developing stable solutions under this institution for farmers with better behaviors.

7. Conclusions and policy implications

Users of common pool resources can develop exploitation plans based on various cooperative management institutions. Comparison of the results of this study with previous studies, using non-cooperative and exogenously imposed regulations suggests that cooperative management institutions are the most efficient methods in prolonging the CPR’s life and increasing the long-term benefits to its users. However, adopting these institutions in practice may be more challenging than the other two categories of institutions, due to their rigorous mathematical nature as well as lack of trust among the users, limited information and knowledge, presence of many users, etc. While implementation of cooperative institutions may be challenging in practice, governments can help enforce these institutions by creating different incentives for cooperation (e.g., tax write-off, development loans, and monitoring mechanisms, technical advice).

The maximum obtainable benefit by the CPR users can be calculated using a social planner solution. Yet, this approach cannot suggest stable and acceptable cooperative solutions because it ignores what each individual will incrementally gain under cooperation. Therefore, cooperative game theory allocation solutions such as the Core, Nash-Harsanyi, Shapley, and Nucleolus can be applied to determine efficient and fair allocation solutions that are acceptable by the users. These methods consider the contribution of each CPR beneficiary to the grand coalition, and their gains in case of non-cooperation and suggest solutions that minimize the users’ incentives to leave the grand coalition to act on their own or form sub-coalitions with other users.

As indicated using a numerical example, application of the plurality rule or measurement of stability through calculation of the propensity to disrupt, power index, and stability index may not necessary lead to an accurate prediction of the most stable and likely outcome. Nonetheless, these methods are helpful in finding the highly unstable outcomes. To better suggest a stable outcome, one should consider the conditions of the problem, and various factors that may affect the stability of a solution in practice (e.g., powers of the parties in allocating more resources to them), and transactions costs.

It is also important to note that the final cooperative solution does not always match the values suggested by the introduced cooperative management institutions. However, with the knowledge
of propensity to disrupt values and power indices, and more information about the problem’s conditions in practice, it is possible to develop a stable solution by tweaking the solutions suggested by the cooperative management institutions. In fact, these institutions can suggest solutions that are close to what will eventually be found stable and fair by the parties in practice. Therefore, they are helpful in suggesting sub-optimal solutions for initiating the bargaining process over the gains out of cooperation.

Results of the study show that as users become less myopic and less ignorant, they benefit less from cooperation with respect to what they gain under non-cooperation. Also, the ranges of acceptable solutions by the users get more limited as they become more considerate of the externalities and long-term benefits from the CPR, resulting in a smaller Core. Thus, the acceptable cooperative solutions are more limited for non-myopic smart users and result in higher propensities to disrupt for these users. While potentially this results in hardship in enforcing cooperative solutions among this type of users, due to a better knowledge about the externalities and long-term benefits, theoretically, developing practical cooperative solutions among these users should be easier than for myopic ignorant users who are more focused on immediate benefits from the resource. Nevertheless, when transaction costs of enforcing cooperation are high, regulators may seek a sustainable use of the CPR through educating the users to replace their myopic ignorant behavior with non-myopic smart behavior.

8. References


Table 1. Values of farmer-dependent parameters (Madani and Dinar 2010)

<table>
<thead>
<tr>
<th>Farmer</th>
<th>$l$ (ha)</th>
<th>$d_0$ (m)</th>
<th>$a_{iA}$</th>
<th>$a_{iB}$</th>
<th>$a_{iC}$</th>
<th>$b_{iA}$</th>
<th>$b_{iB}$</th>
<th>$b_{iC}$</th>
<th>$Q_{i}$ (m$^3$/year)</th>
<th>$\Theta$</th>
<th>$\omega_{iA}$</th>
<th>$\omega_{iB}$</th>
<th>$\omega_{iC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>40</td>
<td>20</td>
<td>9.125</td>
<td>5.423</td>
<td>3.640</td>
<td>140</td>
<td>100</td>
<td>50</td>
<td>1,000</td>
<td>0.08</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>28</td>
<td>14</td>
<td>9.125</td>
<td>5.423</td>
<td>6.684</td>
<td>100</td>
<td>140</td>
<td>115</td>
<td>900</td>
<td>0.07</td>
<td>0.085</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>15</td>
<td>9</td>
<td>6.684</td>
<td>9.125</td>
<td>9.125</td>
<td>50</td>
<td>115</td>
<td>140</td>
<td>750</td>
<td>0.06</td>
<td>0.035</td>
<td>0.075</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2. Values of crop-dependent parameters (Madani and Dinar 2010)

<table>
<thead>
<tr>
<th>Crop</th>
<th>$q$ (Ton/m$^3$/ha/year)</th>
<th>$z$ ($$/Ton)</th>
<th>$i$ ($$/ha^2/year)</th>
<th>$j$ ($$/ha/year)</th>
<th>$k$ ($$/year)</th>
<th>$p$ (Ton/m$^3$/ha$^2$/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0256</td>
<td>150</td>
<td>-9.8175 x 10$^{-4}$</td>
<td>892.5</td>
<td>2.769</td>
<td>-2.49 x 10$^{-10}$</td>
</tr>
<tr>
<td>2</td>
<td>0.0280</td>
<td>134</td>
<td>-9.8485 x 10$^{-3}$</td>
<td>689.4</td>
<td>0.611</td>
<td>-7.51 x 10$^{-11}$</td>
</tr>
</tbody>
</table>

Table 3. Values of independent parameters (Madani and Dinar 2010)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$A$</th>
<th>$B$</th>
<th>$t^*$ (m$^2$/day)</th>
<th>$u$ ($$/m^3/m^3$)</th>
<th>$V$ ($$/m^3$)</th>
<th>$B$ (%/year)</th>
<th>$C_{Tec}$ ($$)</th>
<th>$Q_{ei}$ (m$^3$/year)</th>
<th>$H$ (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9.125</td>
<td>140</td>
<td>365</td>
<td>6,960</td>
<td>7.2</td>
<td>10</td>
<td>0.05</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

$t^*$ should be set equal to 365 in Equations 1 and 2 to calculate the drawdown over one time-step ($h$)

Table 4. The social planner solution to the numerical groundwater problem

<table>
<thead>
<tr>
<th>Farmer</th>
<th>Farmer A</th>
<th>Farmer B</th>
<th>Farmer C</th>
<th>Total Profit ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4,394,518</td>
<td>0</td>
<td>0</td>
<td>4,394,518</td>
</tr>
</tbody>
</table>

Table 5. The values of different coalitional settings excluding one-member coalitions

<table>
<thead>
<tr>
<th>Coalition</th>
<th>Gain Based on the Social Planner Solution ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Farmer A</td>
</tr>
<tr>
<td>{A, B}</td>
<td>3,742,295</td>
</tr>
<tr>
<td>{A, C}</td>
<td>2,682,139</td>
</tr>
<tr>
<td>{B, C}</td>
<td>-</td>
</tr>
<tr>
<td>{A, B, C}</td>
<td>4,394,518</td>
</tr>
</tbody>
</table>
Table 6. The possible values ($) of different one-member coalitions under different non-cooperative management institutions (Madani and Dinar 2010)

<table>
<thead>
<tr>
<th>Non-cooperative management institution</th>
<th>Ignorant myopic management</th>
<th>Smart myopic management with drawdown penalty</th>
<th>Smart myopic management with profit penalty</th>
<th>Fixed ignorant non-myopic management</th>
<th>Variable ignorant non-myopic management</th>
<th>Smart non-myopic management</th>
</tr>
</thead>
<tbody>
<tr>
<td>{A}</td>
<td>1,410,745</td>
<td>1,607,507</td>
<td>1,711,671</td>
<td>2,199,330</td>
<td>2,209,329</td>
<td>2,410,089</td>
</tr>
<tr>
<td>{B}</td>
<td>99,216</td>
<td>344,681</td>
<td>214,975</td>
<td>790,681</td>
<td>744,047</td>
<td>918,662</td>
</tr>
<tr>
<td>{C}</td>
<td>-106,141</td>
<td>-14,466</td>
<td>-8,180</td>
<td>70,617</td>
<td>40,259</td>
<td>167,173</td>
</tr>
<tr>
<td>Sum</td>
<td>1,403,820</td>
<td>1,937,722</td>
<td>1,918,466</td>
<td>3,060,627</td>
<td>2,993,636</td>
<td>3,495,924</td>
</tr>
</tbody>
</table>

Table 7. The minimum and maximum expected benefits of the three farmers who use various types of non-cooperative management institutions in case of non-cooperation

<table>
<thead>
<tr>
<th>Farmer</th>
<th>Expected Allocation</th>
<th>Ignorant myopic management</th>
<th>Smart myopic management with drawdown penalty</th>
<th>Smart myopic management with profit penalty</th>
<th>Fixed ignorant non-myopic management</th>
<th>Variable ignorant non-myopic management</th>
<th>Smart non-myopic management</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Minimum</td>
<td>1,410,745</td>
<td>1,607,507</td>
<td>1,711,671</td>
<td>2,199,330</td>
<td>2,209,329</td>
<td>2,410,089</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>3,664,093</td>
<td>3,418,628</td>
<td>3,548,334</td>
<td>2,972,628</td>
<td>3,019,262</td>
<td>2,934,732</td>
</tr>
<tr>
<td>B</td>
<td>Minimum</td>
<td>99,216</td>
<td>344,681</td>
<td>214,975</td>
<td>790,681</td>
<td>744,047</td>
<td>918,662</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>2,352,563</td>
<td>2,155,802</td>
<td>2,051,637</td>
<td>1,712,378</td>
<td>1,712,378</td>
<td>1,712,378</td>
</tr>
<tr>
<td>C</td>
<td>Minimum</td>
<td>-106,141</td>
<td>-14,466</td>
<td>-8,180</td>
<td>70,617</td>
<td>40,259</td>
<td>167,173</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>1,360,570</td>
<td>1,115,105</td>
<td>1,244,811</td>
<td>669,105</td>
<td>715,739</td>
<td>631,209</td>
</tr>
</tbody>
</table>
Table 8. Allocation of benefits under cooperation, based on the Nash-Harsanyi institution to the three farmers using different non-cooperative institutions under status quo

<table>
<thead>
<tr>
<th>Non-cooperative management institution</th>
<th>Ignorant myopic management</th>
<th>Smart myopic management with drawdown penalty</th>
<th>Smart myopic management with profit penalty</th>
<th>Fixed ignorant non-myopic management</th>
<th>Variable ignorant non-myopic management</th>
<th>Smart non-myopic management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmer A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allocated benefit ($)</td>
<td>2,537,419</td>
<td>2,513,067</td>
<td>2,630,003</td>
<td>2,643,960</td>
<td>2,676,290</td>
<td>2,709,620</td>
</tr>
<tr>
<td>Difference with respect to status quo (%)</td>
<td>80</td>
<td>56</td>
<td>54</td>
<td>20</td>
<td>21</td>
<td>12</td>
</tr>
<tr>
<td>Farmer B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allocated benefit ($)</td>
<td>1,225,890</td>
<td>1,250,241</td>
<td>1,133,306</td>
<td>1,235,311</td>
<td>1,211,008</td>
<td>1,218,193</td>
</tr>
<tr>
<td>Difference with respect to status quo (%)</td>
<td>1,136</td>
<td>263</td>
<td>427</td>
<td>56</td>
<td>63</td>
<td>33</td>
</tr>
<tr>
<td>Farmer C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allocated benefit ($)</td>
<td>631,209</td>
<td>631,209</td>
<td>631,209</td>
<td>515,247</td>
<td>507,220</td>
<td>466,704</td>
</tr>
<tr>
<td>Difference with respect to status quo (%)</td>
<td>695</td>
<td>4,463</td>
<td>7,816</td>
<td>630</td>
<td>1,160</td>
<td>179</td>
</tr>
</tbody>
</table>
Table 9. Allocation of benefits under cooperation, based on the Shapley institution to the three farmers using different non-cooperative institutions under status quo

<table>
<thead>
<tr>
<th>Non-cooperative management institution</th>
<th>Ignorant myopic management</th>
<th>Smart myopic management with drawdown penalty</th>
<th>Smart myopic management with profit penalty</th>
<th>Fixed ignorant non-myopic management</th>
<th>Variable ignorant non-myopic management</th>
<th>Smart non-myopic management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmer A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allocated benefit ($</td>
<td>2,523,888</td>
<td>2,533,285</td>
<td>2,588,577</td>
<td>2,642,046</td>
<td>2,658,211</td>
<td>2,674,876</td>
</tr>
<tr>
<td>Difference with respect to status quo (%)</td>
<td>79</td>
<td>58</td>
<td>51</td>
<td>20</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>Farmer B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allocated benefit ($</td>
<td>1,256,946</td>
<td>1,290,695</td>
<td>1,229,051</td>
<td>1,326,544</td>
<td>1,314,393</td>
<td>1,317,986</td>
</tr>
<tr>
<td>Difference with respect to status quo (%)</td>
<td>1,167</td>
<td>274</td>
<td>472</td>
<td>68</td>
<td>77</td>
<td>43</td>
</tr>
<tr>
<td>Farmer C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allocated benefit ($</td>
<td>613,683</td>
<td>570,537</td>
<td>576,889</td>
<td>425,928</td>
<td>421,914</td>
<td>401,656</td>
</tr>
<tr>
<td>Difference with respect to status quo (%)</td>
<td>678</td>
<td>4,044</td>
<td>7,152</td>
<td>503</td>
<td>948</td>
<td>140</td>
</tr>
</tbody>
</table>
Table 10. Allocation of benefits under cooperation, based on the Nucleolus institution to the three farmers using different non-cooperative institutions under status quo

<table>
<thead>
<tr>
<th>Non-cooperative management institution</th>
<th>Ignorant myopic management</th>
<th>Smart myopic management with drawdown penalty</th>
<th>Smart myopic management with profit penalty</th>
<th>Fixed ignorant non-myopic management</th>
<th>Variable ignorant non-myopic management</th>
<th>Smart non-myopic management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmer A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allocated benefit ($)</td>
<td>2,640,131</td>
<td>2,640,131</td>
<td>2,640,131</td>
<td>2,640,131</td>
<td>2,640,131</td>
<td>2,642,106</td>
</tr>
<tr>
<td>Difference with respect to status quo (%)</td>
<td>87</td>
<td>64</td>
<td>54</td>
<td>19</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>Farmer B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allocated benefit ($)</td>
<td>1,417,778</td>
<td>1,417,778</td>
<td>1,417,778</td>
<td>1,432,082</td>
<td>1,417,778</td>
<td>1,353,220</td>
</tr>
<tr>
<td>Difference with respect to status quo (%)</td>
<td>1,329</td>
<td>311</td>
<td>560</td>
<td>81</td>
<td>91</td>
<td>47</td>
</tr>
<tr>
<td>Farmer C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allocated benefit ($)</td>
<td>336,608</td>
<td>336,608</td>
<td>336,608</td>
<td>350,913</td>
<td>336,608</td>
<td>399,191</td>
</tr>
<tr>
<td>Difference with respect to status quo (%)</td>
<td>417</td>
<td>2,427</td>
<td>4,215</td>
<td>397</td>
<td>736</td>
<td>139</td>
</tr>
</tbody>
</table>
Table 11. Preference orders of the farmers over the cooperative management institutions, based on their non-cooperative characteristics (3 and 1 belong to the most and least preferred options, respectively)

<table>
<thead>
<tr>
<th>Non-cooperative management institution</th>
<th>Ignorant myopic management</th>
<th>Smart myopic management with drawdown penalty</th>
<th>Smart myopic management with profit penalty</th>
<th>Fixed ignorant non-myopic management</th>
<th>Variable ignorant non-myopic management</th>
<th>Smart non-myopic management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmer A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nash-Harsanyi</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Shapley</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Nucleolus</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Farmer B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nash-Harsanyi</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Shapley</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Nucleolus</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Farmer C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nash-Harsanyi</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Shapley</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Nucleolus</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Selected institution based on the plurality rule</td>
<td>Nucleolus</td>
<td>Nucleolus</td>
<td>Nucleolus</td>
<td>Nash-Harsanyi</td>
<td>Nash-Harsanyi</td>
<td>Nash-Harsanyi</td>
</tr>
</tbody>
</table>

Table 12. Propensity to disrupt of the farmers under different cooperative management institutions, based on their choice of management institution in the status quo

<table>
<thead>
<tr>
<th>Non-cooperative management institution</th>
<th>Ignorant myopic management</th>
<th>Smart myopic management with drawdown penalty</th>
<th>Smart myopic management with profit penalty</th>
<th>Fixed ignorant non-myopic management</th>
<th>Variable ignorant non-myopic management</th>
<th>Smart non-myopic management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nash-Harsanyi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farmer A</td>
<td>0.35</td>
<td>0.47</td>
<td>0.33</td>
<td>0.65</td>
<td>0.55</td>
<td>0.75</td>
</tr>
<tr>
<td>Farmer B</td>
<td>0.43</td>
<td>0.51</td>
<td>0.63</td>
<td>1.07</td>
<td>1.07</td>
<td>1.65</td>
</tr>
<tr>
<td>Farmer C</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.26</td>
<td>0.27</td>
<td>0.55</td>
</tr>
<tr>
<td>Shapley</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farmer A</td>
<td>0.37</td>
<td>0.43</td>
<td>0.39</td>
<td>0.66</td>
<td>0.62</td>
<td>0.98</td>
</tr>
<tr>
<td>Farmer B</td>
<td>0.39</td>
<td>0.45</td>
<td>0.48</td>
<td>0.72</td>
<td>0.70</td>
<td>0.99</td>
</tr>
<tr>
<td>Farmer C</td>
<td>0.02</td>
<td>0.10</td>
<td>0.09</td>
<td>0.58</td>
<td>0.55</td>
<td>0.98</td>
</tr>
<tr>
<td>Nucleolus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farmer A</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.12</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Farmer B</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
<td>0.20</td>
<td>0.21</td>
<td>0.27</td>
</tr>
<tr>
<td>Farmer C</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.80</td>
<td>0.88</td>
<td>0.58</td>
</tr>
</tbody>
</table>
Table 13. Power indices of the farmers under different cooperative management institutions, based on their choice of management institution in the status quo.

<table>
<thead>
<tr>
<th>Cooperative Management Institution</th>
<th>Non-cooperative management institution</th>
<th>Ignorant myopic management</th>
<th>Smart myopic management with drawdown penalty</th>
<th>Smart myopic management with profit penalty</th>
<th>Fixed ignorant non-myopic management</th>
<th>Variable ignorant non-myopic management</th>
<th>Smart non-myopic management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nash-Harsanyi</td>
<td>Farmer A</td>
<td>0.38</td>
<td>0.37</td>
<td>0.37</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Farmer B</td>
<td>0.38</td>
<td>0.37</td>
<td>0.37</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Farmer C</td>
<td>0.25</td>
<td>0.26</td>
<td>0.26</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>Shapley</td>
<td>Farmer A</td>
<td>0.37</td>
<td>0.38</td>
<td>0.35</td>
<td>0.33</td>
<td>0.32</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>Farmer B</td>
<td>0.39</td>
<td>0.39</td>
<td>0.41</td>
<td>0.40</td>
<td>0.41</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>Farmer C</td>
<td>0.24</td>
<td>0.24</td>
<td>0.24</td>
<td>0.27</td>
<td>0.27</td>
<td>0.26</td>
</tr>
<tr>
<td>Nucleolus</td>
<td>Farmer A</td>
<td>0.41</td>
<td>0.42</td>
<td>0.37</td>
<td>0.31</td>
<td>0.31</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>Farmer B</td>
<td>0.44</td>
<td>0.44</td>
<td>0.49</td>
<td>0.48</td>
<td>0.48</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>Farmer C</td>
<td>0.15</td>
<td>0.14</td>
<td>0.14</td>
<td>0.21</td>
<td>0.21</td>
<td>0.26</td>
</tr>
</tbody>
</table>
Figure 1. Stability indices under different cooperative management institutions, based on their choice of management institution in the status quo.
Appendix A: Extreme Points of the Core

As an example, the Core equations for cooperation of farmers who use variable ignorant non-myopic management under non-cooperation can be written as follows:

\[
\begin{align*}
\omega_A^* & \geq 2,209,329 \quad (A.1) \\
\omega_B^* & \geq 744,047 \quad (A.2) \\
\omega_C^* & \geq 40,259 \quad (A.3) \\
\omega_A^* + \omega_B^* & \geq 3,763,309 \quad (A.4) \\
\omega_A^* + \omega_C^* & \geq 2,682,139 \quad (A.5) \\
\omega_B^* + \omega_C^* & \geq 1,459,786 \quad (A.6) \\
\omega_A^* + \omega_B^* + \omega_C^* & = 4,394,518 \quad (A.7)
\end{align*}
\]

The above set of inequalities suggests a range of solutions that may be acceptable by the three farmers in case of cooperation when each uses the variable ignorant non-myopic management under non-cooperation. Based on these equations, it is possible to calculate the extreme points of the Core (Shapley 1971) to find the ordering of the farmers’ preferences over the possible cooperative solutions (Dinar and Howitt 1997). To do so, we should consider all the possible sequences for formation of the grand coalition. Table A.1 shows such sequences together with the extreme points of the Core for the farmers who use variable ignorant non-myopic management under non-cooperation, based on the values of Tables 5 and 6.

The extreme points of the Core and the incremental benefit allocation of the farmers are calculated as follows: As an example for the grand coalition sequence ABC, it is assumed that first Farmer A joins the empty coalition with a zero value and creates coalition \{A\} with associated value of $2,209,329. Then Farmer B joins the coalition and creates coalition \{A, B\} with the value of $3,763,309 (given in Table 5). Therefore, the contribution of Farmer B to the new coalition is $3,763,309 − $2,209,329 = $1,553,980, which is the maximum benefit he can expect to obtain from cooperating with Farmer A. By joining Farmer C to this coalition, the grand coalition \{A, B, C\} is created with total worth of $4,394,518. The contribution of Farmer C to the grand coalition with the ABC sequence is $4,394,518 − $3,763,309 = $631,209, which is the maximum he can expect from participating in the grand coalition, when he is the last one to join. The values, given in Table A.1, show the incremental contributions of the farmers to different sequential formations of the grand coalition. In fact, these numbers indicate the minimum and maximum expected benefit allocation of the farmers, or the farmers’ preference orders over the possible allocation. For instance, Farmer A prefers allocations under which he can gain a profit close to $3,019,262 (the highest number in Farmer A’s column in Table A.1) to allocations under which his gain is close to $2,209,329 (the lowest number in Farmer A’s column in Table A.1). This farmer does not accept any allocation scheme that provides him less than $2,209,329.
Table A.1 - Extreme points of the Core for the farmers who use variable ignorant non-myopic management under non-cooperation

<table>
<thead>
<tr>
<th>Maximum incremental benefit allocation Farmer $i$</th>
<th>Grand coalition formation sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$B$</td>
</tr>
<tr>
<td>2,209,329</td>
<td>1,553,980</td>
</tr>
<tr>
<td>2,209,329</td>
<td>1,712,378</td>
</tr>
<tr>
<td>3,019,262</td>
<td>744,047</td>
</tr>
<tr>
<td>2,934,732</td>
<td>744,047</td>
</tr>
<tr>
<td>2,641,880</td>
<td>1,712,378</td>
</tr>
<tr>
<td>2,934,732</td>
<td>1,419,527</td>
</tr>
</tbody>
</table>