Abstract

Since management of a common property resource can only be undertaken by a government of finitely lived agents, a natural way to study common property management is to study the behavior of such governments. This paper proposes that the choice of management objective by a government of finitely lived agents be regarded as a "move" in a game of sequential agents. Given this framework, it is shown that there exist subgame perfect equilibria in which each successive government chooses the same "traditional" management objective. These strategies enable an economy to overcome an intergenerational externality which can occur otherwise. Thus, following a tradition of conservation may be a rational response to an intergenerational externality.

Tradition and common property management

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1. Introduction

Since management of a common property resource can only be undertaken by a government of finitely lived agents, a natural way to study common property management is to study the behavior of such governments[1]. This paper considers the way that such governments choose management objectives for common property resources. It first argues that the choice of management objective by the current government of finitely lived agents be regarded as a "move" in a game of sequential agents. Given this framework, the following two results are established.

1. Absent the ability to condition the choice of management objective on the actions of earlier agents, only one sequence of management objectives is consistent with subgame perfection. Moreover, because of an intergenerational externality which distorts savings incentives, this sequence of management objectives does not result in a Pareto optimal allocation.

[1] I would like to thank Vernon Henderson, Toby Page, Harl Ryder, Steve Kohlagen, Yehuda Kotowitz, and Ralph Winter for many helpful comments. Remaining errors are entirely my own responsibility. This paper is based on Chapter Two of my dissertation, completed at Brown University, 1995. Some revisions were completed during a postdoctoral fellowship at the Woods Hole Oceanographic Institution

2. If current agents are able to condition the choice of management objective on the behavior of prior agents, then many subgame perfect allocations may be possible, including some that are Pareto optimal.

The strategies used to support these outcomes may be thought of as social contracts. However it is also reasonable to regard these strategies as traditions. Taken together these results imply that following a tradition of conservation may be a rational response to an intergenerational externality which distorts savings incentives.

The results in this paper complement the current debate on sustainability (e.g., Solow 1991, 1993) in important ways. First, the notion of sustainability may provide a way to implement the social contracts described here. Second, these contracts may provide an incentive to choose management objectives that are consistent with sustainability, apart from any sense of moral obligation to provide for the future.

2. A description of the regulation game

To investigate the behavior of sequences of governments of finitely lived agents, consider the following simple economy. At $t = 1$ a single old agent, Agent Zero, gives birth to a single young agent, Agent One. At the end of period one, Agent Zero dies and Agent One gives birth to Agent Two. This cycle repeats itself for all natural numbers t. Let c_t^y denote consumption in period t by the young agent born at t, c_t^o denote consumption in period t by the old agent born at $t-1$.

Agents derive utility from their own consumption in each period that they are alive. Preferences are represented by the utility functions,

$$\begin{aligned} &V^0(c_1^o) \\ &V^t(c_t^y, c_{t+1}^o) \qquad\qquad t = 1, 2, 3, \dots . \end{aligned}$$

We assume that consumption is a good, not a bad, so that the $V^t(.)$ are all increasing functions.

Consumption in each period is provided by a natural resource stock Y_t that may be consumed or saved. Let $S_t = Y_t - (c_t^o + c_t^y)$ denote savings in period t. Suppose that any stock not consumed grows according to $Y_{t+1} = F(S_t)$, where $F(0) = 0$, $F'(0) > 0$. An *allocation* is an infinite sequence of consumption pairs,

$\{(c_t^o, c_t^y)\}_{t=1}^{\infty}$. Say that an allocation is *feasible* if and only if $Y_t \geq c_t^o + c_t^y$ for all t. A *steady state allocation* satisfies $(c_t^y, c_t^o) = (c_{t+1}^y, c_{t+1}^o)$ and $Y_t = F(S_t)$, for all t.

Suppose that the resource Y is common property. That is, agents in each period jointly decide on an allocation of the resource stock between consumption and savings, (c_t^o, c_t^y, S_t). Call such a triple a *management objective for period t*. Given that young and old agents both value only their own consumption, they disagree about the choice of management objective—each prefers that the other consume nothing. The role of government is first, to provide a bargaining protocol allowing young and old to agree upon a management objective, and second, to enforce the agreed upon policy.

Given this stylized description of the regulatory process, how should we expect old agents to behave? Since he derives no utility from his child's consumption or from savings, a rational old agent should always choose the bargaining strategy that maximizes his consumption, given his bargaining power.

The remainder of this section develops a framework in which to analyze the decision by each successive young agent about how aggressively he will bargain with his parent. To begin, assume that in each period the young agent proposes a management objective which the old agent either accepts or rejects. If the old agent accepts the policy then it is enforced. If the old agent rejects the proposal then there is no regulation and the old agent receives consumption ηY_t, while the young agent divides $(1-\eta)\, Y_t$ between consumption and savings. The parameter η is an exogenous description of the two agents' relative bargaining strengths[2]. This simple bargaining game captures the aspects of the bargaining problem in which we are interested: It explicitly models the choice of regulation as the outcome of bargaining, and it allows young agents to choose bargaining strategies that are more or less aggressive.

The young agent in each period is permitted to propose any feasible management objective (c_t^o, c_t^y, S_t). "Accept any management objective such that $c_t^o \geq \eta Y_t$" is the unique subgame perfect strategy for each old agent. This means that we can restrict the young agent's choices to those that the old agent will accept, and disregard the old agent's move, without loss of generality. Since $c_t^o + c_t^y + S_t = Y_t$, a management objective in period t is completely specified by the choice of (c_t^o, S_t).

[2]One can tell a number of stories about the origin of the bargaining strength parameter. For example, η could be the share of the resource stock that the old agent captures when bargaining breaks down and open access exploitation occurs. With this said, the source of this limit on the old agent's bargaining strength is irrelevant to the analysis.

Thus the set of possible proposals (or actions) for the young agent t is given by the set $A_t = \{(c_t^o, S_t) | \, c_t^o \geq \eta Y_t, c_t^o + S_t \leq Y_t\}$, where $Y_t = F(S_{t-1})$ for $t \geq 2$. Any proposed management objective in this set is accepted by the old agent, so the old agents' moves can be ignored.

This simple characterization of the young agents' action sets is due to the simple bargaining process specified here. The reasonableness of ignoring the old agents' moves is not. Whatever the bargaining process, the old agents always choose the bargaining strategy that maximizes their consumption. This strategy can be constructed for other bargaining games as well. This done, we can write down the young agents' strategy sets, contingent on consumption maximization by the old agent, just as is done for the ultimatum bargaining game above. In short, regardless of the particular bargaining game used, and regardless of how much bargaining power the old agents have, all of the "action" will be in the young players' strategy choices. The old agents always try to maximize their own consumption.

The choice of management objective by each young agent may now be regarded as a "move" in a game of sequential agents, and resulting allocation may be regarded as an outcome of this game. In particular, the players are the young agents in each period $t = 1, 2, 3, ...$ An action, a_t, for young agent t is a pair $(c_t^o, S_t) \in A_t$. Player t's payoff function may be constructed from preferences over consumption by observing that; $c_t^y = Y_t - c_t^o - S_t = Y_t - (1,1) \bullet a_t$, and $c_t^o = (1,0) \bullet a_t$. Preferences over actions can now be inferred from preferences over consumption. We will abuse notation and denote preferences over actions with $V^t(a_t, \; a_{t+1})$, rather than use the correct but cumbersome, $V^t(Y_t - (1,1) \bullet a_t, \; (1,0) \bullet a_{t+1})$.

3. Equilibrium regulation without memory

Suppose that agents are aware of history and choose to ignore it, or they are unable to recall and interpret the historical record. In either case, if agents do not condition their choice of management objective on history, each agent t can affect his future consumption only through his choice of savings. Holding savings constant, the consumption level of agent t's parent does not affect agent t's old age consumption. Given this, player t is always better off if he drives a hard bargain and gives his parent the disagreement consumption level ηY_t. Moreover, since no other strategy is rational and credible for agent $t+1$, agent t should expect his successor to drive an equally hard bargain with him.

This means that player t should expect a return to savings of $\eta F'(S_t)$ in equilibrium. That is, in equilibrium, his return to savings is only as large as his bargaining powers allow. Since this is less than the social return to savings, $F'(S_t)$, each player t will undersave relative to the Pareto optimal level[3].

Example 1. Consider the extreme case when $\eta = 0$ so that each period's young agent is able to dictate any feasible management objective to the old agent. Also suppose that agents do not condition their actions on the actions of their ancestors. The first young agent does not care about his parent and chooses not to give anything to him. Similarly, this agent expects that his child will not choose to give him any consumption in the future. It follows that the return to savings is zero and that in equilibrium, the first young agent saves nothing and consumes the whole stock. □

4. Equilibria with memory

If it were possible for each agent to sign a binding contract with his unborn child that required the child to permit the parent to consume relatively more of the stock in old age, provided the parent saved relatively more in his youth, then agents could overcome the incentive to undersave and be better off. However, the child will have an incentive to break this contract and there is no external agency to enforce it. Thus we are led to ask whether there exist self-enforcing contracts that permit living agents and their unborn descendants to overcome the intergenerational externality.

This section analyzes a game of sequential agents in order to establish sufficient conditions for a subgame perfect equilibrium. More intuitively, this section describes a "self-enforcing social contract".

Consider a game played by an infinite sequence of players, $t = 1, 2, 3...$, such that each player t takes exactly one action, a_t, in period t. To develop some intuition about this game, suppose that each player t's strategy set does not depend on the history of past moves, and is given by $A_t = \{E, P, D\}$. Let the sequence $h = (a_0, (E)_{t=1}^{\infty})$ denote a socially desirable outcome. Move P will denote a punishment move imposed by a player on his predecessor. Move D will be a move that is not the punishment move or the equilibrium move. In addition, imagine

[3] A more rigorous argument is available in Turner (1995).

Table 1.

(A)	(B)
X ... X X X X X E	X ... X X X X X D
X ... X X X X D P	X ... X X X X E P
X ... X X X E P P	X ... X X X D P P
X ... X X D P P P	X ... X X E P P P
X ... X E P P P P	X ... X D P P P P
⋮	⋮

that there is a cultural norm or "social contract" that requires each player to play E if his predecessor has honored the social contract, and to play P if his predecessor violated the social contract. Finally, suppose that this social contract requires that each player use the logic described below to determine whether his predecessor has "honored" or "violated" the social contract.

If player t observes player $t-1$ to have played E, then player t concludes that $t-1$ honored the contract [4]. If player t observes player $t-1$ to take action D then player t concludes that player $t-1$ violated the contract. But what if player t observes that player $t-1$ played P? Is player $t-1$ punishing a transgressor, or wrongly punishing a player who honored the contract? To answer this question, look at the action taken by player $t-2$. If player $t-2$ played D then player $t-1$ honored the contract by punishing a deviator. If $t-2$ played E then player $t-1$ wrongly punished a player who honored the social contract and thereby violated the contract. What if both $t-1$ and $t-2$ played P? Is $t-1$ punishing $t-2$ for imposing an illegitimate punishment, or is $t-1$ wrongly punishing $t-2$ for punishing a deviator? The answer depends on the moves made at and before $t-3$.

Column (A) of Table 1 gives histories at time $t-1$ that should cause player t to conclude that player $t-1$ honored the social contract. The histories that belong in this column are concluded by an even number (or zero) consecutive punishment moves, preceded by action E, or an odd number of consecutive punishment moves preceded by action D. Column (B) of Table 1 gives histories that should cause player t to conclude that player $t-1$ violated the social contract.

[4] The possibility that agent $t-1$ takes action E when he should be punishing a deviator by playing P will be taken up later.

The histories that belong in this column are concluded by an even number (or zero) consecutive punishment moves, preceded by action D, or an odd number of consecutive punishments preceded by action E. Except for the history where all players play P, every possible history belongs to exactly one column of Table 1. If all earlier players played P then player t should conclude that player $t-1$ honored the social contract if $t-1$ is even, and that player $t-1$ violated the social contract if $t-1$ is odd.

Consider the following sequence of strategies. Player 1 plays E. Each subsequent player plays E if the history at $t-1$ is in column (A) of Table 1, and plays P if the history at $t-1$ is in column (B) of Table 1. In other words, the first agent plays E and subsequent agents follow the social contract; play E if the last player honored the social contract, punish if the last player did not honor the social contract. Under what conditions is this strategy sequence an equilibrium?

Suppose player t observes a history that causes him to conclude that player $t-1$ honored the social contract, i.e. a history in column (A), and player $t+1$ is honoring the social contract. If player t chooses any move other than E, then player $t+1$ will observe a history in column (B) and conclude that player t violated the social contract and should be punished. Given a history in column (A), and that future players are playing the social contract, player t can choose move E and get payoff $V^t(E,E)$, or choose $a \in \{P,D\}$ and get payoff $V^t(a,P)$. Thus player t's best response to a history in column (A) when other players follow the social contract is move E, if

$$V^t(E,E) \geq V^t(a,P), : a \in \{P,D\}. \tag{1}$$

If the strategy profile where all players follow the social contract is to be a subgame perfect equilibrium it is also necessary that the threat to punish be credible. Under what conditions does this occur? Suppose player t observes a history in column (B) and player $t+1$ follows the social contract. If player t plays P or E then player $t+1$ will observe a history in column (A) and play E. If player t plays D then player $t+1$ will observe a history in column (B) and play P. By (1) $V^t(E,E) \geq V^t(D,P)$ so player t prefers action E to action D. Player t will prefer P to E only if

$$V^t(P,E) \geq V^t(E,E). \tag{2}$$

Thus the threat to punish non-cooperative behavior is only credible if (2) holds.

The preceding discussion has argued that if conditions (1) and (2) hold, then playing E after a predecessor has followed the social contract, is the best response to the strategy profile where all agents follow the social contract. Similarly, playing P after a predecessor has violated the social contract is also a best response. This means that at all possible histories, following the social contract is the best response to the strategy profile where all other agents play the same strategy. Therefore the strategy sequence where all agents follow the social contract is a subgame perfect equilibrium of the game of sequential agents. It follows that $(a_0, (E)_{t=1}^{\infty})$ is a subgame perfect equilibrium, if conditions (1) and (2) hold. Alternately, the social contract described above is self-enforcing if (1) and (2) hold.

To generalize this intuition to allow for larger and possibly history dependent action sets, let $h_\tau = (a_t)_{t=0}^{\tau}$ denote a possible history of the game at time τ[5], and let H_τ denote the set of all possible histories at time τ. We also allow each agent's action set to depend upon the history of the game, and denote these (possibly) non-stationary action sets by $A_t(h_{t-1})$. Next, we require two sequences of functions, $(E_t(h_{t-1}))_{t=1}^{\infty}$ and $(P_t(h_{t-1}))_{t=1}^{\infty}$, which correspond to the actions E and P of the example, and describe the feasible "equilibrium" and "punishment" actions that each player will take at each possible history. Denote the sequence that results when all agents choose the action $E_t(h_{t-1})$ by $(a_0, (a_t^*)_{t=1}^{\infty})$.

As in the stationary example above, the sequence of actions $(a_0, (a_t^*)_{t=1}^{\infty})$ can be supported by a self-enforcing social contract provided that punishment is both sufficiently severe and credible. These conditions, which correspond to conditions (1) and (2), and may be stated more formally as,

(3) For all $t \geq 1$ and all possible h_{t-1},

$$V^t(E_t(h_{t-1}), E_{t+1}(h_{t-1}+E_t(h_{t-1}))) \geq V^t(a_t, P_{t+1}(h_{t-1}+a_t)), \text{ for all } a_t \in A_t(h_{t-1}).$$

(4) For all $t \geq 1$ and all possible h_{t-1},

$$V^t(P_t(h_{t-1}), E_{t+1}(h_{t-1} + P_t(h_{t-1}))) \geq V^t(E_t(h_{t-1}), E_{t+1}(h_{t-1} + E_t(h_{t-1}))\ ).$$

In addition, it must always be clear whether the preceding play "honored" or "violated" the contract. Hence the additional condition,

(5) For all $t \geq 1$ and all possible h_{t-1}, $E_t(h_{t-1}) \neq P_t(h_{t-1})$.

[5]An action a_0 at $\tau = 0$ is specified for notational conveinience. Without it h_0 is not defined.

Provided that these three conditions are met, Theorem 1 in the appendix shows that the outcome $(a_0, (a_t^*)_{t=1}^{\infty})$ is a subgame perfect equilibrium outcome of the regulation game, when players follow the social contract described above.

Example 2. As in Example 1, suppose that $\eta = 0$ so that each period's young agent is able to dictate any feasible management objective to the old agent. Suppose that the growth equation of the stock is $Y_{t+1} = 3S_t$, so that savings triples from one period to the next. Let player t's preferences over (c_t^y, c_{t+1}^o) be given by a utility function,

$$V^t(c_t^y, c_{t+1}^o) = \sqrt{c_t^y c_{t+1}^o},$$

so that player t's payoff function is given by,

$$V^t(a_t, a_{t+1}) = \sqrt{(Y_t - (1,1) \bullet a_t)(\ (1,0) \bullet a_{t+1})}.$$

As above, the young agent at t chooses his action a_t from $A_t(h_{t-1}) = \{(c_t^o, s_t) |\ c_t^o + S_t \leq Y_t\}$.

Since each unit of stock saved triples by the next time period, any agent may exchange one unit of consumption in youth for three units of consumption in old age without affecting the consumption of any other agent. It follows that any Pareto optimal allocation must satisfy, $\frac{\partial V^t}{\partial c_t^y} = 3\frac{\partial V^t}{\partial c_{t+1}^o}$, whenever $(c_t^y, c_{t+1}^o) \neq (0,0)$. The unique steady state allocation satisfying this condition is $(c^y, c^o) = (\frac{1}{6}\mathcal{Y}_1, \frac{1}{2}\mathcal{Y}_1)$.

To support this Pareto optimal steady state, construct the following two sequences of functions:

$$\begin{aligned} E_t(h_{t-1}) &= (\frac{1}{2}Y_t, \frac{1}{3}Y_t) \\ P_t(h_{t-1}) &= (0, \frac{1}{3}Y_t) \end{aligned}$$

These two functions satisfy conditions 3-5, hence $(a_0, (a_t^*)_{t=1}^{\infty})$ is a subgame perfect equilibrium outcome. It follows that the Pareto optimal steady state allocation, $(c^y, c^o) = (\frac{1}{6}\mathcal{Y}_1, \frac{1}{2}\mathcal{Y}_1)$, can be sustained by a self-enforcing social contract. $\Box$.

This establishes the possibility of self-enforcing social contracts that allow the agents to overcome the incentive faced by selfish agents to overconsume to avoid sharing with their selfish children. Under such self-enforcing social contracts, each agent will be offered more old age consumption by his child, if and only if he offers his parent a more generous management objective than the parent's bargaining power requires.

Although the Example 2 is interested in supporting a steady state allocation, this is done entirely to lighten notation. The contracts work equally well to support non-steady state outcomes (Turner (1995) provides an example).

Also note that the social contracts do not require that the young be dictators, as in the example. What is required is that punishment be sufficiently onerous. In particular, if the old agents have bargaining power η, then the worst utility that the social contract can impose on agent t is given by

$$\max_{S_t} V^t\left((1-\eta)Y_t - S_t, \eta F(S_t)\right).$$

that is, the social contract must guarantee each agent at least what he could obtain by violating it. This does not necessarily require that each young agent be a dictator, although this case is particularly easy to analyze.

5. Discussion

The possibility of self-enforcing social contracts depends upon the nature of the institution of "government". In particular, the set of possible equilibrium exploitation paths that may be sustained by self-enforcing social contracts shrinks as bargaining power shifts to the old. To see this, let $\{(c_t^y, c_{t+1}^o)\}_{t=1}^{\infty}$ be any allocation, and let $c_{sup}^o = sup\{\frac{c_t^o}{Y_t}\}_{t=1}^{\infty}$. If $\eta > c_{sup}^o$ then for some t', the old agent's bargaining power allows him to consume more than $c_{t'}^o$. Since the only rational action for an old agent is to consume as much as possible, it follows that he consumes more than $c_{t'}^o$ in period t', and the allocation in question is not achieved. As η approaches 1 and bargaining power shifts to the old, the set of possible equilibrium allocation paths converges to the one where the first old agent, Agent Zero, consumes the entire stock. All else equal, as the institutions of government are more skewed toward the old, fewer exploitation paths can be supported by self enforcing social contracts.

The possibility of self-enforcing social contracts does not depend in an obvious way on the rate at which population is growing. To apply the model to an economy where each successive cohort is larger than its predecessor, we imagine that each cohort is able to act collectively and is represented at the bargaining table by any one of its members. Aside from requiring that the resource base be more productive to sustain constant consumption levels, population growth has two likely impacts. First, it may result in relatively more bargaining power for the young cohort. Second, all else equal, it results in lower per capita consumption for the young cohort. These two consequences of population growth have opposite effects on consumption by the young, and their effect on the set of allocations that may be sustained by a social contract is ambiguous.

The analysis does not allow for the possibility that parents care about their children. To see that this simplifying assumption does not qualitatively affect the analysis, suppose that parents value their childrens' welfare. Despite this, depending on the degree of altruism and the old agent's bargaining strength, children may still consume more of the resource stock than the parents want them to. If so, then (just as in the case where there is no altruism) parents have an incentive to undersave to avoid sharing with their children, and the threat to withdraw old age consumption can affect behavior. Since parental altruism need not qualitatively change the incentive to overconsume in youth or the incentive effects of punishment in old age, the absence of altruism in the formal model should be regarded as a simplifying assumption which does not qualitatively affect the analysis. The reader interested in a more exhaustive analysis of the role of parental altruism is directed to Turner 1997.

Note that the regulation game can be thought of as an infinitely long game tree. Each node of this game tree is a history, h_t, the set of possible nodes at time t is the set of possible histories at time t, and a path through the tree is an infinite sequence of moves $(a_t)_{t=0}^{\infty}$. The social contract described earlier allows certain infinite sequences of actions to be supported as subgame perfect equilibria of this game. By definition this requires that the social contract specify Nash equilibrium actions at every possible subgame, no matter how far from the equilibrium sequence of actions in which we are interested. This requires that at every possible subgame, h_{t-1}, the threat of the punishment $P_t(h_{t-1})$ is sufficiently severe that an agent rationally prefers the equilibrium move $E_t(h_{t-1})$ to any actions which invite future punishment. This requires, in order to sustain a particular regulatory path, that the young have access to punishment that is either very severe or whose severity adjusts with the stock level. Hence, the analysis requires that the resource be "big" in that utility depends upon having access to the resource in both periods—there are no substitutes or outside options.

The resource considered in Example 2 is big in the required sense, utility depends upon having access to the resource in both periods. The punishment response is to give the Old Agent zero in old age. Given the utility functions selected in this example, receiving zero consumption in old age results in the worst possible utility level. Consequently, this punishment is sufficiently severe to enforce the equilibrium move, regardless of how far the preceding players have strayed from the desired path. These payoffs require that we interpret the resource stock as being big in the sense that access to the resource stock is essential to maintaining utility levels.

While one might try to list particular resources that are big in this sense, (e.g. ozone or biodiversity), such a list will probably be contentious. It makes more sense to think of the common property resource stock Y as being an aggregate of many resource stocks. As we will see later, this complements the literature on sustainability nicely. This literature is also concerned with a highly aggregated and essential resource stock.

If a resource stock is "small enough" that it makes sense to imagine the existence of a backstop technology, the self-enforcing social contracts described here cease to be rational equilibria. A backstop technology provides an investment which yields a constant exogenous rate of return $1 + R$. In the presence of such an investment, rational utility maximizing agents necessarily maximize the discounted present value of their income. Therefore, in order for Agent One to make a one unit gift to his parent in accordance with a social contract, he must expect a gift of at least $(1 + R)$ from Agent Two. Agent Two must in turn expect a gift of at least $(1 + R)^2$ from agent three, and so on. Hence, the social contracts discussed here require that the transfer from child to parent grow geometrically. An implausible necessary condition for this to occur is that the resource stock also grow geometrically.

Finally, note that the social contract considered here relies on the intuition that the current agent will alter its behavior to secure the cooperation of the next generation. It is not obvious that this intuition requires that future cooperation be essential to the welfare of the current generation, only that it be valuable. Subgame perfection requires that the punishment action be "sufficiently severe" (in the sense of Equation (4)) at *all possible nodes*, no matter how many agents must make irrational decisions to reach the node. This requires the possibility of a very severe punishment, even though this punishment may only be invoked after long histories of irrational action. Hence, the requirement that the resource be essential seems to be at least partly, an unintuitive artifact of the equilibrium concept. Unfortunately, there does not seem to be a weaker equilibrium concept that is useful for this problem.

6. Tradition and social contracts

The Oxford English Dictionary defines tradition as "..., a long established and generally accepted custom or procedure, having almost the force of law; an immemorial usage, ..., handed down by predecessors and generally followed...". For any given generation of young agents, the social contract describes the behavior that was followed by their parents and will be followed by their children through time immemorial. Because of the self enforcing nature of this social contract, it has almost the force of law. As in Example 2, this social contract may require young agents to behave in exactly the same customary way that their ancestors did. In other words, the social contract can be interpreted as requiring that each successive young agent choose the traditional or customary management objective, or behave in the traditional way.

If we interpret a self-enforcing social contracts as traditions, then particular traditions of resource regulation may emerge because they allow rational agents to overcome an intergenerational externality. In short, traditions of conservation may be a *rational* response to an intergenerational externality.

7. Sustainability and Common Property Regulation

The debate about "sustainability" is largely a moral debate that revolves around the question of how much of our resource base we should consume and how much we should conserve. While this debate has not yet settled on a definition of sustainability, Solow (1991) puts forward a promising candidate,

> *the notion of sustainability is about our obligation to the future. It says something about a moral obligation that we are supposed to have for future generations. ... it is an obligation to conduct ourselves so that we leave to the future the option or capacity to be as well off as we are.*

This notion of sustainability requires that we consider a highly aggregated resource stock consisting of all natural and manmade capital that contribute to an economy's ability to satisfy its members' wants. We then say that an economy has selected a sustainable path if each subsequent generation has saved enough of this aggregate stock.

The social contracts considered here affect the management of a resource which is large in exactly the same way as resource upon which the judgement of sustainability is based. Sustainability is concerned with the management of a highly aggregated resource stock consisting of all natural and manmade capital that contribute to an economy's ability to satisfy its members' wants. The analysis conducted here is concerned with a similarly aggregated resource.

While measuring whether we have had the opportunity to be as well off as our predecessors is difficult, Solow (1993) argues that national income accounts can be used to measure our welfare relative to our parents, if these accounts are augmented to reflect changes in natural resource stock levels. In particular, given such augmented national income accounts, the test for whether our parents chose sustainable consumption and management objective is simply whether or not an augmented measure of national net income is above or below a certain threshold.

This is also related to the present analysis. The social contracts described here are "trigger" strategies. If the preceding generation does not save enough or fulfill its obligation to its parents, it is subject to sanctions. Similarly, if the preceding generation does not save enough, its actions are deemed "not sustainable". Hence, sustainability provides a natural punishment threshold, and given appropriately modified national income accounts, one that might even be practical. Thus the debate over sustainability provides both a basis for interpreting this analysis, and suggests a way that the social contracts here might be implemented.

Conversely, this analysis suggests that a rational regulation process might select "sustainable" exploitation policy, even in the absence of any sense of moral obligation or affection towards succeeding generations.

8. Related literature

The intuition behind the social contracts developed here is that children will take apparently altruistic actions towards their parents to avoid punishment by their children in the future. Although the application to the problem of common property management is new, the same intuition is used in other areas.

Kandori (1992) and Cremer (1986), describe games in which overlapping generations of agents play a stage game in each time period, extending the folk theorem of supergames to the case of overlapping generations of players. These authors require that agents play the same stage game in each period. In the analysis of common property, we must allow players' actions to change the size of the resource stock, and hence the stage game, from one period to the next. Thus the problem of common property management is not adequately described by overlapping generations of agents playing a repeated game.

Hammond (1975) considers a game of sequential agents that is slightly more general than the one considered here. However, he is primarily concerned with developing an equilibrium concept. Kotlikoff *et al* (1980) consider a game of sequential agents, however they are interested in understanding a fiscal policy problem. In addition to considering a different application, this paper allows an analysis of how changes in the institution of government affect the set of equilibria, something that Kotlikoff *et al* (1980) do not do.

Finally, there is a large literature analyzing the exploitation of common property in a variety of different frameworks, for example Olson and Knapp (1997) or Clemhout and Wan (1991). However, these papers are usually concerned with the way that exploitation occurs in a competitive environment. This paper differs from the existing literature on common property in that it analyzes regulatory behavior rather than competitive exploitation.

9. Conclusion

This paper examines the problem of common property regulation, and proposes that the choice of management objective by the current government of finitely lived agents be regarded as a "move" in a game of sequential agents. Given this framework, the following two results are established.

First, absent the ability to condition the choice of management objective on the actions of earlier agents, only one sequence of management objectives is consistent with subgame perfection, and because of an intergenerational externality this sequence of management objectives does not result in a Pareto optimal allocation. Second, if current agents are able to condition the choice of management objective on the behavior of prior agents, then many subgame perfect allocations may be possible, including some that are Pareto optimal. The strategies used to support these outcomes may be thought of as social contracts. However it is also reasonable to regard these strategies as traditions. Taken together these results imply that following a tradition of conservation may be a rational response to an intergenerational externality.

Finally, the results in this paper complement the debate on sustainability in two ways. First, the notion of sustainability may provide a way to implement the social contracts described here. Second, these contracts may provide an incentive to choose management objectives that are consistent with sustainability, apart from any sense of moral obligation to provide for the future.

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10. Appendix

This appendix describes a "self-enforcing social contract" and characterizes the outcomes that this contract can be used to enforce.

Consider a game played by an infinite sequence of players, $t = 1, 2, 3...$, such that each player t takes exactly one action, a_t, in period t. For notational convenience, an action a_0 at $t = 0$ is also specified. A sequence $h = (a_\tau)_{\tau=0}^{\infty}$ is an outcome of the game, and a sequence $h_t = (a_\tau)_{\tau=0}^{t}$ is a history at time t. Each h_t should be thought of as describing a node of an infinitely long game tree, while each h should be though of as a path through this tree. Let $h_{t-1} + a'_t = (a_0, ..., a_{t-1}, a'_t)$ denote the history that occurs when move a'_t is played after history h_{t-1}. In period t, player t chooses his action a_t from the an action set $A_t(h_{t-1})$. Let $H_t = \{(a_\tau)_{\tau=0}^{t} : a_\tau \in A_t(h_{t-1}), \tau \geq t \geq 1\}$, denote the set of all possible histories at time t, $(H_0 = \{h_0\})$. Let $H = H_\infty$ denote the set of possible outcomes for the game.

A strategy for player t is a function from the space of histories into the set of actions. More formally, let $A_t(H_{t-1}) = \bigcup_{h_{t-1} \in H_{t-1}} A_t(h_{t-1})$; then a strategy for player t is a function

$$\sigma_t : H_{t-1} \mapsto A_t(H_{t-1})$$

such that $\sigma_t(h_{t-1}) \in A_t(h_{t-1})$ for all $h_{t-1} \in H_{t-1}$. Player t's strategy set Σ_t is the set of all such functions. A strategy sequence is a sequence of strategy choices, one for each player, $\sigma = (\sigma_t)_{t=1}^{\infty}$. Let (σ_{-t}, σ'_t) denote the strategy sequence $(\sigma_1, ..., \sigma_{t-1}, \sigma'_t, \sigma_{t+1}, ...)$. Let $\Sigma = \Pi_{t=1}^{\infty} \Sigma_t$ denote the set of possible strategy sequences. Once selected, the strategy sequence is imagined to be known as common knowledge by all players.

Theorem 1. Let $h^* = (a_0, (a_\tau^*)_{\tau=1}^{\infty})$ denote a particular outcome of a game of sequential agents. h^* can be supported as a subgame perfect equilibrium if there exist two sequences of functions $(E_t(h_{t-1}))_{t=1}^{\infty}$ and $(P_t(h_{t-1}))_{t=1}^{\infty}$ such that:

(a) $E_t(h^*_{t-1}) = a^*_t$, for all $t \geq 1$.

and for all $h_{t-1} \in H_{t-1}$ and $t \geq 1$,

(b) $E_t(h_{t-1}),\ P_t(h_{t-1}) \in A_t(h_{t-1})$, and $E_t(h_{t-1}) \neq P_t(h_{t-1})$.

(c) $V^t(E_t(h_{t-1}), E_{t+1}(h_{t-1} + E_t(h_{t-1}))\ ) \geq V^t(a_t, P_{t+1}(h_{t-1} + a_t))$ for all $a_t \in A_t(h_{t-1})$.

(d) $V^t(P_t(h_{t-1}), E_{t+1}(h_{t-1} + P_t(h_{t-1}))\ ) \geq V^t(E_t(h_{t-1}), E_{t+1}(h_{t-1} + E_t(h_{t-1}))\ )$.

Proof: Let $n(h_t)$ denote the number of consecutive moves immediately prior to and including t at which the punishment action P was taken. Let σ^* be the strategy profile such that:

$$\begin{aligned}
\sigma^*_1 &= E_1(h_0) \\
\sigma^*_2 &= \begin{cases} E_2(h_1) & \text{if } a_1 = E_1(h_0) \\ P_2(h_1) & \text{otherwise} \end{cases}
\end{aligned}$$

and for $t \geq 3$,

$$\sigma^*_t = \begin{cases} E_t(h_{t-1}) & \text{if (i) } n(h_{t-1}) < t-1 \text{ is odd and} \\ & \qquad a_{t-1-n(h_{t-1})} \neq E_{t-1-n(h_{t-1})}(h_{t-1-n(h_{t-1})}), \\ & \text{or (ii) } n(h_{t-1}) < t-1 \text{ is even or zero and} \\ & \qquad a_{t-1-n(h_{t-1})} = E_{t-1-n(h_{t-1})}(h_{t-1-n(h_{t-1})}), \\ & \text{or (iii) } n(h_{t-1}) = t-1 \text{ is even.} \\ & \\ P_t(h_{t-1}) & \text{otherwise.} \end{cases}$$

It is sufficient to show that at every possible node, σ^*_t is a best response to σ^*_{-t}. More formally, σ^* is a subgame perfect equilibrium if and only if, for all t, $h_{t-1} \in H_{t-1}$, and $a_t \in A_t(h_{t-1})$,

$$V^t(\sigma^*_t(h_{t-1}), \sigma^*_{t+1}(h_{t-1} + \sigma^*_t(h_{t-1}))) \geq V^t(a_t, \sigma^*_{t+1}(h_{t-1} + a_t)).$$

$[t = 1]$ $[\sigma^*_1(h_0), \sigma^*_2(h_0 + \sigma^*_1(h_0)] = [E_1(h_0), E_2(h_1)]$ and for all $a_1 \in A_1(h_0)/\{E_1(h_0)\}$, $[a_1, \sigma^*_2(h_0 + a_1)] = [a_1, P_2(h_0 + a_1)]$. Therefore, by (c), σ^*_1 is a best response to σ^*_{-1} for all $h_0 \in H_0$.

$[t=2]$ If $h_1=(a_1^*)$ then $[\sigma_2^*(h_1),\sigma_3^*(h_1+\sigma_2^*(h_1)]=[E_2(h_1),E_3(h_1+E_2(h_1))]$ and for all $a_2\in A_2(h_1)/\{E_2(h_1)\}$, $[a_2,\sigma_3^*(h_1+a_2)]=[a_2,P_3(h_1+a_2)]$. By (c), σ_2^* is a best response to σ_{-2}^* for $h_1=(a_1^*)$. If $h_1\neq(a_1^*)$ then $[\sigma_2^*(h_1),\sigma_3^*(h_1+\sigma_2^*(h_1)]=[P_2(h_1),E_3(h_1+P_2(h_1)]$, $[E_2(h_1),\sigma_3^*(h_1+E_2(h_1))]=[E_2(h_1),E_3(h_1+E_2(h_1)]$, and for all $a_2\in A_2(h_1)/\{E_2(h_1),P_2(h_1)\}$, $[a_2,\sigma_3^*(h_1+a_2)]=[a_2,P_3(h_1+a_2)]$. By (c) and (d) it follows that σ_2^* is a best response to σ_{-2}^* for $h_1\neq(a_1^*)$. Therefore, for all $h_1\in H_1$, σ_2^* is a best response to σ_{-2}^*.

$[t\geq 3]$ If (i) or (ii) or (iii) holds then $[\sigma_t^*(h_{t-1}),\sigma_{t+1}^*(h_{t-1}+\sigma_t^*(h_{t-1})\ )]=[E_t(h_{t-1}),E_{t+1}(h_{t-1}+E_t(h_{t-1})\ )]$, and for all $a_t\in A_t(h_{t-1})/\{E_t(h_{t-1})\}$, $[a_t,\sigma_{t+1}^*(h_{t-1}+a_t)]=[a_t,P_{t+1}(h_{t-1}+a_t)]$. By (c) it follows that σ_t^* is a best response to σ_{-t}^* when (i) or (ii) or (iii) holds.

If none of (i),(ii),(iii) holds then $[\sigma_t^*(h_{t-1}),\sigma_{t+1}^*(h_{t-1}+\sigma_t^*(h_{t-1})\ )]=[P_t(h_{t-1}),E_{t+1}(h_{t-1}+P_t(h_{t-1})\ )]$, $[E_t(h_{t-1}),\sigma_{t+1}^*(h_{t-1}+E_t(h_{t-1}))]=[E_t(h_{t-1}),E_{t+1}(h_{t-1}+E_t(h_{t-1})\ )]$, and for all $a_t\in A_t(h_{t-1})/\{E_t(h_{t-1}),P_t(h_{t-1})\}$, $[a_t,\sigma_{t+1}^*(h_{t-1}+a_t)]=[a_t,P_{t+1}(h_{t-1}+a_t)]$. Therefore, by (c) and (d), σ_t^* is a best response to σ_{-t}^* at all possible nodes, so that σ^* is a subgame perfect equilibrium strategy sequence.

By (a) σ^* requires that $a_1=a_1^*$ and that $a_{t+1}=a_{t+1}^*$ if $h_t=h_t^*$, it follows that $(a_0,(a_t^*)_{t=1}^{\imath})$ is a subgame perfect equilibrium outcome of the game of sequential agents. $\square$