APPLICATIONS OF GAME THEORY IN
AGRICULTURAL ECONOMICS:
REVIEW AND REQUIEM*

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"We can make several things clearer but we cannot make anything clear."
FRANK P. RAMSEY

Game theory — aptly described as the scientific approach to poker, business, women and war — has proved to be no cure-all for the conflict situations studied by agricultural economists. Like Marshall, it has had its day. Still, just as in general economics, game theory has provided an alternative framework for the study of a variety of agricultural problems. This paper aims to review these studies. As background, a brief résumé of the more important economic theories of decision making in risky situations will first be given, followed by an outline of the pertinent aspects of game theory. Agricultural applications are then considered. A general appraisal — pro and con, past and future — completes the review.

Background

Like other decision makers, farmers and agricultural bureaucrats rarely have full information. Some uncertainty will always be present. In consequence, despite the best of planning, hindsight will nearly always yield regrets about past decisions. Reduction of this gap between actual and possible achievement is the normative aspect of decision making. Concomitant is a problem of descriptive economics: How are decisions made? Why this choice and not that?

Stronger recognition of these problems over the last two decades has led to the elaboration of a variety of theories of choice for individuals in risk-taking situations. Oldest and most numerous are theories stressing mechanical application of simple rules of thumb, generally based on the projection of some weighted average of past results. Darcovich (20) and Heady (46, Ch. 16) and Schultz and Brownlee (75) have listed a variety of such rules. Under suitable assumption about the state of information, these naive models can be subsumed under the more general theories of decision making based on von Neumann and Morgenstern's theory of games (58; 62; 80; 92), Wald's theory of statistical decision functions (10; 18; 93), and Savage's subjective probability approach (3; 55; 70; 73) to risky choice. These approaches aim to maximize the decision maker's utility; stressing "rational" behaviour, they have been postulated as normative theories. In contrast, Shackle (1; 76; 77; 78) has vigorously pushed a purely descriptive theory emphasizing a psychological approach based on the decision maker's degrees of belief and potential surprise about possible outcomes. Lying between the above theories in its emphasis on mathematical procedures and psychological variables is Simon's theory (82). Like


(1) No consideration will be given to "sure prospect" decision making such as discussed by Heady (46, Pt. II) and Knight and Greve (57), nor to the pioneering risk analyses of Hart (45), Hicks (50) and Knight (56).
Shackle's it is a descriptive theory, the decision maker being portrayed as merely trying to satisfy some (volatile) level of aspiration so that he behaves as a satisficer rather than as a maximizer. Critical appraisals of these and related theories have been made by Arrow \(4, 5, 6\), Savage \(70\) and Simon \(83\). Edwards \(32\) has given an expository survey of the less-recent literature, while Bross \(13\) and Hildreth \(51\) have given generalized outlines of the decision problem that have had some impact among agricultural researchers.\(^3\)

Over recent years agricultural economists have attempted in varying degree to assess the possible role — both normative and descriptive of all these theories.\(^4\) Indeed, while our present interest is to review applications of game theory, the broad results of these other studies should be noted. So far as the descriptive theories of Simon and Shackle are concerned, the little evidence available \(27, 85\) suggests they play no great role in farmer decisions. Conversely, there is some evidence \(20, 53, 64\) that the use of naive expectation models is not uncommon among farmers and that there are some benefits to be gained by using such rules of thumb.

So much for general background; we now proceed to a brief outline of those aspects of game theory relevant to an appreciation of the agricultural applications made to date.

**Pertinent Aspects of Game Theory**

A “game” is an abstraction of situations involving interacting decision makers whose interests conflict but none of whom can exert full control over the situation. Thus a game is simply an economic model made up of players, their possible patterns of behaviour or strategies, any relevant probability influences, and a set of potential outcomes or payoffs. Game theory is the mathematical analysis of “playing” such games under an array of assumptions about the players and the rules of the game.

The classical assumptions about the players have been (a) that they are intelligent and rational; (b) that each attempts to maximize expected utility \(^5\); and (c) that each knows the available strategies, potential outcomes, and utility functions of all the other players. These assumptions are very restrictive. None the less, their relaxation in various

\(^2\) Space forbids consideration of such related developments of interest as

- (i) stochastic and lexicographic theories of choice \(21, 38, 63, 67\);
- (ii) decision making in an organizational framework \(39, 59, 61, 84\);
- (iii) the possible relation between welfare and aspirations \(95\), and
- (iv) the increasing role of operations research procedures \(30, 69\).

\(^3\) The elements of Hildreth’s model are:

- (i) a set of exogenous events \(Z\);
- (ii) a set of possible actions contingent upon events \(X_x\);
- (iii) a consequence \(y\) arising from choice of an action \(y = f[x, z]\);
- (iv) a set of strategies \(S\), each of which designates a choice of action under a given event; and
- (v) a criterion \(u\) for ordering consequences \(u = g[y]\) as a basis of choice.

\(^4\) Although important, such studies have made up only a small part of the total research on risk and uncertainty in farming. Overall, this research has been concerned with (a) policy measures, (b) farmers’ expectations and attitudes, (c) optimal farm organization, and (d) actual farmer behaviour. See \(12\).

\(^5\) Specifically, a Bernoulli-type utility function is assumed. This is one such that the utility of a lottery is numerically equal to the probability-weighted average of the utilities of the various outcomes if they were certain rather than probabilistic. Such utility functions do not permit interpersonal comparisons of utility. See \(18\), Ch. 4; \(40, 58\), Ch. 2.)
ways [see (58, Chs. 6-9; 71)] has so far not led to major advances in
the usefulness of the theory (unless one attaches heavy weight to the
derivation of such aphoristic insights as “Threats from madmen must
be taken seriously”).

The major split in game theory is between two-person zero-sum
games and other (i.e. n-person) games; zero-sum games being ones in
which the gains and losses of the players balance out. Complete
solutions, in the sense of strategy-choice procedures to maximize the
players’ assumed utility functions, are available for two-person zero-sum
games. In contrast, complete solutions are not available for n-person
games although n-person theory abounds in suggestive ideas about such
possibilities as threats, bribes and coalitions. The difficulty with more
than two players is the possibility of coalitions and the consequent
problem of sharing the loot. Indeed, for n-person games the only
substantial advances of empirical relevance appear to be the work of
Nash and others (8, Ch. 18; 58, Chs. 5-12) on (a) co-operative games,
in which preplay communication and bargaining are permitted, and (b)
the proof of the existence of at least one set of equilibrium strategies in
non-co-operative games such that if each player uses his appropriate
strategy, the other players are not induced to alter their strategies.(7)

Two-person Zero-sum Games

For cooperative games the main result has been the proof that co-
operation pays in the two person case — by joint action the players
are able to achieve a range of (Pareto optimal) solutions yielding pay-
offs in excess of those to be expected from the corresponding non-
cooperative game. This set of solutions is known as the negotiation
set and may represent a substantial narrowing of the range of conflict.

While both the concept of equilibrium strategies and the role of co-
operation may prove useful, they — along with other less fruitful
n-person concepts — have barely been considered by agricultural
economists. Accordingly, we revert to the two-person zero-sum game.
This at least has received a fair amount of agricultural attention.

A two-person zero-sum game may be defined by the triplet $\langle X,Y;K \rangle$
where $X$ and $Y$ denote the set of basic or pure strategies available to
Player 1 and Player 2 respectively; and $K$ is a function of $X$ and $Y$
called the payoff function which determines how much each player
wins or loses. If Player 1 chooses some strategy $x$ from $X$ and Player
2 chooses $y$ from $Y$, the outcome is a payoff in utility of $K(x,y)$ units
to Player 1 and $-K(x,y)$ units to Player 2.(8) So much for the use of

(6) Since a Bernoulli utility function, $U$, admits positive linear transformations,$U^* = aU + b$, from $U$ to $U^*$, there exists for $U_i$ and $U_j$ some transformation $aU_i + b = U_j^*$ such that $U_i = U_j$. If in a particular two-person game all
the pairs of possible payoffs $(u_i^*, u_j^*)$ to players 1 and 2 add to zero, then the
game is zero-sum. Moreover, any n-person non-zero-sum game can be converted to
an $(n + 1)$-person zero-sum game by adding a dummy player.

(7) Only for two-person zero-sum games do these equilibrium strategies imply
utility maximization.

(8) From our pragmatic viewpoint we will only be concerned with matrix
games, i.e. those for which $X$ and $Y$ are finite so that the set of payoffs $K(x,y)$
can be represented by a matrix, in contrast to continuous games in which $K(x,y)$
is a continuous function. Thus the matrix $(u_{ij})$ may represent a two-person zero-
sum game, where, if the first player uses his $i$-th strategy and the second player
his $j$-th, the outcome is a gain of $u_{ij}$ units by the first player and a loss of
$-u_{ij}$ units by the second player.
pure strategies $x$ and $y$. It is also possible for the players to use mixed strategies $x^*$ and $y^*$ where these are mixtures of the pure strategies in $X$ and $Y$, respectively. Of course, a pure strategy $x$ or $y$ is just a special mixed strategy for which $x$ or $y$ has a weight of unity and all other pure strategies have zero weight. With mixed strategies, the payoff $K(x^*, y^*)$ is simply the expected value of the payoff to Player 1 when he uses $x^*$ and Player 2 uses $y^*$. Finally, the game $(X, Y; K)$ has at least one “solution” $(\bar{x}, \bar{y}, v)$ such that $K(\bar{x}, \bar{y}) = v$. The strategies $\bar{x}$ and $\bar{y}$ are optimal in the sense that if Player 1 uses $\bar{x}$ he can be sure of obtaining at least $v$ units of utility (thereby maximizing or putting a floor on his minimum gain), while if Player 2 uses $\bar{y}$ he is sure of losing no more than $v$ units of utility (thereby minimizing or putting a ceiling on his maximum loss).\(^9\) The quantity $v$ is known as the value of the game. If one player diverges from his optimal strategy, the outcome of the game to the other player will be better than $v$. However, since both players are assumed intelligent, they will realize this and only use their optimal strategies. It is in this sense that $(\bar{x}, \bar{y}, v)$ constitutes a solution — neither player can hope to do better against his intelligent opponent.

Various techniques exist for solving two-person zero-sum games. If the matrix of possible payoffs for the various pure strategies contains an element which is the minimum in its row and the maximum of its column, i.e. a saddle point, then the strategies associated with this row and column are optimal. Conversely, if the matrix does not exhibit a saddle point, the solution must involve mixed strategies and inspection will not generally indicate the solution. Recourse must then be made to a variety of solution procedures, as exemplified by Luce and Raiffa (58) and Sasieni et al (69). One common approach is linear programming, making use of the fact that every two-person zero-sum game is formally equivalent to an easily defined programming problem (31; 47).\(^{10}\)

**Games against Nature**

One class of conflict situation closely akin to a two-person zero-sum game has been of particular interest to agricultural economists. Known as games against Nature, the special feature of these conflicts is that “Nature” is not a conscious adversary but just chooses between her possible strategies in some passive fashion. Nature may reflect a variety of phenomena from nature itself (e.g. will it rain or shine?) to mere ignorance (e.g. would this car dealer sell me a lemon?).

Three “types” of game against Nature may be distinguished, depending on whether the situation is approached as one of (i) objective risk, (ii) subjective risk, or (iii) complete ignorance. If Nature chooses among her alternative states on some known probability basis, the situation is one of objective risk; the decision maker should choose his (pure) strategy which has the greatest expected utility across Nature’s possible states. Analytically, such situations are trivial and need not be considered further.

For situations where the decision maker has vague information about

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(9) Mathematically, we have:

$$K(\bar{x}, y^*) \geq v \text{ for all } y^* \text{ from } Y.$$  
and  
$$K(x^*, \bar{y}) \leq v \text{ for all } x^* \text{ from } X.$$  

(10) Conversely, Candler (15) has shown that the general class of “feed-mix” linear programming problems may be solved by a (non-simplex) procedure based on game theory.
Nature’s states, or feels some to be more plausible than others, Savage (70) has shown that a set of subjective probabilities may be defined for Nature so that the problem becomes one of risk, albeit subjective risk. Normative illustrations of this approach are to be found in Debreu (23) and Luce and Raiffa (58, Ch. 13), while Williams (96) has looked at some farmers’ subjective probabilities about various events. Most importantly, along with Wald’s (93) theory of statistical decision, Savage’s subjective probability approach forms the basis of the current ferment in statistical inference (3; 52; 73). This revolution is aimed at replacing “classical” procedures by an approach based on (a) the generation of subjective probabilities from whatever a priori information is available and (b) the use of an economic loss function instead of the sacred cows (5 and 10 percent significance levels) of “classical” inference. To date, except for a hypothetical illustration by Hildreth (51), there have been no agricultural applications of this statistical decision theory. Probably it will continue to be somewhat neglected at the empirical level since its emphasis is personalistic and the implied solutions are not necessarily well-defined. None the less any decision maker who follows the subjective probability approach must be judged as behaving in a most reasonable manner.

Reverting to the third “type” of game against Nature, situations of “complete” ignorance are defined as those where the decision maker cannot (or chooses not to) attach (even subjective) probabilities to Nature’s states (although the states themselves are known). Also known as Decision Problems Under Uncertainty (DPUU), any number of decision approaches have been suggested for such situations. Four of these approaches seem reasonable in terms of the desirable axioms for choice under uncertainty, although it is impossible for any criterion to satisfy all the axioms, as Luce and Raiffa (58, Ch. 13) illustrate. The maximin or Wald criterion treats the DPUU strictly as a two-person zero-sum game, the best choice being the strategy (pure or mixed) with the largest minimum payoff. Nature being passive, this approach is very conservative. In contrast, the Laplace criterion suggests the decision maker might just as well assume each of Nature’s states is equally likely and treat the problem as one of risk. The Hurwicz pessimism-optimism criterion is based on selection of the strategy (necessarily pure) which maximizes the value of $b$ times its minimum payoff plus $(1-b)$ times its maximum payoff, where $b$, lying between 0 and 1, specifies the decision maker’s degree of pessimism. Lastly, selection of the strategy (pure or mixed) which yields the minimum maximum regret about foregone possibilities is suggested by the Savage-Niehans minimax regret criterion. Since they make varying use of the payoff data, these four approaches may obviously lead to different solutions. Equivalently, as Baumol (8, Ch. 19) shows, each criterion implies a distinctive type of indifference surface relating the decision maker’s preferences between outcomes from his available strategies. Moreover, for each of the criteria simple examples can be constructed yielding quite unreasonable “optimal” choices. In fact, there are no theoretical grounds for prescribing one of these criteria instead of another; choice of approach depends on the decision maker and must be expected to change from day to day with the state of his bank account and of his (or his wife’s) liver. Too, against all the DPUU criteria it can be forcefully argued that some information or intuitive feelings are always available so that the most reasonable approach is a subjective probability one.

One point remains to be noted before we consider specific agricultural
applications of game theory. It is that these applications have generally assumed the decision maker's utility function for money to be linear, i.e. that each extra unit of cash is worth the same to an individual whether he starts with none or a million units. The benefit of this assumption is that it enables the payoff matrix to be analysed in money terms. However, as noted later, it may lead to serious error if the optimal strategy is not a pure one.

**Agricultural Applications**

Game theory has been applied to the following range of agricultural problems: (a) production decisions under free competition; (b) the development of vertical and horizontal integration; (c) production under climatic uncertainty; (d) decisions on whether or not to adopt a new production technique; (e) trading or bargaining activities; and (f) conflict within the firm between its household and business sectors. Without exception, these applications have been made by U.S. and Australasian workers. No doubt applications by researchers in other countries (Japan? Sweden?) are not far distant.

**Decisions under Free Competition**

Broadly speaking, farmers operate under free competition; no farmer can influence the price he pays or receives. Concomitantly, as Shubik (79) has noted, no individual could possibly evaluate all his own alternatives (conceived in terms of product type, quality, time of marketing, etc.) relative to the alternatives open to each of his many competitors considered individually. Not only would there be too many people involved (i.e. an \( n \)-person game with \( n \) very large) but there would usually be a very large set of alternative strategies available to the decision maker himself. Recognising the impossibility of full information, Dillon and Heady (28) have argued explicitly (and Baker (7) implicitly) that production decisions by free competitors should be treated as games against Nature. Given the impossibility of full information, they suggest a reasonable approach for an individual entrepreneur would be to consider his alternatives relative to an aggregate opponent made up of all the other members of the freely competitive group taken in combination with other sources of influence such as the weather.(11) Even so, both players would have very many alternatives. Accordingly, it is argued that the decision maker should first stratify both his own and Nature's alternatives and then amalgamate those within each stratum into a single broad possibility. With payoffs represented by the most likely or expected payoff under each broad alternative, the net result of these simplifications would be reduction of the payoff matrix to a workable size.(12)

Lacking full information about the price expectations, planned choices, and general approach of his conferees to the decision problem, the decision maker could not associate objective probabilities with the broad alternatives of his aggregative opponent. In consequence, the payoff matrix depicts a game against Nature which might be tackled either as a DPUU, or — if some states of Nature are thought to be

(11) In a study just to hand, Moglewer (97) has used the concept of an aggregate opponent to cast crop selection into the frame of a continuous two-person zero-sum game. His analysis of U.S. crop data shows fair correlation between actual and predicted minimax acreage.

(12) While they have not examined its implications for free competition, Bruner et al (14), Harig and Smith (42), and Simon (83) have also hypothesized some such simplification of complex decision problems.
more plausible than others — as a subjective risk problem. Thus this
game theoretic model of free competition has the merit of incorporating
uncertainty as an endogenous factor. In contrast, the classical theory
of free competition completely ignores the possibility of uncertainty.
Still, three criticisms can be made of the game against Nature model
of competition. Firstly, the representation of broad groupings of
alternatives by a single payoff value (unless it be a certainty equivalent)
ignores the possibility that the decision maker might wish to consider
the variability of possible payoffs under each broad alternative.
Secondly, optimal strategy choice may vary markedly with the manner
and extent of the stratification of Nature’s alternatives. Apart from
manageability, no criteria have been suggested for the best way of
deciding on Nature’s states. Thirdly, unless the payoffs are measured
in terms of utility, the payoff matrix may make no allowance for any
non-monetary preferences the decision maker may have between his
alternatives. For instance, payoffs in monetary terms would make no
allowance for the fact that some farmers actually like to milk cows!

Ignoring the possibility of a subjective risk interpretation, Dillon and
Heady (24; 27; 29) attempted to assess the descriptive and normative
relevance of the above model in terms of the Wald, Laplace and
Savage-Nichans algorithms for solving DPUU’s. Of a sample of 77
farmers, only 12 appeared to consider some sample real-world problems
in a fashion consistent with the model. None the less, a majority of the
farmers behaved in partial agreement with the model; all considered
some simplified subset of their alternatives; 31 appeared to think in
terms of an aggregate opponent; and 24 made allowance for outcome
variations over two or more states of Nature. But from comparison of
the farmers’ and the theoretical solutions to the real-world problems
studied, nothing could be said of the descriptive relevance of the
decision criteria. It was apparent, however, that the algorithms
played no descriptive role in terms of the decision model. Conversely,
although differences between the criteria in the extent to which they
reduced ex ante resource misallocation were trivial, their possible
normative role was noteworthy. On average a normative approach
would have increased the farmers’ expected profit by at least 21 percent.

*Vertical and Horizontal Integration*

Baker (7) and the present writer (25) have suggested that the
phenomena of vertical integration and the development of farm co-
operatives might be analysed in terms of game theory. For instance,
inclusion might be viewed as the development of coalitions in an
n-person game being played by farmers, processors, retailers and
consumers. Certainly, given such a chain of entrepreneurs whose
decisions interact, coalitions of one type or another would be expected.
As argued by Davis and Whinston (22), such coalitions might be
motivated by the desire to internalize external economies, although the
reduction of uncertainty and the desire for countervailing power are
probably more potent forces.

From a policy and research view, the game theory approach to
integration leads directly to important questions; for example: How
viable are the coalitions? What are their effects on those in them? On
those outside them? Are there better ways of playing the game? To

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(13) In contrast, the farmers response to some hypothetical games against
Nature indicated intuitive uses of the Wald and Laplace criteria to be common.
See (27); and also (97).
some extent these questions flounder on the fact that optimal solutions to \( n \)-person games are unavailable. However, this may be but further reason for studying integration within a game theoretic framework. Not only may integration, either horizontal or vertical, be a feasible solution to the game; it is also an actual one that can be watched through its formative stages. As well, there are any number of suggestive \( n \)-person concepts which might usefully be drawn to the attention of public executives concerned with integration (both inter- and intra-national) and allied problems.

Some justification for the development of integration and government programs in agriculture is also provided by a simple game theory model of Luce and Raiffa (58, p.97). Suppose each farmer in an \( n \)-person game of free competition has two strategies: “full production” and “restricted production”. Since no individual can affect prices, he must always be better off using his full production strategy. But if all use full production, product price will be low. As a result, rational action by the individual producers makes them all worse off and the stage is set for the development of countervailing power through integration, contract farming, cooperatives, or State intervention. Alternatively, through lack of bargaining power, farmers may be forced into disadvantageous contract arrangements. Still, the above comments are no more than suggestive. As yet, there have been no studies of agricultural market structure corresponding to Shubik’s (80) analysis of industrial corporations. Indeed, if Shubik’s efforts are any indication, it would be naive to expect game theory to offer any more than partial guides to the resolution of agricultural market structure problems.

**Climatic Uncertainty**

The consideration of production decisions under climatic uncertainty as DPUU has been the most popular application of game theory in agricultural economics, the most extensive study to date being that of Walker and Heady (94). They applied DPUU criteria to real-world situations involving choice between crop varieties, kinds and amounts of fertilizer, crop enterprises, pasture mixtures, and stocking rates. Typically the situations were such that insufficient climatic records were available to yield reasonable objective probabilities for Nature’s choices. However, this approach suffers from the difficulty — common to many games against Nature — that some of Nature’s states will often be unknown. If so, any derived solutions may be quite misleading.

The chief contribution of Walker and Heady was not the mere casting of climatic uncertainty problems into a game theoretic framework. That had been done before by Schickel (72), Swanson (86; 87) and Thompson (88), all of whom also ignored the possibility of a subjective probability approach. Rather, Walker and Heady’s contribution was to demonstrate that if farm advisers used the various decision criteria, they could give alternative recommendations suited to a wide range of farmer attitudes and goals — especially if the recommendations were couched in terms of the practical characteristics of the criteria. Thus Walker and Heady suggest:

(i) the Laplace criterion is pertinent if the farmer is financially free to follow choices which may lead to highest long-run profits;

(ii) the Hurwicz pessimism-optimism approach is relevant for optimistic farmers who desire and can afford to gamble;

(iii) the Wald maximin criterion is best for farmers who must consider short-run outcomes because of financial commitments;
(iv) the Savage-Niehans minimax regret algorithm is appropriate for farmers who cannot completely ignore short-run outcomes, but can give some weight to long-run profit considerations or are in a sufficiently flexible position to allow for the possible opportunity cost of alternative strategies.

Somewhat similar suggestions have also been made by Throsby (89) on the basis of a game against Nature case study of a farmer's problem in trying to decide when he should sell his livestock in the face of drought possibilities. However, such suggestions are no more than attempts to translate into pragmatic terms the axioms underlying the various decision criteria. So far as they lack mathematical precision, these endeavours are likely to be incomplete if not incorrect.

Innovation

Arguing that decisions about whether or not to adopt an innovation imply complete ignorance, Dillon and Heady (26) have examined innovation as a DPUU. They formulate the payoff matrix as follows:

<table>
<thead>
<tr>
<th>Decision maker's alternatives</th>
<th>Nature's alternative</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Success</td>
</tr>
<tr>
<td>Adoption</td>
<td>z</td>
</tr>
<tr>
<td>Non-adoption</td>
<td>0</td>
</tr>
</tbody>
</table>

The decision maker's alternatives are self-explanatory. For Nature, the only relevant states are the extreme ones of absolute success or absolute failure. For both of these the payoff under adoption is assumed to be estimated by the decision maker. Non-adoption yields zero payoffs regardless of whether the innovation would have succeeded or failed. For convenience, the payoff matrix is normalized in terms of the payoff under adoption if Nature decrees absolute failure. Assuming that a degree of experimentation (partial adoption) $a$, ($0 < a < 1$), results in a payoff of $a$ times the adoption payoff, application of the DPUU criteria yields supposedly optimal strategies. Normatively, however, these solutions are only worthwhile to the extent that reasonable estimates can be made of the adoption payoff. By the nature of the case, this may not be possible. And even if based on correct payoffs, the solutions are only strictly relevant for a decision maker with absolutely no prior information about the innovation's chances of success. Such complete ignorance is rare for new agricultural practices; some vague information on the chance of varying degrees of success is usually available so that a better procedure would more often be the use of subjective probabilities with a "wider" payoff matrix.

The DPUU solutions to the innovation problem follow the pattern expected from the nature of the criteria. The Wald criterion, based on the assumption that Nature will do her worst, always dictates non-adoption. The Laplace criterion, placing equal weight on success or failure, suggests non-adoption or adoption according as the possible gain is less or more than the absolute value of the possible loss. The minimax regret algorithm, concentrating on ex post consideration of foregone gains, tends to emphasize mixed (i.e. experimentation) strategies. Lastly, the Hurwicz approach suggests either non-adoption, experimentation, or adoption, depending on the relative sizes of the pessimism index $b$ and the payoff for successful adoption.

As suggested by Emery and Oeser (35, p. 4) and Ruttan (68), such
game theoretic results may be useful descriptively as an analytical base for the study of the adoption of new agricultural techniques. Thus farmers who never innovate may be following some Wald-type "expect the worst" approach based on wait-and-see attitudes; farmers who follow an experimentation or partial adoption approach may do so because of opportunity cost considerations; while perennial innovators might be characterized by a Hurwicz-type approach with a high degree of optimism. Although no data specifically oriented to these hypotheses is available, there is some tentative evidence that supports them. For instance, Fallding (36) and Rogers (66) have classified farmers in terms of their use of recommended farm practices along lines suggestive of any classification based on the DPUU criteria.

Bargaining

Like other economic agents, farm managers frequently find it necessary to bargain. Typical examples occur in arranging leases, contracts, and the trading of land, plant or stock. The possibility of casting such situations in a game theoretic framework is obvious. To date, no empirical studies appear to have been made although Halter and Hubbard (41) have examined farmers' reactions to alternative strategies in some hypothetical machinery swap situations; while Heady and Candler (49) [cf. (54; 58, p. 231)] have commented briefly on landlord-tenant conflicts.

As illustration, consider the case of a sharefarmer whose lease is due for renewal. The landlord might have three alternatives: to renew the current lease; to sell the farm; or to contract with a better tenant after compensating the present tenant for any improvements. The current tenant could either take no action or incur some costs developing plans in case his lease is not renewed. The potential new tenant might likewise develop alternative plans or merely assume he will receive an offer from the landlord. The situation thus corresponds to a three-person non-zero-sum game with sidepayment possibilities. But to say this much says little; persons involved in such a situation would doubtless appreciate their alternative strategies and the possible payoffs without a game theorist pointing them out! Nor, most probably, would the game theorist be able to offer decent advice. Indeed, such simple bargaining situations seem to offer more hope of providing guidance for game theorists than the reverse. Certainly it would seem advantageous to study some of these real-world situations that abound in agriculture as well as the laboratory-type experimental games [see (65)] that have so far dominated game theory research.

The possible fruitfulness of such studies is enhanced by the findings of Halter and Hubbard's (41) study of a hypothetical machinery swap. Their analysis, based on the response of 362 farmers to queries on whether certain strategies (e.g. bluffing) should be used, showed (a) that the farmers were strategy conscious, and (b) that the set of considered strategies tended to vary systematically with such sociological variables as education, farm background, debt position and family size. Unfortunately, these results are not as clear cut as they may have been; the hypothetical questions confused two and n-person games, and referred to choices between strategies without allowing for any consideration of their associated payoffs. None the less, the results of this study are supported by an Iowa analysis (27) of farmers' reactions to a series of hypothetical games based on real-world data. This study also showed some association between a farmer's decision-making approach and his age, education, net worth and equity. As well, it
was found that the farmers’ approach was influenced more by the availability of outside income than by the timespan to which the games referred.

Firm versus Household

Without doubt, the most ingenious agricultural application of game theory has been Bird’s interpretation of the relationship between the firm and household. He suggests the farmer may be viewed as playing a two-person zero-sum game involving a schizophrenic interpretation of his roles as farm manager and household director.\(^{(14)}\) Two possible strategies — "same plans as before" and "change plans" — are attributed to each sector of the farm, giving the following generalized payoff matrix:

\[
\begin{array}{c|cc}
\text{Farmer in his domestic capacity} & \text{Strategies} & \text{Same plans} & \text{Change plans} \\
\hline
\text{Same plans} & a_{11} & a_{12} \\
\text{Change plans} & a_{21} & a_{22}
\end{array}
\]

Arguing that the payoffs \(a_{ij}\) tend to change systematically over the farmer's lifecycle, Bird suggests that the value of this game follows an evolutionary pattern corresponding to the various stages (beginning, middle and incipient retirement) in the lifecycle. Thus the game's value is hypothesized as negative for the beginning farmer since the domestic sector has to be sacrificed to the business sector. Indeed, for a just beginning farmer there may be no opportunities for choice, the game consisting simply of the degenerate matrix \((a_{11})\) with \(a_{11}\) negative. Gradually, however, choices widen as assets accumulate, and successive games tend to be of higher value since payoffs from the business to the household sector gradually increase as the farmer's lifecycle unfolds. Thus Bird hypothesizes later stages in the establishment period are characterized by matrices of the form \((a_{11}, a_{12})\) with both payoffs negative but implying games of increasing value (except for exogenous setbacks) as the farmer becomes better established. With full establishment the game is characterized by the full 2 by 2 matrix. Towards the end of the lifecycle, private interests will come to dominate business interests, and the matrix may again degenerate to the single element \(a_{11}\) reflecting a positive-valued game for the farmer in his domestic role. Bird also explores the possibility of treating the situation as a cooperative game and traces through possible changes in the negotiation set as the lifecycle unfolds. Since the game involves only a single individual, Bird argues (reasonably enough) that optimal choice within the negotiation set can be decided by a price line reflecting the consumer and producer goods involved in the strategies currently under scrutiny.

Despite the ingenuity of this game theoretic approach, it seems of little immediate value although it might help to identify alternative

\(^{(14)}\) Somewhat similar suggestions have been made relative to household decision making. See \((37)\). Likewise, Shubik \((80, \text{p.}220)\) has hypothesized that decision criteria differ between corporate and noncorporate firms.

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farmer reactions to policy measures. But even if it were a descriptively
ture formalization of the managerial life cycle (which has yet to be
proved) the hypothesis in its present nascent form lacks any strong
explanatory or predictive power. Rather it appears to be but an alter-
native way of describing known features of the farm's firm-household
interrelationships [cf. (46, Ch. 14)]. Still, as with any research, it may
stimulate important developments — one possible avenue being the
use of a similar approach to the study of conflicting policy goals.

Epilogue

In summary, game theory of one sort or another (but mostly pretty
simple) has been applied to agricultural situations involving the market
behaviour of farmers, climatic uncertainty, the adoption of innova-
tions, bargaining, and firm-household relationships. Little success has
rewarded these efforts. Only the game against Nature approach to
climatic uncertainty appears to have any immediate practical value
in so far as it would enable farm advisers to nominate an array of
reasoned recommendations rather than a single one as is typical at
present. Farmers could then make their own choice of a particular
strategy. Of course, such an approach is arbitrarily normative; there is no
guarantee that the assumptions involved correspond to the way farmers
would like to act, or would act if better informed about decision making.
But at least the suggested procedure would widen the farmers' in-
formation base. Even so, the DPUU approach to climatic uncertainty
is rather restricted; most weather problems involve risk (or subjective
risk) rather than uncertainty.

Of the other applications, probably only the approach to innovation
decisions has any significant practical value. Some of this may lie in
normative applications by farm advisers as they consult with farmers
on innovation problems. But the main opportunity probably lies in
integrating the economic, sociological and psychological considerations
involved in the adoption of farm practices. Many past studies of
adoption (and of farmer decision making in general) have proved
useless because of the researchers' failure to use an hypothesis-testing
approach. By suggesting pertinent hypotheses and providing an analytical
framework, the game theoretic approach could lead to some under-
standing and shortening of the lag between the development and
adoption of new practices. Still, a better way to reduce this lag would
be a more rational allocation of funds between basic research on the
one hand and applied development and evaluation on the other.

For further game theoretic research in agriculture, three avenues
might be explored. Firstly, there could be applications to particular
problems. Especially, consideration might be given to questions of
policy — an area so far ignored except for Luce and Raiffa's (58, p.97)
simple model involving full and restricted production alternatives, and
Chacko's (16; 17) none too successful consideration of some inter-
national trade problems.\(^{(15)}\) In particular, game theory might be applied
to such topics as commodity trade problems in the face of alternative
export market structures and contractual arrangements as may occur
with the European Common Market; the role of pressure groups, and

\(^{(15)}\) Heady (48) has given brief consideration to a game theoretic analysis
of policy conflict in a book published since this review was completed. However,
his analysis is no more than suggestive; empirical policy applications have still
to be made.
potential losers and gainers, in the generation of policy compromises through "democratic" processes; the perennial conflict between producer groups; the fights between and within the various organizations concerned with agricultural research and extension; and such smaller questions as the development of coalitions (pies) among buyers at (wool) auctions. As well, for instance, the game against Nature approach could be extended to production or policy decisions involving political and other non-climatic types of uncertainty, such as arise when enterprise decisions have to be made in the face of uncertainty as to the fate of recommendations made to Government by advisory authorities.

Secondly, in tackling particular problems, attempts should be made to examine the relevance of more advanced game theory concepts. Shubik (81), for instance, has noted some possible modifications to the information assumptions used in games against Nature. These variations, and other game theoretic concepts such as equilibrium strategies, cooperation, negotiation sets, imputations, continuous games, etc. [see e.g. (8; 43; 44; 58, Chs. 6-11; 97)], might be investigated in the context of real-world agricultural problems. Doubtless, as exemplified by the recent contributions of Boulding (11) and Schelling (71), such endeavours must necessitate modifications of the classical theory so as to bridge the gap between the real world and the theorist's idealization. Thus while classical game theory is normative, research into its real-world possibilities must be both normative and descriptive, and far less idealized, in orientation. After all, if it took von Neumann a decade or so to prove his minimax theorem, what hope is there for a simple farmer or bureaucrat if he wasn't a wrangler and doesn't even know the rules of the game he's playing?

Thirdly, empirical research is needed to examine the appropriateness for farmers and policy makers of some of the basic assumptions of game theory and such associated topics as Savage's subjective probability approach. Particularly important are the assumptions of a Bernoulli-type utility function and of rationality. As some have noted, rationality is a meaningless concept unless defined in terms of a given time-horizon and set of goals (77; 92). In consequence, investigations of farmer rationality in terms of hypotheses drawn, say, from Schlosser's (74) analysis of the concept of rationality, learning theory, and Ellsberg's (34) comments on subjective probability, appear desirable. Consideration should even be given to the development of theories of irrational behaviour! So far as the question of utility functions is concerned, it has already been noted that agricultural applications of game theory have invariably assumed a constant marginal utility for money. This assumption is obviously unreal unless the payoff matrix has a saddle point or the range of payoffs is not too wide, in which case resultant errors may not be too great. Still, these requirements are not likely to be satisfied too often. An associated problem is the empirical question of what types of utility functions should be imputed to what types of farmers and policy makers. Would a linear function based only on expected payoff values, or a quadratic function involving both the expected value and (semi-)variance of payoffs, serve best to approximate farmer behaviour? Game theory assumes the former, while Allais (2), Markowitz (60) and Tintner (90; 91), among others, have argued that variability considerations are relevant. Accordingly, empirical research to test these alternative hypotheses is needed along the lines suggested by Edwards (33), Halter and Beringer (40), and Markowitz (60, p. 280).
Finally, while it would be naive to expect any major breakthroughs, research along the lines suggested above would further enhance two attractive features of agricultural applications of game theory: first, that such research has involved real-world problems in contrast to the usual laboratory-type studies of game theorists; and, second, that agricultural applications of game theory can serve as prototypes for possible applications in other fields. None the less, (excluding theses), we would place game theory fairly low (but not as low as “facts without theory” projects) on the agricultural research priority list. To quote Colin Clark’s (19) words of 1948; “Any contribution which it (game theory) can yet make to economic reasoning is very small. What it does contain is a set of ideas which may at some future date and after much further development prove to be of very great importance. It is also possible that they may not.” Amen!

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