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 decribed 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.[1] 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

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(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**).[2] 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_z);
- (iii) a consequence (y) arising from choice of an action ($y = f[x,z]$);
- (iv) a set of strategies, (Σ), 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.[6] 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-cooperative 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 $(X,Y;K)$ 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_1 and U_2 some transformation $aU_1 + b = U_1^*$ such that $U_1 = U_2$. If in a particular two-person game all the pairs of possible payoffs (u_1^*, u_2) 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

(9) Mathematically, we have:

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

(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 confreres 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**), Haring 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-Niehans 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.[13] 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, integration 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

(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 Schickele (**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:

Decision maker's alternatives	Nature's alternative	
	Success	Failure
Adoption	z	−1
Non-adoption	0	0

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 guides 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 clearcut 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 (**9**) interpretation of the relationship between the farm 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:

Farmer in his business capacity

	Strategies	Same plans	Change plans
Farmer in his domestic capacity	Same plans	a_{12}	a_{22}
	Change plans	a_{21}	a_{12}

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 exogeneous 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**, p.220) has hypothesized that decision criteria differ between corporate and noncorporate firms.

farmer reactions to policy measures. But even if it were a descriptively true 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 alternative way of descibing 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 innovations, 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' information 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 understanding 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 international 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 Schoeffler'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!

REFERENCES

(**1**) Akerman, J., "Professor Shackle on economic methodology", *Kyklos* 11:341-61, 1958.

(**2**) Allais, M., "Le comportement de l'homme rationnel devant le risque: critique des postulats et axiomes de l'école americaine", *Econometrica* 21:503-46, 1953.

(**3**) Anscombe, F. J., "Bayesian statistics", *American Statistician* 15:21-4, 1961.

(**4**) Arrow, K. J., "Alternative approaches to the theory of choice in risk-taking situations", *Econometrica* 19:404-37, 1951.

(**5**) Arrow, K. J., "Utilities, attitudes, choices", *Econometrica* 26:1-23, 1958.

(**6**) Arrow, K. J., "Functions of a theory of behaviour under uncertainty", *Metroeconomica* 11:12-20, 1959.

(**7**) Baker, C. B., *Decision Making and Financing Farm Assets.* J. S. McLean Memorial Lecture, Ontario Agricultural College, Feb. 1960. (Mimeo.)

(**8**) Baumol, W. J., *Economic Theory and Operations Analysis.* Prentice-Hall, Englewood Cliffs, 1961.

(**9**) Bird, A. R., *Toward a General Formalization of a Managerial Life Cycle.* Michigan State Univ. Agric. Econ. Report 837, July 1961. (Mimeo.)

(**10**) Blackwell, D. and Girshick, M. A., *Theory of Games and Statistical Decision.* Wiley, N.Y., 1954.

(**11**) Boulding, K. E., *Conflict and Defense : A General Theory.* Harper, N.Y., 1962.

(**12**) Bowman, M. J., *Annotated Bibliography on the Treatment of Expectations, Risk and Uncertainty in American Farm Enterprise Economics.* Univ. of Chicago Dept. Econ. 1958. (Mimeo.)

(**13**) Bross, I. D. J., *Design for Decision.* Macmillan, N.Y., 1953.

(**14**) Bruner, J., Goodnow, J. J., and Austin, G. A., *A Study of Thinking.* Wiley, N.Y., 1956. Chs. 4 and 5.

(**15**) Candler, W. V., "A 'short-cut' method for the complete solution of game theory and feed-mix problems", *Econometrica* 28:618-34, 1960.

(**16**) Chacko, G. K., "Certain game situations in regional economic development", *Indian J. Econ.* 37:167-75, 1956.

(**17**) Chacko, G. K., *International Trade Aspects of Indian Burlap.* Bookman, N.Y., 1961.

(**18**) Chernoff, H. and Moses, L. E., *Elementary Decision Theory.* Wiley, N.Y., 1959.

(**19**) Clark, C., Review of *Theory of Games and Economic Behavior, Econ. Record,* 24:257-9, 1948.

(**20**) Darcovich, W., "Evaluation of some naive expectations models for agricultural yields and price". In Bowman, M. J. (ed.), *Expectations, Uncertainty and Business Behaviour.* Soc. Sci. Res. Council, N.Y., 1958. Ch. 14.

(**21**) Davidson, D. and Marschak, J., "Experimental tests of a stochastic decision theory". In Churchman, C. W. and Ratoosh, P., *Measurement.* Wiley, N.Y., 1959.

(**22**) Davis, O. A. and Whinston, A., "Externalities, welfare and the theory of games", *J. Political Economy* 70:241-62, 1962.

(**23**) Debreu, G., *Theory of Value.* Wiley, N.Y., 1959 Ch. 7.

(**24**) Dillon, J. L., "Theoretical and empirical approaches to programme selection within the feeder cattle enterprise", *J. Farm Econ.* 40:1921-31, 1958.

(**25**) Dillon, J. L., "Integration and game theory", *J. Farm Econ.* 42:384, 1960.

(26) Dillon, J. L. and Heady, E. O., "Decision criteria for innovation", *Aust. J. Agric. Econ.* 2:113-20, 1958.
(27) Dillon, J. L. and Heady, E. O., *Theories of Choice in Relation to Farmer Decisions*. Iowa State Univ. Agric. Exp. Sta. Res. Bull. 485. Oct. 1960.
(28) Dillon, J. L. and Heady, E. O., "A model for entrepreneurial decisions under free competition", *Metroeconomica* 13:20-28, 1961.
(29) Dillon, J. L. and Heady, E. O., "Free competition, uncertainty and farmer decisions", *J. Farm Econ.* 43:543-51, 1961.
(30) Dillon, J. L. and Lloyd, A. G., "Inventory analysis of drought reserves for Queensland graziers: some empirical analytics", *Aust. J. Agric. Econ.* 6:50-67, 1962.
(31) Dorfman, R., Samuelson, P. A., and Solow, R. M., *Linear Programming and Economic Analysis*. McGraw-Hill, N.Y., 1958. Ch. 16.
(32) Edwards, W., "The theory of decision making", *Psych. Bull.* 51:380-417, 1954.
(33) Edwards, W., "Utility, subjective probability, their interaction and variance preferences", *J. Conflict Resolution* 6:42-51, 1962.
(34) Ellsberg, D., Fellner, W., and Raiffa, H., "Symposium: Decisions under uncertainty", *Quarterly J. Econ.* 75:643-94, 1961.
(35) Emery, F. E. and Oeser, O. A., *Information, Decision, and Action*. Melbourne Univ. Press, 1958.
(36) Fallding, H., *Precept and Practice on North Coast Dairy Farms*. Univ. of Sydney Dept. Agric. Econ. Res. Bull. 2. 1958.
(37) Foote, N. N. (ed.), *Household Decision Making*. New York Univ. Press, 1961.
(38) Georgescu-Roegen, N., "Choice, expectations and measurability", *Quarterly J. Econ.* 68:503-34, 1954.
(39) Haire, M. (ed.), *Modern Organization Theory*. Wiley, N.Y., 1959.
(40) Halter, A. N. and Beringer, C., "Cardinal utility functions and managerial behaviour", *J. Farm Econ.* 42:118-32, 1960.
(41) Halter, A. N. and Hubbard, J. W., *Farmers' Use of Strategies in Machinery Trades*. Kentucky Agric. Exp. Sta. Progress Report 83. Nov. 1959. (Mimeo.)
(42) Haring, J. E. and Smith, G. C., "Utility theory, decision theory and profit maximisation", *Amer. Econ. Rev.* 59:566-83, 1959.
(43) Harsanyi, J. C., "A bargaining model for the co-operative *n*-person game". In Tucker, A. W. and Luce, R. D. (eds.), *Contributions to the Theory of Games*, Vol. IV, pp. 325-56. Princeton Univ. Press, 1959.
(44) Harsanyi, J. C., "Measurement of social power in *n*-person reciprocal power situations", *Behavioral Science* 7:81-91, 1962.
(45) Hart, A. G., "Anticipations, uncertainty, and dynamic planning", *Studies in Bus. Admin.* 11:1-98, 1940.
(46) Heady, E. O., *Economics of Agricultural Production and Resource Use*. Prentice-Hall, N.Y., 1952.
(47) Heady, E. O., "Application of game theory in agricultural economics", *Canadian J. Agric. Econ.* 6:1-13, 1958.
(48) Heady, E. O., *Agricultural Policy under Economic Development*. Iowa State Univ. Press, Ames, 1962. Ch. 9.
(49) Heady, E. O. and Candler, W. V., *Linear Programming Methods*. Iowa State Univ. Press, Ames, 1958. Ch. 15.
(50) Hicks, J. R., "The theory of uncertainty and profit", *Economica* 11:170-89, 1931.
(51) Hildreth, C., "Problems of uncertainty in farm planning", *J. Farm Econ.* 39:1430-41, 1957.
(52) Hirshleifer, J., "The Bayesian approach to statistical inference: an exposition", *J. Business* 34:471-89, 1961.
(53) Kaldor, D. R. and Heady, E. O., *An Exploration of Expectations, Uncertainty, and Farm Plans*. Iowa State Univ. Agric. Exp. Sta. Res. Bull. 408. April 1954.
(54) Kelsey, M. P. and Janssen, M. R., "Bilateral monopoly in farm leasing", *J. Farm. Econ.* 40:1828-31, 1958.
(55) Koopmans, T. C., *Three Essays on the State of Economic Science*. McGraw-Hill, N.Y., 1957. Pt. II.
(56) Knight, F. H., *Risk, Uncertainty and Profit*. Houghton-Mifflin, N.Y., 1921.
(57) Knight, D. A. and Greve, R. W., *Use and Interrelation of Marginal Analysis to other Analytical Processes by Farmers in Decision Making*. Kansas State Univ. Agric. Exp. Sta. Tech. Bull. 108. June 1960.
(58) Luce, R. D. and Raiffa, H., *Games and Decisions*. Wiley, N.Y. 1957.
(59) March, J. G. and Simon, H. A., *Organizations*. Wiley, N.Y. 1958.
(60) Markowitz, H. M., *Portfolio Selection*. Wiley, N.Y. 1959.
(61) Marschak, J., "Elements for a theory of teams", *Manag.Sci.* 1:127-37, 1955.

(62) von Neumann, J. and Morgenstern, O., *Theory of Games and Economic Behavior*. Princeton Univ. Press. 1947 (3rd ed., 1953).
(63) Papandreou, A. G. *et al.*, "Test of a stochastic theory of choice", *Univ. of Calif. Publications in Economics* 16:1-18, 1957.
(64) Partenheimer, E. J., *Some Expectation Models Used by Selected Groups of Mid-western Farmers*. Michigan State Univ. Dept. Agric. Econ. Ph.D. Thesis Abstract, 1959. (Mimeo.)
(65) Rapoport, A. and Orwant, C., "Experimental games: a review", *Behavioral Science* 7:1-37, 1962.
(66) Rogers, E. M., "Categorizing the adopters of agricultural practices", *Rural Sociology* 23:345-54, 1958.
(67) Roy, A. D., "Safety first and the holding of assets", *Econometrica* 20:431-49, 1952.
(68) Ruttan, V. W., "Research on the economics of technological change in American agriculture", *J. Farm Econ.* 42:735-54, 1960.
(69) Sasieni, M., Yaspan, A. and Friedman, L., *Operations Research*. Wiley, N.Y., 1959. Ch. 7.
(70) Savage, L. J., *The Foundations of Statistics*. Wiley, N.Y., 1954
(71) Schelling, T. C., *The Strategy of Conflict*. Harvard Univ. Press, Cambridge, 1960.
(72) Schickele, R., "Farmers' adaptions to income uncertainty", *J. Farm. Econ.* 32:356-74, 1950.
(73) Schlaifer, R., *Probability and Statistics for Business Decisions*. McGraw-Hill, N.Y., 1959.
(74) Schoeffler, S., "Towards a general definition of rational action", *Kyklos* 7:245-74, 1954.
(75) Schultz, T. W. and Brownlee, O. T., "Two trials to determine expectation models applicable to agriculture", *Quarterly J. Econ.* 56:487-96, 1942.
(76) Shackle, G. L., *Expectation in Economics*. Cambridge Univ. Press, 1949.
(77) Shackle, G. L., *Time in Economics*. North-Holland, Amsterdam, 1958.
(78) Shackle, G. L., *Decision, Order and Time in Human Affairs*. Cambridge Univ. Press, 1961.
(79) Shubik, M., "Information, theories of competition, and the theory of games", *J. Political Economy* 60:145-50, 1952.
(80) Shubik, M., *Strategy and Market Structure*. Wiley, N.Y., 1959.
(81) Shubik, M., *Some Informal Comments on Models of Decision Processes under Uncertainty*. Cowles Foundation Discussion Paper 113. May 1961. (Mimeo.)
(82) Simon, H. A., *Models of Man*. Wiley, N.Y., 1957. Ch. 14.
(83) Simon, H. A., "Theories of decision making in economics and behavioral science", *Amer. Econ. Rev.* 49:253-83, 1959.
(84) Simon, H. A., "New developments in the theory of the firm", *Amer. Econ. Rev. Papers and Proc.* 52:1-27, 1962.
(85) Swanson, E. R., *Agricultural Resource Productivity and Attitudes to the Use of Credit in Southern Iowa*. Iowa State Univ. Dept. Econ. Ph.D. Thesis (Unpublished). 1951.
(86) Swanson, E. R., "Problems of applying experimental results to commercial practice", *J. Farm. Econ.* 39:382-9, 1957.
(87) Swanson, E. R., "Selection of crop varieties: an illustration of game theoretic techniques", *Revista Internazionale di Scienze Economiche e Commerciali* 6:3-14, 1959.
(88) Thompson, G. L., "Decision making and new mathematics", *Naval Res. Logistics Quarterly* 3:141-50, 1956.
(89) Throsby, C. D., "Game theory and a time-of-market decision", *Aust. J. Agric. Econ.* 5:9-22, 1961.
(90) Tintner, G., "The pure theory of production under technological risk and uncertainty", *Econometrica* 9:305-12, 1941.
(91) Tintner, G., "A contribution to the non-static theory of production". In Lange, O. (ed.), *Studies in Mathematical Economics and Econometrics*. Univ. of Chicago Press, 1942.
(92) Wagner, H. M., "Advances in game theory: a review article", *Amer. Econ. Rev.* 48:368-87, 1958.
(93) Wald, A., *Statistical Decision Functions*. Wiley, N.Y. 1950.
(94) Walker, O. L. and Heady, E. O., *Application of Game Theory Models to Decisions on Farm Practices and Resource Use*. Iowa State Univ. Agric. Exp. Sta. Res. Bull. 488. Dec. 1960.
(95) Weckstein, R. S., "Welfare criteria and changing tastes", *Amer. Econ. Rev.* 52:133-53, 1962.
(96) Williams, D. B., "Risk elements in farming", *Quarterly Rev. Agric. Econ.* 6:101-5, 1953.
(97) Moglewer, S., "A game theory model for agricultural crop selection", *Econometrica* 30:253-66, 1962.