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Risk and Reciprocity: Hunter-Gatherer Socioecology and the Problem of Collective Action

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This chapter is concerned with the consequences of risk and uncertainty for the social interactions of human foragers involving resource sharing and land tenure. As part of a broad trend in the social and biological sciences (e.g., Dawkins 1982; Elster 1982; Ortner 1984; Lomnicki 1986; Roemer 1986), a special concern of our analysis is to adhere to the logic of methodological individualism, by showing how the characteristics of groups are best understood as the consequences (intended or not) of the actions and interactions of their individual members. In the present case, this involves some preliminary applications of the theory of games and evolutionarily stable strategies (Maynard Smith 1982; Parker and Hammerstein 1985).

As the opening chapters by Cashdan, Clark, and Stephens make clear, the concepts of "risk" and "uncertainty" have had varied uses and meanings within the fields of economics, decision analysis, and behavioral ecology. Accordingly, the first task we undertake is to set out our own conception of the meaning of these concepts.

Having done this (in the section immediately following), we devote the remainder of the paper to a consideration of the role of risk and (to a much lesser degree) uncertainty in defining the economic logic of resource sharing and reciprocal land use among hunter-gatherers. We first present a simple model of resource sharing between two foragers, assuming risk aversion and some probability of foraging failure. Using elementary game theory, we show that the sharing game has a prisoner's dilemma structure, and that this holds for groups larger than two as well. The conditions under which

sharing might still persist in face of this problem are briefly discussed (but not modelled).

A similar analysis of land use and interaction between members of different local groups in the face of asynchronous variation in yield from their local areas follows. Here, we show that a prisoner's dilemma structure may or may not hold, and that either reciprocal access or mutual territoriality may be stable, depending on specific parameter values (including risk preference and the degree of risk experienced).

RISK AND UNCERTAINTY: SOME GENERAL ISSUES

What Are Risk and Uncertainty?

The concepts of risk and uncertainty are associated with stochastic processes—that is, variation in the value of one or more variables that is at least somewhat unpredictable and exogenous to (beyond the control of) an actor or set of actors. Beyond this, the literature reveals considerable variation in the meaning and measurement of these concepts.

Some decision theorists define the distinction between risk and uncertainty in terms of psychological states—does the actor have any estimates (subjective or not) of the probability of various outcomes? If the answer to this question is yes, then the problem is defined as one of risk; if no, the decision involves uncertainty. There are a number of problems with this approach. For example, an actor could feel certain that a given choice would lead to an unvarying outcome, yet events could subsequently reveal this certainty to be mistaken, and the outcome to be quite variable; the purely psychological view would logically entail that risk and uncertainty did not exist until the decision outcome had “created” them in the actor's mind. On the other hand, definitions of risk and uncertainty that totally ignore the actor's beliefs and knowledge could have equally perverse or limited results.

Following Hey (1979), Stephens and Charnov (1982) have suggested the following analytical distinction: problems of risk concern the effects of stochastic variation in the outcome associated with some decision, while uncertainty refers to the stock of information possessed by an actor as compared to some objective measure of the state of relevant variables. We adopt this distinction here.

Risk. Exactly how to define and measure risk is a matter of some controversy (e.g., Roumasset et al. 1979; Hey 1981), but most technical definitions involve some measure of stochastic variation. The colloquial meaning of the term refers to uncertain outcomes, a “gamble,” as well as to the danger of

losing something in a gamble (“the risk of starving”); this is similar to the meaning in insurance theory and risk assessment studies, where risk equals the probability of loss (Wiessner 1977; Cashdan 1985). While these meanings overlap with the economic definition adopted here, they do so only partially (a point we return to in a moment). But in economic theory responses to risk do not depend simply on the statistical dispersion in outcomes, for such a dispersion only becomes relevant in the face of a specific kind of relationship between outcome variation and the preferences of the actor.

To understand why this is so, one needs to distinguish between *outcomes* and *payoffs*. By outcomes, we mean the measurable results of a given decision or action, as measured in units external to the actor's preferences (e.g., pounds of fish caught, bushels of rice harvested, dollars earned). Payoff, by contrast, refers to the value of outcomes as determined by an actor's preference ranking; this involves a transformation of outcomes, via what economists refer to as a “utility function” and evolutionary biologists analogously refer to as a “fitness function.” (Since we are not concerned here with the difference between utility and fitness, we will simply use the term “payoff function” to stand for either or both).¹

Consider, for example, the matter of risk in the quest for food (Figure 8.1). If a farmer or forager makes a given choice of subsistence technique, and this choice results in stochastically variable outcomes, the response to risk will depend on the functional relationship between outcomes (food harvest, in material units such as kg or kcal) and payoffs (as measured by utility or fitness). A value function that is linear (as in Figure 8.1A) indicates that each additional unit of resource acquired (or lost) produces the same increment (or decrement) in the payoff currency. It is easy to see that in this case the expected payoff of a stochastic distribution of outcomes

¹Briefly, a utility function is a (generally hypothetical) relation between outcomes and preferences (or satisfaction); it is thus essentially a psychological concept. In adapting risk theory to an evolutionary context, biologists have generally substituted fitness for utility, where fitness is the (generally hypothetical) relation between a phenotypic attribute of the organism and its probability of leaving descendants. It is usually assumed that rationality favors maximization of expected utility, while natural selection favors maximization of expected fitness. (There are qualifications to both of these generalizations, however, as when rationality runs against the limits of cognitive processing [Kahneman and Tversky 1984, Machina 1983] or when selection in a temporally varying environment favors geometric mean fitness [Gillespie 1973; Seger and Brockman 1987]). Note that if the phenotypic attribute involves a decision among alternatives, fitness consequences are necessarily filtered through utility consequences. Thus, the complete causal chain is recursive: natural selection → utility functions → behavior → fitness consequences (which of course loop back to natural selection). The necessary presumption in all of this is that there is a strong positive association between fitness and utility, as a consequence of a history of natural selection (i.e., in terms of a causal loop fitting the general pattern just noted). This is convenient to assume, but difficult to demonstrate.

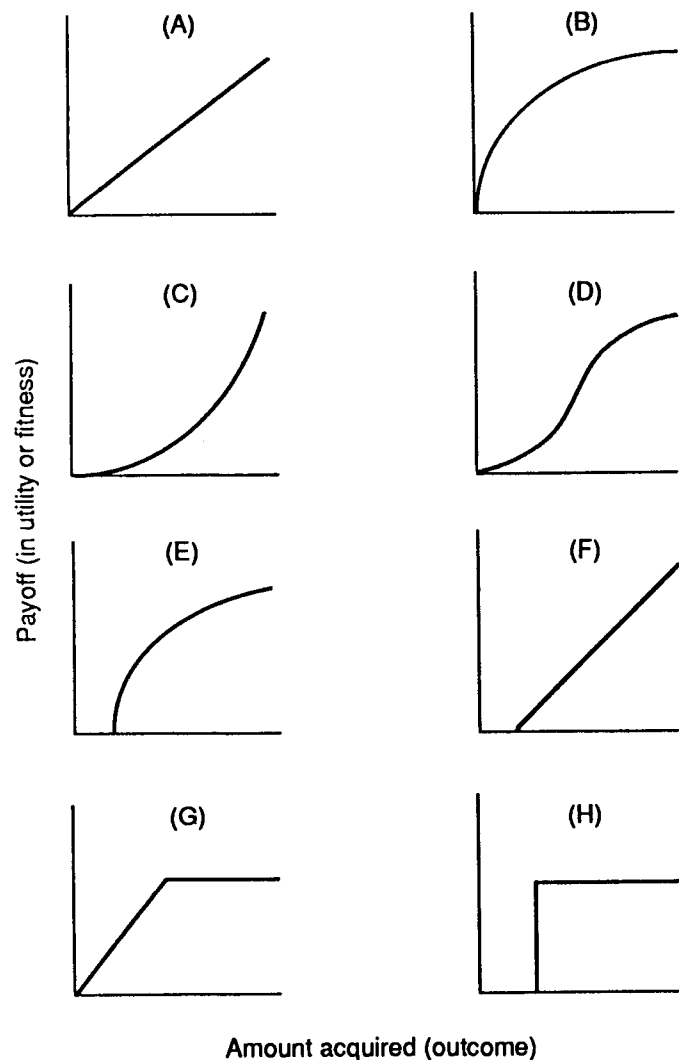


Figure 8.1: Payoff Functions and the Definition of Risk

(A) Linear function (risk-neutral). (B) Simple diminishing returns function (risk-averse). (C) Simple increasing returns function (risk-preferring). (D) Sigmoid function (risk-sensitive). (E) Diminishing returns function with threshold (initially risk-preferring, then risk-averse). (F) Linear function with threshold (initially risk-preferring, then risk-neutral). (G) Concave function: initially linear with plateau (risk-neutral or risk-averse). (H) Step function (risk-sensitive).

is equal to the mean of those outcomes, and no consideration need be paid to the variance (or other moments) of the outcome distribution. In the terminology of risk theory, such a payoff function leads to risk-neutral or risk-indifferent choices. To choose a concrete (if extreme) example, a linear payoff function for food production implies that our forager or farmer is just as happy with a strategy that yields 6,000 kg of food one year in three, and no food at all in the other two years, as with a strategy that yields 2,000 kg every year without fail.

In most cases involving consumable resources like food, a payoff function unlike 8.1A is more realistic.² While a variety of such functions are possible, in terms of risk they are all variations on two themes: curvature and thresholds. Curved functions fall into two main types: concave (bent downwards) and convex (bent upwards). This distinction is important in decision theory because concave payoff functions lead to risk-averse behavior while convex payoffs lead to risk-seeking ones (see Clark, this volume, for an explication). This result is due to the fact that for concave functions, outcome distributions with lower amounts of stochastic variation yield higher expected value than do distributions with the same mean but higher variation, while the opposite holds true for convex payoff functions.

The simplest concave function involves diminishing returns (Figure 8.1B): increases in outcomes yield diminishing marginal values (as measured in payoffs), but the payoffs never become zero or negative (i.e., the function is monotonically increasing). For food resources, we can view this in terms of *gradual* satiation effects: each additional unit (e.g., kg) of food harvested has less value (in utility or fitness).

Conversely, a simple convex function (Figure 8.1C) signifies increasing marginal payoff from each additional unit obtained, a situation that might obtain if the actor is suffering from acute food shortages (the "negative energy budget" discussed by Stephens, this volume) or is using harvested resources in contest competition (Hawkes, this volume). Regardless of the cause, convex payoff functions lead to a prediction of risk-seeking (risk-preferring) decisions.

In many cases we might expect that actors will approach food resources with a payoff function exhibiting a mix between concave and convex payoffs, such as the sigmoid function shown in Figure 8.1D. Here, the initial units of food (or some other resource) obtained in a given period, by reducing the probability of starvation or some other major loss, increase fitness or utility disproportionately, while beyond a certain point diminishing returns

²Whether or not production for exchange (i.e., a commercial rather than subsistence production system) involves non-linear (risk-sensitive) payoff functions is controversial in economics. Since our substantive concern in this paper is with non-commercial foragers, this issue is not important here.

set in.

Thresholds can occur in both linear and non-linear functions (Figure 8.1E and 8.1F). In terms of food, a threshold might indicate that a certain minimum amount must be acquired before any positive payoff is obtained (e.g., a survival minimum). Beyond this threshold, payoffs might be characterized by gradually diminishing returns (Figure 8.1E) or conceivably they might be linear (Figure 8.1F). In the former case, the actor is initially risk-preferring (for variable outcomes distributed across the threshold) and then risk-averse. But with a payoff function like 8.1F, decisions are initially risk-preferring and then risk-neutral; this might be the case if there is a minimum payoff required to "stay in business" but beyond this stochastic variation in outcomes has no effect on utility or fitness (e.g., a well-fed forager may not mind risking a day or two of poor returns in order to get a slightly higher mean return over the whole period).

A threshold effect could also occur at high payoffs (a utility or fitness plateau), and one version of this would be initially linear payoffs until the plateau is reached, beyond which increased outcomes have no effect (Figure 8.1G). In comparison to 8.1B, this signifies *sudden* rather than gradual satiation. For an actor with a payoff function like 8.1G, the attitude toward risk will depend on the dispersion of outcomes: if the interval is only over the initial (linearly increasing) segment, the actor is risk-neutral, while outcomes that include both segments produce a concave function, and hence risk-averse preferences.

The z-score model presented by Stephens (this volume; Stephens and Charnov 1982) and adopted by Winterhalder (this volume; 1986b) assumes a threshold requirement, and predicts risk-seeking or risk-averse preferences depending on the outcome distribution relative to this threshold. However, the z-score model assumes a step function (with the threshold occurring at the step), as in Figure 8.1H, whereas the other threshold functions illustrated here allow for more than two values of the payoff from the range of outcomes.

The meaning of risk adopted here, then, is one based on payoff functions—that is, on the way in which outcomes translate into payoffs. If the payoff function is *linear* from the origin, outcomes translate directly into payoffs, and the decision is unaffected by risk (the actor is risk-neutral). If the function is non-linear (or linear with an initial threshold, as in Figure 8.1F), then variation in outcomes does affect decisions, and the actor will have distinct strategic preferences depending on the outcome and his or her state (see chapters by Stephens and Clark, this volume, for further discussion). The important implication of all this is that it is critical to have some understanding of the payoff function in order to make assertions about decision making under risk—knowledge of probability distributions

(even subjective ones) or stochastic variation in outcomes is not sufficient. While one can make educated guesses concerning the payoff functions characterizing particular actors in particular situations, detailed knowledge of their biology and psychology is obviously preferable.

Uncertainty. Uncertainty is at the same time both simpler to understand and more complex to analyze than risk. The problem of uncertainty is the problem of incomplete information—not knowing all the relevant facts in order to make a fully informed decision about some matter. But uncertainty can come in many forms, and elicit many possible responses. The actor may be uncertain about the *probability* of future states, or even about which future states are *possible*. The actor may be uncertain about the states of the *environment* (at present, or in the future), or about his or her *own* future state (Will I be hungry next week, or well fed?). As for responses, the usual expectation is that actors will take steps to reduce uncertainty by collecting more information, but this raises questions about what steps should be taken, and about the point at which the costs of obtaining information exceed the benefits (a point discussed extensively in Cashdan's chapter). Clearly, the implications of uncertainty are complex and raise a number of distinct issues we cannot discuss here (see also the chapters by Stephens and Clark).

SHARING AND THE PROBLEM OF COOPERATION

Having summarized various aspects of the economic and ecological theory of risk and uncertainty, we want to use this material to analyze selected issues in hunter-gatherer socioecology, particularly those involving resource sharing, land tenure and property rights. These are all topics that have concerned anthropologists for some time, and have often been related to risk and information. Our intention here is to build on this previous work by presenting some formal models of risk management and uncertainty reduction from the perspective of methodological individualism, using the analytical tools of game theory (see also Kaplan and Hill 1985a, and the chapter by Hawkes in this volume).

The Problem

Anthropologists have long noted the extensive food-sharing characteristic of most hunter-gatherers (reviews in Kaplan and Hill 1985a; Smith 1988). Explanations for this phenomenon range from maximization of group survival (Ingold 1980:145) to selfish exploitation (Blurton Jones 1984; Moore 1984; Peterson 1986), but perhaps the most common argument has been

that the risky nature of foraging returns, especially those from hunting, make pooling of the catch individually advantageous. This last view is clearly consistent with the economic theory of risk, given certain assumptions: stochastic variation in foraging outcomes, less than perfect synchrony between different foragers in these outcomes, and diminishing marginal payoffs from food consumption (i.e., a payoff function like that in Figure 8.1B). The risk-reduction hypothesis for food-sharing is developed more fully in the chapters in this volume by Hames, Kaplan et al., and Winterhalder (see also Kaplan and Hill 1985a; Smith 1987; Winterhalder 1986b). It appears to have considerable promise for explaining variation in the degree of sharing empirically noted among hunter-gatherers, but here we are concerned with some of the implications of this hypothesis for social relations.

The problem is this: the risk-reduction hypothesis assumes individual optimization, but ignores conflicts of interest and the potential for some actors to obtain gains (by sharing in others' catch) without paying costs (by contributing shares from their catch). But whenever social interactions take the form that one actor's payoff depends on the strategy pursued by another (and vice versa), strategic analysis via game theory or its equivalent is necessary; in short, we must move from economy *sensu strictu* to political economy. As social theorists from Hobbes onward have argued, the political issue arises because of the potential for cheating or exploitation, and the need to counteract this if the gains from sharing are to be realized in a stable (reliable and persistent) fashion.

Although there are many ways to analyze the problem of cooperation, one approach that has been very fruitful in both social science and evolutionary biology is the theory of games or (in biology) evolutionarily stable strategies. Using this general approach, a great variety of specific models can be constructed, depending on the particular assumptions one makes. An abbreviated list of the alternative assumptions includes the following:

1. Number of players in the game: (a) dyadic (a two-person game); (b) a relatively small group (n -person game); (c) a large population, with each strategy "playing the field" against one or more alternative strategies.
2. Payoff symmetry: the payoff to the players may be (a) symmetric (equal in value), or (b) asymmetric (in some defined way, e.g., by role).
3. Timing of play: each player may make his or her move (a) simultaneously, or (b) sequentially.
4. Frequency of play: any pair or set of players may play (a) only once

- (a "one-shot" model) or (b) repeatedly (an iterated game or "supergame").
5. Stochasticity of payoffs: payoffs may be modeled as (a) certain (a deterministic model) or (b) variable (a stochastic model).
6. Time valuation of payoffs: payoffs may be (a) time-invariant, or (b) they may involve discounting (i.e., later payoffs being worth less).

A realistic model of hunter-gatherer sharing might be one involving asymmetric payoffs in an iterated n -person game with both simultaneous and sequential plays, and with stochastic time-discounted payoffs. But the most realistic model is not necessarily the most useful one, and the set of assumptions just enumerated entails considerable analytical and heuristic complexity. Hence the approach we have chosen is to construct a less realistic model, and then vary some of the assumptions in order to see if this has a major effect on the conclusions.³

It is worth noting that the analytical methods employed here are those characteristic of the theory of evolutionarily stable strategies (Maynard Smith 1982) rather than classical game theory. The relevant distinction is this: in ESS theory, one tests for stability by assuming that groups are homogeneous (with respect to the strategies under investigation) and then asking if a population composed of one strategy (e.g., sharing) can be invaded by a rare mutant strategy (e.g., hoarding). When groups are formed at random, the rare strategy will almost always interact with a group of $n - 1$ adherents to the prevailing strategy, and the payoffs are calculated accordingly. By contrast, in classical game theory strategies are not conceived of as (culturally or genetically) heritable, and hence the initial proportions of the alternative strategies are not constrained to any particular value.

The Resource-Sharing Model

Suppose that there are n foragers who venture forth individually during a given period in search of prey, and return to a central place at the end of the period. Suppose further that during this period every forager has an independent probability p of harvesting C prey, and a $(1 - p)$ probability of coming home empty handed.⁴ After returning to the camp, successful

³For a general defense of simple models in evolutionary biology, see Richerson and Boyd (1987).

⁴Note that two additional assumptions are incorporated here: (1) foraging success is all or nothing rather than being a continuous variable; (2) foragers harvest prey individually rather than cooperatively. The first assumption has no qualitative effect, as shown in Appendix B. The second obviously changes the context of sharing, but it is not clear

Table 8.1: Payoffs for the Two-Person Sharing Game

Play	Action Taken By		Payoff to Ego
	Ego	Other	
Altruism	Share	Hoard	$p^2 \left(\frac{C}{2}\right)^r + p(1-p) \left(\frac{C}{2}\right)^r + p(1-p)0$
Non-social	Hoard	Hoard	$p^2 C^r + p(1-p)C^r + p(1-p)0$
Reciprocity	Share	Share	$p^2 \left(\frac{2C}{2}\right)^r + p(1-p) \left(\frac{C}{2}\right)^r + p(1-p)\left(\frac{C}{2}\right)^r$
Selfish	Hoard	Share	$p^2 \left(C + \frac{C}{2}\right)^r + p(1-p)C^r + p(1-p) \left(\frac{C}{2}\right)^r$

foragers may or may not share their catch with other members of the group. Thus a given individual in the group will receive some amount of prey, X . X represents the outcome (e.g. in calories) for that forager; it can be converted into a payoff in terms of the utility function of a forager, here assumed to follow a power law: payoff = X^r , where r is a positive number. If a forager's utility function is characterized by diminishing returns, $0 < r < 1$, and the forager is risk-averse; if $r = 1$ then $X^r = X$ (a linear utility function) and the forager is risk-neutral, while $r > 1$ implies increasing returns and a risk-seeking forager.

For simplicity, let us first suppose that there are two identical foragers, labeled "Ego" and "Other". Then the probabilities for each of the four possible outcomes can be stated quite succinctly: both successful = p^2 , only Ego successful = $p(1-p)$, only Other successful = $p(1-p)$, and neither successful = $(1-p)^2$. The total expected catch (for the two foragers) is thus

$$p^2 2C + 2p(1-p)C + (1-p)^2(0) = 2pC \tag{8.1}$$

where the first term represents the outcome when both foragers are successful (times the probability of this occurring), the second term that for the two intermediate cases (one or the other, but not both, being successful), and the last term (equal to zero) when neither is successful.

The decision that now faces each forager is whether or not to share, given that he/she has been successful (has returned to camp with C). Since we have assumed symmetrical payoffs, this decision is the same from each player's point of view. The payoffs will vary according to what Ego and Other each do, and thus there are four possible payoffs, each consisting of four terms (the last one, when neither forager is successful, always equalling zero). For the two-person game just described, the payoff structure takes the form given in Table 8.1.

what effect this has on the risk-reduction argument; this effect needs to be analyzed explicitly, something not attempted here.

Note that when foragers are risk averse ($r < 1$), the payoffs in Table 8.1 are arranged in order of increasing value: that is, using the first letter of the play (pair of strategies) to designate the payoff to Ego (e.g., A = payoff to Ego from the Altruism play), we obtain a rank ordering that mnemonically follows the alphabet, $A < N < R < S$. (A proof is provided in Appendix A.) A pays less than N because the altruist gets only an equal share of his/her catch, while a hoarder paired with another hoarder consumes all of his/her catch. Similarly, R pays less than S because the hoarder gets all of his/her own catch plus half of the sharer's, while members of the sharer/sharer pair get only the equal shares in each case. Both of these rankings (that is, $A < N$ and $R < S$) are due purely to the "free-rider problem" that arises when a selfish individual takes advantage of a collective good without paying the costs of providing same; they do not depend on risk averseness.

The advantage of reciprocity over the non-social pairing is not due to free-riding, however (there is none); rather, it is due to risk reduction. In other words, the expected outcomes for hoarders paired with hoarders and sharers paired with sharers are equal, but their expected *payoffs* are not (except when $r = 1$ [i.e., risk neutrality], in which case $N = R$). For risk-averse foragers ($0 < r < 1$), sharing results in less variance, and thus higher mean payoffs. Conversely, for risk-seeking actors, $R < N$.

The two-person sharing game can be represented via a standard game theory payoff matrix (following the convention that Ego's actions are listed by row while Other's are listed by column, and payoffs shown are those to Ego only) as follows:

	Share	Hoard
Share	$p^2(2C/2)^r + p(1-p)2(C/2)^r$	$p^2(C/2)^r + p(1-p)(C/2)^r$
Hoard	$p^2(3C/2)^r + p(1-p)[C^r + (C/2)^r]$	$p^2 C^r + p(1-p)C^r$

What does this model tell us about the viability of sharing as a strategy of risk reduction? Since the payoff rank order is $A < N < R < S$, we might expect every player to want to play Ego's role in S —that is, to receive shares from one's partner but keep all one's catch to one's self. But of course S is preferred by *every* player, which can only mean that S is unstable and will never persist, since hoarding by Ego must be matched by sharing on the part of the other player in order to yield S . In symmetrical fashion, unilateral sharing (A for Altruism) is everyone's lowest-ranked alternative, and will not persist. This means we can concentrate on the strategies yielding R and N . Since $R > N$, we might suppose that any rational forager would choose the Reciprocity strategy. But the logic of game theory reveals that this is not so: for the best response to "share" is to play "hoard" (and thus

receive the maximum payoff, S), while the best response to "hoard" is also to play "hoard" (thus receiving N , which is still better than A). In other words, *no matter what the other player's move*, it is always best to hoard.

The paradox here is what game theorists call "the prisoner's dilemma" (hereafter, PD for short), where self-interested rational (or fitness-maximizing) players, in choosing what is best for themselves, will produce an outcome that is only second best (if that) for the collectivity of players. A PD matrix characterizes the sharing game not only because of the costs of sharing, but because of the unconditional nature of the game: one has to share without any assurance that one's recipients will reciprocate. The lack of sanctions provides the opportunity for cheating, and thus introduces uncertainty (in this case social in origin) into the bargain. In the face of this uncertainty, even an actor who is not so ruthless as to take shares from his fellows and then withhold his own catch might still feel forced to hoard in order to avoid the "sucker's payoff" of unilateral Altruism (A).

But this is a troubling conclusion, given the empirical evidence for widespread sharing of resources, particularly risky food resources, within small-scale human societies (as documented in detail in the chapters by Hames and Kaplan et al., this volume). Is it possible that changing one of the simplifying assumptions incorporated in the present model would lead to qualitatively different conclusions? In a moment we will argue that changing the model either to allow repeated interactions or the possibility that humans are not purely self-interested may allow cooperation to persist.

First, however, let us consider several assumptions that do *not* make a difference. In Appendix B we present a version of the resource-sharing game suggested by Alan Rogers which allows groups to be of any size rather than just two, allows hunting success to vary continuously over a range of values rather than just success or failure, and allows utility to be an arbitrary function of food consumption. We show that as long as players are risk averse, this more general model is what game theorists call an n -person prisoner's dilemma, and leads to the same qualitative conclusion as the simpler one analyzed above: everybody would benefit from sharing, but sharing will not result from individual, self-interested choices. In fact, both the individual temptation to free ride and the group gains from sharing increase with the size of the group.

So far we have assumed that individuals interact only once. Food sharing among hunter gatherers involves repeated episodes of sharing over an extended period of time. Recent analyses of the prisoner's dilemma (Axelrod 1980, 1984; Axelrod and Hamilton 1981; Brown et al. 1982; Aoki 1983; Peck and Feldman 1985; Sugden 1986; Boyd and Lorberbaum 1987) suggest that cooperation can arise via reciprocity when *pairs* of individuals interact repeatedly. These results suggest that the evolutionary equilibrium in this

setting is likely to be a contingent strategy which allows players to discriminate in sharing, by remembering past interactions and refusing to share with those who have cheated them in the past. Recently, one of us (Boyd and Richerson 1988) has analyzed a model in which larger groups of individuals interact repeatedly in a prisoners dilemma. This analysis suggests that the conditions under which reciprocity can evolve become extremely restrictive as group size increases above a handful of individuals. However, since hunter-gatherer groups are quite small and cohesive it is quite possible that the observed sharing results from reciprocity between self-interested individuals.

The ethnographic evidence for mechanisms to guard against free-riding is substantial. They take many forms: the bickering and recriminations that so frequently surround the distribution of meat and other goods (e.g., Marshall 1961), the constant testing of the willingness to share expressed through "demand sharing" (e.g., Peterson 1986) or gift-giving relationships (e.g., Wiessner 1977, 1982), the formation (and dissolution) of formal trading partnerships (e.g., Burch 1970), and so on. The political economy of reciprocity among hunter-gatherers (or other "egalitarian" peoples) has yet to be examined systematically using the logic of game theory and collective action, but it seems likely that doing so will uncover tremendous complexity and tensions beneath the bland exterior of "generalized reciprocity."

The simple model outlined above also assumes that people only value their own food consumption—they are completely indifferent about the consumption of others in their group. Moreover, they value food only for its caloric value, not, for example, the prestige associated with being a successful hunter or generous sharer. Relaxing these assumptions can expand the range of conditions under which sharing is evolutionarily stable. For example, Kreps et al. (1984) analyzed a model of the repeated prisoner's dilemma which suggests that even a very low frequency of "irrational" altruistic individuals can give rise to widespread cooperation in an otherwise selfish population. While such "prosocial" motivations are not consistent with the simplest sociobiological models of human behavior, they readily arise in Darwinian models which allow for cultural transmission and evolution (Boyd and Richerson 1985, in press).

The one-shot PD model, while not a realistic analysis, is a heuristic one. In particular, it uncovers the major weakness of functionalist social theory: the assumption that self-interested actors will cooperate in the provisioning of a public good simply because it would be mutually beneficial to do so, or that (put in other terms) the observation of collective benefits suffices to explain individual actions producing those benefits. In contrast, existing game theory suggests that intensive and on-going sharing will be restricted to situations meeting one of the following sets of conditions: (1)

relatively small groups whose members know each other, and each other's past history of reliable reciprocation, well (which appears to characterize most hunter-gatherers) and who employ long memories and contingent sharing to stabilize systems of reciprocity against the potential ravages of free-riding; or (2) societies that have undergone cultural (or, less plausibly, genetic) evolution favoring group-interested values and beliefs, sufficient to counteract genetically-transmitted biases for selfish behavior.

RISK AND RECIPROCITY BETWEEN LOCAL HUNTER-GATHERER GROUPS

Sharing Between Local Groups

In the risk-reduction model just presented, the two most important variables determining the advantages of sharing are the degree of risk experienced by each actor (as determined by variation in food harvest and the utility function converting this variable outcome into payoff), and the degree of synchrony (temporal correlation) in resource income between actors (see Kaplan and Hill 1985a and Winterhalder 1986b, this volume, for further discussion). Thus far, this risk-reduction model of resource sharing has been restricted to social interactions *within* local groups (settlements, camps, or bands). How might these factors apply to sharing between members of *different* local groups?

Whereas short-term asynchrony may be common among the members of a single local band, prolonged asynchrony, with more marked fitness effects, may often be much greater between members of different bands. That is, within a given region, the asynchrony of foraging success over a period of several days or weeks often increases as the distance between any two individuals sampled increases (Harpending and Davis 1977). The ecological causes for this are varied, but include such factors as patchy rainfall, movement of game, and stable habitat differences in seasonal production or resource availability. Increasing asynchrony as a function of distance implies that risk reduction through sharing should be greatest if conducted over longer distances.⁵ Yet the costs of such sharing, especially transport

⁵Winterhalder's analysis (1987, this volume), as well as empirical results for the Ache (Hill and Hawkes 1983), indicate that it takes a surprisingly small number of foragers pooling their catch in order to realize most of the available gains of risk reduction. These findings might appear to suggest that any further sharing beyond local-group boundaries would be of little value. We do not think this follows, however, given the expanded temporal and spatial scale implied by between-band sharing. The potential gains from sharing depend not only on group size, but on differences between potential sharers in their foraging returns at any given point in time. This difference would usually be substantially greater between members of different bands than within bands, assuming (as seems reasonable) that differences in productivity at a given time generally increase

cost, should also increase with distance, particularly under the conditions of low population density and foot transport characteristic of many hunter-gatherers. This means that risk reduction through sharing of resources may often be most costly precisely where it would be most effective—between rather than within local hunter-gatherer bands.⁶

Under these conditions, there would appear to be a selective advantage to the development of some means of reducing risk other than inter-band resource transfers. Put another way, many hunter-gatherers—even those living in a region characterized by fluctuations in resource availability that decrease in synchrony as a function of distance—may find long-distance (inter-band) sharing too costly (in transport time and effort) as compared with its benefits (of risk reduction). The obvious alternatives are (1) local storage, and (2) movement of *people* (rather than goods) between local groups. These each have their own costs and advantages, of course. Some of the conditions under which one or the other of these alternatives might be favored are discussed by Binford (1980), Cashdan (1985), Ingold (1983), Kaplan and Hill (1985a) and Winterhalder (this volume).

The second alternative—moving foragers between groups—is the one that concerns us here. Anthropologists have often remarked on the extensive visiting and frequent residential shifts noted among band societies, and a number have suggested that this characteristic of fluid local-group composition can be explained as an adaptation to equalize the consumer/resource ratio in situations where local resource availability fluctuates markedly and asynchronously (e.g., Lee 1972; Yellen and Harpending 1972). In this formulation, an extensive network of kin ties and other alliances combined with a communitarian attitude serves to ensure that all have equal access to the land and its fruits.⁷

This "equal access" view of hunter-gatherer land use, widespread though it is, has a number of problems. For one, it overlooks the diversity of

as a function of distance between foraging sites.

⁶Throughout this section (and beginning with the section title), for simplicity of expression we sometimes employ language that (if taken literally) could be construed as referring to collective actors and payoffs. However, we do not mean to imply, nor do our analyses require, that collectivities such as bands or "land-owning groups" actually act as one. Rather, our intent is to analyze relations between members of different local groups (including those revolving around land tenure and access to unharvested resources) in a manner consistent with methodological individualism (as discussed further in Smith 1988). While this approach has its own limitations (as when a group of "visitors" elicits a collective response by a group of "hosts"), we believe it is a sounder starting point for analyzing variation in hunter-gatherer land use than is methodological collectivism.

⁷In a closely parallel fashion, the transfer of resources through feasting and potlatching (e.g., Harris 1974; Piddocke 1965) has been portrayed as a means of reducing income variation between groups, with little attention to the need for controls on cheating, or to whether the transfers actually reduce risk.

systems of land tenure and property rights described for hunter-gatherers (see discussion in Smith 1988). More germane to our present concerns, this view appears rather naive in light of economic and evolutionary theory concerning collective action. Borrowing from the previous analysis, it would appear that the "land-sharing game" would have much the same payoff structure as the "food-sharing game." That is, if a host "shares" his land with a visitor, presumably at some cost of reduced stock of unharvested resources (as well as sharing some harvested ones, as is typical when visitors arrive in a camp), he does it with expectation of future reciprocation. But what is to prevent the visitor from selfish failure to reciprocate, through subsequent enforcement of territorial claims? If there is a potential long-term gain to both parties through reciprocal access (i.e., the reduction in risk from fluctuation in foraging income, which could be realized if host and visitor areas fluctuate asynchronously), how can this potential gain from reciprocity be realized in light of the potential loss from free riders? Do we once again face a PD payoff matrix, requiring the same conditions for stable cooperation (either discrimination against cheaters and an expectation of indefinite future opportunities for interaction, or the evolution of altruistic motivations) that we encountered in the case of within-band food-sharing?

The intuitive answer would seem to be yes: what, after all, is the difference between sharing food and sharing land? There are elements of the land-sharing (or land-tenure) game that are not found in the simple food-sharing game, however. For one, the host-visitor relationship is not really symmetrical, for two reasons: (1) hosts have better (or at least more current) information on local resources than do visitors; (2) in general, it is likely that one spends more time on one's own land (i.e., as a host) than on the land of others (i.e., as a visitor). In addition, there are ongoing costs associated with the "exclude" (non-sharing) strategy that cannot be ignored in the land-tenure game.⁸ These elements considerably complicate formulation of a model and analysis of stability conditions, but a preliminary analysis is still possible.

⁸The exclusion costs incorporated into the land-tenure game are not really absent in the food-sharing game, since denying others a share of one's catch can be costly (in terms of concealing and/or monitoring stores, resisting verbal or physical pressures, etc.). Blurton Jones (1984, 1987c) has argued that these costs can lead to a form of resource division (which he terms "tolerated theft") under the same conditions of asynchronous harvest and diminishing payoff functions implicated in the risk-reduction hypothesis. (For an attempt to distinguish the predictions of the two explanations, see Kaplan and Hill 1985a.) While recognizing the logic of tolerated theft, our assumption here is that the costs of territorial exclusion are higher (more continuous and extensive) than those involved in hoarding harvested resources, thus making their explicit inclusion in the land-tenure game more important than in the food-sharing game. This assumption can of course be questioned, and the inclusion of defense costs for non-sharers (and counter-sanctions by others) would be a useful next step in ESS analyses of the sharing problem.

The Land Tenure Model

Consider a simple model in which there are two foragers each occupying different territories (defined as an area where one has rights through residence or inheritance, and can play the "host" role). For simplicity we treat only dyadic interactions (i.e., the model is a two-person game).⁹ As with the food-sharing game, we assume that foraging returns are stochastic. We assume further that there is an independent probability q that each territory is productive.

When ego's territory is productive, he/she has a potential payoff of H . When the neighbor's territory is productive, Ego's potential payoff from that area (i.e., as a visitor) is V . As host, Ego faces two potential costs: T = the cost of territorial defense, and F = the cost of allowing visitors free access to the resources of one's own area (for simplicity, we define these as mutually exclusive options). It seems reasonable to assume that T is a cost that must be paid whenever Ego's area is yielding (i.e., a monitoring cost); when the home area is unproductive, Ego has little motivation to defend the area, while changes in the productivity of Other's area are not known to Ego and thus cannot affect Ego's decision to monitor the home area against intrusion. On the other hand, we feel the most reasonable assumption about F is that it is only subtracted from Ego's foraging income when there *is* some income (i.e., when H is obtained) *and* Other's area is unproductive (hence motivating Other to seek resources in Ego's area). The payoffs discussed below reflect these assumptions. Finally, as with the food-sharing game, we assume that all outcomes are converted into payoffs via a utility function, $U(x)$.

As before, we can label the payoffs (resulting from interacting pairs of strategies) A (for Altruistic hosts that allow non-reciprocating visitors), N (the Non-social strategy of mutual exclusion), R (the Reciprocal access strategy), and S (Selfish hosts who exclude visitors whose resources they exploit). For each of these payoffs, four different probabilistic values need to be summed: the payoff when both areas yield successful harvests, those when only Ego's area or only Other's area yields, and that when neither yields (always equal to zero). The resulting payoff schedule (again, listing only the payoffs to Ego) is given in Table 8.2.

Turning then to the combination of strategies designated by N (mutual territorial exclusion), what conditions are required for it to be evolutionarily stable? (This can be rephrased by asking under what conditions the land-tenure game will have a PD payoff structure.) First, for N to be stable,

⁹However, it is worth noting that human territoriality is usually *group* territoriality, rather than the simple dyadic interaction modeled here; this implies that territorial exclusion (or any sort of collective property rights) is a public good, which creates a second-order collective action problem not analyzed here (see Brown 1982; Taylor 1987:26ff).

Table 8.2: Payoff Schedule for the Two-Person Land Tenure Game

Strategy		Productive areas	Probability	Outcome
Ego	Other			
Allow (R)	Allow	Both areas	q^2	H
		Home only	$q(1 - q)$	$H - F$
		Other only	$(1 - q)q$	V
		Neither	$(1 - q)^2$	0
Total expected payoff: $q\{qU(H) + (1 - q)U(H - F) + (1 - q)U(V)\}$				
Exclude (N)	Exclude	Both areas	q^2	$H - T$
		Home only	$q(1 - q)$	$H - T$
		Other only	$(1 - q)q$	0
		Neither	$(1 - q)^2$	0
Total expected payoff: $qU(H - T)$				
Allow (A)	Exclude	Both areas	q^2	H
		Home only	$q(1 - q)$	$H - F$
		Other only	$(1 - q)q$	0
		Neither	$(1 - q)^2$	0
Total expected payoff: $q\{qU(H) + (1 - q)U(H - F)\}$				
Exclude (S)	Allow	Both areas	q^2	$H - T$
		Home only	$q(1 - q)$	$H - T$
		Other only	$(1 - q)q$	V
		Neither	$(1 - q)^2$	0
Total expected payoff: $qU(H - T) + q(1 - q)U(V)$				

it must yield a higher payoff than does A (i.e., a shift to playing access against exclude must not pay). This requires that

$$qU(H - T) > q\{qU(H) + (1 - q)U(H - F)\} \tag{8.2}$$

or (dividing by q)

$$U(H - T) > qU(H) + (1 - q)U(H - F) \tag{8.3}$$

Next, $S > R$ requires that

$$qU(H - T) + q(1 - q)U(V) > q\{qU(H) + (1 - q)U(H - F)\} + q(1 - q)U(V) \tag{8.4}$$

or (subtracting common terms and dividing by q)

$$U(H - T) > qU(H) + (1 - q)U(H - F) \tag{8.5}$$

Thus, Ego will be better off excluding as long as (8.5) is satisfied. If $U(x)$ is monotonically increasing (so that more food is always better than less), then (8.5) can be satisfied only if $T < F$. In other words, defending a territory will be favored only if the cost of defense is less than the cost of allowing others to exploit your territory. However, this is only a necessary condition. In addition the probability that the neighbor's territory is productive must be less than a threshold value, q_{crit} , where

$$q_{crit} = \frac{U(H - T) - U(H - F)}{U(H) - U(H - F)}$$

Notice that if territory defense is costless ($T = 0$), (8.5) is satisfied as long as U is monotonically increasing. If $T > 0$, there must be some chance that your neighbor's territory will fail. Otherwise (by the assumption made earlier) there is no reason to pay the cost of defense.

The next thing we can ask is what effect risk has on the predictions of this model. Assume that $T < F$. Then for given values of H , T , and F , q_{crit} increases as U becomes more concave.¹⁰ This means that making ego more risk-averse expands the conditions under which exclusion is the better strategy. Intuitively, risk-averse individuals tend to prefer a certain small loss T to the chance q of a larger loss F .

¹⁰The proof of this assertion is simple. We are always free to pick two values of a utility function to establish the origin and scale of utility measurement. Set $U(H) = 1$ and $U(H - F) = 0$. These points remain fixed as we change the shape of U . Then increasing the concavity of $U(\cdot)$ causes the value of $U(H - T)$ to increase, and therefore the value of q_{crit} to increase.

Next, let us consider the conditions under which allowing access is mutually beneficial (i.e., what payoff combinations lead to $R > N$). This requires that

$$q\{qU(H) + (1 - q)U(H - F) + (1 - q)U(V)\} > qU(H - T) \quad (8.6)$$

which reduces to

$$(1 - q)\{U(H - F) + U(V) - U(H)\} > U(H - T) - U(H) \quad (8.7)$$

This last result is very interesting. First, note that the right-hand term in (8.7) is the net cost of defense (in units of utility or fitness). Now, suppose that defense is costless, so that the right-hand side is zero. Then allowing access to one's area is mutually beneficial whenever the term in braces (which we can call the "gains from trade") is positive. To see what this means, consider the special case in which

$$H - F + V = H \text{ or } F = V$$

This says there is a fixed amount H of resource on a territory, and if you allow others on your territory you get $H - V$ and they get V . (If we set $V = H/2$ then this is analogous to the sharing game). Then it follows that the gains from trade are positive for any concave utility function. Risk-averse individuals would rather have two non-zero portions that sum to the whole than the whole plus nothing.

Now maintain the assumption of a fixed amount of resources, but allow T to be positive. Then the right hand side of (8.7) is negative, and (8.7) can be satisfied even if people are somewhat risk-preferring. Thus, risk-averse payoff functions increase the mutual benefit of reciprocal access, but they are not necessary for such a system to be mutually beneficial.

What if we relax the assumption of a fixed amount of resources that can be harvested per territory? If the visitor and the host produce more resource than the host would alone, this implies that $V > F$. It seems to us that this will be commonly true when there is an important labor input to foraging, or when resources are abundant relative to demand (in this case, the combined demand of visitor and host). In fact, if depletion and interference effects are negligible it could be that F is small and V is approximately equal to H . When $V > F$, sharing can be beneficial even if individuals are risk preferring. Finally, it is also possible that $V < F$. This might result from interference between visitors and hosts, or from the fact that visitors might overexploit the resources because they have a smaller long-term interest in the territory. When $V < F$, our model indicates that sharing may not be beneficial even though people are risk-averse.

There is some reason for hoping that these qualitative predictions are the sort that one might be able to test with cross-cultural data. For example, one could assume risk-averse preferences, and then attempt to estimate the relative magnitudes of T , V , and F based on territory size, technology, subsistence resources and any other relevant factors.

To sum up our discussion of the land tenure game, the results indicate that the payoff structure is not necessarily that of a prisoner's dilemma. This means that, in contrast with the earlier analysis of the sharing game, Reciprocity does not necessarily pay less than the Selfish strategy, even in the one-shot case. In essence, if our models are qualitatively correct, the conditions under which reciprocal access to land can be stable are considerably broader than those for sharing of harvested resources.

Mutual territoriality is stable only when three conditions are simultaneously met: (i) payoffs are a monotonically increasing function of food harvest (more is always better than less); (ii) the costs of territorial defense are less than those of allowing free access ($T < F$); and (iii) the probability that one's neighbor's area fails ($1 - q$) is not too high.

A system of reciprocal access is beneficial to both parties if what we have termed the "gains from trade" are greater than the costs of territorial defense. Since these components are measured in units of utility (or fitness), the actors' risk preferences as well as the probabilities of various environmental states enter into the calculations. Our model suggests several alternative conditions under which mutual access will be beneficial: (i) risk-averse preferences, zero-sum foraging returns ($F = V$), and no territoriality costs ($T = 0$); (ii) risk neutrality (or even slight risk preference), zero-sum foraging, and positive territorial costs; or (iii) reduced competition when visitors are allowed access ($V > F$).

These predictions can be compared to some previous analyses of hunter-gatherer land tenure. The "economic defendability" model (Dyson-Hudson and Smith 1978) incorporated stochastic variation in territory yields and territory defense costs, and overlapped largely with conditions (i) and (ii), but did not pay explicit attention to strategic interaction or evolutionary stability. Condition (iii) has been highlighted in some other, more "mutualistic" views of territorial systems (e.g., Cashdan 1983; Ingold 1986). This last condition can be facilitated by various social institutions, strategies to reduce F that could be attractive to visitor and host alike. Briefly, these involve prevention of foraging area overlap through conventions of requesting permission from hosts before foraging on their territory, something visitors would have incentives to do given the presumed greater stock of information on foraging conditions held by the host (see Cashdan 1983 and Smith 1981, 1988 for further discussion). However, like group territoriality (which is a means of reducing the cost of T), information sharing raises a

collective action problem beyond the scope of this paper.

SUMMARY AND PROSPECTS

The widespread occurrence of food sharing and reciprocal land access among hunter-gatherers (and some other human societies) presents an intriguing problem in ecology and economics. On the one hand, anthropologists have long argued that these practices are designed to reduce or buffer subsistence risk, and some theoretical and empirical results presented elsewhere in this volume certainly conform to that understanding. On the other hand, both neo-Darwinian and neo-classical theory caution against the “functionalist fallacy”—that is, using aggregate welfare alone to account for individual actions, without reference to some process that would lead individuals to act in the interest of the group. We have analyzed decisions to share (or not share) resources and land using evolutionary game theory, as a way of avoiding the functionalist fallacy and adhering to methodological individualism.

The critical issue with sharing, as with any form of voluntary reciprocity, is that one cannot be sure that others will reciprocate one's contributions. In our model of food sharing, we have incorporated simple but explicit formalisms for (stochastic) outcomes, payoffs (diminishing returns), and sharing rules (conditional vs. unconditional). The result, in either the dyadic or n -person versions, is a prisoner's dilemma: given risk-averse preferences, reciprocal sharing yields the highest average payoff, but is vulnerable to free-riding. In light of previous theory (Axelrod and Hamilton 1981; Boyd and Richerson 1988), this suggests that sharing will only be stable if groups are small, sharing is conditional (on past reciprocity), and interactions are indefinitely repeated. It is not clear whether hunter-gatherer food sharing actually meets these conditions, or involves cultural evolution for group-beneficial behavior. Other issues not directly tackled by our analysis include the potential free-riding that could arise if individuals “slack off” on their own foraging and rely on the harvests of others, and the effect of including defense costs for refusal to share (Blurton Jones 1987c).

In the case of land tenure, our model incorporates costs (of defense and of reduced foraging returns) as well as stochastic outcomes (in territory productivity). In contrast to the sharing game, this analysis yields a broader range of possible stable outcomes, from mutual exclusion to mutual reciprocity, depending on the relative values of defense costs and gains from trade (i.e., reciprocity) as well as preferences over risk. While the inclusion of defense costs helps explain this partial “escape” from the prisoner's dilemma, another important factor is the difference between sharing land and sharing harvested resources. The sharing of harvested resources

involves a transfer of goods (and hence, in the short-run, some degree of “altruism”), while sharing of land may have little impact on the host's harvest. However, our model is restricted to dyadic interactions, and thus does not include such realistic complications as communal land tenure, negotiation of property rights via kinship ties, and the like. These, as with the additional complications noted above for resource sharing, await future analysis.

APPENDIX A: PROOF OF THE PREFERENCE RANKINGS IN THE TWO-PERSON SHARING GAME

Here we present a relatively informal proof of the preference ranking asserted in the text concerning the two-person version of the sharing game (i.e., the assertion that it has a prisoner's dilemma structure: $A < N < R < S$ —see text and Table 8.1 for definition of strategies and their payoffs). The proof proceeds by deriving the three inequalities in turn.

(1) To show that $A < N$, we must show that

$$p^2(C/2)^r + p(1-p)(C/2)^r < p^2C^r + p(1-p)C^r \quad (8.8)$$

which by cancelling the probabilities reduces easily to

$$C/2 < C \quad (8.9)$$

and thus is true given positive values for C and r .

(2) For $N < R$, it must be true that

$$p^2C^r + p(1-p)C^r < p^2(2C/2)^r + p(1-p)2(C/2)^r \quad (8.10)$$

Simplifying and rearranging, we have

$$C^r < 2(C/2)^r \quad (8.11)$$

Taking the logarithm of each side,

$$r \log C < \log 2 + r \log C - r \log 2 \quad (8.12)$$

which is satisfied as long as $r > 1$. Since this condition requires that the payoff function be concave, the inequality holds as long as decision makers are risk averse.

(3) Finally, we must show that $R < S$, meaning

$$p^2(2C/2)^r + p(1-p)2(C/2)^r < p^2(C+C/2)^r + p(1-p)[C^r + (C/2)^r] \quad (8.13)$$

which by rearranging becomes

$$p^2 C^r < p^2 (3C/2)^r + p(1-p)[C^r - (C/2)^r] \quad (8.14)$$

and then further reduces to

$$C^r < (3C/2)^r + [(1-p)/p][C^r - (C/2)^r] \quad (8.15)$$

Since (for any positive values of these variables) the last term in (A.8) is positive, and the first term is less than the second, the inequality holds.

APPENDIX B: GENERALIZING THE SHARING GAME TO THE N -PERSON CASE

Here we analyze a model first suggested by Alan Rogers (personal communication) to determine the payoff orderings of the sharing game when there are more than two individuals interacting.

Consider a group of n foragers who gather resources over some time period. The i th forager returns with z_i units of prey (e.g., in kg or kcal). For simplicity, we assume that the z_i are independent, and have identical distributions. As in the two-person case individuals use one of two strategies: they share (S) their catch with other members of the group, or they hoard (H) all of their own catch for themselves. An individual who consumes x total units of resource achieves a utility level $U(x)$.

Let $V(S | j)$ and $V(H | j)$ be the expected payoffs to a sharer and a hoarder (respectively) given that $j-1$ individuals in the group share. Then adopting the convention that Ego is always numbered 1, we have:

$$V(S | j) = E \left\{ U \left[\sum_{i=1}^j z_i/n \right] \right\} \quad (8.16)$$

and

$$\begin{aligned} V(H | j) &= E \left\{ U \left[z_1 + \sum_{i=2}^j z_i/n \right] \right\} \\ &= E \left\{ U \left[(1 - 1/n)z_1 + \sum_{i=1}^j z_i/n \right] \right\} \end{aligned} \quad (8.17)$$

We want to understand the conditions under which sharing is beneficial to the group, while at the same time hoarding will be chosen by rational, selfish individuals. Put another way, we want to know when this game is what game theorists call an n -person prisoner's dilemma. This requires that at least three conditions hold (Taylor 1987):

- (i) $V(S | j) \leq V(H | j)$: Individuals are better off hoarding no matter what the other players do.
- (ii) $V(S | n) \geq V(H | 1)$: Hoarders in a group of all hoarders are worse off than sharers in a group of all sharers.
- (iii) $V(S | j) \geq V(S | j-1)$: Sharers are always better off if more individuals share.

Many authors also require that

- (iv) $V(H | j) \geq V(H | j-1)$: Hoarders are always better off if there are more sharers.

First consider condition (i). Using the definitions, it is easy to show that $V(S | j) > V(H | j)$ as long as U is monotonically increasing and the z_i are positive. A very similar calculation shows that (iii), $V(S | j) > V(S | j-1)$ and (iv), $V(H | j) > V(H | j-1)$ also hold under the same conditions.

The last step is to prove (ii), that $V(S | n) \geq V(H | 1)$. Using the definitions this requires:

$$E\{U\{z_1\}\} \leq E \left\{ U \left[\sum_{i=1}^n z_i/n \right] \right\} \quad (8.18)$$

To prove this let x be a random variable that takes on the values z_1, \dots, z_n with probability $1/n$. Then

$$\sum_{i=1}^n z_i/n = E\{x\}$$

Jensen's inequality says that $E\{U(x)\} < U(E\{x\})$. Thus

$$U \left[\sum_{i=1}^n z_i/n \right] \geq \sum_{i=1}^n U\{z_i/n\} = U\{z_i\} \quad (8.19)$$

since the z_i are identically distributed.

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