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Biographical Note

Daniel Farhat is currently a lecturer in the Economics Department at the University of Otago in New Zealand. His research interests are in complex systems modelling with applications to macroeconomics, labour economics and economic methodology.

The Economics of Vampires: An Agent-based Perspective

Abstract

Vampires are a prominent feature of modern culture. Past research identifies the ecological and economic relationship between vampires and living humans under the assumption that 'representative agents' are capable of characterising entire communities. Whether populations of individuals can coordinate themselves sufficiently or not to achieve the same outcomes as the representative agent is not addressed. The purpose of this study is to create a human-vampire ecosystem using artificial social simulation. An agent-based computational model is constructed in which heterogeneous vampire and human individuals engage in one-on-one interaction within a virtual landscape. These interactions result in the emergence of aggregate-level phenomena. Simulating alternative virtual economies under different model calibrations shows under what conditions these emergent phenomena are similar to those produced by the representative agents in previous studies. This article contends that growing human-vampire economies can shed light on an array of social and economic issues even if vampires never existed at all.

Keywords: economics of vampires, agent-based modelling, artificial social simulation

Introduction

For centuries, humanity has been simultaneously terrified and fascinated by our un-dead brethren: the vampires. The interaction between our community and theirs has been thoroughly explored in literature, film, history and cultural studies. From these works, key characteristics defining this relationship between man and vampire emerge:

a) Vampires rely on humans as an essential food source.
b) Vampires use humans to reproduce.
c) Humans resist the interactions with vampires that result in (a) and (b) above, usually by producing wards (such as garlic) or defence measures (such as wooden stakes).

From these characteristics, an environment consisting of two separate yet interrelated economies emerges. In one economy, vampires must manage their limited food stocks. In the other economy, humans must concurrently produce consumable goods and defend themselves against the vampire scourge.

Past research in economics has provided insights on how this environment functions. Snower (1982) uses a model of population dynamics to describe the human-vampire ecology. He proceeds to advise the human population on the optimal destruction of vampires versus economic production using an optimal control framework. A central result from this analysis is that driving vampires to extinction is often undesirable. Hartl and Mehlmann (1982) focus on the welfare of vampires. They derive efficient human depletion policies for different vampire preferences (i.e. for concave, linear and convex utility functions over blood). Hartl, Mehlmann and Novak (1992) extend this analysis to accommodate known cyclical fluctuations in vampire activity (or 'cycles of fear').

These analyses assume that we need only consider the attributes and decisions of 'representative agents' to capture the important characteristics of the economy. Derived equilibria and optimal policies are meant to reflect those that a coordinated community would produce (i.e. the economy is modelled from the 'top-down'). There are two notable drawbacks to this approach, however. First, representative agents are often given more information and abilities than a normal agent would naturally possess. For example, the representative agents in the above models know how their choices affect the overall growth rates of the vampire and human populations; knowledge that an ordinary human (or vampire) may not have nor consider when making their choices. These representative agents are also infinitely-lived; an awkward assumption since interactions between individual humans and vampires often results in one of the two dying. Second, *how* individuals might organise themselves into a community capable of producing the same outcomes that the representative agent produces is not part of the analysis. We do not know if individuals can coordinate themselves sufficiently to follow the optimal policies described by the representative agent as a result. It becomes questionable whether or top-down methods can truly *explain*[1] aggregate phenomena or should be used to inform policy.

Recent advances in computer science have provided a useful tool for constructing and analysing human-vampire interaction 'from the bottom-up': *artificial social simulation*. Using agent-based computational models, societies populated by heterogeneous, artificially-intelligent agents can be created. These individuals interact with each other and their environment according to pre-determined behavioural rules. Activity at the individual (or 'micro') level results in the emergence of organisation and the production of aggregate (or 'macro') phenomena. Not only can economies be *grown*, they can also be experimented with by augmenting parameters of the model and re-simulating. Readers interested in this method can see Tesfatsion (2002, 2007), Macy and Willer (2002), Mathieu, Beaufils and Brandouy (2005), Tesfatsion and Judd (2006), and Pyka and Fagiolo (2007) for a description of the applicability of ABMs to economics and other social sciences. The purpose of this study is to create a human-vampire dual economy based on individual interaction, to analyse the properties that emerge from this interaction and to compare these features not only to the past literature but also to our historical experiences with the vampire community.

The remainder of this article proceeds as follows. First, an agent-based model of human-vampire interaction is described. Next, several simulation experiments are conducted in which parameters of the model are changed and new economies are produced. Results show that it is possible to generate economies from the bottom-up which possess many of the features analysed by top-down approaches (including 'cycles of fear'). Under certain conditions, we can generate virtual worlds where vampires become extinct at great cost to humans, which explains why vampires

[1] See Epstein (1999, 2006) for further discussion.

have a persona-non-grata reputation in contemporary culture and why they are rarely encountered in great numbers today. The article concludes with a discussion of the relevance of these results, including why growing human-vampire dual economies from the bottom-up can be an insightful exercise even if vampires never existed in the first place.

An Agent-based Human-Vampire Dual Economy

Consider an artificial society populated by two types of agents: humans and vampires. This society exists on a sphere comprised of 1296 square areas (or *patches*, where each patch is 1 unit in length and width). The population of this 'virtual world' is simulated in two phases: the set-up phase and the action phase. The set-up phase establishes the initial population of the world and their characteristics. The action phase consists of an iterative algorithm which describes how the agents of the model interact with each other and the environment. Describing the set-up phase and a single iteration of the action phase (as it is repeated) is sufficient to fully characterise the human-vampire economy.
The set-up phase is run only once and is as follows:

a) A user-specified number of initial humans is created and randomly distributed across the globe. In the following simulations, the initial human population is set to 1000. Each human is born with a pantry of bread and a stock of blood. The pantry of bread is unlimited and each human receives a random initial allocation drawn from a uniform distribution (U[0,50] in the experiments below). A human's blood capacity is limited to 100 units; each initial human has the maximum amount of blood stock.

b) A user-specified number of initial vampires is created and randomly distributed across the globe. The initial vampire population is set to π% of the human population in the simulations below. Vampires have a stock of blood which, like humans, has a maximum capacity of 100 units. Their initial blood stock is randomly drawn from a uniform distribution (U[0,100] below).

Denote t as the current period of simulation. During the action phase, the following subroutines are performed for any period, t:

a) Start of period *t*.

b) Locale.

c) Find-safety.

d) Buy.

e) Feed.

f) Record.

g) Re-set.

h) End of period *t*.

The subroutines are as follows:

Locale subroutine.

i. Patches estimate the local population. Each patch in the virtual world records the population of men within 1 unit of its location.

Find-safety subroutine.

i. Humans move to cities. Each human finds the most populous patch within v_h units of their current location (the human's view) and moves m_h units towards that patch. In the experiments below, $v_h = 3$ and $m_h = 1$.

Buy subroutine.

i. Patches update the population estimate. Each patch updates the size of the human population within a 1-unit radius of its location.

ii. Humans look for vampires. If there is a vampire within v_h units of the human's current location, they observe it with probability, $\rho \in [0,1]$. The total probability a human witnesses a vampire: $P = \rho \times \#$ vampires within a v_h-unit radius. A random draw is performed to determine if the human is a witness.

iii. Humans engage in production:

1. If the human is not a witness, they produce bread. The amount of bread produced by humans is a random draw from a U[0,2.2] distribution. This bread is added to the human's pantry.

2. If the human is a witness, they produce stakes. Stakes are a public good and are held at an armoury located on the human's current patch. To acquire the resources needed to produce a stake, a human must give up 1 unit of bread from their pantry (a capital cost) and forego the opportunity to make bread (a labour cost) during the remainder of the period. The stake is then added to their patch's supply.

Feed subroutine.

i. Vampires establish hunting grounds.

1. A danger rating (Ψ) is determined for each patch in the virtual world. This rating depends on the probability a human sees a vampire (ρ), the probability the human succeeds in killing a vampire when they confront one (defined as $\lambda \in [0,1]$), and the number of stakes held in the patch's armoury. It is assumed:

$$\Psi = \rho \times \lambda \times \# \text{ stakes}$$

2. A desirability measure,Φ, is then computed for each patch. Desirability increases with the total quantity of human blood available at the patch and decreases with the patch's danger rating. It is assumed:

$$\Phi = (\text{sum of blood stock of all humans here}) / (1 + \Psi)$$

3. The hunting ground is established by finding a patch within v_v units of their current location (the vampire's view) with the greatest Φ and move m_v units towards that patch.

iii. Vampires feed:

1. If the number of humans in the vampire's current location is positive, the vampire feeds on one of them.

2. If a human is selected to be a victim, they may become a vampire as a result from the attack. The probability a victim becomes a vampire is denoted as $\sigma \in [0,1]$ and random draw is performed to determine if the victim 'turns'.

   a. If the victim is selected to become a vampire, they forfeit 50% of their blood to their attacker. They become a vampire identical to a vampire at their current location and are assigned to a random location somewhere in the world.

   b. If the victim is not selected to be 'turned', they transfer a random amount of their own blood to their attacker.

iv. Humans feed:

1. Humans consume 1 unit of bread from their pantry if the quantity of their bread holdings is sufficiently large.

2. If the human does not have at least 1 unit of bread in their pantry, they starve to death and are eliminated from the virtual world.

Record subroutine.

Data is collected. The number of units of bread and the number stakes produced by the human population is recorded as are the sizes of the human and vampire populations.

Re-set subroutine.

i. Vampires use blood. Each vampire's blood stock diminishes by b_v units. If their current supply is less than 0, the vampire starves to death.

ii. Vampires are hunted. Each vampire may die during an attack (or counter-attack) from the human population. The danger rating, Ψ, at the vampire's current location is used to determine whether or not they are killed by a human.[2]

iii. Humans heal. Each human's blood stock increases by 1 unit if their current supply is less than 100.

iv. Humans reproduce. Denote the potential population growth rate as $\eta \in [0,1]$. A human is randomly selected with probability, η. If the selected human's blood supply exceeds a defined amount, X (capturing the minimum amount of health a human needs to reproduce), the human produces an offspring ('hatchling'). The hatchling is given 50% of the human's pantry and sent to a random location elsewhere in the virtual world. In the simulations below, η = 2%.

v. Sickly humans die. If a human's blood stock falls below a user-defined amount, Y (a minimum level necessary to survive), the human dies. In the simulations below, Y = 10 units.

vi. Stakes depreciate. In each patch, the stock of stakes depreciates at a rate, $\delta \in [0,1]$. In the simulations below, δ = 10%.

This algorithm repeats.[3]

Experiments and Discussion

The above model is programmed into NetLogo, freely-available software specifically designed to accommodate agent-based simulation models.[4] Each simulation creates a unique virtual world.[5]

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[2] A random number is drawn from a U[0,1] distribution. If the draw falls below Ψ, the vampire dies. Note that Ψ may be greater than 1 if the number of stakes at the vampire's location is sufficiently large. In this case, the vampire will die with certainty.

[3] The number of repetitions varies in the experiments that follow. If the number of humans becomes excessively large, the algorithm performs slowly. If the number of vampires becomes zero, no additional useful information can be gathered from the program. The number of iterations is set to 5,000 maximum, with early stopping if the number of vampires falls to zero or if the number of humans exceeds 16,000 – 20,000.

By changing parameters of the model, new worlds with different properties can be created. The parameters that are experimented with in the discussion below include:

π	The size of the initial vampire population.
ρ	The probability a human sees a local vampire.
λ	The probability a human who sees a vampire can successfully destroy one.
v_v	The vampire's view of the world.
m_v	The distance a vampire in-transit covers.
σ	The probability a bitten human turns vampire.
b_v	The vampire's per-period blood use.
X	The minimum blood supply a human needs to reproduce.

Experiment A – A vampire-free economy.

Figure 1 describes an artificial economy when there are no vampires (π = 0%) present. The both the size of the human population and the quantity of bread produced each period grows exponentially. Humans organise themselves into urban areas with occasional movement of some humans between cities. These results are expected given the set-up of the agent-based model in the previous section.

[Figure 1 here]

Experiment B – Oblivious humans.

What if vampires exist, but humans cannot observe them? In this experiment, a virtual world is simulated with vampires (π = 1%) that are completely invisible (ρ = 0). The vampires in this world are fairly mild (see Table 1 for the other model parameters), but cannot be killed since they

[4] NetLogo is a modelling environment with an easy-to-learn programming language and comes with many convenient features related to spatial management and population growth. The program for this model is available upon request. More information about NetLogo in addition to the software itself is available at ccl.northwestern.edu/netlogo. (Wilensky, 1999)

[5] The results shown for the following experiments describe a single simulation. Some descriptions of ABM validation suggest collecting data from multiple simulations with the same calibrated parameters to highlight the model's ability to consistently produce the phenomena of interest. NetLogo, unfortunately, is limited in its ability to run repeated simulations efficiently. A more robust result-generating process along these lines is left for future research. Interesting implications, however, can be derived by inspecting a single virtual society.

cannot be seen. As a result, starvation is the only reason a vampire dies. Figure 2 displays outcomes from this simulation.

The model produces periodic fluctuations in both human and vampire populations as well as the ratio of the two. These 'cycles of fear', formally modelled by Hartl, Mehlmann & Novak (1992), are an emergent property of the model: they occur at the aggregate level from the human-vampire interaction occurring at the individual level (i.e. generated from the 'bottom-up'). Similar cyclical fluctuations in economic production driven by changes in the human population also occur.

The rate that vampires reproduce, σ (set to 30% above), plays an integral role in the results shown in Figure 2. If σ is high (e.g. 60%), vampires initially flourish. Humans are over-exploited and the vampire population cannot be sustained. Vampires quickly become extinct, but luckily some humans survive to re-populate the world (see Figure 3). Because individual vampires engage in local interactions only, and do not control their behaviour in response to the overall state of the world, their natural attributes affect the sustainability of their community as a whole even in relatively 'safe' environments (recall vampires are completely hidden and thus un-huntable in this experiment). This implies that any vampires hidden among us must be fairly invirile.

[Figure 2 here]

[Figure 3 here]

Experiment C – Observable vampires.

What if vampires are observable? In this experiment, the probability that a human sees a vampire, ρ, is set to a small positive value (ρ = 5% - vampire sightings are rare). Two types of vampires are considered: (1) vampires that are easy to defeat (λ = 1) and (2) vampires that are impossible to kill (λ = 0) when encountered. All other model parameters are the same as in experiment B (see Table 1). Because vampires are now occasionally seen, some humans engage in stake production. Results for these two sub-experiments are illustrated in Figure 4.

[Table 1 here]

[Figure 4 here]

Interestingly, vampires quickly become extinct when they are difficult to overpower. The reason why this is so is related to the useless production of stakes. Humans who see vampires forego the production of goods that can be used to sustain their numbers. They expend resources on the manufacture of ineffective stakes. As a result, pantries deplete and people starve. As humans die out, vampire numbers also dwindle. As in experiment B with a high vampire reproduction rate, vampires eventually become extinct while a few remaining humans re-populate the virtual world.

The vampire community is durably sustained, however, when they are easily defeated. In a world with such fragile vampires, cycles of fear once again emerge. Further, humans maintain a stock of stakes (which fluctuates along with the fear cycle) and a relatively consistent rate of population growth and economic production.

Changing the probability an observed vampire is defeated in a fight, λ, produces vampire populations with different growth and cycle properties. For example, $\lambda = 50\%$ will produce a vampire community that fluctuates in number regularly for 2000 periods before going extinct. $\lambda = 25\%$ will produce a vampire community that fluctuates twice before extinction occurs. (In both cases, the human population, bread production and stake production fluctuate wildly before man takes over the world.) These calibrations can potentially explain why vampire-lore may have developed during different times in history, yet vampires are rarely seen in great numbers today.

Note that changing the probability a vampire is seen, ρ, also affects the cyclical and growth properties of vampire populations. The more visible the vampires are, the more likely humans will devote efforts to stake production versus consumables production. Hence, pantries go bare and humans starve to near extinction rather quickly when ρ is high. As before, vampires starve as their food source diminishes until they disappear and man repopulates the world.

Experiment D – Biological needs.

Two variables related to the biological requirements of humans and vampires can also affect the aggregate properties produced by the model above. These are the per-period blood usage of a vampire (b_v) and the minimum amount of blood needed for humans to reproduce (X – a health requirement). An increase in b_v makes vampires voracious and raises the chances they will starve. A reduction in X makes the human population less susceptible to extinction in the presence of vampires by increasing the population growth rate. Two alternative calibrations for these parameters are simulated: (1) $b_v = 10$ and (2) $X = 50$. All other parameters are the same as experiment B above (see Table 1).

Results are shown in Figure 5. When vampires starve easily, mild but persistent growth in both populations emerges. The overall size of the vampire population rises while the ratio of vampires to humans remains relatively low and stable (approximately 1 vampire for every 7.7 humans). This differs from the results in experiment B which had a smaller vampire community in total that made up a larger fraction of the entire population (about 1 vampire for every 4.2 humans). Cycles of fear are present in this experiment, but these fluctuations impact the human community less than the experiment with more satiable vampires.

[Figure 5 here]

When the health requirements for human reproduction are lowered, the size of both populations remains low, but is stable. The ratio of vampires to humans fluctuates around 1 vampire per 3.7 humans (from a low of 1 vampire per 8.3 humans to a high of 1 vampire per 2.2 humans). Cycles of fear are more pronounced and devastating to the human population than in experiment B even though human's ability to grow their population is enhanced. This paradoxical result occurs because of the severity of reproduction dynamics in the model. A sharp up-swing in the human population produces an over-abundance of vampires which then drives it back down.

Discussion

From the experiments above, we can pull together several illuminating features of the human-vampire dual economy. In virtual societies where vampires are highly visible, the human population suffers terribly for a short period (building up defences which results in starvation) until the vampire population is driven to extinction. Once they have been eradicated, the human community and their corresponding economy proceeds to grow exponentially. Therefore, one reason why we may not come across vampires in modern times is because they have already died out. Vampire-lore, then, is inspired by a historical account of human-vampire interaction.

In virtual societies where vampires are observable but somewhat hidden, they may flourish provided they are easy to destroy in a confrontation. Cycles of fear then emerge. Therefore, if we do not see vampires today it may be because spotting them is rare. Vampire-lore is then inspired by the reports of the occasional witnesses lucky (or *unlucky*) enough to catch a glimpse. If vampires cannot be killed, they increase in numbers, over-exploit the human herd, and then starve. As in (a), vampire stories are a product of history.

In virtual societies where vampires are unobservable, their existence persists. Whether they flourish or stagnate depends on their hunger for blood and the speed of human reproduction. If vampires live on the brink of starvation, both vampire and human populations persistently grow despite mild cycles of fear. If humans reproduce easily, both communities languish with extreme cycles of fear keeping both populations in check. The former is more likely given the persistent growth of our planet's population. If this is the case, we would never encounter vampires (and may even doubt their existence) in reality. Any vampire imagery that exists is an attempt to explain mysterious fluctuations in the human population.

Without the ability to globally coordinate, the opportunities to optimise resource use (blood consumption for vampires, stake versus bread production for humans) described in Snower (1982), Hartl and Mehlmann (1982), and Hartl, Mehlmann and Novak (1992) never actually present themselves. Instead of modelling their behaviour 'from the top-down', we can construct the human-vampire dual economy 'from the bottom-up' using interacting individuals. The agent-based framework presented here shows the types of economies that develop under different natural circumstances and produces similar characteristics to those studied in the previous literature. Implications relating to our real-world experiences with vampires can then be drawn.

Concluding Remarks

Given their potential effect on human welfare, should we be concerned with the activities of the vampire community? In all likelihood, there is no such thing as vampires (hence, there is nothing to fear). Their non-existence does not diminish the importance of understanding how vampires behave, however. As they always have, vampires and their relationship with humans serve as a useful metaphor for a variety of economic problems. Consequently, the agent-based model above provides interesting insights on situations where 'vampires' and 'humans' interact.

Vampires and natural resources. The previous studies cited in this article have used vampire imagery to represent a class of problems in which dynamic optimisation procedures can identify a set of optimal rules for using renewable resources. As noted, these works focus on the choices of one population (either 'humans' or 'vampires') and, given the state of the environment, rely on artificial coordination to derive these rules. There is no active interaction between the two populations. *How* and *if* communities of individuals can coordinate to form the environment and follow the optimal policies is not addressed. These shortcomings seem decidedly 'unnatural'. The agent-based model described above allows both populations to actively make decisions based on 'natural instinct'. Through interaction, individuals actually build their own ecosystem. Heterogeneous agents act individually and not as a coordinated group in such ecosystems, yet similar phenomena to those studied in past optimal control problems seem to emerge at the aggregate level.

Vampires and epidemiology. Nixon (1997) connects vampire imagery in contemporary media with the rise of AIDS cases in the 1980s. The spread of HIV is only one of many communicable diseases which can harm productivity and cost resources to control. The H1N1 influenza epidemic of 2009 is perhaps a more recent notable example. 'Vampires' in the agent-based model above can represent infected workers who spread diseases to healthy workers. Changes in the human population represent decreases in productivity that occur as workers become ill while increases in the production of stakes represent spending resources on measures that limit exposure to the disease. As with natural resources, events in the model occur without artificial coordination and at the individual level (the same level where the disease is transmitted).

Vampires, Marxism and social revolution. Vampire-lore has been used as a literary device to describe a relationship in which one person lives off another. Neocleous (2003) cites the example of the European feudal aristocracy collecting rents from the peasantry. Similar relationships exist between governments and their citizens (governments collect taxes and then spend) and large enterprises and their workers (owners earn profits on the worker's output). As such, the agent-based model above suggests that social revolutions may sometimes occur if those who are fed by the efforts of others consume too much (e.g. governments become corrupt or firms under-pay labourers). Optimistically, the model predicts that the offending party (in these cases, the corrupt government or abusive employer) is inevitably driven to extinction if their actions are discovered.[6]

Latham (1997), Moretti (2000), Neocleous (2003), Godfrey, Jack and Jones (2004), and Parker (2005) point out the use of vampire imagery by Marx when describing the relationship between capital and labour:

> "Capital is dead labour, that, vampire-like, only lives by sucking living labour, and lives the more, the more labour it sucks."
>
> (Marx, 1867: quoted in Godfrey, Jack & Jones (2004))

In order to be productive, capital must draw upon the efforts of labour. Further, capital must use up some of the value created by workers in order to survive (i.e. to avoid erosion from depreciation). Godfrey, Jack and Jones (2004) note that in Marx's perspective, it is capital's nature to extend the working day while labour seeks to restrict it (like all vampires, capital does it's evilest work at night). From this point of view, the agent-base model above is an abstract conceptualisation of production. As capital grows, value is extracted from labour and workers suffer from over-exertion. If capital taxes labour

[6] This perhaps explains the end of feudalism in the 15th century, rise of liberalism in the 18th century, and the advancements of trade unions in the 20th century.

excessively, it is inevitably driven out (i.e. it sews the seeds of its own destruction). Only under certain conditions (i.e. if the capital is sufficiently 'weak' or 'invisible') can labour and capital interactively co-exist.

Generally, the vampire-human dual economy created in the agent-based model above describes a situation in which people play a role in creating economic problems which they must then pay for.[7] Artificial social simulation studies like the one presented here can provide a novel perspective into these types of problems (both real and imaginary). If vampires do live among us, and the model above accurately represents how we interact with them, then our fates are intertwined: a state of affairs worth further investigation. If vampires are simply a symbol of how we interact with each other, there is still much to learn from them.

[7] Problems of this type may include generating pollution or the rise of criminal activities, both of which result in the spending of resources to manage. Such activities occur at the individual level and are difficult to control from the top.

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Tables and Figures

Table 1 – Model parameters

	Experiment					
Parameters	A	B	C1	C2	D1	D2
π	0%	1%	1%	1%	1%	1%
ρ	NA	0	5%	5%	0	0
λ	NA	NA	1	0	NA	NA
v_v	NA	10	10	10	10	10
m_v	NA	2	2	2	2	2
σ	NA	30%	30%	30%	30%	30%
b_v	NA	5	5	5	5	10
X	NA	90	90	90	50	90

Figure 1 – Experiment A

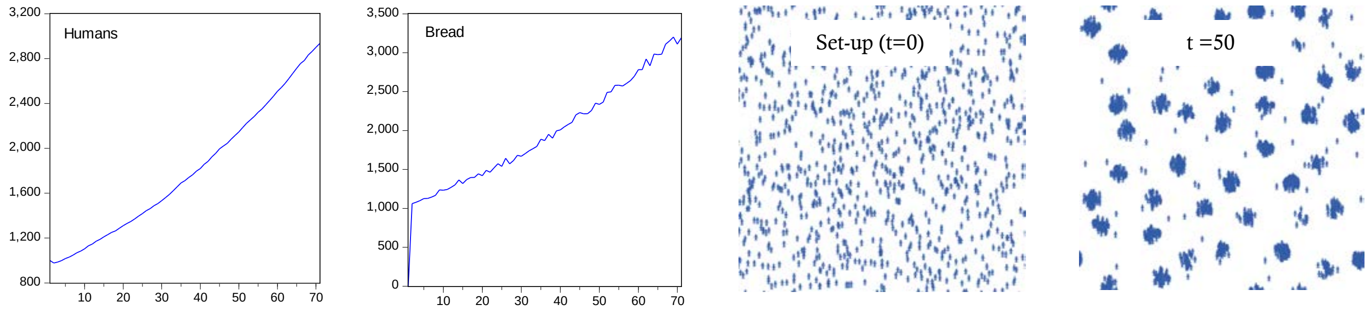

Figure 2 – Experiment B

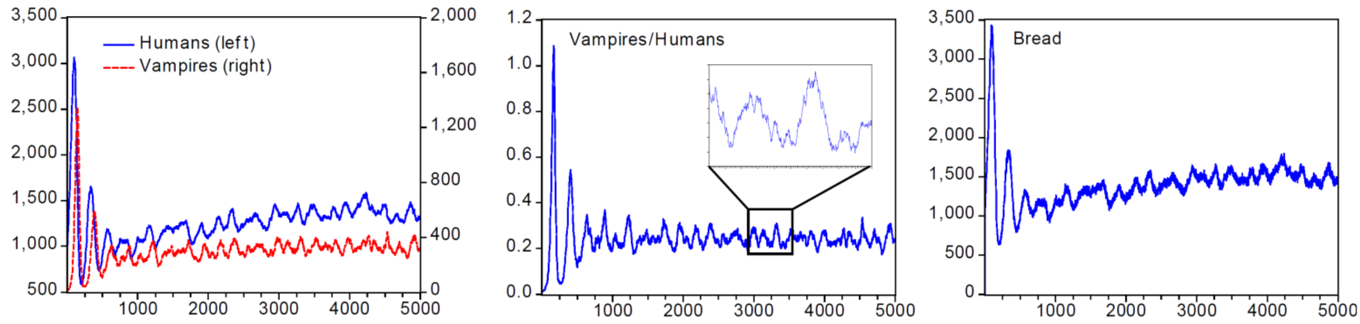

Figure 3 – Experiment B with σ = 60%

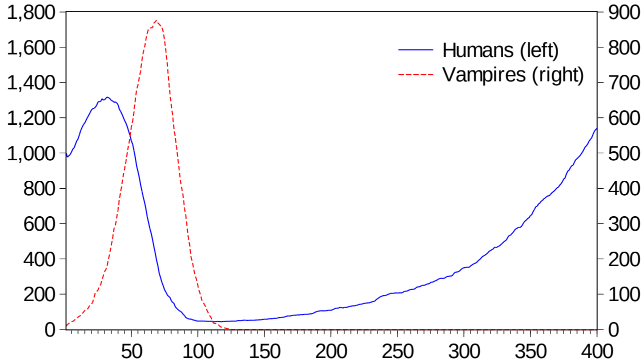

Figure 4 – Experiment C

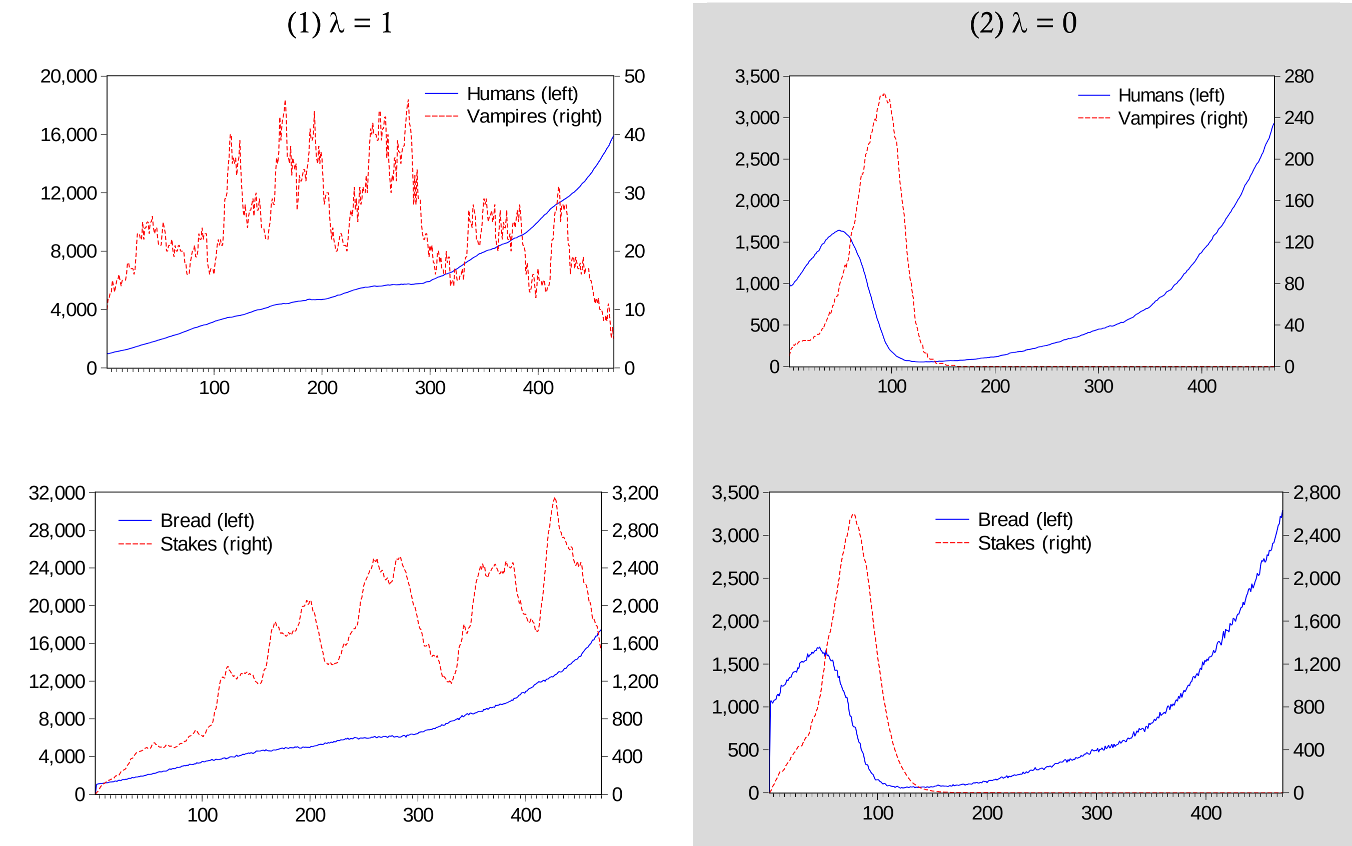

Figure 5 – Experiment D