APPROPRLATION EXTERNALITIES IN THE COMMONS: THEORY AND EXPERIMENTAL EVIDENCE

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To my parents, who always made me eat my lima beans before my dessert.

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ABSTRACT

A common-pool resource (CPR) is defined as any resource in which exclusion is difficult and consumption of resource units is rival. Examples of CPRs include groundwater basins, fisheries, forests, grazing ranges, and irrigation systems in which property rights -- or the ability to uphold such rights -- do not allow for privatization. In situations where these characteristics exist, the predicted outcome is overuse of the resource relative to the social optimum, commonly known as the "tragedy of the commons." This dissertation combines the tools of game theory and experimental methods to gain a broader understanding of the incentives that underlie this prediction.

First, an extensive analysis of a game theoretic CPR model is conducted. A distinction is made between two types of appropriation externalities: those that are restricted to a single period (time-independent), and those that occur across several periods (time-dependent). This study examines the impact of various factors -- including group size, heterogeneities, myopia, and the ability of appropriators to commit to an extraction path -- on the predicted outcome of the CPR game. The behavioral impacts of time-dependency and group size are then examined in a controlled experimental setting designed to capture the essential features of the model.

While the equilibrium of the game theoretic model provides a fairly accurate prediction of aggregate outcomes, it fails to satisfactorily explain behavior at the

individual level. Most notably, individual behavior in time-dependent designs is characterized by myopia, in the sense that subjects appear not to consider the full impact of their current decisions on future payoffs. This myopic behavior exacerbates the predicted tragedy of the commons.

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CHAPTER 1

An Introduction to the Tragedy of the Commons

This dissertation examines individual incentives facing appropriators from a common-pool resource (CPR). A CPR is defied as any resource in which exclusion is difficult, for either economic or political reasons, and resource units are subtractable. Examples of CPRs include groundwater basins, fisheries, forests, grazing ranges, and irrigation systems where designing an enforceable set of property rights is challenging. Strict privatization of ownership rights to both the resource itself and the output from the resource is rarely feasible. In situations where these characteristics exist and where an enforceable set of property rights have not been established, the predicted outcome is overuse of the resource relative to the social optimum. This dissertation examines the incentives that underlie this prediction and the behavior of individuals in controlled experimental settings designed to capture these incentives.

Hardin (1968) coined the term the "tragedy of the commons" to describe the predicted overuse of a CPR. In his article entitled "The Tragedy of the Commons," Hardin illustrates the predicted fate of an open-access CPR with a metaphor of herdsmen sharing a common grazing land:

> The rational herdsman concludes that the only sensible course for him to pursue is to add another animal to his herd. And another, and another ... But this is the conclusion by each and every rational herdsman sharing the commons. Therein is the tragedy. Each man is locked into a system that compels him to increase his herd without limit - in a world that is limited. Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that

> believes in the freedom of the commons. Freedom in the commons brings ruin to all (p. 1244).

Gordon (1954) provides a theoretical framework for the study of the tragedy predicted by Hardin. In his model, the marginal productivity of an ocean fishery is decreasing in the aggregate fishing effort of all fisherman. Thus, an increase in fishing effort by one fisherman decreases the net benefits of others. Using this framework, Gordon concludes that:

> Common-property natural resources are free goods for the individual and scarce goods for society. Under unregulated private exploitation, they can yield no rent; that can be accomplished only by methods which make them private property or public (government) property, in either case subject to a u ed directing power (p. 135).

Together, Hardin and Gordon provide an intuitively appealing argument that CPR outcomes are inherently tragic and can be solved only by establishing private property rights or through external regulation of resource use. Over the years, this logic has been applied to a wide variety of natural and man-made resources. In Hardin's paper alone, this metaphor is applied to population growth, grazing lands, fisheries, national parks, air and water pollution, and the extinction of animal species.

While the incentives described by Hardin and Gordon may, to some degree, be present in a wide variety of situations, there is a danger in assuming that each of these situations is inherently tragic. As Simmons and Schwartz-Shea (1993) note:

> A core reading in our graduate training in political economy was "The Tragedy of the Commons." We were taught to look for commons problems in all kinds of social situations and, not surprisingly, we found the commons problem to be ubiquitous. Specifically, as political scientists, some of our professors used commons problems to justify the state. Another part of our training, however, led us to examine

> property rights solutions to commons problems. But cultural and normative, or **informal,** solutions to commons problems were not emphasized, implying, however, that culture and norms are seldom powerful explanatory variables. In our own research, we found that culture and norms are critical to the understanding of behavior and commons (p. 8).

Similarly, Ostrom (1990) challenges the notion that CPR outcomes are inherently tragic, citing numerous field examples in which the appropriators of a CPR have successfully avoided the tragedy of the commons through self-governance. Like Simmons and Schwartz-Shea, she emphasizes the role that informal institutions can play in successful governance of the commons, arguing that the appropriators of a resource often have a better knowledge of the resource and more incentive to solve the CPR dilemma than do external regulators.

Even before Hardin, Cheung (1970) emphasized the potential for private contracting in the commons. He contends that the tragedy of the commons is based on the presumption of an absence of the right to contract, which may or may not be valid. Rational users of a CPR will exclude "outsiders" to the point where the marginal benefit of exclusion equals the marginal cost. Thus, contracting may provide an alternative to privatization or external regulation as a means of solving the CPR dilemma.

Clearly, the simple logic behind the tragedy of the commons fails to capture the complexities involved in many CPR situations. In the years following Hardin's influential article, game theoretic research has studied various subtleties associated with CPR appropriation. For example, in a series of articles, Comes and Sandler

(1983), Cornes, Mason, and Sandler (1986), and Mason, Sandler, and Comes (1988) examine the issue of optimal group size in a CPR situation in which resource units are sold in an imperfect market. They find that reducing the number of appropriators does not necessarily increase total welfare; instead, the reduced severity of the CPR externality that accompanies such a reduction must be balanced against the deadweight loss of increased market concentration.

Gisser (1983) presents a different argument against limiting the number of users of a CPR. He argues that in situations where appropriators receive declining marginal benefits from the resource extraction, such as irrigators using a groundwater aquifer, a benefit exists in spreading resource use to a larger number of appropriators. This benefit must be weighed against increased severity of the CPR externality associated with increasing the number of appropriators.

Game theoretic models have also addressed dynamic aspects of CPR use. Extraction decisions in a CPR setting are often time-dependent in the sense that current extraction impacts future net benefits. Several authors have shown that the ability of appropriators to commit to an extraction path over time can substantially influence the predicted outcome of a time-dependent CPR game (Eswaran and Lewis, 1984; Reinganum and Stokey, 1985; Negri, 1990; and Dixon, 1991).

While game theoretic models enable the researcher to examine the predicted behavior in a CPR setting, it is an open question as to how well these predictions translate into actual behavior. Recently, experimental methods have been used to examine individual and group decision-making in controlled CPR environments. Such methods enable the researcher to investigate behavior in laboratory settings designed to capture key elements of corresponding game theoretic models. In CPR experiments in which subjects act independently, the observed outcomes have generally been consistent with the game theoretic equilibrium prediction of overuse. For example, in experiments using a repeated, time-independent CPR setting, Ostrom, Gardner, and Walker (1994), Keser and Gardner (1996), and Walker, Gardner, Ostrom, and Herr (1996) report that, at the aggregate level, the Nash equilibrium prediction describes observed outcomes fairly well. Gardner, Moore, and Walker (1996) reach a similar conclusion in experiments involving a time-dependent CPR setting.'

The following chapters of this dissertation investigate predicted and observed behavior in CPR situations with minimal constraints on individual behavior. Using the dynamic CPR game model developed by Gardner, Moore, and Walker (1996) as a basis, this dissertation combines the tools of game theory and experimental methods to gain a broader understanding of factors that impact behavior in a CPR setting. The game theoretic model provides benchmark predictions for behavior, which can then be compared with behavior observed in the experimental sessions.

Chapter 2 introduces the game theoretic model used throughout the dissertation. A distinction is made between the time-independent game, where extraction in the current period does not affect costs in future periods, and the time-dependent game, where current extraction does increase extraction costs in future periods. This chapter discusses the impact of various factors -- including group size, heterogeneities, myopia, and the ability of appropriators to commit to an extraction path -- on the outcome of the CPR game.

Chapter 3 examines the impact of time-dependency on observed behavior. This chapter reports the results of laboratory experiments designed to capture the essential features of a repeated time-independent game and a time-dependent supergame based on the model discussed in Chapter 2. A potential for temporally myopic behavior exists in the time-dependent game that does not exist in the time-independent game, as it is possible for a subject to ignore the full impact of current extraction on his/her own future extraction costs. Myopic behavior results in a lower efficiency than that obtained at the subgame perfect equilibrium. A primary focus of this experimental study is the prevalence of myopic behavior in the time-dependent game.

Chapter 4 investigates the impact of groups size on individual behavior. This chapter reports the results of laboratory experiments with groups of size $n=3$ and $n=7$ using a repeated time-independent design based on the model discussed in Chapter 2. The parameters are chosen so that groups of both sizes earn approximately equal payoffs at the equilibrium of the game. The goal is to examine the possibility that group size may affect behavior in ways not captured by the game theoretic model.

The final chapter summarizes the findings of this dissertation and suggests directions for future research.

ENDNOTES

1. Laboratory experiments have also been used to investigate the impact of institutions designed to improve performance in experimental CPR settings. For example, in time-independent CPR settings, the efficiency of resource use has been substantially improved by introducing face-to-face communication (Ostrom, Gardner, and Walker, **1994)** and voting mechanisms (Walker, Ostrom, Gardner, and Herr, **1996).** In a time-dependent setting, Gardner, **Moore,** and Walker **(1996) find** that observed efficiencies are increased by **limiting** the number of users and by introducing stock quotas, which limit the cumulative extraction level of individual subjects over the entire time horizon.

CHAPTER 2

The Dynamic CPR Model

I. INTRODUCTION

The use of common-pool resources (CPRs) generally implies the existence of appropriation externalities, which arise whenever the appropriation by one individual diminishes the net benefits received by others. An appropriation externality is time-independent if its impact is restricted to within a single decision period. On the other hand, an externality is time-dependent if its impacts exist within and across several decision periods. This chapter investigates time-independent and time-dependent externalities in the context of a CPR game model developed by Gardner, Moore, and Walker (1996) (hereafter GMW).

GMW use the CPR game model primarily as a basis for an experimental study of individual behavior in a CPR setting. This dissertation extends the analysis of GMW both from an experimental and theoretical perspective. The GMW model provides the foundation for the experiments reported in Chapters 3 and 4. Furthermore, the current chapter examines theoretical properties of the GMW. This model is closely related to the CPR model used as the basis for experiments reported in Ostrom, Gardner, and Walker (1994). See Appendix A for a comparison of these two models.

In this chapter, the time-independent and time-dependent cases of the model are analyzed separately. In section 111, the time-independent case of the model is examined in detail. In this section, the equilibrium and optimal solutions are derived for symmetric and asymmetric cases of the time-independent game and the feasibility of using proportional cutbacks from the equilibrium to improve CPR performance is investigated. Section IV of addresses intertemporal issues related the appropriation of a CPR within the context of the time-dependent case of the model. More specifically, this section examines the impact of myopic behavior and the ability of players to credibly commit to an extraction path on the efficiency of resource use. Before turning to these issues, section II develops the general structure of the GMW model.

II. SYMMETRIC GMW MODEL

This section specifies the key equations of the GMW model. The essential features of this model are: (1) the benefits received by each appropriator depend only on the amount of the resource extracted by that appropriator, and (2) the extraction by one appropriator increases the extraction costs of others in the current period and, potentially, in future periods. Thus, an appropriation externality exists on the cost side of the model. This type of model is appropriate in situations in which extraction costs increase as the resource is depleted. For convenience, the CPR will be referred to as a groundwater basin throughout this section; however, the same basic dynamic is present in many other resources, including oil fields, forests, and fisheries.'

Consider the extraction from a groundwater aquifer of n identical appropriators, indexed by i, over an exogenously determined number of periods, T. The aquifer is described by the state variable, depth-to-water in period t, d_t.

Appropriator i extracts an amount of water, x_{it}, in period t, and each unit extracted is assumed to increase the depth-to-water by one unit. In this setting, the depth-to-water evolves according to the following discrete time equation:

$$d_{t+1} = d_t + X_{.t},$$

where $X_{.t}=\Sigma_i x_{it}$ is the total group extraction.

Water pumped to the surface is used in production, providing a benefit to appropriator i in period t, given by:

$$B_{it}(x_{it}) = ax_{it} - bx_{it}^2, \tag{1}$$

where **a** and b are positive constants. This equation implies diminishing returns to production at the surface, an assumption that accords with production experience from aquifers like the Ogallala (Kim et al., *1989).*

The marginal cost of pumping a unit of water to the surface, c_t, evolves according to the following equation:

$$c_{t+1} = c_t + kX_{.t}. \tag{2}$$

where $k > 0$ is a cost parameter linking extraction cost to depth-to-water. The total extraction cost incurred by appropriator i in period, t, C_{it}, is the product of i's own extraction level, and the average extraction cost in t, given by:

$$AC_t = c_t + kX_{.t}/2.$$

Thus, the total cost function faced by appropriator i in period t is given by:

$$C_{it}(x_{it}, X_{.t}, c_t) = x_{it}(c_t + kX_{.t}/2). \tag{3}$$

Together, the benefit and cost functions, *(1)* and **(3)**, define a single-period net benefit function for each appropriator,

$$u_{it}(x_{it}, X_{.t}, c_t) = ax_{it} - bx_{it}^2 - x_{it}(c_t + kX_{.t}/2). \tag{4}$$

For $T > 1$, the cost function *(3)* introduces a time-dependent externality into the model, as the extraction of a unit by one appropriator increases by $k/2$ the average cost of units extracted by all appropriators in period t and in all future periods. The time-independent CPR game is a special case of the model in which the planning horizon, T, is a single period.[2] Thus, the externality that arises in equation *(3)* is limited to within the single-period. For this reason, the time subscript will be dropped when analyzing the time-independent game, so the net benefit function (4) can be rewritten as:

$$u_i(x_i, X, c_0) = ax_i - bx_i^2 - x_i(c_0 + kX/2), \tag{4'}$$

where c_0 is the initial extraction cost.

III. TIME-INDEPENDENT CPR GAME

This section provides an extensive analysis of the time-independent case of the GMW model described in section II. First, the symmetric optimal and equilibrium solutions of the time-independent game are derived. Then, an asymmetry is introduced into the model, and the feasibility of using proportional cutbacks as a mechanism for improving efficiency is examined.

Optimal Solution of the Symmetric Time-Independent Game

The optimal solution of the symmetric time-independent CPR game is the set of extraction levels, $<x_1, x_2, \ldots, x_n>$, that maximizes total group payoff. This solution is derived by solving the following maximization problem:

$$\text{maximize } \Sigma_i\, u_i(x_i, X)] \qquad \text{wrt } \langle x_1, x_2, \ldots, x_n \rangle,$$

where u_i is given by (4'). To ensure that the optimal extraction level is strictly greater than zero, the following condition must be satisfied:

$$a > c_0, \tag{5}$$

where c_0 is the initial extraction cost. Inequality (5) guarantees a positive net benefit to the first unit of water withdrawn from the aquifer and will be assumed throughout.

The maximization problem is solved by invoking symmetry. The resulting optimal individual extraction level is:

$$x_i^o = \frac{a - c_0}{2b + nk}. \tag{6}$$

The optimal group resource value, V^o, results when each player extracts at the level given in (6):

$$V^o = \frac{n(a - c_0)^2}{2(2b + nk)}. \tag{7}$$

Each player receives an equal share of the optimal group resource value, $V_i^o = V^o/n$.

Equilibrium Solution of the Symmetric Time-Independent Game

By definition, the optimal solution maximizes the total group payoffs from the CPR. This solution is not, however, an equilibrium of the game. At the optimal solution, each player equates the marginal benefit of an additional unit with the marginal *social* cost of this unit, which includes both private and external costs. In equilibrium, a rational, self-interested player equates marginal benefits and marginal private costs; thus, equilibrium extraction exceeds optimal extraction whenever external costs exist.

The equilibrium solution requires that each player maximize individual payoffs taking the actions of others as given. In particular, each player i solves a maximization problem of the form:

$$\text{maximize } u_i(x_i, X) \qquad \text{wrt } x_i,$$

where u_i is given by (4').

The maximization problem is solved by invoking symmetry. The resulting equilibrium individual extraction level is:

$$x_i^e = \frac{a - c_0}{2b + (n+1)k/2}. \tag{8}$$

A comparison of (6) and (8) shows that for $n > 1$, $x_i^e > x_i^o$. In other words, the equilibrium extraction level exceeds the socially optimal extraction level whenever there is more than one player. The result of this overextraction is a dissipation of potential payoffs from the resource. The equilibrium group resource value, V^e, results when each player extracts at the level given in (8), as shown below:

$$V^e = \frac{n(2b + k)(a - c_0)^2}{2[2b + (n+1)k/2]^2}. \tag{9}$$

Each player receives an equal share of the equilibrium group resource value, $V_i^e = V^e/n$.

Comparison of Optimal and Equilibrium Solutions: Symmetric Case

In the special case in which $n=1$, the optimal and equilibrium extraction levels are equal. With only one player, there are no external costs; hence, marginal social costs and marginal private costs coincide. Yet, in general, limiting access to the resource to a single player does not maximize total welfare. The optimal resource value, V^o, is monotonically increasing in n; thus, the maximum resource value cannot be attained at $n=1$ as in some other CPR games. Instead, the maximum resource value is approached only as n becomes sufficiently large. This result is verified by differentiating V^o with respect to n:

$$\frac{dV^o}{dn} = \frac{4b(a - c_0)^2}{(4b + 2nk)^2} > 0. \tag{10}$$

In contrast, it is possible for an increase in n to increase the equilibrium group payoffs. This possibility arises due to the assumption that appropriators receive declining marginal benefits from resource use. On the one hand, an increase in n spreads the use of the resource to more users, which increases total group benefits. On the other hand, an increase in n increases the severity of the cost externality. Thus, an increase in n involves a tradeoff between an increase in total benefits and an increase in the severity of the externality. The sign of the effect of an increase in n on equilibrium group payoffs is determined by differentiating V^e with respect to n:

$$\frac{dV^e}{dn} = \frac{(2b + k)(a - c_0)^2}{2[2b + (n+1)k/2]^3}\,[2b - (n-1)k/2]. \tag{11}$$

From (11), it follows that V^* is maximized at $n_0 = 1 + 4bk$ and that V^* is increasing in n for $n < n_0$ and decreasing in n thereafter.

Figure 1 displays V^o and V^* for a specific parameterization of the model

$$a = \$0.867,\ b = \$0.00875,\ c_0 = k = \$0.01.$$

In this parameterization, V^* reaches a maximum at n_0=4.5. It is interesting to note that the equilibrium group payoff for n=20 exceeds the optimal payoff that results when access is limited to a single player (n=1). Thus, in this parameterization, granting exclusive ownership of the CPR to a single player is clearly not the policy that will maximize group payoffs.[3]

The interpretation of the parameters b and k can yield substantial insight into the predicted behavior in a CPR setting. Broadly speaking, appropriation from a CPR encompasses two separate activities on the part of the appropriators, the capture of resource units and the use of these resource units. Appropriation externalities generally arise during the capture activity. For example, in the case of groundwater extraction the externality arises as irrigators pump water; in a fishery, the externality arises as fishermen compete to catch fish, and so on. However, the benefits received as appropriators use the captured resource units also play an important role in the incentives of these appropriators.

In the GMW model, the parameter k measures the severity of the externality related to capture, while b measures the extent to which net marginal benefits decrease with the use of resource units. The severity of the CPR dilemma is inversely related to the ratio b/k. Both parameters are assumed to be nonnegative; thus, the special case in which b=O represents the most severe CPR situation possible. This case implies that appropriators receive constant marginal net benefits from the use of resource units, a situation that might arise when the appropriator sells resource units in a competitive market. In many CPR situations, including fisheries, ***b/k*** may be quite small. In these instances, the appropriate management policy is to limit access to the resource. On the other hand, in the context of groundwater, Gisser (1983) essentially argues that this ratio is quite large and concludes that total welfare could be increased by allowing more irrigators to use the resource.

Proportional Cutbacks in the Symmetric CPR Game

Consider a situation in which n players participate in the CPR game described by the symmetric, time-independent game. In the absence of external regulation, noncooperative game theory predicts that each player will extract at the equilibrium level given by (8). Suppose, however, that players are given the opportunity to form an enforceable agreement whereby each cuts back extraction proportionally from the equilibrium. Specifically, define a uniform proportional cutback from the equilibrium $(1\text{-}s)$ as a case in which each player i decreases extraction from x_i^e to sx_i^e, with $0 \leq s \leq 1$. For convenience of exposition, the term ***proportional cutback*** will hereafter ***be*** taken to mean an agreement in which all players uniformly cutback from the equilibrium by a specified proportion. Define the optimal proportional cutback $(1\text{-}s_o)$ as the cutback that maximizes group payoffs. Because both the equilibrium and group optimum of the symmetric time-independent game are symmetric, the optimal proportional cutback will lead players from the equilibrium to the group optimum, with the scalar s_o given by:

$$s_o = x_i^o/x_i^e = [2b + (n+1)k/2]/(2b + nk). \quad (12)$$

Note also that the optimal cutback is the preferred proportional cutback of all players. Thus, if such a cutback **could** feasibly be monitored and enforced, one would expect players to implement the optimal proportional cutback.

It has often been argued that the existence of asymmetries between players decreases the likelihood that a cooperative agreement to limit extraction from the resource will be reached (see, for example Johnson and Libecap, 1982; Wiggins and Libecap, 1985; Libecap and Wiggins, 1985; and Libecap, 1995). Because both the equilibrium and optimal allocations in an asymmetric game will generally be asymmetric, it is possible that no proportional cutback from the equilibrium exists that will lead to the optimal allocation. In particular, whenever the ratios of extraction for various player types are different at the equilibrium allocation than at the optimal allocation, no such cutback will exist. Furthermore, it may be the case that different player types will prefer different proportional cutbacks. In such cases, the likelihood of gaining agreement on any one proportional cutback is diminished. In the following section, the complications arising from heterogeneous player types are addressed within the context of an asymmetric version of the time-independent game.

Asymmetric CPR Game: **Benchmark Solutions**

Consider the game that results when a single asymmetry is introduced into the time-independent game via the parameter, a, of the benefit function. Again, assume that there are only two types of players, high value types (H-types) and low value types (L-types). The benefit function defining H-types includes the parameter a_H, while the benefit function defining L-types includes the parameter a_L, with:

$$a_H > a_L.$$

Each player type faces the same cost function, given by (3).

For notational convenience, let x_H and x_L denote the CPR extraction levels of representative H- and L-type individuals and X_H and X_L denote the aggregate extraction of H- and L-types. Further, let $X = X_H + X_L$ denote the total extraction by all players. Let n_H and n_L be the number H- and L-type players. Finally, let u_H and u_L denote individual net benefits and U_H and U_L denote group net benefits. Given this notation, the individual net benefits received by each player type are given by:

$$u_H = a_H x_H - b x_H^2 - x_H(c_0 + kX/2) \tag{13}$$

$$u_L = a_L x_L - b x_L^2 - x_L(c_0 + kX/2).$$

The optimal solution of this asymmetric game is derived by solving the following maximization problem:

$$\text{maximize} \quad U_H + U_L \qquad \text{wrt } \langle x_H, x_L \rangle .$$

The interior optimal solution has components satisfying the two first-order conditions:

$$(2b + kn_H)x_H^o + kn_L x_L^o = a_H - c_0 \tag{14}$$

$$kn_H x_H^o + (2b + kn_L)x_L^o = a_L - c_0.$$

The solution to (14) is given by:

$$x_H^o = \frac{(a_H - c_0) + (a_H - a_L)kn_L/(2b)}{2b + kn} \tag{15}$$

$$x_L{}^o = \frac{(a_L - c_0) \ - \ (a_H - a_L)kn_H/(2b)}{2b \ + \ kn}.$$

Given the assumption that $a_H > a_L$, equations *(13)* and *(15)* imply that H-types extract more from the resource and receive higher net benefits than Ltypes at the interior optimal solution.

In addition to the interior solution, there are also two relevant corner solutions that occur for certain **parameterizations** of the model. At the first corner solution, the L-types are inactive, resulting in the following allocation:

$$x_L{}^o = 0 \tag{16}$$

$$x_H{}^o = (a_H - c_0)/(2b + kn_H).$$

The corner solution (16) occurs whenever the value to the L-type is sufficiently low:

$$a_L < \underline{a}_L{}^o = \frac{2bc_0 \ + \ kn_H a_H}{2b \ + \ kn_H}. \tag{17}$$

At the second corner solution, both types are inactive. This arises whenever

$$a_H < c_0. \tag{18}$$

When there is more than one user of the resource, the optimal solution of the CPR game is not an equilibrium. Instead, the equilibrium solution of this game occurs when H- and Ltypes simultaneously solve their respective maximization problems:

maximize u_H wrt $<x_H>$,

and maximize u_L wrt $<x_L>$.

The interior game equilibrium satisfies the system of first-order conditions:

$$[2b + k(n_H+1)/2]x_H^e + (kn_L/2)x_L^e = a_H - c_0 \tag{19}$$

$$(kn_H/2)x_H^e + [2b + k(n_L+1)/2]x_L^e = a_L - c_0.$$

The solution to *(19)* is given by:

$$x_H^e = \frac{(a_H - c_0) + (a_H - a_L)kn_L/(4b+k)}{2b + k(n+1)/2} \tag{20}$$

$$x_L^e = \frac{(a_L - c_0) - (a_H - a_L)kn_H/(4b+k)}{2b + k(n+1)/2}.$$

Again, given the assumption that $a_H > a_L$, *(13)* and *(20)* imply that H-types extract more from the resource and receive higher net benefits than L-types at the interior equilibrium.

In addition to the interior equilibrium, the possibility arises for two corner equilibria for certain parameterizations of the model. At the first, the L-types are inactive, resulting in the following allocation:

$$x_L^e = 0 \tag{21}$$

$$x_H^e = (a_H - c_0)/[2b + k(n_H+1)/2].$$

This equilibrium occurs when the L-type has sufficiently low value:

$$a_L < \underline{a}_L^e = \frac{(4b+k)c_0 + kn_H a_H}{(4b+k) + kn_H}. \tag{22}$$

At the other corner equilibrium, both types are inactive. This corner solution arises whenever inequality *(18)* holds.

Neither of the two corner solutions of the equilibrium are of much interest in the discussion of the asymmetric **CPR** game. At the first corner solution, the game is analogous to the symmetric **CPR** game with n_H H-type players. The second corner solution is particularly uninteresting as the **CPR** is not being used by either type. Thus, throughout this discussion we restrict attention to **parameterizations** that yield the interior **equilibrium** solution.

An important result that follows from equations *(14)* through *(22)* is that the ratio of extraction between H-types and Ltypes is smaller at the equilibrium than at the optimal solution. More formally,

$$x_H^e/x_L^e < x_H^o/x_L^o. \tag{23}$$

The proof of *(23)* is given in Appendix B.

Proportional Cutbacks **in the Asymmetric Game**

Inequality *(23)* implies that Ltypes account for a higher proportion of the total extraction at the equilibrium than at the optimal solution. Thus, it is impossible for a proportional cutback from the equilibrium to result in the optimal solution. Even if **total** extraction is reduced to the optimal level, the distribution of extraction between player types will not be optimal.

A variety of proportional cutbacks concepts are relevant to the asymmetric game. Here, three such cutbacks are described. First, let s_o be the scalar that maximizes group utility among all cutbacks:

$$s_o = \text{arg max} <s> \ u_H(s\mathbf{x}^e) + u_L(s\mathbf{x}^e)$$

Thus, *(1-s_o)* is the proportional cutback chosen by a utilitarian social welfare function with equal distributional weights on the two types.

Next, let s_H be the scalar that maximizes the H-type's utility among all cutbacks:

$$s_H = \arg\max_{<s>} u_H(sx^e).$$

Thus, $(1-s_H)$ is the proportional cutback chosen by a utilitarian social welfare function with full distributional weight on the H-types.

Similarly, let s_L be the scalar that maximizes the L-type's utility among all cutbacks:

$$s_L = \arg\max_{<s>} u_L(sx^e).$$

Thus, $(1-s_L)$ is the proportional cutback chosen by a utilitarian social welfare function with full distributional weight on the L-types.

These three concepts of proportional cutbacks will, in general, lead to different cutback levels. The scalars associated with these proportional cutbacks are given by:

$$s_H = M/N \tag{24}$$

$$s_L = O/P$$

$$s_o = (M+O)/(N+P)$$

where

$$M = (a_H - c_0)n_H x_H^e \tag{25}$$

$$N = 2bn_H(x_H^e)^2 + kn_H x_H^e X^e/2$$

$$O = (a_L - c_0)n_L x_L^e$$

$$P = 2bn_L(x_L^e)^2 + kn_L x_L^e X^e/2.$$

Combining the assumption that $a_H > a_L$ with the equations given in (24) and (25), one can show that:

$$s_H > s_o > s_L. \tag{26}$$

The proof of (26) is given in Appendix B.

Illustration of Proportional Cutbacks

In the following example, the proportional cutbacks and their efficiency and payoff implications are discussed for various levels of asymmetry using a specific parameterization of the asymmetric game.[4] The parameters are chosen so that the cutback favored by L-types, $(1\text{-}s_L)$, leads to efficiencies lower than equilibrium, when the asymmetry is severe enough. This occurs only when n_L is much larger than n_H. The following parameters are used:

$$a_H = \$1.00,\ n_H = 1,\ n_L = 100,\ b = k = c_0 = \$0.01.$$

Different asymmetry levels are obtained by holding a_H constant while varying the value of a_L. This value is varied from $a_L = a_H$, which corresponds to a symmetric game, down to $\underline{a}_L^e = 0.17$, the lowest value of a_L at which L-types are active at the equilibrium.

Figures 2 and 3 display the ability of proportional cutbacks to improve CPR payoffs. Figure 2 plots the cutbacks $(1\text{-}s_H)$, $(1\text{-}s_L)$, and $(1\text{-}s_o)$ over the entire asymmetry range, $0 \leq a_H\text{-}a_L \leq a_H\text{-}\underline{a}_L^e = 0.83$. Notice that for small asymmetries, the three cutbacks are nearly equal; in fact, as the asymmetry vanishes $(a_H\text{-}a_L = 0)$, the three cutbacks converge to:

$$1\text{-}s = 1 - [2b + (n+1)k/2]/(2b + nk),$$

which is the optimal cutback from the symmetric game given by (12). Figure 3 displays the efficiencies that would result if the cutbacks shown in Figure 2 were implemented. For small asymmetries, each of the three cutbacks generates a substantial efficiency improvement over Nash equilibrium; indeed, in the symmetric case (a_H-a_L = 0), each produces an outcome that is 100% efficient. Thus, for small asymmetries, proportional cutbacks enable players to substantially improve the efficiency of resource use, with a relatively small margin for dispute over the cutback level.

However, Figures 2 and 3 also suggest that problems arise with proportional cutbacks as the asymmetry grows. Figure 2 shows that the divergence between (1-s_H) and (1-s_L) increases as the level of asymmetry becomes greater. Furthermore, when the difference between a_H and a_L is sufficiently large, the proportional cutback favored by the Ltypes (1-s_L) results in a lower efficiency than the Nash equilibrium. In contrast, it is impossible for the cutbacks (1-s_H) and (1-s_o) to lead to lower efficiencies than equilibrium. The proof of this result is given in Appendix B.

The inferior outcomes favored by the L-types can be avoided if the H-type player compensates the L-types in exchange for agreeing to the cutback (1-s_H). Figure 4 plots the difference in total payoffs earned by the H-type and the L-types if the preferred cutback -- (1-s_H) for the H-type and (1-s_L) for the L-types -- is implemented rather than the cutback favored by the other type. Notice that for large asymmetries, the H-type player has more to gain if (1-s_H) is implemented rather than (1-s_L) than the L-types have to gain if (1-s_L) implemented rather than (1-s_H). For example, at the asymmetry level a_H-a_L = 0.75, the H-type player earns \$2.73 more if (1-s_H) is implemented rather than $(1-s_L)$. On the other hand, the L-types as a whole will earn only $0.77 more (or less than a penny per player more) if $(1-s_L)$ is implemented rather than $(1-s_H)$. Thus, when the asymmetry is large, there is enough surplus that the H-type could compensate the L-types to accept $(1-s_H)$, thereby producing a highly efficient outcome. This suggests that, even for large asymmetries, the simple mechanism of proportional cutbacks can be a powerful tool in improving the efficiency of resource use if a suitable side-payment rule is adopted.

IV. TIME-DEPENDENT CPR GAME

While many important aspects of the CPR dilemma can be examined using the time-independent game, a time-dependent game is required in order to address certain dynamic issues that arise in many CPR situations. For example, assumptions regarding the existence of intertemporally myopic behavior and the ability of players to commit to extraction paths over time will lead to different solutions of a time-dependent game. In this section, four different solution concepts are derived in the context of the GMW model: the optimal solution, the myopic noncooperative solution, the normal form equilibrium, and the symmetric subgame perfect equilibrium. Below, each of these solution concepts is briefly described.

The optimal and myopic solutions represent opposite extremes in the extent to which players incorporate the impact of their current actions on the present and future costs of themselves and others. At the optimal solution, each player fully internalizes the negative impact that current extraction has on his or her own extraction costs in future periods, as well as on the current and future costs of other players. In contrast, at the myopic solution, each player completely neglects the negative impact that his or her current actions have on others, both in the current and future periods, as well as the fact that current extraction increases his or her own costs in future periods.

In general, the optimal and myopic solutions are not equilibria of the time-dependent game, although each can be supported as an equilibrium under certain circumstances. For example, the optimal solution is an equilibrium of the game when players are able to jointly sign an enforceable agreement at the beginning of the game specifying the extraction of each player in each period. Similarly, the myopic solution is an equilibrium of the game when all players completely discount future payoffs.[5] Still, these concepts provide benchmarks for behavior in dynamic CPR games and have received considerable attention in this literature.

The ability of players to credibly commit to an extraction path can substantially influence the equilibrium of a CPR game. The normal form equilibrium and subgame perfect equilibria, arise from opposite extreme assumptions regarding the ability of players to make such commitments.[6] At the normal form equilibrium, it is assumed that players can credibly commit to an extraction path over the entire lifetime of the resource. In contrast, at the subgame perfect equilibrium, it is assumed that players cannot credibly commit to extraction in any future period.

In many CPR situations, credible commitments are not available; indeed, this lack of commitment in some sense defines the CPR dilemma. Even if credible commitments are available, players would find it in their best interest to commit to the optimal solution rather than the normal form equilibrium. Furthermore, while each player has an incentive to stay on his or her committed extraction as long as all others remain on theirs, players do not have an incentive to stay on this path if others deviate. Thus, the normal form equilibrium neglects strategic implications. The subgame perfect equilibrium takes into account these strategic concerns and is generally considered the more appropriate equilibrium concept for dynamic CPR games. However, the normal form equilibrium generally generates a much simpler expression than the subgame perfect equilibrium, which often takes the form of a set of recursive equations (see Negri, 1990; and GMW). Thus, it is important to examine the degree to which these outcomes differ.

Eswaran and Lewis (1984) and Reinganum and Stokey (1985) show that these equilibrium concepts can result in substantially different outcomes in dynamic CPR games. Both consider cases in which the optimal solution is obtained when players can credibly commit to an extraction path over the entire life of the resource, but, when no credible commitment is available, the resource is exhausted in the initial period. However, as Negri (1990) notes, the extreme impact of the level of commitment implied by these models is due, in part, to the fact that both models assume costless extraction from the resource.

Negri (1990) and Dixon (1991) derive these equilibrium concepts in CPR models that include increasing marginal extraction costs. Both find that under the two extremes of exclusive ownership ($n=1$) and open-access ($n \to \infty$), the two equilibrium concepts coincide but that for intermediate group sizes, the two equilibria do not coincide. However, neither derives a general expression for the difference between these equilibria for a general group size, n.

In this section, a general expression is given for this difference within the context of the GMW time-dependent model. Recall that the GMW time-dependent game is governed by the following single period net benefit function:

$$u_{it}(x_{it}, X_{.t}, c_t) = ax_t - bx_{it}^2 - x_{it}(c_t + kX_{.t}/2). \tag{4}$$

where x_{it} is the extraction by player i in period t, and $X_{.t}=\Sigma_i x_{it}$ is the group extraction in period t. The net benefit function (4) together with the dynamic cost equation (2) define a time-dependent CPR game. Using this setup, the outcomes resulting from the four solution concepts are shown below.

Optimal Solution

The optimal extraction path is symmetric and requires a constant extraction level in each period from each player. This follows from the fact that individuals receive declining marginal benefits in each period and that future net benefits are not discounted. Appendix C derives the extraction level for each player i in each period t given by the optimal solution:

$$x_{it}^o = \frac{a - c_1}{2b + knT}. \tag{27}$$

Define the total group lifetime value of the resource by:

$$V_{..} = \Sigma_i \Sigma_t \, u_{it}(x_{it}, X_t, c_t), \tag{28}$$

where u_{it} is given by (4). Then, at the optimal solution, the group lifetime value of the resource is given by:

$$V_{..}^{o} = \frac{nT(a - c_1)^2}{2(2b + knT)}. \tag{29}$$

Note that as $T \to \infty$, both individual extraction, x_{it}^{o}, and group extraction, $X_{.t}^{o} = \Sigma_i x_{it}^{o}$, approach 0 for finite n. **Furthermore,** as $T \to \infty$, the group lifetime value of the resource is given by:

$$V_{..}^{o} \to \frac{(a - c_1)^2}{2k} \tag{30}$$

Myopic Noncooperative Solution

The myopic solution results when players behave as if each period of the time-dependent game is a single-period game. Thus, the myopic extraction level for player i in period t, x_{it}^{m}, is analogous to the equilibrium extraction level of the time-independent game, given by (8), with an initial cost, c_t:

$$x_{it}^{m} = \frac{a - c_t}{2b + (n+1)k/2} \qquad \forall\, t = 1,2,\cdots,T. \tag{31}$$

In general, c_t is based on the history of the game in all periods prior to t. However, in period 1, the game has no history, which implies $c_1 = kd_1$, and therefore x_{i1}^{m}, can be calculated directly from the specified parameters of the problem. As shown in Appendix D, extraction diminishes exponentially over time, with:

$$\frac{x_{it+1}^{m}}{x_{it}^{m}} = \lambda_m = \frac{2b - (n-1)k/2}{2b + (n+1)k/2} \quad \forall\, t = 1,2, ..., T-1 \tag{32}$$

for $1 \leq n \leq 1 + 4b/k$ and 0 otherwise. From (32), it follows that for $n = 1 + 4b/k$, $\lambda_m = 0$, which implies that $x_{it}^{m}=0$ for $t>1$. For $n \geq n_0$, the aquifer is fully depleted in period 1, and the T-period is essentially reduced to a single-period game.

Notice that x_{i1}^{m} and λ_m completely determine the myopic extraction path. In period 1, each individual extracts x_{i1}^{m}, and, in each subsequent period, extraction diminishes by λ. Appendix E shows that, for any extraction path that diminishes exponentially, the group lifetime value of the resource, $V_{..}$ is given by:

$$V_{..} = X_{.1}\frac{1-\lambda^T}{1-\lambda}\left[(a-c_1) - (b/n)X_{.1}\frac{1+\lambda^T}{1+\lambda} - (k/2)X_{.1}\frac{1-\lambda^T}{1-\lambda}\right], \tag{33}$$

where $X_{.1} = \Sigma_i x_{i1}$ is the group extraction in period 1. The group lifetime value of the resource at the myopic solution is obtained by substituting x_{i1}^{m} and λ_m into (33).

Note that as $T \rightarrow \infty$, neither individual extraction, x_{it}^{m}, nor group extraction, $X_{.t}^{m} = \Sigma_i x_{it}^{m}$, approach 0 for finite n. Appendix E shows that for $T \rightarrow \infty$, the expression for the group lifetime value of the resource given by (33) simplifies to:

$$V_{..} \rightarrow \frac{X_{.1}}{1-\lambda}\left[(a-c_1) - (b/n)\frac{X_{.1}}{1+\lambda} - (k/2)\frac{X_{.1}}{1-\lambda}\right]. \tag{34}$$

At the myopic solution, the group lifetime value of the resource as $T \rightarrow \infty$ is given by:

$$V_{..}^{m} \to \frac{(2b/k + 1)}{(4b/k + 1)} \frac{(a - c_1)^2}{2k} = \frac{n_0 + 1}{2n_0} V^{o}_{..}, \tag{35}$$

where n_0 is the threshold number of players at which the resource is completely depleted in a single period, and $V_{..}^{o}$ is the group lifetime value of the resource at the optimal solution.

Normal Form Equilibrium

At the normal form equilibrium, players commit to a noncooperative strategy prior to period 1, specifying an extraction path for the entire life of the resource. Individuals are noncooperative in that they neglect the fact that their extraction increases the costs of others. Players do not, however, neglect the fact that current extraction increases their own future costs. Prior to period 1, player i chooses a strategy $\mathbf{x}_{i.} = \langle x_{i1}, x_{i2}, \ldots, x_{iT} \rangle$ in order to maximize:

$$V_{i.} = \Sigma_t \, u_{it}(x_{it}, X_t, c_t).$$

As shown in Appendix F,

$$\frac{x_{it+1}^{N}}{x_{it}^{N}} = \lambda_N = \frac{2b - (n-1)k/2}{2b + (n-1)k/2} \quad \forall\, t = 1,2, \ldots, T-1 \tag{36}$$

and

$$x_{it}^{N} = \frac{(a - c_1)}{k} \frac{2\rho}{(1+\rho)(n-\lambda^T)} \tag{37}$$

for $0 < \rho = (n-1)k/(4b) < 1$.

Thus, individual extraction diminishes exponentially at the normal form equilibrium, as in the case of the myopic solution. A comparison of the myopic solutions given by (31) and (32) to the normal form solutions given by (36) and (37) shows that $x_{it}^N \leq x_{it}^m$ and $\lambda_N \geq \lambda_m$. This implies that the resource is depleted less quickly at the normal form equilibrium than at the myopic solution as long as $n < n_0$. For $n \geq n_0$, $\lambda_N = \lambda_m = 0$; in other words, the threshold number of players at which the resource is completely depleted in a single period is the same for the myopic and normal form equilibrium solutions.

The values of x_{i1}^N and λ_N completely determine the normal form equilibrium extraction path. In period 1, each individual extracts x_{i1}^N, and, in each subsequent period, extraction diminishes by λ_N. The group lifetime value of the resource at the normal form equilibrium is obtained by substituting x_{i1}^N and λ_N into (33).

Appendix F shows that, as $T \to \infty$, neither individual extraction, x_{it}^N, nor group extraction, $X_{.t}^N$, approach 0 for finite n. In addition, Appendix E show that, as $T \to \infty$, the group lifetime value of the resource at the normal form equilibrium is given by:

$$V_{..}^N \to \frac{(n+1)}{(2n)} \frac{(a - c_1)^2}{2k} = \frac{n+1}{2n} V_{..}^o. \tag{38}$$

A comparison of equations (34) and (38), shows that, as $T \to \infty$, $V_{..}^N > V_{..}^m$ for $n < n_0$, and $V_{..}^N = V_{..}^m$ for $n = n_0$. Recall that equations (34) and (38), which define these values, only hold for $n \leq n_0$. For $n > n_0$, the game becomes a single period, time-independent game, and both of these solution concepts coincide with the time-independent equilibrium solution.

Subgame Perfect Equilibrium

At the subgame perfect equilibrium, each player adopts a decision rule based on a relevant state variable (in this case the initial cost of extraction in a period, c_t), taking the decision rules of others as given. In this symmetric game, the subgame perfect equilibrium requires that all players adopt the same decision rule.

The subgame perfect equilibrium is calculated through backward induction using the single-period net benefit function, (4), as well as the transition equation (2). In particular, it can be shown that the subgame perfect extraction level for player i in any period t, takes the form:

$$x_{it}^e = L_t(a - c_t), \tag{39}$$

and that the value of the resource at the subgame perfect equilibrium takes the form:

$$V_{it}^e = K_t(a - c_t)^2. \tag{40}$$

For this game model, the proportionality factors, L_{it} and K_{it}, are given by the nonlinear recursive equations:

$$L_t = \frac{1 - 2kK_{t+1}}{2b + (n+1)k/2 - 2nk^2K_{t+1}} \tag{41}$$

and

$$K_t = L_t - (2b + nk)L_t^2/2 + K_{t+1}(1 - nkL_t)^2. \tag{42}$$

A detailed derivation of equations (39) through (42) is given in Appendix G.

A transversality condition defining the value of the resource in period $T+1$ is required to solve for the subgame perfect equilibrium extraction path. Assume that resource has no value in period $T+1$. This implies that:

$$K_{T+1} = 0. \tag{43}$$

The subgame perfect equilibrium is derived recursively beginning in period $T+1$ by substituting (43) into (42) to obtain L_T, which is then used to calculate K_T. With this as a starting point, the entire path can be determined recursively. For $n>1$, the subgame perfect equilibrium path involves relatively high depletion rates in the initial periods that diminish nearly exponentially over time and approach zero in later periods. At the subgame perfect equilibrium, the resource is depleted more slowly than at the myopic solution, but more quickly than at the normal form equilibrium.

Figure 5 shows the lifetime value of the resource, V, resulting from each of the four solution concepts over planning horizons ranging in length from T=1 to T=100 for the parameters:

$$a = \$4.08,\ b = \$0.09,\ k = c_1 = \$0.01.$$

Note that V approaches a steady state value for each of the four solutions. This steady state represents the lifetime resource value as $T \rightarrow \infty$.

The fact that the subgame perfect equilibrium reaches a steady state implies that, for T sufficiently large, $L_{t+1} \rightarrow L_t = L$ and $K_{t+1} \rightarrow K_t = K$, where L_t and K_t are defined by equations (41) and (42). $L_{t+1} \rightarrow L_t = L$ implies that:

$$x_{it+1}^e / x_{it}^e = \lambda_e = 1 - nkL. \tag{44}$$

In other words, as $T \rightarrow \infty$, the subgame perfect path is exponentially declining, just like the myopic and normal form paths. It remains to solve for the individual extraction level in period *1*, $x_{i1} = L(a-c_1)$. This is accomplished by solving *(41)* and *(42)* for their steady state values. These values are obtained by solving the following nonlinear system of equations:

$$L = \frac{1 - 2kK}{2b + (n+1)k/2 - 2nk^2K} \tag{45}$$

and $\quad K = L - (2b + nk)L^2/2 + K(1 - nkL)^2.$

The solution of these equations yields:

$$L = \frac{2\rho + [1 - 1/(2n)] - \sqrt{[1 - 1/(2n)]^2 + 2\rho/n}}{nk[(1 + \rho) - 1/n]}, \tag{46}$$

for $0 < \rho = (n-1)k/(4b) < 1$.[7] Note that ρ is increasing in n and that $\rho=1$ when $n=n_0$. For $n>n_0$, which implies $\rho>1$, the resource is completely depleted in the initial period. Appendix G gives a detailed derivation of equations *(44)* through *(46)*.

Given this value of L, the subgame perfect path is defined by:

$$x_{i1}^e = L(a - c_1) \tag{47}$$

and $$\lambda_e = 1 - nkL. \tag{48}$$

Finally, as shown in Appendix G, the lifetime resource value produced by the subgame perfect equilibrium is given by the following approximation:

$$V_{..}^e \cong \frac{n + \rho}{2n - (1-\rho)} \frac{(a - c_1)^2}{2k}. \tag{49}$$

Comparison of Solution Concepts

The formulations of lifetime resource value as $T \rightarrow \infty$ given in equations (30), (34), (38), and (49) provide a basis for considering the efficiency implications of the various noncooperative solution concepts. In particular, the efficiencies associated with these concepts are:

$$E^e = (n+\rho)/(2n-1+\rho), \tag{50}$$

$$E^N = (n+1)/(2n),$$

and $$E^m = (n_0+1)/(2n_0).$$

Note that if $n_0=n$ (which implies $\rho=1$), each of these efficiencies equals $(n+1)/(2n)$. The other extreme, where n_0 is large relative to n (which implies $\rho \rightarrow 0$), generates the largest differences between these concepts. In particular, for n_0 large relative to n,

$$E^e \rightarrow n/(2n-1), \tag{51}$$

$$E^N = (n+1)/(2n),$$

and $$E^m \rightarrow 0.5.$$

Clearly, as n increases, the differences between these solution concepts diminish, even when n_0 is large relative to n. From (51), the maximum difference between the efficiencies implied by the normal form equilibrium and the subgame perfect equilibrium is given by:

$$E^N - E^e < (n-1)/(4n^2-2n). \tag{52}$$

The difference approaches 0 as n increases. Thus, while the subgame perfect equilibrium may be the more appropriate solution concept in dynamic CPR situations, the normal form equilibrium generally provides a fairly accurate approximation.

Finally, it is now possible to consider the efficiency implication of moving from a time-independent game to relative to **an** timedependent game with **an infinite** horizon. In particular, the **efficiency** of a time-independent game, E^{TI}, is obtained by dividing equation (9) by equation (7):

$$E^{TI} = \frac{(2b + nk)(2b + k)}{[2b + (n+1)k/2]^2}. \tag{53}$$

The time-dependent equilibrium efficiency cannot exceed:

$$E^N = (n+1)/2n.$$

In Appendix H, it is shown that $E^{TI} > E^N$, implying that time-dependency exacerbates the **CPR** dilemma.

V. CONCLUSIONS

This chapter investigates the incentives that underlie predicted behavior in a **CPR** setting within the context of the dynamic CPR game model developed by Gardner, Moore, and Walker (1996). In doing so, some interesting insights have been gained regarding the predicted behavior of individuals facing this type of **CPR** situation and regarding alternative theoretical benchmarks.

As shown, classifying an appropriation externality as either a benefits-side or cost-side externality is a matter of interpretation. A more important consideration in a CPR situation is the severity of the externality associated with the capture of resource units - regardless of whether it is a cost or benefit side externality - relative to the rate at which the marginal private net benefits from the use resource units declines. In the GMW model, the relative size of these factors is captured by ratio, b/k. This ratio is directly related to the group size that will maximize group payoffs at the equilibrium of the noncooperative game, $n_0 = 1 + 4b/k$. Clearly, when b/k is small, which is likely to occur in situations where resource units are sold in a competitive market, restricting access will likely increase total welfare. On the other hand, when b/k is large, this policy prescription can lower total welfare.

Further, the group size noted above, $n_0 = 1 + 4b/k$, also represents the maximum number of players that can extract from the resource noncooperatively without depleting it completely in the initial period. In this case, the timedependent game degenerates into a time-independent game. For group sizes smaller than n_0, the presence or absence of myopic behavior and the ability for players to credibly commit to an extraction path influences the noncooperative outcome. However, as the group size increases toward n_0 these differences vanish. In any case, the difference in the efficiencies resulting from the normal form equilibrium, where players can credibly commit to an extraction path, and the subgame perfect equilibrium, where players cannot commit, is less than $(n-1)/(4n^2-2n)$. This difference is substantially smaller than the difference obtained in previous research by Eswaran and Lewis (1984) and Reinganum and Stokey (1985).

The following two chapters of this dissertation report the results of laboratory experiments designed to capture the essential features of the model discussed in this chapter. In particular, the experiments reported in Chapter 3 examine subject behavior in both time-independent and timedependent settings. Chapter 4 investigates the behavioral impact of group size by reporting the results of time-independent experiments using groups of size 3 and 7.

Figure 1

Optimal and Equilibrium Group Payoffs as a Function of n

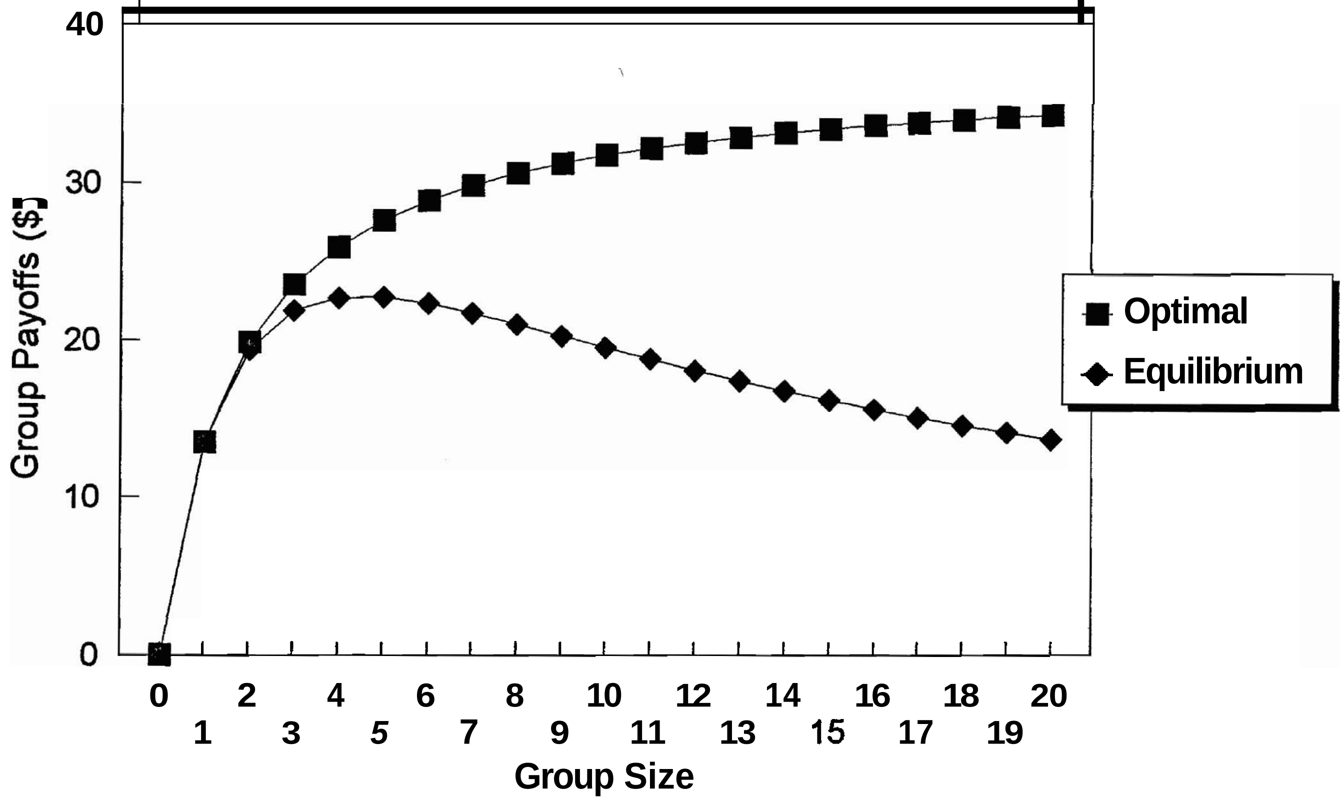
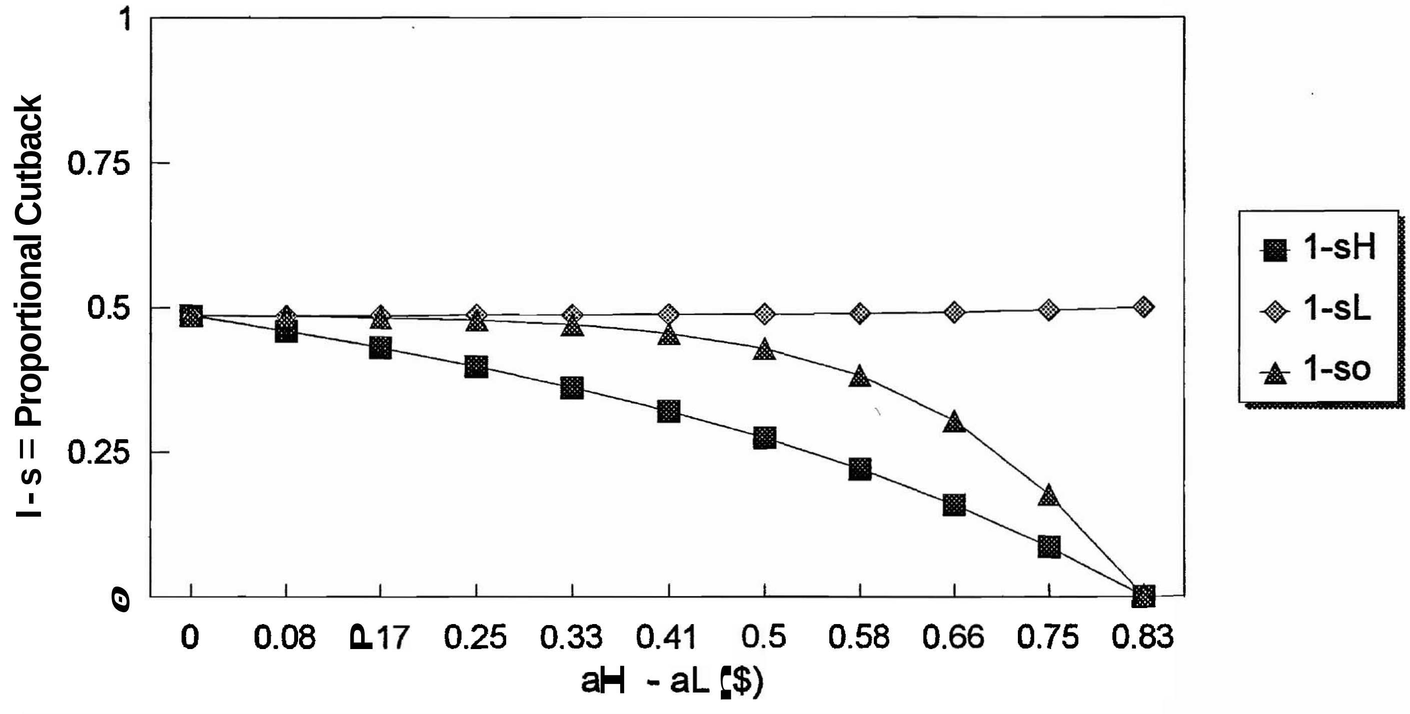


Figure 2

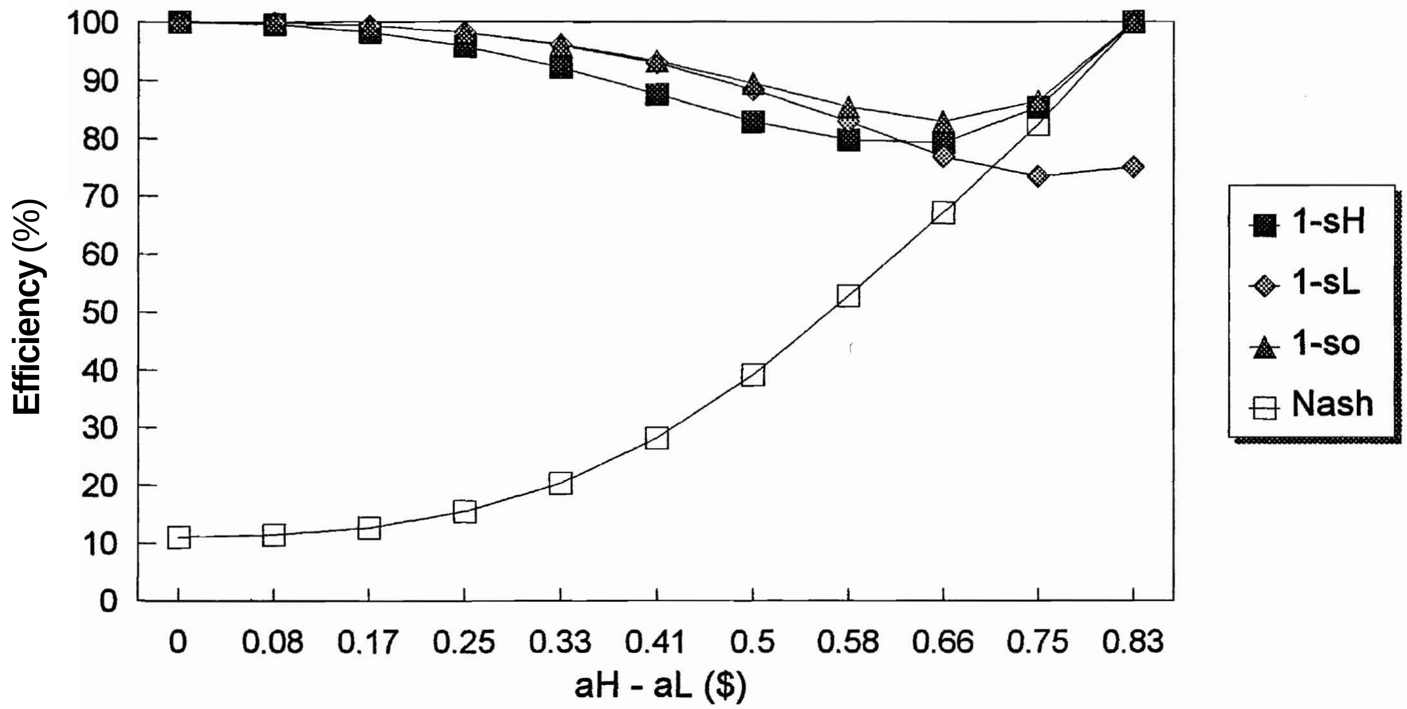
Proportional Cutbacks at Various Asymmetry Levels



aH = $1.00, nH = 1, nL = 100, b = k = c0 = $0.01

Figure 3

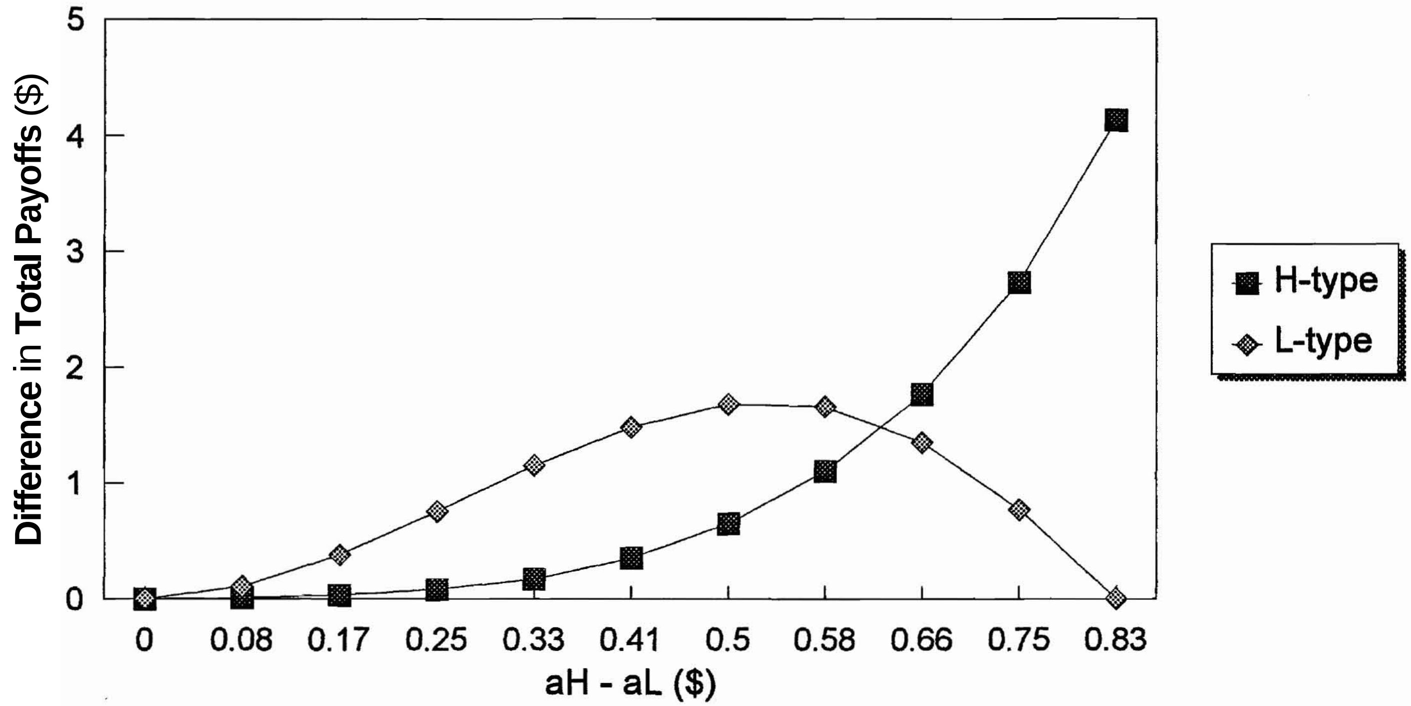
Nash Equilibrium and Cutback Efficiencies at Various Asymmetry Levels



aH = $1.00, nH = 1, nL = 100, b = k = c0 = $0.01

Figure 4

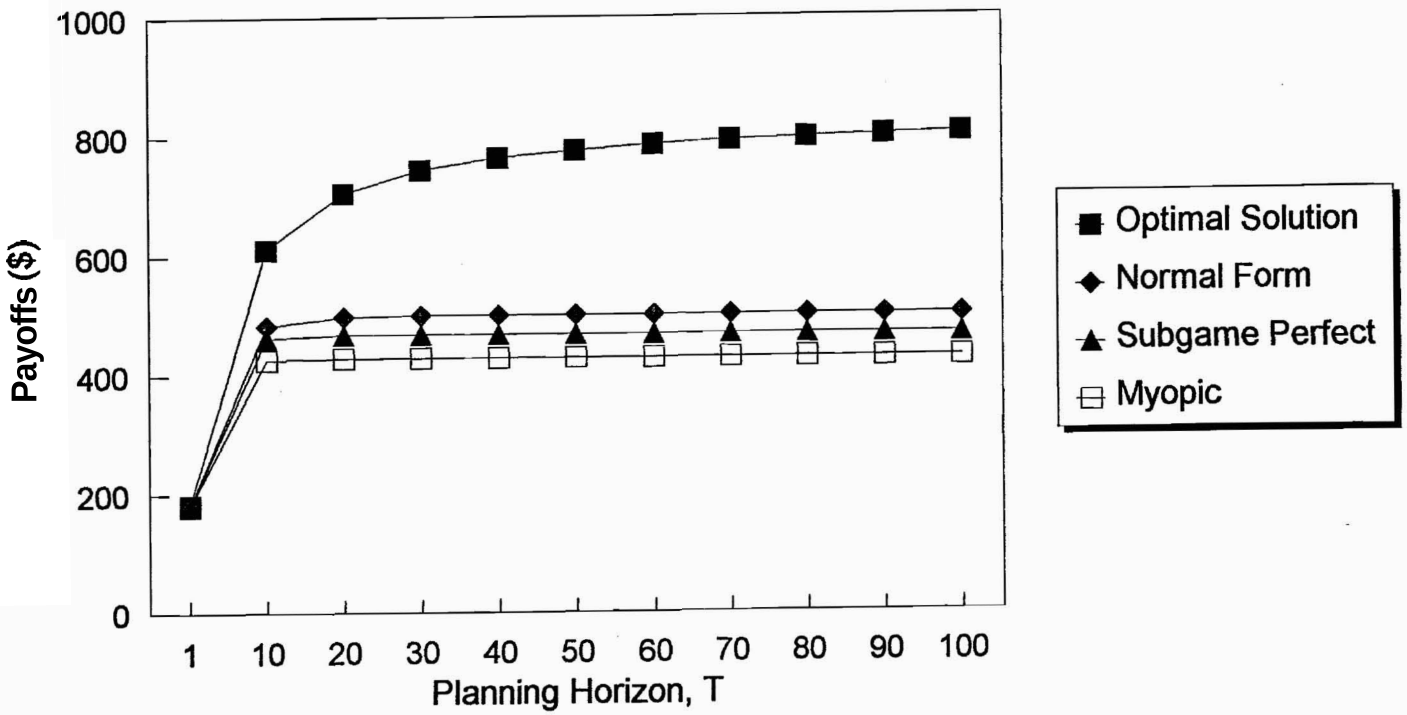
Difference in Total Payoffs to H- and L-types from (1-sH) and (1-sL)



aH = $1.00, nH = 1, nL = 100, b = k = c0 = $0.01

Figure 5

Group Payoffs as a Function of T



a = $4.085, b = $.09, k = $.01, n = 5

APPENDIX A
Comparison of the GMW and OGW Games

The Ostrom, Gardner, and Walker (1994) game (hereafter OGW) captures the essential features of Gordon's (1954) classic fisheries model. Below, these features are summarized. Throughout this discussion, the OGW parameters will be highlighted in bold to distinguish them from the GMW parameters, which will appear in italics.

The OGW game can be summarized in the following manner. Assume that n players have access to a CPR. Each player **i** has an endowment of resources e to invest in either the CPR or an outside opportunity. The payoffs that player **i** receives from the CPR depends on both his or her own level of investment, $\mathbf{x_i}$, and the total group investment, $\mathbf{X=\Sigma_i x_i}$. The total group payoffs from the CPR are given by the quadratic function:

$$\mathbf{F(X) = aX - bX^2},$$

where a and b are positive parameters. Each player **i** receives a percentage of the group payoffs from the CPR equal to the amount of resources he or she invests in the CPR divided by the total resources invested by all players, $\mathbf{x_i/X}$. Thus, the payoffs received from the CPR by player **i** are given by:

$$\mathbf{B_i(x_i,X) = ax_i - bx_iX}. \tag{A.1}$$

Note that the benefit function (A.1) introduces an externality into the OGW game. If player **i** increases $\mathbf{x_i}$ by one unit, this increases the total group investment, X, by one unit. This increase in X decreases the total payoff of each other player **j** by $\mathbf{bx_j}$.

It is assumed that all resources not invested in the CPR are invested in the outside opportunity, which provides a constant marginal payoff of w. Thus, if player **i** invests $\mathbf{x_i}$ into the CPR, his or her remaining resources, $\mathbf{e\text{-}x_i}$, are invested in the outside opportunity, producing a benefit of $\mathbf{w(e\text{-}x_i)}$ from the outside opportunity. Combining the payoffs received from the CPR and the outside opportunity, the total payoffs received by player **i** are given by:

$$\boldsymbol{\pi_i} \mathbf{= ax_i - bx_iX + w(e\text{-}x_i)}. \tag{A.2}$$

In comparison, recall that the net benefit function in the time-independent GMW game is given by:

$$u_i(x_i,X,c_0) = ax_i - bx_i^2 - x_i(c_0 + kX/2), \tag{4'}$$

From this discussion, it is clear that differences between the **OGW** and **GMW** games do exist. First, in the **GMW** game, the strategy of player i is an extraction level, x_i, while in the **OGW** game, the strategy is the amount of resources invested in the CPR, $\mathbf{x}_i$. In either case, the extraction or the investment of input resources yields an output of CPR resource units, which then provide benefits to the players. In this comparison, the different interpretations of what the strategies x_i and $\mathbf{x}_i$ represent will be ignored. Second, the externality in the **GMW** game appears on cost side of the game, while the externality in the **OGW** game arises on the benefit side. Finally, **OGW** game includes an endowment and an outside opportunity that are not included in the **GMW** game. In the discussion that follows, it is argued that these differences do not impact the equilibrium strategy.

In order to see the similarity between the **GMW** and **OGW** games, consider the **first-**order conditions of the maximization problems involving (4') and **(A.2),** which represent the necessary conditions for the equilibria of these games:

$$(a-c_0) - 2bx_i - (k/2)(x_i+X) = 0 \tag{A.3}$$

and

$$(\mathrm{a}-\mathrm{w}) - \mathbf{b}(\mathbf{x}_i+\mathbf{X}) = 0$$

From **(A.3),** the equilibrium strategies x_i^e and $\mathbf{x}_i^e$ coincide under the following parameterization:

$$\mathrm{a} = a,\ \mathrm{b} = k/2,\ \mathrm{w} = c_0,\ \text{and } b = 0.$$

Note that while the equilibrium strategies x_i^e and $\mathbf{x}_i^e$ coincide under this parameterization, the total payoffs received by the players of the two games do not. The players in the **OGW** game receive **an** extra payoff we from their endowment that is not received by players in the **GMW** game.

However, the endowment, e, does not show up in the first-order condition of the OGW game. Thus, from a strategic standpoint, e functions primarily as an upper constraint on the strategy $\mathbf{x}_i$. Unless this constraint binds, e will not impact the equilibrium strategy. Furthermore, in the strategic sense, the payoff from the outside opportunity serves as an opportunity cost of resources not invested in the CPR. If one interprets e to be the upper constraint on $\mathbf{x}_i$ and the constant marginal payoff from the outside opportunity, w, to be a constant cost of CPR extraction, then a cost function for the **OGW** game can be defined as:

$$\mathbf{C}_i(\mathbf{x}_i) = \mathbf{w}\mathbf{x}_i \qquad \mathbf{x}_i \in [0,\mathbf{e}]. \tag{A.4}$$

Together, the cost function (A.4) and benefit function (A.l) define a net benefit function for player i, given by:

$$u_i(x_i,X) = ax_i - x_i(w+bX). \tag{A.5}$$

The net benefit function (A.5) corresponds to the net *yield from the* CPR discussed in OGW. From equations **(A.5)** and (4′), it follows that the net yield from the **CPR** to an individual in the OGW game is equivalent to the net individual benefits in the GMW game under the parameterization:

$$a = a, \ b = k/2, \ w = c_o, \ \text{and } b = 0.$$

Continuing with the interpretation of the payoff **from** the outside opportunity the cost function of the game, consider a quadratic, rather than linear, cost function:

$$C_i(x_i) = wx_i - dx_i^2. \tag{A.4′}$$

With this cost function, the equilibrium strategy and net individual benefits in the GMW game coincide with the equilibrium strategy and individual net yield from the CPR in the OGW game under the following parameterization:

$$a = a, \ b = k/2, \ w = c_0, \ \text{and } d = b.$$

Again, the total payoffs received by players in these two games do not coincide with these parameters. The players of the OGW game still receive a payoff, we, not received by the players of the GMW game. Nevertheless, these two games, which are framed in very different contexts, are, in a strategic sense, quite similar.

An important byproduct of the comparison of these two games is that it enables one to more broadly interpret the GMW game. In particular, this comparison highlights the fact that the strict distinction between benefit and cost externalities in the development of these games is somewhat arbitrary. For example, in the GMW game the parameter b, which determines the slope of the marginal private benefit curve, can alternatively be interpreted as a measure of the slope of an increasing marginal private cost curve, or as a measure of some combination of increasing marginal private cost and declining marginal private benefit. Similarly, the parameter k, which measures the severity of the external cost, can be interpreted to measure externalities on either the benefit or cost side or some combination of the two. The important distinction in the GMW game is that the parameter b measures the rate of decline of private net benefits, while k measures the severity of the externality.

APPENDIX B
Proofs Related to Asymmetric Game

Prove that:

$x_H^e/x_L^e < x_H^o/x_L^o$.

> ***Proof:*** Both sides of this inequality are undefined when players inequality *(18)* from the text holds. Therefore, we restrict attention to the case in which inequality (18) **does not** hold. Low types are inactive in a larger area of the parameter space in the optimal solution **than** in the equilibrium solution. Whenever low types are inactive at the optimal solution but not at the equilibrium solution, the inequality holds. Finally, equations (15) and *(20)* from the text can be manipulated to show that the inequality holds at the interior solution.

$s_H \geq s_o \geq s_L$.

> ***Proof: A*** comparison of cutbacks makes sense only for interior equilibria. Therefore, attention is restricted to this region. Recall that ***a,* > *a,;*** furthermore, equation *(20)* from the text, which defines the interior optimal solution, can be manipulated to yield $x_H^e \geq x_L^e$ in the event that both types are active. From these inequalities, it follows immediately that $M/N \geq O/P$. For any values of M, N, O, and P such that $M/N \geq O/P$, it must be the case that $M/N \geq (M+O)/(N+P) \geq O/P$. Combined with the definitions given in *(24)* and *(25)* in the text, this proves that $s_H \geq s_o \geq s_L$.

The cutbacks s_o and s_H always results in a higher group payoff than the equilibrium group payoff.

> ***Proof:*** By definition, s_o is the scalar that, when applied to the equilibrium allocation produces the largest group payoffs. Since $s_o = 1$ is a possible value of s_o, it must be the case that the payoff resulting from s_o is at least as high as the equilibrium payoff. In order to prove that s_H increases group payoffs, I will show that any value of s in the range $[s_o, 1]$ increases the group payoffs. This, combined with the fact that $s_H \geq s_o$ will prove the proposition.
>
> Let $U(s\mathbf{x}^o)$ denote the total rent earned from the resource when a cutback of $(1\text{-}s)$ from the equilibrium allocation is implemented. The total group payoffs resulting from a proportional cutback $(1\text{-}s)$ is given by:
>
> $$U(s\mathbf{x}^o) = s[X_H^o(a_H - c_0) + X_L^o(a_L - c_0)] - s^2[(X_H^o)^2 b/n_H + (X_L^o)^2 b/n_L + k(X^o)^2/2].$$

From this equation, it can be shown that the derivative of $U(s\mathbf{x}^e)$ with respect to s is less than zero for $s > s_o$. This proves that any value of s in the range $[s_o, 1]$ increases the group payoffs and hence proves the proposition.

APPENDIX C
Optimal Solutions

The optimal extraction path is derived by **maximizing** the group lifetime resource value:

$$\text{Max } \Sigma_t\Sigma_i(B_{it} - C_{it}) \qquad \text{wrt } <x_{it}>, \tag{C.1}$$

where B_{it} and C_{it} are given in equations (1) and (3) of the text. The key insight used in solving this problem is that the optimal path requires that each individual to extract the same amount in each period. This is due to the declining marginal and the fact that future benefits are not discounted.

Consider first the benefits side of expression (C.1), $\Sigma_t\Sigma_i B_{it}$. In each period t, total group benefits are given by:

$$\begin{aligned} \Sigma_i B_{it} &= (ax_{1t} - bx_{1t}^2) + (ax_{2t} - bx_{2t}^2) + \dots + (ax_{nt} - bx_{nt}^2) \\ &= a\Sigma_i x_{it} - b\Sigma_i x_{it}^2. \end{aligned} \tag{C.2}$$

Let $X_{.t} = \Sigma_i x_{it}$. By symmetry, $x_{1t} = x_{2t} = \dots = x_{nt} = X_{.t}/n$. This implies that:

$$\Sigma_i x_{it}^2 = \Sigma_i(X_{.t}/n)^2 = X_{.t}^2/n.$$

Therefore, in each period, total benefits are given by:

$$\Sigma_i B_{it} = aX_{.t} - (b/n)X_{.t}^2. \tag{C.3}$$

Using (C.3), total group benefits over the entire lifetime of the resource are given by:

$$\begin{aligned} \Sigma_t\Sigma_i B_{it} &= [aX_{.1} - (b/n)X_{.1}^2] + [aX_{.2} - (b/n)X_{.2}^2] + \dots + [aX_{.T} - (b/n)X_{.T}^2] \\ &= a\Sigma_t X_{.t} - (b/n)\Sigma_t X_{.t}^2. \end{aligned} \tag{C.4}$$

Denote by $X_{..} = \Sigma_t X_{.t}$ the aggregate extraction of all individuals over the lifetime of the resource. Because the optimal extraction path requires constant extraction in each period, $X_{.1} = X_{.2} = \dots = X_{.T} = X_{..}/T$. This implies that:

$$\Sigma_t X_{.t}^2 = \Sigma_t(X_{..}/T)^2 = X_{..}^2/T.$$

Therefore, when extraction is constant over time, total benefits received over the lifetime of the resource are given by:

$$\Sigma_t \Sigma_i B_{it} = aX_{..} - [b/(nT)]X_{..}^2. \tag{C.5}$$

Unlike total group benefits, the total extraction costs incurred over the lifetime of the resource depend only on the level of total extraction, independent of the distribution of this extraction over time. The average cost of extraction associated with an extraction level $(X_{..})$ is given by:

$$AC(X_{..}) = c_1 + kX_{..}/2.$$

Thus, the total cost of extracting $X_{..}$ resource **units** is given by:

$$\Sigma_t \Sigma_i C(X_{..}) = X_{..}(c_1 + kX_{..}/2). \tag{C.6}$$

Using **(C.5)** and **(C.6)**, the maximization problem **(C.1)** can **be** rewritten in the following manner:

$$\text{Max } (a - c_1)X_{..} - [b/(nT) + k/2]X_{..}^2 \qquad \text{wrt } X_{..}. \tag{C.7}$$

The first-order condition of this maximization is:

$$a - c_1 = [2b/(nT) + k]X_{..}. \tag{C.8}$$

Therefore,

$$X_{..}^{o} = \frac{nT(a - c_1)}{2b + knT}. \tag{C.9}$$

Individual extraction in each period, x_{it}^{o}, is derived by dividing $X_{..}^{o}$ by nT:

$$x_{it}^{o} = \frac{a - c_1}{2b + knT}. \tag{C.10}$$

The group lifetime value of the resource, $V_{..}^{o}$, is calculated by substituting $X_{..}^{o}$ into the expression that is maximized in **(C.7)**. In particular,

$$V_{..}^{o} = (a - c_1)\frac{nT(a - c_1)}{2b + knT} - \frac{2b + knT}{2nT}\left[\frac{nT(a - c_1)}{2b + knT}\right]^2$$

$$\Rightarrow \qquad V_{..}^{o} = \frac{nT(a - c_1)^2}{2(2b + knT)}. \tag{C.11}$$

APPENDIX D
Derivation of λ_m

The parameter that specifies the rate at which myopic extraction diminishes over time, λ_m is calculated in the following manner. As shown in the text, the myopic extraction level for player i in period t, x_{it}^m, is given by:

$$x_{it}^m = \frac{a - c_t}{2b + (n+1)k/2}. \tag{D.1}$$

The rate at which extraction diminishes is given by:

$$\begin{aligned}
\lambda_m &= (x_{it+1}{}^m)/(x_{it}{}^m) \\
&= (a - c_{t+1})/(a - c_t) \\
&= (a - c_t - kX_t)/(a - c_t) \\
&= 1 - kX_t/(a - c_t).
\end{aligned}$$

But, from (D.1),

$$X_t = \frac{n(a - c_t)}{2b + (n+1)k/2}.$$

Therefore,

$$\begin{aligned}
\lambda_m &= 1 - \frac{kn(a - c_t)}{(a - c_t)[2b + (n+1)k/2]} \\
&= 1 - \frac{kn}{2b + (n+1)k/2} \\
&= \frac{2b + (n+1)k/2 - kn}{2b + (n+1)k/2} \\
&= \frac{2b - (n-1)k/2}{2b + (n+1)k/2}.
\end{aligned} \tag{D.2}$$

APPENDIX E
$V_{..}$ for Exponentially Decreasing Extraction Paths

Finite T

Assume the noncooperative game lasts more than one period; which is equivalent to assuming that $n < 1+4b/k = n_0$. Then, (B.4) and (B.6) from Appendix C imply that:

$$
\begin{aligned}
V_{..} &= \Sigma_t \Sigma_i (B_{it} - C_{it}) \\
&= a\Sigma_t X_{.t} - (b/n)\Sigma_t X_{.t}^2 - \Sigma_t X_{.t}(c_1 + \Sigma_t X_{.t} k/2). \qquad \text{(E.1)}
\end{aligned}
$$

For an extraction path that declines exponentially,

$$(X_{.t+1})/(X_{.t}) = \lambda,$$

for all t = 1,2,...,T-1. This implies that:

$$X_{.t} = \lambda^{t-1} X_{.1} \qquad \text{(E.2)}$$

for all t = 1,2,...,T, where $X_{.1}$ is the total group extraction in period 1. Using equation (E.2),

$$
\begin{aligned}
\Sigma_t X_{.t} &= X_{.1}(1 + \lambda + \lambda^2 + \ldots + \lambda^{T-1}) \\
&= \frac{1 - \lambda^T}{1 - \lambda} X_{.1}. \qquad \text{(E.3)}
\end{aligned}
$$

Similarly,

$$
\begin{aligned}
\Sigma_t X_{.t}^2 &= X_{.1}^2(1 + \lambda^2 + \lambda^4 + \ldots + \lambda^{2T-2}) \\
&= \frac{1 - \lambda^{2T}}{1 - \lambda^2} X_{.1} \\
&= \frac{1 - \lambda^T}{1 - \lambda} \frac{1 + \lambda^T}{1 + \lambda} X_{.1}. \qquad \text{(E.4)}
\end{aligned}
$$

Substituting (E.3) and (E.4) into (E.1) yields:

$$V_{..} = X_{.1}\frac{1-\lambda^T}{1-\lambda}\left[(a-c_1) - (b/n)X_{.1}\frac{1+\lambda^T}{1+\lambda} - (k/2)X_{.1}\frac{1-\lambda^T}{1-\lambda}\right]. \tag{E.5}$$

Infinite T (T → ∞)

As $T \to \infty$, $\lambda^T \to 0$, and (E.5) simplifies considerably. In particular,

$$V_{..} \to \frac{X_{.1}}{1-\lambda}\left[(a-c_1) - (b/n)\frac{X_{.1}}{1+\lambda} - (k/2)\frac{X_{.1}}{1-\lambda}\right]. \tag{E.6}$$

Myopic Solution

As shown in Appendix D, $X_{.1}^m$ and λ_m are given by:

$$X_{.1}^m = \frac{n(a - c_1)}{2b + (n+1)k/2} \tag{E.7}$$

and $$\lambda_m = \frac{2b - (n-1)k/2}{2b + (n+1)k/2}.$$

This implies that:

$$1-\lambda_m = \frac{nk}{2b + (n+1)k/2} \tag{E.8}$$

and $$1+\lambda_m = \frac{4b + k}{2b + (n+1)k/2}.$$

Substituting the expressions given in (E.7) and (E.8) into (E.6) yields:

$$V_{..}^m = \frac{a-c_1}{k}\left[(a-c_1) - b\frac{a-c_1}{4b+k} - \frac{a-c_1}{2}\right]$$

$$= \frac{(a-c_1)^2}{2k}\left[1 - \frac{2b}{4b+k}\right]$$

$$= \frac{(a-c_1)^2}{2k}\left[\frac{2b/k + 1}{4b/k + 1}\right]$$

$$= \frac{(a-c_1)^2}{2k}\left[\frac{n_0 + 1}{2n_0}\right], \tag{E.9}$$

where $n_0 = 1 + 4b/k$.

Normal Form Equilibrium

The derivations of λ_N and $X_{.1}^N$ are given in Appendix F. As $T \rightarrow \infty$, these values are:

$$\lambda_N = \frac{2b - (n-1)k/2}{2b + (n-1)k/2} = \frac{1 - \rho}{1 + \rho} \tag{E.10}$$

and $$X_{.1}^N \rightarrow \frac{2\rho n(a - c_1)}{(1+\rho)(\rho nk)} = \frac{2\rho}{1+\rho}\,\frac{(a - c_1)}{k},$$

where $\rho = (n\text{-}1)k/4b$. Note that $\rho < 1$ for $n < n_0$. (E.10) implies that:

$$1\text{-}\lambda_N = \frac{2\rho}{1+\rho} \tag{E.11}$$

and $$1+\lambda_N = \frac{2}{1+\rho}.$$

Substituting the (E.10) and (E.11) into (E.6) yields:

$$V_{..}^N \rightarrow \frac{a-c_1}{k}\left[(a-c_1) - \frac{b\rho(a-c_1)}{nk} - \frac{a-c_1}{2}\right]$$

$$= \frac{(a-c_1)^2}{2k}\left[1 - \frac{2b\rho}{nk}\right]$$

But, $2b\rho/k = (n\text{-}1)/2$, therefore,

$$V_{..}^N \rightarrow \frac{(a-c_1)^2}{2k}\left[1 - \frac{n-1}{2n}\right] = \frac{(a-c_1)^2}{2k}\,\frac{n+1}{n}. \tag{E.12}$$

APPENDIX F
Normal Form Equilibrium Solutions

The normal form equilibrium requires that each player to commit to an extraction path prior to period 1 that maximizes his or her own payoffs over the life of the resource taking the actions of others as given, In other words, each player i solves the following maximization problem:

$$\text{Max } \Sigma_t B_{it} - \Sigma_t C_{it} \qquad \text{wrt } < x_{i1}, x_{i2}, \ldots, x_{iT} > \tag{F.1}$$

where $X_{.t} = \Sigma_i x_{it}$ is the group extraction in period t.

The total benefits received by i over the lifetime of the resource are given by the following expression:

$$\Sigma_t B_{it} = a\Sigma_t x_{it} - b\Sigma_t x_{it}^2 \tag{F.2}$$

Similarly, the total costs incurred by i over the lifetime of the resource are given by the following expression:

$$\begin{aligned}
\Sigma_t C_{it} &= x_{i1}(c_1 + kX_{.1}/2) + x_{i2}(c_2 + kX_{.2}/2) + \ldots + x_{iT}(c_2 + kX_{.T}/2) \\
&= x_{i1}(c_1 + kX_{.1}/2) \\
&\quad + x_{i2}(c_1 + kX_{.1} + kX_{.2}/2) \\
&\quad + x_{i3}[c_1 + k(X_{.1}+X_{.2}) + kX_{.3}/2] \\
&\quad + x_{i4}[c_1 + k(X_{.1}+X_{.2}+X_{.3}) + kX_{.4}/2] \\
&\quad + \ldots + x_{iT}[c_1 + k(X_{.1}+X_{.2}+\ldots+X_{.T-1}) + kX_{.T}/2]
\end{aligned} \tag{F.3}$$

Substitute *(F.2)* and (F.3) into the maximization problem (F.1). For each player, this maximization problem involves T first-order conditions of the following form:

wrt x_{i1}: $\quad (a-c_,) - 2bx_{i1} - k/2(x_{i1}+X_{.1}) - k(x_{i2}+x_{i3}+\ldots+x_{iT}) = 0$

wrt x_{i2}: $\quad (a-c_1) - kX_{.1} - 2bx_{i2} - k/2(x_{i2}+X_{.2}) - k(x_{i3}+x_{i4}+\ldots+x_{iT}) = 0$

wrt x_{i3}: $\quad (a-c_1) - k(X_{.1}+X_{.2}) - 2bx_{i3} - k/2(x_{i3}+X_{.3}) - k(x_{i4}+x_{i5}+\ldots+x_{iT}) = 0$

wrt x_{iT-1}: $\quad (a-c_1) - k(X_{.1}+X_{.2}+\ldots+kX_{.T-2}) - 2bx_{iT-1} - k/2(x_{iT-1}+X_{.T-1}) - kx_{iT} = 0$

wrt x_{iT}: $\quad (a-c_1) - k(X_{.1}+X_{.2}+\ldots+kX_{.T-1}) - 2bx_{iT} - k/2(x_{iT}+X_{.T}) = 0.$

By symmetry, $X_{.t} = nx_{it}$ for all t = 1,2,...,T. Substituting this expression into the first order conditions above, the first-order condition with respect to x_{it} is of the form:

$$nk(\Sigma_{r=1,t-1}x_{ir}) + [2b + (n+1)k/2]x_{it} + k(\Sigma_{s=t+1,T}x_{is}) = a - c_1. \tag{F.4}$$

In particular, consider the first-order conditions with respect to x_{i1} and x_{i2}:

wrt x_{i1}: $$[2b + (n+1)k/2]x_{i1} + kx_{i2} + k(x_{i3}+x_{i4}+\ldots+x_{iT}) = a - c_1 \tag{F.5}$$

wrt x_{i2}: $$nkx_{i1} + [2b + (n+1)k/2]x_{i2} + k(x_{i3}+x_{i4}+\ldots+x_{iT}) = a - c_1. \tag{F.6}$$

Subtracting (F.6) from (F.5) yields:

$$[2b - (n-1)k/2]x_{i1} = [2b + (n-1)k/2]x_{i2}, \tag{F.7}$$

which implies that:

$$x_{i2}^N/x_{i1}^N = \frac{2b - (n-1)k/2}{2b + (n-1)k/2} = \frac{1 - \rho}{1 + \rho},$$

where ρ - $(n-1)k/4b$. Furthermore, the same expression holds for any periods t and t+1. In other words, for t = 1,2,...,T-1,

$$x_{it+1}^N/x_{it}^N = \lambda_N = \frac{1 - \rho}{1 + \rho}. \tag{F.8}$$

The value of λ_N given in (F.8) can be substituted into (F.5) to obtain an expression for x_{i1}, the extraction of player i in period 1. Specifically, (F.5) can be rewritten as:

$$[2b + (n-1)k/2]x_{i1} + k(x_{i1}+x_{i2}+\ldots+x_{iT}) = a - c_1$$

$$\Rightarrow \quad 2b(1+\rho)x_{i1} + kx_{i1}(1+\lambda_N+\lambda_N^2+\ldots+\lambda_N^{T-1}) = a - c_1$$

$$\Rightarrow \quad 2b(1+\rho)x_{i1} + kx_{i1}(1-\lambda_N^T)/(1-\lambda_N) = a - c_1$$

But, from (F.8),

$$(1-\lambda_N) = \frac{2\rho}{1 + \rho}.$$

Therefore,

$$2b(1+\rho)x_{i1} + (1-\lambda_N^T)k(1+\rho)x_{i1}/2\rho = a - c_1$$

$$\Rightarrow \quad x_{i1}k(1+\rho)[2b/k + (1-\lambda_N^T)/2\rho] = a - c_1$$

$$x_{i1}k(1+\rho)[4b\rho/k + 1-\lambda_N^T] = (a - c_1)2\rho.$$

But, by the definition of p,

$$4b\rho/k = n\text{-}1.$$

Therefore,

$$x_{i1}^N = \frac{(a - c_1)}{k} \frac{2\rho}{(1+\rho)(n-\lambda^T)}. \tag{F.9}$$

Note that h $\leq$ 1, so that, as T $\rightarrow \infty$, $h^T \rightarrow 0$. This implies that, as the planning horizon becomes infinite,

$$x_{i1}^N \rightarrow \frac{(a - c_1)}{nk} \frac{2\rho}{1+\rho}. \tag{F.10}$$

APPENDIX G
Subgame Perfect Equilibrium Solutions

Recursive Solutions

In the text, it is asserted that the subgame perfect extraction level and remaining resource value for player i in period t are of the form:

$$x_{it}^{e} = L_t(a - c_t) \tag{G.1}$$

and $$V_{it}^{e} = K_t(a - c_t)^2. \tag{G.2}$$

Furthermore, it is asserted that the proportionality factors, L_t and K_t, are given by the nonlinear recursive equations:

$$L_t = \frac{1 - 2kK_{t+1}}{2b + (n+1)k/2 - 2nk^2K_{t+1}} \tag{G.3}$$

and $$K_t = L_t - (b + nk/2)(L_t)^2 + K_{t+1}(1 - nkL_t)^2. \tag{G.4}$$

These assertions are proven below using mathematical induction. The structure of the proof is as follows. It will be shown that equations (G.1) through (G.4) hold for at least one period, namely period T. It is then shown that if equations (G.1) through (G.4) hold for period t, then they necessarily hold for period t-1. By doing so, this will prove that these equations hold in all periods t = T,T-1,...,1.

At the subgame perfect equilibrium, each player i chooses an extraction level in each period t, that maximizes the total remaining value of the resource to that individual. The remaining value of the resource to i in period t is given by the following recursive equation:

$$V_{it} = B_{it} - C_{it} + V_{it+1}. \tag{G.5}$$

The transversality condition states that the resource has no value in period $T+1$. Thus, in period T, the remaining value of the resource is given by:

$$V_{iT} = B_{iT} - C_{iT}. \tag{G.6}$$

The equilibrium extraction level in period T is then equivalent to the single-period, time-independent equilibrium extraction level given in the text, with the initial marginal cost equal to c_T. In particular,

$$x_{iT}^e = \frac{a - c_T}{2b + (n+1)k/2} \qquad \forall\, i = 1,2,\cdots,n, \tag{G.7}$$

and $$V_{iT}^e = \frac{(2b + k)(a - c_T)^2}{2[2b + (n+1)k/2]^2}. \tag{G.8}$$

Note that **(G.7)** and **(G.8)** can be obtained by substituting $K_{T+1} = 0$ into **(G.3)** and **(G.4).** Thus, equations **(G.l)** through **(G.4)** hold for period T.

Now, assume that these equations hold in period t+1. It must be shown that this implies that these equations must hold in period t. If these equations hold in period $t+1$, then the maximization problem solved by each player i in period t is given by:

$$\text{Max} \quad V_{it} = (ax_{it} - bx_{it}^2) - x_{it}[(c_t + (k/2)X_{.t}] + K_{t+1}(a - c_{t+1})^2 \quad \text{wrt } x_{it}.$$

Rearranging terms and using the fact that $c_{t+1}=c_t+kX_t$, the maximization problem can be rewritten as:

$$\text{Max} \quad V_{it} = (a - c_t)x_{it} - bx_{it}^2 - (k/2)x_{it}X_{.t} + K_{t+1}[(a - c_t) - kX_{.t}]^2 \text{ wrt } x_{it}. \tag{G.9}$$

The first-order condition for player i produced by **(G.9)** is given **by:**

$$x_{it}(2b + k/2) + X_{.t}(k/2 - 2k^2K_{t+1}) = (a - c_t)(1 - 2kK_{t+1}). \tag{G.10}$$

By symmetry, $X_{.t}^e=nx_{it}^e$, thus, **(G.10)** can be rewritten as:

$$x_{it}^e[2b + (n+1)k/2 - 2nk^2K_{t+1}] = (a - c_t)(1 - 2kK_{t+1}).$$

Thus,

$$x_{it}^e = \frac{(a - c_t)(1 - 2kK_{t+1})}{2b + (n+1)k/2 - 2nk^2K_{t+1}},$$

which implies that

$$L_t = \frac{1 - 2kK_{t+1}}{2b + (n+1)k/2 - 2nk^2K_{t+1}}.$$

This verifies equations **(G.1)** and **(G.3)** for period t. Using symmetry and the fact that $x_{it}^e=L_t(a - c_1)$, the expression for V_{it} given in **(G.9)** can be rewritten as:

$$V_{it}^e = (a - c_t)^2[L_t - (b + nk/2)L_t^2 + K_{t+1}(1 - nkL_t)^2].$$

This proves equation *(G.2)*. Furthermore, this implies that:

$$K_t = L_t - (b + nk/2)L_t^2 + K_{t+1}(1 - nkL_t)^2,$$

which proves equation (G.4).

Nonrecursive Solutions ($T \to \infty$)

As $T \to \infty$, L_t and K_t approach steady-state values. In other words, $L_t \to L_{t+1} = L$ and $K_t \to K_{t+1} = K$. Below, the steady-state values of L and K are derived.

First, note that $L_t \to L_{t+1} = L$ implies *that:*

$$\lambda_e = x_{it+1}{}^e/x_{it}{}^e = [L(a - c_{t+1})]/[L(a - c_t)]$$

$$= (a - c_t - kX_t)/(a - c_t)$$

$$= [(a - c_t - nkL(a - c_t)]/(a - c_t)$$

$$= 1 - nkL. \qquad \text{(G.11)}$$

It remains to calculate the L. The first step in this process is to substitute $L = L_t$ and $K = K_{t+1}$ into equation (G.3):

$$L = \frac{1 - 2kK}{2b + (n+1)k/2 - 2nk^2K}$$

$$= \frac{1 - 2kK}{2b - (n-1)k/2 + nk(1 - 2kK)}$$

$$= \frac{1 - 2kK}{2b(1-p) + nk(1-2kK)}, \qquad \text{(G.12)}$$

where $p = (n-1)k/4b$.

Next, substitute $L = L_t$ and $K = K_t = K_{t+1}$ into *(G.4):*

$$K = L - (b + nk/2)L^2 + K(1 - nkL)^2,$$

$$\Rightarrow \quad K[1 - (1 - nkL)^2] = L[1 - (b + nk/2)L]$$

$$\Rightarrow \quad KnkL(2 - nkL) = L[1 - (b + nk/2)L]$$

$$\Rightarrow \quad K = \frac{1 - (b + nk/2)L}{nk(2 - nkL)}. \tag{G.13}$$

The value of L is derived by substituting K from equation (G.12) into equation (G.1I). To simplify the derivation, derive the numerator and denominator of this expression separately.

Numerator

$$\text{numerator} = 1 - 2kK$$

$$= 1 - \frac{2 - (2b + nk)L}{n(2 - nkL)}$$

$$= \frac{2n - n^2kL - 2 + (2b + nk)L}{n(2 - nkL)}$$

$$= \frac{2(n-1) + L[2b - nk(n-1)]}{n(2 - nkL)}$$

$$= 2b\left[\frac{(n-1)/b + L[1 - nk(n-1)/2b]}{n(2 - nkL)}\right]$$

$$= 2b\left[\frac{4\rho/k + L(1 - 2\rho n)}{n(2 - nkL)}\right] \tag{G.14}$$

Denominator

$$\text{denominator} = 2b(1 - p) + nk(1 - 2kK), \tag{G.15}$$

Note that $1 - 2kK$ is given by (G.14). Substituting this expression into (G.15) yields:

$$\text{denominator} = 2b(1 - p) + 2bnk\left[\frac{4\rho/k + L(1 - 2\rho n)}{n(2 -}\right]$$

$$= \frac{2b}{2 - nkL}[(1-\rho)(2-nkL) + 4\rho + kL(1 - 2\rho n)]$$

$$= \frac{2b}{2 - nkL} [2(1+\rho) - kL[n(1+\rho) - 1]]. \qquad (G.16)$$

The value of L is calculated by dividing the numerator, given by (G.14), by *the* denominator, given by (G.16). The result is:

$$L = \frac{4\rho/k + L(1-2n\rho)}{2n(1+\rho) - nkL[n(1+\rho) - 1]}$$

$$\Rightarrow \quad 4\rho/k + L(1-2n\rho) = 2n(1+\rho) - nkL^2[n(1+\rho) - 1]$$

$$\Rightarrow \quad nkL^2[n(1+\rho) - 1] - nL(2 + 4\rho - 1/n) + 4\rho/k = 0$$

$$\Rightarrow \quad kL^2[n(1+\rho) - 1] - L(2 + 4\rho - 1/n) + 4\rho/(nk) = 0 \, . \qquad (G.17)$$

The roots of this quadratic equation are found using the quadratic formula. In particular,

$$L = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \qquad (G.18)$$

where $A = k[n(1+\rho) - 1]$ *(G.19)*

$-B = 2(1+2\rho) - 1/n$

and $C = 4\rho/(nk)$.

But,

$$\begin{aligned} B^2 - 4AC &= 4(1+2\rho)^2 - 4(1+2\rho)/n + 1/n^2 \\ &\quad - 16\rho(1 + \rho - 1/n) \\ &= 16\rho^2 + 16\rho - 8\rho/n + 4[1 - 1/n + 1/(2n)^2] \\ &\quad - 16\rho^2 - 16\rho + 16\rho/n \end{aligned}$$

$$\Rightarrow \quad = 4\{2\rho/n + [1 - 1/(2n)]^2\}. \qquad (G.20)$$

Substituting *(G.19)* and *(G.20)* into *(G.18)* yields:

$$L = \frac{2(1+2\rho) - 1/n \pm 2\sqrt{[1 - 1/(2n)]^2 + 2\rho/n}}{2[nk(1+\rho) - k]}$$

$$\Rightarrow \qquad L = \frac{2\rho + [1 - 1/(2n)] \pm \sqrt{[1 - 1/(2n)]^2 + 2\rho/n}}{nk[(1+\rho) - 1/n]}.$$

The solution with the "+" sign preceding the square root can be eliminated because it yields a value of L greater than $(nk)^{-1}$. From (G.11), *it* is clear that a value of L greater than $(nk)^{-1}$ implies that λ_e is less than this, which would imply negative extraction in all periods beyond period 1. Thus, the resulting value of L is given **by:**

$$L = \frac{2\rho + [1 - 1/(2n)] - \sqrt{[1 - 1/(2n)]^2 + 2\rho/n}}{nk[(1+\rho) - 1/n]}. \tag{G.21}$$

The subgame perfect equilibrium extraction of an individual in period 1, x_{il}^e is obtained directly from (G.21):

$$x_{i1}^e = \frac{a - c_1}{nk} \frac{2\rho + [1 - 1/(2n)] - \sqrt{[1 - 1/(2n)]^2 + 2\rho/n}}{(1+\rho) - 1/n}. \tag{G.22}$$

Furthermore, the rate at which extraction diminishes is given by:

$$\lambda_e = 1 - nkL$$

$$= \frac{(1+\rho) - 1/n - 2\rho - 1 + 1/(2n) + \sqrt{[1 - 1/(2n)]^2 + 2\rho/n}}{(1+\rho) - 1/n}$$

$$\lambda_e = \frac{\sqrt{[1 - 1/(2n)]^2 + 2\rho/n} - [\rho + 1/(2n)]}{(1+\rho) - 1/n} \tag{G.23}$$

Finally, the group lifetime value of the resource produced by the subgame perfect equilibrium, $V_{..}^e = nK(a - c_1)^2$ is obtained by substituting L into **(G.13)** to obtain K. The result is a complicated expression. In the text, I have given a much simpler approximate expression for this value:

$$V_{..}^e \cong \frac{n + \rho}{2n - (1-\rho)} \frac{(a - c_1)^2}{2k},$$

which results in an efficiency relative the optimal solution of:

$$E^e = \frac{n + \rho}{2n - (1-\rho)}. \tag{G.24}$$

This expression slightly underestimates the efficiency at the **subgame** perfect equilibrium. To see this, consider the following example with n = 2 and k = 1. In order for the resource to last more than one period, $b > 0.25$ (recall $n_0 = 1 + 4b/k$). Below, the exact and **approximate** efficiencies for various values of b.

b	Exact	Approximate	Difference
0.25	0.7500	0.7500	0.0000
1	0.6972	0.6923	-0.0049
10	0.6703	0.6694	-0.0009
100	0.6670	0.6669	-0.0001

The largest absolute difference the approximate and exact efficiency observed for any value of b is -0.0053, which occurs at b = 0.75. Thus, at $n = 2$, this efficiency approximation is correct within approximately one-half of a percent. Furthermore, as n increases, accuracy of this approximation increases. At $n = 3$, the largest error occurs at b = 1.25, which results in a difference of -0.0028. At n = 10, the largest difference is -0.0003.

APPENDIX H

Proof that $E^{TI} > E^{N}$

From the text,

$$E^{TI} = \frac{(2b + nk)(2b + k)}{[2b + (n+1)k/2]^2} \tag{H.1}$$

and $$E^{N} \rightarrow (n+1)/(2n) \text{ as } T \rightarrow \infty, \tag{H.2}$$

for $n \leq n_0$. Recall that for $n > n_0$, the entire resource is depleted in the initial period at all of the noncooperative solutions. Thus, when this is the case, the group resource value at any of noncooperative solutions of the time-dependent game is equal to the equilibrium group resource value of the time-independent game. On the other hand, the optimal resource value is monotonically increasing T; hence for $n > n_0$, it must be the case that $E^{TI} > E^{N}$.

Consider the case where $n \leq n_0$. From (H.1) it follows that:

$$E^{TI} = \frac{4b^2 + 2bk + nk(2b+k)}{4b^2 + 2bk + (n+1)^2k^2/4}$$

$$\Rightarrow \quad E^{TI} > \frac{nk(2b+k)}{2bnk + (n+1)^2k^2/4}$$

$$\Rightarrow \quad E^{TI} > \frac{4n(2b+k)}{8bn + (n+1)^2k}$$

$$\Rightarrow \quad E^{TI} > \frac{4n(2b+k)}{4n(2b+k) + (n-1)^2k} \tag{H.3}$$

Given (H.2) and (H.3) it is the case that $E^{n} > E^{N}$ if and only if:

$$(4n)(2n)(2b+k) > (4n)(n+1)(2b+k) + (n+1)(n-1)^2k$$

$$\Leftrightarrow \quad (4n)(n-1)(2b+k) > (n+1)(n-1)^2k$$

$$\Leftrightarrow \quad (4n)(2b/k + 1) > (n+1)(n-1)$$

$$\Leftrightarrow \quad 2nn_0 > n^2 - 1. \tag{H.4}$$

But, $n_0 > n$, therefore, (H.4) holds if and only if

$$n^2 + 1 > 0. \tag{H.5}$$

Clearly, (H.5) holds for $n > 0$; hence, it must be the case that $E^n > E^N$.

ENDNOTES

1. The following convention will be used in referring to the users of the resource. In this section, where the model is specified in the context of a groundwater aquifer, users are referred to as "appropriators." In later sections, where the solutions of the CPR game are presented and discussed, users are referred to as "players." Finally, in later chapters, where the results of laboratory experiments are reported, the users are referred to as "subjects."

2. Alternatively, the time-independent game may be viewed as a case in which the resource fully replenishes after each period.

3. Another useful measure of the severity of the inefficiency caused by overextraction is the equilibrium efficiency of resource use, E. This measure is defined as the equilibrium group resource value divided by the optimal resource value:

$$E = V^e/V^o = [(2b+k)(2b+nk)]/[2b + (n+1)k/2]^2.$$

In both the time-independent and time-dependent games, efficiency is monotonically decreasing in n.

4. Efficiency is defined as the total payoffs earned by all players divided by the total payoffs earned at the optimal solution.

5. Gordon (1954) concludes that fully discounting the future may be a rational response of fishermen to the open-access conditions of an ocean fishery. He notes, "wealth that is free for all is valued by none because he who is foolhardy enough to wait for its proper time of use will only find that it has been taken by another... the fish in the sea are valueless to the fisherman, because there is no assurance that they will be left for him tomorrow if they are left behind today." (p. 135) For n sufficiently large, Gordon's analysis applies to the GMW time-dependent game. In particular, for $n \geq n = 1 + 4b/k$, the resource will be depleted of all of its profitable resource units in the initial period, regardless of the discount factor.

6. The normal form and subgame perfect equilibria described here are often referred to as the open-loop and closed-loop solutions, respectively.

7. There is a second solution to this set of equations involving the positive root; however, this solution leads to a value of L $>$ $(nk)^{-1}$. This solution would lead to $\lambda_e < 0$; therefore, this is not a feasible solution in this context.

CHAPTER 3

An Experimental Study of Time-Independent and Time-Dependent Externalities in the Commons

I. INTRODUCTION

As discussed in Chapter 2, the use of common-pool resources (CPRs) generally implies the existence of appropriation externalities. From a behavioral perspective, it is important to make a distinction between two types of appropriation externalities: those that are strictly restricted to within a period (time-independent), and those that occur within and across several periods (time-dependent). One important result from Chapter 2 is that, in theory, time-dependency exacerbates the CPR problem. More specifically, the efficiency of resource use at the subgame perfect equilibrium of a CPR time-dependent game is lower than that of a time-independent game with the same parameter values.

From a behavioral standpoint, the nature of the time-dependent game may lead to an even lower efficiency than that predicted by the subgame perfect equilibrium. In particular, a potential for temporally myopic behavior exists in the time-dependent game that does not exist in the time-independent game. In theory, each player considers the full impact of current extraction on his/her own future extraction costs when devising an equilibrium strategy to the time-dependent game. In practice, however, such a solution process is difficult, and players may instead opt for a myopic strategy, ignoring the future costs of their actions.

This chapter examines the behavioral implications of these two types of externalities separately. Using laboratory experiments designed to capture the essential elements of the model described in Chapter 2, the behavior of subjects is examined in the context of both a repeated time-independent game and a time-dependent supergame. One motivation for this type of study is that a set of policies designed to address one type of externality may fail to address the other, particularly if the behavioral impacts are sufficiently different.

The remainder of this chapter is organized as follows. Section II reviews the important elements of the CPR game model analyzed in Chapter 2. Section III presents the experimental design and decision setting. Section IV provides laboratory results and discussion. Section V offers concluding comments.

II. GAME MODEL of a CPR

Consider a CPR extraction game played by a group of n identical players. The players, indexed by i, extract from the resource over an exogenously determined number of periods, T. In each period t, player i makes a single extraction decision, x_{it}. The benefits received by player i in period t are given by:

$$B_{it}(x_{it}) = ax_{it} - bx_{it}^2. \tag{1}$$

Thus, the benefits received by each player are a function of his or her own extraction only. On the other hand, the costs incurred by a player are a function of his or her extraction and the total group extraction, $X = \Sigma_i x_{it}$. In particular, the cost incurred by player i in period t is given by:

$$C_{it}(x_{it},X_t,c_t) = x_{it}[c_t + kX_t/2], \tag{2}$$

where the initial cost of extraction, c_t, evolves according to the equation:

$$c_{t+1} = c_t + kX_t. \tag{3}$$

Together, equations (1) and (2) define a single-period net benefit function for each player:

$$u_{it}(x_{it},X_t,c_t) = ax_{it} - bx_{it}^2 - x_{it}[c_t + kX_t/2]. \tag{4}$$

The payoff function (4), together with the dynamic cost equation (3) define an extensive form game. Below, the extraction paths and resulting resource values are presented for the following three benchmark outcomes of this game: the joint payoff maximization outcome (MAX), the symmetric subgame perfect equilibrium outcome (SSPE), and the myopic outcome (MYOP).

The MAX outcome requires a constant extraction level in each period from each player, $x_u = x°$, with:

$$x^o = \frac{a - c_1}{2b + Tnk}. \tag{5}$$

The resulting value of the resource to each player i is then given by:

$$V_i^o = \frac{T(a - c_1)^2}{2(2b + Tnk)}. \tag{6}$$

The MAX extraction level and resource value for the time-independent game are calculated by substituting $T = 1$ into equations (5) and (6). Note that behavior consistent with MAX does not correspond to a noncooperative game equilibrium. Still, it provides a benchmark for calibrating observed payoffs. In particular, it allows one to measure the efficiency of play, given by the ratio of observed total payoffs to maximum total payoffs.

At the SSPE, the extraction path of each individual is governed by a decision rule strategy based on the observable state variable, c_t. This strategy is calculated through backward induction using the single-period net benefit function, (4), as well as the transition equation (3). The SSPE extraction level for player i in any period t, takes the form:

$$x_{it}^{e} = L_t(a - c_t), \tag{7}$$

and the value of the resource at the SSPE takes the form:

$$V_{it}^{e}(c_t) = K_t(a - c_t)^2. \tag{8}$$

The proportionality factors, L_t and K_t, are given by the nonlinear recursive equations:

$$L_t = \frac{1 - 2kK_{it+1}}{2b + (n+1)k/2 - 2nk^2K_{it+1}} \tag{9}$$

and

$$K_t = L_t - (2b + nk)(L_t)^2/2 + K_{t+1}(1 - nkL_t)^2. \tag{10}$$

A transversality condition defining the value of the resource in period T+1 is needed in order to solve for the SSPE extraction path. Assume that the resource has no value in period T+l. This implies:

$$K_{T+1} = 0. \tag{11}$$

The SSPE is derived recursively beginning in period T+1 by substituting (11) into (9) to obtain L_T, which is then used to calculate K_T. With this as a starting point, the entire path can be determined recursively. For $n > 1$, the SSPE path involves relatively high depletion rates in the initial periods that diminish nearly exponentially over time and approach zero in later periods. In the literature on groundwater extraction, this phenomenon is commonly known as "racing for the water," as each player acts on his or her incentive to deplete the relatively less expensive water at the top of the aquifer before others do so.

The SSPE extraction level and resource value of the time-independent game are calculated from equations (7)-(11), as in period T of the time-dependent game. In particular, it can be shown that in the time-independent game:

$$x_i^e = \frac{a - c_1}{2b + (n+1)k/2}, \tag{12}$$

and

$$V_i^e = \frac{(2b + k)(a - c_1)^2}{2[2b + (n+1)k/2]^2}. \tag{13}$$

The MYOP outcome results when players behave myopically, neglecting the fact that current extraction decreases the future value of the resource. The MYOP extraction level for player i in period t, x_{it}^m, is analogous to equation (12), given the initial cost, c_t:

$$x_{it}^m = \frac{a - c_t}{2b + (n+1)k/2}. \tag{14}$$

Similarly, the payoff received by player i in any period t, π_{it}^m, is equivalent to the single-period equilibrium value of the resource in (13), given c_t:

$$\pi_{it}^{m} = \frac{(2b + k)(a - c_t)^2}{2[2b + (n+1)k/2]^2}. \tag{15}$$

In general, c_t is based on the history of the game in all periods prior to t. However, in period 1, the game has no history, which implies $c_1 = kd_1$; Thus, x_{i1}^{m}, can be calculated directly from the parameterization of the problem. Extraction diminishes exponentially over time, with:

$$\frac{x_{it+1}^{m}}{x_{it}^{m}} = \frac{2b - (n-1)k/2}{2b + (n+1)k/2} \tag{16}$$

for $n < n_0 = 1 + 4b/k$ and 0 otherwise. Relative to the SSPE, the MYOP outcome results in lower payoffs, due to a more intense race for the resource.

m. EXPEREMENTAL DESIGN

The experimental environment is designed to capture the essential elements of the game defined by equations (l)-(4). The extraction of players is replaced by token orders of subjects. A subject earns cash benefits based on his or her token order, according to a specified parameterization of equation (1). Similarly, a subject incurs costs based on both his or her own token order and the group token order, according to equation (2).

Both a time-independent and a time-dependent setting are examined. In each setting, the incremental cost parameter, k, defines the increase in the marginal token cost *within* a given decision round. However, the two settings differ with respect to the base token cost, c_t, that is used *across* decision rounds. Consider, for example, a case in which both the base token cost in round 1 and the incremental cost parameter are $0.01.[1] In the time-independent setting, the base token cost is reset to $0.01 at the beginning of each round. In the time-dependent setting, the base token cost in any round is equal to the cost of the last token ordered in the previous round plus $0.01. Thus, in the time-dependent setting, token costs are monotonically increasing throughout the experiment.

Design Conditions and Parameterization

A design condition is defined by the values of the parameters (a,b,c_1,k,n,T) and by whether a time-independent or time-dependent setting is used. Five different design conditions are considered; three are time-independent and two are time-dependent. Table I presents the parameters used in each design condition.

The three time-independent designs are denoted TIN2 (time-independent, $n=2$), TIN5-High (time-independent, $n=5$, high efficiency at SSPE), and TIN5-Low (time-independent, $n=5$, low efficiency at SSPE). The parameters of the TIN5-High design produce an SSPE efficiency of 79.3%, which is considerably higher than the 59.5% produced by the TIN5-Low design.

The two time-dependent designs are denoted TDN2 (time-dependent, $n=2$) and TDN5 (time-dependent, $n=5$). The benefit parameters of the TDN2 and TDN5 designs were chosen so that the SSPE efficiencies were approximately equal.

Table I also displays the per capita MAX and SSPE token orders for the time-independent designs and the efficiency at the SSPE for all designs. Table II displays the per capita token order by round for MAX, SSPE, and MYOP in the time-dependent designs. Note the intensification in the number of tokens ordered in the initial round when moving from MAX to SSPE to MYOP.

Experimental Implementation

All experiments were conducted at Indiana University utilizing the NovaNet computer system. Subjects were recruited from a pool of undergraduates who had previously participated in experimental sessions using a similar design condition.[2] Prior to volunteering, subjects were informed that they would participate in a decision-making experiment similar to the one in which they had previously participated, lasting approximately 1.5 hours.[3]

Each experimental session was conducted in the following manner. A sufficient number of subjects were recruited so that two or three groups could participate simultaneously. At the beginning of each session, subjects were asked to privately read through a series of computerized instructions and to complete two practice examples after finishing the instructions.[4] After each subject had successfully completed the examples, all subjects proceeded to the first decision round. Experimenters were available at all times during the experiment to answer questions.

During an experimental session, each subject participated in two experimental series. In the time-independent sessions, a series consisted of 10 repetitions of the one-shot constituent game. In the time-dependent sessions, a series consisted of a single, 10-round supergame. In the time-dependent sessions, it was possible for a series to end prior to round 10; in particular, if the base token cost ever became high enough to prohibit positive profits, the series would end. Hereafter, the two series within each experimental session will be referred to as Series 1 and Series 2.

Prior to Series 1, subjects were assigned to groups without being told the identity of the other group members. Each group participated in Series 1 using one of the five design conditions. The subjects were then randomly regrouped, and each of the new groups participated in Series 2 using the same parametric design condition. In sessions where $n=2$, subjects were informed that they were not grouped with the same person in Series 2. In sessions where $n=5$, subjects were informed that their Series 2 group would not be the same as their Series 1 group. Subjects were explicitly informed of the number of rounds in a series, but they were not informed before Series 1 that a second series would follow. At the beginning of Series 2, however, subjects were informed the experiment would end following that series.

Decision Setting

In each decision round, each subject independently made a token order for that round. Individual token orders were restricted to integer values in the range [0,80].[5] As shown in Tables I and II, the SSPE token orders for the time-independent designs range from 16 to 21, and the largest token order predicted by any of the solution concepts in the time-dependent designs is 41.

All subjects made token orders simultaneously. Subjects were provided with a benefits table, which presented the total benefits that an individual would receive for each possible token order in the allowable range. Subjects were also explicitly informed of how individual costs would be calculated. The instructions specified that the total cost to a subject in a given round would equal the average token cost in that round multiplied by the number of tokens ordered by the subject and that the average token cost would be a function of the total group token order.[6] Furthermore, the instructions specified the formula used to calculate both the average cost and the total cost incurred by a subject. The benefit and cost values were expressed in terms of "computer dollars," and subjects were given the exchange rate that would be used to convert computer earnings into US dollars. The parameters, together with the exchange rate, were chosen to produce individual payoffs at MAX of approximately $1 per round.

Subjects were informed of the size of the group in which they were playing, and it was common information that each member of the group faced the same benefit function and average token cost. Prior to each decision round, subjects were informed of the base token cost for that round. Following each decision round, each subject was informed of the total number of tokens ordered by the group, the average token cost, and his or her own profits for that round. Subjects could review the results of any previous round at any point during the decision-making process.

IV. EXPERIMENTAL RESULTS

Table III summarizes the experimental sessions. A total of seven experimental sessions were conducted, each involving the simultaneous participation of multiple decision-making groups. Together, these sessions produced a total of 32 experimental series. The results are presented in the form of summary observations.

Observation 1: In the time-independent designs, the individual token orders more closely follow the SSPE prediction than the MAX prediction.

Figure 1 displays the mean, minimum, and maximum individual token order by round for each series, pooling across all individuals in a given design. Despite the considerable variability of individual token orders displayed in Figure 1, the mean token orders provide support for Observation 1. More precisely, in the TIN2 design, the mean token order is closer to the SSPE token order than to the MAX token order in all 20 rounds. Similarly, the mean token order is closer to the SSPE prediction in 13 of the 20 rounds of the TIN5-High design, as well as in 19 of the 20 rounds of the TIN5-Low design.

Table IV provides further support for Observation 1. Each entry of this table displays the mean squared deviation (MSD) of individual token orders from predicted token orders (either MAX or SSPE) for a single group over a 10 round series. Thus, each row of the table provides a comparison of the MSD from the SSPE prediction and the MAX prediction for a particular group. The smaller of the two MSDs for a group is denoted by a "*". For 16 of the 22 groups reported in Table IV, the MSD from the SSPE prediction is smaller than the MSD from the MAX prediction. Under the null hypothesis that it is equally likely for either of the two outcomes (MAX or SSPE) to result in the smaller MSD, the probability that the SSPE prediction results in the smaller MSD in 16 or more of the 22 observations is 0.026.[7]

Observation 2: In the time-dependent designs, individual token orders more closely follow the MYOP path than either the SSPE or MAX paths.

Figure 2 displays the token order path of each time-dependent group by design and series. Note that token orders generally decay over time. This pattern is consistent with both the MYOP and SSPE paths, but inconsistent with the constant path predicted by MAX, suggesting that the MYOP and SSPE paths organize the individual token order data better than the MAX path.

Table V addresses this issue by computing the MSD of individual token orders from the three benchmark paths. This table presents analogous information regarding individual token orders in the time-dependent designs as Table IV does for the time-independent designs. In particular, each entry of this table displays the MSD of the individual token orders of a group from the specified solution path (MAX, SSPE, or MYOP) over an entire series. The smallest of the three MSDs for a group is denoted by a "*". For 8 of the 10 groups reported in Table V, the MSD from the MYOP path is smaller than the MSD from either the SSPE or MAX path. Under the null hypothesis that it is equally likely for any of the three outcomes (MAX, SSPE, or MYOP) to result in the smallest MSD, the probability that the smallest MSD is from the MYOP path in 8 or more of the 10 observations is 0.004.[8]

Observation 3: In the time-independent designs, the ratio of observed group payoffs to the SSPE predicted group payoffs, r, increases as the SSPE predicted efficiency decreases.

Table VI displays the ratio, r, of observed group payoffs to SSPE predicted group payoffs for each group in each series. The SSPE predicted efficiencies for the

TIN2, TIN5-High, and TIN5-Low designs are 94.5%, 79.3%, and 59.5%, respectively. Meanwhile, the respective overall value of *r* for each design is 0.940, 1.043, and 1.235.[9] Thus, as the SSPE efficiency decreases, *r* tends to increase. Using a two-sided Mann-Whitney test with $a = .05$, one can reject the null hypothesis that *r* is the same in the TIN2 and TIN5-Low designs. However, similar hypotheses comparing the TIN2 and TIN5-High designs and comparing the TIN5-High and TIN5-Low designs *cannot* be rejected.[10]

Observation 4: The value of r in the time-independent designs is significantly higher than the value of r in the time-dependent designs.

From Table VI, the mean value of *r* across all time-independent groups is 1.085, compared to 0.849 for the time-dependent groups. Thus, overall, time-independent groups earn more than the SSPE predicted payoffs, while time-dependent groups earn less than the SSPE predicted payoffs. Using a two-sided Mann-Whitney test with $a = .05$, one can reject the null hypothesis that *r* is the same in the time-independent and time-dependent designs.[11]

V. CONCLUSIONS

This chapter focuses attention on appropriation externalities that exist in the use of common-pool resources. Such externalities arise when the cost of appropriation is a function of all players' appropriation. A comparison is made between time-independent externalities, which are restricted to within a single period, and time-dependent externalities, which carry over to future periods.

The benchmark predictions of the theoretical model are examined for several time-independent and time-dependent designs in an experimental setting based on the theoretical model. The results of these experiments generate two principal findings. First, subject behavior is consistently closer to the symmetric subgame perfect equilibrium prediction than to the efficient outcome, both in the time-independent and time-dependent designs. Second, relative to the symmetric subgame perfect equilibrium prediction, the payoffs observed in the time-dependent designs are significantly lower than those observed in the time-independent design. The lower payoffs observed in the time-dependent designs may be attributed, in part, to myopic behavior. Tests comparing the goodness-of-fit of individual token orders by subjects to equilibrium and myopic behavior consistently favor the latter.

These results have important policy implications. First, they suggest that, in a world with minimal institutional constraints on behavior, the tragedy of the commons indeed exists. Further, the presence of myopic behavior in a time-dependent setting exacerbates this problem. Even rational appropriators, who factor all costs, current and future, into extraction decisions, may be forced into a more severe race for the resource if they believe others might be myopic. Appropriation from many natural resources -- including groundwater, oil fields, fisheries, and forests -- involves time-dependent externalities. The results of these experiments suggest the need for future research investigating the prevalence of myopic behavior in such decision environments and the potential for institutional arrangements to improve performance by containing this behavior.

TABLE I
Parameterization of Laboratory Experiments

	Design Condition				
	Time-Independent			Time-Dependent	
	TIN2	TIN5-High	TIN5-Low	TDN2	TDN5
Group Size (n)	2	5	5	2	5
Maximum # of Rounds (T)	10	10	10	10	10
Benefit Function ($ax-bx^2$)	a=.45125 b=.003125	a=.709 b=.007	a=2.8536 b=.0036	a=1.307 b=.0085	a=4.085 b=.09
Token Cost Increment (k)	.01	.01	.05	.01	.01
MAX Strategy	17	11	11	6	6
SSPE Strategy	21	16	18	See Table II	See Table II
Available Range of Token Orders	[0,80]	[0,80]	[0,80]	[0,80]	[0,50]
Efficiency at SSPE	94.5%	79.3%	59.5%	76.1%	75.5%

TABLE II
Solutions Paths for Time-Dependent Designs

Round	TDN2 Design			TDN5 Design		
	MAX Path	SSPE Path	MYOP Path	MAX Path	SSPE Path	MYOP Path
1	6.00	33.83	40.69	6.00	17.75	19.43
2	6.00	16.25	15.26	6.00	13.90	14.80
3	6.00	7.81	5.72	6.00	10.89	11.28
4	6.00	3.75	2.15	6.00	8.54	8.59
5	6.00	1.80	0.80	6.00	6.69	6.55
6	6.00	0.87	0.30	6.00	5.25	4.99
7	6.00	0.42	0.11	6.00	4.13	3.80
8	6.00	0.20	0.04	6.00	3.25	2.90
9	6.00	0.10	0.02	6.00	2.58	2.21
10	6.00	0.05	0.01	6.00	2.05	1.68

TABLE HI
Summary of Experimental Sessions

<table>
<tr><th>Design Category</th><th>Design Condition</th><th>Experimental Sessions</th><th># Experimental Series Produced</th></tr>
<tr><td rowspan="4">Time-Independent</td><td>TIN2</td><td>Exp. 8</td><td>6</td></tr>
<tr><td>TIN5-High</td><td>Exp. 11, 14</td><td>8</td></tr>
<tr><td>TIN5-Low</td><td>Exp. 18, 19</td><td>8</td></tr>
<tr><td>TI Total</td><td>5 sessions</td><td>22 series</td></tr>
<tr><td rowspan="3">Time-Dependent</td><td>TDN2</td><td>Exp. 9</td><td>6</td></tr>
<tr><td>TDN5</td><td>Exp. 17</td><td>4</td></tr>
<tr><td>TD Total</td><td>2 sessions</td><td>10 series</td></tr>
</table>

TABLE IV
Mean Squared Deviation of Individual Token Orders from Solution Paths for Time-Independent Sessions[1]

Design Condition	Series	Solution Path	
		MAX	SSPE
TIN2	1	852.0	324.0*
		363.5	207.5*
		284.5	192.5*
	2	40.5*	92.5
		558.5	162.5*
		259.0	115.0*
TIN5-High	1	487.6	177.6*
		343.8	227.8*
		89.6*	447.6
		105.2*	355.2
	2	534.4	300.4*
		551.8	231.8*
		87.8*	339.8
		713.8	625.8*
TIN5-Low	1	660.2	251.4*
		566.0	328.0*
		314.2	151.8*
		178.4*	298.8
	2	682.0	253.6*
		892.0	351.6*
		103.2*	324.4
		522.4	178.0*

[1] Each entry in this table represents the mean squared deviation of the individual token orders of a given group from the corresponding solution path. For example, in the "SSPE" column, each entry represents the following calculation for a single series of a single group:

$$\Sigma_t \Sigma_i (x_{it} - x^e_{it})^2 / n.$$

* Denotes the solution path that results in the lowest mean squared deviation for a group in a given series.

TABLE V
Mean Squared Deviation of Individual Token Orders from Solution Paths for Time-Dependent Sessions[1]

Design Condition	Series	Solution Path: MAX	SSPE	MYOP
TDN2	1	242.5* 1277.5	544.0 307.7*	890.8 319.1
	2	2087.0 1275.5	994.0 327.2	976.8* 317.2*
TDN5	1	532.2 566.6 397.8	91.1 82.3 50.9	75.6* 58.3* 44.0*
	2	520.4 426.2 394.0	81.2 54.3 31.9	66.2* 44.1* 24.6*

[1] As in Table IV, each entry in this table represents the mean squared deviation of the individual token orders of a given group from the corresponding solution path. For example, in the "SSPE" column, each entry represents the following calculation for a single series of a single group:

$$\Sigma_t\Sigma_i(x_{it}-x^e_{it})^2/n.$$

* Denotes the solution path that results in the lowest mean squared deviation for a group in a given series.

TABLE VI
Ratio of Observed to SSPE Group Payoffs

	Design Condition				
	Time-Independent			Time-Dependent	
	TIN2	TIN5-High	TIN5-LOW	TDN2	TDN5
Series 1	0.765 0.956 0.982	0.887 1.064 1.219 1.223	1.057 1.257 1.333 1.555	0.947 1.236	0.683 0.695 0.866
Series 1 Mean	0.901	1.098	1.301	1.092	0.748
Series 2	0.869 0.976 1.049	0.868 0.903 0.945 1.237	0.908 1.042 1.124 1.608	0.704 0.938	0.710 0.845 0.865
Series 2 Mean	0.964	0.987	1.171	0.821	0.807
Overall Mean	0.940	1.043	1.235	0.957	0.777
Overall Efficiency	94.5%	79.3%	59.5%	76.1%	75.5%

FIGURE 1
Individual Token Orders: Low, High, and Mean

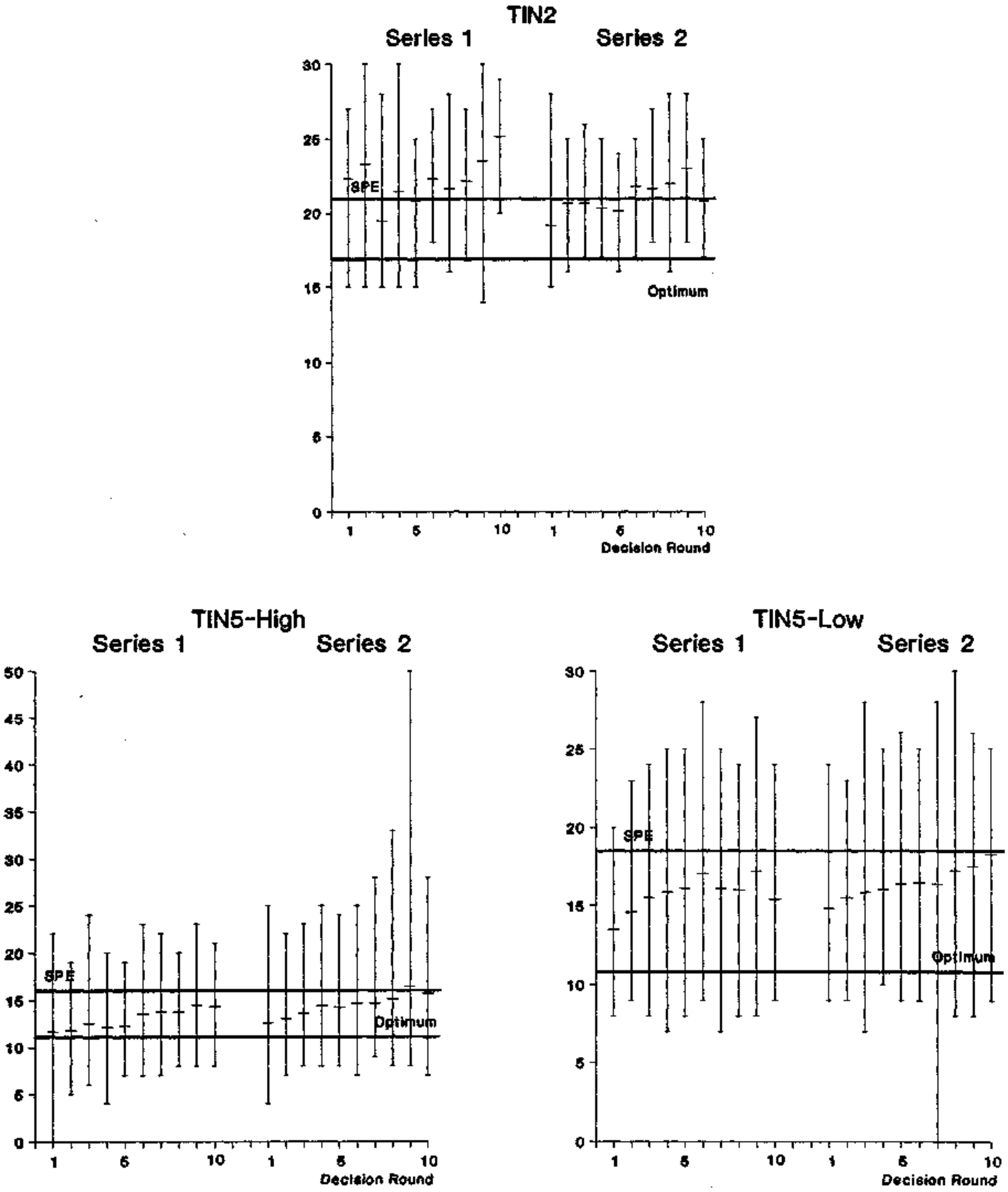
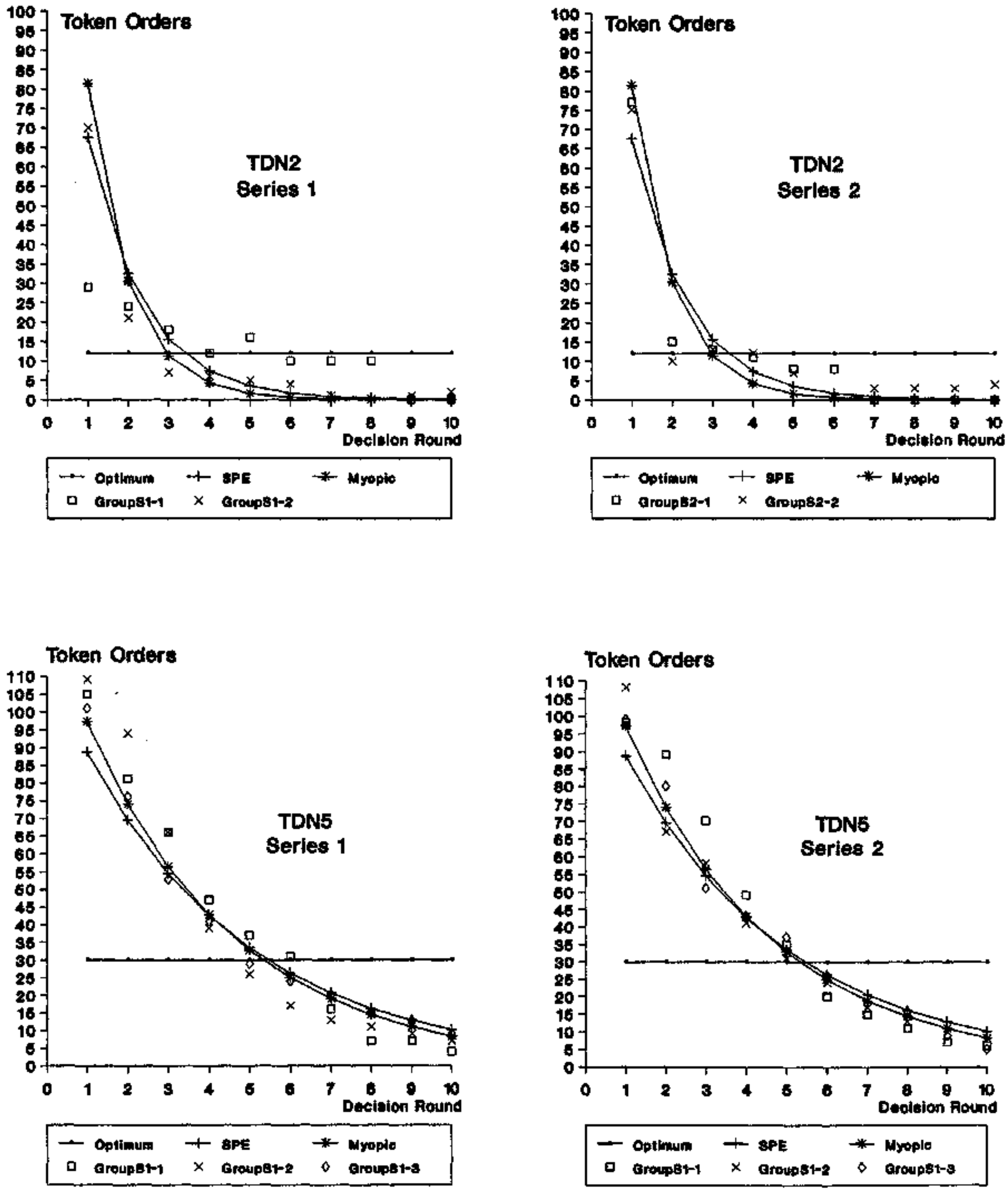


FIGURE 2
Time Dependent Designs: Group Token Orders



APPENDIX A

Time-Independent Instructions and Handouts

Computerized Instructions

Before entering the instructions, you need to be assigned an identification number. Please press the -NEXT- key:

Your identification number is 1.

Please type your last name after the arrow and then press the -NEXT- key. This information will aid us in paying you at the end of the experiment.

HERR ok

Thank You: Please Press -NEXT- to proceed. Press -BACK- to redo your name.

This is an experiment in decision making. The National Science Foundation has provided funds for conducting this experiment. The instructions are designed to inform you of the types of decisions you will be making and the results of those decisions. All profits you make during the experiment will be totalled and paid to you in privacy in cash at the end of the experiment. If you have any questions concerning the instructions feel free to raise your hand and one of the experiment monitors will assist you.

Press -NEXT- to Proceed

IMPORTANT NOTICE: You should consider all monetary values (including your profits) as "computer dollars." At the end of the experiment we will pay you in cash an amount equal 0.250 times your computer earnings.

For example:

1) If your computer earnings are $100, we would pay you 0.250 * $100 = $25.00.

2) If your computer earnings are $10, we would pay you 0.250 * $10 = $2.50.

Are there any questions on this point?

If not, Press -NEXT-

The experiment consists of a sequence of decision rounds. There is 1 other participant in this experiment. In each round, you will be asked to place an order for tokens. Tokens ordered in one round cannot be carried over to other rounds.

Why would you want to order tokens? Because you can earn money from those tokens.

Tokens you order each round will earn you a cash BENEFIT which we describe below. But, any tokens you order will also COST you money, which we also describe below.

Press -NEXT- to Proceed

CASH BENEFITS FROM TOKENS YOU ORDER

Each token you order earns you a cash return. The Cash Benefits you earn for various token orders will be displayed to you as the "Token Benefits Table." This table is the same for every participant and the same for each decision round.

Press -NEXT- to see the "BENEFITS FROM TOKENS" table.

BENEFITS FROM ALTERNATIVE TOKEN ORDERS
Toks=Tokens Ordered and Bens=Total $ Benefits for each order

TOKs	BENs	TOKs	BENs	TOKs	BENs	TOKs	BENs
1	$ 0.45	21	$ 8.10	41	$ 13.25	61	$ 15.90
2	$ 0.89	22	$ 8.41	42	$ 13.44	62	$ 15.97
3	$ 1.33	23	$ 8.73	43	$ 13.63	63	$ 16.03
4	$ 1.76	24	$ 9.03	44	$ 13.80	64	$ 16.08
5	$ 2.18	25	$ 9.33	45	$ 13.98	65	$ 16.13
6	$ 2.60	26	$ 9.62	46	$ 14.15	66	$ 16.17
7	$ 3.01	27	$ 9.91	47	$ 14.31	67	$ 16.21
8	$ 3.41	28	$ 10.19	48	$ 14.46	68	$ 16.24
9	$ 3.81	29	$ 10.46	49	$ 14.61	69	$ 16.26
10	$ 4.20	30	$ 10.73	50	$ 14.75	70	$ 16.28
11	$ 4.59	31	$ 10.99	51	$ 14.89	71	$ 16.29
12	$ 4.97	32	$ 11.24	52	$ 15.01	72	$ 16.29
13	$ 5.34	33	$ 11.49	53	$ 15.14	73	$ 16.29
14	$ 5.71	34	$ 11.73	54	$ 15.26	74	$ 16.28
15	$ 6.07	35	$ 11.97	55	$ 15.37	75	$ 16.27
16	$ 6.42	36	$ 12.20	56	$ 15.47	76	$ 16.25
17	$ 6.77	37	$ 12.42	57	$ 15.57	77	$ 16.22
18	$ 7.11	38	$ 12.64	58	$ 15.66	78	$ 16.18
19	$ 7.45	39	$ 12.85	59	$ 15.75	79	$ 16.15
20	$ 7.78	40	$ 13.05	60	$ 15.83	80	$ 16.10

This table shows "cash benefits" for various token orders. For example, let's say you order 10 tokens in a given decision round. That token order will earn you BENEFITS of $4.20. Press -NEXT- to continue.

Study this table carefully. If you have any questions raise your hand and one of the experiment monitors will help you. Note, this table will be readily available to you during the experiment. If you don't have questions, Please press -NEXT-

---

Ordering "tokens" earns you a CASH BENEFIT. BUT, you must pay for all tokens that your order. Press -NEXT- to see how your COSTS are calculated.

TOKEN COSTS

At the beginning of each round, the computer will display a BASE COST for tokens that are ordered in that round.

The BASE COST is the cost of the first token ordered in that round. Each additional token ordered in that round costs $0.01 more than the previous token ordered. The Base Cost in each decision round will equal $0.01.

Assume 30 tokens are ordered by the group in a given decision round. The 1st token costs $0.01. The 2nd token costs $0.02. The 3rd token costs $0.03, and so on, until the 30th token, which costs $0.30.

The TOTAL COSTS to the group for all 30 tokens ordered in that round would thus be:

$0.01 + 0.02+...$0.30=$4.65,

for an average token cost of $0.155 per token.

Press -NEXT- for further discussion of TOKEN COSTS
Press -BACK- to Review.

In a decision round, what YOU PAY for tokens that you order equals the number of tokens you order times the Average Token Cost for that round. Further, the Average Token Cost for that round depends on how many tokens you order, as well as how many tokens other individuals order.

In the example just shown, the Average Token Cost was $0.155 per token. Now let's assume you had ordered 6 of the 30 tokens ordered by the group. Your token costs would thus be 6 X $0.155 = $0.930.

In any given decision round, it will always be the case that your Average Token Cost is greater than the Base Cost, but less than the highest token cost in that round. Further, the AVERAGE Token Cost in a round will be the same for each participant. But, the TOTAL Token Cost per round will be different for each participant if participants place orders for a different number of tokens.

Press -NEXT- for more discussion on TOKEN COSTS
Press -BACK- to REVIEW

TOKEN COSTS

Please look at the printed materials you were handed at the beginning of the experiment and find the table labeled "COST OF TOKENS." This table shows how token costs change as more and more tokens are ordered by the group. Starting at the BASE COST of $0.01, each token ordered by the group costs $0.01 more than the previous token.

NOTE: The "average token cost" in a given decision round can easily be computed as:

[(Base Cost)+(Cost of the Last Token Ordered in the Round)]/2

Do you have any questions regarding computing "token costs?" If so raise your hand, otherwise Press -NEXT- to continue the instructions. Or, press -BACK- to review.

FINAL COMMENTS

In each round of the experiment, every participant faces an identical BENEFITS schedule for tokens they order, the same BASE COST for tokens they order, and the same AVERAGE TOKEN COST. Earnings in the experiment may differ between participants because they may place different orders for tokens.

Press -NEXT- to continue "FINAL COMMENTS"
Press -BACK- to review

FINAL COMMENTS "CONTINUED"

NOTICE: The experiment will last 10 Rounds.

At the beginning of each round, you will be asked to enter a "TOKEN ORDER" on the computer. After all participants have placed an order, the computer will tabulate orders, compute token benefits and token costs, and then inform you of:

1) the total number of tokens ordered by the group,
2) the average token cost for the round,
3) your total BENEFITS for the round,
4) your total COSTS for the round, and
5) your total PROFITS for the round.

Press -NEXT- for a Practice Example
Press -BACK- to Review

PRACTICE EXAMPLES:

The practice examples are designed to insure that you understand how BENEFITS AND TOKENS COSTS are computed. Please turn to the "blue" handout entitled "PRACTICE EXAMPLES." Please complete this "questionnaire" and then raise your hand. Or, if you have any questions on how to complete the questionnaire, raise your hand.

For your use, a copy of the "BENEFITS" table and the "TOKEN COSTS" table are also included in your packet. When you have completed your practice examples and have had them checked by an experimenter:

Press -NEXT- to see a summary of "experimental procedures," or Press -BACK- if you wish to review any part of the instructions.

EXPERIMENTAL PROCEDURES and CONSEQUENCES: A SUMMARY

1) At the beginning of a decision round, the BASE TOKEN COST will be displayed to each individual. The Base Cost is the cost of the first token sold in that round AND IS THE SAME FOR ALL PARTICIPANTS. Each additional token costs $0.01 more than the previous token.

2) At the beginning of each round, each individual will place a token order. The more tokens an individual orders the greater the AVERAGE TOKEN COST to that individual and to ALL OTHER INDIVIDUALS.

3) Tokens cannot be carried over to future rounds.

4) The computer will total all token orders, compute the "average token cost", and then compute the "total token cost" for each individual.

5) The computer will then display: (1) the group's total token order for that round, (2) each individual's own average and total token costs for that round, (3) each individual's own total benefits, total costs, and total profits for that round, and (4) each individual's own profits totaled over all decision rounds.

IF YOU HAVE ANY QUESTIONS - RAISE YOUR HAND. OTHERWISE, PRESS -NEXT- TO PROCEED

Handouts Given to Subjects in Time-Independent Designs

CONSENT FORM

This experiment is one in a series of experiments being conducted to investigate individual decision making. Funding for this experiment has been provided by several agencies of the Federal Government.

Having reviewed the instructions for this experiment, we are required by Indiana University procedures to record your formal consent to participate in this experiment.

Your participation in the experiment involves making investment decisions as described in the instructions. At the end of the experiment, you will be paid your earnings privately in cash. Your individual decisions will remain anonymous to the group. Your identity will never be identified as part of the published results from this experiment. The experiment is expected to last from one to two hours.

If you have any questions concerning the experiment please feel free to ask the experimenter. Your participation is voluntary. If you wish not to participate, please inform the experimenter now. Otherwise, please sign the consent statement below.

I have received a copy of this consent form. My participation in this research study is completely voluntary. I may choose not to participate or may withdraw at any time without prejudice concerning any future contact I may have with any of the researchers. I wish to participate in this experiment:

Signed________________________Date______________________

If you wish further information concerning this experiment, contact:

James M. Walker	**Roy Gardner**
Dept. of Economics	**Dept. of Economics**
Ballantine 805	**Ballantine 822**
Phone: 855-2760	**Phone: 855-8974**

If you have questions regarding your rights as a subject, contact:

Research Risk Office
Human Subjects Committee
Bryan 10
Bloomington, Indiana 47405
Phone: 855-3067

BENEFITS TABLE - TIN2

This Table Displays Total Benefits for Various Token Orders

TOKs	BENs	TOKs	BENs	TOKs	BENs	TOKs	BENs
1	$ 0.45	21	$ 8.10	41	$ 13.25	61	$ 15.90
2	$ 0.89	22	$ 8.41	42	$ 13.44	62	$ 15.97
3	$ 1.33	23	$ 8.73	43	$ 13.63	63	$ 16.03
4	$ 1.76	24	$ 9.03	44	$ 13.80	64	$ 16.08
5	$ 2.18	25	$ 9.33	45	$ 13.98	65	$ 16.13
6	$ 2.60	26	$ 9.62	46	$ 14.15	66	$ 16.17
7	$ 3.01	27	$ 9.91	47	$ 14.31	67	$ 16.21
8	$ 3.41	28	$ 10.19	48	$ 14.46	68	$ 16.24
9	$ 3.81	29	$ 10.46	49	$ 14.61	69	$ 16.26
10	$ 4.20	30	$ 10.73	50	$ 14.75	70	$ 16.28
11	$ 4.59	31	$ 10.99	51	$ 14.89	71	$ 16.29
12	$ 4.97	32	$ 11.24	52	$ 15.01	72	$ 16.29
13	$ 5.34	33	$ 11.49	53	$ 15.14	73	$ 16.29
14	$ 5.71	34	$ 11.73	54	$ 15.26	74	$ 16.28
15	$ 6.07	35	$ 11.97	55	$ 15.37	75	$ 16.27
16	$ 6.42	36	$ 12.20	56	$ 15.47	76	$ 16.25
17	$ 6.77	37	$ 12.42	57	$ 15.57	77	$ 16.22
18	$ 7.11	38	$ 12.64	58	$ 15.66	78	$ 16.18
19	$ 7.45	39	$ 12.85	59	$ 15.75	79	$ 16.15
20	$ 7.78	40	$ 13.05	60	$ 15.83	80	$ 16.10

BENEFITS TABLE - TIN5-High

This Table Displays Total Benefits for Various Token Orders

TOKs	BENs	TOKs	BENs	TOKs	BENs	TOKs	BENs
1	$ 0.70	21	$ 11.80	41	$ 17.30	61	$ 17.20
2	$ 1.39	22	$ 12.21	42	$ 17.43	62	$ 17.05
3	$ 2.06	23	$ 12.60	43	$ 17.54	63	$ 16.88
4	$ 2.72	24	$ 12.98	44	$ 17.64	64	$ 16.70
5	$ 3.37	25	$ 13.35	45	$ 17.73	65	$ 16.51
6	$ 4.00	26	$ 13.70	46	$ 17.80	66	$ 16.30
7	$ 4.62	27	$ 14.04	47	$ 17.86	67	$ 16.08
8	$ 5.22	28	$ 14.36	48	$ 17.90	68	$ 15.84
9	$ 5.81	29	$ 14.67	49	$ 17.93	69	$ 15.59
10	$ 6.39	30	$ 14.97	50	$ 17.95	70	$ 15.33
11	$ 6.95	31	$ 15.25	51	$ 17.95	71	$ 15.05
12	$ 7.50	32	$ 15.52	52	$ 17.94	72	$ 14.76
13	$ 8.03	33	$ 15.77	53	$ 17.91	73	$ 14.45
14	$ 8.55	34	$ 16.01	54	$ 17.87	74	$ 14.13
15	$ 9.06	35	$ 16.24	55	$ 17.82	75	$ 13.80
16	$ 9.55	36	$ 16.45	56	$ 17.75	76	$ 13.45
17	$ 10.03	37	$ 16.65	57	$ 17.67	77	$ 13.09
18	$ 10.49	38	$ 16.83	58	$ 17.57	78	$ 12.71
19	$ 10.94	39	$ 17.00	59	$ 17.46	79	$ 12.32
20	$ 11.38	40	$ 17.16	60	$ 17.34	80	$ 11.92

BENEFITS TABLE - TIN5-Low

This Table Displays Total Benefits for Various Token Orders

TOKs	BENs		TOKs	BENs
1	$ 2.85		21	$ 58.34
2	$ 5.69		22	$ 61.04
3	$ 8.53		23	$ 63.73
4	$ 11.36		24	$ 66.41
5	$ 14.18		25	$ 69.09
6	$ 16.99		26	$ 71.76
7	$ 19.80		27	$ 74.42
8	$ 22.60		28	$ 77.08
9	$ 25.39		29	$ 79.73
10	$ 28.18		30	$ 82.37
11	$ 30.95		31	$ 85.00
12	$ 33.72		32	$ 87.63
13	$ 36.49		33	$ 90.25
14	$ 39.24		34	$ 92.86
15	$ 41.99		35	$ 95.47
16	$ 44.74		36	$ 98.06
17	$ 47.47		37	$100.65
18	$ 50.20		38	$103.24
19	$ 52.92		39	$105.81
20	$ 55.63		40	$108.38

TOKs	BENs		TOKs	BENs
41	$110.95		61	$160.67
42	$113.50		62	$163.08
43	$116.05		63	$165.49
44	$118.59		64	$167.88
45	$121.12		65	$170.27
46	$123.65		66	$172.66
47	$126.17		67	$175.03
48	$128.68		68	$177.40
49	$131.18		69	$179.76
50	$133.68		70	$182.11
51	$136.17		71	$184.46
52	$138.65		72	$186.80
53	$141.13		73	$189.13
54	$143.60		74	$191.45
55	$146.06		75	$193.77
56	$148.51		76	$196.08
57	$150.96		77	$198.38
58	$153.40		78	$200.68
59	$155.83		79	$202.97
60	$158.26		80	$205.25

COST TABLE

THIS TABLE DISPLAYS THE SPECIFIC COST PER TOKEN FOR TOKENS PURCHASED BY THE GROUP

TOKEN NUMBER (COST)

1 ($0.01)	64 ($0.64)	127 ($1.27)	190 ($1.90)	253 ($2.53)	316 ($3.16)	379 ($3.79)	442 ($4.42)
2 ($0.02)	65 ($0.65)	128 ($1.28)	191 ($1.91)	254 ($2.54)	317 ($3.17)	380 ($3.80)	443 ($4.43)
3 ($0.03)	66 ($0.66)	129 ($1.29)	192 ($1.92)	255 ($2.55)	318 ($3.18)	381 ($3.81)	444 ($4.44)
4 ($0.04)	67 ($0.67)	130 ($1.30)	193 ($1.93)	256 ($2.56)	319 ($3.19)	382 ($3.82)	445 ($4.45)
5 ($0.05)	68 ($0.68)	131 ($1.31)	194 ($1.94)	257 ($2.57)	320 ($3.20)	383 ($3.83)	446 ($4.46)
6 ($0.06)	69 ($0.69)	132 ($1.32)	195 ($1.95)	258 ($2.58)	321 ($3.21)	384 ($3.84)	447 ($4.47)
7 ($0.07)	70 ($0.70)	133 ($1.33)	196 ($1.96)	259 ($2.59)	322 ($3.22)	385 ($3.85)	448 ($4.48)
8 ($0.08)	71 ($0.71)	134 ($1.34)	197 ($1.97)	260 ($2.60)	323 ($3.23)	386 ($3.86)	449 ($4.49)
9 ($0.09)	72 ($0.72)	135 ($1.35)	198 ($1.98)	261 ($2.61)	324 ($3.24)	387 ($3.87)	450 ($4.50)
10 ($0.10)	73 ($0.73)	136 ($1.36)	199 ($1.99)	262 ($2.62)	325 ($3.25)	388 ($3.88)	451 ($4.51)
11 ($0.11)	74 ($0.74)	137 ($1.37)	200 ($2.00)	263 ($2.63)	326 ($3.26)	389 ($3.89)	452 ($4.52)
12 ($0.12)	75 ($0.75)	138 ($1.38)	201 ($2.01)	264 ($2.64)	327 ($3.27)	390 ($3.90)	453 ($4.53)
13 ($0.13)	76 ($0.76)	139 ($1.39)	202 ($2.02)	265 ($2.65)	328 ($3.28)	391 ($3.91)	454 ($4.54)
14 ($0.14)	77 ($0.77)	140 ($1.40)	203 ($2.03)	266 ($2.66)	329 ($3.29)	392 ($3.92)	455 ($4.55)
15 ($0.15)	78 ($0.78)	141 ($1.41)	204 ($2.04)	267 ($2.67)	330 ($3.30)	393 ($3.93)	456 ($4.56)
16 ($0.16)	79 ($0.79)	142 ($1.42)	205 ($2.05)	268 ($2.68)	331 ($3.31)	394 ($3.94)	457 ($4.57)
17 ($0.17)	80 ($0.80)	143 ($1.43)	206 ($2.06)	269 ($2.69)	332 ($3.32)	395 ($3.95)	458 ($4.58)
18 ($0.18)	81 ($0.81)	144 ($1.44)	207 ($2.07)	270 ($2.70)	333 ($3.33)	396 ($3.96)	459 ($4.59)
19 ($0.19)	82 ($0.82)	145 ($1.45)	208 ($2.08)	271 ($2.71)	334 ($3.34)	397 ($3.97)	460 ($4.60)
20 ($0.20)	83 ($0.83)	146 ($1.46)	209 ($2.09)	272 ($2.72)	335 ($3.35)	398 ($3.98)	461 ($4.61)
21 ($0.21)	84 ($0.84)	147 ($1.47)	210 ($2.10)	273 ($2.73)	336 ($3.36)	399 ($3.99)	462 ($4.62)
22 ($0.22)	85 ($0.85)	148 ($1.48)	211 ($2.11)	274 ($2.74)	337 ($3.37)	400 ($4.00)	463 ($4.63)
23 ($0.23)	86 ($0.86)	149 ($1.49)	212 ($2.12)	275 ($2.75)	338 ($3.38)	401 ($4.01)	464 ($4.64)
24 ($0.24)	87 ($0.87)	150 ($1.50)	213 ($2.13)	276 ($2.76)	339 ($3.39)	402 ($4.02)	465 ($4.65)
25 ($0.25)	88 ($0.88)	151 ($1.51)	214 ($2.14)	277 ($2.77)	340 ($3.40)	403 ($4.03)	466 ($4.66)
26 ($0.26)	89 ($0.89)	152 ($1.52)	215 ($2.15)	278 ($2.78)	341 ($3.41)	404 ($4.04)	467 ($4.67)
27 ($0.27)	90 ($0.90)	153 ($1.53)	216 ($2.16)	279 ($2.79)	342 ($3.42)	405 ($4.05)	468 ($4.68)
28 ($0.28)	91 ($0.91)	154 ($1.54)	217 ($2.17)	280 ($2.80)	343 ($3.43)	406 ($4.06)	469 ($4.69)
29 ($0.29)	92 ($0.92)	155 ($1.55)	218 ($2.18)	281 ($2.81)	344 ($3.44)	407 ($4.07)	470 ($4.70)
30 ($0.30)	93 ($0.93)	156 ($1.56)	219 ($2.19)	282 ($2.82)	345 ($3.45)	408 ($4.08)	471 ($4.71)
31 ($0.31)	94 ($0.94)	157 ($1.57)	220 ($2.20)	283 ($2.83)	346 ($3.46)	409 ($4.09)	472 ($4.72)
32 ($0.32)	95 ($0.95)	158 ($1.58)	221 ($2.21)	284 ($2.84)	347 ($3.47)	410 ($4.10)	473 ($4.73)
33 ($0.33)	96 ($0.96)	159 ($1.59)	222 ($2.22)	285 ($2.85)	348 ($3.48)	411 ($4.11)	474 ($4.74)
34 ($0.34)	97 ($0.97)	160 ($1.60)	223 ($2.23)	286 ($2.86)	349 ($3.49)	412 ($4.12)	475 ($4.75)
35 ($0.35)	98 ($0.98)	161 ($1.61)	224 ($2.24)	287 ($2.87)	350 ($3.50)	413 ($4.13)	476 ($4.76)
36 ($0.36)	99 ($0.99)	162 ($1.62)	225 ($2.25)	288 ($2.88)	351 ($3.51)	414 ($4.14)	477 ($4.77)
37 ($0.37)	100 ($1.00)	163 ($1.63)	226 ($2.26)	289 ($2.89)	352 ($3.52)	415 ($4.15)	478 ($4.78)
38 ($0.38)	101 ($1.01)	164 ($1.64)	227 ($2.27)	290 ($2.90)	353 ($3.53)	416 ($4.16)	479 ($4.79)
39 ($0.39)	102 ($1.02)	165 ($1.65)	228 ($2.28)	291 ($2.91)	354 ($3.54)	417 ($4.17)	480 ($4.80)
40 ($0.40)	103 ($1.03)	166 ($1.66)	229 ($2.29)	292 ($2.92)	355 ($3.55)	418 ($4.18)	481 ($4.81)
41 ($0.41)	104 ($1.04)	167 ($1.67)	230 ($2.30)	293 ($2.93)	356 ($3.56)	419 ($4.19)	482 ($4.82)
42 ($0.42)	105 ($1.05)	168 ($1.68)	231 ($2.31)	294 ($2.94)	357 ($3.57)	420 ($4.20)	483 ($4.83)
43 ($0.43)	106 ($1.06)	169 ($1.69)	232 ($2.32)	295 ($2.95)	358 ($3.58)	421 ($4.21)	484 ($4.84)
44 ($0.44)	107 ($1.07)	170 ($1.70)	233 ($2.33)	296 ($2.96)	359 ($3.59)	422 ($4.22)	485 ($4.85)
45 ($0.45)	108 ($1.08)	171 ($1.71)	234 ($2.34)	297 ($2.97)	360 ($3.60)	423 ($4.23)	486 ($4.86)
46 ($0.46)	109 ($1.09)	172 ($1.72)	235 ($2.35)	298 ($2.98)	361 ($3.61)	424 ($4.24)	487 ($4.87)
47 ($0.47)	110 ($1.10)	173 ($1.73)	236 ($2.36)	299 ($2.99)	362 ($3.62)	425 ($4.25)	488 ($4.88)
48 ($0.48)	111 ($1.11)	174 ($1.74)	237 ($2.37)	300 ($3.00)	363 ($3.63)	426 ($4.26)	489 ($4.89)
49 ($0.49)	112 ($1.12)	175 ($1.75)	238 ($2.38)	301 ($3.01)	364 ($3.64)	427 ($4.27)	490 ($4.90)
50 ($0.50)	113 ($1.13)	176 ($1.76)	239 ($2.39)	302 ($3.02)	365 ($3.65)	428 ($4.28)	491 ($4.91)
51 ($0.51)	114 ($1.14)	177 ($1.77)	240 ($2.40)	303 ($3.03)	366 ($3.66)	429 ($4.29)	492 ($4.92)
52 ($0.52)	115 ($1.15)	178 ($1.78)	241 ($2.41)	304 ($3.04)	367 ($3.67)	430 ($4.30)	493 ($4.93)
53 ($0.53)	116 ($1.16)	179 ($1.79)	242 ($2.42)	305 ($3.05)	368 ($3.68)	431 ($4.31)	494 ($4.94)
54 ($0.54)	117 ($1.17)	180 ($1.80)	243 ($2.43)	306 ($3.06)	369 ($3.69)	432 ($4.32)	495 ($4.95)
55 ($0.55)	118 ($1.18)	181 ($1.81)	244 ($2.44)	307 ($3.07)	370 ($3.70)	433 ($4.33)	496 ($4.96)
56 ($0.56)	119 ($1.19)	182 ($1.82)	245 ($2.45)	308 ($3.08)	371 ($3.71)	434 ($4.34)	497 ($4.97)
57 ($0.57)	120 ($1.20)	183 ($1.83)	246 ($2.46)	309 ($3.09)	372 ($3.72)	435 ($4.35)	498 ($4.98)
58 ($0.58)	121 ($1.21)	184 ($1.84)	247 ($2.47)	310 ($3.10)	373 ($3.73)	436 ($4.36)	499 ($4.99)
59 ($0.59)	122 ($1.22)	185 ($1.85)	248 ($2.48)	311 ($3.11)	374 ($3.74)	437 ($4.37)	500 ($5.00)
60 ($0.60)	123 ($1.23)	186 ($1.86)	249 ($2.49)	312 ($3.12)	375 ($3.75)	438 ($4.38)	
61 ($0.61)	124 ($1.24)	187 ($1.87)	250 ($2.50)	313 ($3.13)	376 ($3.76)	439 ($4.39)	
62 ($0.62)	125 ($1.25)	188 ($1.88)	251 ($2.51)	314 ($3.14)	377 ($3.77)	440 ($4.40)	
63 ($0.63)	126 ($1.26)	189 ($1.89)	252 ($2.52)	315 ($3.15)	378 ($3.78)	441 ($4.41)	

PRACTICE EXAMPLES

These examples are for illustrative purposes only. The numbers used in the example have been chosen to simplify the illustration.

EXAMPLE 1:

Assume you are in the 1st Round of the Experiment. Suppose you place an order for 10 Tokens and the other member of the group orders 14 Tokens - for a total group order of 24 Tokens.

Using the BENEFITS AND COSTS TABLE:

1) What will be your CASH BENEFIT?___________

2) What will be the BASE COST for the first token ordered in this round?______

3) What will be the AVERAGE TOKEN COST this round?__________

4) What will be YOUR TOTAL TOKEN COSTS this round?___________

5) What would be YOUR PROFIT for this round? _ _ _ _ _ _

EXAMPLE 2:

Assume you are in the 4th Round of the Experiment. Suppose you place an order for 50 Tokens and the other member of the group orders 35 Tokens - for a total group order of 85 Tokens.

Using the BENEFITS AND COSTS TABLE:

1) What will be your CASH BENEFIT?___________

2) What will be the BASE COST for the first token ordered in this round?_______

3) What will be the AVERAGE TOKEN COST this round?__________

4) What will be YOUR TOTAL TOKEN COSTS this round?___________

5) What would be YOUR PROFIT for this round? ___________

ARE THERE ANY QUESTIONS?

APPENDIX B

Time-Dependent Instructions and Handouts

Before entering the instructions, you need to be assigned an identification number. Please press the -NEXT- key:

Your identification number is 1.

Please type your last name after the arrow and then press the -NEXT- key. This information will aid us in paying you at the end of the experiment.

HERR ok

Thank You: Please Press -NEXT- to proceed. Press -BACK- to redo your name.

This is an experiment in decision making. The National Science Foundation has provided funds for conducting this experiment. The instructions are designed to inform you of the types of decisions you will be making and the results of those decisions. All profits you make during the experiment will be totalled and paid to you in privacy in cash at the end of the experiment. If you have any questions concerning the instructions feel free to raise your hand and one of the experiment monitors will assist you.

Press -NEXT- to Proceed

IMPORTANT NOTICE: You should consider all monetary values (including your profits) as "computer dollars." At the end of the experiment we will pay you in cash an amount equal 0.250 times your computer earnings.

For example:

1) If your computer earnings are $100, we would pay you 0.250 * $100 = $25.00.

2) If your computer earnings are $10, we would pay you 0.250 * $10 = $2.50.

Are there any questions on this point?

If not, Press -NEXT-

The experiment consists of a sequence of decision rounds. There is 1 other participant in this experiment. In each round, you will be asked to place an order for tokens. Tokens ordered in one round cannot be carried over to other rounds.

Why would you want to order tokens? Because you can earn money from those tokens.

Tokens you order each round will earn you a cash BENEFIT which we describe below. But, any tokens you order will also COST you money, which we also describe below.

Press -NEXT- to Proceed

CASH BENEFITS FROM TOKENS YOU ORDER

Each token you order earns you a cash return. The Cash Benefits you earn for various token orders will be displayed to you as the "Token Benefits Table." This table is the same for every participant and the same for each decision round.

Press -NEXT- to see the "BENEFITS FROM TOKENS" table.

BENEFITS FROM ALTERNATIVE TOKEN ORDERS
Toks=Tokens Ordered and Bens=Total $ Benefits for each order

TOKs	BENs	TOKs	BENs	TOKs	BENs	TOKs	BENs
1	$ 1.30	21	$ 23.70	41	$ 39.30	61	$ 48.10
2	$ 2.58	22	$ 24.64	42	$ 39.90	62	$ 48.36
3	$ 3.84	23	$ 25.56	43	$ 40.48	63	$ 48.60
4	$ 5.09	24	$ 26.47	44	$ 41.05	64	$ 48.83
5	$ 6.32	25	$ 27.36	45	$ 41.60	65	$ 49.04
6	$ 7.54	26	$ 28.24	46	$ 42.14	66	$ 49.24
7	$ 8.73	27	$ 29.09	47	$ 42.65	67	$ 49.41
8	$ 9.91	28	$ 29.93	48	$ 43.15	68	$ 49.57
9	$ 11.07	29	$ 30.75	49	$ 43.63	69	$ 49.71
10	$ 12.22	30	$ 31.56	50	$ 44.10	70	$ 49.84
11	$ 13.35	31	$ 32.35	51	$ 44.55	71	$ 49.95
12	$ 14.46	32	$ 33.12	52	$ 44.98	72	$ 50.04
13	$ 15.55	33	$ 33.87	53	$ 45.39	73	$ 50.11
14	$ 16.63	34	$ 34.61	54	$ 45.79	74	$ 50.17
15	$ 17.69	35	$ 35.33	55	$ 46.17	75	$ 50.21
16	$ 18.74	36	$ 36.04	56	$ 46.54	76	$ 50.24
17	$ 19.76	37	$ 36.72	57	$ 46.88	77	$ 50.24
18	$ 20.77	38	$ 37.39	58	$ 47.21	78	$ 50.23
19	$ 21.76	39	$ 38.04	59	$ 47.52	79	$ 50.20
20	$ 22.74	40	$ 38.68	60	$ 47.82	80	$ 50.16

This table shows "cash benefits" for various token orders. For example, let's say you order 10 tokens in a given decision round. That token order will earn you BENEFITS of $12.22. Press -NEXT- to continue.

Study this table carefully. If you have any questions raise your hand and one of the experiment monitors will help you. Note, this table will be readily available to you during the experiment. If you don't have questions, Please press -NEXT-

---

Ordering "tokens" earns you a CASH BENEFIT. BUT, you must pay for all tokens that your order. Press -NEXT- to see how your COSTS are calculated.

TOKEN COSTS

At the beginning of each round, the computer will display a BASE COST for tokens that are ordered in that round.

The BASE COST is the cost of the first token ordered in that round. Each additional token ordered in that round costs $0.01 more than the previous token ordered. The Base Cost in each decision round will equal $0.01.

Assume 30 tokens are ordered by the group in a given decision round. The 1st token costs $0.01. The 2nd token costs $0.02. The 3rd token costs $0.03, and so on, until the 30th token, which costs $0.30.

The TOTAL COSTS to the group for all 30 tokens ordered in that round would thus be:

$0.01+$0.02+...$0.30=$4.65,

for an average token cost of $0.155 per token.

Press -NEXT- for further discussion of TOKEN COSTS
Press -BACK- to Review.

In a decision round, what YOU PAY for tokens that you order equals the number of tokens you order times the Average Token Cost for that round. Further, the Average Token Cost for that round depends on how many tokens you order, as well as how many tokens other individuals order.

In the example just shown, the Average Token Cost was $0,155 per token. Now let's assume you had ordered 6 of the 30 tokens ordered by the group. Your token costs would thus be 6 X $0.155 = $0.930.

In any given decision round, it will always be the case that your Average Token Cost is greater than the Base Cost, but less than the highest token cost in that round. Further, the AVERAGE Token Cost in a round will be the same for each participant. But, the TOTAL Token Cost per round will be different for each participant if participants place orders for a different number of tokens.

Press -NEXT- for more discussion on TOKEN COSTS
Press -BACK- to REVIEW

Each round, the BASE COST for that round will be $0.01 higher than the cost of the LAST token ordered in the previous round. This means that token costs will only GO UP during the experiment, NEVER DOWN. Tokens purchased earlier in the experiment will always be cheaper than tokens purchased later in the experiment.

In the example just discussed, the base cost of tokens in the first round was $0.01 and 30 tokens were ordered. This meant the last (the 30th) token ordered in that round had a cost of $0.30. This means that the base cost in the second round would be:

$0.30+$0.01=$0.31.

Thus, the first token ordered in the second round would cost $0.31. The second would cost $0.32, the third $0.33, etc.

Let's assume that 20 tokens were ordered in the second round, with a base cost of $0.31. This means that the total token cost for that round would be:

$0.31+$0.32+...$0.50=$ 8.10,

with an average token cost of $0.41 per token. Press -NEXT- for more discussion on TOKEN COSTS. Press -BACK- to REVIEW

TOKEN COSTS

Please look at the printed materials you were handed at the beginning of the experiment and find the table labeled "COST OF TOKENS." This table shows how token costs change as more and more tokens are ordered by the group. Starting at the BASE COST for a given decision round each token ordered by the group costs $0.01 more than the previous token.

NOTE: The "average token cost" in a given decision round can easily be computed as:

[(Base Cost)+(Cost of the last Token Ordered in the Round)]/2.

Do you have any questions regarding computing "token costs?" If so raise your hand, otherwise Press -NEXT- to continue the instructions. Or, press -BACK- to review.

FINAL COMMENTS

In each round of the experiment, every participant faces an identical BENEFITS schedule for tokens they order, the same BASE COST for tokens they order, and the same AVERAGE TOKEN COST. Earnings in the experiment may differ between participants because they may place different orders for tokens.

Press -NEXT- to continue "FINAL COMMENTS"
Press -BACK- to review

FINAL COMMENTS "CONTINUED"

NOTICE: The experiment will last up to 10 Rounds. But, if the BASE TOKEN COST ever reaches a level at which individuals cannot earn a positive profit in subsequent rounds, the experiment will end.

At the beginning of each round, you will be informed of the BASE COST for that round and asked to enter a "TOKEN ORDER" on the computer. After all participants have placed an order, the computer will tabulate orders, compute token benefits and token costs, and then inform you of:

1) the total number of tokens ordered by the group,
2) the average token cost for the round,
3) your total BENEFITS for the round,
4) your total COSTS for the round, and
5) your total PROFITS for the round.

Press -NEXT- for a Practice Example. Press -BACK- to Review

PRACTICE EXAMPLES:

The practice examples are designed to insure that you understand how BENEFITS AND TOKENS COSTS are computed. Please turn to the "blue" handout entitled "PRACTICE EXAMPLES." Please complete this "questionnaire" and then raise your hand. Or, if you have any questions on how to complete the questionnaire, raise your hand.

For your use, a copy of the "BENEFITS" table and the "TOKEN COSTS" table are also included in your packet. When you have completed your practice examples and have had them checked by an experimenter:

Press -NEXT- to see a summary of "experimental procedures," or Press -BACK- if you wish to review any part of the instructions.

EXPERIMENTAL PROCEDURES and CONSEQUENCES: A SUMMARY

1) At the beginning of a decision round, the BASE TOKEN COST will be displayed to each individual. The Base Cost is the cost of the first token sold in that round AND IS THE SAME FOR ALL PARTICIPANTS. Each additional token costs $0.01 more than the previous token.

2) At the beginning of each round, each individual will place a token order. The more tokens an individual orders the greater the AVERAGE TOKEN COST to that individual and to ALL OTHER INDIVIDUALS.

3) Tokens cannot be carried over to future rounds.

4) The computer will total all token orders, compute the "average token cost", and then compute the "total token cost" for each individual.

5) The computer will then display: (1) the group's total token order for that round, (2) each individual's own average and total token costs for that round, (3) each individual's own total benefits, total costs, and total profits for that round, and (4) each individual's own profits totaled over all decision rounds.

IF YOU HAVE ANY QUESTIONS - RAISE YOUR HAND. OTHERWISE, PRESS -NEXT- TO PROCEED.

Handouts Given to Subjects in Time-Dependent Designs

CONSENT FORM

This experiment is one in a series of experiments being conducted to investigate individual decision making. Funding for this experiment has been provided by several agencies of the Federal Government.

Having reviewed the instructions for this experiment, we are required by Indiana University procedures to record your formal consent to participate in this experiment.

Your participation in the experiment involves making investment decisions as described in the instructions. At the end of the experiment, you will be paid your earnings privately in cash. Your individual decisions will remain anonymous to the group. Your identity will never be identified as part of the published results from this experiment. The experiment is expected to last from one to two hours.

If you have any questions concerning the experiment please feel free to ask the experimenter. Your participation is voluntary. If you wish not to participate, please inform the experimenter now. Otherwise, please sign the consent statement below.

I have received a copy of this consent form. My participation in this research study is completely voluntary. I may choose not to participate or may withdraw at any time without prejudice concerning any future contact I may have with any of the researchers. I wish to participate in this experiment:

Signed__________________________Date________________________

If you wish further information concerning this experiment, contact:

James M. Walker	Roy Gardner
Dept. of Economics	Dept. of Economics
Ballantine 805	Ballantine 822
Phone: 855-2760	Phone: 855-8974

If you have questions regarding your rights as a subject, contact:

Research Risk Office
Human Subjects Committee
Bryan 10
Bloomington, Indiana 47405
Phone: 855-3067

BENEFITS TABLE - TDN2

This Table Displays Total Benefits for Various Token Orders

TOKs	BENs		TOKs	BENs
1	$ 1.30		21	$ 23.70
2	$ 2.58		22	$ 24.64
3	$ 3.84		23	$ 25.56
4	$ 5.09		24	$ 26.47
5	$ 6.32		25	$ 27.36
6	$ 7.54		26	$ 28.24
7	$ 8.73		27	$ 29.09
8	$ 9.91		28	$ 29.93
9	$ 11.07		29	$ 30.75
10	$ 12.22		30	$ 31.56
11	$ 13.35		31	$ 32.35
12	$ 14.46		32	$ 33.12
13	$ 15.55		33	$ 33.87
14	$ 16.63		34	$ 34.61
15	$ 17.69		35	$ 35.33
16	$ 18.74		36	$ 36.04
17	$ 19.76		37	$ 36.72
18	$ 20.77		38	$ 37.39
19	$ 21.76		39	$ 38.04
20	$ 22.74		40	$ 38.68

TOKs	BENs		TOKs	BENs
41	$ 39.30		61	$ 48.10
42	$ 39.90		62	$ 48.36
43	$ 40.48		63	$ 48.60
44	$ 41.05		64	$ 48.83
45	$ 41.60		65	$ 49.04
46	$ 42.14		66	$ 49.24
47	$ 42.65		67	$ 49.41
48	$ 43.15		68	$ 49.57
49	$ 43.63		69	$ 49.71
50	$ 44.10		70	$ 49.84
51	$ 44.55		71	$ 49.95
52	$ 44.98		72	$ 50.04
53	$ 45.39		73	$ 50.11
54	$ 45.79		74	$ 50.17
55	$ 46.17		75	$ 50.21
56	$ 46.54		76	$ 50.24
57	$ 46.88		77	$ 50.24
58	$ 47.21		78	$ 50.23
59	$ 47.52		79	$ 50.20
60	$ 47.82		80	$ 50.16

BENEFITS TABLE - TDN5

This Table Displays Total Benefits for Various Token Orders

TOKs	BENs		TOKs	BENs	TOKs	BENs		TOKs	BENs
1	$ 4.00		21	$ 46.10	41	$ 16.20			
2	$ 7.81		22	$ 46.31	42	$ 12.81			
3	$ 11.45		23	$ 46.35	43	$ 9.24			
4	$ 14.90		24	$ 46.20	44	$ 5.50			
5	$ 18.18		25	$ 45.87	45	$ 1.58			
6	$ 21.27		26	$ 45.37	46	$ -2.53			
7	$ 24.19		27	$ 44.68	47	$ -6.81			
8	$ 26.92		28	$ 43.82	48	$-11.28			
9	$ 29.48		29	$ 42.78	49	$-15.93			
10	$ 31.85		30	$ 41.55	50	$-20.75			
11	$ 34.05		31	$ 40.15					
12	$ 36.06		32	$ 38.56					
13	$ 37.90		33	$ 36.80					
14	$ 39.55		34	$ 34.85					
15	$ 41.02		35	$ 32.72					
16	$ 42.32		36	$ 30.42					
17	$ 43.43		37	$ 27.93					
18	$ 44.37		38	$ 25.27					
19	$ 45.12		39	$ 22.43					
20	$ 45.70		40	$ 19.40					

COST TABLE

THIS TABLE DISPLAYS THE SPECIFIC COST PER TOKEN FOR TOKENS PURCHASED BY THE GROUP

TOKEN NUMBER (COST)

1 ($0.01)	64 ($0.64)	127 ($1.27)	190 ($1.90)	253 ($2.53)	316 ($3.16)	379 ($3.79)	442 ($4.42)
2 ($0.02)	65 ($0.65)	128 ($1.28)	191 ($1.91)	254 ($2.54)	317 ($3.17)	380 ($3.80)	443 ($4.43)
3 ($0.03)	66 ($0.66)	129 ($1.29)	192 ($1.92)	255 ($2.55)	318 ($3.18)	381 ($3.81)	444 ($4.44)
4 ($0.04)	67 ($0.67)	130 ($1.30)	193 ($1.93)	256 ($2.56)	319 ($3.19)	382 ($3.82)	445 ($4.45)
5 ($0.05)	68 ($0.68)	131 ($1.31)	194 ($1.94)	257 ($2.57)	320 ($3.20)	383 ($3.83)	446 ($4.46)
6 ($0.06)	69 ($0.69)	132 ($1.32)	195 ($1.95)	258 ($2.58)	321 ($3.21)	384 ($3.84)	447 ($4.47)
7 ($0.07)	70 ($0.70)	133 ($1.33)	196 ($1.96)	259 ($2.59)	322 ($3.22)	385 ($3.85)	448 ($4.48)
8 ($0.08)	71 ($0.71)	134 ($1.34)	197 ($1.97)	260 ($2.60)	323 ($3.23)	386 ($3.86)	449 ($4.49)
9 ($0.09)	72 ($0.72)	135 ($1.35)	198 ($1.98)	261 ($2.61)	324 ($3.24)	387 ($3.87)	450 ($4.50)
10 ($0.10)	73 ($0.73)	136 ($1.36)	199 ($1.99)	262 ($2.62)	325 ($3.25)	388 ($3.88)	451 ($4.51)
11 ($0.11)	74 ($0.74)	137 ($1.37)	200 ($2.00)	263 ($2.63)	326 ($3.26)	389 ($3.89)	452 ($4.52)
12 ($0.12)	75 ($0.75)	138 ($1.38)	201 ($2.01)	264 ($2.64)	327 ($3.27)	390 ($3.90)	453 ($4.53)
13 ($0.13)	76 ($0.76)	139 ($1.39)	202 ($2.02)	265 ($2.65)	328 ($3.28)	391 ($3.91)	454 ($4.54)
14 ($0.14)	77 ($0.77)	140 ($1.40)	203 ($2.03)	266 ($2.66)	329 ($3.29)	392 ($3.92)	455 ($4.55)
15 ($0.15)	78 ($0.78)	141 ($1.41)	204 ($2.04)	267 ($2.67)	330 ($3.30)	393 ($3.93)	456 ($4.56)
16 ($0.16)	79 ($0.79)	142 ($1.42)	205 ($2.05)	268 ($2.68)	331 ($3.31)	394 ($3.94)	457 ($4.57)
17 ($0.17)	80 ($0.80)	143 ($1.43)	206 ($2.06)	269 ($2.69)	332 ($3.32)	395 ($3.95)	458 ($4.58)
18 ($0.18)	81 ($0.81)	144 ($1.44)	207 ($2.07)	270 ($2.70)	333 ($3.33)	396 ($3.96)	459 ($4.59)
19 ($0.19)	82 ($0.82)	145 ($1.45)	208 ($2.08)	271 ($2.71)	334 ($3.34)	397 ($3.97)	460 ($4.60)
20 ($0.20)	83 ($0.83)	146 ($1.46)	209 ($2.09)	272 ($2.72)	335 ($3.35)	398 ($3.98)	461 ($4.61)
21 ($0.21)	84 ($0.84)	147 ($1.47)	210 ($2.10)	273 ($2.73)	336 ($3.36)	399 ($3.99)	462 ($4.62)
22 ($0.22)	85 ($0.85)	148 ($1.48)	211 ($2.11)	274 ($2.74)	337 ($3.37)	400 ($4.00)	463 ($4.63)
23 ($0.23)	86 ($0.86)	149 ($1.49)	212 ($2.12)	275 ($2.75)	338 ($3.38)	401 ($4.01)	464 ($4.64)
24 ($0.24)	87 ($0.87)	150 ($1.50)	213 ($2.13)	276 ($2.76)	339 ($3.39)	402 ($4.02)	465 ($4.65)
25 ($0.25)	88 ($0.88)	151 ($1.51)	214 ($2.14)	277 ($2.77)	340 ($3.40)	403 ($4.03)	466 ($4.66)
26 ($0.26)	89 ($0.89)	152 ($1.52)	215 ($2.15)	278 ($2.78)	341 ($3.41)	404 ($4.04)	467 ($4.67)
27 ($0.27)	90 ($0.90)	153 ($1.53)	216 ($2.16)	279 ($2.79)	342 ($3.42)	405 ($4.05)	468 ($4.68)
28 ($0.28)	91 ($0.91)	154 ($1.54)	217 ($2.17)	280 ($2.80)	343 ($3.43)	406 ($4.06)	469 ($4.69)
29 ($0.29)	92 ($0.92)	155 ($1.55)	218 ($2.18)	281 ($2.81)	344 ($3.44)	407 ($4.07)	470 ($4.70)
30 ($0.30)	93 ($0.93)	156 ($1.56)	219 ($2.19)	282 ($2.82)	345 ($3.45)	408 ($4.08)	471 ($4.71)
31 ($0.31)	94 ($0.94)	157 ($1.57)	220 ($2.20)	283 ($2.83)	346 ($3.46)	409 ($4.09)	472 ($4.72)
32 ($0.32)	95 ($0.95)	158 ($1.58)	221 ($2.21)	284 ($2.84)	347 ($3.47)	410 ($4.10)	473 ($4.73)
33 ($0.33)	96 ($0.96)	159 ($1.59)	222 ($2.22)	285 ($2.85)	348 ($3.48)	411 ($4.11)	474 ($4.74)
34 ($0.34)	97 ($0.97)	160 ($1.60)	223 ($2.23)	286 ($2.86)	349 ($3.49)	412 ($4.12)	475 ($4.75)
35 ($0.35)	98 ($0.98)	161 ($1.61)	224 ($2.24)	287 ($2.87)	350 ($3.50)	413 ($4.13)	476 ($4.76)
36 ($0.36)	99 ($0.99)	162 ($1.62)	225 ($2.25)	288 ($2.88)	351 ($3.51)	414 ($4.14)	477 ($4.77)
37 ($0.37)	100 ($1.00)	163 ($1.63)	226 ($2.26)	289 ($2.89)	352 ($3.52)	415 ($4.15)	478 ($4.78)
38 ($0.38)	101 ($1.01)	164 ($1.64)	227 ($2.27)	290 ($2.90)	353 ($3.53)	416 ($4.16)	479 ($4.79)
39 ($0.39)	102 ($1.02)	165 ($1.65)	228 ($2.28)	291 ($2.91)	354 ($3.54)	417 ($4.17)	480 ($4.80)
40 ($0.40)	103 ($1.03)	166 ($1.66)	229 ($2.29)	292 ($2.92)	355 ($3.55)	418 ($4.18)	481 ($4.81)
41 ($0.41)	104 ($1.04)	167 ($1.67)	230 ($2.30)	293 ($2.93)	356 ($3.56)	419 ($4.19)	482 ($4.82)
42 ($0.42)	105 ($1.05)	168 ($1.68)	231 ($2.31)	294 ($2.94)	357 ($3.57)	420 ($4.20)	483 ($4.83)
43 ($0.43)	106 ($1.06)	169 ($1.69)	232 ($2.32)	295 ($2.95)	358 ($3.58)	421 ($4.21)	484 ($4.84)
44 ($0.44)	107 ($1.07)	170 ($1.70)	233 ($2.33)	296 ($2.96)	359 ($3.59)	422 ($4.22)	485 ($4.85)
45 ($0.45)	108 ($1.08)	171 ($1.71)	234 ($2.34)	297 ($2.97)	360 ($3.60)	423 ($4.23)	486 ($4.86)
46 ($0.46)	109 ($1.09)	172 ($1.72)	235 ($2.35)	298 ($2.98)	361 ($3.61)	424 ($4.24)	487 ($4.87)
47 ($0.47)	110 ($1.10)	173 ($1.73)	236 ($2.36)	299 ($2.99)	362 ($3.62)	425 ($4.25)	488 ($4.88)
48 ($0.48)	111 ($1.11)	174 ($1.74)	237 ($2.37)	300 ($3.00)	363 ($3.63)	426 ($4.26)	489 ($4.89)
49 ($0.49)	112 ($1.12)	175 ($1.75)	238 ($2.38)	301 ($3.01)	364 ($3.64)	427 ($4.27)	490 ($4.90)
50 ($0.50)	113 ($1.13)	176 ($1.76)	239 ($2.39)	302 ($3.02)	365 ($3.65)	428 ($4.28)	491 ($4.91)
51 ($0.51)	114 ($1.14)	177 ($1.77)	240 ($2.40)	303 ($3.03)	366 ($3.66)	429 ($4.29)	492 ($4.92)
52 ($0.52)	115 ($1.15)	178 ($1.78)	241 ($2.41)	304 ($3.04)	367 ($3.67)	430 ($4.30)	493 ($4.93)
53 ($0.53)	116 ($1.16)	179 ($1.79)	242 ($2.42)	305 ($3.05)	368 ($3.68)	431 ($4.31)	494 ($4.94)
54 ($0.54)	117 ($1.17)	180 ($1.80)	243 ($2.43)	306 ($3.06)	369 ($3.69)	432 ($4.32)	495 ($4.95)
55 ($0.55)	118 ($1.18)	181 ($1.81)	244 ($2.44)	307 ($3.07)	370 ($3.70)	433 ($4.33)	496 ($4.96)
56 ($0.56)	119 ($1.19)	182 ($1.82)	245 ($2.45)	308 ($3.08)	371 ($3.71)	434 ($4.34)	497 ($4.97)
57 ($0.57)	120 ($1.20)	183 ($1.83)	246 ($2.46)	309 ($3.09)	372 ($3.72)	435 ($4.35)	498 ($4.98)
58 ($0.58)	121 ($1.21)	184 ($1.84)	247 ($2.47)	310 ($3.10)	373 ($3.73)	436 ($4.36)	499 ($4.99)
59 ($0.59)	122 ($1.22)	185 ($1.85)	248 ($2.48)	311 ($3.11)	374 ($3.74)	437 ($4.37)	500 ($5.00)
60 ($0.60)	123 ($1.23)	186 ($1.86)	249 ($2.49)	312 ($3.12)	375 ($3.75)	438 ($4.38)	
61 ($0.61)	124 ($1.24)	187 ($1.87)	250 ($2.50)	313 ($3.13)	376 ($3.76)	439 ($4.39)	
62 ($0.62)	125 ($1.25)	188 ($1.88)	251 ($2.51)	314 ($3.14)	377 ($3.77)	440 ($4.40)	
63 ($0.63)	126 ($1.26)	189 ($1.89)	252 ($2.52)	315 ($3.15)	378 ($3.78)	441 ($4.41)	

PRACTICE EXAMPLES

These examples are for illustrative purposes only. The numbers used in the example have been chosen to simplify the illustration.

EXAMPLE 1:

Assume you are in the 4th Round of the Experiment and by the end of the 3rd Round the group had ordered a total of 30 Tokens.

Now suppose you place an order for 10 Tokens and the other member of the group orders an additional 14 Tokens - for a total group order of 24 Tokens.

Using the BENEFITS AND COSTS TABLE:

1) What will be your CASH BENEFIT?__________

2) What will be the BASE COST for the first token ordered in this round?__________

3) What will be the AVERAGE TOKEN COST in this round?________

4) What will be YOUR TOTAL TOKEN COSTS this round?__________

5) What would be YOUR PROFIT for this round? __________

EXAMPLE 2:

Assume you are in the 4th Round of the Experiment and by the end of the 3rd Round the group had ordered a total of 120 Tokens.

Now suppose you place an order for 10 Tokens and the other member of the group orders an additional 14 Tokens - for a total group order of 24 Tokens.

Using the BENEFITS AND COSTS TABLE:

1) What will be your CASH BENEFIT?__________

2) What will be the BASE COST for the first token ordered in this round?__________

3) What will be the AVERAGE TOKEN COST in this round?________

4) What will be YOUR TOTAL TOKEN COSTS this round?__________

5) What would be YOUR PROFIT for this round? __________

ARE THERE ANY QUESTIONS?

ENDNOTES

1. In fact, this is the case in four of the five design conditions. In the remaining design condition, the base cost and incremental token cost are set at $0.05.

2. In all but one design condition, subjects had previously participated in an experimental session using the same design condition. The exception is the TIN5-Low design, where no "inexperienced" sessions were conducted. The subjects participating in these experiments were experienced in the TIN5-High design, and were therefore familiar with the general setup of the experiment. The rationale for not reporting the results of the inexperienced sessions is related to the complexity of the decision task facing the subjects. It appears that substantial learning takes place as subjects become more experienced in the decision environment. In general, in experiments with inexperienced subjects, greater variability in token orders is observed.

3. For each experimental session, more subjects were recruited than were actually needed, in case some volunteers did not show. In cases where the number of individuals who showed up exceeded the number needed for the experiment, "over-recruited" subjects were paid $5 to leave without participating in the experiment.

4. Appendix A provides the computerized instructions and handouts used in the time-independent designs. Appendix B provides the same information for the time-dependent designs.

5. In the TDN5 design token orders were limited to the range [0,50]. This is due to the fact that the specific benefit parameters of this design implied that individual token orders larger than 45 would result in negative total benefits.

6. Recall that for the TIN5-Low design, the base cost and cost increment were $0.05 rather than $0.01.

7. The exact probability is $(110{,}056)(^1/_2)^{22}$ and is calculated in the following manner. Define "success" as an observation in which the MSD from the SSPE path is smaller than the MSD from the MAX path. Under the null hypothesis that it is equally likely for either of the two outcomes to result in the smaller MSD, the probability of success (and failure) is 1/2. In our data, success is observed in 16 of the 22 observations. There are 110,056 potential combinations that lead to 16 or more successes in 22 observations. Thus, under the null hypothesis, the probability of observing at least 16 successes is $(110{,}056)(^1/_2)^{22}$.

8. The exact probability is (224)/(59,049) and is calculated in the following manner. Define "success" as an observation in which the MSD of individual token

orders from the MYOP path is smaller than that produced by either of the other two solution paths. Under the null hypothesis that it is equally likely for any of the three solution paths to result in the smallest MSD, the probability of success is 1/3, and the probability of failure is 2/3. In our data, success is observed in 8 of the 10 observations. There 56 potential combinations that lead to 8, 9, or 10 successes in 10 trials. Thus, under the null hypothesis, the probability of observing at least 8 successes is $(1/3)^8(2/3)^2(56) = (224)/(59{,}049)$.

9. In other words, the average observed group payoff is 6.0% the SSPE payoff for TIN2 groups, 4.3% above SSPE for TIN5-High groups, and 23.5% above SSPE for TIN5-Low groups.

10. Given the data reported in Table VI, the Mann-Whitney U statistic in the test between the TIN2 and TIN5-Low designs is $U=5$. In the test between the TIN2 and TIN5-High designs, $U=17$. Finally, in the test between the TIN5-High and TIN5-Low designs, $U=18$.

11. Given the data reported in Table VI, the Mann-Whitney U statistic in the test between the time-dependent and time-independent designs is $U=23$.

CHAPTER 4

An Experimental Study of Group Size Effects in the Commons

I. INTRODUCTION

In many CPR game models, the aggregate equilibrium rent earned from the resource by the group is monotonically decreasing in the number of appropriators (see, for example, Gordon, 1954; Cheung, 1970; and Ostrom, Gardner, and Walker, 1994). In contrast, in the time-independent case of the CPR game model examined in detail in Chapter 2, the aggregate equilibrium rent is increasing in group size, *n*, for *n* sufficiently small. The crucial assumption leading to this result is that individuals receive declining marginal benefits from the resource.

In a CPR setting, the possibility exists that group size can impact individual behavior in ways not captured by the CPR game model discussed in Chapter 2. Indeed, in a setting quite similar to that of a CPR, oligopolistic competition between firms, it is widely argued that the ability of firms to collude is inversely related to group size. For example, Selten (1973) presents a model in which groups of four always form a cartel, while groups of six or more almost never do. As Cheung (1970) notes, the incentive of firms to restrict entry and output in an imperfect market is quite similar to the incentive of CPR appropriators to limit access to, and extraction from, the resource. Furthermore, field studies have shown that successful self-governance of a CPR is more likely to occur with small, as opposed to large, user groups (see Ostrom, 1990).

This chapter examines the impact of group size on individual behavior in an experimental CPR setting. In particular, experiments are conducted using the time-independent setting described in Chapter 3 with groups of size n=3 and n=7. These groups face the same benefit and cost parameters, which are chosen so that equilibrium group payoffs are approximately the same for the two group sizes. If observed payoffs are markedly different for the two group sizes, this would suggest the existence of group size effects not captured by the noncooperative theory as stated.

The remainder of this chapter is organized in the following manner. Section II reviews the important elements of the time-independent game analyzed in Chapter 2 of this dissertation. Section III presents the experimental design and decision setting. Section IV provides laboratory results and discussion. Section V offers concluding comments.

II. **GAME MODEL of a CPR**

Consider a CPR extraction game played by a group of n identical players, indexed by i. Each player i makes a single extraction decision, x_i. The benefits received by player i:

$$B_i(x_i) = ax_i - bx_i^2. \tag{1}$$

Thus, the benefits received by each player are a function of his or her own extraction only. On the other hand, the costs incurred by a player are a function of his or her extraction and the total group extraction. In particular, the cost incurred by player *i* is given by:

$$C_i(x_i,X,c_0) = x_i[c_0 + kX/2], \tag{2}$$

where $X = \Sigma_i x_i$ is the total group extraction and c_0 is the initial cost of extraction. Equations (1) and (2) define a single-period net benefit function for each player:

$$u_i(x_i,X,c_0) = ax_i - bx_i^2 - x_i[c_0 + kX/2]. \tag{3}$$

The optimal solution of the CPR game defined by (3) is the set of extraction levels, $<x_1,x_2,\ldots,x_n>$, that maximizes total group payoff. At the optimal solution of this game, each player i extracts an equal amount, given by:

$$x_i^o = \frac{a - c_0}{2b + nk}. \tag{4}$$

The optimal group resource value, V^o, results when each appropriator extracts at the level given in (4):

$$V^o = \frac{n(a - c_0)^2}{2(2b + nk)}. \tag{5}$$

Each appropriator receives an equal share of the optimal group resource value, $V_i^o = V^o/n$.

The equilibrium solution requires that each appropriator maximize individual payoffs taking the actions of others as given. At the equilibrium of this game, each player i extracts the same amount, given by:

$$x_i^e = \frac{a - c_0}{2b + (n+1)k/2}. \tag{6}$$

A comparison of (5) and (6) shows that for $n > 1$, $x_i^e > x_i^o$. In other words, the equilibrium extraction level exceeds the socially optimal extraction level whenever there are multiple appropriators. The result of this overextraction is a dissipation of potential payoffs from the resource. The equilibrium group resource value, V, results when each appropriator extracts at the level given in (6), as shown below:

$$V^e = \frac{n(2b + k)(a - c_0)^2}{2[2b + (n+1)k/2]^2}. \tag{7}$$

Each appropriator receives an equal share of the equilibrium group resource value, $V_i^e = V^e/n$.

HI. EXPERIMENTAL DESIGN

The experimental environment is designed to capture the essential elements of the game defined by equations (l)-(3). The extraction of players is replaced by token orders of subjects. A subject earns cash benefits based on his or her token order, according to a specified parameterization of equation (1). Similarly, a subject incurs costs based on both his or her own token order and the group token order, according to equation (2). The remainder of this section details the design conditions, parameters, experimental implementation, and decision setting.

Design Conditions and Parameters

A design condition is defined by: (1) the exchange rate used to convert "computer dollars" into U.S. currency; (2) the group size *(n);* and (3) the values of the benefit and cost parameters, (a,b,c_o,k). The benefit and cost parameters are presented in computer dollars, and subjects are explicitly given the exchange rate used to convert their computer earnings into cash. In each design, the group size is either n=3 or n=7. In order to isolate the effect of group size on subject behavior, the same cost and benefit parameters are used in all designs. The parameters are chosen so that the equilibrium group payoff is approximately the same for each group size. This is shown by the equilibrium group payoff curve of Figure 1, which plots the group value of the resource at the equilibrium and optimal solution for various group sizes. Note that the equilibrium group payoffs for n=3 ($21.82) are approximately equal to the equilibrium group payoffs for $n=l$ ($21.66).

Three design conditions are considered: (1) N3a, with a group size of n=3 and an exchange rate of 0.25 (in other words, 1 computer dollar converts to 0.25 U.S. dollars); (2) N3b, with a group size of $n=3$ and an exchange rate of 0.125; (3) and N7, with a group size of $n—7$ and an exchange rate of 0.25. Thus, the only two features distinguishing the three designs are group size (n=3 or n=7) and exchange rate (0.25 or 0.125).[1]

Each design condition involves a total of 30 decision rounds, which are separated into three experimental series of 10 rounds. The same benefit parameters are used in all 30 rounds; however, the cost parameters vary by series. Series 1 (Rounds 1-10) consists of 10 repetitions of the constituent game where the incremental cost parameter and the base token cost for each round are set at $0.01. Series 2 (Rounds 11-20) consists of 10 repetitions of the constituent game with both cost parameters set to $0.02 rather than $0.01.[2] Finally, Series 3 (Rounds 21-30) consists of 10 repetitions of the constituent game with the cost parameters reset to $0.01.

Table I specifies the parameters used in Series 1 and 3 for each design, and Table II contains the same information for Series 2. These tables also give the optimal and equilibrium token orders and payoffs for each design. The payoffs are reported in terms of computer dollars, with the exchange rates given in the last row.

Experimental Implementation and Decision Setting

All experiments were conducted at Indiana University using the NovaNet computer system. Subjects were recruited from undergraduate introductory economics courses. Prior to volunteering, subjects were informed that they would participate in a decision-making experiment that would last approximately 1.5 hours in which they would earn cash based on their decisions and the decisions of others.

The experimental sessions were conducted in the following manner. A sufficient number of subjects were recruited so that two or three groups could participate simultaneously. At the beginning of each session, each subject was assigned to a group without being told the identity of the other group members. Subjects remained in the same group for all 30 decision rounds. Prior to the first decision round, subjects were asked to privately read through a series of computerized instructions and to complete several practice examples.[3] After each subject had successfully completed the examples, all subjects proceeded to the first decision round. Experimenters were available at all times during the experiment to answer questions.

In each decision round, each subject made a single token order, which was restricted to integer values in the range [0,80]. All subjects made token orders simultaneously. Subjects were provided with a benefits table, which presented the total benefits that an individual would receive for each possible token order in the allowable range. Subjects were also explicitly informed of how individual costs would be calculated. The instructions specified that the total cost to a subject in a given round would equal the average token cost in that round multiplied by the number of tokens ordered by the subject and that the average token cost would be a function of the total group token order. Furthermore, the instructions specified the formula used to calculate both the average cost and the total cost incurred by a subject. The benefit and cost values were expressed in terms of "computer dollars," and subjects were given the exchange rate used to convert computer earnings into US dollars.

Subjects were explicitly informed of the number of people in their group, the number of rounds in the series, and that each subject in their group faced the same benefit function and average token cost. Following each decision round, subjects were informed of the total number of tokens ordered by the group, the cost per token, and their own profits for that round.

IV. EXPERIMENTAL RESULTS

The experiments reported in this paper were conducted in two phases. Nine groups participated in Phase I. Each group participated in only one experimental session using a single design condition. A total of three groups participated in each of the three design conditions. Six additional groups participated in Phase II. Three groups participated in N3b design and three in the N7 design; the N3a design was not implemented in Phase II. The subjects participating in Phase II had *not* participated in the Phase I experiments. The primary difference between the two phases is that in Phase II, subjects participated in five practice decision rounds prior to Series 1. Following these practice rounds, Phase II subjects participated in three experimental series of 10 rounds, just as their Phase I counterparts.

The remainder of this section reports the results of the Phase I experiments, followed by the Phase II results. Throughout, the results are presented in the form of summary observations.

Phase I Results

Observation 1-1: The Phase I group payoffs are significantly below the equilibrium group payoff.

Table III displays the Phase I group payoffs. Each individual entry of this table represents the total payoff (in computer dollars) earned by a group over a 10 round series. The ratio of the observed group payoff to the equilibrium group payoff, *r*, is also shown in parentheses next to each group payoff entry. Aggregating over all 30 rounds of the experiment, the mean value of *r* for the N3a, N3b, and N7 groups is 0.93, 0.87, and 0.40, respectively, and, for eight of the nine groups, *r* is less than 1. Using a two-sided Wilcoxon signed-rank test with $\alpha=.01$, one can reject the null hypothesis that *r* equals 1.[4]

In later decision rounds, r tends to increase. In Series 1, the mean value of *r* for N3 groups *(r_{N3})* and for N7 groups *(r_{N7})* are 0.87 and 0.09, respectively, and, for all nine groups, r is less than 1.[5] Meanwhile, in Series 3, r_{N3} and r_{N7} increase to 0.94 and 0.90, and, for two of the nine groups, r exceeds 1. Still, using a two-sided Wilcoxon signed-rank test with $\alpha=.10$, one can reject the null hypothesis that r equals 1 for each of the three series separately.[6]

Observation I-2: In Phase I, r_{N7} is significantly lower than r_{N3}.

Aggregating over all 30 rounds, $r_{N7}=0.40$, compared to $r_{N3}=0.90$. Clearly, Group 1 of the N7 design, which *lost* \$125.10 in computer dollars over the course of the experiment, contributed heavily to the low value of r_{N7}.[7] However, even excluding this group, the combined value of r_{N7} for the two remaining groups is only 0.72, which is still well below r_{N3}. Using a two-sided Mann-Whitney test with $\alpha=.05$, one can reject the null hypothesis that r_{N7} and r_{N3} are equal.[8]

The difference between r_{N3} and r_{N7} diminishes with experience. Aggregating over Series 1 and 2, $r_{N7}=.05$ (0.65 excluding Group 1), compared to $r_{N3}=0.88$. In contrast, in Series 3, the mean values of r_{N7} and r_{N3} are nearly equal (0.90 vs 0.94). Using a two-sided Mann-Whitney test with a=.10, one *cannot* reject the null hypothesis that r_{N7} and r_{N3} are equal for Series 2 and 3.[9]

Observation I-3: Contrary to the equilibrium prediction, the per round mean token order of the N3 individuals is less than that of the N7 individuals in each of the first five decision rounds of Phase I.

As shown in Tables I and II, the equilibrium individual token order in the N3 designs exceeds that of the N7 designs. However, Figure 2, which plots the mean token orders of the N3 and N7 individuals in the Phase I experiments, shows that the mean token order of the N3 individuals *is less than* that of the N7 individuals in each of the first five rounds.[10] Furthermore, using a two-sided Mann-Whitney test with $\alpha = .05$, one can reject the null hypothesis that the token orders of the N3 and N7 individuals are equal in Rounds 1 and 2.[11] In all rounds after Round 5, the mean token order for the N3 individuals exceeds that of the N7 individuals in each round, suggesting that, with experience, subjects learn to make decisions that are more consistent with the equilibrium prediction.

Observation I-4: In Phase I, the mean individual token orders of both the N3 and the N7 individuals tend toward the equilibrium token order with experience, but from different directions. The mean N3 token order approaches equilibrium from below, while the mean N7 token order approaches it from above.

Figure 3, which plots the deviation of the mean token orders of the N3 and N7 individuals from the corresponding equilibrium token order, shows that the mean token order of the N3 individuals is *below* the equilibrium order in each of the first 13 rounds and in 18 of the first 20 rounds. In contrast, the mean token order of the N7 individuals is *above* the equilibrium token order in each of the first 11 rounds and in 17 of the first 20 rounds. Under the null hypothesis that it is equally likely for the mean token order in any round to be above or below the equilibrium, the probability of observing the mean greater than the equilibrium in 18 or more rounds out of 20 is approximately .0002, while the probability of observing the mean less than the equilibrium in 17 or more rounds out of 20 is approximately .0013.[12] Thus, in the first 20 rounds of the experiment, the token orders of the N3 individuals relative to the equilibrium prediction is markedly different than that of the N7 individuals. In the final 10 rounds of the experiment, this contrast between the token orders of the N3 and N7 individuals is not observed.

Summary of Phase I Experimental Results

In Phase I, the N7 group payoffs are significantly lower, relative to the equilibrium prediction, than the N3 group payoffs. It appears that the first five decision rounds play a crucial role in this difference in payoffs. In these five rounds, the mean token order of the N7 individuals *exceeds* that of the N3 individuals, contrary to the equilibrium prediction. As a result of the large token orders of the N7 individuals, the three N7 groups combined for *negative* earnings of $99.87 in computer dollars in the first five rounds. In the remaining five rounds of Series 1, these three groups combined for *positive* earnings of $155.37. In contrast, in Rounds 1-5 and 6-10, the N3 groups earned $280.35 and $237.28, respectively.[13] It is possible that the initial negative earnings impact the individual decisions of group members in later rounds. In particular, subjects may attempt to "make up" for initial losses through higher token orders. The Phase II experiments were conducted to address this possibility.

Phase II results

In the Phase II sessions, subjects played five practice rounds prior to Series 1. They were informed that the computer payoffs earned or lost in these practice rounds would *not* be added to, or deducted from, the payoffs earned in the rest of the experiment. The parameters used in Phase II were identical to those used in the Phase I sessions. Series 1 parameters were used in the five practice rounds. In the remainder of this section, the results of the Phase II experiments are presented in a manner that is parallel with the presentation of the Phase I results. In particular, Observations II-1, II-2, II-3, and II-4 from the Phase II experiments correspond directly to Observations I-1, I-2, I-3, and I-4 from the Phase I experiments.

Observation II-1: The Phase II group payoffs are significantly below the equilibrium group payoff.[14]

Table IV displays the Phase II group payoffs and corresponding values of r. Aggregating over all 30 rounds of the experiment, r_{N3} and r_{N7} are 0.81 and 0.87, respectively, and, for five of the six groups, r is less than 1. Using a two-sided Wilcoxon signed-rank test with α=. 10, one can reject the null hypothesis that r equals 1.[15] The value of r tends to increase in the later decision rounds. In Series 1, r_{N3} and r_{N7} are 0.75 and 0.74; meanwhile, in Series 3, r_{N3} and r_{N7} are 0.89 and 0.92. Using a two-sided Wilcoxon signed-rank test with α=. 10, one can reject the null hypothesis that r equals 1 for Series 1 and 3, but not for Series 2.[16]

The observation of payoffs below the equilibrium payoff level is consistent with the results of Phase I. Combining the results of the two phases provides strong evidence that observed payoffs are significantly below the equilibrium levels. Using a two-sided Wilcoxon signed-rank test with α=.01, one can reject the null hypothesis that the cumulative value of r over 30 rounds equals one for the pooled Phase I and Phase II data.[17] Furthermore, using a Wilcoxon signed-rank test with a=.05, one can reject the null hypothesis that r equals 1, for each individual series separately.[18] Thus, one robust result from the Phase I and II experiments is that the observed payoffs are significantly below the equilibrium payoffs predicted by noncooperative game theory.

Observation II-2: In Phase II, r_{N7} groups is slightly higher than r_{N3}.

Aggregating over all 30 rounds, r_{N3} and r_{N7} are 0.81 and 0.87; thus, relative to the equilibrium prediction, N7 group payoffs are slightly higher than N3 group payoffs in Phase II. This is in contrast to Phase I, where N7 group payoffs are *significantly lower* than N3 group payoffs. On average, N7 payoffs are *substantially higher* in Phase II than Phase I ($456.22 vs. $211.05),[19] while N3 payoffs are *slightly lower* in Phase II than Phase I ($452.47 vs. $506.96).

Table V displays the Phase I and Phase II payoffs by series. It is interesting to note that the mean payoffs earned by N7 groups in the five practice rounds of Phase II (-$62.77) are comparable to those earned by N7 groups in the first five rounds of Series 1 in Phase I (-$33.29). However, in the decision rounds that count, N7 group payoffs are substantially higher in Phase II than in Phase I.

<u>Observation II-3</u>: The mean token order of the N3 individuals exceeds the mean token order of the N7 individuals in every non-practice round of Phase II.

Figure 4 plots the mean individual token orders for the N3 and N7 individuals in the Phase II experiments. Recall that in Phase I, the mean token order of the N3 individuals is less than that of the N7 individuals in each of the first five rounds. In contrast, Figure 4 shows that in Phase II, the mean token order of the N3 individuals exceeds that of the N7 individuals in all non-practice rounds. However, it is interesting to note that in two of the five practice rounds of Phase II, the mean token order of the N3 individuals is less than that of the N7 individuals. In this respect, individual behavior observed in the five practice rounds of Phase II is similar to the behavior observed in the first five rounds of Phase I.

Observation 11-4: In Phase II, the mean token order of both the N3 and the N7 individuals tends toward the equilibrium token order with experience. However, in contrast to Phase I, the mean token orders do not appear to approach the equilibrium from any particular direction.

Figure 5, which plots the deviation of the mean individual token orders of the N3 and N7 individuals from the corresponding equilibrium token order, shows that the mean token orders of the N3 and N7 individuals vary both above and below the equilibrium. The mean N3 (N7) token order is below the equilibrium in 5 (5) of the 10 rounds of Series 1, in 7 (6) of the 10 rounds of Series 2, and in 7 (6) of the 10 rounds of Series 3. Thus, in Phase II, there is no distinguishable trend in the direction of the deviation of individual token orders from the equilibrium. This is in contrast to Phase I, in which the mean token order for the N3 individuals is *below* the equilibrium in each of the first 13 rounds, and the mean token order of the N7 individuals is *above* the equilibrium in each of the first 11 rounds. However, in the five practice rounds, a pattern similar to that of Phase I is observed. The mean token order of the N3 individuals is *below* the equilibrium, and the mean token order of the N7 individuals *above* the equilibrium, in each of the five practice rounds.

Summary of Phase II Experimental Results

In Phase II, the N7 group payoffs are slightly higher than the N3 group payoffs. This is in contrast to Phase I, where the N7 group payoffs are significantly lower than the N3 group payoffs. The individual token orders and group payoffs observed in the five practice rounds of Phase II are similar to those observed in the first five rounds of the N7 sessions of Phase I. However, the fact that the losses resulting from these practice rounds were forgiven appears to have enabled N7 groups to earn substantially higher cumulative payoffs in Phase II than in Phase I. In contrast, the practice rounds seemed to have little impact on N3 payoffs and individual token orders. The N3 group payoffs are slightly lower in Phase II than in Phase I.

V. CONCLUSIONS

The primary goal of this chapter is to examine whether, in an experimental common-pool resource setting, group size impacts behavior in ways not captured by the noncooperative game theoretic analysis of Chapter 2.

Laboratory experiments are conducted in which groups of size $n=3$ (N3) and $n=7$ (N7) face the same parametric conditions. The experiments yield several important results. First, the observed group payoffs of both group sizes are significantly below the predicted equilibrium payoffs. Although payoffs do increase with experience, they remain significantly below the equilibrium level even in later rounds. Because both N3 groups and N7 groups earn payoffs below the equilibrium prediction, these results provide little support for the notion that small groups are likely to coordinate on cooperative strategies to improve payoffs above those predicted by noncooperative game theory.[20]

In the Phase I experiments, N7 groups earn significantly lower payoffs than

N3 groups. This is due, in part, to negative payoffs earned in the first five rounds of the experiment. Nevertheless, the relative to equilibrium payoffs, the mean group payoffs for N7 groups are lower than those of N3 groups in each of the three experimental series. This difference in payoffs between N7 and N3 groups vanishes in Phase II, where subjects participate in five practice rounds prior to Series 1. In fact, in Phase II, N7 groups earn slightly higher payoffs than N3 groups. The practice rounds seem to help N7 groups to earn higher payoffs, but have little effect on the payoffs of N3 groups.

Although the token orders of the N7 and N3 individuals relative to the equilibrium prediction differ substantially in the initial rounds of the experiment, the results of these experiments generally suggest that no significant group size effects exist once subjects gain sufficient experience. In the later rounds of the experiment, the aggregate token orders and efficiencies of both N3 and N7 groups closely follow the equilibrium prediction.

Table I
Experimental Design for Rounds 1-10 and 21-30

Specification	Design Condition		
	N3a	N3b	N7
Benefits ($ax-bx^2$)	a = 0.8675 b = 0.00875	same	same
Incremental and Base Cost	0.01	same	same
Optimal Token Order	18.16	18.16	9.86
Optimal Payoff [1]	G = \$23.49 I = \$7.83	G = \$23.49 I = \$7.83	G = \$29.75 I = \$4.25
Equilibrium Token Order	23	23	15
Equilibrium Payoff	G = \$21.82 I = \$7.27	G = \$21.82 I = \$7.27	G = \$21.66 I = \$3.09
Equilibrium Efficiency	92.9%	92.9%	72.8%
Exchange Rates	0.25	0.125	0.25

[1] G = Group Payoffs per round; I = G/n = Individual Payoffs per round. All payoffs are in computer dollars per round. To calculate the corresponding payoffs in U.S. currency, multiply by the appropriate exchange rate, which is given on the bottom row of this table.

Table II
Experimental Design for Rounds 11-20

Specification	Design Condition		
	N3a	N3b	N7
Benefits ($ax-bx^2$)	a = 0.8675 b = 0.00875	same	same
Incremental and Base Cost	0.02	same	same
Optimal Token Order	11.06	11.06	5.44
Optimal Payoff [1]	G = \$14.23 I = \$4.74	G = \$14.23 I = \$4.74	G = \$16.34 I = \$2.33
Equilibrium Token Order	14.91	14.91	8.79
Equilibrium Payoff	G = \$12.43 I = \$4.14	G = \$12.43 I = \$4.14	G = \$9.37 I = \$1.34
Equilibrium Efficiency	87.3%	87.3%	57.4%
Exchange Rates	0.25	0.125	0.25

[1] G = Group Payoffs per round; I = G/n = Individual Payoffs per round. All payoffs are in computer dollars per round. To calculate the corresponding payoffs in U.S. currency, multiply by the appropriate exchange rate, which is given on the bottom row of this table.

Table III
Phase I: Group Payoffs

Design Condition	Group	Series 1: Rounds 1-10	Series 2: Rounds 11-20	Series 3: Rounds 21-30	Cumulative: Rounds 1-30
N3a	1	$211.66 (.97)	$99.56 (.80)	$194.55 (.89)	$505.77 (.90)
	2	$215.92 (.99)	$133.22 (1.07)	$208.42 (.96)	$557.56 (.99)
	3	$195.08 (.89)	$114.11 (.92)	$197.90 (.91)	$507.90 (.91)
	Mean	$207.55 (.95)	$115.63 (.93)	$200.29 (.92)	$523.47 (.93)
N3b	1	$147.10 (.67)	$58.82 (.47)	$192.52 (.88)	$398.44 (.71)
	2	$207.55 (.95)	$134.96 (1.09)	$228.66 (1.05)	$571.17 (1.02)
	3	$163.48 (.75)	$127.79 (1.03)	$210.45 (.96)	$501.72 (.89)
	Mean	$172.71 (.79)	$107.19 (0.86)	$210.54 (.96)	$490.44 (.87)
Combined N3 Mean		$190.13 (.87)	$111.41 (.90)	$205.42 (.94)	$506.96 (.90)
N7	1	-$213.43 (-.99)	-$142.96 (-1.53)	$231.29 (1.07)	-$125.10 (-.24)
	2	$158.13 (.73)	$76.17 (.81)	$152.50 (.70)	$386.80 (.73)
	3	$110.80 (.51)	$58.17 (.62)	$202.48 (.93)	$371.45 (.70)
	Mean	$18.50 (.09)	-$2.87 (-.03)	$195.42 (.90)	$211.05 (.40)
Equilibrium (N=3)		$218.20	$124.30	$218.20	$560.70
Equilibrium (N=7)		$216.60	$93.70	$216.60	$526.90

Table IV
Phase II: Group Payoffs

Design	Group	Practice: Rounds P1-P5	Series 1: Rounds 1-10	Series 2: Rounds 11-20	Series 3: Rounds 21-30	Cumulative: Rounds 1-30
N3	1	$64.46 (.59)	$109.15 (.50)	$55.45 (.45)	$164.47 (.75)	$329.07 (.59)
	2	$97.77 (.90)	$217.79 (1.00)	$124.03 (1.00)	$217.78 (1.00)	$559.60 (1.00)
	3	$105.82 (.97)	$162.99 (.75)	$105.24 (.85)	$200.49 (.92)	$468.72 (.84)
	Mean	$89.35 (.82)	$163.31 (.75)	$94.91 (.76)	$194.25 (.89)	$452.47 (.81)
N7	1	-$80.01 (-.74)	$75.14 (.35)	$75.60 (.81)	$193.01 (.89)	$343.75 (.65)
	2	-$26.04 (-.24)	$209.88 (.97)	$101.62 (1.08)	$217.64 (1.00)	$529.14 (1.00)
	3	-$82.26 (-.76)	$195.77 (.90)	$111.73 (1.19)	$188.28 (.93)	$495.78 (.94)
	Mean	-$62.77 (-.58)	$160.26 (.74)	$96.32 (1.03)	$199.64 (.92)	$456.22 (.87)
Equilibrium (N=3)		$109.10	$218.20	$124.30	$218.20	$560.70
Equilibrium (N=7)		$108.30	$216.60	$93.70	$216.60	$526.90

Table V
Comparison of Phase I and II Group Payoffs

Rounds of Comparison	N=3		N=7	
	Phase I	Phase II	Phase I	Phase II
Phase I: Rounds 1-5 vs. Phase II: Practice Rounds	$93.45 (.86)	$89.35 (.82)	-$33.29 (-.31)	-$62.77 (-.58)
Phase I: Series 1 vs. Phase II: Series 1	$190.13 (.87)	$163.31 (.75)	$18.50 (.09)	$160.26 (.74)
Phase I: Series 2 vs. Phase II, Series 2	$111.41 (.90)	$94.91 (.76)	-$2.87 (-.03)	$96.32 (1.03)
Phase I: Series 3 vs. Phase II: Series 3	$205.42 (.94)	$194.25 (.92)	$195.42 (.90)	$199.64 (.92)
Phase I: Series 1-3 vs. Phase II: Series 1-3	$506.96 (.90)	$452.47 (.81)	$211.05 (.40)	$456.22 (.87)

Figure 1

Optimal and Equilibrium Group Payoffs as a Function of n

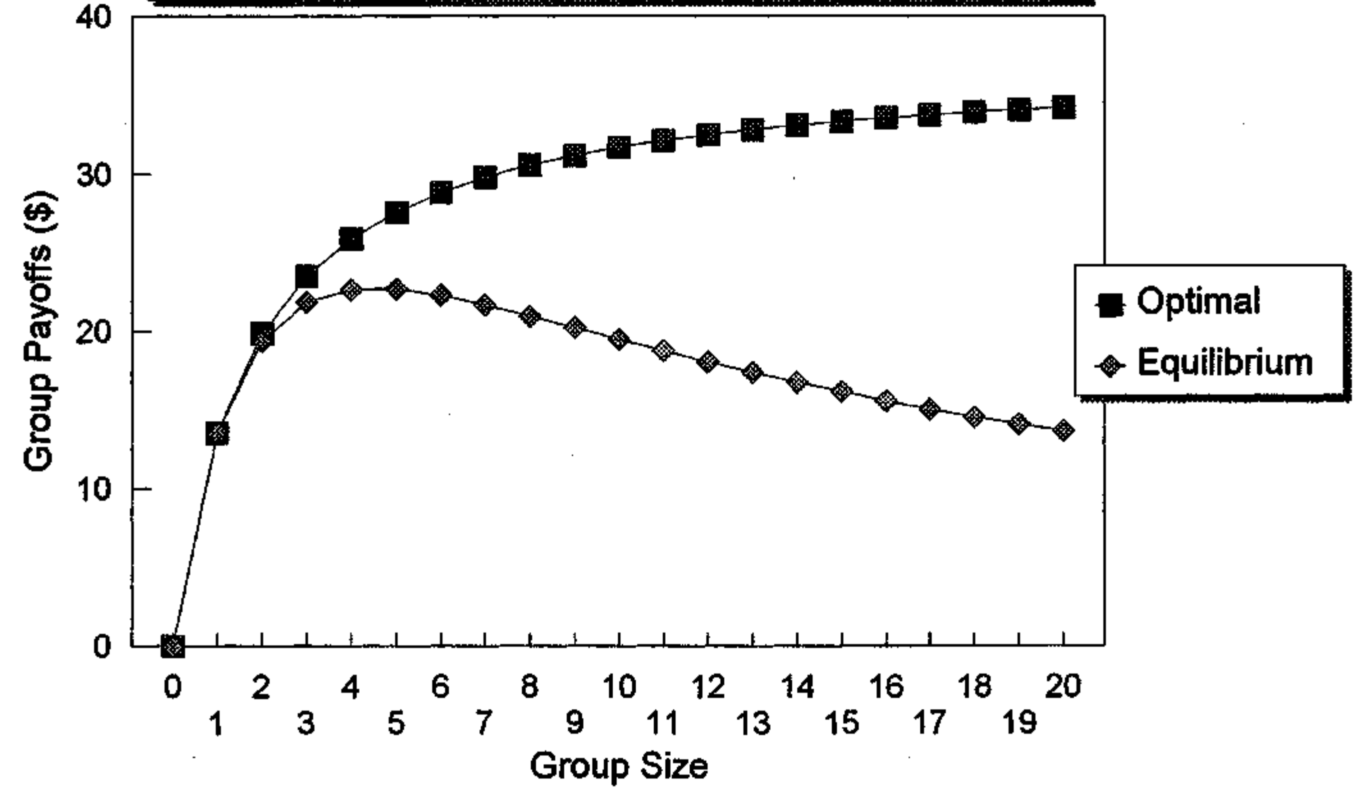
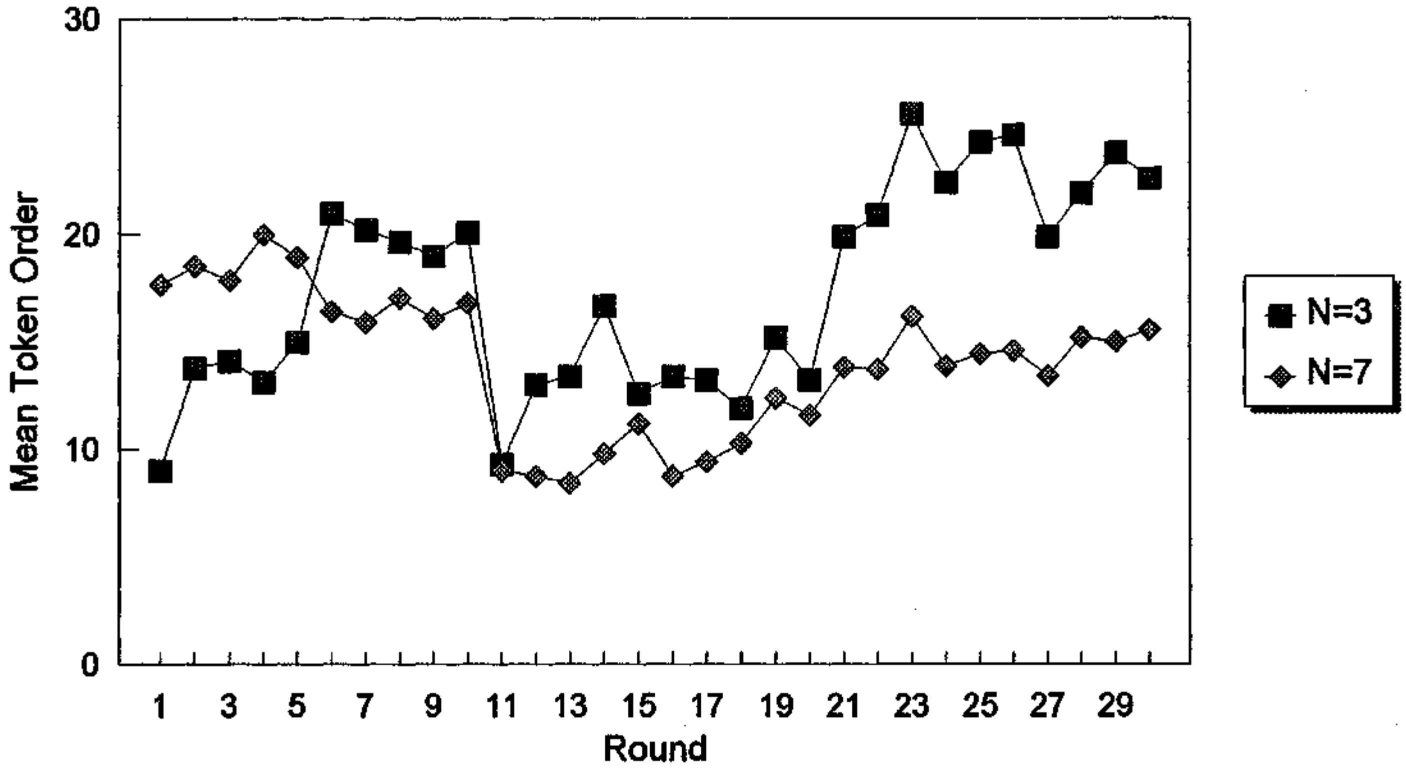


Figure 2

Phase I: Mean Token Orders



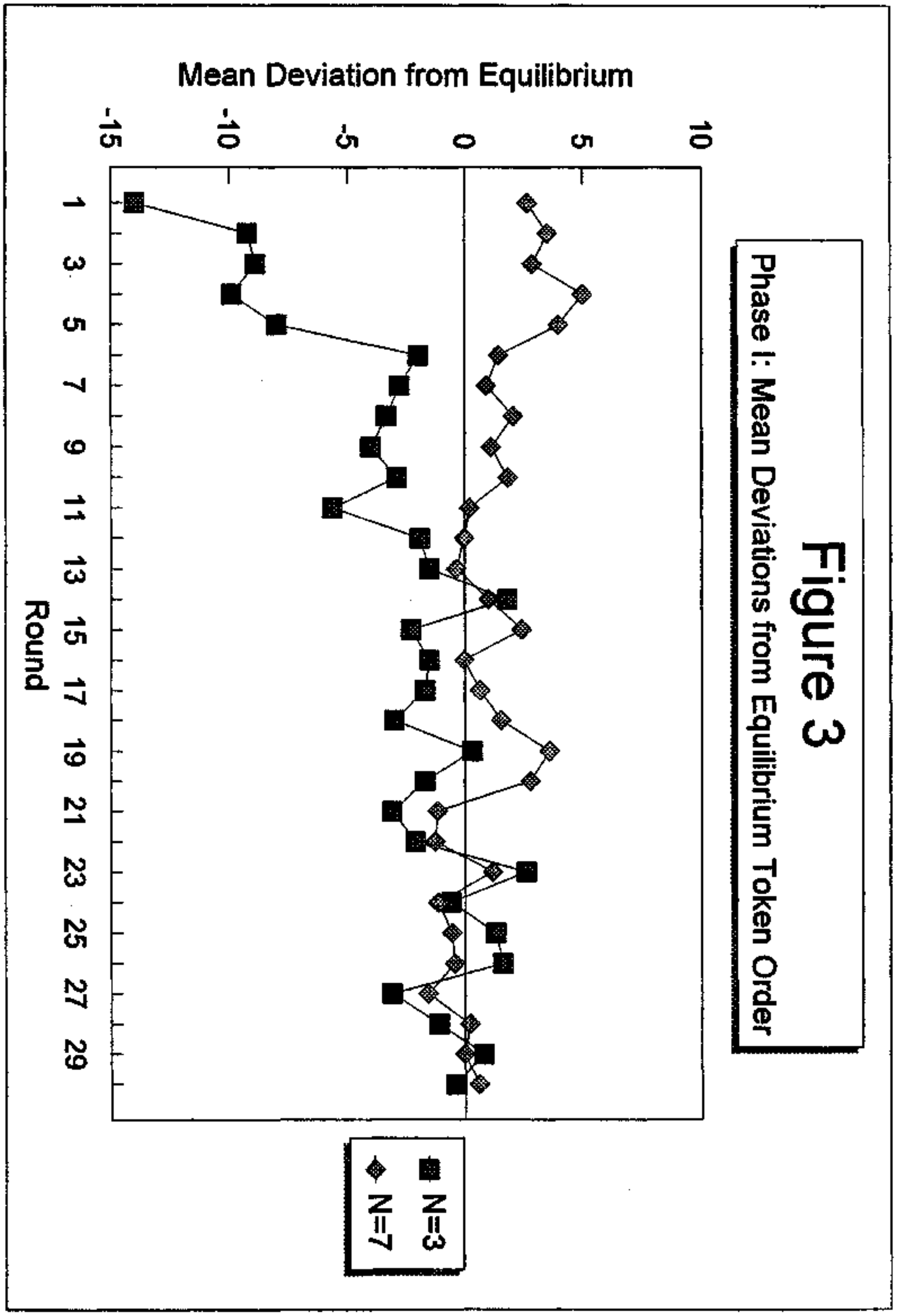


Figure 3

Phase I: Mean Deviations from Equilibrium Token Order

Figure 4

Phase II: Mean Token Orders

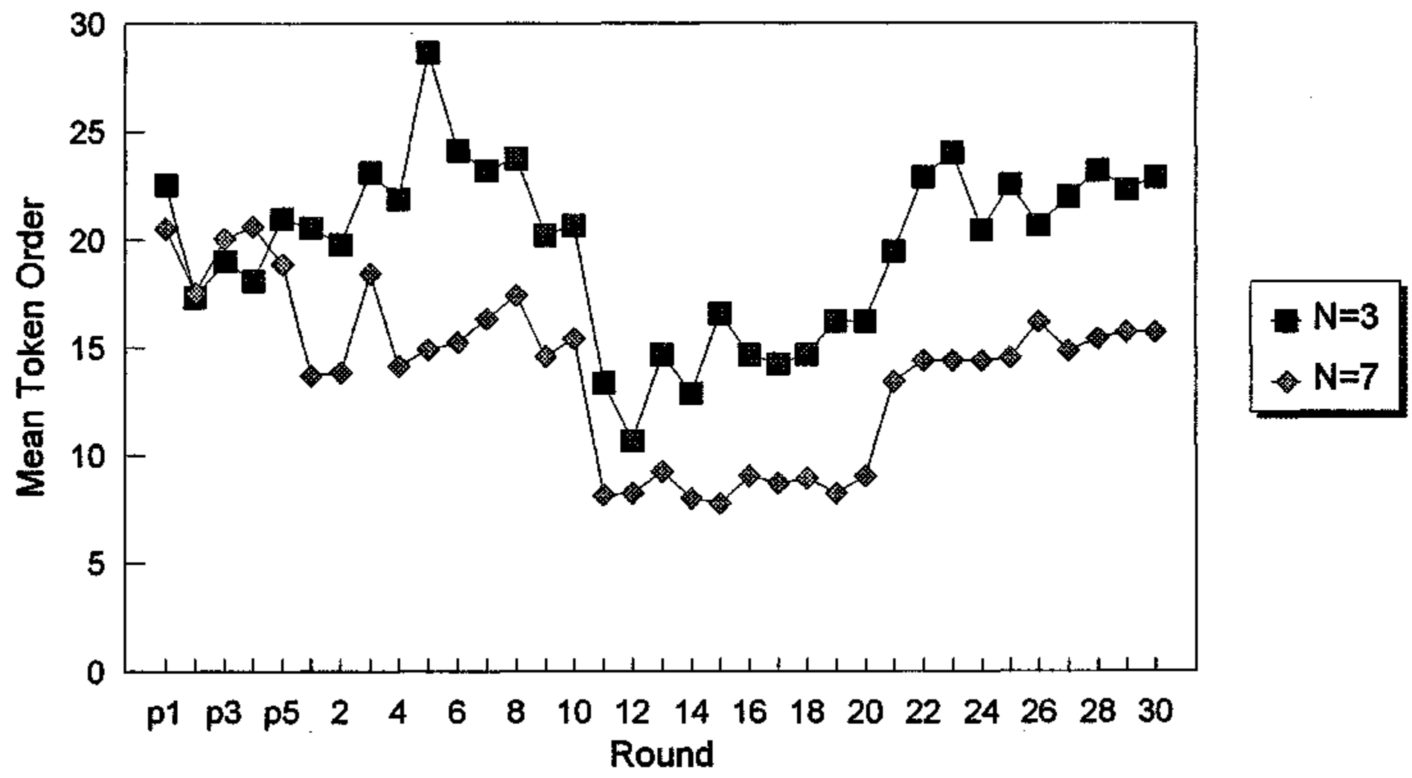
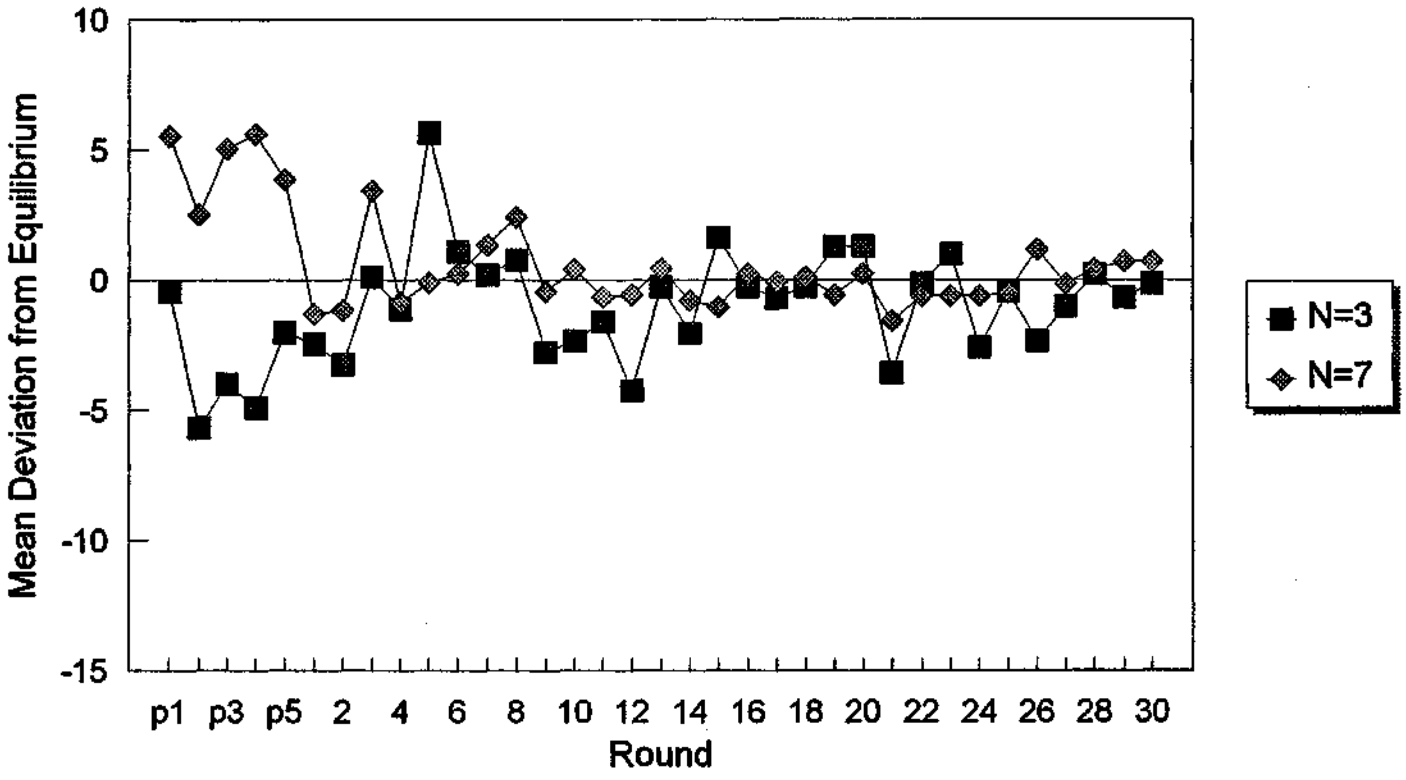


Figure 5

Phase II: Mean Deviations from Equilibrium Token Order



APPENDIX A

Handouts Given to Subjects

CONSENT FORM

This experiment is one in a series of experiments being conducted to investigate individual decision making. Funding for this experiment has been provided by several agencies of the Federal Government.

Having reviewed the instructions for this experiment, we are required by Indiana University procedures to record your formal consent to participate in this experiment.

Your participation in the experiment involves making investment decisions as described in the instructions. At the end of the experiment, you will be paid your earnings privately in cash. Your individual decisions will remain anonymous to the group. Your identity will never be identified as part of the published results from this experiment. The experiment is expected to last from one to two hours.

If you have any questions concerning the experiment please feel free to ask the experimenter. Your participation is voluntary. If you wish not to participate, please inform the experimenter now. Otherwise, please sign the consent statement below.

I have received a copy of this consent form. My participation in this research study is completely voluntary. I may choose not to participate or may withdraw at any time without prejudice concerning any future contact I may have with any of the researchers. I wish to participate in this experiment:

Signed________________________Date______________________

If you wish further information concerning this experiment, contact:

James M. Walker	Roy Gardner
Dept. of Economics	Dept. of Economics
Ballantine 805	Ballantine 822
Phone: 855-2760	Phone: 855-8974

If you have questions regarding your rights as a subject, contact:

Research Risk Office
Human Subjects Committee
Bryan 10
Bloomington, Indiana 47405
Phone: 855-3067

BENEFITS TABLE

This Table Displays Total Benefits for Various Token Orders

TOKs	BENs		TOKs	BENs	TOKs	BENs		TOKs	BENs
1	$ 0.86		21	$ 14.36	41	$ 20.86		61	$ 20.36
2	$ 1.70		22	$ 14.85	42	$ 21.00		62	$ 20.15
3	$ 2.52		23	$ 15.32	43	$ 21.12		63	$ 19.92
4	$ 3.33		24	$ 15.78	44	$ 21.23		64	$ 19.68
5	$ 4.12		25	$ 16.22	45	$ 21.32		65	$ 19.42
6	$ 4.89		26	$ 16.64	46	$ 21.39		66	$ 19.14
7	$ 5.64		27	$ 17.04	47	$ 21.44		67	$ 18.84
8	$ 6.38		28	$ 17.43	48	$ 21.48		68	$ 18.53
9	$ 7.10		29	$ 17.80	49	$ 21.50		69	$ 18.20
10	$ 7.80		30	$ 18.15	50	$ 21.50		70	$ 17.85
11	$ 8.48		31	$ 18.48	51	$ 21.48		71	$ 17.48
12	$ 9.15		32	$ 18.80	52	$ 21.45		72	$ 17.10
13	$ 9.80		33	$ 19.10	53	$ 21.40		73	$ 16.70
14	$ 10.43		34	$ 19.38	54	$ 21.33		74	$ 16.28
15	$ 11.04		35	$ 19.64	55	$ 21.24		75	$ 15.84
16	$ 11.64		36	$ 19.89	56	$ 21.14		76	$ 15.39
17	$ 12.22		37	$ 20.12	57	$ 21.02		77	$ 14.92
18	$ 12.78		38	$ 20.33	58	$ 20.88		78	$ 14.43
19	$ 13.32		39	$ 20.52	59	$ 20.72		79	$ 13.92
20	$ 13.85		40	$ 20.70	60	$ 20.55		80	$ 13.40

COST TABLE

THIS TABLE DISPLAYS THE SPECIFIC COST PER TOKEN FOR TOKENS PURCHASED BY THE GROUP

TOKEN NUMBER (COST)

1 ($0.01)	64 ($0.64)	127 ($1.27)	190 ($1.90)	253 ($2.53)	316 ($3.16)	379 ($3.79)	442 ($4.42)
2 ($0.02)	65 ($0.65)	128 ($1.28)	191 ($1.91)	254 ($2.54)	317 ($3.17)	380 ($3.80)	443 ($4.43)
3 ($0.03)	66 ($0.66)	129 ($1.29)	192 ($1.92)	255 ($2.55)	318 ($3.18)	381 ($3.81)	444 ($4.44)
4 ($0.04)	67 ($0.67)	130 ($1.30)	193 ($1.93)	256 ($2.56)	319 ($3.19)	382 ($3.82)	445 ($4.45)
5 ($0.05)	68 ($0.68)	131 ($1.31)	194 ($1.94)	257 ($2.57)	320 ($3.20)	383 ($3.83)	446 ($4.46)
6 ($0.06)	69 ($0.69)	132 ($1.32)	195 ($1.95)	258 ($2.58)	321 ($3.21)	384 ($3.84)	447 ($4.47)
7 ($0.07)	70 ($0.70)	133 ($1.33)	196 ($1.96)	259 ($2.59)	322 ($3.22)	385 ($3.85)	448 ($4.48)
8 ($0.08)	71 ($0.71)	134 ($1.34)	197 ($1.97)	260 ($2.60)	323 ($3.23)	386 ($3.86)	449 ($4.49)
9 ($0.09)	72 ($0.72)	135 ($1.35)	198 ($1.98)	261 ($2.61)	324 ($3.24)	387 ($3.87)	450 ($4.50)
10 ($0.10)	73 ($0.73)	136 ($1.36)	199 ($1.99)	262 ($2.62)	325 ($3.25)	388 ($3.88)	451 ($4.51)
11 ($0.11)	74 ($0.74)	137 ($1.37)	200 ($2.00)	263 ($2.63)	326 ($3.26)	389 ($3.89)	452 ($4.52)
12 ($0.12)	75 ($0.75)	138 ($1.38)	201 ($2.01)	264 ($2.64)	327 ($3.27)	390 ($3.90)	453 ($4.53)
13 ($0.13)	76 ($0.76)	139 ($1.39)	202 ($2.02)	265 ($2.65)	328 ($3.28)	391 ($3.91)	454 ($4.54)
14 ($0.14)	77 ($0.77)	140 ($1.40)	203 ($2.03)	266 ($2.66)	329 ($3.29)	392 ($3.92)	455 ($4.55)
15 ($0.15)	78 ($0.78)	141 ($1.41)	204 ($2.04)	267 ($2.67)	330 ($3.30)	393 ($3.93)	456 ($4.56)
16 ($0.16)	79 ($0.79)	142 ($1.42)	205 ($2.05)	268 ($2.68)	331 ($3.31)	394 ($3.94)	457 ($4.57)
17 ($0.17)	80 ($0.80)	143 ($1.43)	206 ($2.06)	269 ($2.69)	332 ($3.32)	395 ($3.95)	458 ($4.58)
18 ($0.18)	81 ($0.81)	144 ($1.44)	207 ($2.07)	270 ($2.70)	333 ($3.33)	396 ($3.96)	459 ($4.59)
19 ($0.19)	82 ($0.82)	145 ($1.45)	208 ($2.08)	271 ($2.71)	334 ($3.34)	397 ($3.97)	460 ($4.60)
20 ($0.20)	83 ($0.83)	146 ($1.46)	209 ($2.09)	272 ($2.72)	335 ($3.35)	398 ($3.98)	461 ($4.61)
21 ($0.21)	84 ($0.84)	147 ($1.47)	210 ($2.10)	273 ($2.73)	336 ($3.36)	399 ($3.99)	462 ($4.62)
22 ($0.22)	85 ($0.85)	148 ($1.48)	211 ($2.11)	274 ($2.74)	337 ($3.37)	400 ($4.00)	463 ($4.63)
23 ($0.23)	86 ($0.86)	149 ($1.49)	212 ($2.12)	275 ($2.75)	338 ($3.38)	401 ($4.01)	464 ($4.64)
24 ($0.24)	87 ($0.87)	150 ($1.50)	213 ($2.13)	276 ($2.76)	339 ($3.39)	402 ($4.02)	465 ($4.65)
25 ($0.25)	88 ($0.88)	151 ($1.51)	214 ($2.14)	277 ($2.77)	340 ($3.40)	403 ($4.03)	466 ($4.66)
26 ($0.26)	89 ($0.89)	152 ($1.52)	215 ($2.15)	278 ($2.78)	341 ($3.41)	404 ($4.04)	467 ($4.67)
27 ($0.27)	90 ($0.90)	153 ($1.53)	216 ($2.16)	279 ($2.79)	342 ($3.42)	405 ($4.05)	468 ($4.68)
28 ($0.28)	91 ($0.91)	154 ($1.54)	217 ($2.17)	280 ($2.80)	343 ($3.43)	406 ($4.06)	469 ($4.69)
29 ($0.29)	92 ($0.92)	155 ($1.55)	218 ($2.18)	281 ($2.81)	344 ($3.44)	407 ($4.07)	470 ($4.70)
30 ($0.30)	93 ($0.93)	156 ($1.56)	219 ($2.19)	282 ($2.82)	345 ($3.45)	408 ($4.08)	471 ($4.71)
31 ($0.31)	94 ($0.94)	157 ($1.57)	220 ($2.20)	283 ($2.83)	346 ($3.46)	409 ($4.09)	472 ($4.72)
32 ($0.32)	95 ($0.95)	158 ($1.58)	221 ($2.21)	284 ($2.84)	347 ($3.47)	410 ($4.10)	473 ($4.73)
33 ($0.33)	96 ($0.96)	159 ($1.59)	222 ($2.22)	285 ($2.85)	348 ($3.48)	411 ($4.11)	474 ($4.74)
34 ($0.34)	97 ($0.97)	160 ($1.60)	223 ($2.23)	286 ($2.86)	349 ($3.49)	412 ($4.12)	475 ($4.75)
35 ($0.35)	98 ($0.98)	161 ($1.61)	224 ($2.24)	287 ($2.87)	350 ($3.50)	413 ($4.13)	476 ($4.76)
36 ($0.36)	99 ($0.99)	162 ($1.62)	225 ($2.25)	288 ($2.88)	351 ($3.51)	414 ($4.14)	477 ($4.77)
37 ($0.37)	100 ($1.00)	163 ($1.63)	226 ($2.26)	289 ($2.89)	352 ($3.52)	415 ($4.15)	478 ($4.78)
38 ($0.38)	101 ($1.01)	164 ($1.64)	227 ($2.27)	290 ($2.90)	353 ($3.53)	416 ($4.16)	479 ($4.79)
39 ($0.39)	102 ($1.02)	165 ($1.65)	228 ($2.28)	291 ($2.91)	354 ($3.54)	417 ($4.17)	480 ($4.80)
40 ($0.40)	103 ($1.03)	166 ($1.66)	229 ($2.29)	292 ($2.92)	355 ($3.55)	418 ($4.18)	481 ($4.81)
41 ($0.41)	104 ($1.04)	167 ($1.67)	230 ($2.30)	293 ($2.93)	356 ($3.56)	419 ($4.19)	482 ($4.82)
42 ($0.42)	105 ($1.05)	168 ($1.68)	231 ($2.31)	294 ($2.94)	357 ($3.57)	420 ($4.20)	483 ($4.83)
43 ($0.43)	106 ($1.06)	169 ($1.69)	232 ($2.32)	295 ($2.95)	358 ($3.58)	421 ($4.21)	484 ($4.84)
44 ($0.44)	107 ($1.07)	170 ($1.70)	233 ($2.33)	296 ($2.96)	359 ($3.59)	422 ($4.22)	485 ($4.85)
45 ($0.45)	108 ($1.08)	171 ($1.71)	234 ($2.34)	297 ($2.97)	360 ($3.60)	423 ($4.23)	486 ($4.86)
46 ($0.46)	109 ($1.09)	172 ($1.72)	235 ($2.35)	298 ($2.98)	361 ($3.61)	424 ($4.24)	487 ($4.87)
47 ($0.47)	110 ($1.10)	173 ($1.73)	236 ($2.36)	299 ($2.99)	362 ($3.62)	425 ($4.25)	488 ($4.88)
48 ($0.48)	111 ($1.11)	174 ($1.74)	237 ($2.37)	300 ($3.00)	363 ($3.63)	426 ($4.26)	489 ($4.89)
49 ($0.49)	112 ($1.12)	175 ($1.75)	238 ($2.38)	301 ($3.01)	364 ($3.64)	427 ($4.27)	490 ($4.90)
50 ($0.50)	113 ($1.13)	176 ($1.76)	239 ($2.39)	302 ($3.02)	365 ($3.65)	428 ($4.28)	491 ($4.91)
51 ($0.51)	114 ($1.14)	177 ($1.77)	240 ($2.40)	303 ($3.03)	366 ($3.66)	429 ($4.29)	492 ($4.92)
52 ($0.52)	115 ($1.15)	178 ($1.78)	241 ($2.41)	304 ($3.04)	367 ($3.67)	430 ($4.30)	493 ($4.93)
53 ($0.53)	116 ($1.16)	179 ($1.79)	242 ($2.42)	305 ($3.05)	368 ($3.68)	431 ($4.31)	494 ($4.94)
54 ($0.54)	117 ($1.17)	180 ($1.80)	243 ($2.43)	306 ($3.06)	369 ($3.69)	432 ($4.32)	495 ($4.95)
55 ($0.55)	118 ($1.18)	181 ($1.81)	244 ($2.44)	307 ($3.07)	370 ($3.70)	433 ($4.33)	496 ($4.96)
56 ($0.56)	119 ($1.19)	182 ($1.82)	245 ($2.45)	308 ($3.08)	371 ($3.71)	434 ($4.34)	497 ($4.97)
57 ($0.57)	120 ($1.20)	183 ($1.83)	246 ($2.46)	309 ($3.09)	372 ($3.72)	435 ($4.35)	498 ($4.98)
58 ($0.58)	121 ($1.21)	184 ($1.84)	247 ($2.47)	310 ($3.10)	373 ($3.73)	436 ($4.36)	499 ($4.99)
59 ($0.59)	122 ($1.22)	185 ($1.85)	248 ($2.48)	311 ($3.11)	374 ($3.74)	437 ($4.37)	500 ($5.00)
60 ($0.60)	123 ($1.23)	186 ($1.86)	249 ($2.49)	312 ($3.12)	375 ($3.75)	438 ($4.38)	
61 ($0.61)	124 ($1.24)	187 ($1.87)	250 ($2.50)	313 ($3.13)	376 ($3.76)	439 ($4.39)	
62 ($0.62)	125 ($1.25)	188 ($1.88)	251 ($2.51)	314 ($3.14)	377 ($3.77)	440 ($4.40)	
63 ($0.63)	126 ($1.26)	189 ($1.89)	252 ($2.52)	315 ($3.15)	378 ($3.78)	441 ($4.41)	

PRACTICE EXAMPLES
N=3, Base cost = $0.01, Increment = $0.01

These examples are for illustrative purposes only. The numbers used in the example have been chosen to simplify the illustration.

EXAMPLE 1:

Assume you are in the 1st Round of the Experiment. Suppose you place an order for 10 Tokens and the other members of the group order 56 Tokens - for a total group order of 66 Tokens.

Using the BENEFITS AND COSTS TABLE:

1) What will be your CASH BENEFIT?___________

2) What will be the BASE COST for the first token ordered in this round?________

3) What will be the AVERAGE TOKEN COST this round?__________

4) What will be YOUR TOTAL TOKEN COSTS this round? _ _ _ _ _

5) What would be YOUR PROFIT for this round? ___________

EXAMPLE 2:

Assume you are in the 4th Round of the Experiment. Suppose you place an order for 40 Tokens and the other members of the group order 100 Tokens - for a total group order of 140 Tokens.

Using the BENEFITS AND COSTS TABLE:

1) What will be your CASH BENEFIT?___________

2) What will be the BASE COST for the first token ordered in this round?________

3) What will be the AVERAGE TOKEN COST this round?__________

4) What will be YOUR TOTAL TOKEN COSTS this round?___________

5) What would be YOUR PROFIT for this round? ___________

ARE THERE ANY QUESTIONS?

PRACTICE EXAMPLES (CONT)
N=3, Base cost = $0.01, Increment = $0.01

The following two examples are given in order to illustrate the payoffs associated with potential token order combinations. The numbers used in the example have been chosen to simplify the illustration.

EXAMPLE 3:
Suppose that in a given round each player orders 10 tokens, so that the total group token order is 30. (Note: it will generally NOT be the case that all players order the same number of tokens, this is simply an example). The following table calculates the payoff for each player.

(1) Player	(2) Order	(3) Total Benefit	(4) Average Cost	(5)[1] Total Cost	(6)[2] Total Payoff
1	10	$7.80	$0.155	$1.55	$6.25
2	10	$7.80	$0.155	$1.55	$6.25
3	10	$7.80	$0.155	$1.55	$6.25

[1] [column (2)] X [column (4)] [2] [column (3)] - [column (5)]

EXAMPLE 4:
Suppose that in a given round, player 1 orders 20 tokens, player 2 orders 40 tokens, and player 3 orders 60 tokens, so that the total group token order is 120. The following table calculates the payoff for each player.

(1) Player	(2) Order	(3) Total Benefit	(4) Average Cost	(5)[1] Total Cost	(6)[2] Total Payoff
1	20	$13.85	$0.605	$12.10	$1.75
2	40	$20.70	$0.605	$24.20	($3.50)
3	60	$20.55	$0.605	$36.30	($15.75)

[1] [column (2)] X [column (4)]. [2] [column (3)] - [column (5)].

PRACTICE EXAMPLES

N=3, Base cost = $0.02, Increment = $0.02

These examples are for illustrative purposes only. The numbers used in the example have been chosen to simplify the illustration.

EXAMPLE 1:

Assume you are in the 1st Round of the Experiment. Suppose you place an order for 10 Tokens and the other members of the group order 56 Tokens - for a total group order of 66 Tokens.

Using the BENEFITS AND COSTS TABLE:

1) What will be your CASH BENEFIT?___________

2) What will be the BASE COST for the first token ordered in this round?________

3) What will be the AVERAGE TOKEN COST this round?__________

4) What will be YOUR TOTAL TOKEN COSTS this round?___________

5) What would be YOUR PROFIT for this round? ___________

EXAMPLE 2:

Assume you are in the 4th Round of the Experiment. Suppose you place an order for 40 Tokens and the other members of the group order 100 Tokens - for a total group order of 140 Tokens.

Using the BENEFITS AND COSTS TABLE:

1) What will be your CASH BENEFIT?___________

2) What will be the BASE COST for the first token ordered in this round?________

3) What will be the AVERAGE TOKEN COST this round?__________

4) What will be YOUR TOTAL TOKEN COSTS this round?___________

5) What would be YOUR PROFIT for this round? ___________

ARE THERE ANY QUESTIONS?

PRACTICE EXAMPLES
N=3, Base cost = $0.02, Increment = $0.02

The following two examples are given in order to illustrate the payoffs associated with potential token order combinations. The numbers used in the example have been chosen to simplify the illustration.

EXAMPLE 5:
Suppose that in a given round each player orders 10 tokens, so that the total group token order is 30. (Note: it will generally NOT be the case that all players order the same number of tokens, this is simply an example). The following table calculates the payoff for each player.

(1) Player	(2) Order	(3) Total Benefit	(4) Average Cost	(5)[1] Total Cost	(6)[2] Total Payoff
1	10	$7.80	$0.31	$3.10	$4.70
2	10	$7.80	$0.31	$3.10	$4.70
3	10	$7.80	$0.31	$3.10	$4.70

[1] [column (2)] X [column (4)]. [2] [column (3)] - [column (5)]

EXAMPLE 6:
Suppose that in a given round, player 1 orders 20 tokens, player 2 orders 40 tokens, and player 3 orders 60 tokens, so that the total group token order is 120. The following table calculates the payoff for each player.

(1) Player	(2) Order	(3) Total Benefit	(4) Average Cost	(5)[1] Total Cost	(6)[2] Total Payoff
1	20	$13.85	$1.21	$24.20	($10.35)
2	40	$20.70	$1.21	$48.40	($27.20)
3	60	$20.55	$1.21	$72.60	($52.05)

[1] [column (2)] X [column (4)]. [2] [column (3)] - [column (5)].

PRACTICE EXAMPLES
N7, Base cost = $0.01, Increment = $0.01

These examples are for illustrative purposes only. The numbers used in the example have been chosen to simplify the illustration.

EXAMPLE 1:

Assume you are in the 1st Round of the Experiment. Suppose you place an order for 10 Tokens and the other members of the group order 56 Tokens - for a total group order of 66 Tokens.

Using the BENEFITS AND COSTS TABLE:

1) What will be your CASH BENEFIT?___________

2) What will be the BASE COST for the first token ordered in this round?________

3) What will be the AVERAGE TOKEN COST this round?__________

4) What will be YOUR TOTAL TOKEN COSTS this round?___________

5) What would be YOUR PROFIT for this round? ____________

EXAMPLE 2:

Assume you are in the 4th Round of the Experiment. Suppose you place an order for 40 Tokens and the other members of the group order 100 Tokens - for a total group order of 140 Tokens.

Using the BENEFITS AND COSTS TABLE:

1) What will be your CASH BENEFIT?___________

2) What will be the BASE COST for the first token ordered in this round?________

3) What will be the AVERAGE TOKEN COST this round?__________

4) What will be YOUR TOTAL TOKEN COSTS this round?___________

5) What would be YOUR PROFIT for this round? ____________

ARE THERE ANY QUESTIONS?

PRACTICE EXAMPLES (CONT)
N7, Base Cost = $0.01, Increment = $0.01

The following two examples are given in order to illustrate the payoffs associated with potential token order combinations. The numbers used in the example have been chosen to simplify the illustration.

EXAMPLE 3:

Suppose that in a given round EACH PLAYER ORDERS 10 TOKENS. (Note: it will generally NOT be the case that all players order the same number of tokens, this is simply an example). The following table calculates the payoff for each player.

(1) Player	(2) Order	(3) Total Benefit	(4) Average Cost	(5)[1] Total Cost	(6)[2] Total Payoff
1	10	$7.80	$0.355	$3.55	$4.25
2	10	$7.80	$0.355	$3.55	$4.25
3	10	$7.80	$0.355	$3.55	$4.25
4	10	$7.80	$0.355	$3.55	$4.25
5	10	$7.80	$0.355	$3.55	$4.25
6	10	$7.80	$0.355	$3.55	$4.25
7	10	$7.80	$0.355	$3.55	$4.25

[1] [column (2)] X [column (4)]
[2] [column (3)] - [column (5)]

PRACTICE EXAMPLES (CONT)
N7, Base Cost = $0.01, Increment = $0.01

EXAMPLE 4:

Suppose that in a given round, player 1 orders 10 tokens, player 2 orders 20 tokens, player 3 orders 30 tokens, player 4 orders 40 tokens, player 5 orders 50 tokens, player 6 orders 60 tokens, and player 7 orders 70 tokens. The following table calculates the payoff for each player.

(1) Player	(2) Order	(3) Total Benefit	(4) Average Cost	(5)[1] Total Cost	(6)[2] Total Payoff
1	10	$7.80	$1.405	$14.05	($6.25)
2	20	$13.85	$1.405	$28.10	($14.25)
3	30	$18.15	$1.405	$42.15	($24.00)
4	40	$20.70	$1.405	$56.20	($35.50)
5	50	$21.50	$1.405	$70.25	($48.75)
6	60	$20.55	$1.405	$84.30	($63.75)
7	70	$17.85	$1.405	$98.35	($80.50)

[1] [column (2)] X [column (4)].
[2] [column (3)] - [column (5)].

Also note that parentheses indicate negative payoffs.

PRACTICE EXAMPLES
N7, Base cost = $0.02, Increment = $0.02

These examples are for illustrative purposes only. The numbers used in the example have been chosen to simplify the illustration.

EXAMPLE 1:

Assume you are in the 1st Round of the Experiment. Suppose you place an order for 10 Tokens and the other members of the group order 56 Tokens - for a total group order of 66 Tokens.

Using the BENEFITS AND COSTS TABLE:

1) What will be your CASH BENEFIT?___________

2) What will be the BASE COST for the first token ordered in this round?________

3) What will be the AVERAGE TOKEN COST this round?__________

4) What will be YOUR TOTAL TOKEN COSTS this round?___________

5) What would be YOUR PROFIT for this round? ___________

EXAMPLE 2:

Assume you are in the 4th Round of the Experiment. Suppose you place an order for 40 Tokens and the other members of the group order 100 Tokens - for a total group order of 140 Tokens.

Using the BENEFITS AND COSTS TABLE:

1) What will be your CASH BENEFIT?___________

2) What will be the BASE COST for the first token ordered in this round?________

3) What will be the AVERAGE TOKEN COST this round?__________

4) What will be YOUR TOTAL TOKEN COSTS this round?___________

5) What would be YOUR PROFIT for this round? ___________

ARE THERE ANY QUESTIONS?

PRACTICE EXAMPLES (CONT)
Base Cost = $0.02, Increment = $0.02

The following two examples are given in order to illustrate the payoffs associated with potential token order combinations. The numbers used in the example have been chosen to simplify the illustration.

EXAMPLE 3:

Suppose that in a given round EACH PLAYER ORDERS 10 TOKENS. (Note: it will generally NOT be the case that all players order the same number of tokens, this is simply an example). The following table calculates the payoff for each player.

(1) Player	(2) Order	(3) Total Benefit	(4) Average Cost	(5)[1] Total Cost	(6)[2] Total Payoff
1	10	$7.80	$0.71	$7.10	$0.70
2	10	$7.80	$0.71	$7.10	$0.70
3	10	$7.80	$0.71	$7.10	$0.70
4	10	$7.80	$0.71	$7.10	$0.70
5	10	$7.80	$0.71	$7.10	$0.70
6	10	$7.80	$0.71	$7.10	$0.70
7	10	$7.80	$0.71	$7.10	$0.70

[1] [column (2)] X [column (4)]
[2] [column (3)] - [column (5)]

PRACTICE EXAMPLES (CONT)
Base Cost = $0.02, Increment = $0.02

EXAMPLE **4:**

Suppose that in a given round, player 1 orders 10 tokens, player 2 orders 20 tokens, player 3 orders 30 tokens, player 4 orders 40 tokens, player 5 orders 50 tokens, player 6 orders 60 tokens, and player 7 orders 70 tokens. The following table calculates the payoff for each player.

(1) Player	(2) Order	(3) Total Benefit	(4) Average Cost	(5)[1] Total Cost	(6)[2] Total Payoff
1	10	$7.80	$2.81	$28.10	($20.30)
2	20	$13.85	$2.81	$56.20	($42.35)
3	30	$18.15	$2.81	$84.30	($66.15)
4	40	$20.70	$2.81	$112.40	($91.70)
5	50	$21.50	$2.81	$140.50	($119.00)
6	60	$20.55	$2.81	$168.60	($148.05)
7	70	$17.85	$2.81	$196.70	($178.85)

[1] [column (2)] X [column (4)].
[2] [column (3)] - [column (5)].
Also note that parentheses indicate negative payoffs.

APPENDIX B

This appendix lists the Novanet experiment names in "watermon" with experiments reported in this chapter.

Phase I, N3a:	Experiment 21, groups 1,2,3
Phase I, N3b:	Experiment 23, groups 1,2 Experiment 24, group 2
Phase I, N7:	Experiment 22, groups 1,2 Experiment 24, group 1
Phase II, N3:	Experiment 27, group 2 Experiment 28, group 2 Experiment 29, group 2
Phase II, N7:	Experiment 27, group 1 Experiment 28, group 1 Experiment 29, group 1

ENDNOTES

1. The different exchange rates are employed for the following reason. When *groups* of n=3 and n=7 earn roughly the same payoffs at the equilibrium, the equilibrium payoffs of *individuals* in the n=3 group are over twice as large as that of the individuals in the n=7 group. The exchange rate in the N3b design is reduced by 50% to control for this potential difference in individual payoffs.

2. This increase in the cost parameters from \$0.01 to \$0.02 is not the focus of the present study. These experiments also served as trainers for subsequent experiments in which the cost parameters were varied.

3. The computerized instructions used in these experiments were the same as those used in the time-independent experiments reported in Chapter 3. These instructions are shown in Appendix A of Chapter 3. However, different handouts were given to subjects. The handouts used in these experiments are given in Appendix A of this chapter.

4. The test statistic is $T=2$.

5. In Table III, there is little difference between the computer payoffs earned by groups in the N3a design compared to groups in the N3b design. For this reason, the results of the N3a and N3b design will be pooled and reported as results of N3 groups for the remainder of the results section.

6. The test statistics for Series 1, 2, and 3 are T=0, T=7, and T=8, respectively.

7. Subjects were told that if they earned negative profits in the experiment they would not be required to pay the experimenters the amount of their losses; instead, they were told that they would simply earn no money for the experiment.

8. The test statistic is £7=1.

9. The test statistics for Series 2 and 3 are U=3 and U=7, respectively. For Series 1, £7=1; therefore, in Series 1, the null hypothesis that r_{N3} and r_{N7} can be rejected at α=.05.

10. Due to a computer malfunction, the Series I individual token order data for Phase I subjects participating in the N3a design was lost. Thus, the N3 token orders for this Series 1 shown in Figures 2 and 3 include only the token orders of the 9 subjects in the N3b design. The Series 2 and 3 data shown in these figures includes the orders of all 18 of the N3 subjects.

11. The test statistics in Rounds 1 and 2 are U=41 and U=48.5, respectively. Because both sample sizes are larger than 8, the distribution of U is closely approximated by the normal distribution. The relevant z-statistics for Rounds 1 and 2 are $z=-2.42$ and $z=-2.08$. Thus, the null hypothesis that the individual token orders for the N3 and N7 individuals are the same can be rejected at $\alpha=.05$ for Rounds 1 and 2.

12. The exact probabilities are 211/1,048,576 and 1351/1,048,576 and are calculated in the following manner. Define "success" to be the observation of a mean greater than the equilibrium prediction in a given round. Under the null hypothesis, the probability of success and the probability of failure both equal 0.5. In 20 independent trials, the number of combinations producing exactly 20, 19, 18, or 17 successes or failures is 1, 20, 190, and 1140, respectively. Thus, the probability of observing 18 or more successes in 20 trials is $(.5)^{20}(211)$, and the probability of observing 17 or more failures is $(.5)^{20}(1351)$,

13. The per period earnings for the N3a groups was also lost for Series 1 due to the computer malfunction. Thus, the N3 group earnings for Rounds 1-5 and 6-10 include only the N3b groups.

14. Unless otherwise stated, observed group payoffs throughout this section do *not* include the five practice rounds.

15. The test statistic is T=2.

16. The test statistics for Series 1, 2, and 3 are T=0, T=6, and T=2, respectively.

17. The test statistic is T=6.

18. The test statistics for Series 1, 2, and 3 are T=0, T=25, and T=14, respectively.

19. A comparison of Tables 4 and 6 shows the dramatic increase in the payoffs earned by N7 groups in Phase II as compared to Phase I. However, with the sample size (three Phase I N7 groups and three Phase II N7 groups), the difference between the N7 Phase I and II means would be significant using the Mann-Whitney test only if the three Phase I groups ranked 1, 2, and 3 when the six Phase I and II N7 payoffs are ranked in ascending order. In reality, the Phase I groups rank 1, 3, and 4. Thus, while the Phase II payoffs are considerably higher than the Phase I payoffs for N7 groups, I have been careful to use the term "substantially higher" rather than "significantly higher.[M]

20. This result needs to be qualified. In some sense, even the groups of three in this experimental design were not "small." In the context of collusive behavior, smallness generally implies the existence of mechanisms through which the members of the

group can coordinate their actions. In this experimental design, no such mechanisms exist. In other experimental studies in coordinating mechanisms such as face-to-face communication (Ostrom, Gardner, and Walker, 1994) or voting mechanisms (Walker, Gardner, Ostrom, and Herr, 1996) exist, groups of seven and eight are able to coordinate on efficiency-improving strategies.

CHAPTER 5

Concluding Comments

This dissertation examines the behavior of individuals appropriating from a common-pool resource (CPR) using the tools of game theory and experimental methods. The game theoretic CPR model developed by Gardner, Moore, and Walker (GMW) provides a foundation for both the theoretical and experimental analyses. This dissertation builds on the work by GMW by providing an extensive study of the properties of the game theoretic model (Chapter 2) and experimental studies of the impacts of time-dependency (Chapter 3) and group size (Chapter 4) in a CPR setting.

The GMW model attempts to capture important elements of the CPR dilemma. The benefits received by player i in period t depend only on i's own extraction, x_{it}:

$$B_{it}(x_{it}) = ax_{it} - bx_{it}^2, \tag{1}$$

while the costs incurred by i depend on his or her own extraction as well as the total group extraction, X_t:

$$C_{it}(x_{it}, X_t) = x_{it}(c_{it} + kX_t/2). \tag{2}$$

Thus, the individual net benefit function in each period, t, is made up of two components, one of which depends only on the extraction of the individual, B_{it}, and the other, which also depends on individual and group extraction, C_{it}.

Chapter 2 derives several important properties of the GMW model. The first relates to the number of appropriators using the resource (group size) that maximizes the equilibrium group payoffs from the resource. This group size is an important consideration in situations where it is feasible to limit access to the resource but not to monitor the extraction of individuals allowed to extract from the resource. In the time-independent game, equilibrium group payoffs are maximized at the group size:

$$n_0 = 1 + 4b/k. \tag{3}$$

Note that n_0 is increasing b, but decreasing in k. From (1), b can be interpreted as the rate at which marginal benefits decrease due to an increase in an individual's own extraction. In other words, b measures the extent to which an individual will limit his or her own extraction, regardless of the extraction of others. On the other hand, k is a measure of the severity of the externality, as shown in (2).

With these interpretations of b and k, it is not surprising that n_0 is increasing b and decreasing in k. For larger values of b, there are greater gains from spreading resource use among many appropriators; thus, it makes sense that n_0 is increasing in b. Conversely, for severe externality levels, k, equilibrium group payoffs will reach a maximum at smaller group sizes. Equation (3) provides insight into the preferred group size in a CPR setting. This equation is consistent with Gisser (1983), who argues that the existence of declining marginal benefits in groundwater pumping implies the possibility that total welfare can be increased by increasing the number of irrigators. It is also consistent with the notion that when resource units are sold in a competitive market, which leads to a small value of b, restricting access will likely increase total welfare.

This group size, n_0, which maximizes *equilibrium* group payoffs, is in contrast to the group size that would maximize social welfare if all externalities were internalized by players or by a planner. In this model, due to declining marginal benefits, the group size that maximizes social welfare is infinite for $b > 0$.

A second important theoretical result relates to the ability of players commit to an extraction path in the time-dependent game. Eswaran and Lewis (1984) and Reinganum and Stokey (1985) present CPR models in which the ability of players to commit to an extraction path has an extreme impact on the equilibrium of the CPR game. Chapter 2 shows that, in the context of the GMW game, this ability to commit does impact the equilibrium, but not as severely as suggested by these other authors. In particular, it is shown that the difference the efficiencies obtained when players can commit (E^N) as compared to when they cannot *(JET)* is given by:

$$E^N - E^* = (n-1)/(4n^2-2n) \tag{4}$$

It is easily seen from (4) that the efficiency difference vanishes as the group size, n, gets large. Thus, the results reported by Eswaran and Lewis (1984) and Reinganum and Stokey (1985) should be considered as an extreme case.

The experimental studies reported in Chapters 3 and 4 provide important insights into the behavior of individuals in CPR settings. Chapter 3 focuses on the behavioral impact of time-dependency in a CPR setting. Two principal findings emerge from this study. First, observed behavior is consistently closer to the subgame perfect equilibrium prediction than to the efficient outcome, both in the time-independent and time-dependent designs. Second, relative to the subgame perfect equilibrium prediction, the payoffs observed in the time-dependent designs are significantly lower than those observed in the time-independent design. It appears that the lower payoffs observed in the time-dependent designs are due, at least in part, to myopic behavior by subjects. Indeed, the individual token orders more closely follow the myopic path than either the subgame perfect equilibrium or optimal paths for eight of the ten time-dependent groups.

The experiments reported in Chapter 4 focus on impact of group size in the time-independent CPR setting. The primary finding of this study is that, once subjects gain sufficient experience, there are no significant differences in the behavior of individuals participating in groups of size 72=3 as compared to those participating in groups of size n=7. However, in the initial rounds of the experiment, the individuals in the *n*=3 groups order more tokens than individuals in 72=7 groups, contrary to the equilibrium prediction. As a result, the 72=3 groups earn consistently higher payoffs in the initial rounds than the *n=7* groups. With experience, aggregate token orders of both n=3 and 72=7 groups tend toward the equilibrium prediction; however, the two groups approach this level from different directions. The groups of 72=3 tend to approach the equilibrium prediction from below, while the groups of 72=7 approach this prediction from above.

The results of these experimental studies have important policy implications. First, they suggest that, in a world with minimal institutional constraints on behavior, the tragedy of the commons indeed exists. In both studies, the equilibrium provides a reasonable prediction of behavior at the aggregate level. The myopic behavior observed in the time-dependent setting further exacerbates this problem. In addition, the low payoffs earned by groups of 72=7 further suggests that subjects in an experimental CPR setting fail to fully consider the costs that their actions impose on themselves, as well as others. The results of these experiments suggest that future research is needed to investigate the prevalence of myopic behavior in such decision environments and the potential for institutional arrangements to improve performance by containing this behavior.

This dissertation contributes to the literature on CPRs in the following ways. The CPR game model attempts to capture the essential features of CPR dilemmas occurring in the field. Within the context of this model, simple formulas are derived to address the impacts of group size, heterogeneity, and the ability of players to commit to an extraction path on the equilibria of the game. These formulas give insight into the magnitude of these impacts as a function of the parameters of the model. Furthermore, the experiments reported in this dissertation represent a new approach to studying the CPR dilemma. To this point, few authors have conducted CPR experiments, however, such experiments provide an excellent opportunity to examine behavior under various physical and institutional CPR environments.

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