Water Resources Research

RESEARCH ARTICLE
10.1029/2018WR023575

Key Points:
- Myopic stakeholders allow public goods to deteriorate not realizing they are in a long-term game of chicken
- Foresight allows them to resolve conflicts earlier and cheaper through strategic loss
- The incentive for foresight is ambiguous, depending on differentiation between players

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Citation:
Ristić, B., & Madani, K. (2019). A game theory warning to blind drivers playing chicken with public goods. *Water Resources Research*, *55*. https://doi.org/10.1029/2018WR023575

Received 26 JUN 2018
Accepted 28 JAN 2019
Accepted article online 5 FEB 2019

A Game Theory Warning to Blind Drivers Playing Chicken With Public Goods

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Abstract We develop a game theoretic model of the role of foresight in games involving users interacting over a public good. Previous research in this area has applied game theory to understand social dilemmas and inform policy initiatives. However, considerations of the “evolving structure” of natural resource games over time and agents' planning horizon raises the complexity of game analysis substantially and has often been overlooked. We analyze a simple model of an irrigation system shared by two users and consider how players will act under different levels of foresight. Without foresight into game changes over time, players are blind to the fact that they are in a game of chicken. We model agents with foresight by interconnecting games across time and show how this creates opportunities for “strategic loss” early on, allowing players with foresight to reduce total costs. High future costs can thus be avoided with foresight if the rising costs of inaction are made apparent. We consider the effect of discounting and differences between players to provide policy recommendations regarding incentives for foresight.

1. Introduction

Sustainable resource management is a perennial issue of cooperation among resource users. If users do not consider long-term outcomes of short-sighted strategies, it is likely that investment, maintenance, or conservation measures will be postponed. This delay often leads to more expensive restoration required later as the resource further degrades. We formally explore the role of foresight in a model of a public good.

This problem type can be understood under the umbrella term of social dilemmas, which include common-pool resource (CPR) use or the provision of public goods (Hardin, 1968; Ostrom, 1990). Variations on these models have been used to explain problems across a range of social and environmental problems, such as climate change mitigation (Madani, 2013; Nordhaus, 1999; Paavola, 2012), irrigation maintenance (Podimata & Yannopoulos, 2015), and others (Baumol & Oates, 1988). Building on previous work considering irrigation system maintenance (Madani, 2010), we also focus our narrative around the irrigation system version of public goods.

In both public goods and CPRs, users draw a benefit from the good or resource. The key difference is that in CPRs, users subtract from the resource imposing an external cost on others. In CPRs such as a fishery, users' fishing effort has a detrimental effect on availability for others. The cost that user a thereby imposes on user b is ignored by a and leads to over-exploitation. Public goods do not incorporate such resource “subtractability.” Public goods problems center on the externality one user's action has on others. User a contributes to maintaining an irrigation system, from which user b also benefits without contributing. Hence the prediction is that public goods are underprovided as b “free-rides” a's contribution.

These problems have conventionally been characterized using the game theoretic model of a prisoner's dilemma. There, after arrest, two criminal partners are asked for information by the police in exchange for lighter sentences. It would be best for the two together to keep quiet and incur light sentences. However, each is tempted by the possibility of getting off free if they talk. Even if one talks, the other can reduce their sentence by also talking. While group rationality justifies silence, individual rationality leads them to incriminate each other. This style of reasoning has been applied to social dilemmas also. Just as regardless of whether a talked, b is better off talking, so too, regardless of a's contribution to the public good, b will be better off free-riding. Users a and b would be best off if they both contributed but individual rationality drives them to free ride. As both free ride, the public good is underprovided—leaving both worse off.

As suggested by (Madani, 2010; Madani & Lund, 2012; Madani & Zarezadeh, 2014) users can then find themselves in a game of chicken if their free riding leads to decay in the public good. The "chicken' " game structure comes from an analogy to two drivers speeding toward each other, with the potentially catastrophic result for both if they crash. However, the first player to "chicken out" and swerve out of the way is worse off than his opponent. This incentive structure gives the best payoff to the player who continues dead ahead when his opponent swerves. Relating this back to a shared irrigation system, the highest payoff goes to the user who free rides the system without payment when other users pay. While in the prisoner's dilemma neither player would contribute, in the game of chicken one of the two would. The key difference from the prisoner's dilemma is that a is no longer content not to contribute when b is not contributing.

If users free ride for too long, the public good degrades and the game structure changes from what appeared not to be a conflict, through a prisoner's dilemma to a game of chicken (Madani, 2013). It has been argued (Madani & Lund, 2012) that the changing benefit, or utility, accruing to users due to the changing conditions over time has been overlooked in modeling natural resource management. The concept of "evolving game structure" was proposed in Madani (2010) and used to show how players' optimal choices can change over time due to these changing conditions. This was followed by the evaluation of the effect of evolving game structures on optimal choices in different natural resource management games (Hui et al., 2016; Madani, 2010, 2013; Madani & Lund, 2012). As the system degrades from neglect, one or a group of users are eventually better off investing in an overhaul even if others continue to free ride.

This dynamic can be seen in regard to climate change mitigation (Madani, 2013). Small emissions had no impact on the atmosphere, but over time the climate began to change—imposing costs on countries and eventually rising above costs of mitigation. Initially, countries were happy to emit (no conflict), eventually finding that if they could all cut emissions together they would be better off, but each still was better off emitting (prisoner's dilemma). Increasingly, some will wish to incur costs of emissions reduction even as others free ride (chicken).

Another example in which the same dynamic holds is the case of California's San Joaquin River Delta (Madani & Lund, 2012). In this case, multiple stakeholders and interests (including water traders, environmentalists, and the state government) interact in the management of the resource and the allocation of water to the different uses. Unsustainable water allocations to these competing interests continue even as the Delta's ecosystem degrades. Each interested party continues to overuse water, waiting for others to reduce their water share or invest in new water infrastructure. This type of evolving game structure was also explored for the case of two jurisdictions interacting over a lake (Madani & Zarezadeh, 2014).

In both climate change and water resources, remedial and preventative measures are often delayed due to uncertainty about changes in the underlying resource or the possibility that other actors will take on responsibility. As the resource degrades, risks become more apparent or the resource suffers a sudden rapid deterioration and one or more parties eventually takes on the costs and responsibilities of more sustainable practices.

In modeling users' decision making, interconnecting across temporally evolving games has already been explored in Madani (2011). There, the concept of "strategic loss" was introduced in the context of temporally interconnected games. Strategic loss occurs when a player's loss in some subgame results in their increased gain in the overall interconnected game. Contributing to a public good or reducing CPR use early on despite others' free riding is such a strategic loss.

Strategic loss in interconnected games has been analyzed using the solution concepts of cooperative game theory in Madani (2011). Here, we instead employ the Nash equilibrium solution concept from noncooperative game theory. While cooperative game theory assumes players coordinate their actions (when mutually beneficial) and provides axiomatic formulae for how gains are divided, noncooperative game theory makes no such assumption. Each decision is modeled solely on the basis of individual utility maximization where mutual optimal responses generate equilibrium points (see Madani & Hipel, 2011 for more details).

Here we analyze a model of two users contributing to a deteriorating irrigation system conceived of as a public good (as based on Madani, 2010; Madani & Lund, 2012; Madani & Zarezadeh, 2014). We model myopic play as a series of games played independently without information being passed through time (Madani & Dinar, 2012a; Madani & Hipel, 2011). Under myopia, opportunities for strategic loss are not identified by the players and thus are not in equilibrium. Under Nash equilibrium, users allow the resource to degrade over time. We then show how, with foresight, temporally changing games are interconnected across, and opportunities for strategic loss become Nash equilibria once players recognize their game as a public goods game of chicken. The drivers are then no longer blind to future resource degradation and invest to ensure its sustainability.

2. The Irrigation Maintenance Game

We model two farmers $I := \{a, b\}$. In this initial model, they are involved in a set of games $G = \{\Gamma^1, \ldots, \Gamma^\omega\}$ for every time step $t \in \{1, \ldots, \omega\}$. For every farmer $i \in$ I, let $S_{i,\ t}$ denote farmer i's set of possible strategies for time period t. We assume all farmers face the same choice of simply paying or not paying for irrigation system maintenance $S_{i,\ t} = \{p_{i,\ t}, \neg p_{i,\ t}\}$. For this initial setup, we set for every $t \in \{1, \ldots, \omega - 1\}$, Γ^t as represented by the matrix in Figure 1 for every time step $t < \omega$. If only one farmer pays, they pay the full maintenance cost of the irrigation system. If both farmers pay, they split the costs equally: $\frac{-c_t}{2}$. For simplicity, we ignore the benefits farmers are getting from using irrigated water. These are wholly captured in the cost of system collapse in a later game. Hence, when a farmer is incurring no irrigation maintenance costs in these early games their cost is 0 (the lowest cost option), but postponing payment to the next time step ($t + 1$) raises the costs of maintenance (c_t). Therefore,

$$c_t < c_{t+1} \tag{1}$$

This rising maintenance cost, however, does not change the game structure (i.e., the ordinal rankings of the four possible outcomes) until the final time step ω. Not only does postponing payment raise the costs of maintenance, but eventually, this leads to system failure (F) in the final time step if no one pays for maintenance at the last opportunity in Γ^ω. This collapse in the irrigation system induces substantial losses to the farmers.

$$c_\omega < F \tag{2}$$

If neither player pays for irrigation, the game moves to the next time step until ω. If one or both players pay before ω, the game also ends. Myopic players, however, only solve one game at a time.

2.1. Equilibrium Analysis of $\Gamma^{t\ <\ \omega}$

Figure 1 shows the game in normal form, that is, the payoff (cost) matrix for $\Gamma^{t\ <\ \omega}$. Each cell shows farmers a's and b's costs, respectively, given their strategies. Using this matrix, Nash equilibria can be determined by evaluating each player's best response to each of the opponent's strategies. i's best response is the strategy that minimizes i's cost given j's strategy (underlined values). All cells in the matrix, where i's strategy is a best response to j's best response, are Nash equilibria. Figure 1 gives another matrix where each cost is assigned an ordinal preference ranking.

By going through each column in Figure 1, it can be seen that a's cost is always lower when a is not paying than paying. This is called strict dominance, since regardless of what b does this is a's best response. The same holds for farmer b. Therefore, neither paying is the only Nash equilibrium.

2.2. Equilibrium Analysis of Γ^ω

The final game (Γ^ω) is depicted in normal form in Figure 2. This game structure is that of a game of chicken. Since the cost of system failure is greater than paying the full maintenance costs, a single player would rather pay for the entire maintenance costs than incur the costs of failure. If one pays, the other is better off not paying rather than splitting costs. For the initial games, $\Gamma^{t\ <\ \omega}$, equilibrium analysis only involved strict dominance relations. In Γ^ω, these no longer hold. In the chicken game, the best response is to do the opposite of what the other player does. If a is not paying, b is better off paying and vice versa. So there are at least these two equilibria, each involving one farmer "chickening out" and paying the full maintenance costs thereby avoiding the costs of irrigation system collapse.

A third equilibrium involves mixed strategies where players assign probabilities to their strategies instead of playing one or another. However, we will ignore mixed strategy equilibria here for two main reasons. First,

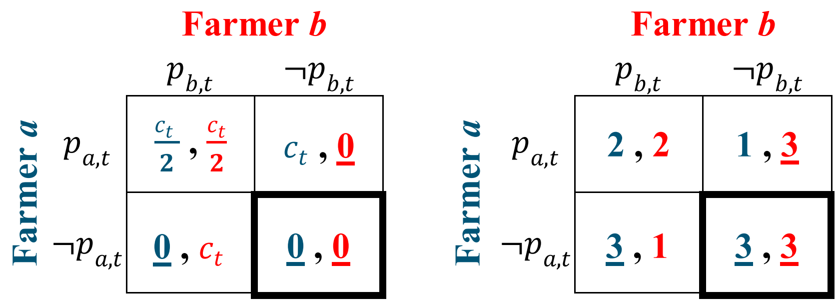

Figure 1. Irrigation maintenance costs for every $t \in \Gamma^{\{1 \leq t < \omega\}}$ in parametric values (left) and ordinal rank (right). The higher the ranking the more preferred this outcome is. Underlined values show best responses and Nash equilibria are the cells with the thick outline. Myopic farmers do not pay for maintenance in these early game equilibria.

no mix of strategies can give a higher expected value than a pure strategy response to any strategy (pure or mixed) by the opponent in our games. This would be one practical application of randomization (Perea, 2012). Second, randomization does not provide a reasonable strategy recommendation to players in a nonrepeated one-shot game with complete information. This applies to our later interconnected game also, as that is also just a one-shot game.

2.3. Modeling and Interpreting Myopia

We have thus far assumed that agents are myopic and do not have foresight to future games. We modeled this by solving each game as it arises without solving across all the games at once as agents with foresight would. Effectively, myopic agents do not realize that they are playing interconnected games, solving each independently. If they had foresight, they would consider theirs and their opponents' future actions in their contemporary decision making.

3. Strategic Loss in Temporally Interconnected Games

If agents adopt foresight, they interconnect the set of subgames G from each time step into a larger game. Let the temporally interconnected game be Φ^{ψ}, where ψ is the number of games ahead that agents have foresight to. Farmers with $\psi = 1$ have information on current payoffs only. The Φ^{ω} is the interconnected game across the full set G. Strategy set S_i in Φ^{ω} consists of strategies available in each temporally distributed subgame Γ^t. Each strategy in Φ^{ω} is then a plan for all subgames Γ^t. Either or both players paying ends the game Φ^{ψ}. Therefore, we write the strategy set as the time step of payment or not paying at all: $S_i = \{(p_{i,\ 1}), \ \dots\ , (p_{i,\ \psi}), (\neg p_i)\}$. This reflects the fact that whichever player pays first finishes the game. After one pays, the other's decision makes no further difference. If player i chooses $p_{i,\ t}$ and player j chooses $p_{j,\ u > t}$, both players receive the payoff for the outcome $p_{i,\ t}, \neg\, p_b$ regardless of u. Figure 3 shows Φ^{ω} in normal form, where

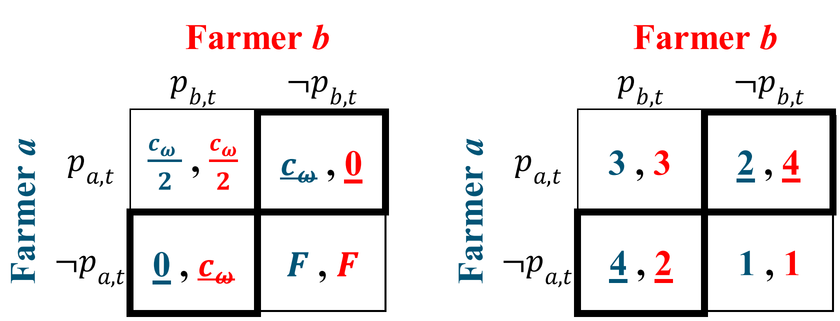

Figure 2. The irrigation game in the final time-step (Γ^{ω}) in parametric values (left) and ordinal rank (right). Nash equilibria are the cells with the thick outline. When the cost of failure is high, one or the other farmer pays.

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Farmer a \ Farmer b	$p_{b,1}$	$p_{b,\{1<t\leq\omega\}}$	$\neg p_b$
$p_{a,1}$	$\frac{c_1}{2}, \frac{c_1}{2}$	$c_1, 0$	$c_1, 0$
$p_{a,\{1<t\leq\omega\}}$	$0, c_1$	x, y	$x, 0$
$\neg p_a$	$0, c_1$	$0, y$	F, F

Figure 3. Payoff matrix for the interconnected irrigation game Φ^{ω}. Values x and y change with each time step, reflecting rising costs. Nash equilibria are the cells with the thick outline. The interconnected game has the same equilibrium outcomes as the game of chicken with one or the other farmer paying.

$$(x, y) = \begin{cases} (c_t, 0), & p_{a,t}, \neg p_b \\ \left(\frac{c_t}{2}, \frac{c_t}{2}\right), & p_{a,t}, p_{b,t} \\ (0, c_t), & \neg p_a, p_{b,t} \end{cases}$$

This denotes that if both pay at the same time, they split the costs, and if only one player pays, they pay the full costs.

3.1. Equilibrium Analysis of Φ^{ω}

Nash equilibria can be determined using only the information given in equations (1) and (2). Splitting the costs is not in equilibrium because paying is never the best response to the other player also paying. If *a* pays in any subgame including the first, *b*'s best response is to pay at any of the later stages of the game or not pay at all. If *b* does not pay, *a* has one best response: pay in the first instance because of rising costs (equation (1)). Therefore, in one equilibrium *a* pays the maintenance costs at the beginning and *b* never pays. Given symmetric payoffs the second equilibrium sees payment by *b* instead. Having connected the earlier game involving only maintenance costs, with the chicken game at ω, we have shown that Φ^{ω} is a larger version of the game of chicken with a lower cost to the "nonmyopic chicken."

Figure 4 gives a graphical representation of Φ^{ω}. The y axis depicts costs, and so cost-minimizing farmers will be looking to choose states lower down. Labels s_{ψ}^{*} indicate the equilibrium strategies for farmers of different levels of foresight ψ. When $\psi = 1$, farmers have no foresight except the game they are playing at that point in time. They therefore do not foresee the incoming game of chicken at ω and blindly stumble into it by not paying in the two previous games. When $\psi = \omega$, farmers interconnect and can strategically lose in the first instance at lower cost to the payee.

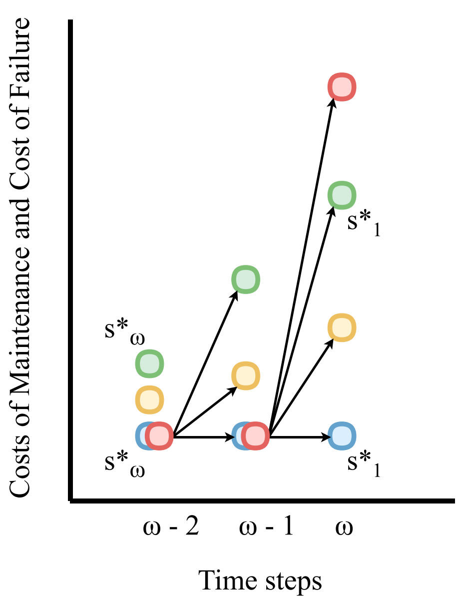

Figure 4. The temporally interconnected game Φ^{ω} from the view of one of the farmers (i). Cost of failure is expressed as an expected cost and so is shown on the same scale as cost of maintenance. Nodes represent costs for player i if the game were to end there. Green nodes indicate player i paying, yellow nodes where costs are split, blue nodes player i not paying but player j paying, and red nodes where neither pays. Arrows show that red nodes lead to subsequent subgames. Equilibrium outcomes s_{ψ}^{*} indicate how myopic players pay at the end, whereas foresighted players pay in the first subgame.

3.2. Strategic Loss

While for myopic players paying in the first game is irrational as it incurs a higher cost than not paying, players with foresight to the point of system collapse will "strategically lose" in this game in order to avoid the higher costs later on. Hence, the term strategic loss does not imply irrational play (Madani, 2011). It rather refers to an optimal play given a larger interconnected game where what appeared as a loss under myopia is actually a cost-reducing optimization, leading to a higher utility for the player.

4. The Model With Continuous Time

In the previous formulation of the game, system failure emerged suddenly in Γ^{ω} with no intermediate changes in game structure. We now drop the piecewise function for system failure F and the assumption in equation (2) about F being strictly greater than any maintenance cost. Instead, we create a function to represent expected costs.

$$C_{i,t} = \left(p_{i,t}\right) \frac{M(t)}{1 + p_{j,t}} + \left(1 - p_{i,t}\right) F(t) \tag{3}$$

where $C_{i,\,t}$ is the cost to player i at time t; $p_{i,\,t} \in \{0, 1\}$ is farmer i's payment at time t; $M(t)$ is the maintenance cost as a rising function of time t; $F(t)$ is the cost of system failure which also rises as a function of t. As before, players have an option to pay or not, the choice being between the two terms of the equation: either incur maintenance costs or incur cost of failure. Since equation (3) will not hold after someone pays and ends the game, we must also assume no payment for any time $q < t$:

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Farmer *a* \ Farmer *b*	$p_{b,2}$	$p_{b,4}$	$p_{b,6}$	$\neg p_b$
$p_{a,2}$	1 , 1	2 , 0	2 , 0	2 , 0
$p_{a,4}$	0 , 2	2 , 2	4 , 0	4 , 0
$p_{a,6}$	0 , 2	0 , 4	3 , 3	6 , 0
$\neg p_a$	0 , 2	0 , 4	0 , 6	∞ , ∞

Figure 5. The interconnected irrigation game Φ^{∞} with cardinal cost values at time {2, 4, 6}. Nash equilibria are the cells with the thick outline. Equilibria indicate that the interconnected game is a game of chicken with one or the other farmer paying.

$$\int_0^{q<t}\left(p_{a,q}+p_{b,q}\right)=0 \tag{4}$$

For now, we keep F equal among players. We assume that even when split, initial maintenance costs are higher than initial cost of system failure $\frac{M(0)}{2}>F(0)$. The cost of system failure, however, rises faster than the maintenance costs $\frac{dF(t)}{dt}>\frac{dM(t)}{dt}$. Figure 5 depicts the payoff matrix of the interconnected game Φ^{∞} for $t=\{2,4,6\}$ assuming $\frac{dM(t)}{dt}=1$. In this formulation, different subgame structures exist, including the prisoner's dilemma in the 2×2 matrix in the middle. Here myopic players have let the cost of failure rise and would be jointly better off if they both paid. However, the "chicken" payoff structure holds across the interconnected game as a whole. The same reasoning as for the analysis of the discrete time game in Figure 5 holds for Φ^{∞}. Two pure strategy equilibria are in states where one or the other side pays the full amount immediately and the other never pays.

4.1. Equilibrium Under Myopia

Figure 6 shows the changing game structure over continuous time. The phase where the red line is above the yellow line but below the green line is a set of prisoner's dilemma games for myopic agents. There, paying together the players would have a lower total cost; however, the $\neg p$ strategy is strictly dominant. This ensures that myopic players continue not paying and moving toward the final phase of the game. They only stop the game once the cost of inaction for one individual becomes higher than if that single player simply pays everything. At that stage they have entered the game of chicken. When they reach the point where the red line reaches and surpasses the dark green one, the expected cost of system failure is higher than the maintenance cost borne by one player, and so this phase is a game of chicken where one or the other player ends the game. The s_1^* is then where

$$F\left(t^1\right)=M\left(t^1\right) \tag{5}$$

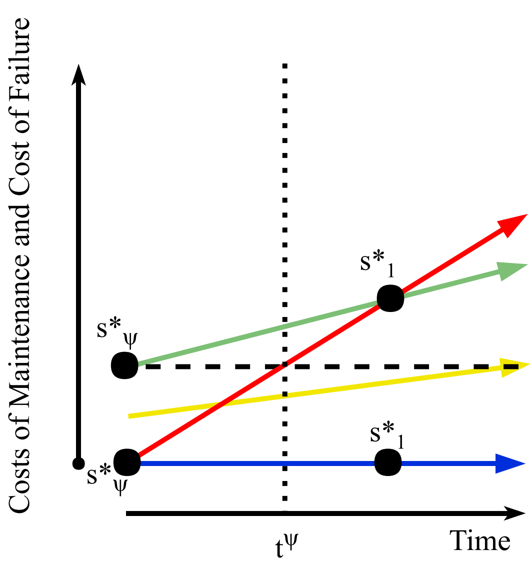

Figure 6. Cost functions in the temporally interconnected game from the view of one of the farmers (i). Green shows i paying while j does not; yellow shows equally split maintenance costs; and blue shows i not paying with j paying instead. Red is the cost of system failure to both. The dashed line indicates initial costs of maintenance which later costs can be compared against under foresight. The dotted line indicates where the cost of failure exceeds the initial maintenance cost, hence the extent of foresight required to support strategic loss at the start of the game. The points labeled s_{ψ}^* denote equilibrium under foresight to time t^{ψ}. Points labeled s_1^* denote equilibrium under myopia.

4.2. Equilibrium Under Foresight

Players with foresight can compare their initial costs to the costs incurred by delaying across all the games they have foresight to. If foresight reaches to where cost of failure rises above costs of cooperative payment, the game becomes a prisoner's dilemma. With foresight to the point t^{ψ}, where cost exceeds costs for a sole payer at the beginning of the game, players gain an opportunity for strategic loss. Strategic loss here involves losing the initial game $t=0$ (i.e., paying immediately) in order to avoid future costs—yielding the equilibrium strategy s_{ψ}^*.

The horizontal dotted lines in Figure 6 show how players with foresight compare future costs to the current cost of maintenance. The expected costs of system failure due to inaction rise above the initial costs of maintenance after t^{ψ} where

$$F\left(t^{\psi}\right)=M(0) \tag{6}$$

Foresight to the point at which myopic players pay (t^1) is not necessary because costs of inaction will necessarily rise above initial costs of action earlier. When comparing equations (5) and (6), we get the following inequality:

$$F\left(t^{\psi}\right)=M(0)<M\left(t^1\right)=F\left(t^1\right) \tag{7}$$

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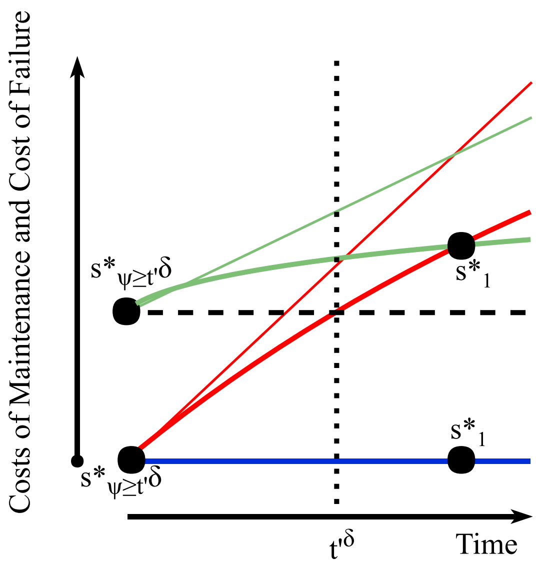

Figure 7. Cost functions over time without discounting and with an illustrative discount rate (represented in thick lines). The further into the future a cost is, the less its present value. Hence, linearly rising costs become curves.

This will necessarily hold because maintenance costs at t^1 will be greater than at $t = 0$ and hence $t^\psi < t^1$. In other words, players with foresight will necessarily pay earlier and hence the costs will necessarily be lower. The size of this inequality (as determined by the rate of growth in maintenance costs over time) represents the size of cost savings due to strategic loss.

5. Discounting

Linking games across time involves comparing future to the present values. Future costs and benefits are typically discounted relative to contemporary costs. Discounting is expressed with the following function:

$$PV = \frac{v}{(1+\delta)^t} \tag{8}$$

where PV is the present value of some cost; v is the cost being discounted; t is how far into the future v is; and δ is the discount rate. Figure 7 depicts the same functions used earlier in thin lines and the discounted values in thick lines. Note that an arbitrary discount value was chosen for illustrative purposes and that different discount rates would induce different discounted curves.

The result of discounting is to lower the future costs relative to the present ones. For myopic players discounting does not change the game because they only consider current costs. Also, since all values at a given point in time are discounted equally, the curves cross at the same point time regardless of the discount rate. Discounting does however dim foresight by extending the foresight required to see the point at which expected costs of inaction rise above initial maintenance costs. This is shown by the difference between where the thin and thick red lines intersect the dotted line. This effect is noted by the fact that the equilibrium that supports strategic loss at the beginning of the game now requires foresight $\psi \geq t'^{\delta}$.

6. Who Pays?

Our models have considered two perfectly identical players. This has meant that the two pure strategy equilibria we consider are exactly the same (either a or b pays). Hence, thus far we have left unanswered which of the players will end up paying.

In practice, such a strong symmetry is unlikely. Discount rates are not always the same across different players. Different players may also be differently affected by system failure. One may be more exposed, having fewer opportunities to adapt their farming practice or source water elsewhere. They may hold different beliefs about changes in the cost of system failure. Their expected valuations also depend on their risk tolerance. For example, for different institutional stakeholders such risk tolerance may be mandated differently by different regulations on which return period droughts or floods they must consider in planning and system design. All of these differences can be in play at the same time, constituting differences in their understanding of the game.

Figure 8 shows the changing expected costs of nonpayment relative to the initial maintenance costs in a situation where b's expected cost of failure rises more rapidly than a's. The x and y axes indicate the costs to farmers a and b, respectively. Players then strive for nodes closer to the origin on their scale. As the games are interconnected over time, the cost of failure $F_i(t)$ can be plotted as moving through the cost space in the direction indicated by the arrow, indicating b's cost of failure is rising more rapidly than a's.

In order for the game structure to enter a game of chicken, cost of failure must rise equally for both. Figure 8 shows a scenario where this is not the case. Costs pass through the prisoner's dilemma phase before entering the region marked in red where farmer b can reduce costs by paying while this is still not the case for farmer a. If such a difference exists between a and b, the game of chicken will not come

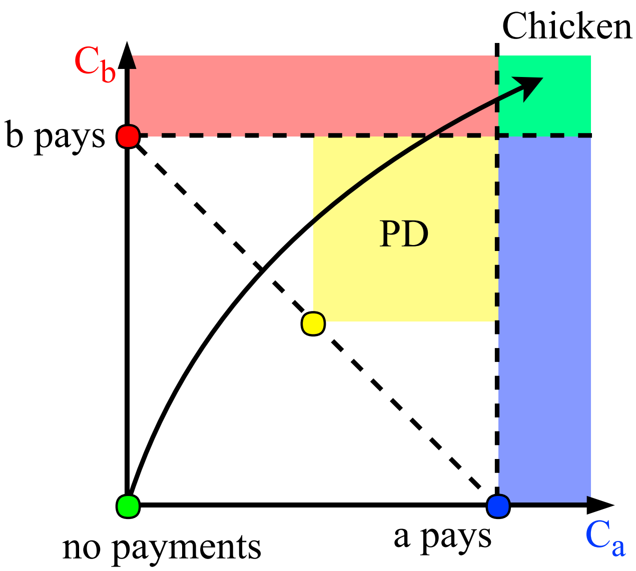

Figure 8. A scenario where the cost of failure rises faster for b. The diagonal dashed line represents initial maintenance cost $M(0)$; the yellow node represents initial maintenance costs shared equally, the blue and red nodes indicate $p_{a,\,0}$ and $p_{b,\,0}$, respectively. The green node indicates the expected costs of neither player paying $F_i(t = 0)$ with the arrow showing how the cost of failure grows faster for b than for a over time.

about because b cannot commit to not paying in the red region. With foresight to this, a will free ride player b's payment.

7. To Foresee or Not to Foresee?

There are several countervailing incentives for foresight. The first incentive rewards foresight with opportunities for lower costs through strategic loss. In our model this involved "chickening out" earlier to avoid higher future costs. However, there are also disincentives for foresight.

Clearly, foresight itself is not necessarily freely available. Estimating future changes through acquiring information, research, and modeling can be costly even if these costs are small relative to the other costs in our model. Additional costs of foresight may involve costly actions undertaken on the basis of incorrect expectations, but uncertainty induces a more complex game structure involving imperfect and incomplete information (see section 8.4). Foresight is incentivized where the equilibrium state under foresight offers a greater cost reduction than the costs of acquiring the foresight itself:

$$C_i(\psi) < C_i\left(s_1^*\right) - C_i\left(s_\psi^*\right) \tag{9}$$

where $C_i(\psi)$ is the cost of foresight to player i and we will assume that $C_i(\psi) > 0$; $C_i\left(s_\psi^*\right)$ and $C_i\left(s_1^*\right)$ are costs in equilibrium with and without foresight, respectively.

Given that before developing foresight, players do not know their future costs, we can distinguish between three cases based on the earlier analysis of asymmetric costs. Three possible cases are that if myopic players do not adopt foresight:

1. ***a* pays**: $C_a\left(s_1^*\right) = F(t^1)$ and $C_b\left(s_1^*\right) = 0$;
2. ***b* pays**: $C_a\left(s_1^*\right) = 0$ and $C_b\left(s_1^*\right) = F(t^1)$; or
3. ***a* and *b* enter a game of chicken**.

In Case 1, if a were to develop foresight, equation (9) would hold since the cost savings would exceed the cost of developing foresight. Here, a is able to exploit the opportunity for strategic loss.

In Case 2, since $C_a\left(s_1^*\right) = 0$, the right-hand side of equation (9) will be less than or equal to 0, and so the inequality will not hold and it will not be optimal for a to develop foresight. Since b would have been paid first, a could have reduced costs by not developing foresight. Additionally, assuming the difference in costs between a and b is not large, a will be the one to pay because (as shown in equation (7)) expected costs of failure will exceed initial maintenance costs before myopic players pay. If the difference in costs is large, then it is possible that b's expected costs of failure rise so rapidly that they reach future maintenance costs before a's expected costs of failure reach initial maintenance costs. In this case of large cost differences, a's cost will only be the cost of foresight. By developing foresight, a has incurred the costs of foresight as well as potentially ensuring it is the one that will pay for maintenance (if cost differences are small).

In Case 3, costs rise symmetrically for a and b. This is the same case as when small cost differences were considered in Case 2. It is optimal for a to pay immediately if it develops foresight, even as a would have delayed under myopia with the possibility that b would have paid in the end.

The incentive for developing foresight is dependent on whether the game has strongly asymmetric costs and who it is that will end up paying. If a would have paid anyway (Case 1), then a will be able to reduce its costs under foresight, whereas if it would have been the one not to pay (Case 2 and one of the equilibria in Case 3), developing foresight will raise its costs. The expected value of developing foresight then depends on prior assumptions about the size and likelihood of cost differences. A model exploring strategic choice over maintenance as well as the development of foresight would involve a more complex game structure with incomplete information (see section 8.4).

8. Discussion

We showed how foresight can allow public goods users to incur strategic losses, highlighting the role of discounting, differentiation, and ambiguous incentives for developing foresight. We now discuss the applicability of our model to real world cases by exploring extensions and alternative modeling approaches, the issue of myopia in practice, interconnection across water use sectors, and risk and uncertainty.

8.1. Assumptions, Extensions, and Alternative Modeling Approaches

Our model was developed from a set of structural assumptions: two users, binary maintenance choice, nonrepetition, and the assumption of rationality for Nash equilibrium analysis. As these assumptions do not always reflect real world situations, it is worth commenting on the applicability of this model, effects of violating assumptions, and alternative approaches for further research.

8.1.1. Additional Users

Most natural resources involve more than two users, hence the assumption of 2 players is often unrealistic. With three or more farmers in our model, splitting costs would still not be an equilibrium as contributor i would still be able to cut their costs by free riding remaining contributors. Assuming homogeneous cost of failure, an N number of players would mean an N number of equilibria, each involving only one payer. Therefore, the principle conclusion of strategic loss and free riding generalizes to any number of players with player differentiations driving which player ends up paying as shown in section 6.

8.1.2. Bargaining and Alternative Maintenance Levels

Our model offers players a simultaneous binary choice whether or not to pay. In most real world cases users could bargain in advance. This could be explicitly modeled using an ultimatum game: i makes an offer on splitting some value. j then must either accept the offer or reject it (in which case neither gets any of the value; Roth, 1985). In these models bargaining power accrues to the player making the final ultimatum. The other might accept small shares of the value rather than not receiving any whatsoever. In infinitely repeated bargaining games, j can make a counteroffer even as the value declines (or costs rise as in our model). There the user with lower discounting has greater bargaining power and pays less in an immediate agreement over cost splitting (Rubinstein, 1982). This is analogous to how differentiated discounting in our model differentiates cost of failure driving who pays.

Splitting a cost still assumes a fixed total cost without alternative maintenance levels. Real world decisions are sometimes conducted over a set of discrete choices. In the case of California's Delta water exports controversy these were: business-as-usual operations, one of the new infrastructure design options *or* fully stopping operations (Madani & Lund, 2012). In so far as decisions are made over a binary choice our model remains applicable, but choices can range through a space of cost, time, and performance variables (e.g., Matrosov et al., 2015). Rational users would then select the project that minimizes their costs given their level of foresight and expectation of other's actions. Evaluating this requires defining costs and benefits across the choice range.

8.1.3. Benefits

Our model ignores benefits (e.g., crop yields due to irrigated water). Without maintenance, supply would diminish over time. To include this, assume benefit b_t is earned each period. For foresighted players, these benefits cumulate, forming a downward sloping curve (on our cost figures), flattening over time as declining supply reduces per period benefits. Adding this function to the failure and maintenance functions would not change points of intersection but would decrease future net costs against current net costs, increasing the foresight necessary for early strategic loss (as with discounting in section 5). A large enough b_t would even induce a new optimal net cost point on the maintenance costs curve at $t > 0$. However, the strategic dynamics around this point (free riding and strategic loss) would not change.

8.1.4. Repeated Games

In our model, the game is over once someone pays. In practice, users might face the same strategic choices once again after payment. In repeated games, reputation becomes important as noncooperation can be punished. Using a so-called "grim trigger" strategy, players cooperate initially, but if the opponent deviates they switch to the equilibrium worst for the deviator (Abreu, 1988). Cooperative outcomes of a one-shot game can thereby be supported in equilibrium in infinitely repeated games (given low enough discounting of future rewards). With infinite repetitions of our interconnected game, splitting maintenance costs at $t = 0$, could be supported in equilibrium by punishing free riders with the equilibrium where they are the sole payer. This can also apply to finite repetitions although cooperation becomes problematic in the late game as future rewards of cooperation decline (Fudenberg & Maskin, 1984). Many more complex strategies encouraging a return to cooperation, rewarding punishers, and other aspects of cooperation over natural resources have been explored in the literature (Ostrom, 2009). Real world water management cases involve such ongoing relationships inducing such cooperative strategies. Some however can involve participants without an ongoing interest in the system (e.g., suppliers or contractors with time—limited or project specific contracts) or users with low foresight who would not consider the future benefits of cooperation (explored further in section 8.2).

8.1.5. Alternative Solution Concepts

We employed Nash equilibrium analysis building on previous work employing cooperative-game theory solution concepts (Madani, 2011). Refinements and variations on Nash equilibrium have been developed and an integrative approach to these can be found in Perea (2012) and in Kilgour and Hipel (2005). Following Madani and Dinar (2012b), we modeled myopia by solving subgames independently, but alternative "myopias" exist also (Spiegler, 2011).

Which concept is most appropriate rests on beliefs about the decision style. Concepts not presuming individual optimization (as in Nash equilibrium) include replicator dynamics, where successful strategies are promoted among a population as opposed to individuals choosing strategies. For an example of replicator dynamics applied to irrigation systems, see Yu et al. (2015). Concepts of evolutionary stability in replicator dynamics are by definition a refinement of Nash equilibria (Smith & Price, 1973) and Nash equilibria are generally effective predictors of replicator dynamics (Cressman & Tao, 2014). Simulations and agent-based modeling can, however, explore dynamic behaviors to give further nuance to static Nash analysis (An, 2012; Bousquet et al., 2001; Cressman & Tao, 2014; Ghorbani & Bravo, 2016). Other concepts reflecting a range of decision-maker characteristics not captured by the Nash equilibrium concept, have been also proposed in the literature (see Fang et al., 1989, 1993; Kilgour et al., 1984). Applications of such concepts modeling different behaviors lead to different equilibria and insights worthy of further exploration as shown in previous water and environmental management studies (Madani, 2013; Madani & Hipel, 2011).

8.2. How Can Myopia Be Reduced?

Myopia applies to relatively certain prospects ignored by decision makers unlike difficulties with uncertainty considered in section 8.3. In practice, all decision makers (implicitly or explicitly) employ a planning horizon for strategic decisions, setting how far into the future are likely outcomes considered in assessing different courses of action.

Unfortunately, examples of myopia abound. The case of the Aral Sea is a widely studied environmental catastrophe and a case in point. Already by 1988, massive and inefficient irrigation (largely for cotton exports) had been shown to be causing recession of and would lead to a complete disappearance of the Aral Sea (Micklin, 1988). A dispute ensued between local proponents of a Siberian water transfer and central planners favoring local irrigation efficiency improvements. This dispute can be seen as a prisoner's dilemma where both saw the need for action but each could improve their short-term benefits by not taking on any responsibility. Neither were Soviet planners willing to incur the political and financial costs of the Siberian diversion project, nor was the basin's agriculture willing to incur the cost of overhauling irrigation and curbing production. Despite some irrigation improvements, the sea lost 75% of its volume by 2012 creating numerous health and environmental problems (FAO, 2013). As the situation deteriorated the game changed to one of chicken, with one party taking on the costs. Efforts are now aimed at damming and restoring the North Aral Sea as wider restoration is deemed too costly (Micklin, 2016). Comparable situations have taken place in Lake Urmia (AghaKouchak et al., 2015; Khazaei et al., 2019), Lake Chad (Gao et al., 2011), the Dead Sea (Malkawi & Tsur, 2016), and the San Joaquin River Delta (Madani & Lund, 2012), where a myopic dash for development has led to environmental degradation and costly restoration which could have been avoided with foresight.

What then does foresight look like? In practice, water sector planning horizons vary considerably between 15 years (Pennsylvania), 50 years (Australia), and 100 years (UK flooding and coastal erosion planning; Baker et al., 2016). Setting appropriate planning horizons for Water Resources Management Plans should initiate at around 40–60 years but should be adjusted according to the ability to forecast scenarios, the size of net costs, typical asset life spans, the availability of flexible solutions, and concerns about low-probability high-impact events beyond the planning horizon.

Usually, local or national governments use longer planning horizons than companies, which may be sold off or closed down. However, government decision making can be focused on electoral or news cycles while individuals can pursue lifetime or civilizational goals. In an in-depth history of water in the Western United States, Reisner (1993) presents Mormon settlements as the most successful in irrigated agriculture due in part to the long-term vision and solidarity enshrined by that community's shared beliefs and persecuted status.

Government and corporate planning horizons are partly driven by formal institutions potentially more easily established or amended than informal institutions such as a Mormon ethic (North, 1991). Company bonuses linked to quarterly earnings encourage myopia while longer-term incentives may promote it. UK water companies, for example, are mandated to consider long-term supply-demand balance and their price controls include expenditure for investment to support this (Ofwat, 2014). Likewise, governments can be legally mandated to think long term. The Climate Change Act 2008 established the independent Climate Change Commission to monitor and evaluate UK governments on climate change targets with a similar law being proposed for environmental planning more generally (Environmental Audit Committee, 2018). The European Union Water Framework Directive (WFD) mandates 25-year River Basin Management Plans (European Commission, 2000), encouraging foresight and timely investments.

International environmental agreements can bind governments to a system of governance mandating long-term planning and the establishment of dedicated research bodies. This research function is a key predictor of the success of international environmental agreements, as it can improve the quality of foresight, prevention, and preparedness (Helmut et al., 2011). Research more generally improves foresight by collecting data, identifying likely outcomes and crucially disseminating this information.

However, as shown in section 7, it is not always in the interest of myopic agents to develop foresight. If it increases their costs, it will not be pursued or may be suppressed. Interested parties have sponsored misinformation campaigns on climate change (Supran & Oreskes, 2017) or denial of the extent of water stress (Reisner, 1993). Climate change denial and criticisms of economic costs of the Paris Agreement by the current President of the United States, Donald Trump, are good examples of intentional myopia in favor of short-term benefit maximization at the expense of increased long-term costs to the whole world, including the United States. Recently, the second author of this paper was subject to accusations of espionage by member of Iran's political and intelligence establishment (Madani, 2018; Stone, 2018) for efforts to address the country's water challenges (Madani, 2014; Madani et al., 2016). These groups face short-term costs if more sustainable practices were to be adopted. A warning to blind drivers in a game of chicken by disseminating findings on environmental degradation, challenging misleading narratives, and raising awareness about the future undermines the ability of interest groups to act myopically and can enable or even force strategic losses.

8.3. Myopia Across Sectors?

We showed how interconnection across time creates opportunities for cost reductions via strategic loss and discussed how such myopia can potentially be reduced. A similar logic can be applied for linkage across other dimensions such as by linking across issues or in-kind trade between measures across food, energy, land, and other sectors (Bruce & Madani, 2015; Just & Netanyahu, 2004; Madani & Hipel, 2011; Madani & Hooshyar, 2014).

International policy measures such as the Sustainable Development Goals (SDGs; United Nations General Assembly, 2018) and WFD (European Commission, 2000) promote integration across sectors to advance sustainable water management. Yet as with temporal myopia, institutions can drive myopia in cross-issue interconnection. The WFD for example, encourages but does not mandate integration among sectors. One study showed how institutional differences between centralized/local and water-specific/generic authorities given WFD implementation responsibility interact in complex ways with the success of integration across sectors (Liefferink et al., 2011). Interconnection over time is simpler to model, involving a single system, while issue interconnection involves multiple systems. However myopia across issues may be as important as intertemporal myopia with regard to potential optimizations and opportunities for strategic loss.

8.4. Risk and Uncertainty

Information availability is of great importance in economics, game theory, and water management. The game theory literature distinguishes between two types of information constraints: imperfect information (what moves the opponent has played) and incomplete information (the structure of the game including the strategies of the opponents, their payoffs, and other aspects; Harsanyi, 1967).

Incomplete information is typically represented by players not being aware of which "type" of player they may be facing (i.e., the utility function of the opponent or indeed themselves). Uncertainties around technical and environmental variables can be expressed in terms of expected value and risk only if the probability density functions are known (Knight, 2012). Players' beliefs around these conditions drive the perceived game. In water management, key uncertainties include future precipitation and temperature changes, and magnitudes of floods and droughts. For some of these uncertainties good historical data may allow reliable probability estimates but often based on the assumption of stationarity (Hui et al., 2018). For other uncertainties, such as runaway global warming, commodity prices, technological advances, and socio-political changes estimating expected values can be very problematic.

Estimating expected value suffers from a series of issues in real world application. Low-probability high-impact events may only rarely or never have taken place making probability estimates problematic (Taleb, 2007). Even a small change in the estimated likelihood of a dramatic drought could justify large investment in a new reservoir or costly policy reforms. More generally, estimating expected value suffers from uncertainty about the full characterization of the probability density function (tail behavior, variance, higher-order moments). With less and less certainty around the system at hand come increasing issues of "deep uncertainty" where probability estimates are essentially impossible to infer (Walker et al., 2010). For these uncertainties, alternative approaches not relying on expected value such as the precautionary principle, scenario analysis, robust decision making, adaptation tipping points, dynamic adaptive policy pathways, and bottom up approaches to assessing system vulnerability have been used (Babovic et al., 2018; Biggs et al., 2011; Haasnoot et al., 2013; Herman et al., 2015).

What matters for the purposes of our model is the effect the adopted approach toward uncertainty has on the willingness to incur maintenance costs. Decision makers may simply not tolerate a given level of risk as noted in section 6. Does i estimate a high enough risk to be willing to pay for maintenance? The maintenance decision of j depends on i's type in this sense, but with either high or low risk estimates i would want to signal low risk to induce j to pay. In the game of chicken, signals about player type offer no information about the player's real type due to this incentive (Fudenberg & Tirole, 1991). If i were to develop a precautionary estimate of drought risk, j could reasonably expect i to pay sooner and would hence delay her own payment. As with foresight itself, uncertainty in this strategic context creates a perverse incentive against taking on strategic loss.

9. Conclusion

We showed how the lack of foresight can cause unsustainable management of a public good. Players with myopic decision-making are akin to blind drivers in a game of chicken. A myopic view of the future and uncertainty over changes in the resource over time lead to postponing necessary measures. Uncertainty as to resource performance, the functions governing changes in cost of failure over time are important culprits in this regard. This prevents actors knowing when they have entered a game of chicken and can mean a further extension of time spent in the prisoner's dilemma phase of the game despite continued deterioration in the underlying resource.

We showed how interconnecting games over time create opportunities to reduce costs via strategic loss. In our discrete time model, the agents had to have foresight to the point at which the game became an actual game of chicken in order to exploit strategic loss. If they have some awareness of the function governing rising cost as in the continuous time model, they do not need to have that level of foresight. They only need to see the cost of inaction rise above the cost of early action. We showed how for differentiated players the one to reach this level first would be the one to take on the strategic loss.

The problem of myopia is exacerbated when discounting is high which further extends the foresight required to prompt action. Finally, we showed there to be ambiguous incentives for players to develop foresight. If they can be credibly myopic, other players with a longer view are more likely to take up the costs. A warning to blind drivers in a game of chicken can reduce costs by reducing the cost of foresight, inducing strategic losses, and reducing the credibility of myopic strategies.

Acknowledgments
The authors would like to thank the U.K.'s National Environmental Research Council for supporting this research and the reviewers for their valuable remarks. This manuscript draws on no particular data set.

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