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Authors
Lejano, R. P
Ingram, H.

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Modeling the commons as a game with vector payoffs

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Raul P. Lejano
Department of Policy, Planning, and Design, University of California, Irvine, USA

Helen Ingram
Departments of Political Science and Policy, Planning, and Design, University of California, Irvine, USA

Abstract

Since Hardin first formulated the tragedy of the commons, researchers have described various ways that commons problems are solved, all based on the model of individual rationality. Invariably, these institutional solutions involve creating some system of property rights. We formulate an alternative model, one not founded on property rights but on decision-making around so-called vector payoffs. The model is formalized and an existence proof provided. The new model is shown to be effective in explaining some anomalous results (e.g., unanticipated cooperation) in the experimental games literature that run counter to the rational model. We then use the case of the buffalo commons to illustrate how the new model affords alternative explanations for examples like the rise and fall of the buffalo herds in the Great Plains. We find the vector payoff model to complement, though not displace, that of individual rationality.

Keywords

commons; game theory; rationality: vector payoffs

1. Introduction

It has been more than four decades since Garrett Hardin first wrote about the remorseless logic that drove environmental despoliation (Hardin, 1968). His model depicts a group of herders, all using a common pasture, and the utilitarian mode of reasoning that moved each herder to put out more cows than the pasture could hold. The model is a general one, used to diagnose a wide variety of social problems, from population growth to global warming, most often concluding with either of two opposing prescriptions – either strong state control or privatization of the domain.

Corresponding author:
Raul P. Lejano, Department of Policy, Planning, and Design, SE-I, Room 218G, University of California, Irvine, CA 92697-7075, USA.
Email: rplejano@yahoo.com

And yet, scores of real-world examples have since been described which suggest a third, community-based solution to this dilemma. The most compelling explanation, backed by considerable case study work, was forwarded by Elinor Ostrom, who attributed solutions to the repeated nature of these games (Ostrom, 1990). Such explanations invariably build on the same basic premise of individual utility maximization. In this paper, we build yet another model, based on a more complex mode of decision-making, one where a dimension of fairness seems to be built in. In our model, individuals make decisions on the basis of a payoff vector, where individual utility is but one dimension. Our model complements the more traditional one of individual rationality and explains some anomalous results in the literature that run counter to the latter.

2. The tragedy of the commons

We first summarize Hardin's example of an open-access commons, to show how the game changes when we move from scalar payoffs to vectors. In Hardin's game, each herder's decision problem concerns how many cows to raise on the pasture.1 There is an optimal, sustainable number of cows per herder that yields the greatest aggregate present value. More than this optimal number of cows, and the pasture suffers congestion effects – i.e., cows get in each other's way, spend too much time foraging, become leaner, etc. The tragedy is that each puts out too many cows and ruins the pasture for all, a universally Pareto inefficient outcome.

The classic two-person illustration of the commons game is represented in strategic form in Table 1, where each player considers two strategies (C, to cooperate and send out the responsible number of cows, or NC, not to cooperate and overgraze). Table 1 shows the payoffs (5, 5), encircled to indicate the equilibrium outcome of the game.

The tragedy results from institutional designs that lock people into unsustainable resource use. The culprit, according to Hardin, is the absence of property rights (a point shown earlier by Coase, 1960; also see Dasgupta and Heal, 1979; Gordon, 1954). This leads to two classic solutions to the game, the first being complete state control, mandating the socially efficient solution. The second is complete privatization, where the use of fences or other means of exclusion eliminates the externality. Hardin also describes a number of variations on how private and public systems of rights might be employed (e.g., auctions, fees, etc.). To Hardin's universal prescriptions of the market and the state, Ostrom added a third: that of common-pool resources (Ostrom, 1990; Ostrom et al., 1999). Other conceptual contributions to this literature can be found in Bromley et al. (1992), Ciriacy-Wantrup and Bishop (1975), Clark (1980), Kaitala and Pohjola (1988), Wade (1994), among others. Parallel to Ostrom's work is an impressive assemblage of case studies (early examples including Berkes (1987), McCay and Acheson (1987), National Research Council (1986), Sengupta (1991), Feeny (1990); also Poteete, Janssen, and Ostrom (2010)), which suggested a way out of Hardin's remorseless logic – the repeated game. In a sense, researchers were finding concrete manifestations of the Folk theorem, which states that any individually rational outcome (i.e., at least equal to or better than each player's reservation payoff) of the game can emerge as a Nash equilibrium when the game is played repeatedly (origins of the proof can be found in Aumann and Shapley, 1976 and Rubinstein, 1979; experimental work traces back to Axelrod, 1985; also see Dutta, 1995).

Table 1. Two-Person Commons Game.

		Player B: C	Player B: NC
Player A	C	(10 , 10)	(0 , 12)
	NC	(12 , 0)	**(5 , 5)**

Since then, a host of researchers have refined these insights. There have been attempts to model common-pool resources as dynamic games, with various assumptions about discounting, and payoffs either independent of resource stock (Benhabib and Radner, 1992; Cave, 1987; Dutta, 1995) or dependent on stock (Hannesson, 1997; Laukkanen, 2003; Tarui et al., 2008). These models have also introduced a range of assumptions about monitoring, from perfect monitoring and individual sanction (Casari and Plott, 2003; Ostrom, 1990) to imperfect monitoring and unobservable individual actions (Cason and Khan, 1999; Chermak and Krause, 2002; Isaac and Walker, 1988). This ongoing work has only reinforced the strength and validity of Ostrom's common-pool resource (CPR) model.

What is required in all of the institutional solutions above is the clear definition of property rights, which, in the CPR case, means well-defined rules for group membership and resource access (see Ostrom, 2003). More fundamentally, all these models are governed by strictly utilitarian logic, where the basis of behavior is the maximization of individual utility.

We will introduce an entirely new model wherein the game provides vector payoffs (e.g., a player's individual payoff, payoffs for the player's neighbors, etc.), instead of the (scalar) one-dimensional payoffs assumed above. As we will discuss, one motivation for this new model stems from ample evidence from experimental economics around the so-called ultimatum game, which produces results (such as unexpectedly fair play) that contradict the predictions of the rational model. Our new model provides an explanation for these seemingly anomalous results. And unlike the literature on common-pool resources, our model produces collectively superior outcomes even when the game is not repeated. The new model readily simulates fairness-based behavior (also referred to as other-regard) in a powerful yet simple way that may lead to new efforts at theory-building.

There have been other models in the literature where other-regard has been modeled, but almost always as a quantity that is lumped into an overall, scalar measure of the decision-maker's utility. For example, Dixit (2008) proposes an additive utility function that can include other players' utilities. Rabin (1993) investigates a range of possible decision functions (and Nash equilibria) associated with each player's maximization or minimization of the other's utility. One might also refer to Fehr and Schmidt's work on inequity aversion (Fehr and Schmidt, 1999; also see Frohlich et al., 2004). However, missing in almost all extant approaches is the logical next step of simply assuming vector payoffs. Though there have been arguments in favor of vector formulations (e.g., see Etzioni, 1986), this has not been systematically employed. For example, Margolis (1990) forwarded a dual utility model, but essentially keeps the two dimensions (self-interest and other-regard) separate, precluding decision-making over all dimensions simultaneously or a utility function that includes all dimensions. In other words, we have no equivalent notion of an equilibrium solution in Margolis' formulation. In our treatment, we formulate a vector payoff model that is generalizable over a whole range of possible decision rules. Furthermore, we define equilibrium solutions for these vector utilities and prove existence for a general class of decision functions. We feel that this is the most general approach to portraying other-regard. We find it readily applicable to the class of games we refer to as commons problems. We have not found any previous application, in this systematic fashion, of vector payoff formulations to the commons, collective action, and related games.

Games with vector payoffs have been treated in the literature at various times, beginning with Shapley (1959). Others who have addressed the existence of equilibrium solutions in vector payoff games include Wang (1991), Zhao (1991), and Borm et al., (1999). However, these treatments invariably assume decision rules that employ simple non-domination or strict Pareto efficiency. What is needed, in the case of collective action games such as the commons problem, is a solution concept that allows for the possibility of different, sometimes complex, decision rules. Real-world decision-makers do make sharp decisions, using logics that go beyond simple dominance or Pareto efficiency. Later in the paper, we consider examples using decision rules such as the maximin or Cobb-Douglas functions. We first show the existence of Nash equilibria for these higher-order decision rules, and then demonstrate their application to the commons problem.

In the latter part of the paper, we make a second point, which is to conjecture how games with vector payoffs might naturally result from a network design of governance, where transactions are governed by interpersonal relations rather than formal market exchange or state-centered rule systems. The model of network governance, where numerous policy actors can engage in direct face-to-face interaction outside formal institutional arrangements, adds new and hitherto unanalyzed dimensions to Hardin's dilemma. Our *vector payoff model* helps explain how informal networks are able to effectively govern. At present, we focus the model around individual decision-making, though there is a growing literature on how group processes affect decisions (e.g., Gillet et al., 2009).

We will formalize the game-theoretic model later in this paper and prove the existence of solutions to the vector payoff game. First, we set the stage by providing, for illustration's sake, a counter-narrative to Hardin's tale that provides graphic justification for the new model. For this, let us return to his pastoral example, but with a different bovine this time.

3. Counterexample: The buffalo commons[2]

We seek an alternative model for understanding how commons problems are solved. To do this, we turn the clock back several centuries to the buffalo herds that populated the Great Plains of the American West. From the mid-17th to the mid-19th centuries, almost three dozen Native American tribes evolved into horse-driven bison-hunting cultures and created an entire economy around the American buffalo. For centuries, Native Americans wove a nomadic way of life around these wandering buffalo and seemingly managed the system in sustainable fashion (leading to much overly idealized literature on the 'ecological Indian').

We use the commons model to analyze the rise and fall of this economy. We caution the reader, however, that this is not meant to explain the fate of the buffalo but merely to introduce a possible counter-narrative to Hardin's and Ostrom's models. This will then lead us to the main focus of the paper, which is to formalize this new model of collective action.

Several authors have analyzed the ecological sustainability of bison hunting (Flores, 1991; Roe, 1951). Flores calculates that by the mid-1800s the Cheyennes, Comanches, and other Southern Plains tribes had settled into a rate of around 195,000 buffaloes a year (Flores, 1991). This, when combined with natural mortality, the rate of predation by wolves, and grassland competition with the herds of horses, seemed to be in equilibrium with the bison birth rate. This equilibrium rate averaged around 6.5 bison per hunter per year, which seemed to maintain roughly eight million bison in the Southern Plains alone.

Here was, potentially, a grand example of Hardin's commons. There was certainly no formal system of property rights, certainly not in the sense of spatially fixed parcels of land. So, the first question is, how did this open system allow for the maintenance of large numbers of bison on the plains for such a prolonged period of time?

But the story does not end there, as this sustainable ecological (and economic) pattern came to a crisis almost overnight. Over a short period of time (beginning around 1870), the demise of the buffalo would proceed so rapidly that, by the latter part of the 19th century, scarcely a hundred buffalo were left in the Southern Plains. And this brings us to a second question: as much as the system was maintained for more than a century, what caused its sudden devolution?

As West describes, it is most plausible that the bison's demise came from a confluence of multiple factors in this complex ecosystem (West, 1995). First, there was a natural shrinking of the bison population due to a prolonged drought that, beginning in 1846, saw 30 percent less annual rainfall in nine out of the ten years of the drought (Schulman, 1956). There may have been the spread of diseases such as anthrax from the introduction of feral and stolen cattle from Texas. Some have also implicated the spiritual world view of the tribes, particularly the belief in the efficacy of ritual to maintain bison populations (Hämäläinen, 2008). But compounding these factors, there was, undeniably, a dramatic increase in bison hunting, by white hide hunters but also the Native Americans themselves. White settlers were said to have killed at least 10 million bison during this period

(Roe, 1951). By the late 1800s, the Cheyenne had increased their annual take to about 44 bison per hunter (Flores, 1991). But, bringing the case back to the frame of analysis of Hardin's dilemma, we seek to understand how the prisoner's dilemma was solved, in the first place, and why, exactly, did this stable solution unravel?

In the following discussion, we counterpose two contrasting explanations. The first, consistent with extant theory, revolves around the issue of property rights. The second explanation, which we later formalize into a new game-theoretic model, eschews the property rights framework for that of vector payoffs. Later, we will weaken the sense of these two models as being alternatives, but suggest the possibility that these represent distinct but overlapping mechanisms that might operate in tandem. Lastly, we remind ourselves that this is not historical research, and we do not pretend to solve the mystery of the bison in the Great Plains. Rather, we use this rich example to illustrate how alternative institutional explanations might be possible and, in fact, offer new insights.

4. The property rights explanation

How was the tragedy of the commons solved, without any system of property rights? One compelling explanation is that there was indeed a virtual system of rights, though not formalized as such nor resembling private property rights. Was this a case of Ostrom's common pool resources (CPR), with community processes engendering cooperation over time? While we can easily imagine a community-based CPR regime maintaining in-group cooperation, this would not hold between sometimes hostile tribes.

But some sources point to another phenomenon. In the dynamic, constantly negotiated balance of power that was struck between tribes, there emerged distinct areas not occupied by any, essentially serving as buffer zones between them. More important to our discussion is the distinct possibility that these neutral zones also became, by default, ecological preserves of a sort. Writing about the great Comanche nation, Hämäläinen suggests that their bison-harvesting patterns were already in excess of carrying capacity at the beginning of the 19th century. What saved the bison were these buffer zones, such as the 'largely depopulated hundred-mile-wide buffer zone' that 'separated the Apache realm from the southern border of Comancheria' (Hämäläinen, 2008: 66). This theory was originated by Elliott West, who wrote that, in these buffer zones, '…if no single tribe was strong enough to keep its neighbors out, a curious result followed…native hunters were restrained by fear for their own safety…they could not hunt at will. Thus, game enjoyed a measure of protection' (West, 1995: 61). This is all consistent with Baden et al. (1981), who argued that Native Americans were invariably economic agents, who needed some system of property rights to govern resource use.

Returning to the construct of the bimatrix game, the buffer zone solution essentially worked by creating a new penalty for tribes who ventured into these neutral zones to hunt. This is illustrated, in Table 2, by a penalty, designated by the variable c, that is exacted upon a violating tribe by the other. In the non-cooperative regime, (NC, NC), each tribe would obviously have to pay this penalty, c (which might be the cost of a skirmish). However, in the case of only one tribe acting non-cooperatively, the offending tribe forays into the neutral zone with some risk, designated by the probability, p, of being caught by the other tribe. The resulting payoff matrix is as shown in Table 2. It is easy to

Table 2. Two-Person Buffer Zone Game.

		Tribe B	
		C	NC
Tribe A	C	**(10 , 10)**	(0 , 12 – *pc*)
	NC	(12 – *pc* , 0)	(5 – *c* , 5 – *c*)

verify, for this particular matrix, that when the following conditions hold: $c \geq 5$ and $p \geq 3/c$, then the Nash equilibrium of the game reverts to the cooperative solution, (C, C).

Eventually, this system of buffer zones came apart. In Hämäläinen's account, this was due to the Comanche empire's increasing commercial activity – having developed a dependence on more and more extensive trading relations, the Comanches began easing restrictions to these lands in exchange for better trading relations with other tribes (2008). More generally, West attributes it to the famous peace treaty between the Comanches and Kiowas and rival Cheyenne and Arapahos (West, 1995: 62), perhaps necessitated by the emerging threat from a new wave of entrants, including the Texas frontiersmen, into the territory (Flores, 1991: 483).

The buffer zone phenomenon is related to the evolution of extra-legal systems of rules and rights (such as land clubs) that evolved among settlers in the West, as described by Anderson and Hill. Building on Friedman's notion of a 'machinery of freedom', they describe various extra-legal mechanisms employed by settlers that introduced order to what conventional wisdom supposes is the anarchy of the Wild West (Anderson and Hill, 2004; Friedman, 1973)The buffer zonehypothesis is supported by Kay's analysis of the Lewis and Clark journals (Kay, 2007: 6, especially Figures 4 and 5).

As such, the buffer zone hypothesis is both theoretically consistent with extant models as well as some historical evidence. We do not intend to refute this compelling theory. However, we suggest that there is room for yet other parallel explanations. For one thing, it has not been conclusively shown that these buffer zones were large and fertile enough to support all of the estimated millions of bison in the early 1800s. Similarly, we cannot be sure that the great increase in bison hunting resulted only from opening up these buffer zones. Elliott West himself suggests that other forces were also at work:

> The *détente* among western plains tribes loosed their hunters more freely onto the herds, which soon began shrinking alarmingly. To say that, however, only turns the puzzle another way…If Cheyennes, Comanches, and other Indians were a significant force in killing the buffaloes, what were the circumstances and motives? Hypothetically, they could have been setting out to slaughter as many as they could to generate the greatest possible trade and convert these animals into maximum material wealth, just as white professional hunters would do twenty years later, but that seems unlikely. These animals, after all, were also supplying much of their daily needs, and Indians presumably would want to have large numbers of them around indefinitely (West, 1995: 63).

To explain this, we turn to our new model.

5. An alternative explanation

We will now develop another mechanism, one not inherently based on a property rights formulation. In doing this, we will speculate on the accelerated rate of buffalo harvesting that proceeded from around 1870 onwards.

Though it is entirely possible that Native American bison harvesting patterns were already out of equilibrium with natural rates of bison reproduction even in the early 1800s, some sources suggest otherwise. Several authors suggest ecologically sustainable bison hunting patterns (Flores, 1991; Roe, 1951). Flores calculates that by the mid-1800s the Cheyennes, Comanches, and other Southern Plains tribes had settled into a rate of around 195,000 buffaloes a year (Flores, 1991). This, when combined with natural mortality, the rate of predation by wolves, and grassland competition with horse herds, seemed to be in equilibrium with the bison birth rate. This rate averaged around 6.5 bison per hunter per year, which seemed to maintain roughly eight million bison in the Southern Plains alone.

In this alternative explanation, what was by far the biggest shock to the system was the dramatic increase in bison hunting, by white hide hunters but also the Native Americans themselves. White settlers were said to have killed at least 10 million bison during the 1870s (Roe, 1951). By the late 1800's, the Cheyenne had increased their annual take to about 44 bison per hunter (Flores, 1991).

A number of scholars argue that the main factor was the entry of the economy of the plains into the Euro-American hide market (Flores, 1991; Roe, 1951; Taylor, 2001). It had started with Bent's trading post in 1833 but did not escalate into full involvement in the worldwide network until transcontinental hide trading began in the late 1800s. As Taylor has surmised, with entry into the world market, the demand for buffalo hides from the Great Plains suddenly shifted upwards, from a demand curve that reflected the local needs of the plains people to one that must have seemed nearly unlimited (i.e., perfectly elastic) in its capacity to consume ever-increasing numbers of hides each year (Taylor, 2007). There were no feedback loops in this situation.

If demand were locally driven, we would expect the prices buyers were willing to pay to dip as more and more hides were harvested, with the effect of eventually limiting the harvest. We might also expect the Native Americans' demand for buffalo products to decrease (i.e., a downward shift in the demand curve) when supply began to be exhausted, as seen in their historical practice of fasting during low periods in the buffalo cycle (Roe, 1951). But none of this happened. Rather, hunters kept supplying a market whose demand seemed insatiable, with prices that remained steady throughout.

Hämäläinen adds another phenomenon that added to the increasing encroachment of market logic: by the mid 1800s, Native Americans had lost the capacity to produce sufficient supplies of some commodities (e.g., sources of carbohydrates) by virtue of learning to depend on trading. Similarly, they developed an insatiable need for other commodities (including alcohol) that they could only gain through trade (Hämäläinen, 2008). All these served to further accelerate buffalo-harvesting.

The role of uncertainty and speed of harvest is important. Market demand pushed harvesting rates beyond a hitherto unknown tipping point, beyond which the buffalo population could never recover. In such complex systems, researchers point to the need for learning processes and adequate time for adaptive management to emerge (Berkes et al., 2003). What knowledge is sought in adaptive regimes? Among others, we need to know about the carrying capacity of the resource, the equity of patterns of exchange, and implications of resource use for the sustainability of the tribe and its ecology. Adaptive management requires that interaction between players allow for information-rich signals to be transmitted.

In a localized economy, equity between bison hunters and consumers was possible. Even if, in a limited sense, hunters competed with each other, they could still take into account the aggregate good. With the onset of the global hide market, however, none of this information mattered. The price of bison hide was constant, regardless of the level of scarcity. There was no considering the aggregate good, since with a worldwide market, hunters were up against the global chain of suppliers of leather – in this sense, what things meant in the aggregate were incalculable. This phenomenon is echoed in ongoing research on the effect of market integration and global commodities prices on local commons management (e.g., Copeland and Taylor, 2009).

As we will discuss, it is not simply whether or not a market exists, it is whether the market is one that looks like the classic model of competition where actors are simple price-takers, or whether the market still resembles a local network, with its direct person-to-person interactions.

6. Counter-logic: Equity in ultimatum games

What is the underlying logic of this alternative mode of governance? We look for clues in the realm of experimental behavioral games. Ever since Axelrod's experimental work, there has been a lot of research done on simulating bargaining situations. The most famous of these is the so-called ultimatum bargaining game. In this game, a player is asked to offer to apportion a certain amount (e.g., $1) between herself and a second player. If the second player accepts the offer, each player receives the corresponding amount, but if he does not, both players receive nothing. Rationality suggests that the first player offer a minimal amount, as close to zero as possible, which the second player would accept. Results of such experimental games reveal an anomaly however: the first player most often tends to offer allocations that approach an equal split between the two players, and when the allocation is significantly less than equal, the second player tends to reject if even if the amount offered to him is significantly greater than zero. Different groups of researchers have repeatedly confirmed the regularity of fairness-seeking behavior (Bolton and Zwick, 1995; Henrich et al., 2004; Roth, 1995; Thaler, 1988). One study confirmed this pattern even across previously warring ethnic groups (Whitt and Wilson, 2007).

The fact that the second player (the receiver of the proposal) in these games routinely rejects non-zero offers is a direct contradiction of the rational utility-maximizing hypothesis. Some have suggested that proposers make substantial offers not because of equity considerations but because they are acting strategically to avoid these rejections. For this reason, a second game has been employed in the literature, called the dictator game, in which the second player is forced to accept and where the first player has no reason to fear rejection. And yet, in experiment after experiment, these dictator games have shown that players continue to offer substantial amounts, often approaching the level of offers in the ultimatum games (Eckel and Grossman, 1996; Hoffman et al., 1996; Johannesson and Persson, 2000).

What do these simulations tell us? When the game is played repeatedly, they confirm Axelrod's notion about learning cooperation through repeated interaction. However, players will play cooperatively even in the very first round of the game, or even when the game is played only once. Learning cooperation through repeated (selfish) play seems not to be the only determinant of cooperative behavior. At some point, many researchers reach the inescapable conclusion that regard for the other is a basic human motivation in these experimental games (Forsythe et al., 1994; Kahneman et al., 1986; Thaler, 1988).

These patterns of play should not be thought of as irrational anomalies – they may well reflect, in fact, basic patterns of human behavior. Flescher and Worthen (2007) make the argument that normative concerns (i.e., seeking equity in transactions) may in fact be hard-wired by evolution into our genetic code. The argument starts with a notion forwarded by Dawkins (1989) of the selfish gene. In simple terms, other-regarding behavior such as altruism is associated with individual behavior that seeks to preserve the welfare of others, sometimes at the expense of self. By being a strategy that optimizes the chances of survival of the group (and hence, the genetic material they carry), it is this type of behavior that tends to survive from generation to generation. There is some recent evidence that patterns of play in ultimatum games, at least to some extent, may be traced to heritable, genetic patterns (Wallace et al., 2007). Other researchers have linked the degree of altruistic play in dictator games to basic genotypic characteristics (Knafo et al., 2008).

Familiarity affects these results. In many cases, these equity-seeking patterns of behavior seemed to lessen when the game involved less familiarity and more anonymity (e.g., Barr, 2004). In one experiment, researchers observed a decreasing level of equitable offers as social distance was increased and, at the point where complete anonymity was assured (i.e., a double-blind experiment where even the researchers did not know the offers), only 11 percent of the subjects made offers of 30 percent or more (Hoffman et al., 1996).

7. The model

How would we incorporate the equity criterion into the two-person game shown in Table 1? Most simply, we can consider this as a second consideration, separate from personal utility, that enters into a person's decision calculus. What this translates to,

Table 3. Modified Commons Game Using a Maximin Decision Function.

		Player B		
		C	M	NC
	NC	**([10,10] , [10,10])**	([7,11] , [11,7])	([0,12] , [12,0])
Player A	M	([11,7] , [7,11])	**([8,8] , [8,8])**	([6,8] , [8,6])
	NC	([12,0] , [0,12])	([8,6] , [6,8])	([5,5] , [5,5])

mathematically, is a person's payoff being not a scalar as previously assumed (i.e., a single number representing personal utility) but a multidimensional vector (i.e., the first dimension being personal utility, and a second dimension being a measure of the degree of equity, group benefit, or some other other-regarding measure). We might, for example, assume the second dimension to be the payoff that the other person receives. Another, more communitarian, variation would be to represent the second vector by the aggregate payoff that all the players receive.

Consider the modified commons game in Table 3. To construct this game, we first posit that each player's utility function is not, as before, simply based on the individual player's own (scalar) payoff but, now, based on a vector of payoffs. Let us suppose that Player A simply considers not just her own payoff but Player B's as well. So, using the same payoff structure as before, Player A's vector payoff when both cooperate is now (10, 10) where the first dimension is her own payoff, and the second dimension, Player B's. If Player A cooperates, while B does not, then A's vector payoff is (0, 12) while B's is (12, 0). We also introduce another wrinkle in that, in this game, we have more than two possible actions, represented by an intermediate action, M (where a player might put out cows that number somewhere between the cooperative and non-cooperative strategies).

How would Player A make decisions when considering a multidimensional vector? There are any number of known ways of solving this, but let us use, for this illustration, one of the simplest: the maximin solution. That is, A chooses that action that maximizes the least-valued dimension in the vector payoff. For example, if A assumes that Player B would play M, then A would choose to also play M since the minimum result obtained is 8, which is greater than the minimum dimension that results when A plays C (which is 7) or NC (which is 6). To be clear, when A chooses to reject action NC, she is considering the low payoff received in the second dimension of its vector payoff (which is the individual payoff received by the other player). This is because A considers not just her individual payoff but others', as well.

The interesting thing that happens when we modify the game and the mode of decision-making in this way is that (NC, NC) now ceases to be an equilibrium solution of the game. In fact, there are two pure strategy Nash equilibria for the game in Table 3: (C, C) and (M, M). First, note that this provides us some clue as to other mechanisms that might escape the tragedy of the commons. Secondly, note that, if we were to limit the game to only two alternative actions as before, (NC, NC) would remain a Nash equilibrium.

We can also consider other decision rules for the vector payoff case. For example, we might employ a standard Cobb-Douglas utility function, wherein instead of the function being defined over multiple goods, it is now defined over multiple players' payoffs. The general form of the utility function would then be:

$$
\begin{aligned}
u_i &= k p_i^{\alpha} p_{\mathrm{j}}^{1-\alpha} \\
\text{where } u_i &= \text{player } i's \text{ utility} \\
k &= \text{constant} \\
p_i &= \text{payoff to player } i \\
p_{\mathrm{j}} &= \text{payoff to player } j \\
\alpha &= \text{coefficient where } 0 < \alpha < 1
\end{aligned}
$$

Supposing, for the sake of the example, that $\alpha = 0.9$ and $k = 1$, we derive the outcome matrix shown in Table 4. The table on the left shows the payoff matrix, while the one on the right shows the final utilities resulting from the use of the Cobb-Douglas utility function. If we solve for a pure strategy Nash equilibrium, we find just one – (M, M). Thus, we see that, when players consider vector payoffs and intermediate strategies, there is the possibility of avoiding a tragedy of the commons and achieving 'midway-cooperative' outcomes by using 'middle-range' strategies. Using the vector payoff model, we can explain cooperative outcomes even in one-shot games.

In fact, we can generalize this further to games where the set of possible actions for each player is a compact, convex set. One standard way this is achieved is to allow players to employ mixed strategies – i.e., to set probabilities over each alternative in a finite set of strategies. Or, even more generally, we can simply assume that players can vary their strategies over a continuous range. For example, a polluter's choice of how much smoke to emit from a smokestack is, practically speaking, a continuous variable. An angler might mull over how much time to spend each day fishing on a lake, and so on. We also realize that the maximin and Cobb-Douglas formulations are just two examples of a wide range of possible decision functions that might be employed. Note that, with the notable exception of Bolton (1991), consideration of a range of possible decision functions is missing from the literature. Lastly, we generalize the game to any finite set of two or more players. We now formalize the game as follows.

Table 4. Modified Commons Game Using a Cobb-Douglas Utility Function.

([10,10],[10,10])	([7,11],[11,7])	([0,12],[12,0])		(10,10)	(7.3,10.5)	(0,0)
([11,7],[7,11])	([8,8],[8,8])	([6,8],[8,6])	→	(10.5,7.3)	**(8,8)**	(6.2,7.8)
([12,0],[0,12])	([8,6],[6,8])	([5,5],[5,5])		(0,0)	(7.8,6.2)	(5,5)
					$\alpha = \mathbf{0.9}$	

8. Formal description

Define a normal form game of complete information with a finite number, n, of players. Define the following variables:

$$
\begin{aligned}
S_i &= \text{player } i\text{'s strategy space}\\
s_i &= \text{player } i\text{'s individual strategy, } \ s_i \in S_i\\
S &= \text{strategy space of the game, } S = S_1 \times S_2 \times \cdots \times S_n\\
s &= n\text{-tuple combination of individual strategies, } s = s_1 \times s_2 \times \cdots \times\\
&\quad\ s_n, s \in S\\
s_{-i} &= s/s_i, \ \text{i.e., } \ (n-1) - \text{tuple combination of strategies not including}\\
&\quad\ \text{player } i\\
p_i(s) &= p_i(s_1, s_2, \ldots, s_n) = \text{payoff for player } i \text{ for strategy } n\text{-tuples,}\\
&\quad\ (p : R^n \rightarrow R)\\
u_i(p_1, p_2, \ldots, p_n) &= \text{utility function for player } i (u : R^n \rightarrow R)\\
u \circ p_i(s_i, s_{-i}) &= \text{composition of functions } u_i \text{ and } p_i\\
u \circ p(s) &= \text{product of individual } u \circ p_i, \ \text{ where } u \circ p = u \circ p_1 \times u \circ p_2 \times \cdots \times u \circ p_{\mathrm{n}}
\end{aligned}
$$

In other words, individual utility in this model is a function of a vector, the dimensions of which can include payoffs to other players. We now prove the existence of Nash equilibria in these vector payoff games.

> **Proposition**. Each S_i is nonempty, compact, and convex, and each p_i, u_i are continuous functions. Then a Nash equilibrium for the game, $s^* \in S$ such that $u^\circ p(s^*) = s^*$, exists.

8.1. Proof

Define a best response function for each player i as

$$b_i(s_{-i}) = \{s_{\mathrm{i}} \in S_i : u{\circ}p_i(s_i, s_{-i}) \geq u{\circ}p_i(s_{\mathrm{i}}', s_{-i}) \forall s'_i \in S_{\mathrm{i}}\}.$$

The composition $u{\circ}p_i(s_1, s_2, ..., s_n)$ is continuous, since it is known that the composition of two continuous functions is continuous. Since we assumed that each S_i is compact and convex, then $b_i(s_{-i})$ is nonempty. To show that b_i is continuous, we need to demonstrate that for any convergent sequence of points, $(s_i^m, s_{-i}^m) \to (s_i, s_{-i})$ where $b_i(s_{-i}^m) = s_i^m \forall m$, then $b_i(s_{-i}) = s_i$.

First, assume the converse, i.e., there is some $t_i \neq s_i$ such that

$$u^{\circ}p_i(t_i, s_{-i}) - u^{\circ}p_i(s_i, s_{-i}) => 0 \tag{1}$$

Since $u^{\circ}p_i$ is continuous, we have for any $\varepsilon > 0$, there exists:

$$\delta_1 > 0 \text{ such that } |\ u^{\circ}p_i(t_{\mathrm{i}}s_{-i}) - u^{\circ}p_i(t_i, s_{-i}^m)\ | \ < \varepsilon \tag{2}$$

$$\delta_2 > 0 \ \text{ such that } |\ u^{\circ}p_i(s_i, s_{-i}) - u^{\circ}p_i(s_i^m, s_{-i}^m)\ | \ < \varepsilon \tag{3}$$

and let $\delta = \min(\delta_1, \delta_2)$.

Case (i): Suppose the quantities within the absolute value operator in [2] and [3] above are both positive, then $[u^{\circ}p_i(t_i, s_{-i}) - u^{\circ}p_i(t_i, s_{-i}^m)] - [u^{\circ}p_i(s_i, s_{-i}) - u^{\circ}p_i(s_i^m, s_{-i}^m)] < \varepsilon$ rearranging, $[u^{\circ}p_i(t_i, s_{-i}) - u^{\circ}p_i(s_i, s_{-i})] + [u^{\circ}p_i(s_i^m, s_{-i}^m) - u^{\circ}p_i(t_i, s_{-i}^m)] < \varepsilon$ and, since $u^{\circ}p_i(t_{\mathrm{i}}s_{-i}) - u^{\circ}p_i(s_i, s_{-i}) > 0$ as assumed in [1], and $u^{\circ}p_i(s_i^m, s_{-i}^m) - u^{\circ}p_i(t_i, s_{-i}^m) > 0$ since $b_i(s_{-i}^m) = s_i^m$, we have $u^{\circ}p_i(t_i, s_{-i}) - u^{\circ}p_i(s_i, s_{-i}) < \varepsilon$ and, setting $\delta = \varepsilon$, the above result is a contradiction of [1], so we conclude

$$u^{\circ}p_i(s_i, s_{-i}) \geq u^{\circ}p_i(t_i, s_{-i}) \text{ and } b_i(s_{-i}) = s_i.$$

Case (ii): Suppose the quantities in [2] and [3] above are both negative, then $[u^{\circ}p_i(t_i, s_{-i}^m) - u^{\circ}p_i(t_i, s_{-i})] - [u^{\circ}p_i(s_i^m, s_{-i}^m) - u^{\circ}p_i(s_i, s_{-i})] < \varepsilon$ rearranging, $[u^{\circ}p_i(t_i, s_{-i}) - u^{\circ}p_i(s_i, s_{-i})] + [u^{\circ}p_i(s_i^m, s_{-i}^m) - u^{\circ}p_i(t_i, s_{-i}^m)] < \varepsilon$ and since $u^{\circ}p_i(t_i, s_{-i}) - u^{\circ}p_i(s_i, s_{-i}) > 0$ and $u^{\circ}p_i(s_i^m, s_{-i}^m) - u^{\circ}p_i(t_i, s_{-i}^m) > 0$ as shown above, we have $u^{\circ}p_i(t_i, s_{-i}^m) - u^{\circ}p_i(s_i^m, s_{-i}^m) + u^{\circ}p_i(s_i, s_{-i}) - u^{\circ}p_i(t_i, s_{-i}) > -\varepsilon$, which gives $u^{\circ}p_i(s_i, s_{-i}) - u^{\circ}p_i(t_i, s_{-i}) < \varepsilon$ as in Case (i), and the rest follows similarly.

Case (iii): Suppose the quantities in [2] and [3] are positive and negative, respectively, then it is straightforward to obtain

$$u^{\circ}p_i(t_{\mathrm{i}}s_{-i}) - u^{\circ}p_i(t_i, s_{-i}^m) + u^{\circ}p_i(s_i^m, s_{-i}^m) - u^{\circ}p_i(s_i, s_{-i})] < 2\varepsilon,$$

which gives $u^{\circ}p_i(t_{\mathrm{i}}s_{-i}) - u^{\circ}p_i(s_i, s_{-i}) < 2\varepsilon$ and, setting $\varepsilon = \delta/2$, the rest follows similarly.

Case (iv) follows along the same lines of Case (iii).

We have shown that b_i is continuous. Define $b : S \to S$ where $S = S_1 \times S_2 \times \cdots \times S_n$ as $b(s_1, s_2, \ldots, s_n) = b_1(s_{-1}) \times b_2(s_{-2}) \ldots \times b_n(s_{-n})$, i.e., a function mapping S into itself.

S is compact and convex, being the product of compact, convex sets. Also, $b : S \to S$ is continuous, since the product of continuous functions is continuous. By Brouwer's fixed point theorem, there must exist a fixed point $x^* \in S$ such that $b(x^*) = x^*$, which is, by definition, a Nash equilibrium. QED.

In our treatment of the commons game, we have assumed decision-makers who employ decision rules that return point solutions (i.e., in the commons game, a definite number of cows instead of an imprecise range) as this is most consistent with real-life decision-making. In this case, the existence proof would use Brouwer's theorem (as shown above) rather than other fixed point theorems such as Kakutani's. Again, we are trying to make the model most compatible with the real-world situation.

To illustrate the existence of these equilibria, consider the two decision functions mentioned above, i.e., the maximin and Cobb-Douglas. These two are examples of two different ways of solving the vector payoff problem – first, by using a decision function that operates directly on the payoff vector (the maximin) and, alternatively, by using a decision procedure that first calculates a higher-order utility and operates on the corresponding scalar utilities (Cobb-Douglas). At any rate, both are continuous functions. Thus, we can be assured of finding at least one Nash equilibrium for the game when either of these two functions is employed. If there is no pure strategy Nash equilibrium in the game, then the solution will be an interior one representing 'middle-range' strategies.

To summarize our progress up to this point, we have reformulated the game into a form where players consider a vector of payoffs instead of simply their own individual payoffs.[3] We have shown how solutions other than that of universal non-cooperation can result from this more complex model. That is, games in which players can decide based on vector payoffs will, under certain conditions discussed above, have solutions that resolve the dilemma.

The question at this point is: what conditions might prevent players from reaching solutions through vector-based reasoning? We suggest, below, that one important obstacle may lie in institutional design.

9. Institutional design

What is the significance of the observation that these egalitarian or communitarian tendencies decrease with level of anonymity? Plausibly, that these tendencies are strongest with direct interaction between the players, exemplified by direct, face-to-face contact but also through other media (e.g., phone calls, text, social networking sites, etc.). We reason that, to motivate players to seek equity, we need arrangements where individuals engage each other directly. In network modeling terms, we seek arrangements where each node has a direct link to at least one other node, and where there is a path of direct linkages that connect any two nodes in the system. What we have just described equates, essentially, with the geometric definition of a network.

We will construct a highly simplified depiction of institutional designs. A stylized portrayal of a network, with its boundary-crossing interpersonal linkages, is shown in Figure 1. Taking Figure 1 to depict the buffalo commons, we see how networks link not only producers and consumers but also a host of other parties that, we argue, introduce complex meaning into the network.

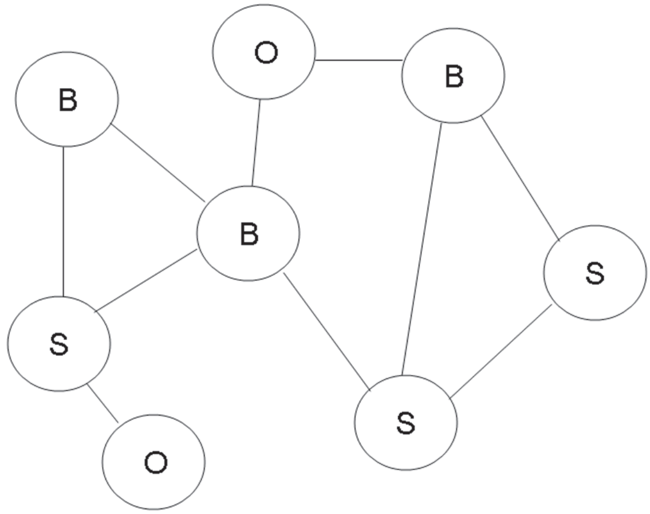

Figure 1. Diagram of a network configuration (B = Buyer, S = Seller, O = Other).

Contrast the network of Figure 1 with the classic model of the market, as depicted in Figure 2. In the perfectly competitive market, buyers and sellers only see a common, universal price dictated by the market. That is, imagine that the market is a vending machine where a price is listed and, if a buyer is willing to pay it, puts in his money and receives a buffalo hide – here, there is no theoretical role for face-to-face interactions.

In the ideal market, rich information cannot be exchanged between seller and seller, or buyer and buyer, and buyer and seller (e.g., European leather-user and Native American hunter). There are no conversations about traditional ways of production, or the equity of the transaction. Instead, all buyers are reduced to price-takers. Rather than information-rich communication being exchanged between players, signals are reduced to scalar prices.

In its ideal form, the market has uncountable numbers of buyers and sellers. What this does to the game in Table 3 is to essentially remove the second dimension and reduce the game to that of scalar utility. There is no calculating the effect of one's actions on the aggregate or on the neighbor since the latter is now incalculable.

Direct linkages between nodes in the network are severed and, instead, all are linked to the global market, where coordination is achieved through the pricing signal (Figure 2). Other players (e.g., farming tribes, village elders) have no role in the market at all. The tragedy of the institutional design is that it precludes inclusion of complex decision criteria. We can also use Figure 2 to depict a state-centered model of governance, where we simply locate the state institution in the large, gray body in the middle of the figure. The admittedly simplistic contrast between Figures 1 and 2 helps us appreciate the value-added of the network model.

The study of network modes of governance has become a staple in sociology (e.g., Podolny and Page, 1998; Powell, 1990) and management (see Agranoff and McGuire,

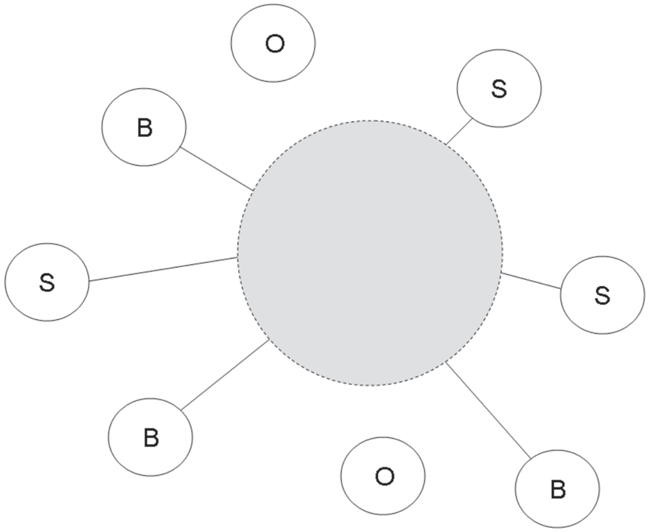

Figure 2. Diagram of a market configuration (B = Buyer, S = Seller, O = Other).

1999; Kickert et al., 1997; O'Toole, 1991). The political science literature, too, has evaluated the ability of networked institutions to foster greater cooperation (e.g., see Siegel, 2009; Scholz and Wang, 2009). More recently, there have been important strides in economic theories of network governance (e.g., formulations by Goyal and Vega-Redondo, 2005 and Jackson, 2008). To this literature, we introduce a distinctly different model, one where players explicitly exhibit fairness-centered motivations, and one which perhaps will lend a fresh perspective to this important literature.

Returning to the bison example, the entry of the global market explains the alienation of buyers (i.e., Americans and Europeans in the market for special leather) from place, but what about the producers/hunters? This is easy to explain in the case of the white hide hunter. The new entrant, not having ties to place, operates in classic mode, essentially not being guided by vector payoffs but only the single dimension of personal utility. But what about the Native American hunter? To understand the latter's regression to non-cooperative behavior, let us revisit Table 3. Now suppose we replace player B in this table with one that stands in for the white hunter, while keeping player A to represent the Native American. What changes is that all the payoffs for player B revert to a single dimension, while player A maintains its multidimensional payoffs. Player B predictably plays strategy, NC. Why, then, would player A not continue to play M, as shown before? As we saw before, playing this way, player A would sacrifice self-interest in favor of the community (i.e., the payoff vector for A is [6, 8], where A suffers the lower payoff in order to gain a positive gain for the other). But somehow the Native American gradually began reverting to the classic mode, acting as if only one dimension (personal utility) mattered.

To understand why, we return to the experimental research and recall how other-regarding behavior becomes less pronounced with loss of familiarity. To the nomadic tribes of the plains, the distant buyers of buffalo hide and the white hide hunter represented the unfamiliar. Moreover, the market began to impose an alien logic upon the natives. Hämäläinen described the effect of the new trading posts in this manner:

> Comanches had traded bison meat and robes for generations, but that exchange had largely been limited to local subsistence bartering. Now, Comancheria's bison became an animal of enterprise, slaughtered for its commodified hides and robes for distant industrial markets' (2008: 156).

He also adds:

> The silent investors, fixed rendezvous, varied merchandise, and sheer volume of the exchange point to a fundamental change in the comanchero commercie: the ancient border land institution of face-to-face transactions was becoming integrated into a capitalist system of formal market relations' (2008: 318).

It is that transition, from face-to-face relationships and their inherent familiarity, to the invisible hand of the market, that we seek to capture in our new model (and contrasted in Figures 1 and 2).

In the language of vector payoffs, in the presence of strangers, locals reverted to behaving as if only one dimension mattered. The other way to understand this is to return to Table 3 and imagine a much larger table with players approaching an infinite number (e.g., the classic market). When this happens, payoffs to 'others' are not anymore allocable to individuals but distributed over the entire market. The second dimension in the payoff vector starts approaching zero – and the game reverts to a one-dimensional prisoner's dilemma.

In fact, as illustrated in Table 5, we can simulate the above patterns in the ultimatum game modeled using two-dimensional vector payoffs – in this case, capturing both self-utility and the relative payoff to the other player. We employ the maximin decision rule and test the effect of varying anonymity using a weighting function, δ. We apply the weight, δ, to the second dimension of the vector and, applying the maximin rule, the higher the weight, the less importance the decision-maker attaches to this dimension. We show the results in Table 5, where we see, for the original game with $\delta = 1$, we have two pure strategy equilibria, (C, C) and (N, N). When we set δ to 0.2, however, we see the equilibrium shifting to the cooperative solution (i.e., the greater the importance of the other's payoff, the more cooperative the result). On the other hand, when we set δ to higher values, the converse result emerges. In fact, as δ approaches infinity, the game reverts to the one-dimensional payoff structure, where we have the usual tragedy of the commons as an outcome. In other words, when institutional designs minimize (or remove) the salience of the other's payoff, other-regarding, communitarian behavior disappears, as suggested by Marglin (2008).

Some argue for the presence of cooperative behavior only in in-group settings, not between groups. For example, Dawes et al. point to cooperation as emerging from optimism regarding others' behavior as an offshoot of group solidarity (Dawes 1990, 1991). But this is not necessarily incompatible with the vector payoff model – in fact, the model attempts to formally depict other phenomena like group solidarity. Indeed, the findings of Dawes et al., that humans are motivated beyond egoistic concerns, may necessitate a model such as ours. Certainly, as pertains to bison management within the territory

Table 5. Incorporating Familiarity into the Vector Payoff Model.

		C	NC
$\delta = 1$	C	([20, 20] , [20, 20])	([3, 24] , [24, 3])
	NC	([24, 3] , [3, 24])	([10, 10] , [10, 10])
$\delta = 0.2$	C	([20, 4] , [4 ,20])	([3, 4.8] , [4.8, 3])
	NC	([24, 0.6] , [0.6, 24])	([10, 2] , [2, 10])
$\delta \rightarrow \alpha$	C	(20, 20)	(3, 24)
	NC	(24, 3)	(10, 10)

controlled by the tribe, the notion of other-regard can explain responsible resource management. The extension of this other-regarding logic beyond the immediate group might be modeled as varying degrees of familiarity, as in Table 5. To return to the Native Americans of the 1800s, Hämäläinen describes the relatively inclusive nature of the Comanches and their ability to accord a measure of kinship with outsiders who establish relations with them (2008). It would be interesting to see how and in what ways a vector model can be adapted to incorporate cognitive and social phenomena such as the kind of group solidarity described by Dawes and others (also see Orbell et al., 1988). For example, the notion of 'group' may be a fuzzy concept – i.e., in some situations, not just in-group versus out-group. Perhaps our model may also allow for the ability of policy actors to imagine a ‘collective intentionality’ that Urpelainen suggests is needed for collective action – here, the vector formulation might allow for supra-individual institutional factors (2011).

We have argued that network designs can allow for preservation of the multidimensionality of decision-making around the commons (also see Libecap 1994, on the heterogeneity of preferences). This is consistent with emergent literature on how collaborative, network arrangements allow a more effective response to environmental complexity (e.g., Innes and Booher, 2010; also see Dietz et al., 2003 and Eckersley, 2004).

Conclusion

In this paper, we developed a new model of the commons as a game with vector payoffs. The employment of vector payoffs allows us to explicitly capture fairness-based motivations in individual decision-making. Unlike by now classic explanations of cooperative behavior (e.g., the common-pool resource model) which posit repeated interaction, our model yields cooperation even in one-shot games, which the experimental literature on ultimatum games has borne out.

We used the example of the buffalo commons to illustrate the narrative that justifies the vector payoff model. In this example, the severing of ties that linked players in a local network is a possible reason behind the sudden demise of the buffalo. This logically follows from the observation that ‘other-regard’ comes from the direct interpersonal interaction (Flescher and Worthen, 2007) that network arrangements allow. The use of vector representations is seen to be one reasonably effective way of incorporating various degrees of familiarity (i.e., from purely individualistic to completely other-regarding behavior).

We feel that directly assuming decision outcomes in all their multidimensionality, i.e., as vector payoffs, will afford new options for the thick description of commons and related policy problems (Lejano, 2006). Future research will involve employment of the vector payoff model to better explain other real-world phenomena or to provide alternative explanations of experimental data.

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Notes

1. The model of the herders and the open-access commons traces was actually first taken up in a much earlier paper (Lloyd, 1833).

2. The term, buffalo commons, comes from Deborah Popper and Frank Popper who argued for a grand nature preserve in the Great Plains and reintroduction of the bison (http://gprc.org/research/buffalo-commons/).
3. Other alternative models can be found in the literature. For example, Frohlich and Oppenheimer (2006: 259) propose a decision model where preferences are a function of elements of context. We might see the suddent increasein harvest as a punctuated equilibrium (Repetto, 2006). Nor do we reject optimization but simply remain open to what people optimize (Hanemann, 2000).

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