Non-Cooperative Institutions for Sustainable Management of Common Pool Resources

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December 2010

Abstract

As demands for limited natural resources increase, developing management institutions that ensure the sustainability of such resources is essential. Natural resources are Common Pool Resources (CPRs), managed under different non-cooperative, cooperative, and externally imposed management frameworks. While early studies of non-cooperative CPR management suggest inevitable “tragedy of the commons,” here we discuss how users can avoid tragic outcomes by changing their decision making rationales and exploitation strategies even in a non-cooperative environment. This paper introduces and compares various types of non-cooperative institutions that are available to manage CPRs. These management institutions are then applied, using a numerical groundwater exploitation example, to determine how different planning variables are affected by the choice of management institution. Results indicate that CPR users can improve their gains by considering the externalities and developing long-term exploitation plans, as opposed to short-term plans with no consideration of externalities that result in rapid exhaustion of the resource and lead to the so-called “tragedy of the commons.”

Keywords: common pool resource, myopic behavior; institutions; heuristic behavior; groundwater; sustainable management.

JEL Codes: Q25, H41

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1 Financial support from the UC Davis Watershed Sciences Center is acknowledged. We would like to thank Michael Moore and Hugo Loaiciga for useful comments on a previous version of this paper.

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1. Introduction

Many of the world’s natural Common Pool Resources (CPRs) (e.g., groundwater, forests, pastures, and fisheries) face overuse and congestion due to increased competition for and the subtractability of their use. By focusing on current needs and short-term benefits, and ignoring the consumption externalities, users have exhausted many natural resources without considering the needs of future generations. Generally, any resource system whose size or characteristics make it costly, but not impossible, to exclude potential beneficiaries from obtaining benefits from its use is considered to be a CPR (Ostrom et al. 1994). Therefore, CPRs are not limited only to natural resources. They also include human-made resource systems, such as irrigation systems, public infrastructures, radio frequency spectra, etc. Similar to natural resources, many human-made resource systems face the problems of congestion or overuse, because they are subtractable. The alarming outcomes of unsustainable resource management have raised the global concern about the impacts of increasing population and developing societies on CPRs, stimulating the growth in studying natural resource depletion, environmental degradation, and sustainable development, mainly over the last two decades (Ludwig 1993, Schaller 1993, Goodland 1995, Arrow et al. 1996, Goodland and Daly 1996, Stern et al. 1996, Callicott and Mumford 1997, Duraiappah 1998, Gleick 1998, Dincer and Rosen 1999, Munasinghe 1999, Dargupta et al. 2000, Loucks 2000, Davis and Gartside 2001, McMichael et al. 2003, Meadows et al. 2004, Hjorth and Bagheri 2006, Bagheri and Hjorth 2007, Behrens et al. 2007, Madani and Marino 2009, Calzadilla et al. 2010). The growing body of studies has built a consensus among different disciplines, believing that a shift in the CPR management paradigm and changes in the CPR’s governing policies and institutions are essential toward sustainability.

In early attempts to understand CPR problems, the negative outcomes of CPR exploitation in the presence of multiple beneficiaries (e.g., overuse, congestion, pollution, destruction, etc.) were associated with users’ non-cooperative behavior and their choice of acting, based on individual rationality rather than group rationality. This resulted in the “tragedy of the commons” (Gordon 1954, Hardin 1968), which can be well explained within the Prisoner’s Dilemma game structure, (e.g. see Madani (2010)), using the Nash non-cooperative solution concept (stability definition) (Nash 1951). Therefore, traditional CPR research suggests enforcing external exploitation regulations and ownership rights to avoid negative outcomes and to overcome the CPR dilemma (Ostrom 1990, Castillo and Saysel 2005, Ostrom 2010). More recent studies of CPR problems suggest that CPR’s future may be somewhat better than what was expected within the Prisoner’s Dilemma structure. The main reason is that the beneficiaries may base their actions on group rationality (as opposed to individual rationality), develop cooperative CPR exploitation framework, and/or develop heuristic CPR management rules which are individual behavioral rules based on learning and past experience (Ostrom 1990, Ostrom et al. 1994, Ostrom 1998, McCarthy et al. 2001, Fehr and Fischbacher 2002, Castillo and Saysel 2005, Ostrom 2010). Such suggested exploitation frameworks make the Nash non-cooperative solution concept inappropriate for justifying the CPR users’ decisions (Ostrom et al. 1994, Fehr and Fischbacher 2002, Ostrom 2010, Madani and Hipel in press).

Three major categories of CPR governance framework can be recognized by reviewing the CPR literature:

Non-cooperative management institutions. Individual actions are common under these institutions. CPR beneficiaries may either adopt non-cooperative CPR management plans, which
are based purely on individual rationality in which externalities are ignored, or develop heuristic CPR management plans, based on learning from past experience (Ostrom et al. 1994). Such heuristic behavior, while attempting to maximize individual benefits, considers also future outcomes and externalities and may contribute to the sustainability of the CPR as well. Our analysis in this paper allows identifying the effectiveness of various heuristic management plans.

**Exogenous institutions.** A regulator interferes by enforcing governing policies that regulate the exploitations (e.g., assigning exploitation rights, imposing maximum exploitation limits, taxation, etc.). The CPR beneficiaries react individually to the regulations. Cooperation among the CPR users is not expected under these institutions and increased benefits are obtained only when they obey the rules enforced by the higher authority. The analysis of exogenous institutions will be dealt in a future paper.

**Cooperative management institutions.** CPR users base their decisions on group rationality only and cooperate to minimize the externalities, prolong the CPR’s life, and increase their gains. The analysis of cooperative institutions will be dealt in a future paper.

Selection of the optimal CPR management institution out of these three major categories is challenging, as each institution category has various advantages and disadvantages. While, typically, parties gain more under cooperative management institutions, the implication of cooperative schemes may be complicated in practice due to high transaction costs. Success of each management institution may depend on a variety of factors, including, but not limited to, size of the CPR, number of beneficiaries, trust level among the users, total demand imposed on the CPR, and wealth and education levels of the beneficiaries (Tang 1991, Agrawal 2003). Indeed, the optimal CPR governance framework is case-dependant. Thus, it is unreasonable to suggest one management institution category as the superior and optimal one, believing that it works best for any CPR, for any society of users, and under any situation.

Considering the value of each CPR management institution category and its suitability for a given CPR and group of users, an in-depth study of each category is essential to compare the range of options available under each institution to increase the efficiency of CPR management, leading to sustainable CPRs. This paper focuses on the first category of the introduced CPR governance institutions, namely the non-cooperative CPR management institutions. By introducing various non-cooperative management institutions and examining them, using a numerical example (a groundwater system), this paper recognizes different alternatives to increase the gains of CPR beneficiaries under non-cooperative arrangements, while preserving the CPR. The paper also derives useful CPR non-cooperative management lessons and discusses their policy implications.

The paper is structured as follows: In the next section, various non-cooperative CPR management institutions are introduced and formulated. In sections 3, 4, and 5, a groundwater exploitation problem is introduced and modeled, based on different non-cooperative CPR management methods. The management institutions are applied, in section 6, to the groundwater exploitation problem and the results are compared and discussed. The paper concludes in section 7 with policy implications for sustainable management of CPRs in non-cooperative frameworks.
2. Non-cooperative CPR management institutions

A CPR exploitation problem can be defined as a pair \((e, S)\) where \(e = (e_1, e_2, \ldots, e_n) \geq 0\) and \(0 \leq \sum_{i=1}^{n} e_i \leq S\). \(e\) represents the vector of beneficiaries’ actual exploitations \((e_i \geq 0\) for beneficiaries \(i=1, 2, \ldots, n)\) and \(S\) is the total available (remaining) amount of CPR to be exploited. The beneficiaries’ actual utility in this problem is an \(n\)-tuple \(u = (u_1(e_1), u_2(e_2), \ldots, u_n(e_n))\) where \(u_i(e_i)\) is the utility of beneficiary \(i\) from his actual exploitation \((e_i)\). The beneficiaries’ expected utility in this problem is an \(n\)-tuple \(Eu = (Eu_1(ee_1), Eu_2(ee_2), \ldots, Eu_n(ee_n))\), such that \(e \leq ee_i\) and \(u_i(e_i) \leq Eu_i(ee_i)\) due to the effect of externalities\(^3\), where \(ee_i\) is beneficiary \(i\)’s expected amount of exploitation from \(S\) (\(\sum_{i=1}^{n} ee_i\) may be greater or smaller than \(S\), and \(Eu_i(ee_i)\) is the expected utility of beneficiary \(i\) from his expected exploitation \((ee_i)\).

One important characteristic of most non-cooperative CPR management environments is the lack of perfect information on the part of each beneficiary about the decisions and plans of other beneficiaries. In such a situation, users may benefit from speculations about plans of other users, based on their past experience and observations, to internalize the externalities in their planning.\(^4\)

In a non-cooperative framework, each beneficiary may adopt different decision rules to determine the amount he wants to exploit from the CPR. The set of decision rules indicates that a beneficiary may range from being an ignorant decision maker, who totally ignores the externalities, resulting in a big difference between his \(Eu(ee)\) and \(u(e)\), to being a smart decision maker, who learns from his past experience and continuously revises his exploitation plans, setting his \(Eu(ee)\) close to his \(u(e)\). In addition, heterogeneity in each decision maker’s ability (e.g., due to his location, accessibility of the CPR, and other initial conditions) affects his ability to adjust and his expected utility level. Below, we introduce and formulate a range of CPR management institutions for making decisions in non-cooperative situations.

2.1. Ignorant myopic management. Within this institution, the decision maker considers only his own short-term benefits (e.g., Holland and Moore (2003), Brooks et al. (1999), and Gordon (1954)). Therefore, instead of maximizing his benefits from the CPR exploitation over a long horizon \(H\), where \(h = 1, 2, \ldots, H\), he limits the planning time horizon to one time step \((h=1, or h=2, and so on)\) at a time, ignoring the externalities (effects of decisions of the other users on the CPR status and on his utility). Such a decision maker is ignorant. Although he may know about the externalities, because of his imperfect information about the decisions of other users, he simply maximizes his expected utility (\(Max Eu(ee)\)) over one time step without internalizing the externalities in his decision model. At the end of each time step, the ignorant myopic decision maker makes a new exploitation plan for the next time step, based on the latest status of the CPR as a result of his decision and other beneficiaries’ decisions in the previous time step. Therefore, within this institution, a decision maker has to develop \(H\) ignorant myopic exploitation plans (each specific to one time step), for using a CPR over a long time horizon, \(H\).

\(^3\) Externality is defined as the cost (or benefit), incurred by a CPR beneficiary who did not agree to the action causing that cost (or benefit).

\(^4\) In a game theoretic setting, the problem of imperfect information is solved by allowing repeated games (e.g., over time) so that the agents may acquire the needed information and improve their performance.
2.2. *Smart myopic management.* Similar to the ignorant myopic management institution, within this institution decision makers only consider their short-term benefits and limit their plans to one time step at a time. However, under this management institution, a decision maker is not considered to be ignorant as he tries to reflect the externalities by subjecting his decision making rationale (Max \( Eu(\epsilon e) \)) to heuristic constraints he develops through learning (e.g., penalties on exploitation, expected utility, etc.). This makes his decision model more accurate (less optimistic), resulting in a smaller difference between \( Eu(\epsilon e) \) and \( u(e) \) in comparison with the ignorant myopic management institution (in section 4, we introduce several heuristic constraints for reflecting the externalities). Similar to the ignorant myopic management institution, under the smart myopic management institution, a decision maker has to develop \( H \) exploitation plans (each specific to one time step), for using a CPR over the time horizon, \( H \).

2.3. *Fixed ignorant non-myopic management.* Within this management institution, each decision maker maximizes his gains over a long planning horizon, \( H \), by selecting one set of decisions (i.e., fixed \( \epsilon e \) over the whole planning horizon). Although being a long-term planner, the decision maker still acts ignorantly as he considers no constraint to represent the externalities in his planning model, which maximizes the total expected utility from the fixed \( \epsilon e \) over the planning horizon (Max \( \sum_{h=1}^{H} \epsilon u(h, \epsilon e) \)). While \( \epsilon e \) does not vary between time steps, \( Eu(\epsilon e) \) may vary between time steps, given the changing conditions of the CPR and the externalities. Under this institution, the decision maker develops only one exploitation plan at the beginning of the planning period without considering any revision during the exploitation period. While this is an interesting benchmark institution, it may seem as a naïve one.

2.4. *Variable ignorant non-myopic management.* Similar to the fixed ignorant non- myopic management, within this institution the decision maker considers a long planning horizon ignorantly. However, under this institution the decision makers’ exploitation rate (\( \epsilon e_h \)) may vary between time steps. Developing a single exploitation plan at the beginning of the planning horizon for maximizing the total expected utility (Max \( \sum_{h=1}^{H} \epsilon u(h, \epsilon e) \)) over the planning horizon is sufficient under this institution.

2.5. *Smart non-myopic management.* Under this institution, the decision maker updates his long-term exploitation plan on a continuous basis. A smart non-myopic management plan for time horizon \( H \) is composed of \( H \) variable ignorant non- myopic management plans. In other words, the decision maker develops one variable ignorant non-myopic management plan at the beginning of the planning horizon (Max \( \sum_{h=1}^{H} \epsilon u(h, \epsilon e) \)). At the end of the first time step, the decision maker develops a new variable ignorant non-myopic management plan for the next \( H \) years (Max \( \sum_{h=2}^{H+1} \epsilon u(h, \epsilon e) \)). This continues until the decision maker develops his last variable ignorant non-myopic plan for \( h= H, H+1, \ldots, 2H-1 \) (Max \( \sum_{h=H}^{2H-1} \epsilon u(h, \epsilon e) \)). Although the decision maker develops numerous ignorant non-myopic plans during the planning horizon, he is considered to be smart. The reason is that he tries to consider the externalities and address the
imperfect information problem by revising his long-term plan at the beginning of each time-step, based on the latest information about the status of the resources.

For clarification, a numerical CPR example is developed in the next section for application of the various management institutions.

3. Groundwater exploitation problem

Groundwater is one of the most studied types of CPRs (Gisser 1980, Worthington et al. 1985, Tsur and Graham-Tomasi 1991, Blomquist 1992, Provencher and Burt 1993, Schlager et al. 1994, Gardner et al. 1997, Herr et al. 1997, Koundouri 2004, Loaiciga 2004, Vrba and van der Gun 2004, Harou and Lund 2008). The complexity in estimating the externalities and monitoring exploitation when multiple groundwater users are present make the management of this CPR challenging. While to prevent overexploitation and to minimize the externalities, groundwater has been regulated to some extent in many areas (e.g., Metropolitan Water District of Southern California (MWD 2007) and other places (van Steenbergen No Date Provided)), this resource is still facing overdraft, mostly due to complexity in enforcing the groundwater rights and monitoring groundwater withdrawal. In some other places (e.g., the Eastern and Western La Manch Aquifer in Spain (Esteban and Albiac 2010a, Esteban and Albiac 2010b)) groundwater is not yet regulated or is poorly regulated, requiring the users to manage it in using a non-cooperative or cooperative institution. Groundwater has been selected in this study as a sample CPR. By developing a numerical groundwater use example and formulating various non-cooperative groundwater decision models, it is shown how groundwater can be managed in a non-cooperative environment.

Groundwater has been treated in the various groundwater management studies reported earlier, using either a command and control or cooperative approaches. This study extends the previous works by treating groundwater management in a non-cooperative way and applying mathematical formulations, which better reflect the groundwater behavior and the hydrogeologic characteristics of the problem, as well as the strategic nature of the user behavior. Below, we present the governing equations and main components of the groundwater decision-making models developed in this study.

3. 1. Groundwater drawdown and response functions. The drawdown of groundwater level during time \( t \) at distance \( \lambda \) from the center of a well with a discharge rate of \( Q \) can be approximated, using the following equation (Loaiciga 2004):

\[
s = \frac{Q}{4\pi T}(a \cdot \ln t + b), \quad \forall \lambda \quad (1)
\]

where, given the distance \( \lambda \), aquifer transmissivity \( (T) \) and storativity, coefficients \( a \) and \( b \) are estimated (Equation 1 varies by \( \lambda \)) by regression of Equation 1 against the predicted drawdown through the Theis equation for groundwater drawdown (Theis 1935), resulting in a reasonable approximation of drawdown (Loaiciga 2004).

When multiple (say \( n \)) wells tap water from the same aquifer, the drawdown in a given well (say well \( i \)) is not only affected by its own discharge, but also by the discharges of the \( n-1 \) wells around, each at distance \( \lambda_{ij} \) from well \( i \). For such condition, Equation 1 can be rewritten as (Loaiciga 2004):
\[ s_i = \frac{Q}{4\pi T} (a_i \ln t + b_i) + \sum_{j=1 \atop j \neq i}^{n} \frac{Q}{4\pi T} (a_{ij} \ln t + b_{ij}) \quad \forall \lambda_{ij} \]  

(2)

where the first term in the right-hand side of Equation 2 represents the drawdown caused by the \( i \)th well itself, and the second term represents the drawdown caused by the other \( n-1 \) wells around. In this equation, coefficients \( a_{ij}, b_{ij}, a_{ij}, \) and \( b_{ij} \) depend on the relative locations of other wells with respect to well \( i \) (Loaiciga 2004).

Equation 2 clearly indicates that groundwater is a subtractable resource. So, any exploitation from the resource by one user, limits the available amount to others. In other words, pumping and lowering the water table at one well lowers the water level in other wells, as well.\(^5\) Indeed, Equation 2 is the key element for estimation of the externalities, if perfect information about the amounts of groundwater use at other pumps is at hand. Nonetheless, in practice, not only such information is not available (or reliable), but also estimation of actual drawdown is not easy for groundwater users, given the complexity of Equation 2.

3.2. Cost functions. Energy is used for pumping groundwater. Thus, groundwater pumping has some costs to the users. The following equation can be used to estimate the groundwater pumping cost at a given well (modified from Loaiciga and Leipnik (2000)):

\[ C_{irr} = (us + v + d_{i-1})Q \]  

(3)

where \( u \) and \( v \) are cost parameters, \( d_{h-1} \) is the water depth in the well at the end of previous time step \( (h-1) \), \( Q \) is the total pumped volume (discharge), and \( s \) is the groundwater drawdown, resulting from \( Q \) (calculated based on Equation 1 or 2).

Groundwater may be used by farmers who withdraw water for growing crops. A farmer who pumps groundwater for irrigated agriculture has to pay for irrigation water and other farming production costs (including harvesting costs, and irrigation facilities and well maintenance costs). The total cost to a farmer is:

\[ C = C_{irr} + C_{Tech} + C_{Other,x} \]  

(4)

where \( C_{Tech} \) is a one-time initial investment for buying pumps and other irrigation technologies, represented by the annual-equivalent cost, and \( C_{Other,x} \) (cost of seeds, fertilizer, planting, harvesting, etc.) assumed to be:

\[ C_{Other,x} = i_{lx} l^2 + j_{lx} l + k_{lx} \]  

(5)

where \( l_x \) is the area under irrigation for growing crop \( x \), and \( i_{lx}, j_{lx}, \) and \( k_{lx} \) are cost parameters that depend on the crop type \( (x) \) (these parameters should be defined such that \( C_{Other,x} \geq 0 \) and \( i_{lx} < 0, \frac{dC_{Other,x}}{dQ} \geq 0 \)).

3.3. Yield function: Assuming that the total crop yield is a function of the crop type \( (x) \), the area under irrigation for growing crop \( x \) \( (l_x) \), and the amount of water used for irrigation of crop \( x \) \( (Q_x) \), the total crop yield can be defined as:

\(^5\) Negri (1989) distinguishes between a pumping cost externality and a strategic externality that arises from the competition among users to capture the groundwater reserves. Our model addresses the pumping cost externality only.
\[ Y_l = (p_l^2 + q_l)Q \]  
(6)

where \( p \) and \( q \) are the parameters (\( Y_x \geq 0, p_x < 0, q_x > 0, \) and \( \frac{dY}{dl} \geq 0 \)).

3.4. Profit function: The revenue, gained through selling the crop at the end of the growing season equals:

\[ R = \sum_x z_x Y_x \]  
(7)

where \( z_x \) is the price per weight unit of the crop \( x \). Given Equations 4 and 7, the total profit of a farmer equals:

\[ P = R - C \]  
(8)

In planning for farming operations, each farmer needs to estimate the total present value of his profit over the planning horizon. The present value of the profit received in time step \( h \) equals:

\[ P_r = Pe^{-rh} \]  
(9)

where \( r \) is the time-step dependent discount rate. Given Equation 9, the total present value of his profit over the planning horizon is:

\[ Z = \int_0^H Pe^{-rh} dh \]  
(10)

where \( H \) is the length of the planning horizon or the number of time steps (e.g., years) that the decision maker considers at the beginning of the planning horizon.

Normally, each farmer is willing to maximize his total profit over his planning period. However, within the CPR context, the status of the resource is affected by operations of all exploiters, which may fail to operate the resource in an optimal and sustainable manner. Next, we will discuss how the objective function of the farmers may vary, depending on the non-cooperative operation institution they select\(^6\).

4. Non-cooperative groundwater management institutions

The groundwater exploitation problem is formulated below, based on the various non-cooperative CPR management institutions, introduced in section 2

4.1. Ignorant myopic management. Using this institution, each farmer maximizes his expected profit (\( P_{h,i} \)) at a given time step, \( h \), at the beginning of each time step, given the status of the CPR at \( h \) from farmer \( i \)'s point of view (each farmer only considers the groundwater level in his own well). Mathematically, each farmer uses the following optimization model \( H \) times (for \( h = 1, 2, \ldots, H \)):

Maximize \( P_{c,h} \)  
(11)

\(^6\) We assume that all farmers apply the same management institution. Therefore, there is a public choice issue here that to be addressed. We refer to it in a later section.
subject to:

Equation 1

Equations 3-8

where for farmer \( i = 1, 2, ..., n \): \( R_{i,h} \) is the farmer \( i \)'s profit in time step \( h \).

While at the beginning of each time step, decisions are made based on Equation 1 without consideration of the effects of other farmers’ exploitation rates (the externalities), at the end of each time step, the farmer finds the actual drawdown based on Equation 2 and his actual profit. Using the latest information about the status of the CPR from his point of view (the water depth in the well under his operation), the farmer finds his optimal operation policies for the next period, and so on. The total gain of a farmer during the planning horizon (\( H \)) can be calculated using Equation 10 and the realized profits, (with possible complete dissipated rents (Gordon 1954, Brooks et al. 1999)) at the end of each step.

4.2. Smart myopic management. Farmers develop heuristic rules, based on their learning from the past in order to act non-myopically, when making short-term decisions. These rules help to minimize the difference between the expected profit and drawdown, based on Equation 1, and the actual profit and drawdown, based on Equation 2. To apply the heuristic rules, the farmers may revise the ignorant myopic management model (presented in section 4.1) by revising the objective function or constraints and/or by adding new constraints. As examples, two of these heuristic rules and their corresponding decision model’s mathematical formulations are presented below. This is equivalent to some extent to the Pigouvian tax (Tietenberg and Lewis 2008), levied, by a social planner, on a production process that creates negative externalities and aimed at internalizing individual externalities.

4.2.1. Smart myopic management with drawdown penalty. Over time, farmers learn that, as a result of pumping by other farmers, the actual drawdown (Equation 2) is normally more than what they predict at the beginning of that time-step (Equation 1). Therefore, they may impose a drawdown penalty to make their decision model less optimistic and to account for such possible differences. Nevertheless, in developing short-term plans, farmers make decisions for one time step only. In that case, the decision model can be formulated as:

Equation 11

subject to:

\[
\begin{align*}
    s_{i,h} &= \frac{Q_{i,h}}{4\pi T} (a ln h + b) + sp_{i,h} \\
    sp_{i,0} &= 0 \quad \text{(initial condition)} \\
    sp_{i,h} &= \sum_{h=1}^{h-l} sp_{i,h-l} \quad (h=2, 3, ..., H) \\
    sp_{i,h} &= s_{i,h} - 1 \cdot Eq2 - s_{i,h-1} \cdot Eq3
\end{align*}
\]  

Equations 3-8
where for farmer \( i = 1, 2, \ldots, n \): \( \overline{sp}_i \) is the drawdown penalty for farmer \( i \) in time step \( h \), equal to the average of drawdown penalties in the previous time steps; \( sp_{i, h} \) is the drawdown penalty for farmer \( i \) at time step \( h \); \( si_{i, h-1: \text{Eq 2}} \) is the actual drawdown in the previous time-step, calculated based on Equation 2; and \( s_{i, h-1: \text{Eq 13}} \) is the expected (pre-estimated) drawdown in the previous time-step, calculated based on Equation 13. At the end of each time step, the farmer finds the actual drawdown and his profit. The total gain of a farmer during the planning horizon \( (H) \) can be calculated using the actual profits, based on Equation 10.

In this study, only a few different heuristic rules are presented. But, in practice, farmers do not always use the heuristic rules suggested here to reflect their learning and past experiences. They may develop many different forms of heuristic constraints to account for the externalities (van Steenbergen No Date Provided). For example, in our management model, a more conservative (or pessimistic) farmer, who uses drawdown penalties in his decision model, may replace \( s_{i, h-1: \text{Eq 13}} \) in Equation 16 with \( si_{i, h-1: \text{Eq 1}} \) and calculate the expected drawdown in the previous step using Equation 1 (or the first term in Equation 13), resulting in higher drawdown penalties and more conservative decisions (this case is not considered in the present paper). Another example is a forgetful farmer with a short-term memory, who only considers the difference between the expected and actual drawdown in the previous time step, as opposed to the average of differences over the previous time steps. Such a farmer bases his decisions on his latest experience, resulting in less conservative decisions (this case is not considered in the present paper).

4.2.2. Smart myopic management with profit penalty. Instead of a drawdown penalty, farmers may use a profit penalty to account for the possible difference between their expected and actual gains. In that case, the farmers’ decision model may be formulated as follows:

Maximize \( P_{i, h} - \overline{Pp}_{i, h} \) \quad (17)

subject to:

Equation 1

Equations 3-8

\[ \overline{Pp}_{i, 1} = 0 \quad \text{(initial condition)} \] \quad (18)

\[ \overline{Pp}_{i, h} = \frac{\sum_{l=1}^{h-1} Pp_{i, l}}{h-1} \quad (h=2, 3, \ldots, H) \] \quad (19)

\[ Pp_{i, h} = P_{i, h-1: \text{Eq 17}} - P_{i, h-1: \text{Eq 2}} \] \quad (20)

where for farmer \( i = 1, 2, \ldots, n \): \( \overline{Pp}_{i, h} \) is the profit penalty for farmer \( i \) in time step \( h \) equal to the average of profit penalties in the previous time steps; \( Pp_{i, h} \) is the profit penalty for farmer \( i \) at time step \( h \); \( P_{i, h-1: \text{Eq 2}} \) is the actual profit in the previous time-step, calculated based on the actual drawdown (Equation 2); and \( P_{i, h-1: \text{Eq 17}} \) is the expected profit in the previous time-step, calculated based on the expected drawdown in the previous step (Equation 1), using Equation 17. At the end of each time step, the farmer finds his actual profit. The total gain of a farmer during the planning horizon \( (H) \) can be calculated using the actual profits and Equation 10. An application of this management institution can be found in Kotchen and Salant (Kotchen and Salant 2009).
A more conservative (or pessimistic) farmer may replace $P_{i, h-1}; \text{Eq } 17$ in Equation 20 with $P_{i, h-1}; \text{Eq } 1$ and calculate the expected drawdown in the previous step using Equations 1 and 8 (or the first term in Equation 17), resulting in higher profit penalties and more conservative decisions (this case is not considered in the present paper). For a less conservative and more forgetful farmer, the profit penalty may equal the difference between his actual and expected profits in the previous time step only (these cases are not considered in the present paper). The choice of the decision rule and heuristic decision model depends and a variety of factors including, but not limited to, behavioral characteristics of the decision maker, his trust level to other farmers, his first-hand experience and learning.

4.3. Fixed ignorant non-myopic management: Based on this institution, each farmer determines his optimal operation policies at the beginning of the planning horizon by maximizing his total present profit over the planning horizon without considering the effects imposed by other farmers on the status of the CPR from his point of view. Having a fixed management decision set (which includes decision variables such as pumping rate, drawdown, crop type, area under irrigation, etc.) is the important characteristic of this management institution. For the groundwater exploitation problem, farmer $i$ ($i=1, 2, ..., n$), who farms at farm $i$ and pumps from well $i$, maximizes his total present profit ($Z_i$), using the following optimization model:

$$\text{Maximize } Z \quad (21)$$

subject to:

$\text{Equation 1}$

$\text{Equations 3-8}$

$\text{Equation 10}$

where decision variables $Q, s, x, l_s$ do not vary between time steps (as opposed to $Q_{h}, s_{h}, x_{h}, l_{s,h}$). A farmer, who makes his decisions based on this management institution, finds the selection of a fixed decision set to be more convenient than a variable decision set, especially in the absence of perfect information. Within this institution, the farmer ignores the imposed effects of other farmers (Equation 2). Therefore, his actual gained profit and operations will be different from the estimated profit and operations, using the above model. For instance, the actual drawdown, which will be higher than the predicted drawdown by each farmer (the actual drawdown can be determined by simultaneous solving of the above optimization model for all farmers), may make pumping uneconomical before the end of the planning horizon. An application of this management institutions is presented in Loaiciga (2004).

4.4. Variable ignorant non-myopic management: The general structure of the variable ignorant non-myopic management model is similar to the fixed ignorant non-myopic management model. However, under this management institution farmers use the above model with some modifications to find decision variables that vary between time steps ($Q_{h}, s_{h}, x_{h}, l_{s,h}$ as opposed to $Q, s, x, l_s$). A farmer who chooses a variable decision set believes that by changing his decisions between years, he can gain more and also prevent other farmers from having perfect information about his decisions.

4.5. Smart non-myopic management: A farmer who is smart (considers the externalities) and acts non-myopically (considers a long planning horizon) may adopt this management institution in a non-cooperative CPR environment with imperfect information. Based on this method, a farmer
develops his long-term plan using the variable ignorant non-myopic decision model and starts exploiting the resource. At the end of the first time-step, since he learns his actual gains are different from what he had planned as a result of externalities, he develops another variable ignorant non-myopic plan, based on the latest status of the CPR from his point of view (depth of water in his well). The strong belief in long-term planning and consideration of the externalities motivates the farmers within this institution to develop and revise long-term plans. The continuous update of the long-term plan makes the farmers smart, although they develop ignorant plans at the beginning of each time step.

As an alternative, farmers may replace variable ignorant non-myopic plans with fixed ignorant non-myopic plans at the beginning of each time step (this case is not considered in the present paper).

5. Numerical example

We provide an illustrative example to demonstrate how the introduced non-cooperative groundwater management institutions can be applied in practice to develop various policy options. This example shows how choice of management institution can affect the status of the CPR and its beneficiaries in the long-run. The example includes three farmers ($i= A, B, C$) who tap the same aquifer (Figure 1). Although, having only three farmers makes the problem somewhat simplistic, it allows capturing the basic characteristics of a CPR exploitation problem. Here, the three wells are benefiting from natural recharge, which varies across the wells. Some recharge also results from the water use of each farmer on his land, as well as the water use of other farmers located at higher elevations. Thus, the net well discharge can be calculated as:

$$Q_{\text{net}} = Q_i - (Q_{i,r} + \theta_i + \sum_{j \neq i} \omega_{i,j} Q_j) + Q_{e,i}$$  \hspace{1cm} (22)$$

where: $Q_i$ is the amount of pumped discharge at the $i$th well; $Q_{i,r}$ is the natural recharge of the $i$th well; $\theta_i$ is the ratio of return flow to well $i$ from water use on farm $i$; $\omega_{i,j}$ is the ratio of return flow to well $i$ from water use on a nearby farm $j$; and $Q_{e,i}$ is the evaporative losses from well $i$. It is implicit that in calculating the drawdown (using Equations 1 and 2) the net discharges should be used.

Tables 1 and 2 present the values of farmer-dependent and crop-dependent parameters used here, respectively. Here, the farmers, each operating only one well, are assumed to have two crop options (crop 1 and crop 2). The values of independent variables are $a= 9.125$, $b= 140$, $t= 365$ (given the values of other parameters, in this example, $t$ should be set equal to 365 in Equations 1 and 2 to calculate the drawdown over one time–step ($h$), which represents one year), $T= 6,960 \text{ m}^2/\text{day}$, $u= 7.2 \text{ \$ m}^{-3}/\text{m}^1$, $v= 10 \text{ \$ m}^{-3}$, and $r= 5 \%/\text{year}$. It is also assumed that the farmers stick to the technology they are currently using. So, $C_{\text{Tech}}$ is assumed to equal zero during the planning horizon. For simplicity, the evaporative losses from the wells are assumed to be minimal ($Q_{e,i}= 0$). As shown in Figure 1, the farms are located on land with some slope. Thus, the vertical pumping distances are not equal (the initial well’s water depth is represented by $d_0$, given in Table 1).
6. Results

Since studying the long-term effects of different management policies on the CPR status is the focus of this study, the numerical example is solved using the suggested management institutions over a 50-year planning period ($H=50$), which is considered to be reasonably long for the purposes of this study, considering the computational limitations. The groundwater quality issues are not considered in this study and can be the scope of future research.

Results of different model runs are presented in Figures 2 to 4 and Table 3, indicating how some key variables of farmers’ decision models change under different management institutions. Below, we discuss the modeling results under each management institution.

6.1. Ignorant myopic management. Since the long-term effects of withdrawal policies are ignored under this management institution, farmers try to maximize their profit within each time step, with no future consideration. Therefore, the ignorant myopic decision makers start operations with an aggressive exploitation of the resource. As shown in Figure 2a, the annual drawdown is greater in the beginning, and decreases over time as the growing water depth increases the pumping cost dramatically, putting some farmers out of business (Farmers B and C, as shown in Figure 3a and 4a). Farmers with higher levels of wealth (i.e., Farmer A who owns a larger land area, resulting in lower costs and higher crop yield per unit area due to economies of scale (Equations 5 and 6)), can stay in business for a longer period of time than farmers with lower levels of wealth (i.e., Farmer C, who does not grow crops in one-third of the years). Therefore, the total groundwater withdrawal and drawdown over the planning horizon are higher for the wealthy farmers who benefit from their power during the implicit competition. In this example, at the beginning of the period, Farmer A grows a higher-value crop (crop 1), which also has higher water demand and growing costs overall. As the groundwater depth and the resulting pumping costs increase, this farmer prefers to grow the lower-value crop (crop 2). Due to the high costs of growing crop 1 and the smaller farm size (diseconomies of scale) Farmer C never grows crop 1 during the 50-year period. Farmer B grows crop 1 only in the beginning of the planning period (6% of the years).

As shown in Figures 2a and 3a, all farmers experience differences between their anticipated drawdown and profit at the beginning of each time step. They also experience differences between their actual drawdown and profit at the end of that time step, due to the unaccounted externalities. Over time, the difference gets smaller for all parties as they lower their withdrawals. The relative difference between the perceived and actual water depths and profits are the lowest for Farmer A, with the highest pumping rate (Figures 2a and 3a, and Table 3). Therefore, the amount of externalities that other farmers create for him is less than the amount he creates for other farmers. The opposite is true for Farmer C, with the lowest pumping rate (due to the lowest farm size, or wealth). As indicated in Table 3, the difference between the overall actual and perceived profits may range from 12% for Farmer A, to 258% for Farmer C, with the actual gain always less than the perceived gain, due to the unaccounted externalities. Although, Farmer C pumps water from the well with the lowest depth to water table (the lowest pumping costs (Equation 3)), and the highest recharge flows, due to the smallest farm size, he appears to be weakest in this competition, ending up with economic losses or negative profit (Figure 3a).

---

7 This result has important policy implications with regards to impact of policy interventions on equity distribution, especially in developing countries (Seema et al. 2008).
and the highest difference between the perceived and actual gains over the 50-year horizon (Table 3). In this example Farmer B is the middle case between Farmers A and C, considering his farm size and vertical distance from the water table. The total gains of the farmers are lowest under the ignorant myopic management institution (Table 3), making this management institution inferior to other possible non-cooperative management methods. Although changes in the discount rate result in changes in the overall gain of the farmers, their operation policies are insensitive to the discount rate as long as they are planning for short term.

6.2. Smart myopic management. In comparison with ignorant myopic management, both types of smart myopic management (with drawdown penalties (Figures 2b and 3b) and with profit penalties (Figures 2c and 3c)) are superior in terms of the overall profit to the farmers (Table 3) and the differences between the actual and perceived water depth (Figure 2b and 2c), and profits (Figure 3b and 3c). Comparison of Figure 2a with Figures 2b and 2c indicates that the annual drawdown trend does not vary significantly with changing the management institutions as long as the plans include short-term management institutions.

By acting smartly (considering the externalities), Farmer A can estimate his total gain over the 50-year period with 1% error. As a result of overestimating the penalties in some years (based on past experience), some farmers may end up with actual gain, that is higher than the perceived gain in those years (Figure 3b and 3c). Despite overestimating the penalties in some years, Farmer C still suffers from overestimation of his annual profit and experiences negative profit overall. Nevertheless, this farmer can reduce his losses by acting smartly even with short-term planning. Over time, the difference between the actual and perceived drawdown and profit decreases, as a result of a decrease in total withdrawal (reduced externalities) and learning.

The farmers’ choice of crop (Figures 4b and 4c) does not change significantly by considering the externalities, using different types of penalties. That is not true for Farmer B, who does not grow crops in 50% of the years when he considers profit penalties, resulting in less drawdown and gain overall, compared to the case in which drawdown penalties are used. Planning with consideration of profit penalties is a better choice of management institution for Farmers A and C. Though, the sum of farmers’ total gain in the 50-year period is larger when they consider drawdown penalties, as opposed to revenue penalties. The withdrawal policies are insensitive to the interest rate under this management institution, as the farmers plan for one time step at a time.

6.3. Fixed ignorant non-myopic management. Table 3 and Figures 2d and 3d show how farmers can increase their profit during their planning period by replacing short-term policies with long-term ones. Based on this management institution, farmers develop fixed decisions to maximize their profit over their planning horizon. Since each farmer’s annual withdrawal and the resulting annual drawdown are constant, water depth (Figure 2d) and pumping cost (Equation 3) increase linearly over time, resulting in a linear drop in the farmer’s annual profit.

Although, more profit at the beginning of the planning period is preferred over more profit toward the end of the planning period (considering the non-zero discount rate), the farmers do not exhaust the resource entirely in the beginning. Farmers do not replace higher profit levels in the earlier years with no profit in later years, as a continuous exploitation of the resource is more profitable than a disrupted exploitation pattern. However, by increasing the discount rate, the fixed exploitation rate increases, underlying the impact of interest rate on the withdrawal policies of groundwater users. Figure 4d indicates that farmers grow crops in all years. When planning
long term, to reduce the water depth and pumping costs in later time steps, farmers prefer to
grow the low-value crop (crop 2) during the entire planning period, which has less water needs
and also lower growing costs.

Based on the difference of the perceived water depth curves of the three farmers (Figure 2d), one
may conclude that wealthier farmers (with larger farm size) prefer to withdraw more from the
resource, while farmers with lower levels of wealth prefer to withdraw less from the resource. To
be able to use the resource in the long run, poorer farmers try to withdraw from the resource at a
sustainable rate, using a fixed pumping rate over the planning horizon. In this example (Figure
2d), Farmer C who has the lowest wealth level prefers to pump at the sustainable rate (withdraw
equal to recharge). Therefore, the slope of his perceived drawdown curve is zero. This farmer
prefers a continuous business with lower annual profits to an interrupted business, even if
gaining higher profits in the beginning is possible. On the other hand, Farmers A and B, who are
wealthier, pump more than the sustainable rate, with Farmer A (who has a larger farm) pumping
at the higher rate. The rate of pumping is highly dependent on the length of the planning horizon.
Here, a 50-year period has been selected as the planning horizon. Therefore, the optimization
model seeks the most profit during this period with no consideration of future (beyond the 50-
year limit). Therefore, the model suggests pumping at rates higher than the sustainable rate for
Farmers A and B, who can stay in business during the whole planning horizon with such a
pumping rate. If a longer planning horizon is considered, the decision model suggests lower
fixed pumping rates for both farmers to ensure their continuous stay in business. By expanding
the planning horizon, the farmers lower their fixed pumping rates until they reach a sustainable
exploitation rate. In this example, the planning horizon, which requires a fixed sustainable
pumping rate, is shorter for Farmer B than for Farmer A. For Farmer C, the 50-year planning
horizon is long enough to force him to set his exploitation rate equal to the recharge rate.

The difference between the slopes of the actual and perceived water depth and profit curves of
each farmer (Figures 2d and 3d) indicates in relative terms how much that farmer is affected by
the externalities. Based on this figure, one may conclude that the farmers with higher wealth
levels, who can withdraw more from the resource, are less affected by the externalities.
Therefore, the slope difference between the anticipated and actual drawdown or profit curves is
lower for a farmer who withdraws more (Farmer A in this case) than for a farmer who withdraws
less (Farmer C in this case).

Since farmers behave ignorantly and do not consider the externalities in their long-term plans,
they underestimate the actual drawdown and profit (Figures 2d and 3d). As a result of ignorant
planning, Farmers B and C end up with losses in later years. However, since the farmers plan for
long term, their estimations are relatively better than their estimations based on different short-
term planning options. Thus, the difference between the actual and perceived total profit is
smaller when ignorant farmers plan for long term, compared with planning for short-term (Table
3), even if they are smart (consider the externalities). Also, the final water depth in each well and
the total profit of each farmer decrease and increase respectively, when short-term planning is
replaced with long-term planning.

6.4. Variable ignorant non-myopic management. Based on ignorant non-myopic plans with
variable decisions, farmers increase their withdrawal over time, as shown in Figure 2e. The
lower pumping rates in the beginning of the period allow the farmers to stay in business in later
time steps. Since farmers do not consider any point beyond the end of the planning horizon, their
decision models suggest aggressive withdrawal and exhaustion of the resource in the last years of the planning horizon. Similar to the fixed ignorant non-myopic management, under this institution farmers grow the lower-value crop (Figure 4e) to ensure a sustainable resource withdrawal and business. Since externalities are ignored under this institution (ignorant planning), with increasing the withdrawal, the difference between the perceived and actual drawdown curves of each farmer increases over time (Figure 2e). The total drawdown in each well is less than the case in which short-term plans are developed, and not significantly different from the case in which fixed ignorant non-myopic exploitation policies are used.

Similar to other management institutions, under the variable ignorant non-myopic management institution, farmers’ revenue decreases over time with increasing pumping costs (Figure 3e). As a result of ignorant planning, Farmers B and C incur negative profits toward the end of the planning horizon. While under this type of management institution, Farmer A’s total gain is slightly more than his gain under the fixed ignorant non-myopic management institution, Farmers B and C gain less by replacing their fixed decisions with variable decisions in their long-term plans (Table 3). The sum of the farmers’ total gains under this management institution is higher than the sum of total gains under other management institutions, reviewed so far. An increase in the discount rate motivates the farmers to use the resource more aggressively in earlier years while a decrease in the discount rate has an opposite effect.

Comparison of Figures 2d and 2e suggests that when variable decisions are allowed within a long-term exploitation plan, Farmer C deviates from the sustainable exploitation rate in the last decade of the planning horizon. This puts him in a worse position compared with the case in which fixed decisions are used in the long-term plan. Therefore, a planning horizon longer than 50 years is required for this farmer under this institution to converge his pumping to the sustainable rate. Similarly, the planning horizon that enforces sustainable exploitation by other farmers under this management institution is longer than the planning horizon under the fixed ignorant non-myopic management institution. The required length of the planning period increases with the wealth of the farmers.

Since the sum of the farmers’ gains increases by replacing variable decisions with fixed decision in an ignorant non-myopic plan, one may conclude that the variable ignorant non-myopic management institution is inferior to the fixed ignorant non-myopic management institution. However, since the difference between the sums of the farmers’ gains under the two management institutions is not significant, more study is required to derive such a conclusion with certainty. The difference between the exploitation rates under the fixed and variable ignorant non-myopic management institutions is expected to decrease by extending the planning horizon. If the planning horizon is long enough, both management institutions result in withdrawal at a sustainable rate over the entire planning horizon.

6.5. Smart non-myopic management. As shown in Figure 2f, under this institution farmers’ exploitation rates in the first years are similar to those under ignorant non-myopic management institution. However, since farmers plan smartly under this institution, they soon realize that in order to reduce the future costs, there is a need for reducing the withdrawal. Therefore, after the first few years, the slope of the water depth curves diminishes. As discussed, the slope of the water depth curve depends on the wealth level of the farmer. Here, Farmer C reaches the zero slope very soon. The other farmers need a longer planning horizon to equal their exploitation to the recharge rate. The continuous revision of the exploitation plan reduces the difference
between the anticipated and actual resource level and profit, resulting in the best predictions by the decision makers among all different management institutions studied here (Table 3). Farmers A and B stay in the business during all years by growing the lower-value crop. Although, after few years Farmer C plans to exploit at the sustainable rate to keep the water depth at a constant level, the externalities imposed on this farmer force him to quit the business in some years and wait until the water depth gets higher through recharge. Although this farmer does not grow any crop in 30% of the years, his overall profit is higher now than in the other management institutions in which. In fact, under this type of management institution, this farmer never incurs any negative profit (true for other farmers, too) and he only grows crops when profitable. Therefore, even staying out of business for some years does not make his overall profit less than other cases in which he incurs profit losses. Similar to other long-term planning institutions, increase in interest rates can encourage more aggressive exploitation of the resource in earlier years.

The smart non-myopic management of the resource also results in the highest profit for all the CPR beneficiaries, making this management institution strictly superior to all other management options in this study.

7. Conclusions and policy implications

By focusing on non-cooperative CPR management, this paper demonstrated how different non-cooperative management institutions can affect the status of the CPR and the gains of its beneficiaries in the long run. The ignorant myopic management is the worst type of management, which results in a rapid exhaustion of the resource and in the least profit to users, as suggested by “tragedy of the commons” literature. However, results of our analysis indicates that even within a non-cooperative framework, parties can obtain less tragic outcomes and improve their gains by: 1) acting smartly and considering the externalities; and 2) acting non-myopically and developing long-term exploitation plans. Results show that long-term planning is more effective than ignorant short-term planning in increasing the gains to the CPR users. The best results were obtained under the smart non-myopic management institution, making this institution superior to all other options. Considering a very long planning horizon can result in a sustainable use of the resource.

Externalities may be addressed in exploitation plans through consideration of different penalties, based on learning and past experience. The users’ long-run benefits are highly sensitive to the length of the planning horizon. Results indicate that while both smart and non-myopic planners gain more than the ignorant short-term planner, the smart myopic planner gains less than an ignorant non-myopic planner. Therefore, long-term planning is more effective in improving the users’ benefits than short-term planning with penalties. The maximum gain occurs under the smart non-myopic management in which externalities and long-term effects are considered simultaneously.

CPR users should be encouraged to consider the long-term effects of their actions on the CPR and the economic losses they may incur in the future by aggressive exhaustion of the resource in early stages. A user who considers a very long planning horizon will exploit at a sustainable rate.

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8 A similar result was obtained by Dinar and Xepapadeas (1998, 2002).
Therefore, the longer the planning horizon, the higher the overall profit. Due to learning and experience, CPR users deviate over time from the ignorant myopic planning and adopt institutions that can increase their overall gains. Therefore, in practice, outcomes are not as tragic and pessimistic as suggested by the “tragedy of the commons” theory. When external intervention is possible, various incentives (e.g., tax incentives for sustainable use of the resource) may be imposed to achieve better outcomes (than those predicted by “tragedy of the commons”).

Results also imply that the CPR users may change their exploitation strategy over time, not only as a result of learning, but also as a result of lower CPR levels. In our example, farmers reduced their groundwater withdrawals with time. Farmers will eventually set their exploitation rate equal to the recharge rate and pump at a sustainable exploitation rate. In case of renewable CPRs, natural limitations (e.g., lower groundwater levels) are eventually imposed on the users to prevent them from further exhaustion of the resource in an unsustainable manner. However, the natural limitations are not always desirable and, in some cases, CPRs may become unusable over a period before exploitation is resumed. For instance, groundwater over-pumping not only increases energy costs, but also can create land subsidence and water quality issues, which may make the resource unusable for some period. When external intervention is possible, to avoid undesirable conditions caused by natural limitations, external limitations, such as quotas, pumping curfew, and size and type of pumping technology, may be also imposed on the users, via effective policies, to prevent them from further exhaustion of the resource in an unsustainable manner.

The difference between the perceived and actual profit decreases as users get wealthier, suggesting that wealthier users are less vulnerable to the externalities, created by other users. This means they are less likely to respond to regulations, which is consistent with theory. When governments can interfere, different policy measures may be adopted to protect the poor users against wealthier users (e.g., imposing revenue taxes, removing electricity price subsidies for wealthier users).

While short-term exploitation plans are insensitive to the discount rate, high discount rates can motivate the long-term CPR exploitation planners to exhaust the resource more aggressively, as higher profits in early stages are more desirable to lower profits in the years to come. Therefore, an unstable economy can encourage unsustainable CPR exploitation by users with a long foresight level. However, in regions with stable economies with low-interest rates, these users benefit from trust to the future economic conditions and have incentives to develop long-term sustainable exploitation plans, supporting continuous business and profit.

The opposite slopes of the drawdown and revenue curves have an important policy implication, suggesting that rush for exhaustion of the resource results in a sharp drop in the gains of the parties. However, when the parties lower their exploitation rate, they can expect longer use of the resource (if renewable). The dominant strategy for a renewable CPR user is to set the slope of the drawdown curve equal to zero, which results in a revenue curve with the same slope, ensuring a sustainable use of the resource and benefit to the user. When all parties exploit at a sustainable rate, the externalities are minimal. Therefore, a sustainable resource extraction can be achieved even within a non-cooperative framework. However, in practice, the fear of other users using the resource at a rate higher than the sustainable withdrawal rate may result in a competitive behavior and deviation from sustainable exploitation. Communication, education, and
governmental incentives can help create trust among the users and ensure sustainable CPR use within a non-cooperative management environment, which is often the case when a large group of users is involved.

The results presented in this study belong to cases in which all CPR beneficiaries use the same management institution. In practice, however, users may adopt different types of management institutions, based on their preferences, knowledge, experience, foresight level, and behavioral characteristics. Future work may consider studying the situations in which a mix of management institutions is used by different CPR users.

8. References


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Table 1: Values of farmer-dependent parameters

<table>
<thead>
<tr>
<th>Farmer</th>
<th>Parameter</th>
<th>a_A</th>
<th>a_B</th>
<th>a_C</th>
<th>b_A</th>
<th>b_B</th>
<th>b_C</th>
<th>l (ha)</th>
<th>Q_p (m^3/year)</th>
<th>r</th>
<th>Θ</th>
<th>ω_i,A</th>
<th>ω_i,B</th>
<th>ω_i,C</th>
<th>d_0 (m)</th>
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<tbody>
<tr>
<td>A</td>
<td></td>
<td>9.125</td>
<td>5.423</td>
<td>3.640</td>
<td>140</td>
<td>100</td>
<td>50</td>
<td>40</td>
<td>1,000</td>
<td></td>
<td>0.08</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>20</td>
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<tr>
<td>B</td>
<td></td>
<td>5.423</td>
<td>9.125</td>
<td>6.684</td>
<td>100</td>
<td>140</td>
<td>115</td>
<td>28</td>
<td>900</td>
<td></td>
<td>0.07</td>
<td>0.085</td>
<td>-</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>3.640</td>
<td>6.684</td>
<td>9.125</td>
<td>50</td>
<td>115</td>
<td>140</td>
<td>15</td>
<td>750</td>
<td></td>
<td>0.06</td>
<td>0.035</td>
<td>0.075</td>
<td>-</td>
<td>9</td>
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Table 2: Values of crop-dependent parameters

<table>
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<tr>
<th>Crop</th>
<th>Parameter</th>
<th>i ($/ha^2/year)</th>
<th>j ($/ha/year)</th>
<th>k ($/year)</th>
<th>p (ton/m^3/ha^2/year)</th>
<th>q (ton/m^3/ha/year)</th>
<th>z ($/ton)</th>
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<tr>
<td>1</td>
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<td>-9.8175×10^{-3}</td>
<td>892.5</td>
<td>2.769</td>
<td>-2.49×10^{-10}</td>
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<td>689.4</td>
<td>0.611</td>
<td>-7.51×10^{-11}</td>
<td>0.0280</td>
<td>134</td>
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Table 3: Perceived and actual gains of the farmers under different non-cooperative management institutions over the 50-year planning horizon

<table>
<thead>
<tr>
<th></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>
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</thead>
<tbody>
<tr>
<td>Farmer A</td>
<td>Perceived</td>
<td>1,596,319</td>
<td>1,620,489</td>
<td>1,730,938</td>
<td>2,337,687</td>
<td>2,354,075</td>
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<tr>
<td></td>
<td>Actual</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>
</tr>
<tr>
<td>Difference</td>
<td>-12%</td>
<td>-1%</td>
<td>-1%</td>
<td>-6%</td>
<td>-6%</td>
<td>1%</td>
</tr>
<tr>
<td>Farmer B</td>
<td>Perceived</td>
<td>513,249</td>
<td>490,020</td>
<td>588,556</td>
<td>1,190,444</td>
<td>1,193,564</td>
</tr>
<tr>
<td></td>
<td>Actual</td>
<td>99,216</td>
<td>344,681</td>
<td>214,975</td>
<td>709,681</td>
<td>744,047</td>
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<tr>
<td>Difference</td>
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<td>-30%</td>
<td>-63%</td>
<td>-33%</td>
<td>-38%</td>
<td>-8%</td>
</tr>
<tr>
<td>Farmer C</td>
<td>Perceived</td>
<td>67,191</td>
<td>38,376</td>
<td>80,099</td>
<td>347,625</td>
<td>351,887</td>
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<tr>
<td></td>
<td>Actual</td>
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<td>-14,466</td>
<td>-8,180</td>
<td>70,617</td>
<td>40,259</td>
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<tr>
<td>Difference</td>
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<td>-138%</td>
<td>-110%</td>
<td>-80%</td>
<td>-88%</td>
<td>-24%</td>
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<td>Sum</td>
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<td>2,176,759</td>
<td>2,148,855</td>
<td>2,399,594</td>
<td>3,875,757</td>
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<tr>
<td></td>
<td>Actual</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>
</tr>
<tr>
<td>Difference</td>
<td>-35%</td>
<td>-10%</td>
<td>-20%</td>
<td>-21%</td>
<td>-23%</td>
<td>-3%</td>
</tr>
</tbody>
</table>
Figure 1: Vertical cross section of the wells and aquifer at the beginning of planning horizon.
Figure 2: Perceived and actual annual groundwater depth (in wells A, B, and C) under different non-cooperative management institutions (a- Ignorant myopic management, b- Smart myopic management with drawdown penalty, c- Smart myopic management with profit penalty, d- Fixed ignorant non-myopic management, e- Variable ignorant non-myopic management, f- Smart non-myopic management) over the planning horizon (50 years)
Figure 3: Perceived and actual annual profit of the farmers (A, B, and C) under different non-cooperative management institutions (a- Ignorant myopic management, b- Smart myopic management with drawdown penalty, c- Smart myopic management with profit penalty, d- Fixed ignorant non-myopic management, e- Variable ignorant non-myopic management, f- Smart non-myopic management) over the planning horizon (50 years)
Figure 4: Farmers’ (A, B, and C) crop choice under different non-cooperative management institutions (a- Ignorant myopic management; b- Smart myopic management with drawdown penalty; c- Smart myopic management with profit penalty; d- Fixed ignorant non-myopic management; e- Variable ignorant non-myopic management; and f- Smart non-myopic management) over the planning horizon (50 years).