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Simulation of crop choice dynamics: an application of nested Master-Equation models

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Abstract

One of the most intractable problems faced by decision-makers is the possible effect of policy tools on the decisions of actors operating within the environment of interest. The paper contributes to the study of this issue by reporting a novel modelling approach to the analysis of farmer - environment - policy interactions, that of using nested Master Equations. The model simulates a multi-function assessment of various economic, technological and environmental constraints affecting farmers in the Argolid region of southern Greece. We obtain an approximate *eigenvector* of a dynamically variable transition matrix of infinite dimension. This *eigenvector* represents a probability density function in thirteen dimensions that governs crop choice behaviour on a theoretical representation of the Argolid Plain. Regularities observed in the model's output resonate clearly with observations from sociological and anthropological fieldwork which were not knowingly integrated at the design phase, thus providing an independent empirical check on the work. The output from the simulation model is compared with observations from the field, and the technique is discussed in terms of its novelty and significance as a micro-simulation tool.

Keywords: crop choice, modelling, master equation, simulation.

Résumé

Simulation de la dynamique des choix de culture. Modélisation à base d'Equations Maîtresses hiérarchisées. *Un des principaux problèmes auxquels sont confrontés les décideurs tient à la difficulté d'apprécier les conséquences possibles des nouvelles réglementations politiques sur les décisions des acteurs visés. Cet article apporte une contribution à ce débat en présentant une technique originale de modélisation pour l'étude des interactions agriculteur - environnement - réglementations politiques, celle de l'utilisation d'Équations Maîtresses hiérarchisées. Le modèle, basé sur les données d'une enquête sociale dans la région d'Argolid en Grèce, simule les décisions de choix de cultures sur la base d'une évaluation multi-fonctionnelle de diverses contraintes économiques, technologiques et environnementales. Cette approche permet la définition d'un eigenvector dans une matrice de transition dynamique à dimensions infinies. Ce vecteur représente une fonction de la densité de probabilité dans les 13 dimensions supposées jouer un rôle dans le comportement de choix de cultures, ceci sur une représentation théorique de la plaine d'Argolid. Les régularités observées dans les résultats de la simulation vont clairement dans le même sens que les observations sociologiques et anthropologiques effectuées sur le terrain, et qui n'ont pas été intégrées au modèle. Les résultats du modèle de simulation sont comparés avec les observations de terrain, et la technique est discutée du point de vue de sa nouveauté ainsi que de sa signification en tant qu'outil de micro-simulation.*

Mots-clés : *choix des cultures, modélisation, équation maîtresse, simulation.*

Introduction

This text presents results from an ongoing study of the Argolid region of Southern Greece. One of the study's objectives is to understand the determinants of changes in farming practice in the area and this involves interdisciplinary collaboration between researchers from a range of disciplines including anthropologists, sociologists, hydrologists and computer modellers. In many ways the nature of collaboration is unique. Unlike the vast majority of cooperative cross-disciplinary ventures where the social sciences are used as data generation engines for modellers, this project has promoted a symbiotic relationship. The formats of the contributions are not comparable at the level of data compatibility, but they are mutually informative in terms of knowledge. Considered together, the findings provide a richer picture of agricultural development in the study area.

We begin with a description of the contemporary farming landscape, highlighting the key role played by the use of, and access to, water. We then present a summary of data collated from field work (surveys, documentary evidence etc.) which describe those factors which can be seen to influence crop change. This material provides a framework for interpreting the results of a computer model designed to investigate aspects of farmer behaviour with regard to crop change. The computer model itself is then described in some detail and its output discussed with reference to issues of crop change. Finally, we discuss some of the methodological issues associated with the use of simulation models in this context.

Water has been a preoccupation in the Argolid Valley since ancient times when the area was characterised as *polidipsion* (very thirsty) or *anhydron* (lacking water). Greek mythology refers to this relationship in the killing, over water, of Hydra by Hercules near the spring of Lerni. Historical records of the area convey a picture of rain-fed farming and grazing with salt marshes along some of the coastal strips. Throughout the Turkish occupation, agriculture in the Argolid valley was varied (olives, rice, cereals, tobacco, vegetables, melons and grazing). Very little irrigated farming was undertaken and the main perennials, vines and olives, were also rain fed. In the 1930's and 40's one farmer recalls that « *the valley was all stubble, some olive trees and pear trees. All the fruit trees you see now have been planted since 1960. Everything started after the bore holes and the access to water* ». The coastal area had relatively little agricultural activity because of wetland areas and poor soils with high salt levels.

Since the late 1950's there has been a movement of irrigated agriculture outwards from the plain to the foothills. The irrigated area of the Argolid Valley expanded from 5,500 hectares with 45 million cubic metres of water being applied in 1945 to 19,500 hectares with 145 million cubic metres in 1990. This expansion has been supported by the increased use of water pumps and bore holes. Where previously irrigation water was hand or animal drawn from wells or supplied from the spring at Kefalari in the West of the plain, there are now eight thousand electric pumps in use for water raising. The Greek Government provided support for agricultural technologies, and thereby irrigation, between the 1960's and 1980's, providing subsidies of up to 20% of total cost for the installation of sprinkler systems and bore holes. This funding role has since been taken over by the European Community.

The Argolid Plain is now characterised by a carpet of lush green vegetation, with a profusion of citrus trees, and by the sight and sounds of the water technologies that have been introduced to support their production. These include concrete irrigation canals ranging from six metres in diameter to small channels which skirt individual fields with metal sluice gates for supplying « flood » irrigation to the crops. Elsewhere, irrigation pipes snake through the orchards taking water from the crudely built brick bore-hole housings to the sprinkler irrigation systems that are also used in winter to protect the crops against frost. Adjacent to some of these housings can be found the old surface wells that were animal driven.

Increasing use of irrigation has been accompanied by a decline in the condition of the ground water in both qualitative and quantitative terms. Salination in the central plain has occurred through sea water intrusion as aquifer levels have dropped. The peripheral areas have experienced an even more pronounced lowering of aquifers, to below 450 metres in places, with increased uncertainty about finding water when existing bore holes have run dry. An early belief in the ability of technology to determine the course of nature has given way to a resigned acceptance that it offers the only possibility of managing a degraded system and of generating an income from agricultural production.

1. Influences on crop choice - field evidence.

The number of different crops grown in the region has clearly decreased over the last 100 years. The main reasons cited by farmers for the emergence of less varied agriculture (although not necessarily for the expansion of irrigated land), are the internal support for production prior to the 1980's and, alongside the saturation of the internal market, the arrival of EEC price support and subsidies after Greece's accession in 1981. There are two forms of crop related policy instruments to take into account to help explain this. The first is concerned with the level of price support made available for specific crops (e.g. oranges). The second is based upon subsidies that are paid to encourage changes in the existing crop balance, in response either to a diminishing market for a crop or to the presence of a disease or virus to which a crop is vulnerable.

A key consideration in the farmers' decision as to which crop to grow is clearly the anticipated price which could be secured for the produce. Although certain crops tend to be sold through particular markets (oranges through co-operatives, olives through dealers, vegetables through local markets), these are not exclusive. Where choice is exercised by farmers it is strongly influenced by two central factors; the social formation of the farm household and the capacity to spend more time selling the crop at a higher price, and the propensity of farmers to deal with risk and the willingness to forsake a lower guaranteed price for crops with price support in favour of the possibility of a higher price on the open market.

Price support has been introduced since accession to the EEC and those that are relevant to the Argolid mainly relate to citrus crops, although there is also a complicated guaranteed pricing procedure for olive oil. Unlike the majority of subsidies (which apply to individual farmers), support for citrus crops is generally only provided when certain production criteria are met and representation is made through co-operative marketing structures. The EEC guaranteed price is central to farmers' decision-making because it provides the benchmark by which they can estimate their income for the following year from citrus fruit. The price support paid for oranges extends to the dumping (burying) of excess fruit, to its use in fruit processing, particularly for juice, and to its distribution for welfare purposes (i.e. to schools in areas of special need).

Whereas price support is in effect a market guarantee, subsidies are a way of restructuring agricultural land use in response to concern about the market potential of a crop or its vulnerability to disease or a virus. Before accession to the EEC the Greek government subsidised the planting of new crops, mainly Merlin oranges, but also grapefruit, clementines and satsumas. Since 1981 a number of restructuring measures have been introduced. Some of these were designed to extend agricultural production through the year (i.e. the replacement of Merlin oranges with other citrus crops) whereas other programmes were intended to uproot and replace existing crops. Subsidy take-up for uprooting has generally been high. However, the second phase of these programmes, which provide support for planting suggested replacement crops, has often been less successful. A number of reasons have been cited in explanation of this. For example, the crops may have been untried in the area and farmers are not prepared to « risk » or « champion » their introduction (i.e. pistachio nuts were recommended as a response to the removal of apricot trees but had an extremely low take up rate).

Where the adoption of suggested crops has been more successful, it has tended to be with citrus crops (i.e. the replacement of Merlin oranges and common mandarins with other mandarin varieties such as clementines). This has had two significant and related effects. Firstly there has often been a weak correlation between replacement crops and the existence of a « real », as opposed to an artificial or guaranteed, market. Secondly, and of particular relevance to the Argolid, has been the fact that adopted crops have tended to be heavily water dependent and as such have exacerbated the degradation of that resource in the area.

The initial impact of irrigation technologies on crop was to provide agronomic options that previously did not exist. However, profitable citrus crops have a low labour requirement (predominantly related to the picking period) so that irrigation changed the nature of farming and land owners who otherwise may not have farmed have entered the industry. This is especially evident in the central Argolid Plain where many orange producers are part-time farmers.

2. Conservatism, time and money: simulating crop choice on the Argolid plain.

There are two principal difficulties that must be addressed when modelling crop choice. The first is that the population of farmers is not a single unit but a large group of actors spread across the landscape. Each actor is capable of making isolated decisions and it is the collective dynamic generated by all the actors that impinges on the terrestrial ecosystem. Modelling crop choice as if the Argolid were a single unit requires us to take account of the many, potentially independent agents that make up the Argolid farming community. The second problem is that the cognitive mechanisms underpinning crop choice are poorly understood. It is clearly possible to recognise certain predispositions among farmers either by traditional elicitation methods or by sophisticated mathematical analysis but it is impossible to simulate, or even to observe the cognitive processes involved.

Modelling the dynamics between the behaviour of individual farmers or communities of farmers on the one hand, and land use, technique adoption and resource management on the other, is an emergent domain of enquiry. However, impetus to research in this area has recently been provided by contributions which have highlighted the advantages to be gained from an integrated analysis of farm / environment dynamics, e.g. Dent *et al.*. (1995). As has been the case with many other fields of research, the problem of how to represent human behaviour at various scales is to the fore. In agricultural focused research, they have been both theoretically and formally considered as rationally acting utility maximisers (Amir *et al.*, 1991). Two recent contributions are typical of this type of approach. For example, goal programming has been used to disaggregate optimisation strategies into multi-objective functions (Sumpsi *et al.*, 1997) and a logistic regression model was used by Cary & Wilkinson (1997) to show the influence of perceived profitability and technical feasibility on farmers' conservation practices. However, although recent work has illustrated the variety of factors which influence decisions on the farm (e.g. Gasson & Errington, 1993), approaches which capture the diversity of behaviour of a community of farmers have been hindered by methodological difficulties.

We would point out that the types of model discussed above are primarily focused on the individual farmer, either trying to make sense of the reasoning behind specific types of behaviour, or seeking to derive generalisable functions which can be used to represent or predict changes in behaviour (decision-making). Generating prescriptive frameworks which optimise behaviour, (and through behaviour, production) is the objective of such research. The modelling approach adopted in this text is significantly different in that it does not address the question « what is the best way to achieve situation x? » Rather it seeks to explore how a particular sequence of observed trends and events could have evolved given our understanding of the relationships between various phenomena. Formal representations (equations) are used to capture the dynamics of change at the community level rather than some equilibrium point at the level of the individual. In terms of alternative contemporary approaches we draw attention to the work of Gremillion (1996) on crop adoption and MacFarlane (1996), who uses a GIS based methodology to investigate farm adjustment to policy change.

It is important, therefore, to be clear about the nature of the modelling problem being addressed. Each farmer can be represented as looking at the current range of crops grown, monitoring their profitability, grubbing out and replacing unprofitable crops, drilling boreholes and abstracting water in the expectation of future profits. Clearly, the problems we must address with regard to the perception of environment are not insignificant. We can make some fairly basic generalisations as follows.

Suppose a farmer has one profitable crop. If he decides to grow that crop on one plot, he will get one unit of profit, if it is grown on two, he will get two units and so on. The more he grows, the more he earns, up to the number of plots he holds. Consider two crops. The farmer now sits on a sort of landscape in which « altitude » actually represents profit. Every point on that landscape will correspond to a given mix of crops (x plots of crop 1 and y plots of crop 2). Each point will have its own altitude (profitability). The farmer cannot travel an infinite distance across this landscape because he is constrained by the number of plots he holds. Given 100 plots, 80 of which are under crop 1, the most plots he can put under crop 2 is 20. We can reasonably think of crop choice as the process of searching this landscape for hills to climb. The summit of the highest hill represents the most profitable mix of crops to grow but there may be many hills, some higher than others, some out of reach because the farmer does not hold enough plots of land to locate them. Personal predispositions and starting position may mean that the farmer will never locate the best solution to his problem. Note that we are not describing the cognitive processes of a real farmer but a conceptual model of those processes. The model suggests that it might be useful and interesting to think of crop choice as the process of searching some constrained and intricate landscape for high places (profitable configurations).

Eleven crops (representative of those grown in the Argolid in recent times) were selected for use in the model, including a « null » crop. Those crops selected were Apricots, Oranges, Lemons, Cereals, Olives, salt tolerant vegetables, non salt tolerant vegetables, Tobacco, Pistachios, Vines and a Null crop. A plot under « null » is representative of an abandoned parcel of land. This means that this particular conceptual model of an Argolid farmer is of an actor exploring a constrained 11-dimensional landscape where humps and hollows represent good and bad places to be located. According to this conception, a farmer is simply an assembly of plots each of which is a dynamic system in its own right. The plot lives in an attribute space of eleven points and, at every time step, the plot has the opportunity to hop from one point to another. It may hop or it may stay still. Additionally, there will be some conditional probabilities that determine the transition rates between different points and, if we can generate transition rates for the plot, we can put an assembly of plots together and call it a « farmer ». By this conception of crop choice the Farmer's behaviour can be understood in terms of a *Master Equation* of the plot.

To define a Master Equation, we represent the assembly of plots at time t by a vector, $|A_t>$ whose ith element, $A_t(i)$ contains the probability that a plot is under crop i at time t. If we believe all the plots are carrying one crop (crop j, say) we put 1.0 in the jth element of

$|A_t>$ and 0.0 in all the others. After a single time step actors will make transitions and our probability densities will need to be redistributed accordingly. We can write an equation for this redistribution;

$$A_{(t+\Delta t,i)} = \Sigma\, T_{(i,j)} * A_{(t,j)} \;.......(1)$$

or, in the more compact notation of matrix algebra

$$|At+\Delta t> = T|At> \;.......(2)$$

where Δt is a small time step and $|A_t>$ is a vector whose ith element gives the proportion of plots under crop i at time t. Equation (2) is a dynamic system. It maps an n-dimensional co-ordinate vector (of probabilities) onto itself. The equation describing the evolution of these probabilities is the Master Equation. At first glance, the Master Equation appears to be a linear dynamic system. As t tends to infinity, the assembly, $|A_t>$ will tend to a fixed point with a constant probability assigned to each state. Note that at this fixed point, the individual plots will still be making transitions, but the probability flow out of a given crop will be perfectly balanced by counter-flows in. The steady-state distribution corresponds to the principal eigenvector of a matrix. This matrix is called the *propagator* (T) of the Master Equation. In practice, however, the propagator may itself be dynamically variable. As T changes, the dynamic system represented in Equation (2) will tend towards different steady states. For example, a farmer who drills a borehole will have free access to water and consequently different attitudes to irrigated crops than one who has no borehole or whose borehole has dried up. As circumstances change, the propagator will change and this dynamic may introduce non-linearities into the Master Equation which can, under certain circumstances, generate irreversible change and spontaneous self-organisation. (see Allen *et al.*, 1983; Prigogine & Stengers, 1987 for reviews of these processes)

The advantage of the Master Equation formalisation is that the process of navigating on an intricate 11-dimensional surface can be seen to consist of the collective behaviour of an assembly of plots, each hopping from one of eleven points to another in accordance with some incompletely understood deterministic rules that have potentially knowable probabilistic implications. In order to capitalise on this advantage we must write down expressions for the 121 transition probabilities in the propagator and link these dynamically to the availability of water and so on. These probability expressions are the *equations of motion* for the individual plot. Of course, the probability distribution among crops is not the same as the number of plots each farmer has under those crops; a probability is not a frequency. However, the latter can be generated from the former by means of a *Monte Carlo Simulation* which uses a random number generator to make decisions consistent with the Master Equation. This process will be discussed further in the final section of this paper. For present purposes, it is useful to use what we already know about the constraints a farmer is operating under because these can help specify the general « shape » of the propagator.

If a farmer has olives on a given plot, he must grub them up to plant oranges and that is expensive. If he has wheat, grubout costs are negligible so oranges may be more attractive. The route by which a plot approaches a crop may determine its likelihood of getting there. Similarly, if the farmer has a well with freshwater, crops that need irrigation are attractive. If there is no well, he must consider the cost of the borehole and that makes them less attractive. Wheat planted this year will bear next, olives will not. Infra-structure costs, lead-in times and grub-out costs must somehow determine the shape of the eleven dimensional cost-benefit landscape the farmer explores by changing the transition rates of the individual plots. As if this were not sufficiently complicated, different farmers will have different predispositions to change. In terms of the profitability landscape discussed above, some farmers will be able to see across small valleys while others will be reluctant to move through tiny hollows to reach a large peak on the other side.

All these factors must be considered when specifying transition rates for the individual plot. It is possible (though unlikely) that each farmer is using decision rules that can be simulated mathematically, but even if this were so, no elicitation method currently available would enable us to specify the equations and parameters needed to replicate it. We simply cannot simulate what real farmers actually do when they make decisions. This stark fact is the principal reason many social scientists are skeptical about the usefulness of dynamic and mathematical models in social research. If we cannot simulate socio-natural dynamics in the real world, what is the point of using mathematical and simulation methods in social science? Part of the answer to this query is that we can sometimes build simulation models that are consistent with well-defined theories about socio-natural dynamics and, by simulating these, learn something about the range of behaviours consistent with those theories.

3. A model farmer

We know that we cannot model a farmer's decision processes exactly. However, it should be possible to create a Master Equation model that decides between crops in a coherent and rational way using fairly well defined cost-benefit data. We start by giving each farmer a nominal 100 plots of land carrying a selection of crops including small amounts of oranges and lemons, together with wheat, olives and vines. This configuration approximated the typical crop mix we would have expected from a pre- 1950s farmer. No farmer has access to water but some have the potential to get water (at a cost). The farmer looks at each plot in turn and calculates the likely value of the crop standing on that plot, the cost of removing it and the likely value of all the other crops that could be grown. In doing this he takes account of the loss of profit while waiting for the crop to mature and yield, and any loss or gain of earned income facilitated by moving from a high labour crop to a low labour crop or vice versa. Information concerning cost-benefit data, grubout and labour costs, infrastructural requirements and lead-in intervals were elicited from farmers and agronomists in the Argolid as part of the study carried out by sociologists and anthropologists reported above.

The next step is to generate a crude set of conditional probabilities of crop change. The simulated farmer is effectively asking the question « what is the probability of changing to crop i given that I currently grow crop j? » These probabilities are obtained using a multinomial model of the form;

$$P_{(i,j)} = k * e^{\beta * C\_B(i,j)} \qquad ....(3)$$

Where *k* is a normalisation constant that ensures all conditional probabilities sum to 1.0, C_B(*i,j*) is the projected cost-benefit of replacing crop j with i, *e* is the exponential constant and *ß* is a small constant determined by the need to avoid overflow errors in the exponent.

The absolute size of ß is, in practice determined by the currency unit chosen. If a small currency unit (the Drachma, for example) is used, ß must be very small to keep the exponent of C_B(i,j) within manageable bounds. Conversely, if profits were evaluated in Sterling or ECU, the numbers returned for C_B(i,j) would be smaller and the selected value of ß could be somewhat larger.

At this stage of model definition, farmer decision-making is represented by the Master Equation of a small unit of territory, the plot. Each plot explores an attribute space of 11 points (one for each crop) and Equation (1), articulated with cost-benefit data specifies the transition rates for moving from one crop to another. A farmer is an assembly of 100 plots and its decision behaviour is determined by the propagator of the Master Equation of an individual plot. As noted above, the situation is a little more complicated because a farmer who decides to grow an irrigated crop will be forced to drill a borehole. As soon as this decision is taken, the cost of the hole is deducted from his bank balance *whether he finds water or not.* If he finds water, irrigated crops will be more attractive because their infrastructural costs have been met and the water is available. If he does not find water, irrigated crops will fail. The cost of drilling a borehole will recur in the cost-benefit computation that underpins the decision process until he has been successful. Every time he decides to change to or persist with an irrigated crop, that cost will be deducted from his bank balance until he has been successful. As soon as he has been successful, he is free to grow irrigated crops on *any* of his plots without incurring any further infrastructural costs.

A good borehole will change the propagator by obviating the need to drill any more holes. The plots (of which this model is the Master Equation) are instances of a *split system* (Winder, 1995). Such systems can, on occasion, make critical transitions, which in this context represent a move from traditional to irrigated agriculture. The reader should note that research currently underway will integrate this model with a dynamic model of the Aquifer itself. This will facilitate critical transitions in the opposite direction as water supplies dry up or become salinised and will permit us to investigate the full range of human ecodynamics in a much more sophisticated way as the collective behaviour of a population of farmers alters the hydrology of the Plain which in turn modifies the farmer's decision space.

Individual farmers may modify the propagator in one of two obvious ways. Firstly, they may exhibit a tendency to resist or encourage changes of crop. This can be simulated by giving each farmer a numerical attribute representing their propensity to change crop or Jumpiness (call the variable « Jump ») which takes on a value between 0.0 and 1.0. If Jump = 0.0 the farmer is highly conservative and all transitions to new crops are suppressed. If Jump = 1.0 the farmer never grows the same crop on the same plot two years running. An intermediate value will have an intermediate effect. Thus if Jump = 0.3, for example, 30% of the probability will be spread among transitions away from the current crop in proportion to their relative attractiveness, while 70% is concentrated on the probability of staying with the current crop. The effect of Jumpiness is to determine the extent to which the probability density in the propagator is concentrated on the diagonal (conservative, Jump = low) or off the diagonal (changeable, Jump = high).

The second factor that may modify the propagator is the time horizon over which cost-benefit calculations are made. Clearly a farmer who considered cost-benefits one year ahead is very much less likely to contemplate transitions with high grubout costs and long lead in times than one who spreads these costs over several years. Each farmer is attributed a time horizon value (called « Timeframe ») between 1 and 50 years. Different values of Timeframe will produce different cost-benefit calculations and, by implication, different propagators. The propagator of the plot is determined by substituting the equations of motion into Equation (2) above where the ijth element of T is

$$T_{(i,j)} = 1/10*(JUMP)*k * e^{\beta (C\_B(i,j,timeframe))} \quad ..(4)$$

when i is not equal to j and;

$$T_{(j,j)} = (1-JUMP)*k \; .....(5)$$

Equations (4) and (5) are the equations of motion for the plot. Note that C_B(*i,j,timeframe*) is the projected cost-benefit of the transition from j to i evaluated over the given timeframe and *k* is a normalisation constant. The choice of Equation (4) to underwrite the Master Equation of the plot has theoretical implications that should be clearly appreciated. The transition rates are obtained by the manipulation of cost-benefit data mediated by the predisposing factors Jump and Timeframe. Human decisions seldom reduce perfectly to questions of profit and loss but in this case, we had sufficient testimony from the farming community itself to justify the simplification. Note that C_B(j, j, timeframe), the cost-benefit of the standing crop, is never negative or zero because all infrastructural costs have been met for this crop. C_B(i, j, timeframe) may be positive or negative because the farmer must incur grubout and infrastructural costs. If the cost benefit term is negative, crop i will be relatively unattractive so that T(i,j) will be small and positive. If however, it is positive, crop I will be more attractive and T(i,j) will be a larger positive number. The more profitable crop i appears relative to j, the larger will be the number associated with T(i,j) subject to the constraint that T(j,j), the probability of retaining crop j must equal 1.0-Jump.

We have already seen that each farmer's decision strategy represents the Master Equation of the individual plot. Each farmer is, in effect, 100 micro-models. We must now begin to model a large population, an assembly of farmers. For this we need to be able to specify the Master Equation of the Master Equation of the plot. The nested Master Equation which represents a population of farmers cannot be specified by analysis from first principles, each individual plot is exploring a split system, the transition surface may change as water is sought and different farmers will have different values of Jump and Timeframe which, in turn, modify the crop-choice landscape being explored. At our present state of understanding, the only way we can handle a Master Equation of the Master Equations of the plots (which is what the assembly of Argolid farmers constitutes) is by simulating it on a computer. The computational problems that must be addressed when building this sort of simulation are non-trivial though not of any particular interest in the context of the present study. It is sufficient to note here that the model was run on a 166 MHz Pentium with the source code written in Fortran 90. The program allowed the simulation of 29,420 farmers (2,942,000 plots).

4. Model output

The 29,420 farmers with values of Jump rectangularly (i.e. uniformly) distributed between 0.0 and 1.0 and values of Timeframe with an independent uniform distribution between 1 and 49 years were created and allowed to select crops in the manner described above. Two major simulations were effected, one over 100 years and the other over 200 years. The results described below were from the 200 year simulation which resembled those from the 100 year simulation in every respect, a result which we took to indicate that a steady-state solution had been found. Each farmer was given an initial bank balance (set to zero) and awarded a salary for every plot untenanted or set to a low-labour crop. Farmers also received income from their crops (after the initial lead-in period), less the cost of all infrastructure (principally boreholes). At the end of 200 cycles some farmers, presumably those making better decisions, were in credit at the bank. Others had made enormous losses. A histogram of their final bank balances (in millions of notional Drachma) is presented in Figure 1.

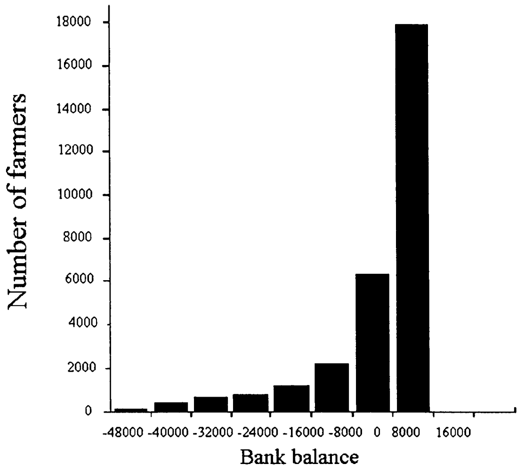

Figure 1: Final bank balances for farmers at end of simulation.

It is natural to ask whether there is any systematic relationship between Timeframe, Jump and final bank balance at the equilibrium state. In Figure 2 we see the relationship between Jump and bank balance. (Each point plotted on this and subsequent figures represents the final situation of a single farmer). The result is a very interesting pattern. Two striated swathes of farmers can be seen on this graph. The leftmost (poorer) swathe, corresponds to those who have no access to water while the rightmost swathe have access to water. In fact almost all the farmers who can reach water have drilled boreholes and moved into irrigated agriculture. Clearly, very Jumpy farmers are generally poorer than their conservative neighbours though this effect is much less marked in farmers with access to water. Clearly, decision-making strategies that lead to financial disaster are not likely to survive and we can safely ignore as unviable those farmers who ended up with overdrafts at the bank. Space precludes a detailed consideration of all the farmers who survive this basic « viability test » so we will try to impart the flavour of the simulation results by concentrating on the subset of viable farmers who have access to water. The first thing to note is that although we started with a population whose values of jump and timeframe were uniformly distributed, the viable sub-population at equilibrium exhibit a strikingly patterned distribution of these values.

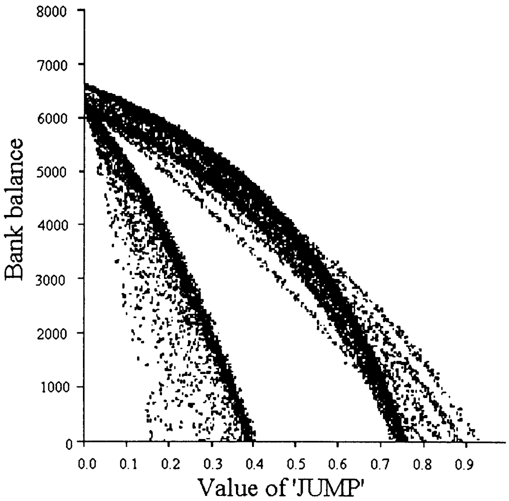

Figure 2: Influence of propensity to change crop (Jump) on final bank balance

Figure 3 plots timeframe against bank balance for the most jumpy, viable farmers. These are farmers who have Jump set between 0.9 and 1.0 and so change their crops very frequently. As noted in Figure 2 jumpy farmers tend to be relatively poor. Note that the richest of these jumpy farmers is using a Timeframe of about 4 years. Interestingly, 4 years is the lead-in period for tree crops. It seems likely that the only Jumpy farmers who break even are those who, by dint of their short-term view, never contemplated planting additional tree crops. These Jumpy farmers would have been restricted to cereal and vegetable crops which would have been abandoned or rotated most years.

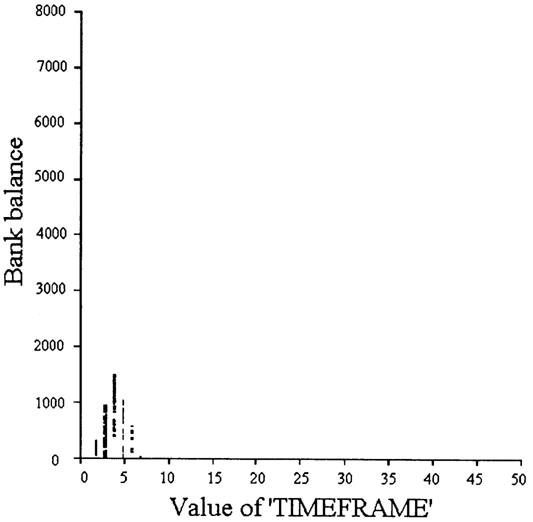

Figure 3: Influence of planning horizon (Timeframe) on final bank balance for farmers with Jump = 0.9 to 1.0.

In Figure 4 we present a similar plot for farmers with Jump between 0.3 and 0.4. These moderately conservative farmers are generally richer than their highly jumpy neighbours. The peak at 4 years is still visible but 4 years is no longer the optimum timeframe. It is possible for farmers to be wealthier still if they are both moderately conservative and use a timeframe in excess of 18 years.

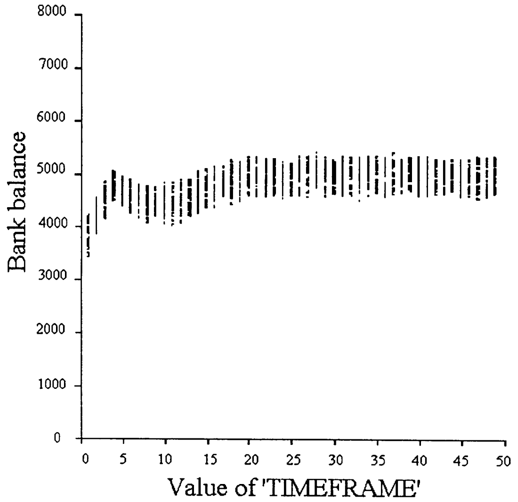

Figure 4: Influence of planning horizon on final bank balance for farmers with Jump = 0.3 to 0.4

In Figure 5 we have the most conservative and richest group of all; those with jump less than or equal to 0.1. Note that the local optimum at 4 years has now almost disappeared. The highest probability of being very rich is associated with conservative farmers who calculate cost-benefits over an extremely long timescale. However, note the small scatter of conservative farmers who have healthy bank balances and yet take a very short term view. These have jump set so close to zero they hardly ever change their crops. The fact that they base their judgements on a short timeframe cannot damage them because they hardly ever act on these judgements and so have stuck with the initial, viable starting configuration.

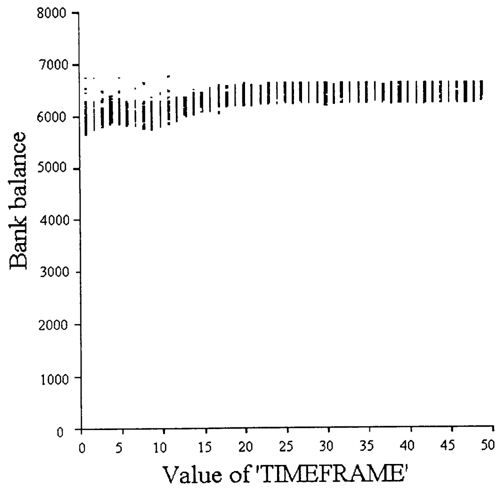

Figure 5: Influence of planning horizon on final bank balance for farmers with Jump = 0.0 to 0.1.

Finally, we close with a brief consideration of the crop types under cultivation. Perhaps surprisingly, successful farmers (in terms of their final bank balance) were more or less indifferent to all crops except apricots. Figure 6 depicts the relationship between final bank balance and percentage of a farmer's total holding which is under apricots.

There are two fronts on this plot, the lower front corresponds to farmers without access to water and the higher front to those with water. Note that very many of the successful farmers have almost all their holdings under apricots.

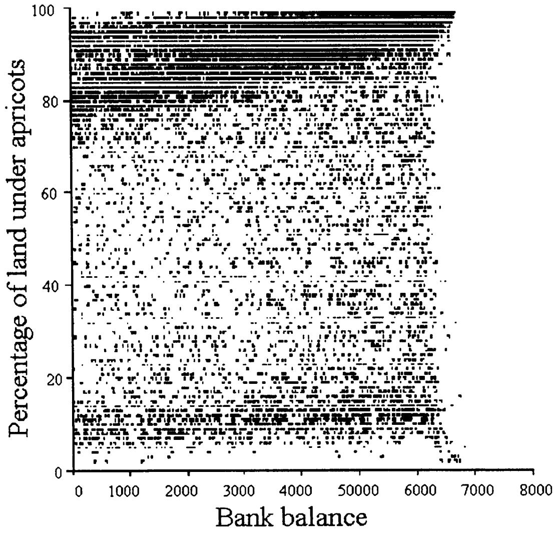

Figure 6: Relationship between final bank balance and percentage of farm under apricots.

5. Interpreting the experimental results.

The « farmers » just described cannot be said to represent the true decision process of a real farmer. However, the more successful among them exhibit regularities in their crop choice and predispositions that resonate so strongly with those of real farmers that it is hard to avoid describing them as if they were farmers. Indeed, the crop choices made by the farmers as represented in the computer model are characteristic of those made in the contemporary Argolid in several respects. Farmers cultivating perennial crops with a long lead-in time and high grubout costs must take a long-term view and will be reluctant to remove those crops. Farmers who like to change crops regularly must concentrate on annual crops, some of which are labour intensive and may sometimes neglect part or all of their holding to take a salary. Such farmers cannot afford to take a long-term view because their tendency to change crops means tree crops will probably not last long enough to break-even. It is possible to grow trees without irrigation but many annuals need extra water. Rapid crop rotation is less profitable in areas where water is inaccessible.

A significant group of successful simulated farmers has recognised the apricot as a favoured cash crop and have most of their holdings under this fruit. Some of these are dry farmers who have successfully recognised the profitability of the crop and planted it. They will have failed to sink good boreholes and so will get no return. Their sole source of income is earned outside agriculture (apricots are a low labour crop) and they will have effectively abandoned their holdings. In reality, apricots will yield a reduced crop without irrigation but this smaller yield was not incorporated into the present model.

Irrigated farmers who have holdings under apricot are receiving both a salary and an income from apricots. Many of the most successful farmers have values of Jump and Timeframe so configured as to be able to benefit from this opportunity. If financial success is the principal determinant of crop choice, this model suggests that the Argolid Plain should be covered with apricots when in fact it is covered with citrus. However, this was not always the case. When irrigated agriculture first started on the Plain, an important crop was, indeed, the apricot which was grown for the canning industry. Eventually, so much of the Plain was covered with apricots that a virus disease (Sharka) was able to proliferate through the crop, reducing yields and profitability. EC subsidies were provided to uproot the apricots and this land was then put under citrus (the next most profitable crop). Initially lemon was favoured until this too fell prey to disease and gave way to oranges.

All these facts were well known to agronomists, hydrologists and sociologists working in the Argolid. Furthermore, the necessary relationship between Jump and Timeframe which is patent *a posteriori* was not recognised *a priori* as a determinant of economic success. Sociologists working in the region were repeatedly informed that the biggest source of difficulty experienced by citrus farmers was coping with the unpredictable effects of EC policy on markets. The model illustrates graphically why this should be so. Farmers who are dependent on this type of crop need to look eighteen or more years into the future to get the right cost-benefit figures. Markets that change every year must be a serious worry.

To conclude this contribution we would make two sets of observations concerning the use of nested master-equation models. The following two sections examine the significance of the approach firstly in terms of the Argolid case study, and secondly in terms of microsimulation modelling. Section 7 is written in accessible terms and is of particular relevance to readers who may be interested in the application of these types of model to the study of agricultural systems. In contrast, the second part of the conclusions (Section 8) is intended to provide some guidance for those interested in the use of nested master-equation models as a simulation tool and is necessarily of a technical nature. However, we feel that the modelling approach will appeal to a wide range of interest groups and would therefore advocate perseverance on the part of those who might find the text somewhat theoretical.

6. Nested master-equation models; significance for investigating farming systems

The nested Master Equation model described above is not a support model but a process model. It is presented as a test-bed for *theories* about the way the socio-natural world works, not as a test-bed for *policies*. It was never suggested, for example, that the modified exponent of the cost-benefit as represented in Equation 4 (above) really is a constant multiple of the transition probability *in the real world*. Rather it is proposed that the rank order of these terms is the same as that of the transition probabilities that would have been obtained from almost any rational cost-benefit analysis modified by certain personal predisposing factors. The largest term in Equation (3) corresponds to the most profitable crop, the second largest to the second most profitable crop and so on. Equation (3) is *consistent* with our understanding of the crop choice strategy but is not an inevitable *consequence* of it. This is an important methodological point, often skated over in the mainstream modelling literature, particularly in policy-relevant research. When we simulate Equation (3) we will obtain results that *could* follow from the given theory but we cannot argue that they *would* follow from it.

We would suggest that the manifest imperfections of the model as presented above are strengths of this approach, not weaknesses. None of us would pretend that real farmers really use a multinomial term to decide whether to drill boreholes or plant crops. Indeed, attempts to elicit decision rules for the model directly (either from farmers or agronomists) were unsuccessful because the questions being asked were often nonsensical. One informant (an agronomist) refused even to discuss the likely transition rate from wheat to citrus because « *no sensible farmer would grow wheat on the Plain these days* ». Despite this, the same agronomist was perfectly clear that cost-benefit was a key factor in crop choice. Equation (3) enables us to take simple cost-benefit data and build a consistent set of rules that would hold over the whole decision space explored by the individual plot.

It is significant that the patterns generated by the resulting program resonate clearly with those observed in the real world. It was not foreseen that the relationship between agriculture, irrigation and personal perceptions of time would be thrown into such clear relief. Furthermore, in predicting the crop favoured by farmers in the early 1960s (apricots), the model focused our attention on possible embellishments that would make it much more realistic. For example, simulating the effect on cost-benefit of rare, density-dependent diseases would allow the model to represent the onset of the Sharka virus in apricots, of Coryphoxera in lemons and, within the last few months, the threat of the Adromycosis fungus which attacks the roots and trunk of orange trees. Each of these diseases changes the cost-benefit landscape in an irreversible way by imposing a delayed negative feedback on economic success. Once a crop is widely adopted, conditions are generated which will make it unsustainable at some stage in the future. Irreversible changes of this sort generate a range of possible histories which are consistent with our understanding of the decision process and so supplement our understanding of the (real world) system under investigation.

The long-term strategic aim of the study reported here is to integrate the simulated farmers with local hydrology so that groups of farmers who exhaust their water will experience the converse critical transition from irrigated to dry farming. Only then will we have captured a simple analogy of the underlying tension between the socio-economic system which drives farmers to use more water and the hydrological system which sets limits on the quantity of sweet water available. Although we still have some distance to travel before this composite model can be built, our intuitive understanding of the model output presented above has actually changed our perception of human ecodynamics in the Argolid Plain.

Apricots are a well established Mediterranean crop and will produce a usable crop under rain-fed agriculture in many regions. When the Greek Government decided to promote this crop by subsidising the canning industry, it provided incentives for irrigation which would improve the quality of the crop. However, the process was to some extent reversible *as long as apricots were grown* because water abstraction was not a prerequisite of this crop. When the Sharka virus struck, the system could have been left to crash but a political decision was made to subsidise the removal of apricots. Land previously under apricots was put under citrus and the Argolid Plain was, for the first time, locked in to irrigated agriculture. Citrus growers need water to control frost and provide a high yield of uniform, saleable fruit. Every time disease or salination became a problem, funds were allocated to « solve » it. Lemons were replaced with oranges, the Anavalos Canal was built to provide sweet water, aquifer recharge was attempted and so on.

However, none of these strategies will proof the system against density-dependent epidemic disease so further crashes are to be expected *as long as the cost-benefit landscape is so configured as to favour irrigated monocropping.* The energy and resources of politicians seem to have been geared towards facilitating an unsustainable agricultural system which emerged as an unforeseen consequence of policies designed to provide an income for Argolid farmers in the late 1950s and early 1960s.

7. Nested master equation models; significance as a research tool.

It has been our intention in writing this paper to present the substantive insights gained from the modelling exercise without labouring the details of model construction and implementation. However, this paper would be sadly incomplete without an appendix to explain the nature of the computational problems solved to date and the prospects for further work in this field. The Master Equation approach comes from the physical sciences, particularly such fields as Quantum Mechanics and Thermodynamics. There is now a small but valuable body of literature (e.g. Haken, 1978; Nicolis, 1995) encouraging natural and social scientists to consider these methods. Unfortunately, this literature is necessarily difficult and the solution methods recommended often employ simplifying assumptions that are difficult to justify in biological and sociological applications. The technique of micro-simulation can get us past these obstacles but we need to develop a clear, business-like competence in these methods if they are to be used more widely. Furthermore, the application and further development of this type of modelling approach is partially dependent on the integration of knowledge from the social, historical and anthropological sciences with formal mathematical and algorithmic representations of behavioural dynamics. In this respect, investigations such as those carried out by, for example, Hossain & Crouch (1992), Beus & Dunlap (1994), Cerf (1996), Battershill & Gilg (1997) and Backus *et al.* (1997) are significant.

At the heart of the Master Equation approach is some small object (in physics it may be a gas particle, in this case study it is a field plot) which explores some *phase space* in accordance with deterministic rules that are either unknown or present insuperable analytical difficulties. Our first step is to subdivide the phase space into a number of mutually exclusive and exhaustive classes which we will call *states*. We decided, for example, that the plot could carry one of eleven crops. We could have made other decisions, distinguishing tomatoes from courgettes, aggregating oranges with lemons and so on. At some level, the Master Equation approach always entails an act of classification.

Once we have a number of mutually exclusive and exhaustive states, we then invoke an equation like equation (2) above. Anyone who has ever attended a course of lectures in theoretical ecology or advanced statistics will have encountered equations like this before. For example, the Leslie matrix used to investigate population dynamics, or the Markov processes used to investigate stratigraphic sequences both imply the existence of such an equation. Equation (2) is a linear dynamic system and there is a large body of textbook literature dealing with this. So by classifying phase space, we have embedded our analytically intractable microsystem in a tractable metasystem (the Master Equation) which can sometimes be handled quite neatly.

Our next stage is to focus attention on the propagator, T, and to generate some equations of motion that give us transition probabilities either directly or by implication. Sometimes this is simply a matter of thinking hard and writing down a simple stochastic model like equation (3). In physics it may require truly inspired guesswork. Of course, every classification of phase space implies a different propagator and it is perfectly proper to choose a classification likely to correspond to a propagator whose equations of motion we can reasonably generate. Finding the right propagator is part of the art of dynamic modelling and it gets easier as practice enhances competence.

The final stage of work is to investigate the evolution of the probabilities associated with each state. This is usually easy in familiar random walk problems with small, finite propagators because these tend to well-defined equilibria. The problem can be hideously complicated for Master Equation systems where the propagators are dynamically linked to external and internal factors. Non-linear perturbations may, under certain circumstances, generate surprisingly complicated dynamics which can be very difficult to handle analytically. In this paper, we have suggested an alternative approach. By constructing very many Monte-Carlo microsimulations we can track the distribution of micro models through phase space. Our simulation involved 29,420 farmers or 2,942,000 plots, all running in parallel on a single micro computer. After a large number of cycles, the distribution of these micro systems through phase space can be taken as a proxy for the distribution of probability that would have been obtained from an analysis of the Master Equation. The graphs presented as Figures 2 to 6 of this paper are each 2-dimensional projections of the 13-dimensional probability density function implied by the Master Equation of the farmer.

The use of nested Master Equation models as described above actually enhances the power of the method dramatically. The object that was of primary interest to us in this study is not the field plot but the farmer. The farmer, as we have already suggested, lives in a phase space of 13 dimensions (11 crops plus Jump and Timeframe) with 12 degrees of freedom (once the probabilities associated with 10 crops are given, that of the 11th is determined). To get a Master Equation for the farmer, we need to subdivide the 12-dimensional phase space into states and build a propagator for those states. We could have arbitrated, simply carved the phase space into a largish finite number of states but this would have been problematic. We would have needed to generate equations of motion that give the probability of moving from one arbitrary chunk of phase space to another when we know that small variations in, for example, Jump or Timeframe may have a profound impact on the behaviour of the farmer. We would have had no grounds for believing that any arbitrary chunk of phase space could be taken as probabilistically uniform. The only rigorous way of generating the Master Equation of the farmer was to define a unique state for every possible point in phase space but this would require us to generate an n-dimensionally infinite classification. Our Master Equation would have as a propagator, a transition matrix of n-dimensionally infinite dimension.

Our solution was to represent each farmer by two real variables (Jump and Timeframe) and an assembly of 100 plots. The propagator for each plot was merely 11-dimensional but was dynamically linked to the availability of water, to Jump and Timeframe. By executing nearly 3 million Monte Carlo simulations of plot behaviour, we were able to generate probability density distributions through the 13-dimensional phase space explored by the farmer. The local density of simulated farmers in this phase space was taken as a proxy for the probability density that would have been obtained from the analysis of the Farmer's Master Equation. In this way we were able to characterise an eigenvector of a dynamic propagator of infinite dimension whose equations of motion we could not specify from first principles.

It is remarkable that the probability density distributions generated by the model are readily interpretable in the context of data obtained by traditional elicitation techniques and we take this resonance between model output and empirical data as an encouraging sign. Although our nested Master Equation is still in a relatively early stage of development, we believe this approach to be novel and potentially of widespread applicability.

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