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Abstract

This paper is a study of the structure and dynamics of consumption behaviour using cellular automata to model interaction among individual consumption units. Special attention is given to the relation between the micro and the macro behaviour of the system; how is the macro performance of our system related to the degree of step in the behaviour of microunits?. The approach has two sources of inspiration; the artificial life approach to modelling developed within computer science, and the consumption theory of J.S. Duesenberry, which deserves a reconsideration after the appearance of computers and cellular automata. Artificial life is a bottom-up approach characterized by parallel processing and local determination of behaviour and the idea of using synthesis rather than analysis. The approach has been developed to study emergence of life and dynamics of complex systems which are very hard to handle analytically. The key concepts for Duesenberry's approach are irreversibility of time and interrelatedness of preferences. Common features for the two sources of inspiration are rule-based behaviour rather than rational optimization and a behaviour that depends on local circumstances for the agent in question rather than the state of the entire system. To study consumption, given these features, a cellular automaton model is developed.

A Model of Consumption Behaviour Using Cellular Automata

1. Introduction

Focusing on consumption demand and the interplay between micro and macro relations, this work studies suboptimal behaviour of economic systems. Using a representative agent approach or a pure macro approach, it is hard to understand why economies should operate at a suboptimal level. There may, however, be an explanation in the way economic agents interact. This interaction is studied by application of methods developed within the project of artificial life. Rather than modelling one representative agent, a population of autonomous agents is modelled. This method has been applied to economics in order to model the selforganizing features of economic systems. Selforganization, however, often leads to solutions that are not absolute optima. The question we purpose to answer is whether the way agents interact may cause non-optimal behaviour.

Consumption demand has rarely been considered a source of suboptimal behaviour of economic systems - everyone seem to agree with the declared insatiability of consuming agents. We shall not contest this claim with respect to the long term consumption by an individual agent, but purpose to investigate whether there is a possible constraint on consumption demand by the way agents interact. This is done by simulating a model that is demand-driven without any restrictions on the supply side and with endogenous created credit money. Thus there are no constraints on the aggregate system - it may experience an "eternal boom". If we modelled a representative agent in this world, consumption demand would be infinite - is this still the case if we model a population of agents interacting?

To model the interaction of economic agents a cellular automaton is used where each cell represents an agent. Consumption demand is determined by an interpretation of Duesenberry's consumption theory, where consumption is characterized by interrelatedness and irreversibility. We observe both the aggregate outcome of the system and the behaviour of each individual agent in order to study the interplay between the two.

2. Micro, Macro and Accounting

For the past decades economics has been haunted by a requirement of microfoundation. Unfortunately this has not been met with a general concern for relations between micro and macro, not to mention a requirement of macrofoundation for microrelations - a requirement that is logically as well-founded as the requirement of microfoundation. The emphasis on microeconomics has made us call it paradoxical when aggregate relations are not obvious from their microeconomic counterparts, e.g. the paradox of thrift and the widows cruse - relations for which the paradoxical nature disappear once the use of a representative agent is abandoned.

The conflict between micro and macro relations arises when macro magnitudes are not obtainable by a simple summation of micro magnitudes. If this is ignored we end up in compositional fallacies. A framework for handling the relation between micro and macro relations has been set up by Stützel (1958). This framework explicitly allows for the interplay between statements applicable only to a part of the system and statements applicable only to the system as a whole. Partial or micro theorems are theorems that are valid for individuals or partial groups when feedback mechanisms offset by the global theorems are ignored. Global or macro theorems, on the other hand, are theorems that are only valid for the system as a whole. What Stützel wants us to study is relational theorems, i.e. theorems that are valid for individuals or partial groups when feedback mechanisms offset by the global theorem are taken into consideration.

Relational theorems, however, easily become very hard to handle; "if one group of agents increase their savings more than their complimentary group...", "if a group of entrepreneurs increase their consumption more than their complimentary good..", are theorems that are very hard to work with analytically[1]. Not only does it become impossible to use the construct of a representative agent, we have to keep track of global as well as partial theorems. To ease this work Stützel uses the concept of step; if a system is characterized by step then all agents carry out the exact same action, and in this case only global theorems matters.

With respect to expenditures the degree of step may be measured in monetary balances; if all agents decide to increase their expenditure, then the income of all agents will increase as well , and in the special case, where each individual experience an increase in his income of the same size as the increase in expenditures, no one will experience an increase or a decrease in their monetary wealth[2]. In Stützels framework this is a situation characterized by step. He also measure different degrees of step by observing changes in monetary position for each individual agent.

To the question we have posed the degree of step is of interest because disstep may be the cause of suboptimal behaviour. If one agent with positive monetary holdings decides to spend less while the rest of the population decides to keep their expenditures constant, then the rest of the population is forced to dissave and we have a situation characterized by disstep. If the resulting debt structure has an impact on future expenditures, then the action taken has an impact on the aggregate behaviour of the system beyond the immediate decrease in expenditure. Notice that if an agent with a negative monetary balance decides to spend less this leads to a higher degree of step, while the same action by an agent with positive monetary balances leads to a lower degree of step. This gives an idea of how complex analysis becomes.

Stützels work is fully based on observations of monetary stocks and flows; he introduces no behavioural assumptions or metaphysical value theory. Thus the relation between micro and macro theorems is based on the way accounting takes place in a monetary economy. The importance of accounting relations as a feedback mechanism from macro to micro has also been emphasized by Schelling (1978) "Micro motives and macro behaviour". Because monetary flows necessarily has both a sender and a receiver, and because monetary stocks necessarily has both a creditor and a debtor, agents are related in such a way that simple adding up of micro actions is not possible. Schelling's favourite analogy is the game of musical chairs; no matter how aggressively or intelligent the children behave, there will always be one chair missing, just as expenditures will always equal incomes no matter how much we save.

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[1] Let us set up the paradox of thrift in Stützel's framewrok to illustrate the technique:
Partial theorem: The larger the expenditure of an individual unit, the smaller its wealth, given the size of receipts.
Relational theorem: An individual or a group can spend more of its current receipts (i.e. decrease its wealth) if its complementary group spends less of its current receipts (i.e. increases its wealth).
Global Theorem: By an arbitrary increase or decrease of the aggregate expenditure, the change in aggregate expenditure will always be equal to the change in aggregate receipts.

[2] This made Stützel claim that an increase in economic activity was likely to be accompanied by a decrease in the demand for money rather than an increase, simply because he found a larger degree of step to be likely in the upswing.

Stützel takes economics as far as it can go without implicating behaviour or metaphysics, while Schelling takes his starting point in behavioural observations. Stützels work ends up in a complicated quantity equation that cannot be checked empirically while Schelling ends up discussing the game of life, i.e. rather than applying analytical methods he suggests that a bottom-up method is used. Both emphasize that the relation between micro and macro and that the degree of step are important concepts when investigating economical phenomena. The complexity of Stützels analysis induces us to follow the suggestions made by Schelling - how is it that the game of life can help us study relations between micro and macro? To see how let us take a look at the approach that within economics has been named "agent-based economics"[3].

3. Agent-Based Economics

The most famous analogy of economics must be the invisible hand of Adam Smith; though inhabited by self-interested individuals, the economic system functions as if it was guided by an invisible hand towards a position that is optimal for the system as whole. If one wants to model the dynamics of the economic system one can either make use of the analogy and attempt to find the equation that could guide the invisible hand if it existed (e.g. by using a representative agent), or one could try to model a number of selfish individuals making their own calculations. The latter method has become known as the bottom-up method since it works from the behaviour of autonomous agents to the behaviour of the system without implicating a central unit controlling the agents. With the mathematical and computational techniques available until the appearance of the computer, the obvious choice was to model the invisible hand, but with the computer it has become possible to model a number of units performing parallel computations. This possibility has been taken up by the project of artificial life; an approach that started within computer science and biology, but has since been applied to many other areas. The defining feature of artificial life is representation of organisms by programs, and the idea is to use synthesis to model possible worlds. The macrobehaviour of such worlds is not designed but emerges from the specification of the microunits.

Why use artificial life or agent-based methods in economics? First of all complexity, selforganization and evolution appear to be central phenomena to economics. But there are additional motivation for using a synthetic method in economics. First of all it is a problem for economists that we cannot experiment with the real world version of the object of our interest; we cannot magnify some aspects of economic activity to see how other parts react, nor can we make small changes to test the stability of our system, not to mention our inability to perform political experiments. An other problem the economists face, is that we cannot even decide individually what data we want to use from the real world experiment. The principles for national income accounting where worked out about fifty years ago and data collection was build up on them, and are not changed because a scientist wants a new perspective on things. And even if the National statistical bureau's could be persuaded, they may not be able to obtain the desired data.

Many economists have looked with envy at the physical sciences and complained about this impossibility of applying experimental methods to economics. With the use of synthetic computer econo-

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[3] Readers with general interest in the approach are referred to the following internet address: http://www.econ.iastate.edu/tesfatsi/abe.htm

mies, economists are finally granted the possibility of experimenting. Artificial life models are capable of capturing much of the complexity of economic systems, yet they are manipulatable, repeatable and precisely controlled experiments, and you can measure the performance of a system any way you want to. However, experiments cannot fulfil the role that many economists who complain about the impossibility of experimenting in economics would typically want them to fulfil; experimenting need not improve our ability to predict since we cannot use the experiments for simple induction. What we can do is to use experiments to improve our understanding of the structure of economic systems by using induction in the form of analogy.

Besides these more general methodological advantages, an agent-based approach has the advantage that it combines micro- and macro economics without doing it on the terms of either one of them. As soon as we start modelling a population of agents rather than a representative agent, we make room for micro as well as macro relations. It is impossible for a representative agent to have positive or negative monetary holdings - his expenditures and incomes must always equal out. This is not true of one among several agents in a bottom-up approach. All that has to be done to get beyond the micro-macro chasm is to model more than one agent and to make sure that accounting rules are always respected.

4. Cellular Automata

In our agent-based model we have chosen to use cellular automata. A cellular automaton is a way of representing the interaction accompanying decentralized computations since it consists in a number of cells, each cell representing a computer or an automaton. Cellular automata represents dynamic systems in discrete time and space - at each discrete point of time, cells update their position in parallel depending on the state of neighbouring cells in the discrete space. In this way there is no single equation or central computation that determines the state of the dynamic system. Computation is decentralized, and each cell performs its computation independent of the other cells.

Besides parallelism, cellular automata are characterised by locality and homogeneity. Locality means that the input for the computation that each cell performs comes from its neighbours in the discrete space. This makes any central organisation of information redundant. The input is transformed into the state of the cell by the use of a rule or a set of rules. Homogeneity means that all cells are characterized by the same rules. Usually models are determinate and have a finite number of states.

In my economic interpretation, the cellular automaton is the economic system and each cell represents an agent in the economic system. Locality means that economic agents do not have (or do not use) full information and that the preferences of economic agents depends on the preferences of his neighbours. Parallelism is not essential to an economic interpretation. In my model it means that all agents go shopping simultaneously. Homogeneity means that we only have one type of agents. The principles of parallelism, locality and homogeneity are defined within cellular automata theory, but there is nothing to hinder a relaxation of the requirements in a specific application, e.g. the homogeneity requirement may be relaxed in order to allow for a functional division of agents. This model diverge from the standard cellular automaton in a few respects which will be discussed later.

We now have a number of economic agents characterized by the same set of rules and organized in a cellular space. What may we use this set-up for? Gutowitz (1991) sets up two types of problems within cellular automaton theory; (1) *The forward problem* - given a cellular automaton rule, determine (predict) its properties and (2) *The inverse problem* - given a description of some properties, find a set of rules which have these properties. We are going to apply cellular automata to the inverse problem; given certain properties of the economic system (e.g. self-organisation, growth, cycles), find a set of rules which generates these properties. In other words we want to find a set of rules which quantitatively reproduce observations of an economic system.

If we look at the methodology of artificial life, the basic principle of the approach is to use whatever factual knowledge we have about the system to be modelled in order to constrain the set of automata which must be considered, and then to search through the remaining set of automata. This model may then be used for experiments, i.e. the manipulations that are not possible in the real world. In economics it seems that the use of factual knowledge has to take place at a high level of abstraction. It would take an extremely complex automaton if we where to produce consumption data that, within reasonable limits, could be compared to consumption data from the real world.

Rather than using real world data as our factual input we have chosen to use the institutional setting of real world economic systems as our central factual input. This allows us to operate at a high level of abstraction while maintaining contact with the real world. We take factual knowledge as knowledge that must be true for all economic systems rather than factual knowledge for one particular economic system. Besides the institutional characteristics of the economic system, we have to import some hypothesis about human behaviour from other sciences and treat this as factual knowledge. Our best chance of modelling human decision making in a realistic way must be to turn towards cognitive science and some of the work that has been done with respect to artificial intelligence.

5. Factual Input - Institutional Setting

Our first set of input, and the only input that we can treat as fact, is the institutional setting of an economic system. The most characteristic institutional fact about real world economic systems is the use of money as a unit of account. All aspects of economic activity is measured in money; it is measured how much you contribute to the system (labour, produced goods or services) and how much you take from the system (consumption goods or investment goods). The difference between giving and taking by one individual is measured as monetary balances. By imposing a limit on negative balances the system may assure that an agent cannot continuously take from the system without ever giving, but this limit cannot be treated as a fact. In the systems we know from the real world, there are no constraints on positive balances.

The accounting system is balanced through double entry and as already mentioned a positive balance of one agent must have its counterpart as a negative balance somewhere else in the system, and a payment flow must have a sender as well as a receiver. In principle there is no limit to the size of gross balances[4], and its magnitude will shift as transactions take place. Monetary balances may have different forms, e.g. different maturities. Monetary balances whose size shifts with ordinary payment transactions are called short term balances, credit or with respect to positive balances, simply money. These balances may be transformed into balances of longer duration.

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[4] Gross balances being the sum of all positive balances, net balances the consolidated balance for a part of the whole.

The system has a peculiarity called interest payment that makes positive balances more attractive and negative balances less attractive[5]. Each period balances are simply multiplied by a certain fraction, the size of which cannot be treated as factual knowledge. In the real world the interest payment on negative balances is larger than the interest paid to holders of positive balances. The difference is absorbed by the institutions in charge of the accounting system (e.g. banks) as payment for the services granted.

By the use of a unit of account, the accounting system registers all sales and purchases and all monetary holdings, but it does not register any holdings of goods that an agent has held from previous periods, or any goods that are produced by the unit itself and not sold. Not all that is taken from the system by agents is taken to be held for ever, and not everything is voluntarily held (e.g. undesired stocks). Agents may take things into their position that they only want to hold for a period or things that are only held in order to be used in the production of other goods. In the latter case they are called capital goods. Goods whose value is not set to zero in the accounting system the moment they are taken by an agent are difficult to handle since they have no place in our accounting system. Only the goods that are traded within the period automatically have a monetary value assigned to them. If we want to evaluate non-traded goods we have to use judgement; what value would the good have had, had it been traded within the period.

Since holdings of such real goods may have an impact on the behaviour of an agent, and the possible behaviour of an agent (e.g. by affecting the credit limit), one would expect that the system had some way of evaluating such real holdings. However this is not the case. Economic theory has not been able to come up with a consistent way of measuring it, and if a consistent theoretical measure was available, it would not necessarily be the relevant measure for us since it would not be the measure affecting behaviour, i.e. the "feeling" of wealth. This implies that monetary evaluation of real assets cannot be treated as a fact, but is determined together with our behavioural assumptions.

The income of the system as a whole is measured as everything that is given to the system and did not exist before the period started. Thus changes in the monetary evaluation of real wealth is not considered as an income, and goods that agents wanted to give to the system, but nobody wanted to take (e.g. unemployed labour), is not measured as part of income. Thus income equals the wagebill which equals the value of goods produced. This is the definition devised by Keynes in Treatise on Money[6].

[5] As noted by Albert Hahn (1920), there is no economic motivation for banks to demand interest payment on short term credit since as a system they have no constraints in creating the credit. The only motiation for interest payments on short term credit is the risk the banks run of the loantaker not repaying, and the individual bank has to consider its liquidity, i.e. its ability to clear with other banks. Interest payment on short term deposits was described as a historical peculiarity by Hahn, and today we can observe that they have disappeared.

[6] In the general theory it appear that Keynes attempted to add some of the subjectively evaluated real goods to the national income through his user cost concept - a method that is not applied here.

6. Behavioural Assumptions

Unfortunately human behaviour cannot in principle be treated as factual input to our system - we simply do not know enough about the way human beings make decisions. We have to turn towards artificial intelligence and cognitive science in order to find some help in modelling behaviour. Since we are interested only in the macrobehaviour of our system, and are satisfied with stupid agents, we shall not discuss principles for formalizing human behaviour in length, but only suggest that simple rules may be just as valid a first approximation of behaviour as rationality.

According to Russell and Norvig (1995), work within artificial intelligence may be divided into four groups; (1) Systems that think like humans, (2) Systems that think rationally, (3) Systems that act like humans, (4) Systems that act rationally. Thus we have to choose between systems that are similar to humans and rational system and between systems that think and systems that act, where thinking involves the process that goes before the action. If we want to operate with a system that thinks or acts rationally, then it must be assumed that behaviour has a well-defined purpose. This is what rational choice theory assumes; agents want to optimize their utility. This approach, however, has serious difficulties since it cannot be demonstrated how agents are capable of ordering their preferences in such a way that optimization may take place[7]. Psychological experiments further more suggest that human beings do not act rational[8], and it is the human behaviour, not the rational behaviour, that we are pursuing.

Then, do we have to consider the process of thinking, or is it satisfactory to settle for a good correspondence between the way our agents act and the way human beings act? Since we want to be able to manipulate our system (i.e. experiment), we must consider the thinking part. If we do not understand the process leading to a given action, manipulating the system may have an impact on the decision process in the real system but not in the synthetic system, and our conclusions would be wrong. Apparently human beings do not use logical thinking. Instead we simplify the world by dividing it into categories and we use heuristics and rules of thumb when we make decisions.

There is however one problem with leaving the assumption of rational behaviour, since it is very much this assumption that has defined economics as a science. One must have very good reasons for throwing overboard this assumption. If the decision process using the rationality assumption is not computable and does not correspond to the way human beings make decisions, then we do have two very good reasons for exploring alternative routes. If we want systems that think like humans the alternative appear to be cognitive science.

In our model we have chosen to use "dumb agents", i.e. we only use simple fixed decision rules. Our purpose is not to model evolution of economic systems or learning by economic agents, and we purpose to do our study of consumption behaviour with as simple means as possible.

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[7] Rustem and Vellupillai (1990) demonstrates that the decision process assumed in rational choice theory is uncomputable.

[8] Kahneman and Tversky have found that not only are human beings irrational - they are irrational in a systematic and predictable way.

7. Duesenberry's Consumption Theory

As an example of how cellular automaton theory and the project of artificial life may be used in implementing new modelling techniques to economics, I have chosen to model James S. Duesenberry's theory of consumer behaviour. Duesenberry's theory immediately allows for the use of cellular space, i.e. his theory does not have to be restated to make use of the cellular structure and Duesenberry himself introduces habit formation as a genetic process; thus introducing rule-based behaviour does not conflict with Duesenberry's convictions. We shall, however, not use Duesenberry's theory for discussion of the same problems as followed its presentation in the fifties where it was discussed why the short term propensity to consume appear to be smaller than the long term propensity to consume. Here we shall use it to discuss the relation between income distribution and the level of income.

Motivated by empirical discrepancies, Duesenberry's starting point is a twofold critique of Keynesian type consumption functions as well as the utility theory of consumer preferences. Both of these theories operate with independent consumption decisions, i.e. the consumption decision of one agent is independent of the consumption decisions of other agents. Both of the theories also operate with timereversibility, i.e. consumption decisions are independent of historical time, in particular they are independent of the history of the individual agent. Duesenberry claims that these two assumptions are invalid. According to him interrelatedness of agents and irreversibility of time are important characteristics of consumption behaviour.

A consumption decision is the outcome of two basically different motives; the desire to consume and the desire to save. The desire to save may be presented as a desire to consume tomorrow, but one cannot wave aside the idea of a desire to hold financial assets for their own sake. The desire to consume may be presented as a need to fulfil certain physical needs, but consumption certainly also have strong cultural and sociological motivations. Since a consumption decision is presented as the outcome of a conflict between the two motives, a shift in consumption may be due to a shift in the desire to consume or a shift in the desire to save.

In our culture we tend to have a latent and insatiable preference for goods. A preference that is not activated by the mere existence of goods (I need not have a preference for space shuttles although I know they exist), but is activated when people we associate with purchase the good in question (I do have a preference for the car my neighbour just bought). This implies, that in the long run consumption demand is insatiable, but in the short run demand may be satiable, i.e. the savings ratio may increase for a part of the society. If a relatively poor area of society suddenly strikes gold, their savings ratio may increase in the short run, but as new goods find their way to the community through experimenting individuals, consumption demand increases and the savings ratio falls back into place. In a comparative equilibrium setting Duesenberry's theory does not produce results that are much different from e.g. a Keynesian consumption function. The difference is in the process taking place between equilibria. In Keynesian theory a change in income immediately cause a change in consumption so that the savings ratio remains constant. According to Duesenberry's approach, consumption will not increase in proportion to income since the agent does not see that consumption of neighbours has increased as well. Thus in the short run the savings ratio increases, but in the long run, income and consumption is proportionate.

8. An Outline of the Model[9]

The model consists in a 40*40 cellular space, each cell representing an economic agent. The agents purchase consumption goods and real assets which are durable goods for which a resale market exists. Agents may also hold monetary wealth, where only one type is modelled[10]. The model is demand-driven with production modelled as a black box that transforms purchases of consumption goods or newly produced real assets, into an income of the system. Thus demand for a good generates a production of that good and an income of equal size is generated in the system. Treating production as a black box also means that only the monetary side of economic activity is modelled, i.e. we do not know what happens to the level of prices on consumption goods and newly produced real assets since we only have information on monetary magnitudes.

Duesenberry emphasized "learning and habit formation", but since our focus is not on learning processes we shall use static rules. Learning only take place in the sense that the rules are feedback based, i.e. the agent that experience a decrease in income will have to learn to consume less because of an imposed credit limit. This "learning" is however built into fixed decision rules.

Consumption

The cellular structure is used to model the interrelatedness of consumption. In Duesenberry's theory, agents compare their own consumption to the consumption of other agents with the same social status. In our model, agents compare their own consumption with the consumption of neighbours in the cellular space. For this purpose Von Neuman neighbourhood is used (5 neighbours including the cell in question). Edges in the cellular space are "joined" so that all agents have the same number of neighbours.

The long-term goal of the agent is to consume *at least* as much as the average of his neighbours. In reaching this goal the agent is constrained by his monetary position, a stickiness of his own habits (described by Duesenberry as irreversibility) and the fact that the agent only has historical information about the consumption of his neighbours (due to parallel updating).

If the agent has a negative monetary position of a certain size (related to an externally fixed existential minimum which is also used for determining initial consumption[11]), he will set his consumption 25% below last periods average in order to increase his chances of catching up in the long run. If, on the other hand, an agent has a large monetary surplus it will make him feel confident that he can also measure up in the long run, and he will increase his consumption 25% above last periods average consumption. If not constrained or induced by his financial position, it is not possible for the agent to increase or decrease his consumption with more than 10% from period to period. This assumption is motivated in Duesenberry's idea of time-irreversibility and habit formation.

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[9] The writer may be contacted for a transcript of the simulation program (Pascal code).

[10] The modelled monetary asset is a hybrid of known types since it is used as a means of payment and both positive and negative balances carry interest.

[11] Initial consumption is randomly distributed around twice the existential minimum.

Real Assets

Besides spending his income on consumption or holding monetary assets, an agent may choose to hold real assets. Holding real assets does not pay any interest, but the market value of real assets may increase (or decrease) and the agent is also assumed to attach utility to holding the asset. Since the model treats production as a black box, real assets have no relation to production. The best example of a real asset is probably real estate. The feature that is introduced through these real assets is that consumption may be influenced by a monetary evaluation of a real good - an evaluation that is not anchored by any real aspect of the economy. This means that the aggregate of individuals may "feel" richer or poorer without any changes in production taking place.

The volatility of the monetary evaluation of real assets has been deliberately exaggerated in order to "make things happen" in our model. On the one hand we do not want to force the system into particular cyclical patterns, on the other hand we are, for our particular experiments, not interested in a very smooth development in consumption. It must be possible for small differences to generated large deviations. Only by deliberately generating the small differences can we see how the system reacts to them.The real assets are introduced as a simple way to overcome this problem, and a way that is also similar to what happens in the real world, where monetary evaluations of company stock certainly have an impact on what happens in the economy.

The causation from evaluation of real goods to consumption may be indirect as well as direct. If an agent experience that the market value of his real asset increases, he may feel more confident that he can keep up with his neighbours in the long run, e.g. by selling the real good if his monetary position deteriorates, and this increased confidence in his position may encourage him to increase his consumption. The indirect mechanism goes through production of new real assets, i.e. increased values of real assets will increase production of real assets through a mechanism à la Tobin's q. This will increase income and may relax the monetary constraint on consumption for some agents[12].

In each period a market clearing price for real assets is found. Buyers as well as sellers are assumed to have a fixed reservation price so that prices cannot increase or decrease with more than 20% from one period to the next. The market clearing price is used to evaluate all holdings of real assets, whether traded or not. Since we are assuming perishable goods, the monetary value is written down with 5% every period.

An agent decides how much real wealth to purchase by reference to his neighbours, his monetary wealth position and his expectation for the price development at the market for real assets. The bear/bull position is determined by the agents own experience at the market as well as a random factor, weighted with respect to the historical development. Agents expect prices to fluctuate so that more will take a bull position if prices have been rising for a longer period. Thus agents have an idea of the "normal" development in the prices of real assets[13].

Once a purchase of real assets has been decided upon, the agent must decide whether to purchase on the resale market or demand newly produced assets. This decision depends on whether the prices of real assets rose or fell in the last period. If prices rose last period then 75% of purchase will be for

[12] This is not a multiplier argument, and the causation only works if the gross balance is reduced, i.e. if it results in a more uniform distribution of monetary wealth.
[13] This way of thinking is similar to the behaviour described by Keynes in his General Theory with respect to the rate of interest.

new assets and 25% will be purchased on resale market, and vice versa if prices fell in the last period. If prices did not change the division will be fifty-fifty.

Income

Income is generated by demand for consumption goods and newly produced real assets. Income may be distributed evenly among all units, or it may be distributed among the neighbours of the purchasing unit. In our experiments income is distributed to the Von Neuman neighbours of the purchasing unit. It may be argued that incomes should be distributed to a wider district, but again the tool of exaggeration has been used; by using this construct it becomes possible for rich and poor neighbourhoods, not only to evolve, but also to keep on existing.

Tax

It has been necessary to impose a tax of 2% on wealth holdings (real as well as monetary) to increase the stability of the system. The tax payments are distributed among agents with negative monetary wealth.

9. Running the Model

The model we have just specified may be used for doing a lot of different experiments. We may choose to study how the system reacts to external shocks or different initial settings, experiment with the financial setting or perform experiments with political interventions. Another alternative would be to experiment with different types of neighbourhoods (e.g. Moore versus Von Neuman) or different distributions of income. In our experiments we have chosen to focus on the relation between the rate of change of consumption and the distribution of consumption over the cellular space. Do increases in the level of consumption require a uniform level of consumption, or is it necessary to have a high income area as a locomotive for development?

From the specification of our model we know that given a uniform distribution of consumption over the cellular space, it is possible for the level of consumption to increase without limits; there are no external limitations on consumption at all. The only limitation on consumption is the generation of positive and negative monetary balances, which only occur when consumption differ. With this relation in mind one should expect a uniform distribution of consumption in periods with a rising level of consumption and larger deviations in consumption in periods where the level of consumption declines. One should also expect the size of monetary balances that release an impact on consumption, i.e. the size of monetary balances that forces or persuades an agent to let his consumption deviate from the consumption of his neighbours, to have an impact on the aggregate level of consumption. To study these relations we have run the model with four different settings;

Experiment 1:

- Monetary balances below **-2.5***existential minimum reduces consumption with 25%
- Monetary balances above **2.5***existential minimum increases consumption with 25%
- Monetary balances below zero reduces purchase of real assets with 25%
- Monetary balances below **-2.5***existential minimum leads to sale of real assets
- Monetary balances above **10***existential minimum increases purchase of real assets with 25%

Experiment 2:
- Monetary balances below -5*existential minimum reduces consumption with 25%
- Monetary balances above 10*existential minimum increases consumption with 25%
- Monetary balances below zero reduces purchase of real assets with 25%
- Monetary balances below -2.5*existential minimum leads to sale of real assets
- Monetary balances above 10*existential minimum increases purchase of real assets with 25%

Experiment 3:
- Monetary balances below -2.5*existential minimum reduces consumption with 25%
- Monetary balances above 2.5*existential minimum increases consumption with 25%
- Monetary balances below zero reduces purchase of real assets with 25%
- Monetary balances below -2.5*existential minimum leads to sale of real assets
- Monetary balances above 2.5*existential minimum increases purchase of real assets with 25%

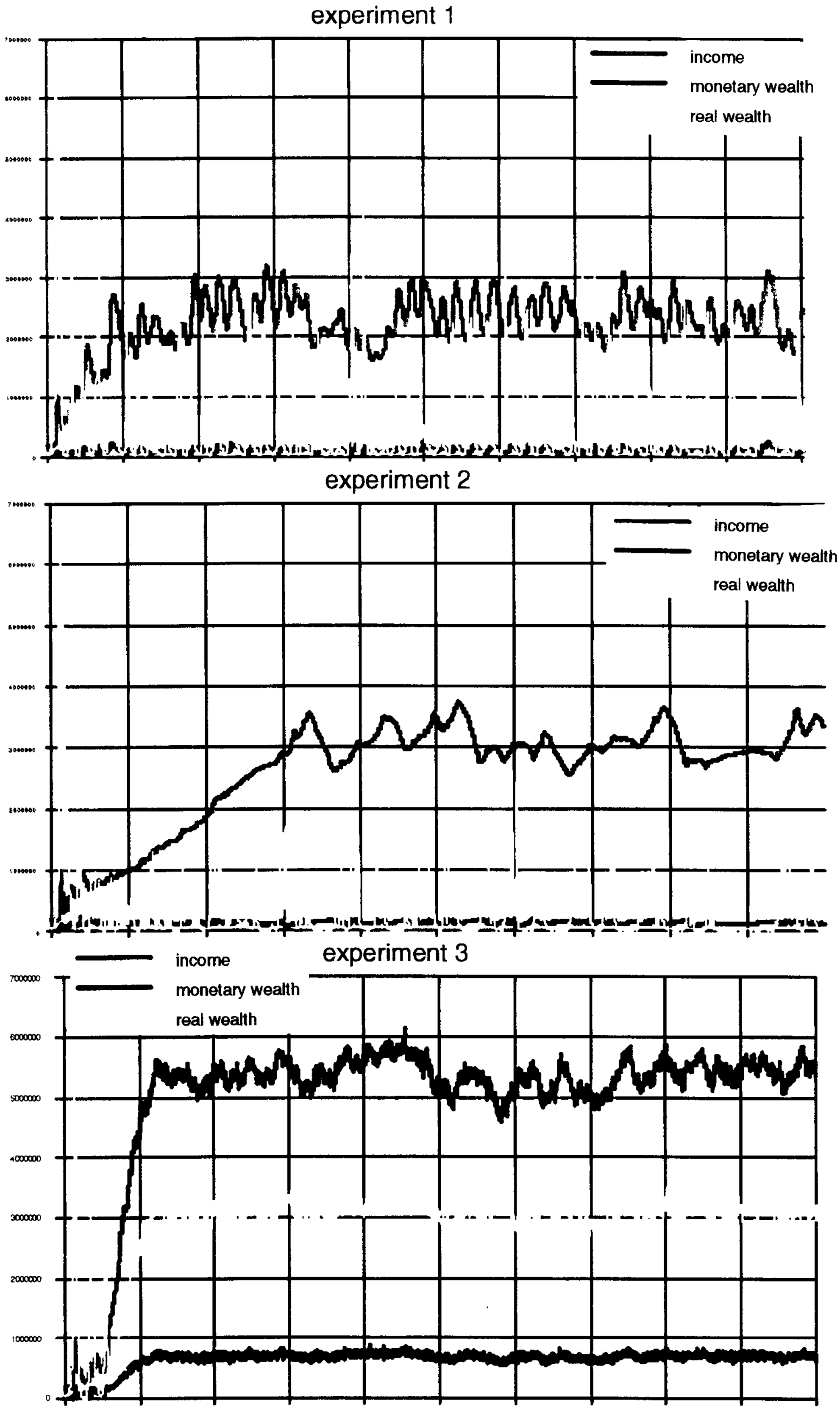
Experiment 4:
- Monetary balances below -5*existential minimum reduces consumption with 25%
- Monetary balances above 5*existential minimum increases consumption with 25%
- Monetary balances below zero reduces purchase of real assets with 25%
- Monetary balances below -5*existential minimum leads to sale of real assets
- Monetary balances above 5*existential minimum increases purchase of real assets with 25%

Let us first have a look at the aggregate performance of the system in our first 3 experiments(**fig.1**) represented by; (1) *income* which equals consumption plus purchase of real assets produced within the period, (2) *monetary wealth* (gross) which is measured as the sum of all positive monetary balances, and (3) *real wealth* which is the current monetary evaluation of real assets as it is set on the resale market for real assets. Both with respect to the average level of aggregate income and stability of aggregate income the three systems perform quite differently.

In the first experiment we have short fluctuations of about 100 periods, in the second experiment fluctuations do not follow a nice pattern as in the first experiment, and duration of a cycle tend to be much longer. In the third experiment we have a larger degree of small short term fluctuations. The difference between the first two experiments is obvious; in the first experiment agents with accelerating positive or negative monetary balances react quickly, whereas reaction is more slow in the second experiment. In the third experiment we speed up the reaction in the first experiment by letting units with positive monetary balances above 2.5*existential minimum increase their purchase of real wealth. This adds to the short term instability.

With respect to the level of income it is remarkable how large the impact of the faster reaction from positive monetary balances to purchase of real assets is on the level of income. The average level of income is almost doubled compared to the first experiment. Since the production of real assets does not surpass 1 million pr. period this increase is not directly caused by the income generated by this activity.

Fig.1 Aggregate Behaviour



In neither of the three experiments do we experience a large volatility of monetary balances, and the size of balances tend to be related to the level of income, it is, however not a simple relation, especially not in the second experiment[14]. In some areas we find rising monetary balances together with a decreasing level of income (e.g. experiment 2 around period 1500).

As expected the value of real wealth is much more volatile[15], especially in the first two experiments where it takes very large monetary holdings before the purchase of real assets is increased. In the first experiment a large increase in the value of real assets tend to offset an increase in the level of income, but again there is no simple relation (see e.g. period 2000-2200). In the third experiment there is a strong correlation between the level of income, the level of monetary balances and the value of real assets.

Before we discuss the different properties of the 3 experiments further, let us have a look at the cellular spaces that generates the aggregate properties (**fig.2** and **fig.3**). In **fig.2** an excerpt (period 1000 - 1500) of the simulation of experiment 1 is presented. We have taken a snapshot of the cellular space every 50 period corresponding to the 10 intervals in the display of aggregate consumption in the bottom right. At the peak at point 1 we find a large deviation in consumption with a high-consuming area and a low-consuming area, while at the following through at point 2 we find no units in the lowest of the 6 categories, and only a few units, scattered in the area, are in the high-consuming category. The pattern of generation and dissolution of high- and low-consuming areas is repeated in the following cycles.

The same method has been applied to the second experiment (**fig.3**) where we only find one peak during the 500 periods (1400-1900). Again we find a concentration of consumption at the peak, although it is not as strong as in our first experiment. Apparently the acceptance of larger monetary balances bring about a lower deviation in consumption. We have chosen not to present corresponding snapshots from the third experiment since here we found a strong concentration of consumption throughout the simulation. The reader is referred to the appendix (**fig. A1**) for the microbehaviour of experiment 3.

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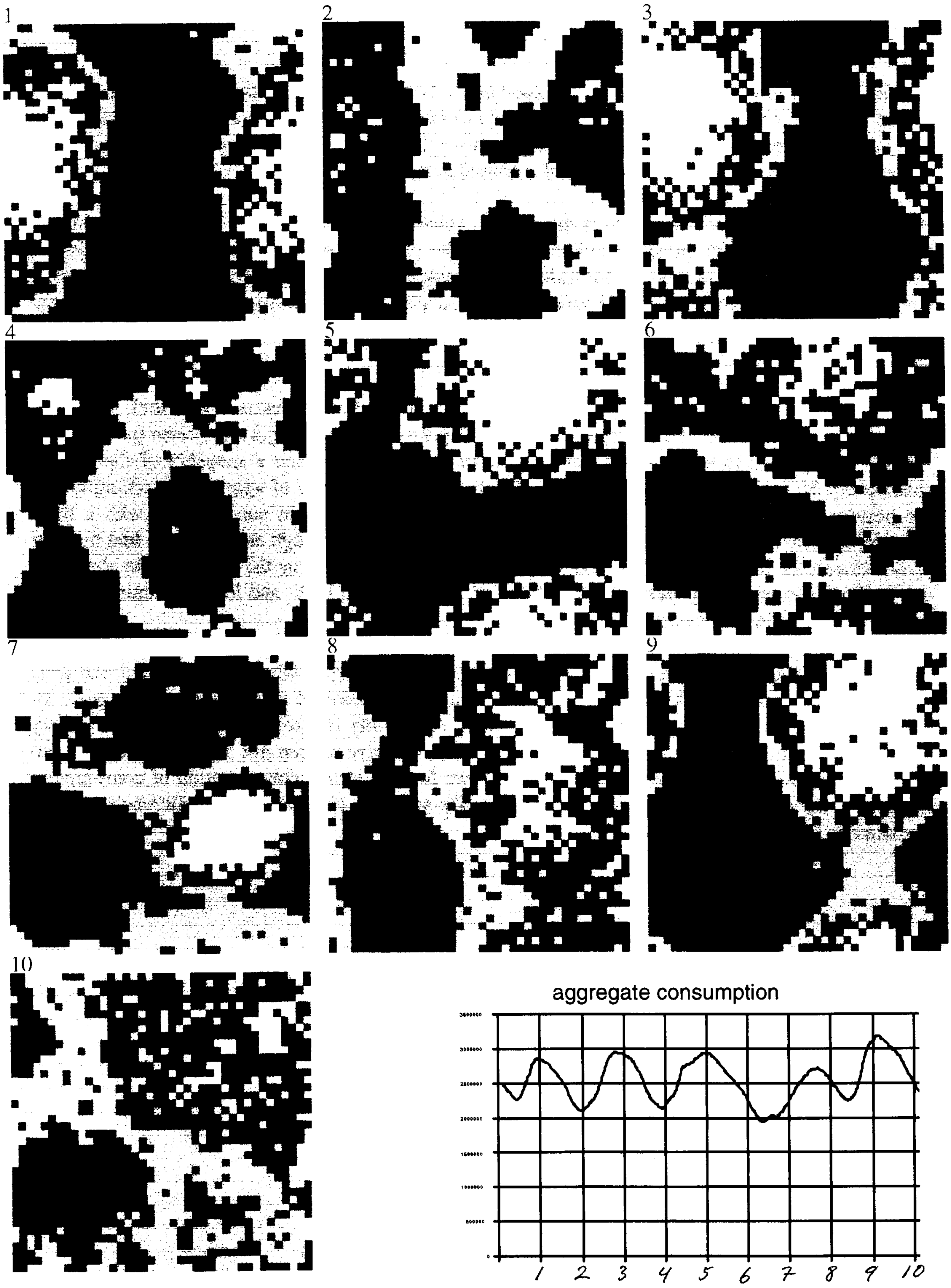
[14] The correlations are; experiment 1: 0.61, experiment 2: 0.22, experiemnt 3: 0.98.

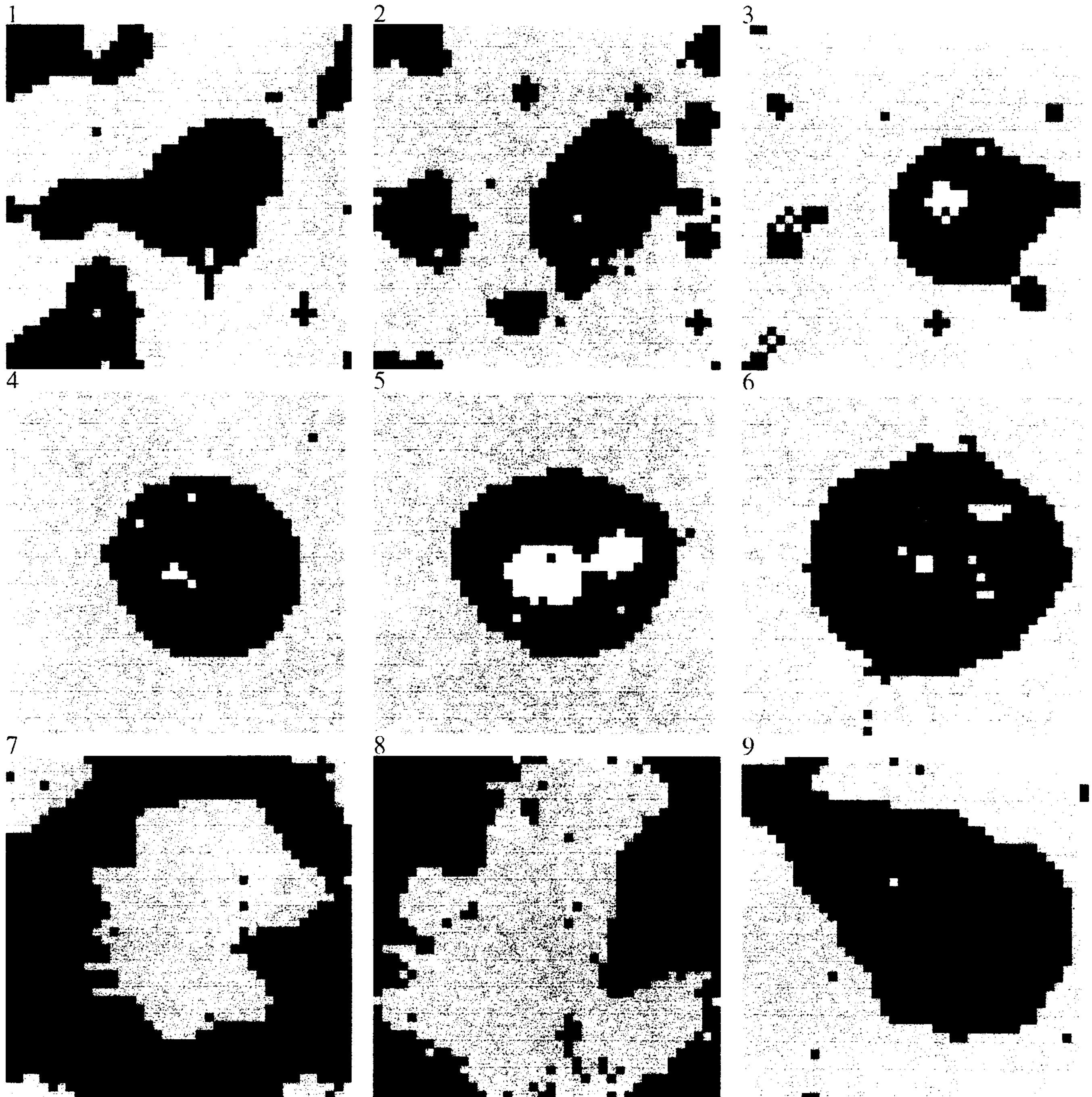
[15] The volatility of the value of real assets has deliberately been exagerated in order to study its impact on consumption and in order to have larger changes in consumption so that the relation between changes in consumption and changes in the distribution of consumption could be studied.

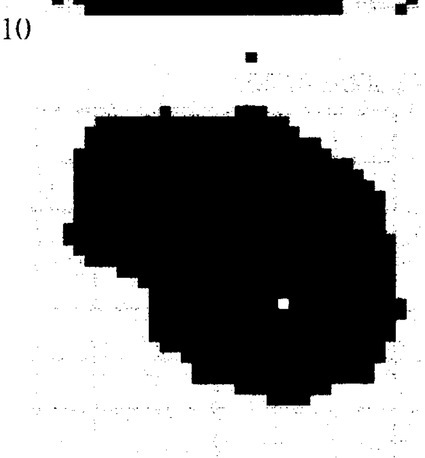
Fig.2 Microbehaviour of Experiment 1

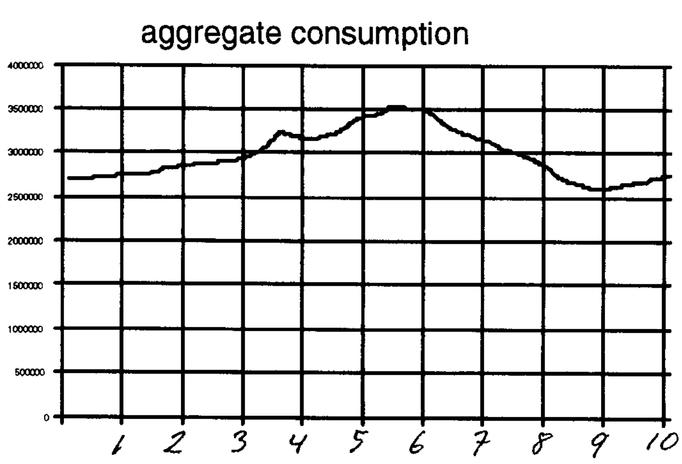


consumption above 1.5*average
■ consumption above 1.25*average
■ consumption above average
consumption below average
■ consumption below 0.75*average
■ consumption below 0.5*average

Fig.3 Microbehaviour of Experiment 2

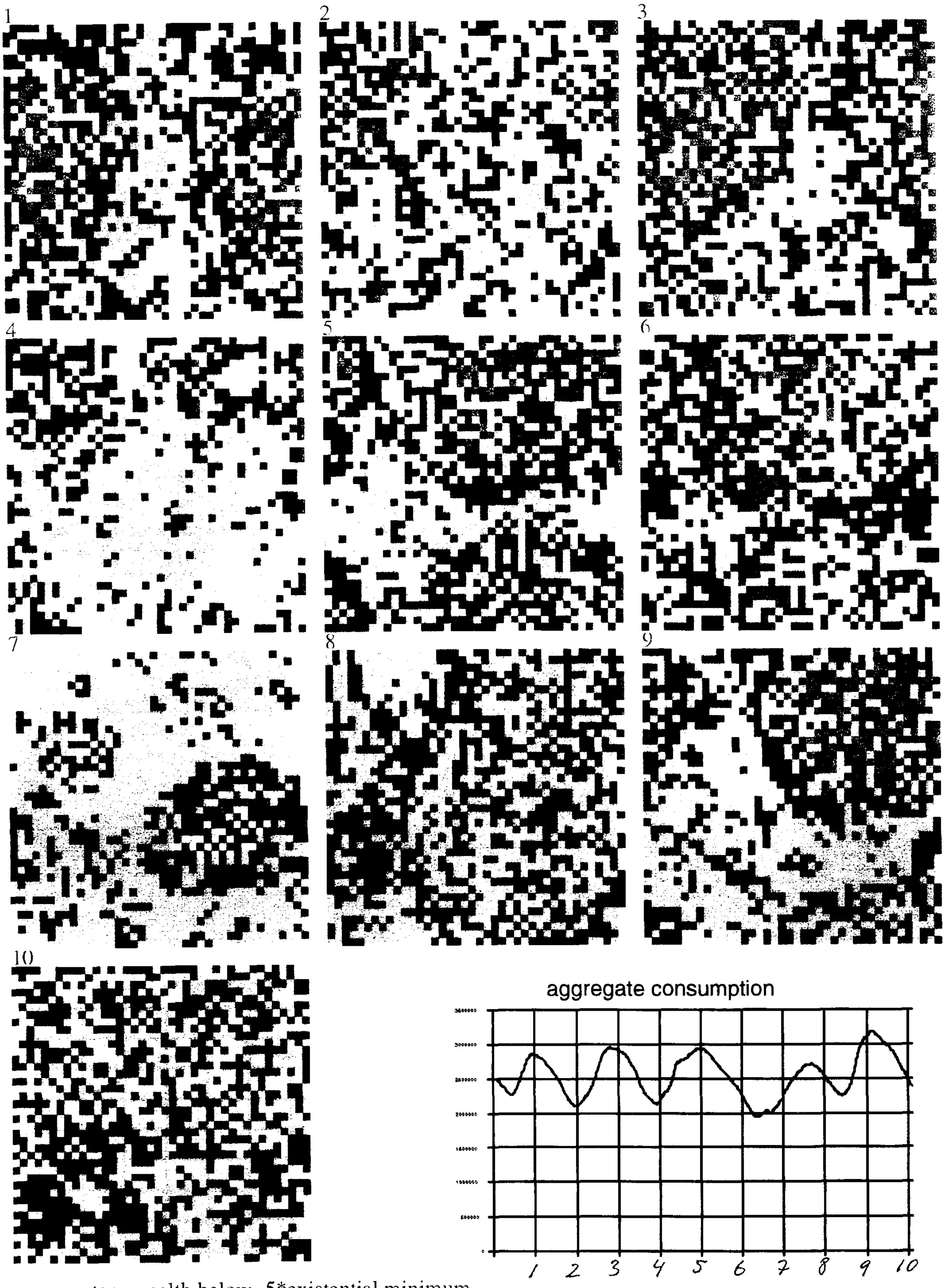






consumption above 1.5*average
■ consumption above 1.25*average
■ consumption above average
consumption below average
■ consumption below 0.75*average
■ consumption below 0.5*average

Fig. 4 Distribution of Monetary Wealth in Experiment 1



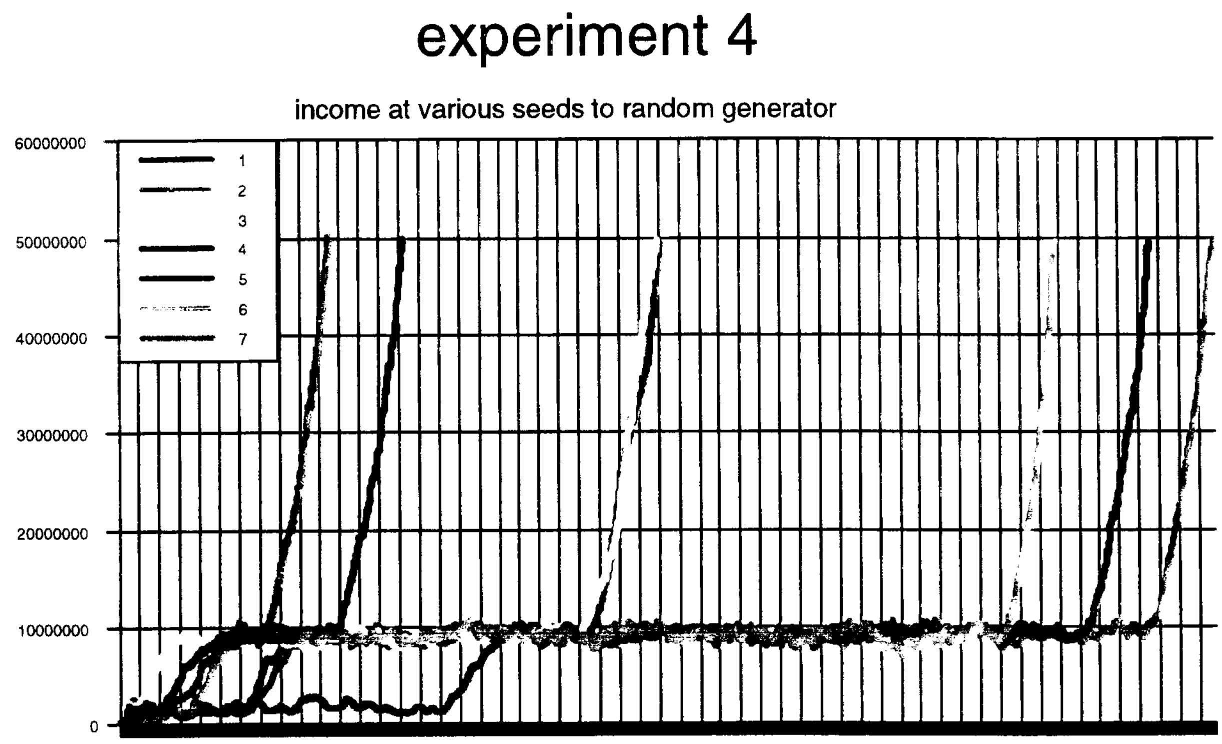
monetary wealth below -5*existential minimum
■ monetary wealth below -2.5*existential minimum
■ monetary wealth below existential minimum
monetary wealth above existential minimum
■ monetary wealth above 2.5*existential minimum
■ monetary wealth above 5*existential minimum

As demonstrated in **fig.2** and **fig.3** we have found a tendency for increases in income to take place simultaneously with the formation of high-income areas. This is the opposite relation of our expectations; we expected movement in step of all units to be a necessary requirement for growth in consumption. It is, however, too early to conclude that a high consuming elite is necessary as a locomotive for growth. If we look at the distribution of monetary wealth in experiment 1 (**fig4**) we find very high differences in monetary wealth within the high-consuming area, and not what one might expect, positive monetary wealth in the high consuming area and negative monetary wealth in the low consuming area. However it does not appear to be much unlike the real world picture to find the largest positive balances as well as the largest negative balances within the high consuming area. Agents in low consuming areas, on the other hand, do not accumulate large balances.

Assuming that there is a natural tendency in our system for generation of high consuming areas, our observations in fig. 2 and fig. 3 merely suggest that the upswing carries with it its own downturn. The fact that some agents allow their monetary balances to grow very large before they react and increase their expenditures, as is the case in the first two experiments, means that other agents are forced to have negative monetary balances. The ones that have the negative balances forced upon them, are agents that are situated next to the "rich" agents and attempt to keep up with their consumption. Small initial differences in monetary wealth are amplified by interest payments and this gives rise to the uneven distribution of monetary wealth. At a point "poor" units within the high-consuming area are forced to consume less than their neighbours, what in the end will dissolve, or tend to dissolve, the high-consuming area.

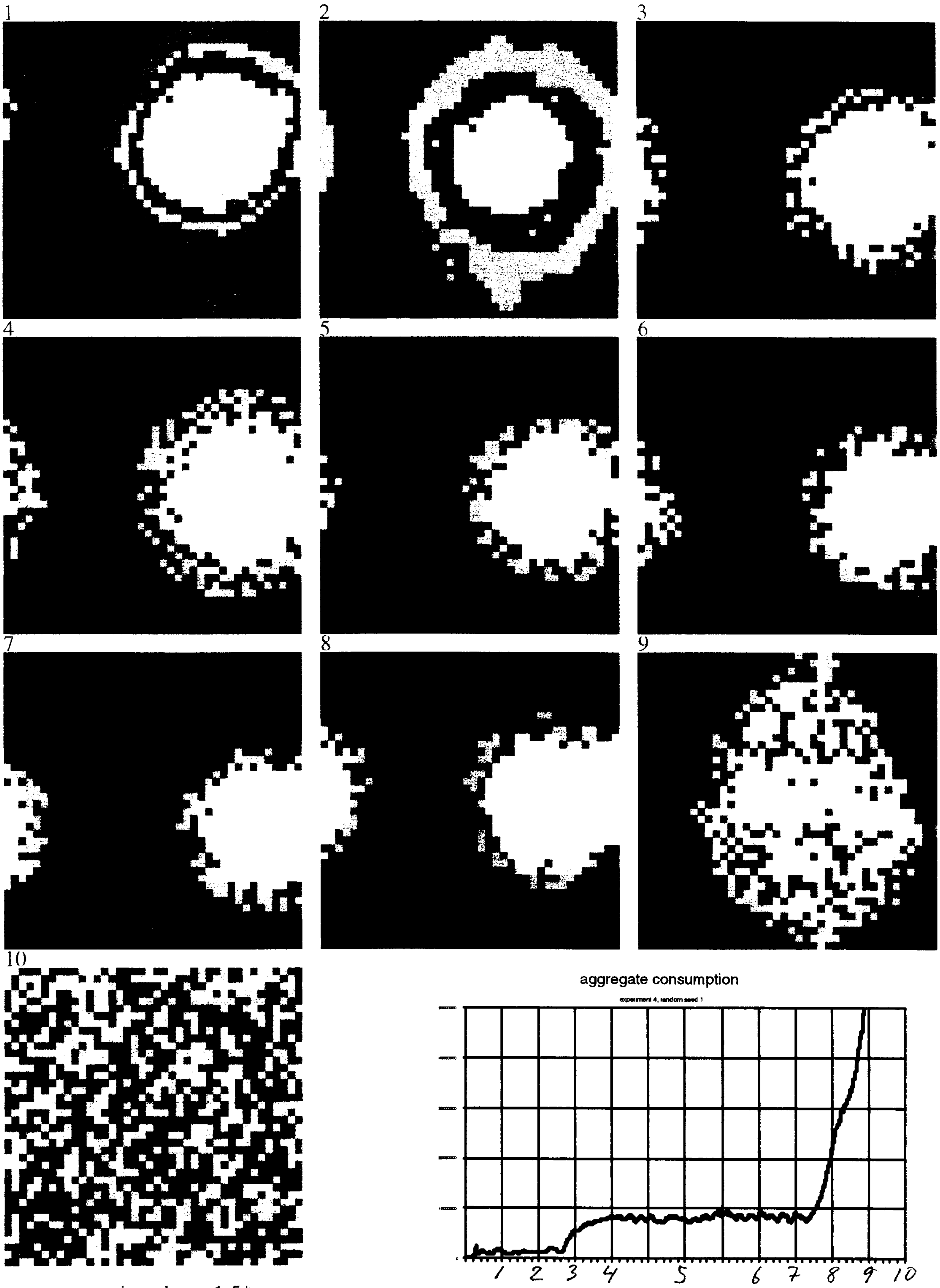
The same pattern cannot be found in the third experiment since here there is an apparently stable high consuming area (fig. A1). There may be two reasons for this deviation. First of all it may be because monetary balances for the individual unit are not allowed to grow as large as in the first two experiments. This forces the system to move in step. Secondly it may be due to the fact that positive and negative reaction are symmetric. The downturn in the first two experiments require that agents with negative balances are more prone to react and decrease their expenditures than agents with positive monetary balances are at increasing their expenditures. If the reaction of surplus units and deficit units is symmetric, as is the case in the third experiment, growth is not constrained to the same degree by an unequal distribution of consumption. The fact that in the aggregate monetary balances are large in the third experiment (fig. 1) support the symmetry argument.

Fig.5 Macrobehaviour of experiment 4



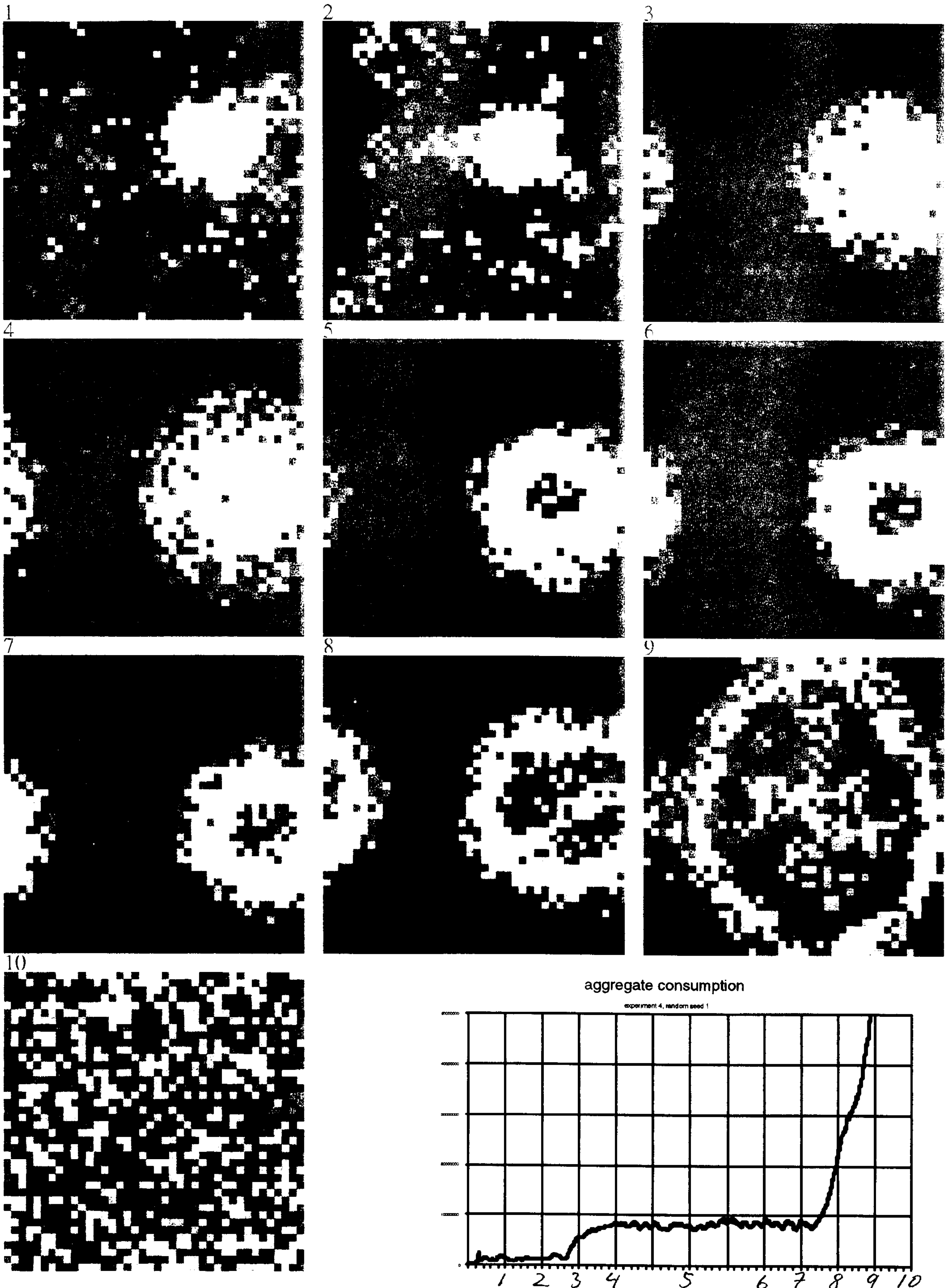
To get a better idea of causes and effects we must look at our fourth experiment which is also symmetric, but allows monetary balances to grow larger. Here we get a course that is similar to that of experiment 3, except that the level at which income settles is higher (around 9 mio. rather than 5 mio.) (**fig.5**). The system, however, does not stay at this level, but tends to go into an "eternal boom". The point at which this happens depends upon the initial setting, i.e. on the seed given to the random generator used to generate initial settings - a sensitivity to initial setting that has not been registered in any of the other experiments. Looking closer at the different courses reveal three different phases; an initial phase around 2 mio, a middle phase at about 9 mio. and in the end the eternal boom. Looking at the micro data (**fig.6**) we find that there is a pattern to each of these three phases. First we have a high consuming area with a large transition area to a low-consuming area, which has about as many high consuming as low-consuming units. In the second phase the border area becomes much more narrow (about 1/3 high-consuming and 2/3 low-consuming), and in the boom the high-consuming area is dissolved and we get what almost looks like a random distribution of high and low consuming areas.

Fig.6 Microbehaviour of Experiment 4, ranseed 1



consumption above 1.5*average
■ consumption above 1.25*average
■ consumption above average
consumption below average
■ consumption below 0.75*average
■ consumption below 0.5*average

Fig.7 Distribution of real wealth in Experiment 4, ranseed 1



real wealth above 1.5*average
real wealth above 1.25*average
real wealth above average
real wealth below average
real wealth below 0.75*average
real wealth below 0.5*average

Observing the three transition phases of experiment 4 still does not tell us about the causes of the changes. The transition in microdata appear to take place after the transition has taken place in the macrodata, so we still do not know what causes the change in the macrobehaviour. What about the distribution of monetary wealth and real wealth? Observing the distribution of monetary wealth again tells us that the poorest and the wealthiest agents with respect to monetary wealth are situated within the high consuming area. When the system goes into the boom and consumption gets more evenly distributed, the same thing does not hold with respect to monetary wealth - everybody appear to be very rich or very poor. This picture is however distorted since the existential minimum that is used to measure deviation looses its relevance as consumption booms.

Looking at the distribution of real wealth (**fig.6**) we may finally find the reason for the transition from the second to the third phase. Before the transition takes place we find that inside the high consuming area there is a small but growing group of units with very low holdings of real wealth. The units situated in the middle of the high consuming area are apparently not able to keep up both with respect to consumption goods and real wealth. This inability implies that some of their neighbours will lack the income to keep up as well, and in the end the high consuming area disappears. Having suppressed the boom, the dissolution of the high consuming area takes the system into a boom. In the appendix the same pattern is shown for experiment 4, ranseed 4.

Although the boom in experiment 4 was accompanied by a dissolution of the high consuming area, it was far from a situation with step. Using Stützels analytical method to analyse the stepphenomenon, the transitions of experiment 4 might not be apparent since, in the boom phase there still is a large dispersion of consumption. The most significant change is that high consuming and low consuming units are not clustered at the cellular space but evenly distributed. This fact alone seems to make it worth the while to perform simulations of this kind.

The different phases of our fourth experiment and the differences between our asymmetric experiments (1 and 2) and our symmetric experiments (3 and 4), suggest that our system is subject to different kinds of constraints. In the asymmetric experiments, the asymmetric appear to be the hardest restriction while in the third experiment it is the size of monetary balances, and thus disstep, that places the constraint. This is confirmed by the fact that monetary balances never get to grow very large in the first two experiments compared to the third (**fig.1**). In the fourth experiment the constrained put on the system by the size of monetary balances is removed in the boom stage, not by transition to a mode of step, but by less stability at the microlevel. In one period a unit is high consuming, a few periods later it may be low consuming as the consumption of its neighbours and its monetary position is also changing all the time. Imposing step on an agent-based model by not allowing monetary balances to accumulate does not appear to be the way to promote growth.

9. Conclusion

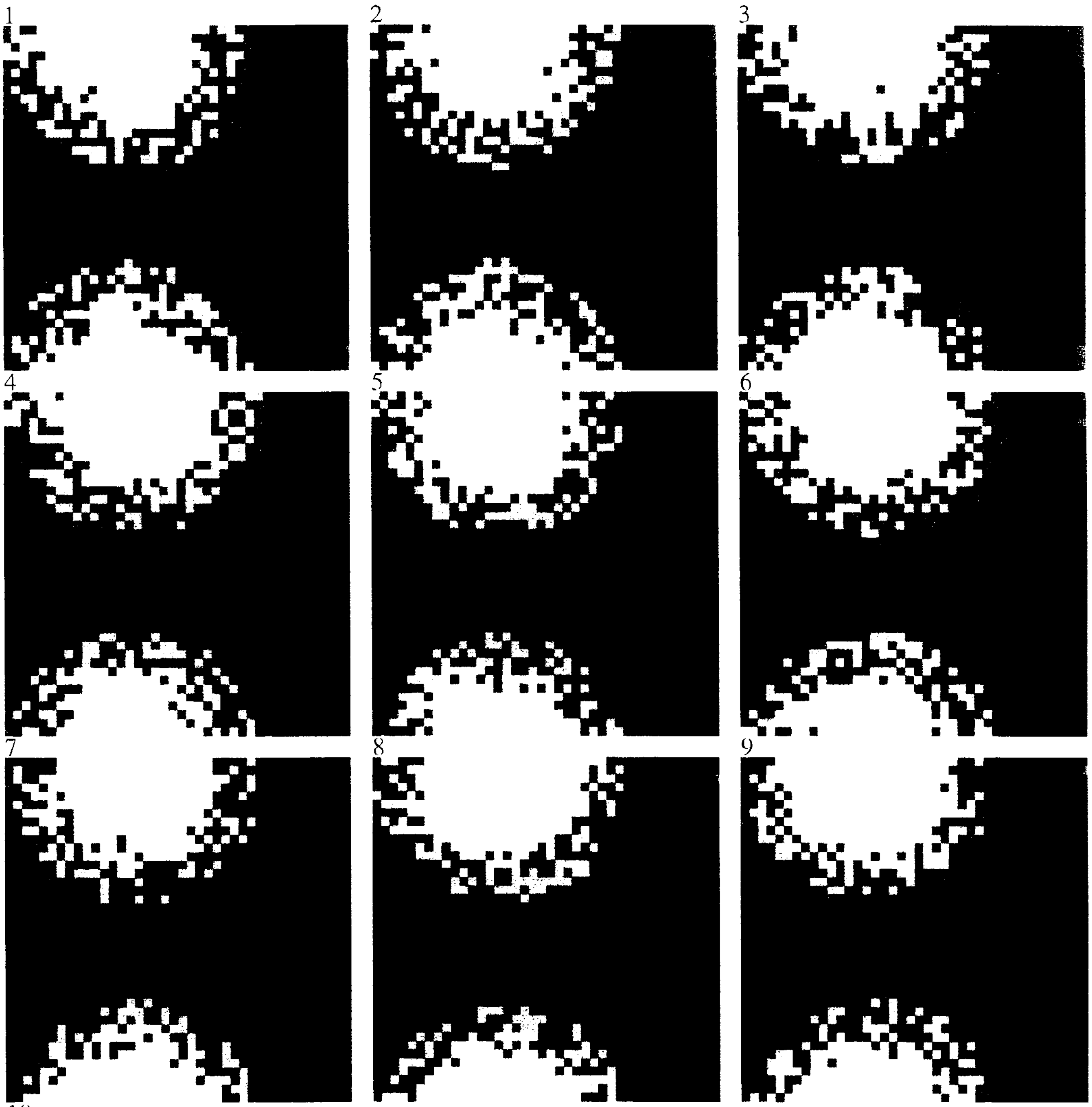
Our requirement of a macrofoundation of micro as well as a microfoundation for macro has forced us to look for new modelling techniques. It has made us reject the idea of a representative agent and instead model a population of agents, and it has made us assign a central role to accounting relations as the feedback mechanism from macro to micro. This staring point made us model the economy as a cellular automaton; a model technique developed within artificial life and introduced to economics under the heading "agent-based economics".

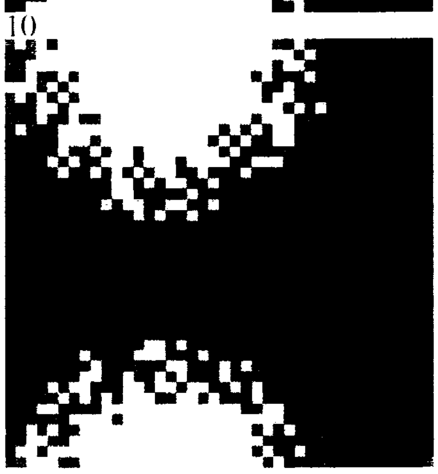
With the problem of constraining artificial life models follows a problem of evaluating such models. Where does the line between toy-models and scientific models go, for surely, as noted by Bonabeau and Theraulaz (1995), "Not everything is serious in the AL [artificial life] community". According to them, phenomenological relationships are practically the only criterion we have in evaluating artificial life models. But with as large and complex a system as economic systems, even phenomenological relationships are hard to evaluate since the model must operate at a high level of abstraction.

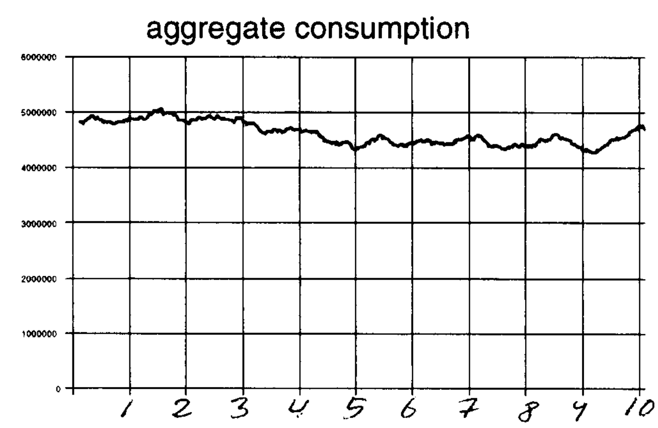
The method of constraining the set of possible rules and searching through the rest has not been possible to apply. We have had to use Occam's razor and look for the most simple set of rules that would fulfil our most basic requirements. Yet we have had to introduce features as real assets in order to assure that some of the complexity of the real world is present. Once we have a solid framework we can start refining, but we have a long way to go before we can start making use of data from the real world.

The model presented here is very preliminary and cannot justify any general conclusions with respect to the structure and dynamics of aggregate consumption. We have, however, found several interesting features. The question asked was whether consumption behaviour of interacting agents was likely to take the aggregate system to a suboptimal position. We found that although there are no constraints to our system, the system does not as a rule go into an "eternal boom". On a pure macro or a pure micro level it is hard to understand why a non-constrained model should operate at a suboptimal level. Our model suggests that the reason for suboptimal behaviour of economic systems may be found in the way interaction takes place. The interaction by autonomous agents gives the system a high degree of selforganization, but it does not necessarily take the system to the optimum an analytical method would find.

Fig. A1 Microbehaviour of experiment 3

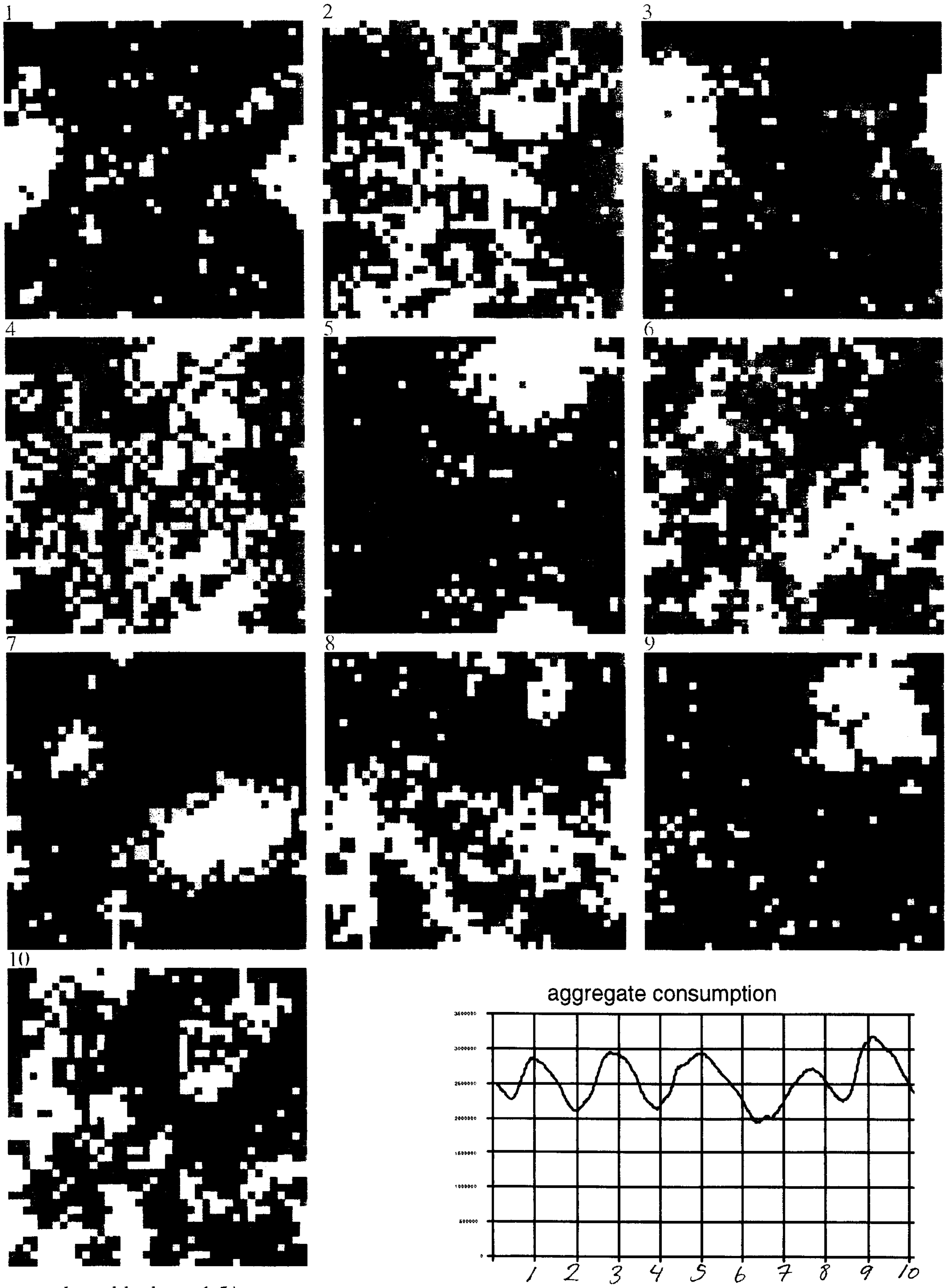






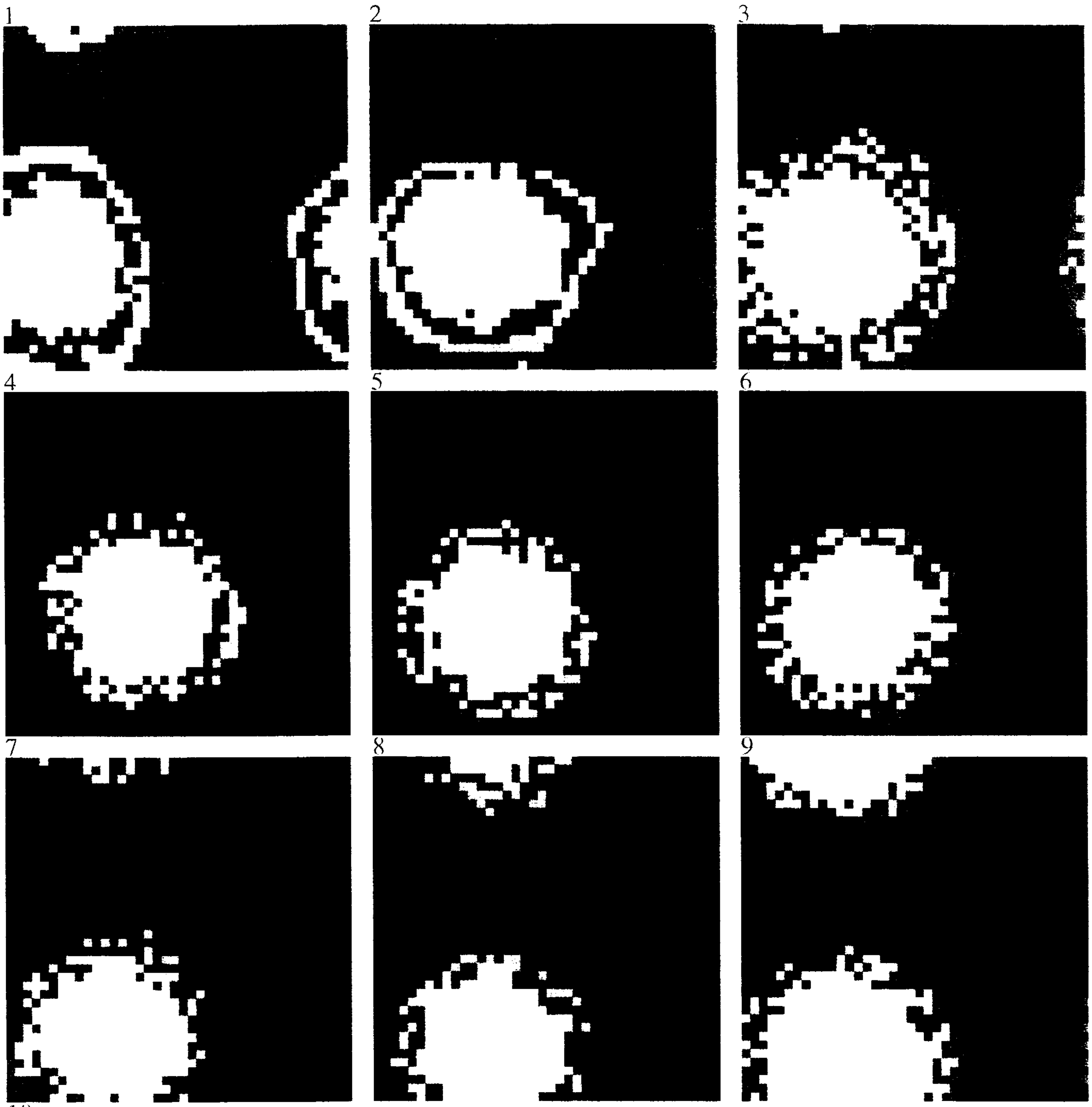
consumption above 1.5*average
■ consumption above 1.25*average
■ consumption above average
consumption below average
■ consumption below 0.75*average
■ consumption below 0.5*average

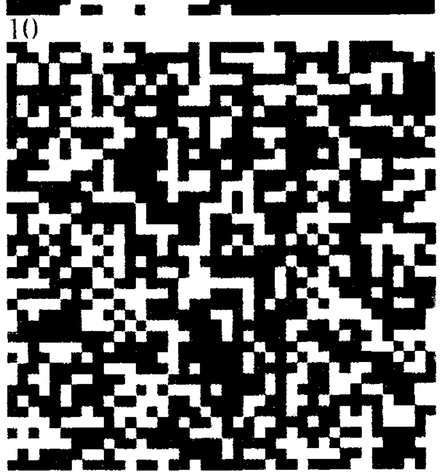
Fig. A2 Distribution of real wealth in experiment 1

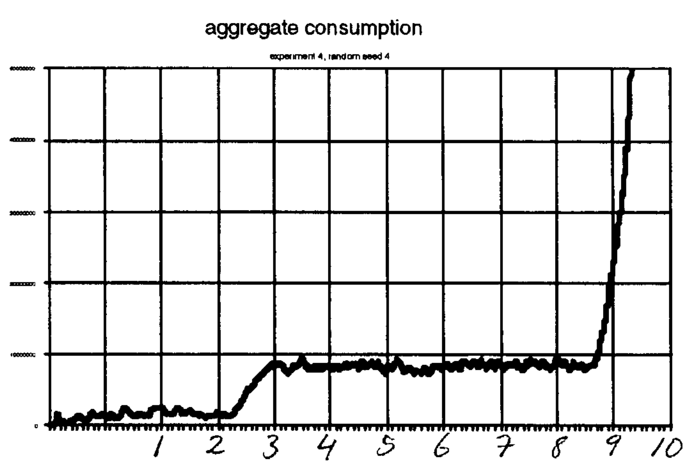


real wealth above 1.5*average
■ real wealth above 1.25*average
■ real wealth above average
real wealth below average
■ real wealth below 0.75*average
■ real wealth below 0.5*average

Fig. A3 Microbehaviour of experiment 4, ranseed 4







consumption above 1.5*average
consumption above 1.25*average
consumption above average
consumption below average
consumption below 0.75*average
consumption below 0.5*average

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