WHEN SMALLER FAMILIES SEEM CONTAGIOUS
A SPATIAL LOOK AT THE FRENCH FERTILITY DECLINE USING AN AGENT-BASED SIMULATION MODEL♣

Sandra González-Bailón
sandra.gonzalezbailon@nuffield.ox.ac.uk
Oxford Internet Institute and Nuffield College
University of Oxford

Tommy E. Murphy
tommy.murphy@unibocconi.it
IGIER and Centro Dondena
Università Bocconi

Preliminary paper - Please do not quote

<u>This draft</u>: February 23, 2009

Latest version at: http://www.igier.unibocconi.it/murphy

Abstract

Despite some disagreements about specific timing, it is now widely accepted that France was the first European country to experience a systematic decline in fertility, a decline that took place in a very distinctive geographical pattern. Whereas two areas of low birth rates (the Seine valley and the Aquitaine region) kept spreading, two 'islands' of high fertility (Bretagne and the Massif Central) shrank until they more or less disappeared in the early 1900s. In an attempt to provide a sensible explanation of this pattern, we build an agent-based simulation model which incorporates both historical data on population characteristics and spatial information on the geography of France, and allows us to study the role of social influence in fertility decisions. We assess how different behavioural assumptions and network topologies cause variations in diffusion patterns, using quantitative data on the Ecclesiastical Oath of 1791 to proxy for the impact the Revolution had. Analysis of several simulations shows that a combination of both endogenous and exogenous factors help to explain the way in which the diffusion took place and suggests some of the mechanisms through which this was materialised.

1. INTRODUCTION

France was the first country in Europe to experience a systematic fall in birth rates in the nineteenth century, but at least two further features make the French fertility decline particularly noteworthy: how long it took and how persistent internal heterogeneity was throughout. The uneven development of fertility rates took place in a quite distinctive geographical pattern, where two clear areas of low fertility (the Seine valley and the Aquitaine region) appeared to spread their influence while two 'islands' of high fertility (Bretagne and the Massif Central) kept shrinking until they more or less disappeared in the early 1900s. Standard quantitative analyses have shed light on some of the factors driving this dynamic [e.g. Weir, 1983; Watkins, 1991; Murphy, 2008], but to better understand the mechanisms underlying this apparent diffusion we need other tools. In an attempt to advance the understanding of this salient feature of the French fertility decline, we present an agent-based simulation model which incorporates both historical data on population characteristics and spatial information on the geography of France, and assess how different behavioural assumptions on social interaction might have affected variations in the patterns followed by fertility rates.[1]

The model incorporates two components normally neglected in the literature. On the one hand, it introduces the role of social influence in fertility decisions, as hinted by recent studies [e.g. Kohler, 2001]. Whatever their desired family size is, couples do not want their actual family size to be too far from that of their neighbours, and they will look at them when deciding the number of children they will have.[2] This sets up an endogenous process of social influence that I investigate by introducing different assumptions on the strength of that influence. We also bring in the effect of the French revolution. The simultaneity of the onset of the decline with the events that took place since the summer of 1789 is quite suggestive already, but an increasing literature is now pointing towards a more regular connection between social upheavals and fertility decline [Binion, 2001; Caldwell, 2004; Bailey, 2006]. Building on these studies, we introduce the revolution in the model as a heterogeneous, exogenous shock to population dynamics. Individuals in more 'progressive' *départements* are more likely to be affected by a shock that makes them want to have fewer children,[3] and we use *département* level quantitative data

---

[1] In that sense, the paper connects with the literature that instead of focusing on *why* there was a fertility decline it is more concerned with *how* it took place [e.g. Bocquet-Appel and Jakobi, 1998]

[2] There are potentially many reasons why this might be the case. Kohler suggests, for example, that the presence of positive externalities in adopting low fertility makes that decision a coordination problem [Kohler, 2001: chapter 5].

[3] This also goes in line with the observation of Weir that the fertility decline was the consequence of the effort of an efficient group and not the gradual reduction of the whole population [Weir, 1983: 104; 1984b: 612].
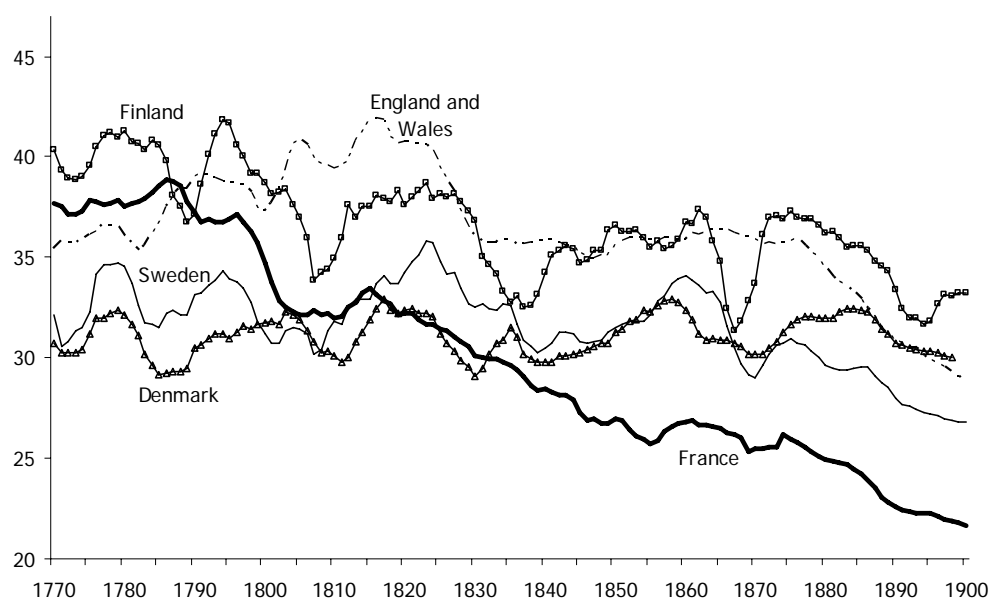
on the Ecclesiastical Oath of loyalty to the Revolution of 1791 [Tackett, 1986] to proxy for the percentage of agents switching to this new status. The assumption we make here is that the proportion of priests swearing the Oath reflects the proportion of the population adhering to more modern or secular attitudes, or to the general ideas or policies of the revolution. For the sake of simplicity, the model takes as exogenous the maximisation process carried out by individuals when deciding their fertility rates. This is not a costless stylisation, as the factors driving the decline could be important in understanding the dynamics, but the extensive literature on these factors [e.g. van de Walle, 1976; Flandrin, 1979; Weir, 1983, Murphy, 2008] allows us to hypothesise about them; the aim of the model proposed here is rather to study factors that are normally neglected in standard approaches (such as social interaction and geographical diffusion) trying to keep the assumptions as simple as possible. In that way this paper attempts the difficult task of bridging two recently developed lines of research using agent-based simulation, a quantitative technique that only lately has gained a space in the toolkit of the social scientist as computational limitations that used to impede its extensive use are now slowly becoming less relevant [Axelrod, 1997, 2005; Arthur, 2005; Hedström, 2005; Gilbert, 2008; Gilbert and Troitzsch, 2005; Tesfatsion, 2005].

As a preliminary approach to a new methodology, the aims of this paper are rather modest in terms of explanatory power. The model developed here is relatively naïf and, in its simplicity, it does not incorporate many potentially relevant components. It addresses a relatively simple question: does a model that includes some sort of social interaction and incorporates the impact of the revolution perform better at predicting the evolution of fertility rates than a model that does not? The results we obtain here suggest a positive answer. Simulations where personal choices dominate the model dynamics are able to mimic well the aggregate behaviour of the population growth, but not so well that of fertility; however, when social influence is brought in, the fall in birth rates resembles better the actual decline, especially when the impact of the revolution is allowed to spread across the population. The model also performs reasonably well at micro level, suggesting that the choice of the proxy for the 'modernisation factor' is a good one. Although the model fails to fully capture the impact on the *départements* leading the decline, simulated fertility trends –and in many cases levels—follow actual patterns in intermediate areas, and in those that lagged behind in the demographic transition. Overall, this simple model provides new insights into an old problem and serves as a benchmark to assess alternative behavioural hypotheses. Perhaps more importantly, the exercise here shows that the approach of agent-based simulation offers a promising way of relating formal economic models to empirical facts in situations where the latter are relatively limited, unfortunately too often the case in economic history.

2. Understanding the Puzzle

The decline of fertility in Europe is one of those momentous events in human history that, despite a considerable amount of research in the area, still remains poorly understood. From the early attempts of the demographic transition theory to the monumental European Fertility Project, our understanding of demographic dynamics has increased considerably,[4] yet little consensus has been reached and the renewed interest triggered by the unified growth debate [Galor and Weil, 1999, 2000] calls for a re-evaluation of what we know about the topic. Records available suggest that throughout medieval and early modern times families all over the continent were quite large.[5] If the early twentieth century encountered more often than not families consisting of just two or three children, it is because at some stage in the nineteenth century different areas began to show a more or less steep, but definitely steady decline in birth rates.

Figure 1. **Crude birth rates (births per 1000 population) for selected European countries, 1770-1900**

Sources: For France, INED [1977: 332-333]; Wrigley and Schofield [1981: 531-535] for England and Wales; for Sweden, Denmark, and Finland, Gille [1949: 63] and Chesnais [1992: 518-541]. Values are 5-year averages, centred in the year.

---

[4] Much has been written on the demographic transition and the fertility decline, and there is no lack of pieces trying to make sense of that voluminous literature. Some outstanding examples include the work of Kirk [1996] on demographic transition theory, and that of Saito [1996] on historical demography, which effortlessly discusses the achievements of the French school started by Louis Henry, to the contributions of the Cambridge Population Group, and the monumental Princeton Project [Coale and Watkins, 1996].

[5] Total fertility rates generated from age-specific rates tables [Flinn, 1981] suggest a woman married before her twenties would have seven to nine children during her life. The presence of the European marriage pattern [Hajnal, 1965] brought down that number for the average family, but households of four children or more were most likely the norm rather than the exception.

Crude birth rates in Figure 1 illustrate some of the different national experiences. Before 1800 there was some diversity across regions, but the levels did not show any clear trend. By the second half of the nineteenth century, however, declining trends are already in motion. This macro perspective already provides a reason why France, leading the decline at a slower pace by almost half a century, is one of the most interesting cases. A closer look at what was happening within the country only makes this case even more puzzling. Systematic historical information on fertility rates covering different geographical areas for the whole country is available at *département* level.[6] The best estimates we have so far during the nineteenth century correspond to the Princeton indexes as calculated by van de Walle [1974] for the I_g index of marital fertility (beginning in 1831),[7] and by Bonneuil [1997] for the I_f index of overall fertility (beginning in 1806).[8] These estimates are available every five years and we have plotted some selected dates corresponding to the nineteenth century for each index in Figures 2 and 3. The story conveyed there is quite telling. Although addressing two different populations of reference,[9] both series of graphs indicate more or less the same pattern. Looking at the index of marital fertility is of particular interest because, by focusing on the group at higher risk of procreating, it reflects more clearly how intensively control might have manifested.

---

[6] *Départements'* total number and actual shape fluctuated with the gain or losses of nineteenth century wars but, except perhaps for the Paris area, their general pattern today differs little from that of 1790, when they were created. During the nineteenth century their total number fluctuated between 86 and 90.

[7] These values also appeared in the main publication of the European Fertility Project, Coale and Watkins [1986], from where we obtained them.
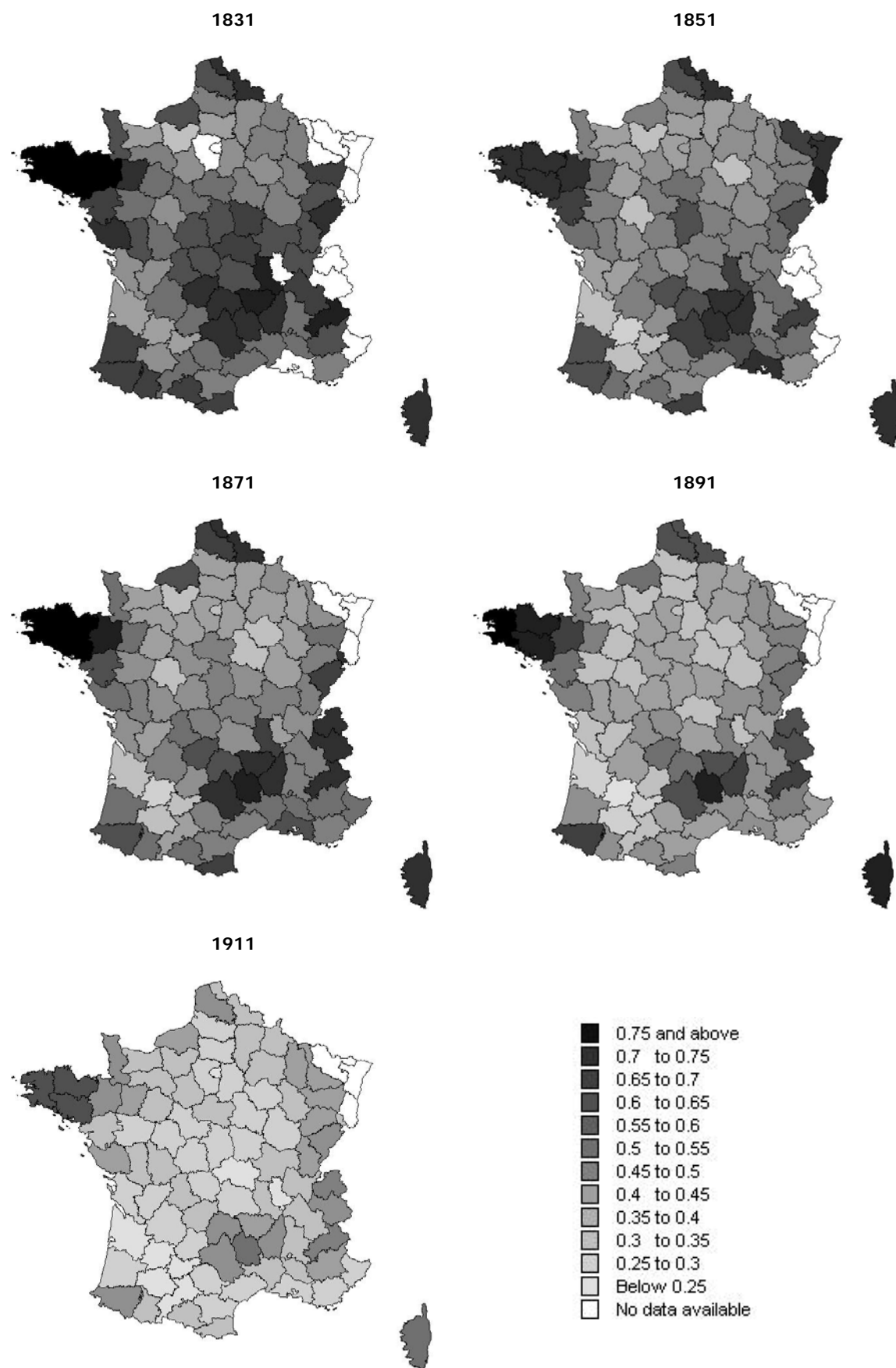
[8] These indexes of marital fertility were developed in the context of the European Fertility Project [Coale and Watkins, 1986] and the unit of reference chosen was the biologically maximum fertility attainable. They are defined as:

$$I_g = \frac{B_t^m}{\sum\limits_{a=15-19}^{45-49} N_{a,t} m_{a,t} h_a} \qquad I_f = \frac{B_t}{\sum\limits_{a=15-19}^{45-49} N_{a,t} h_a}$$

Where the numerator is number of births in year t (only legitimate ones with the superscript m), $N_{a,t}$ is the number of women of age a in year t, $m_{a,t}$ is the proportion of women of age a actually married in year t and h_a is the rate of childbearing of married Hutterites at age a. Considering that Hutterite fertility establishes a proxy for the ceiling of what is biologically possible (they are an Anabaptist sect that adheres scrupulously to precepts forbidding the practice of contraception or abortion, and their mothers do not nurse their infants more than a few months, so they have the highest fertility rates recorded to date), *Ig* represents *the proportion of births with respect to the maximum biologically attainable given the age structure of married women*.

[9] Numerator is perhaps very similar, as one is the number of legitimates births and the other the total number of births (which differed by 2% to 5%), but denominators might have differed greatly as one considers the potential fertility of married women, and the other the potential fertility of all women of child-bearing age.

Figure 2. **Marital fertility index (Ig) in France for each *département*, 1831-1911**

1831

1851

1871

1891

1911

■	0.75 and above
■	0.7 to 0.75
■	0.65 to 0.7
■	0.6 to 0.65
▨	0.55 to 0.6
▨	0.5 to 0.55
▨	0.45 to 0.5
▨	0.4 to 0.45
░	0.35 to 0.4
░	0.3 to 0.35
░	0.25 to 0.3
░	Below 0.25
□	No data available

<u>Sources</u>: Maps are ours, constructed using data from Coale and Watkins [1986: 94-107].

Figure 3. **Overall fertility index (If) in France for each** *département*, **1811-1891**

1811 **1831**

1851 **1871**

1891

■	0.70 and above
■	0.65 to 0.70
■	0.55 to 0.60
■	0.50 to 0.55
▨	0.45 to 0.50
▨	0.40 to 0.45
▨	0.35 to 0.40
▨	0.30 to 0.35
▨	0.25 to 0.30
▨	0.2 to 0.25
□	Below 0.20
□	No data available

Sources: Maps are ours, constructed using data from Bonneuil [1986: 197-205].

All throughout the period it is easy to see –quite distinctively– at least two zones of low fertility, in the valley of the Seine (the Bassin Parisien) and the region of Aquitaine (the Bassin Aquitaine, in the south-west), increasingly spreading while the two 'islands' of high fertility, the region of Bretagne in the north-west and the Massif Central in the centre-south-east, keep shrinking. As early as 1831, for example, one can find *départements* with indexes below 0.40 (evidencing clear fertility limitation), such as Gironde, Lot-et-Garonne or Eure, whereas as late as 1911 places like Finistère or Côtes-du-Nord were resisting change and still had indexes above 0.70 (showing little or no limitation at all). The index of overall fertility is relatively small everywhere because it takes as a reference the whole female population of child-bearing age and not only those married. Here it is interesting to note that Bretagne performs quite high with both indexes, indicating that married couples had large families and women were married at a quite young age. This does not seem to be the case with the Massif Central where high marital fertility seems to be sustained by a smaller number of married women, though north of that area a few *départements* also have a relatively high number of women married at a young age.

The maps suggest a (slow) process of diffusion from the Parisian and Aquitaine basins towards these 'islands' of high fertility, making France stand again in contrast with other European regions where such a process was either too fast,[10] or not obvious at all. Here the comparison with England, the new industrial economy across the channel, seems inevitable (although it should be taken cautiously, as the size of the region is only half of the French one in terms of population). Regional comparable data is available only after 1851 but, then again, England arrived quite late in the fertility transition. Figure 4 below shows a clear contrast with the French case. Throughout the five decades displayed it is quite difficult to say whether a particular region behaved as a leader and another as a follower. Changes in fertility seem to be pretty homogeneous across the country and at best it is pretty hard to say at any time that there is a clear heterogeneity among counties.[11] If there was a process of diffusion taking place in England, it was indeed much faster.
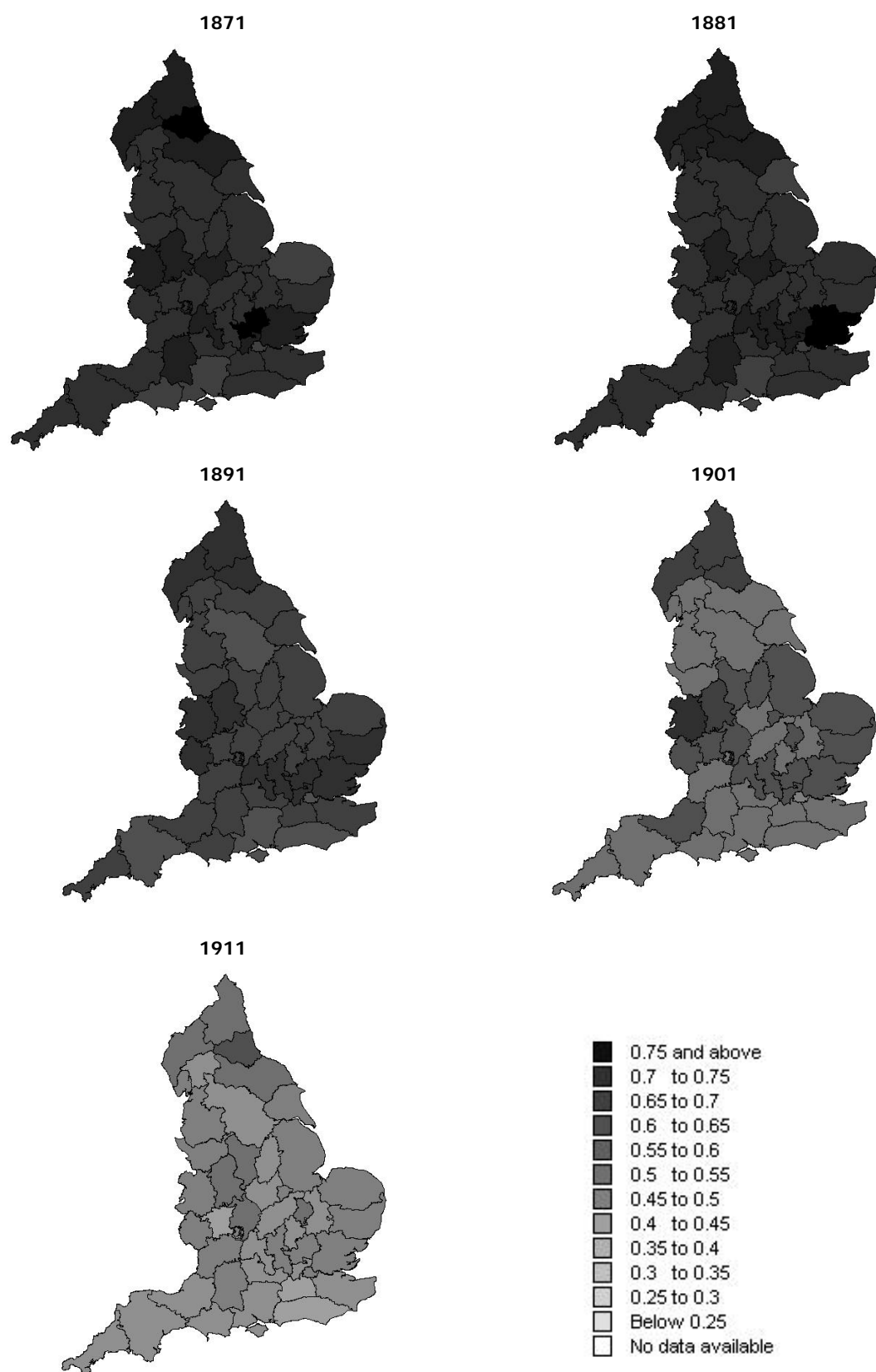
---

[10] As suggested in the case of England by Bocquet-Appel and Jakobi [1998].

[11] If English counties were larger (as a percentage of England) than the French *département* they might be hiding some heterogeneity and look more homogeneous. Nevertheless, they are not. In the early 1870s, if we take out London (as it is a clear outlier), both France and England had two large administrative areas (Seine and Nord, and Lancashire and West Riding in Yorkshire) and the rest were distributed in a pretty similar way. If anything, French *départements* were larger in size (an average of 387 thousand individuals -s.d. 150.3-, versus 304 in England -s.d. 173.7-), so they might be hiding *more* heterogeneity [English data comes from Mitchell, 1988: 30-31].

Figure 4. Marital fertility index (Ig) in England for each county, 1871-1911

1871

1881

1891

1901

1911

■	0.75 and above
■	0.7 to 0.75
■	0.65 to 0.7
■	0.6 to 0.65
■	0.55 to 0.6
■	0.5 to 0.55
■	0.45 to 0.5
■	0.4 to 0.45
■	0.35 to 0.4
■	0.3 to 0.35
■	0.25 to 0.3
■	Below 0.25
□	No data available

<u>Sources</u>: Maps are ours, constructed using data from Coale and Watkins [1986: 88-93].

3. SOCIAL INTERACTION AND DIFFUSION

Both the presence of clustering and the spatial evolution of rates described so far points towards diffusion as an appealing way of describing what happened in France,[12] but it is certainly not the only plausible way to understand the evidence. One of the problems is that data limitation does not allow assessing whether what we see is the beginning of the story or a situation where things were already in motion. By 1831 there is some degree of heterogeneity within France, but we can only speculate on whether that heterogeneity was (at least partly) already present there in the eighteenth century or not. Henry and Houdaille indeed found in their analysis of the INED sample that there were some regional differences, though age of marriage still largely appeared to explain fertility levels [Henry, 1972, 1978; Henry and Houdaille, 1973; Houdaille, 1976]. One of the arguments that could be built is that what goes on during the nineteenth century results from a process of (downward) homogenisation motivated by a change affecting the whole of the country as, for example, the introduction of the Napoleonic Code as originally suggested by Le Play [1874]. But, under the hypothesis of homogenisation to a lower fertility level, we should see a declining mean fertility and a declining variance among *départements*, while under the hypothesis of diffusion, mean levels should also decline, but population heterogeneity must *first increase and then decrease*. In Figure 5 we plot a time series of the mean and the coefficient of variation across *départements* for the time since we have some data available.

The mean level of fertility is indeed falling as expected, until it stabilises around 0.32, a value that is maintained at least until the mid-twentieth century. The other line, which plots the values for the coefficient of variation for all *départements*, describes the evolution of heterogeneity. It clearly depicts an upward trend throughout the nineteenth century, sharply falling around the turn of the century, and falling further, reaching values of 0.13 for 1961.[13] Heterogeneity across *départements* in marital fertility was not the greatest in the early nineteenth century, but towards the end of the century. It is certainly possible that differences in fertility levels existed beforehand and that these differences were rooted in socio-economic differences across the regions,
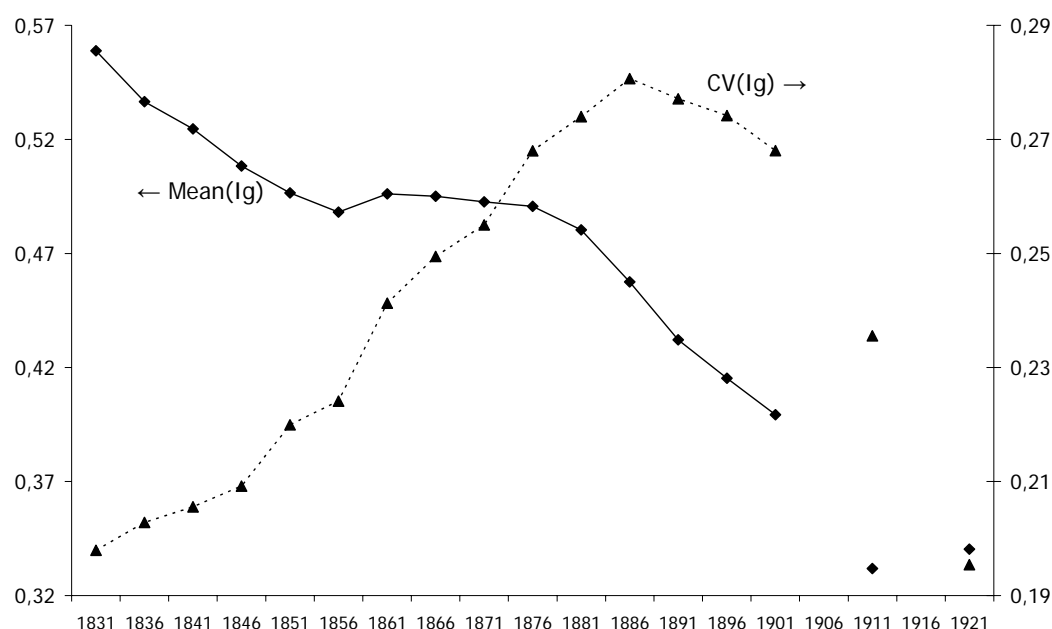
---

[12] Systematic clustering is an indication that a feature of some areas is contaminated to other areas as a contagious virus. If contraception does *not* behave like a virus, we should expect to see *départements* randomly distributed in terms of fertility level [Bocquet-Appel and Jakobi, 1998: 190].

[13] When doing the same exercise for England one can be even more conclusive about the presence of diffusion, though it does seem to take place not only later, but at a faster rate. The level of the coefficient of variation remains constant until 1881, the 'bell' of diffusion takes barely more than half a century (versus a whole century for France) and the whole process does not drive the coefficient of variation above 0.15, when in France it is always above 0.19. More sophisticated analyses suggest similar conclusions, as in Bocquet-Appel and Jakobi [1998].

but the discussion in this section suggests that even if that is the case something was diffusing throughout the nineteenth century that was somehow correlated with fertility.

Figure 5. **Mean and coefficient of variation of marital fertility (Ig) within departments, 1831-1921**

Sources: Our calculations, using data in Coale and Watkins [1986: 94-107]. Arrows indicate axis of reference.

Economists look at diffusion stories of the fertility decline with scepticism [e.g. Brown and Guinnane, 2007], as diffusion appears to be somewhat at odds with the adaptation hypothesis, which is grounded on the idea that people are rational,[14] but this does not need to be the case. One of the simplest ways to interpret the presence of diffusion of family limitation is associated with the appearance of a new contraceptive technique. There are at least a couple of reasons to think this is not a crucial reason behind the French case. The first is that there is no clear evidence that a new contraceptive technique was instrumental in driving fertility down. Most family planning techniques used during the nineteenth century (basically *coitus interruptus* and abortion) were extensively known before then [McLaren, 1978, 1990; Van de Walle and Muhsam, 1995]. The second reason is that such diffusion (i.e. that of knowledge) is expected to be relatively fast, and that was not the case in France.

Knowledge about contraception is, however, not the only thing that could diffuse, and the literature well recognises this point [Pollak and Watkins, 1993: 471-472]. One of the things that

---

[14] This is particularly true if we understand diffusion in a horizontal rather than a vertical sense. A particular trait could diffuse in many different ways, at least vertically (from one social strata to another), horizontally (from one place to the other), or both [Bocquet-Appel and Jakobi, 1998: 181-182].

could be diffusing is the *notion* of fertility control, or numeracy about children [van de Walle, 1992]. It might well be that in societies where traditionally control was lacking (for example, because for generations having as many children as possible was a reasonable strategy anyway), the idea that the number of children is something over which one could exercise some control is not obvious and this could take some time to be assimilated. The other is *preference for a different family size*. In some situations fertility control might begin to make sense economically for a particular community, but some degree of uncertainty on how that strategy would impact on individual couples could make them reluctant to pursue it (waiting for others to pursue it first). In either case, as people tend to be conservative and avoid change [Edwards, 1968], some sort of diffusion would manifest and, in these cases, it might spread more slowly than technology.

A corollary of this is that, even without the appearance of a new contraceptive technique, we may still find some kind of diffusion. The results of the European Fertility Project go roughly in this direction, as they suggest that things like linguistic differences explain a substantial part of the fertility variation [Knodel and van de Walle, 1979: 239]. This does not deny the possibility that economic factors might indeed play a role in the decline of fertility, as there might be a change in preferences triggered by economic factors that takes time to spread. But, especially in the early stages of the fertility decline, the interplay between economic and cultural factors was probably not trivial. Most decisions about family behaviour are heavily embedded in tradition and more often than not reflect some degree of path-dependency. The relevance of diffusion effects in understanding the dynamics of fertility decline is now gaining some support in the literature [Mason, 1997] and several recent papers have began to explore this line of research [Rosero-Bixby and Casterline, 1993; Montgomery and Casterline, 1993, 1996; Montgomery *et al.*, 2001]. Most notably Kohler [2001] provides a full formal model rooted in micro-foundations where social interaction affects rational, utility maximising couples that face the possibility of adopting low fertility. Social interactions give "rise to multiple equilibria that imply a Malthusian 'high-fertility trap', and a population can be stuck in an inefficient situation with high fertility although a sustainable fertility decline with higher individual welfare is possible" [Kohler, 2001: 185]. The source of these multiple equilibria are to be found partly in the presence of a coordination problem: the benefits of choosing low or high fertility are dependent on the unknown fertility choices of others, hence expectations are a relevant component of the equilibrium selection. If these expectations show any degree of hysteresis (e.g. if they are adaptative), deviations could come from either a radical change in conditions that individuals could easily identify with a change in expectations (as maybe was the case with the Industrial Revolution), or from a shock that directly affected these expectations (for example, if a local social leader is actively promoting some sort of fertility control).

In what follows we propose a simulation model that, though not within the overlapping genera-tion framework proposed by Kohler, it maintains in spirit the main characteristics of his argu-ment. There, agents look at their environment and consider the choices of other agents at the moment of making their own fertility choices. The role of an event like the French revolution is to change the expectations of agents, which then finally consider the possibility of aiming for a low fertility level.

4. THE SIMULATION MODEL

Agent-based simulation offers a new approach to the problem of social influence because it opens an experimental space to analyse the relationship between individual behaviour and the emerging collective patterns. Simulation experiments allow a systematic analysis of how col-lective regularities change when the rules guiding individuals' behaviour are modified [Gilbert, 2008]. In doing so, agent-based models contribute to open the 'black box' in many econometric models, which do not deal with the generative mechanisms that underlie the patterns they de-tect: statistical relationships hint at possible explanations, but they do not provide the explana-tion themselves [Hedström, 2005: 23]. This is the gap that agent-based models contribute to fill in by using the interactions between agents as the basic building block of its dynamics and pro-ducing outcomes at the collective level that can be contrasted, and validated, with the empirical trends. As with any other modelling technique, the key in using agent-based simulation is to find the right trade-off between an accurate description of the world and the necessary simplifi-cation that requires modelling it [Axelrod, 1997: 5]; but unlike econometric approaches, the logic of agent-based simulation allows a richer exploration of the complex link between the in-dividual and the social, that is, of how small changes in the interaction of individuals can gener-ate significantly different social outcomes [Hedström 2005: 75]. Because of this, this tool of analysis is especially attractive for the development of demographic models [Billari and Prskawetz, 2005].

The model here is an attempt to formalise the rules of behaviour that underlay the uneven demo-graphic transition in France, keeping in mind the recent discussion about the impact of social interaction on fertility choice. In doing so, it explicitly focuses on some aspects of the process and disregards others. The main experimental aim is to analyse the correspondence between behavioural assumptions at the level of individuals' interactions and the diffusion of fertility rates over space and time. In that sense, the model treats the evolution of family size as the de-pendent variable and the demographic and geographical constraints, calibrated empirically, as

controls; the explanatory factors are the rules that determine how agents influence each other. The model will also evaluate how these rules of social influence interact with the exceptional impact of the revolution, which is treated as an exogenous shock to the dynamics of the model. Ultimately, the model is intended as a 'middle range' simulation [Gilbert 2008: 42], as we expect to find qualitative resemblances between the dynamics of the model and the observed dynamics, and a similar distribution of outcomes. The simulation is intended to cover the historical period between 1740 and 1900, and the connection of the model with empirical data is done in at least two levels: in the initial demographic set-up, by defining how many agents of each class are in a particular place; and in part of its dynamics, by defining how likely it is for an agent to die at different stages of its life and how likely it is to die with no offspring at all.

Agents in this model are born to reproduce. From the moment they are created they have an inclination to have a certain amount of children, but they can actually have them only when they reach a mature age, and they do so at a rate of one child per period. For the sake of simplicity we have abstained from gender distinctions and marriage dynamics (agents can be interpreted as the female part of the population), but allowed them to live for fifteen periods. To facilitate comparison with demographic data, agents are classified into different groups of 'age': newborns, young1 to young3, mature1 to mature5, and old1 to old6.[15] Agents have two attributes associated to their age: the probability of death, a rate that is determined empirically; and fertility, which results from rules endogenous to the model. Only agents classified as mature are able to create new agents and therefore reproduce the population. The particular characteristic that we give the agents is that they do not only consider their own inclination to have children, but also the desired offspring of their neighbours. In other words, the number of offspring agents will create is a function of the number of offspring *they* and *their neighbours* want to have. In order to decide the number of offspring they want to have, mature agents are endowed with the following decision rule:

$$y_{i,t}^m = \alpha z_i + \beta \frac{1}{n_p} \sum_{j=1}^{n_p} y_{j,t-1}^m + (1-\alpha-\beta)\frac{1}{n_v} \sum_{j=1}^{n_v} y_{j,t-1}^m$$
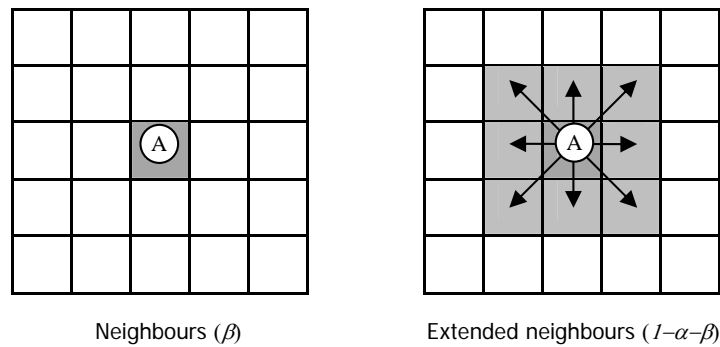
When the agent becomes mature at time *t*, she establishes her desired number of offspring ($y_{i,t}^m$) by considering not only her own inclination to have children (z_i), but also the average desired offspring ($y_{j,t-1}^m$) of all those agents that were mature in the previous year and are relatively close

---

to her. Own inclination is determined by a normal distribution with mean μ and standard deviation σ, parameters that are inherited from her mother.[16] We distinguish two levels of impact of the environment, that generated by n_p neighbours and that by n_v extended neighbours. Figure 6 illustrates this.

Figure 6. **Agent's neighbours in the grid**

Neighbours (β)   Extended neighbours ($1-\alpha-\beta$)

The landscape agents populate is modelled as a grid. Various agents can cohabit in the same cell and it is the influence of these agents that the parameters α and β capture: they determine the relative weights of the desired offspring of an agent and that of its neighbours, respectively, and they provide the basic experimental space of the model. Basically, the larger the value of α, the more weight agents will give to their own preferences, and the less vulnerable they will be to social influence. On the other hand, the larger the value of β, the more relevant the neighbours' inclination will be to determine an agent's decision. Finally, the lower α becomes with respect to the same β, the more relevant the extended neighbourhood will be in influencing an agent. In a nutshell, these parameters regulate the scope of social influence and it is by tuning their values that the simulation tests to what extent social influence affects the collective outcomes.
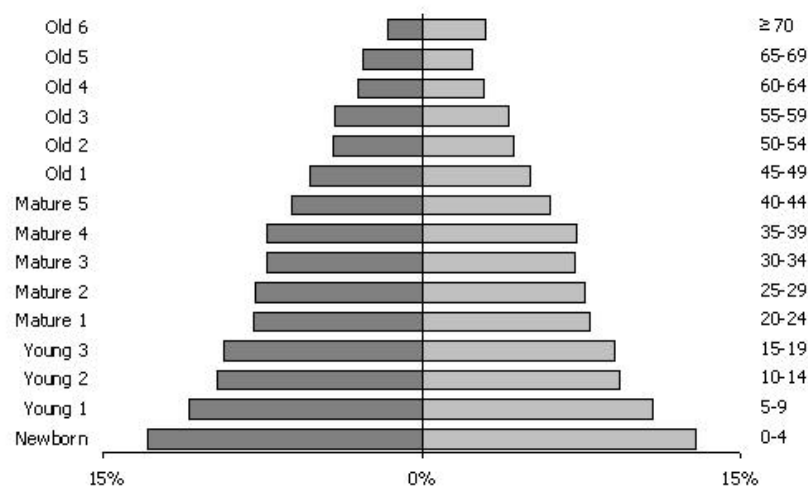
To make the model resemble reality we incorporated some of the things we know about the geography and demographic history of France in the set-up of the environment where the agents interact. The space that agents occupy is a grid that reproduces the map of France.[17] The simulation starts with roughly 100,000 agents which are placed on the grid following some empirical guidelines. Due to the lack of estimates about the amount of people in the different age groups

---

[16] From this formulation it is clear that we are treating fertility choice more or less as a black-box. Given the complexity of making all agents simultaneously choose the fertility level, making them assess other variables such as income, education levels, or mortality rates could increase computational costs enormously, but that is not technically impossible and future research could address this.

[17] Each cell in the grid represents roughly 100 square kilometres (i.e. roughly a 10x10 km area), and there are a total of 5308 cells.

for each *département* around 1740 (let alone for every other 100 square kilometres), we had to make some assumptions. Henry and Blayo have estimated age pyramids for early modern France and we have taken as reference the one corresponding to 1740 [Henry and Blayo, 1975: 92-93]. Figure 7 shows the correspondence between our set-up of the model and actual data. As can be seen there, the resemblance is rather good.[18] We are making the assumption, here, that this relationship among ages remains more or less constant throughout France, which is probably not the case, but this is not a major drawback for the purposes of the model.

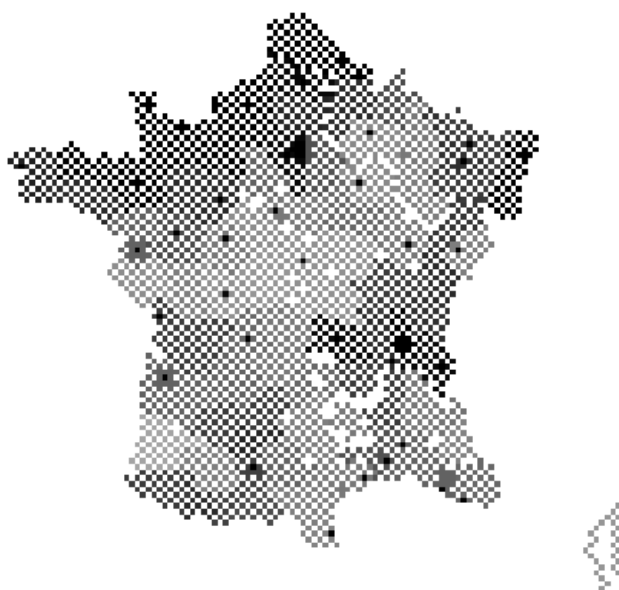<u>Figure 7.</u> **Comparison between empirical age structure and that of the simulation**

<u>Notes:</u> The axis in the bottom indicates the proportion of each age-group with respect to the total population. Actual data for 1740 France comes from Henry and Blayo [1975: 92-93].

Population densities provide a second anchoring point between the set-up of the model and actual data. The earliest year for which we have some information about population density is 1801 [Service de la Statistique Général de France, 1878], and agents are distributed in the grid according to these data. Basically, we considered the population of each *département* and that in their major cities and produced a rough estimate of the proportion of the total population living in a particular geographical area. We applied this proportion to the initial 100,000 agents to figure out how many agents to put in any square of the grid, and we did so following more or less the age structure described before. The map in figure 8 shows how this was done.

---

[18] If anything, only for the oldest population are there some substantial differences because, for simplicity, in the simulations we allow agents to live only until they are 75. Since most of the relevant action is taking place for younger ages, this should not be a substantial problem.

Figure 8. Population density in the artificial society

<u>Notes</u>:   Population density as simulated in the model; darker patches are more populated.

According to this initial set-up, not all agents will eventually have children. After Hajnal's seminal contribution [Hajnal, 1965] it is a more or less agreed that Europe was characterised by a particular marriage pattern, where women married late and some did not marry at all. We follow here the estimates of Weir [1994] for the proportion of women married by age-group. As expected, these proportions do not remain completely constant over the whole period under study here, but they are more or less stable until the beginning of the second part of the nineteenth century. The values we picked are the average proportion of unmarried women for the 1740-1850 period: 72%, 43%, 28%, 23%, and 22% for each age group corresponding to mature1 to mature5. Another thing that is relevant when modelling this type of demographic process is to take into account the role of decreasing fecundity with age, or lack of fecundity. Although male sterility is not uncommon, it is normally female sterility that is more binding and this is present in at least three forms. From the time they are born, women are sterile until they reach menarche around the mid-teens. For simplicity, in the model we assumed that only from the mature state are agents going to have children, so we are implicitly considering that all agents are sterile (or unmarried) until then. Then, we could distinguish primary sterility, which is for women that can never be fecund, and secondary sterility, which kicks off at some stage after being fertile for a period [Boongarts, 1975: 293]. There are different biological factors affecting both types of sterility, so estimates could vary between populations considerably, and it is often difficult to disentangle from historical data sterility from actual contraception, especially for younger ages. Hence, we take the conservative approach of assuming no primary sterility at all, and secondary sterility affecting only the last two groups of matures. For this, we take as reference Henry's estimates for a series of European populations in the modern period

[Henry, 1961: 85] as upper-bounds and impede procreation of 15% of mature4 and 30% of mature5 (that might be married or not). With these data we obtain a series of expected proportions of agents in the risk of having children. Following this rule, mature agents can generate new agents until they reach the number determined by the behavioural equation or until they enter the old category.

The simulation runs for a total of 36 periods, each representing five years, starting from 1720 and stopping in 1900. Every time step, agents move upwards in the age scale. Once an agent is born, it will live for up to 15 periods, although random agents in all categories can disappear at any time in proportion to the mortality rate attached to their age.[19] The simulation keeps track of the number of agents in each age group; it also records the number of offspring that agents want to have and calculates the average for each cell in the map. This creates a census of the simulated population as it evolves over time. The simulation applies then the mortality rates in accordance to the age of the agents and the *département* in which they are located; it next shifts the remaining agents one level up (let them grow up): agents with age > 70 all die and are replaced by the agents in the previous age group; and the agents entering the mature category are given a desired number of offspring as determined by the behavioural equation. New agents classified as newborns are finally created in the last procedure: if a mature agent has not yet reached the maximum number of offspring she wants to have, is married and not sterile, she will create a new agent. This loop is repeated 36 times, at which point the simulation stops.

5. THE IMPACT OF THE REVOLUTION

The only exogenous impact we allow in the simulation from the moment it starts is the shock of the revolution, which activates when the internal calendar of the model reaches 1790. There are many reasons to think the events of 1789 might have been connected with the fertility decline. A recent body of literature suggests (more as an empirical regularity than in terms of a theory) that social upheavals have a profound effect on the evolution of birth rates [Binion, 2001; Caldwell, 2004; Bailey, 2006]. Caldwell highlights, for example, the negative consequences these crises have on both the expectations of individuals and their material resources, which in turn affect short- and long-term fertility choice. Binion, on a more optimistic view similar to that of Bailey, points out how the democratic nature of the French and American revolutions changed the relationship between the individual and the society, and ultimately her attitude towards an

---

[19] Mortality rates were estimated by Bonnieul [1997] for all age ranges every five years throughout the nineteenth century. For pre-1800 simulations we assumed the earliest rates available. Post-1800 we adjusted every ten years infants' mortality, as this is the one that is most affected during the period, and kept constant the rest at early nineteenth century levels.

active control of her own future (including the size of her family). In a similar vein, some arguments build on the effect on conjugal relationships, related to the improvement in the rights of women.[20]

Another aspect usually brought up is that of religion. There is extensive evidence suggesting a connection between religion and fertility behaviour.[21] The secular nature of the Revolution, and the break it instigated between society and the church, might partly explain the decline. The fact that France remains Catholic to this day could suggest that the impact of the Revolution was probably not felt in religion. But the shock seems to have been more subtle, as in the nineteenth century "the liturgical aspects of Catholicism […] were in popular demand; the attempt to impose on the mass of the people a rigorous code of thought and behaviour was not […] It was of course especially unacceptable where sexual matters were concerned" [Gibson, 1989: 244]. Up to the early nineteenth century Catholicism, a religion with a particular code with respect to family behaviour, remained as the main norm-setter in France and had a strong attitude against contraception, condemning heavily the 'sin of Onan,' the main technique couples had to control fertility at the time [Flandrin, 1979: 194-196; Gibson, 1989: 185-186]. But already during the eighteenth century there were signs of de-Christianisation. Attendance at mass became less frequent, the number of people joining the clergy diminished, and the proportion of religious books owned by those rich enough to buy them fell considerably [Gibson, 1989: 3]. 'Anomalies' in sexual behaviour also became increasingly common, and evidence suggests it was not only contraception becoming more common, but also illegitimacy and bridal pregnancy. Although the early nineteenth century saw a religious revival, the anticlericalism and de-Christianisation of the Revolution had shaken the church to its very foundations; this might have created the link between revolution, religion and fertility. "The hiatus in clerical control consequent upon the Revolution seems to have enabled at least some French men and women to break free from old constraints." [Gibson, 1989: 244-245].

The secularisation triggered (or simply manifested) by the Revolution could be interpreted in many ways. Some of the potential impacts of religion over fertility are obvious. Religion, after all, conveyed much of the normative framework and was a key component of the social capital of French society. The recent work mentioned earlier on the role of social networks in fertility choice has raised the point that fertility could well be a coordination problem [Kohler, 2001:

---

[20] Doepke and Tertilt [2008], for example, suggest that increased women's rights (which might well be one of the outcomes of the Revolution) could have motivated a search for quality of children, not only due to increases in the opportunity costs of the mother, but also on that of the daughters. See also Flandrin [1979].

[21] See Derosas and van Poppel [2006] for an extensive overview of recent research on this.
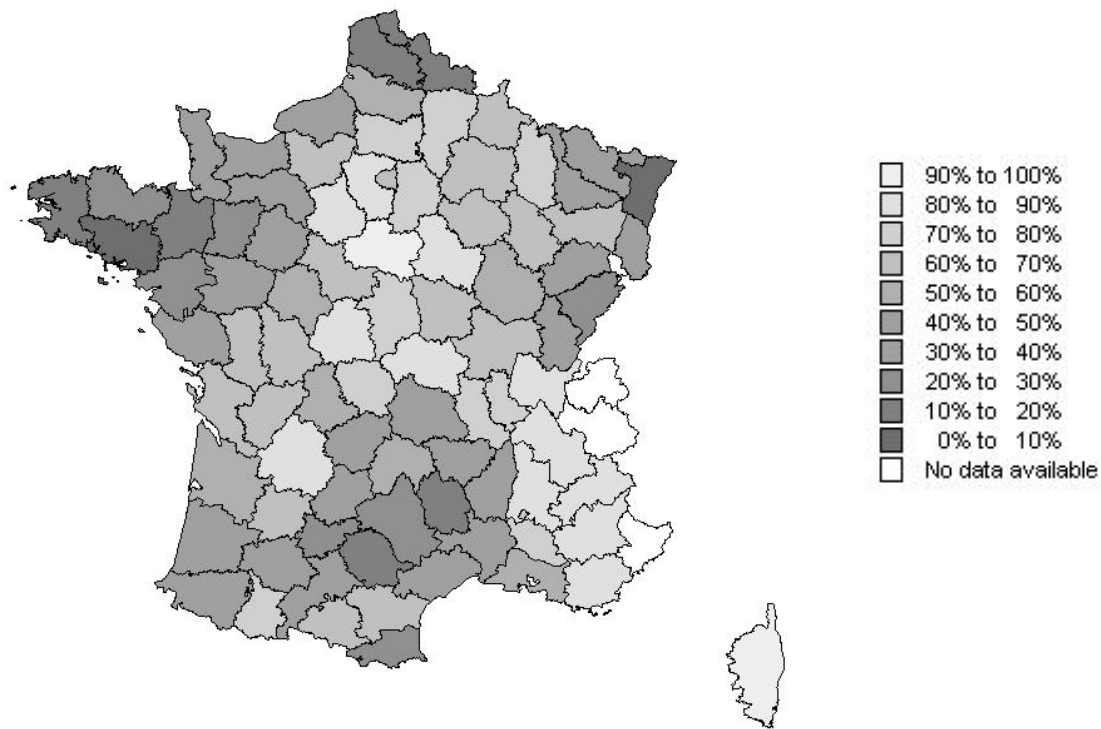
143-144]. If that was the case, *both* history and expectations play a role in determining fertility levels; a major social upheaval could break their long-term equilibrium, making room for a change. Causality, nevertheless, could go in the other direction. We can see families wanting to have less children and being impeded by the Church. The effect of the Revolution in this respect is to reduce the costs of not following some of the mandates of the church. An alternative reading of our model is that there are some external reasons driving fertility down and that the Revolution provides the trigger to make preferences and behaviour coincide. And yet, arguments not primarily religious are still consistent with the decreasing influence of the Church. Weakly religious areas could have been more sensitive to the institutional changes brought by the Revolution and *these* changes could have had an impact on fertility. A clear example of this is the laws on inheritance that were affected by the new government. Although supposedly affecting the whole nation simultaneously, it has been suggested these laws were unequally applied according to custom [Brandt, 1901], and in this the influence of the Church (by promoting or opposing its implementation) could have been instrumental. A similar point was made by Weir [1984b: 613-614] related to the change in land property rights.

The discussion above suggests that we need some kind of measure of the impact of the Revolution on the population or the level of intensity Catholic faith had in different areas. Such a map is probably impossible to build, but there are reasons to believe this geographical division did not change that much until the detailed *carte Boulard* of 1947.[22] It is not really clear when these regional differences were first established, but we claim that at least by the time of the Revolution they were already somewhat present. The variable we consider here resembles the *carte Boulard* but it has a direct association with the Revolution. In 1791 the National Assembly required priests to swear an oath of loyalty to the Revolution, ultimately implying that they were servants of the public. The proportion of priests voting allegiance to the Revolution varied substantially throughout the country and it is this variance that we use in the analyses. The map in Figure 9 shows this.

---

[22] The *carte Boulard* is a detailed description of the areas of stronger influence of the Catholic Church made by Canon Boulard for the year 1947. This map appears in the classic work of Gabriel Le Bras [1955: 324]. It is indeed impressive how in the middle of the twentieth century the same areas that remained attached to a strong Catholic faith were the same identified with strong religiosity by other measures, such as students' participation in religious schools for the second part of the nineteenth century (see next chapter). Gibson points out that scattered indices of vocation to priesthood, publication of religious books and attendance to mass suggest a pattern rather similar to that of mid-twentieth century [Gibson, 1989: 170-177].

Figure 9. Proportion of priests taking the oath of loyalty to the Revolution in France, 1791

Legend:
- 90% to 100%
- 80% to 90%
- 70% to 80%
- 60% to 70%
- 50% to 60%
- 40% to 50%
- 30% to 40%
- 20% to 30%
- 10% to 20%
- 0% to 10%
- No data available

Sources: My calculations, constructed using data from Tackett [1986: 364-366].

It is not our intention here to oversimplify the interpretation of the oath. As emphasised extensively by Timothy Tackett, probably the outmost authority on the history of the oath, the reasons behind the heterogeneity of the oath are hard to figure out [Tackett, 1986: 287-300, and 2006: 545-546]. But there are indeed reasons to believe the pattern of oath-taking could be correlated with the impact of religion on society that we want to measure, so this interpretation is not entirely forced.[23] Tackett himself suggests that "almost everywhere laypeople exerted pressure on the clergy to accept or reject the oath, with the oath ceremony providing the occasion for a *de facto* referendum on the general religious and secular policies of the Revolution" [Tackett, 2006: 546].

As discussed above, the revolution can be thought of as contributing to weaken the link between religion (or, more generally, pre-existing social norms) and reproduction. I incorporate its impact as follows: we mentioned earlier that agents in the model draw their own inclination to have children from a normal distribution with mean μ; we will now assume that at the time of the Revolution a certain number of agents will draw that inclination from another distribution

---

[23] The measure has already been used as a proxy for religiousness in a recent study on trust and financial markets by Hoffman et al. [2007: 16-17]. Further, that very same study points out that other authors have already identified a connection between the Ecclesiastical oath and fertility patterns, notably Sutherland [2003: 345].

with a lower mean (μ_{rev}). This modelling strategy could be read in terms of Kohler's argument as the Revolution providing an opportunity to coordinate in a new equilibrium by altering their long-term expectations on the behaviour of other agents. Further, this assumption is in line with the work of David Weir who found out that fertility decline in post-Revolutionary rural France was the consequence of the effort of only a minority of highly-motivated and efficient members of the population and not the gradual reduction of fertility by all [Weir, 1983: 104; 1984b: 612].[24]

The number of agents in each *département* that become 'revolutionary' will be determined by the proportion of priests in that area swearing the oath of faith. In this very simple specification the French Revolution has only a one-time shock on religious practices; some lineages become 'revolutionary' and other families are not affected beyond the scope of the behavioural equation each agent follows. Later we drop this rather conservative assumption of intergenerational in-fluence and assume that the Revolution 'spreads' among agents of the same generation: under this subsequent setting, non-revolutionary agents look around and if a proportion γ of neighbours are revolutionary, they will switch to that state as well.
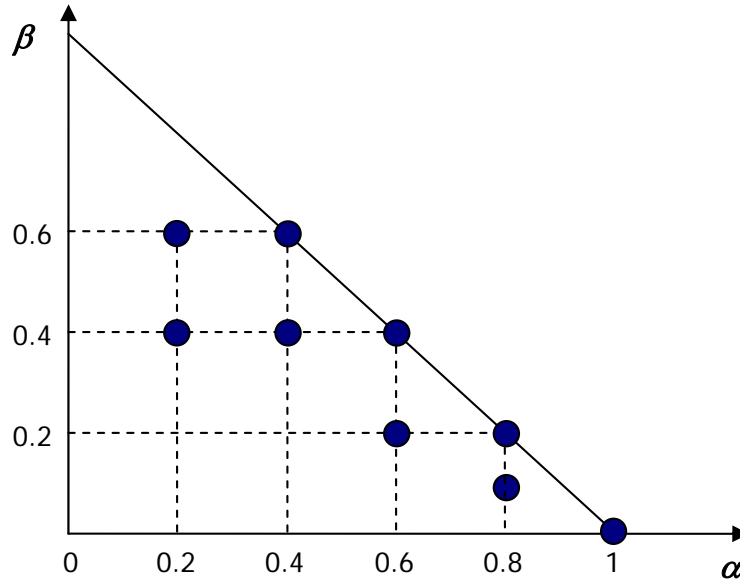
6. RE-PLAYING THE TAPE OF HISTORY: PRELIMINARY RESULTS

With all the components of the model in place we can turn now to its calibration, which we did by running several simulations and figuring out which set of parameters fit the data better. Since we wanted to assess the impact of different patterns of social interaction we produced simulations for several sets of parameters (α, β) ranging from very large social influence to no influence at all, as plotted in Figure 10.

---

[24] Among the key results of his extensive research, the fact that only a third of the women in the post-1790 cohort were controlling and the fact that many individuals appear to not have controlled their fertil-ity at all is strongly consistent with this model.

Figure 10. Different levels of social influence

For each of these pairs we let the programme generate sets of 10 simulations starting in 1740 and up 1790 for all different μs within a sensible range (from 1.0 –equivalent to 2 children per family in actual data- to 3.0 –equivalent to 6-, with increments of 0.05). We assessed how these different parametric combinations affected the evolution of population levels by plotting the average of 10 simulations against the empirical data.[25] It makes sense to begin the calibration of this model within that interval because it is more or less agreed in the literature that until this period fertility levels appear to be stable. We found that the degree of social influence has already some effect on what is the best μ to match the data. Simulations where social influence was larger required a smaller μ to sustain the same population levels. This probably has to do with the families aiming towards more stable means and having small families in fewer cases. Using a sum of squared errors with respect to actual data, it turned out that goodness of fit was maximised at $\mu = 1.6$ for $\alpha = 0.2$, $\mu = 1.85$ for $\alpha = 0.6$, and $\mu = 1.95$ for $\alpha = 1$. Changes in β did not contribute much to generate significant differences, suggesting that the inclusion or not of an extended neighbourhood (and therefore expanding the scope of agents' influence) did not greatly affect the conditions necessary to obtain the same macro-patterns.

With these results in mind, and knowing that μs in the range of 1.8-2.0 are more or less consistent with historical data if we apply marriage rates to age-specific fertility rates, we generated

---

[25] All throughout the simulations we have assumed σ to be 0.45, which is more or less the average value for empirical populations as estimated from age-specific fertility tables in Flinn [1981]. Further research could explore how different assumptions on this parameter might have affected the evolution of the system.

simulations for the whole period for two parametric spaces (μ, α, β): (1.85, 0.6, 0.4) and (1.90, 0.8, 0.2). Not surprisingly, running simulations that maintained fertility at pre-1790 levels always over-estimated population growth. We know from the earlier discussion that the trivial solution of inducing a homogeneous decline across the country would not be consistent with the evidence, which points to a spatial diffusion. The exercise suggested here is to consider possible causes driving the heterogeneous decline and, in particular, to assess how well the model performs under two assumptions: first, that a proportion of agents in each *département* aims at (a common) lower fertility, and second that this proportion is correlated with how strongly supported the Revolution was there.[26] Regarding the proportion of agent switching to this new equilibrium, and in line with the discussion in the previous section, we propose to proxy that proportion with the percentage of priests swearing the oath of loyalty to the Revolution. That is, if in a *département* we have that 25% of the priest swore the oath, then a quarter of the agents in that same *département* will now draw their personal inclination to have children (z_i) from a distribution that has a mean of μ_{rev} instead of μ.

Starting with the same two parametric spaces we then generated a series of simulations to figure out which μ_{rev} is more consistent with the data. Best fits for each (μ, α, β) set are plotted in Figure 11. Overall, the performance of the model for these aggregate values was rather good at the level of the evolution of population and, again, smaller α required smaller μ_{rev}s (a larger fall in the new equilibrium) to maintain *ceteris paribus* the same level of population. The performance in tracking fertility, on the other hand, was relatively poor.[27] For the pre-1800 period fertility was underestimated by about 21% if we consider the I_g index and by about 14% if we consider I_f instead.[28]
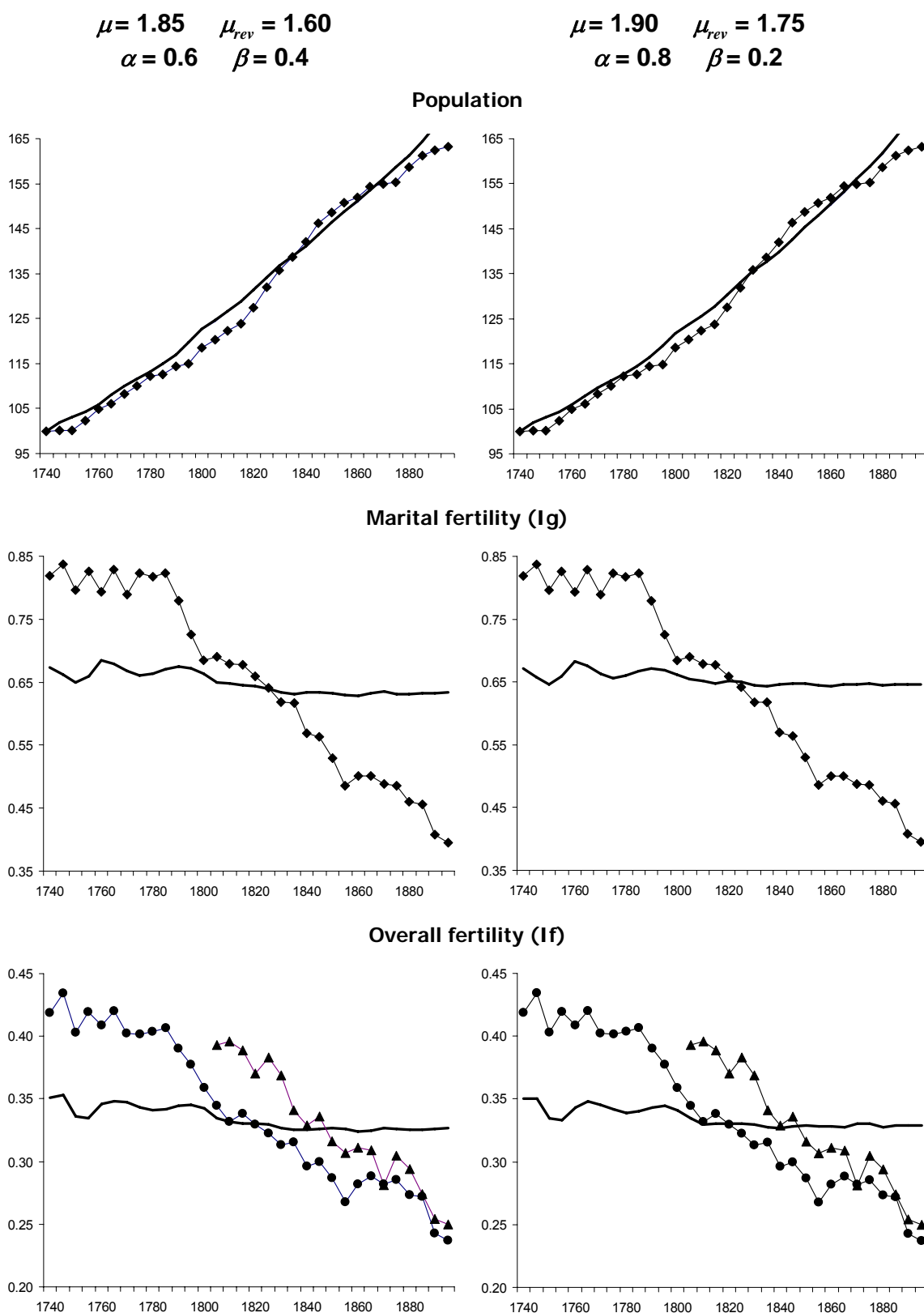
---

[26] The choice of modelling this in terms of a proportion of agents aiming at a common level (as opposed to making all agents aim at different lower levels) is not casual, and really addresses two findings of the literature. One is the observation made by Weir that the fertility decline in France was the consequence of the effort of an efficient group and not the gradual reduction of the whole population [Weir, 1983: 104; 1984b: 612]. The other is the suggestion of Kohler that fertility choice can be partly understood as a co-ordination problem that induces multiple equilibria, which implies that sometimes shocks (like a revolution) can make agents update their expectations to coordinate in a new equilibrium.

[27] Since we have built the model in such a way that we know the married population of females or each age cohort (i.e. the matures that are allowed to have children) and the amount of births, with only the fertility rates of the Hutterites [in Henry, 1961] we were able to estimate directly from the output of the computer program the values of I_g and I_f for the simulated society.

[28] It is perhaps worth noting that, nevertheless, the divergence between the results of my simulations and available estimates is not substantially different in magnitude to that found between Weir's and Bonnueil's estimates for overall fertility.

Figure 11. **Actual and simulated levels of population and fertility for France, 1740-1900**

$\mu = 1.85$ $\mu_{rev} = 1.60$ $\mu = 1.90$ $\mu_{rev} = 1.75$
$\alpha = 0.6$ $\beta = 0.4$ $\alpha = 0.8$ $\beta = 0.2$

Population

Marital fertility (Ig)

Overall fertility (If)

Notes: Dotted lines indicate actual values and smooth lines correspond to average of ten simulations. Actual and simulated populations are set equal to 100 in 1740. Actual population is from INED [1977: 332-333] and IN-SEE [1961: 36], marital and overall fertility 1740-1900 as estimated by Weir [1994: 330-331], and shorter series of overall fertility 1806-1901 (indicated with triangles) as estimated by Bonneuil [1997: 197-205].

Part of this has to do with the fact that the model is not including some potential relevant components, such as more detailed marriage patterns or a percentage of illegitimate births, and the prediction is suffering from that omission. The mismatch is also due to the fact that the comparison between simulated and real data is not straightforward and some values have to be estimated in an indirect way. Arguably, the index of marital fertility was more affected because of the simplifying assumption we had to make regarding homogeneous marriage patterns, which we imposed not only across space, but also across time. To be sure, many of these issues could be solved in future, as more sophisticated versions of the model and better estimates could then be generated.
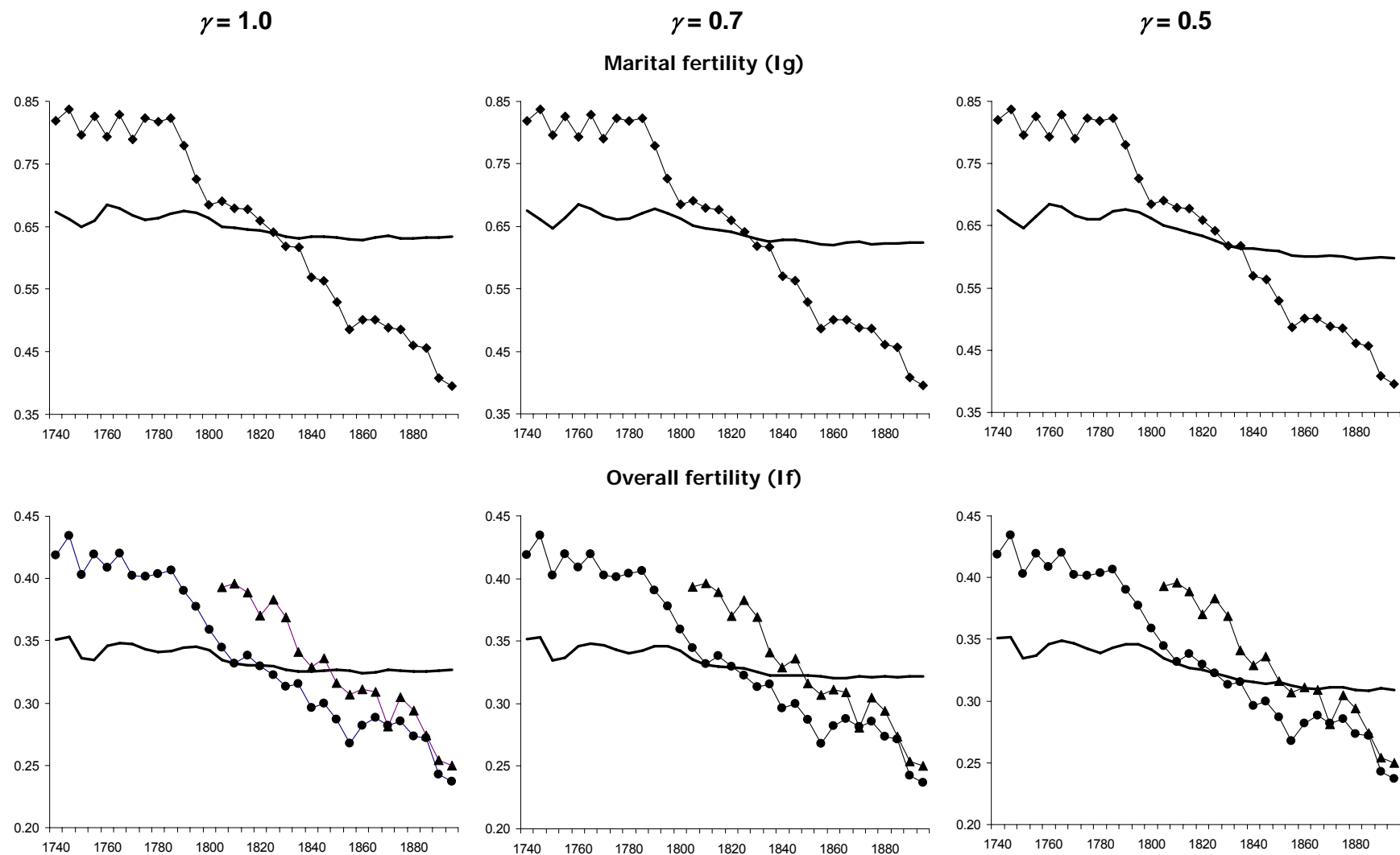
A disappointing result, nevertheless, is that the decreasing trend in fertility is quite mild in both sets of simulations. The one with $(\mu, \mu_{rev}, \alpha, \beta) = (1.85, 1.60, 0.6, 0.4)$ performs slightly better, but in both cases there seems to be a fall around the time of the Rrevolution that stabilises a few periods afterwards. This is probably consequence of the model not allowing families to *become* revolutionary after 1800, which puts an upward pressure on those *départements* where progressive attitudes might have influenced other lineages. It is indeed plausible to think that not only 'dynasties' become revolutionary, which implies that social influence takes place only between generations, namely from parents to children; it is arguably more realistic to assume that fertility behaviour expands throughout the population if enough persons in the surrounding neighbourhood are adopting a lower fertility.[29] We decided to incorporate this potential effect in the model by defining a new parameter that describes this threshold of influence, that is, the number of agents that need to lower their fertility before a given agent decides to join the trend. By introducing this modification, agents that were not affected by the initial revolutionary shock will look at their surroundings at each time period and decide to become 'revolutionary' if a proportion of neighbours equal to or larger than the threshold γ are 'revolutionary' themselves.

We then applied this new specification to the model that performed best so far, $(\mu, \mu_{rev}, \alpha, \beta) = (1.85, 1.60, 0.6, 0.4)$, trying different levels of γ. Values of γ too close to 1 clearly did not change the previous results much: it is too stringent since the practical totality of neighbours needs to be revolutionary before an agent decides to become revolutionary itself. And the lower values produced substantial falls in the total population towards the end of the period. Figure 12 depicts, along with the baseline case of $\gamma = 1$, two intermediate cases.

---

[29] It has been argued in the literature that localised conformity of norms and behaviour could be explained by informational cascades that follow more or less this dynamic. See, for example, Bikhchandani *et al.* [1992].

Figure 12. Actual and simulated levels of fertility for different degrees of social influence when $(\mu, \mu_{rev}, \alpha, \beta) = (1.85, 1.60, 0.6, 0.4)$, 1740-1900
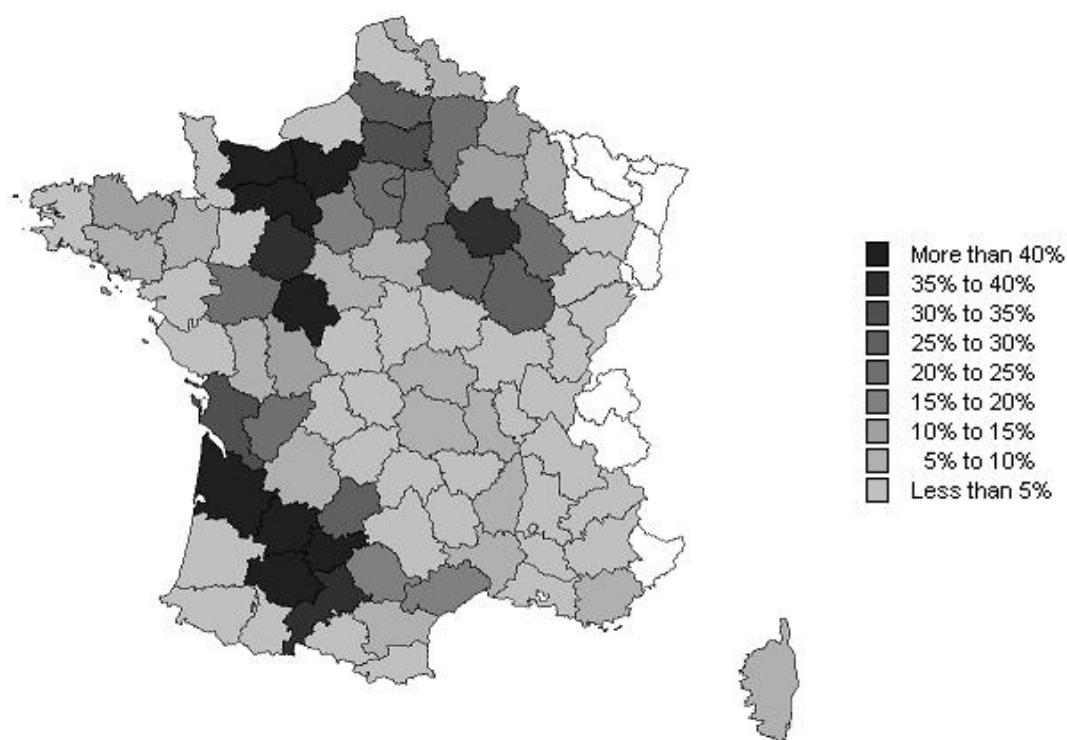

Notes: Dotted lines indicate actual values and smooth lines correspond to average of ten simulations. Marital and overall fertility 1740-1900 as estimated by Weir [1994: 330-331], and shorter series of overall fertility 1806-1901 (indicated with triangles) as estimated by Bonneuil [1997: 197-205].

27

Although still not fully tracking the decline, simulations including this sort of social influence represent an improvement from previous results, as the fall is milder than the one in the actual data, but now more noticeable. If we look into the overall fertility estimates, now the results corresponding to the first two-thirds of the nineteenth century fall between the two available estimates. Marital fertility, on the other hand, is not as well tracked and this is probably due to the fact that the model takes the implicit age of marriage as constant (by restricting the proportion of agents that can actually procreate) when it is well established in the literature that it was going down – above all for women – [see, e.g. Bardet, 1998: 320], hence increasing substantially the denominator. The reasons behind the persistent underestimation of the pre-transitional period are not that obvious, especially taking into consideration that the rate of growth of population is in fact mimicked well. One plausible argument to explain this has to do with the potential interaction between child mortality and births, which we have not considered in this initial version of the model. If regions with higher mortality had in fact higher fertility than the rest, both average indexes of fertility would probably be higher with only a marginal contribution to total population. Since for the sake of simplicity we have imposed homogeneity in the initial conditions and a basic behavioural rule that did not consider the status of mortality in the area, the model as it is tends to underestimate fertility in this period. These are certainly things that future work with similar models can correct. But, as we show in the below, the model as it is still provides some insights into the particular geographical pattern we see in the different areas of France.

Now, how well does this model perform at local level? One of the advantages of this agent-based simulation model is that it is well defined geographically, so we can study in detail what happens in every region and compare that with actual data as well. Taking the case where $\gamma = 0.5$, we run a series of simulations with the aim of comparing their results with the indexes of marital fertility at *département* level as estimated by Van de Walle [1974]. It is somewhat difficult to assess properly performance at micro level, but here we provide a series of graphs that illustrate that the matching is relatively good. The map in Figure 13, for example, shows that with the exception of some areas (associated with the regions leaders of the decline) and a few places in the neighbourhood of Paris, the model seems to have predicted more or less evenly the trends in the rest of the country. There, the error in prediction (defined as % deviation from the confidence interval) was more or less homogeneous across the country, which is not a trivial result, as it means that the model deviated equally in areas that experienced a decline than those lagging behind.
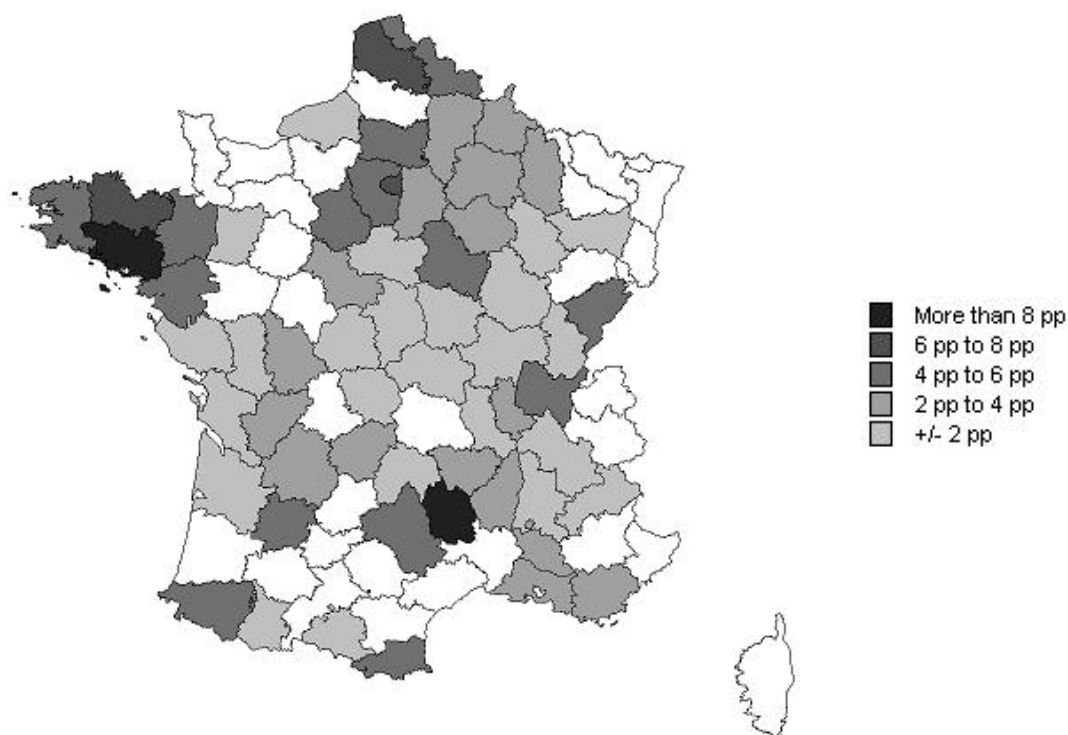
■	More than 40%
■	35% to 40%
■	30% to 35%
■	25% to 30%
■	20% to 25%
■	15% to 20%
□	10% to 15%
□	5% to 10%
□	Less than 5%

Notes: Values indicate the average percent error falling outside the 95% interval when predicting Ig.

A key empirical question to validate the use of the oath as applied in this model is to ask: does this model improve with respect to one where the same proportion of individuals is affected by the shock of the Revolution but in a random fashion? We did that exercise and the results are summarised in Figure 14, which plots the average percentage points of the best fit model with the oath as compared with the random model.

Figure 14. Improvement over random in predicting actual fertility levels when $(\mu, \mu_{rev}, \alpha, \beta, \gamma) = (1.85, 1.60, 0.6, 0.4, 0.5)$, 1830-1900
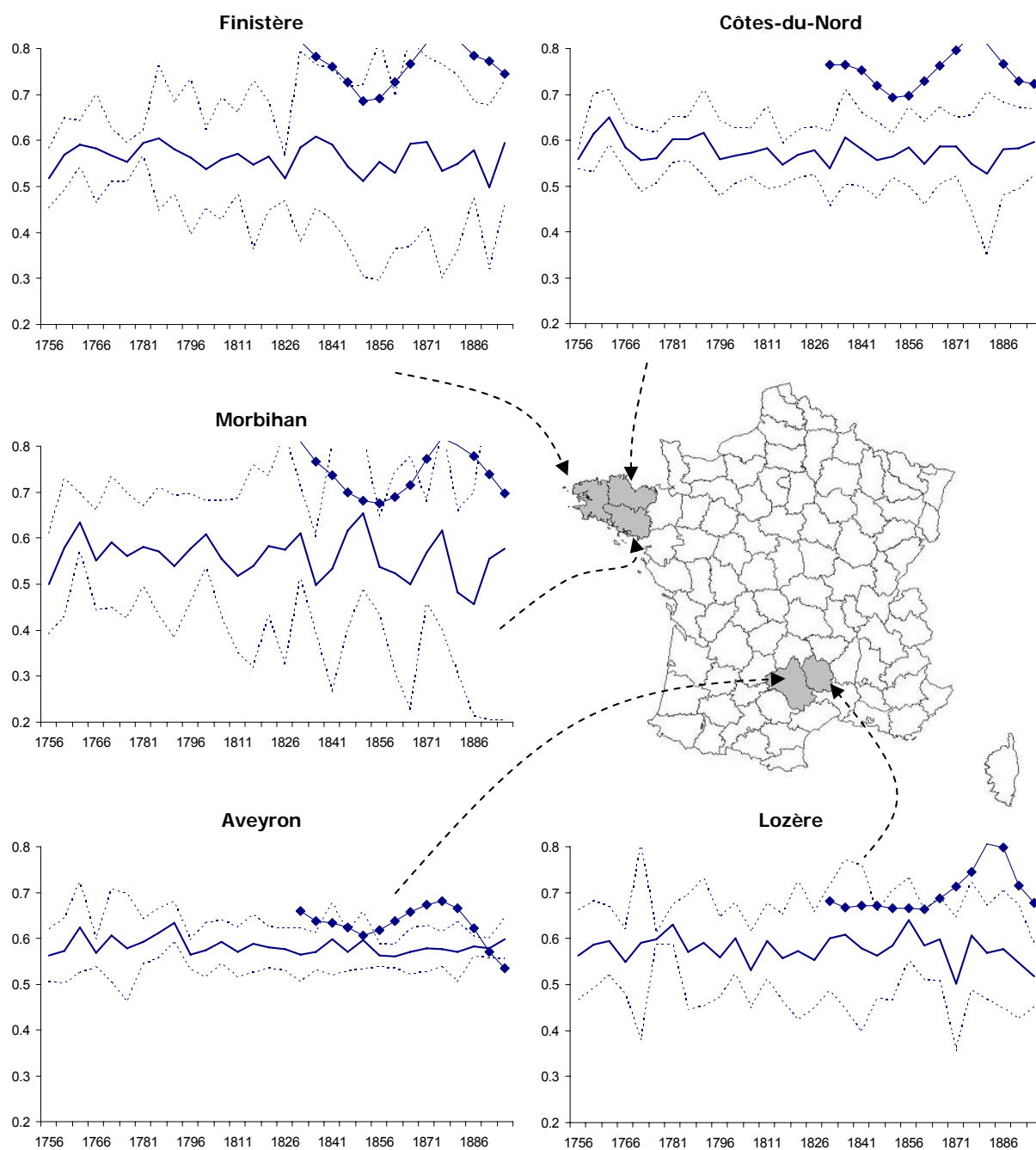

Legend:
- More than 8 pp
- 6 pp to 8 pp
- 4 pp to 6 pp
- 2 pp to 4 pp
- +/- 2 pp

Notes: Values indicate the difference in percentage points between error when using a random distribution of agents switching to low fertility and that when using the oath instead.

If we take out the *départements* where the absolute difference was within 2 percentage points, the model with the oath outperforms the random in 36 *départements*, whereas the opposite occurs only in 22. Most importantly the oath model outperforms the random model in a few key places, like the 'islands' of high fertility, part of the Aquitaine valley and the Paris area. A few selected graphs on the actual evolution of the predictions of the simulation model vis-à-vis the actual data at *départements* level could further illustrate its explanatory accomplishments.[30] Figures 14 and 15 look at some examples of areas that were leaders and laggards in the decline.
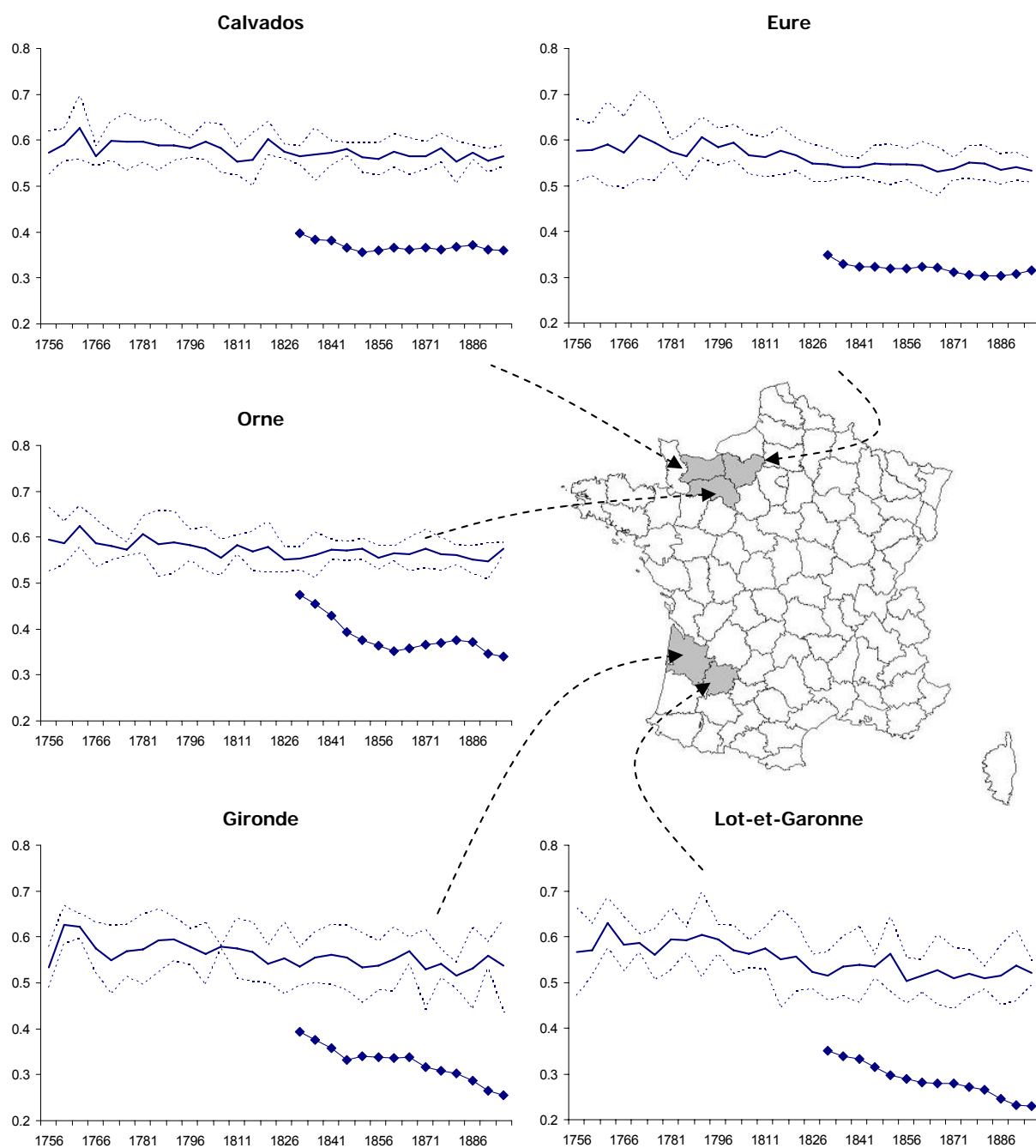
---

[30] We constructed these graphs for all *départements* and for both marital and overall fertility index, and can provide them upon request.

Figure 15. Actual and simulated marital fertility levels when $(\mu,\ \mu_{rev},\ \alpha,\ \beta,\ \gamma) = (1.85,\ 1.60,\ 0.6,\ 0.4,\ 0.5)$, lagging *départements*, 1740-1900

Finistère

Côtes-du-Nord

Morbihan

Aveyron

Lozère

Notes: Dotted lines indicate actual values starting in 1831 [van de Walle, 1974], whereas smooth lines correspond to simulation starting in 1741. Both finish in 1896.

Figure 16. Actual and simulated marital fertility levels when $(\mu, \mu_{rev}, \alpha, \beta, \gamma)$ = (1.85, 1.60, 0.6, 0.4, 0.5), leading *départements*, 1740-1900

Notes: Dotted lines indicate actual values starting in 1831 [van de Walle, 1974], whereas smooth lines correspond to simulation starting in 1741. Both finish in 1896.
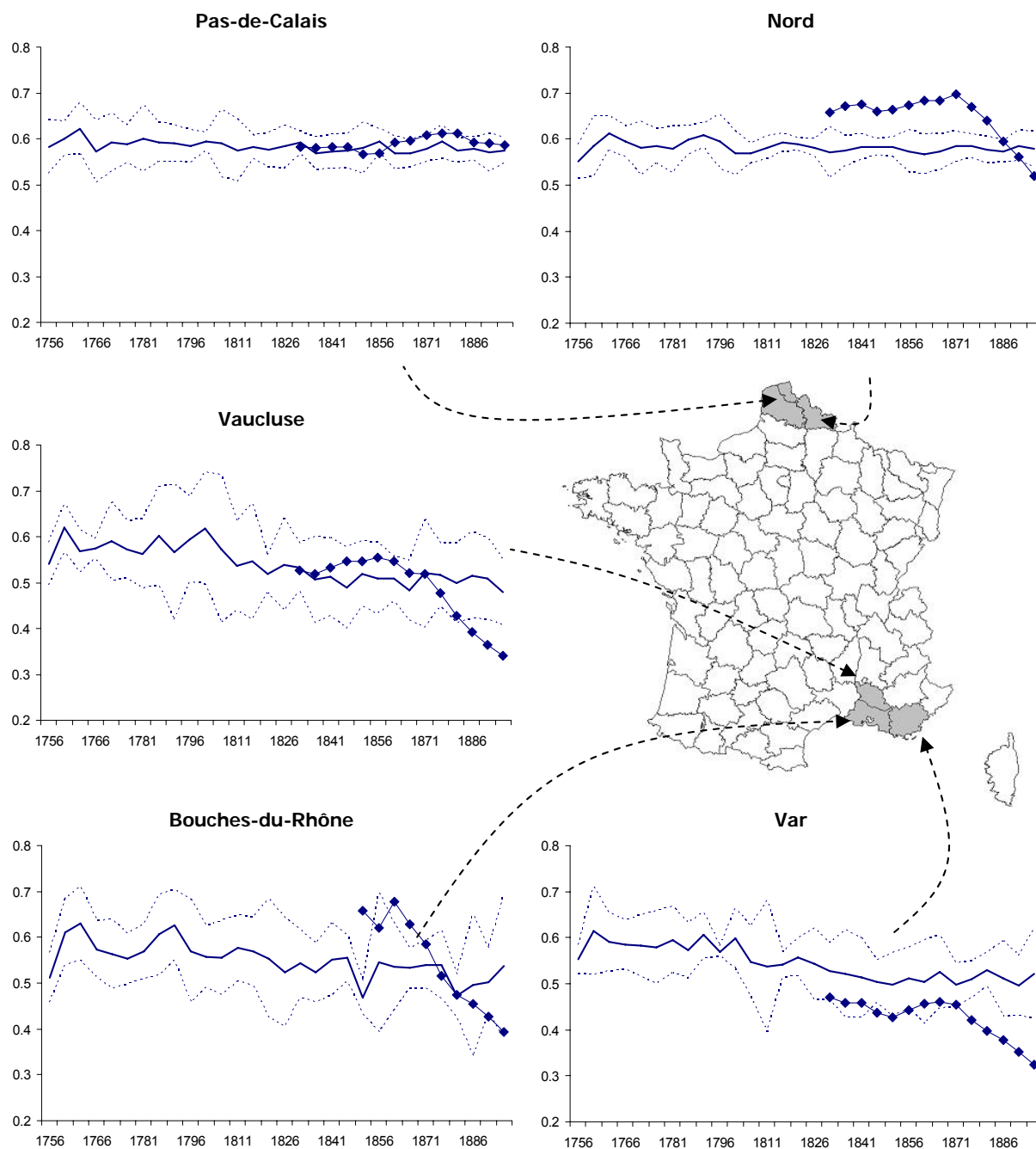
It is clear from those graphs that the model tracks quite well the laggards, as the simulation mimics the high level of fertility they maintained into the nineteenth century. However, the simulation largely overstates the levels of fertility for the leaders, although it picks a small general downward trend. A few characteristics of the model could explain this problem. On the one hand, the model assumes homogeneity across all individuals in terms of social influence (that is, α and β remain constant for all agents). It is certainly not implausible to think that the propensity to follow others could vary across regions and, in particular, it is likely that areas leading the decline were more prone to be more 'individualistic'. On the other, it could well be that the oath is not really a linear transformation of the variable we are trying to perceive. Although in conservative or moderate areas the correlation might be good, political reasons can motivate church leaders to press priests in very liberal areas to vote *against* the Revolution as a way to make an example or to establish a clear stake. If this is the case, the impact of the Revolution could be underestimated in the leading areas. These effects might of course be reinforced by other sources of heterogeneity that the model is simply not incorporating and are 'hidden' in the normal distribution that agents use to draw their desired family size, such as differences in income, or education (factors that I will explore further in the following chapter).

The model still does a good job for many of the non-extreme areas, as some of those illustrated in Figure 17 can show. In every case the general trend of the decline appears to be tracked well, in some cases with outstanding results. For areas not plotted here results were mixed but trends tended to coincide. The few cases where tracking was not that good were associated with areas only scantly populated (where simulations were less stable), those on the north-east borders, where influence from other countries probably played a non-minor role,[31] and –again- with areas that were leaders rather than followers in the decline.
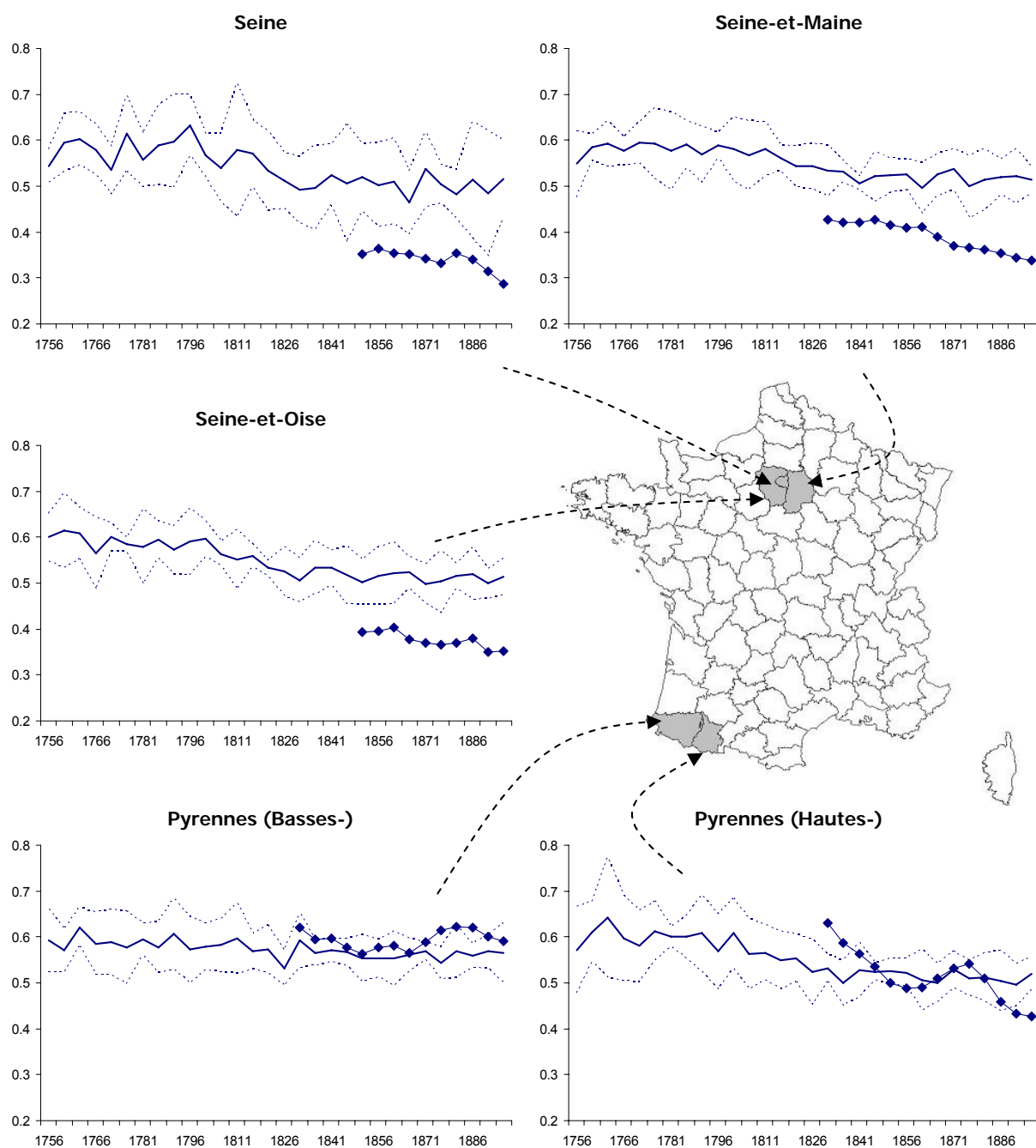
---

[31] Interestingly enough, this was not the case in the Pyrenees, an area that limits with other country, but where the towns on the other side of the border are rather small.

Figure 17. Actual and simulated marital fertility levels when (μ, μ_{rev}, α, β, γ) = (1.85, 1.60, 0.6, 0.4, 0.5), other *départements*, 1740-1900

Notes: Dotted lines indicate actual values starting in 1831 [van de Walle, 1974], whereas smooth lines correspond to simulation starting in 1741. Both finish in 1896.

Figure 17 (cont.) Actual and simulated marital fertility levels when (μ, μ_{rev}, α, β, γ) = (1.85, 1.60, 0.6, 0.4, 0.5), other *départements*, 1740-1900
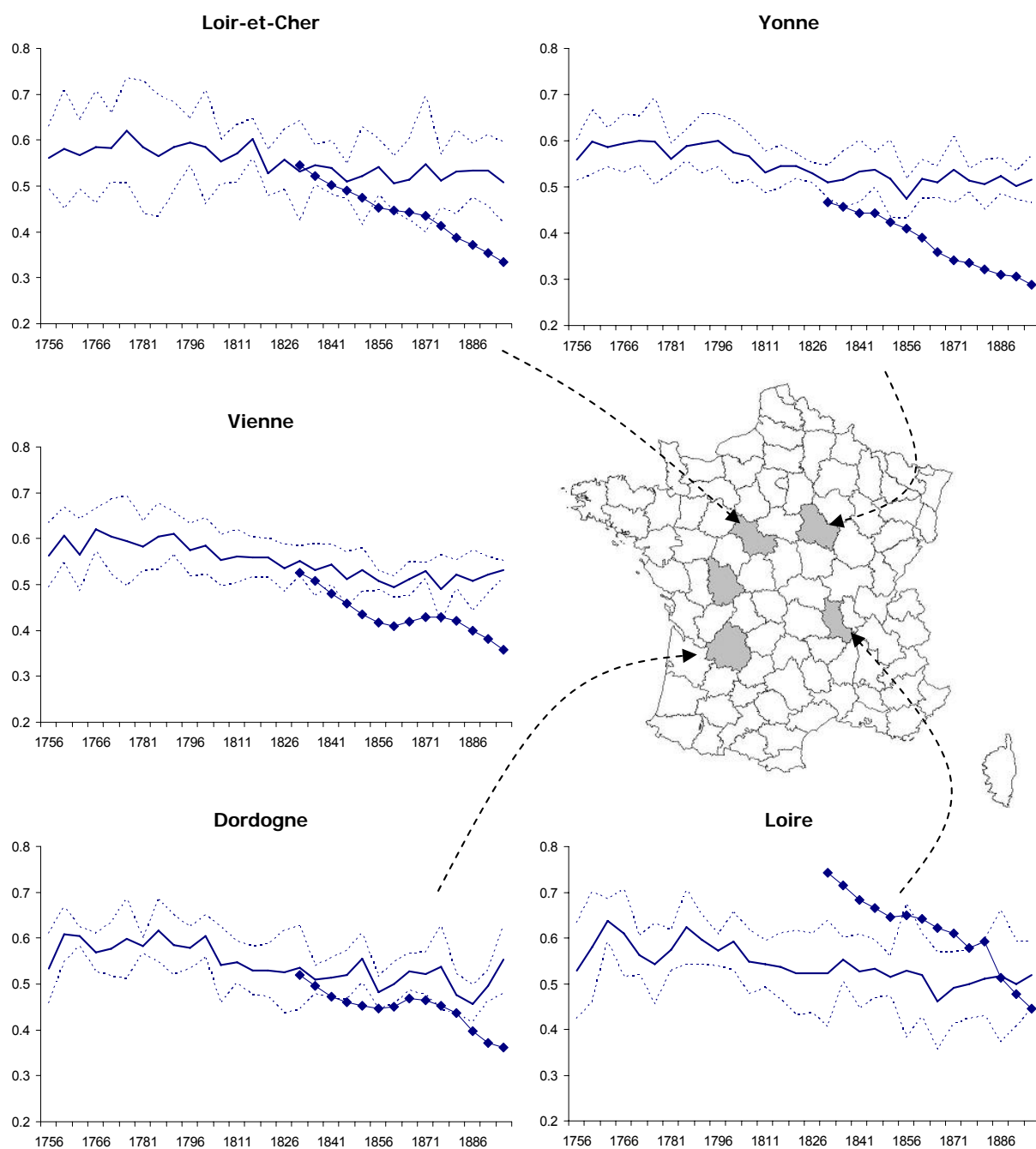

Notes: Dotted lines indicate actual values starting in 1831 [van de Walle, 1974], whereas smooth lines correspond to simulation starting in 1741. Both finish in 1896.

Figure 17 (cont.) Actual and simulated marital fertility levels when (μ, μ_{rev}, α, β, γ) = (1.85, 1.60, 0.6, 0.4, 0.5), other *départements*, 1740-1900

Notes: Dotted lines indicate actual values starting in 1831 [van de Walle, 1974], whereas smooth lines correspond to simulation starting in 1741. Both finish in 1896.

7. CONCLUDING REMARKS

In many respects the model developed here is rather naïf but, despite its simplicity, it is a good first approximation at describing the fertility decline in France using agent-based simulation techniques. It shows that social influence probably played a role in the particular dynamic followed by fertility rates and suggests that part of the different regional trends could be traced back to the heterogeneous impact of the Revolution. Simulations where some (but not total) social influence was present were better able to track the fall in birth rates than those where this influence was ignored. Far from being trivial, this outcome highlights that interpersonal interactions –an issue only marginally discussed in the literature– do matter. The results at micro level were also quite satisfactory, suggesting that the choice of the proxy for the 'modernisation factor' was probably appropriate. This calls for attention to revisit the relationship between institutional framework (religious or other) and fertility choice during the decline. Even if there are economic reasons behind the desired fall in fertility (the fall in μ, which in our model remains as an exogenous shock), cultural constraints can indeed be affecting the specific dynamics of the system and we need to learn more about them.

The failure to fully capture the impact on those *départements* leading the fall in birth rates, on the other hand, points towards some of the model's limitations, but it uncovers the ways in which it could be improved. At least two potential extensions are worth mentioning. Firstly, studying ways in which a behavioural rule can make better use of the information provided by the system. Perhaps the most straightforward example would be to incorporate information on child mortality on the parents' rule (where they increase the desired level of fertility if the chances of loosing an infant are high). Secondly, as an initial approximation the basic model presented here ignored certain information that could otherwise be incorporated. It takes the whole population of France as homogeneous and this was probably not the case. Further information on demographic details such as differences on age at marriage in the early modern period could be crucial to get a grasp of this. The development of these two lines of research could, of course, have certain synergies, as richer environments may allow richer and more realistic behavioural rules to be explored. Although computationally more costly, these extensions are indeed possible using similar agent-based models and could illuminate other aspects of this momentous transformation.

REFERENCES

Arthur, W. Brian [2005]; "Out-of-Equilibrium Economics and Agent-Based Modeling," in K. Judd and L. Tesfatsion (Eds.) [2005]; *Handbook of Computational Economics - Volumen 2: Agent-Based Computational Economics* (Elsevier/North-Holland, Amsterdam), pp. 1551-1564

Axelrod, Robert [1997]; *The Complexity of Cooperation: Agent-Based Models of Competition and Collaboration* (Princeton University Press, Princeton)

Axelrod, Robert [2005]; "Agent-Based Modeling as a Bridge between Disciplines," in K. Judd and L. Tesfatsion (Eds.) [2005]; *Handbook of Computational Economics - Volumen 2: Agent-Based Computational Economics* (Elsevier/North-Holland, Amsterdam), pp. 1565-1584

Bailey, Amy Kate [2006]; "Fertility and Revolution: How Does Political Change Influence Reproductive Behavior?," *MIMEO* (http://sneps.net/RD/uploads/ASEN_Bailey.pdf)

Bardet, Jean-Pierre [1998]; "La France en déclin," in J.-P. Bardet and J. Dupâquier [1998]; *Histoire des populations de l'Europe – Vol. 2: La révolution démographique, 1750-1914* (Fayard, Paris), pp. 287-325

Bikhchandani, Sushil, David Hirshleifer and Ivo Welch [1992]; "A Theory of Fads, Fashion, Custom, and Cultural Change as Informational Cascades," *Journal of Political Economy*, Vol. 100, No. 5, pp. 992-1026

Billari, Francesco and Alexia Prskawetz [2005]; "Studying population dynamics from the bottom-up: the crucial role of agent-based computational demography," *MIMEO* (http://iussp2005.princeton.edu/download.aspx?submissionId=51988)

Binion, Rudolph [2001]; "Marianne in the Home. Political Revolution and Fertility Transition in France and the United States," *Population (English Selection)*, Vol. 13, No. 2, pp. 165-188

Bocquet-Appel, Jean-Pierre and Lucienne Jakobi [1998]; "Evidence for a Spatial Diffusion of Contraception at the Onset of the Fertility Transition in Victorian Britain," *Population (English Selection)*, Vol. 10, No. 1, New Methodological Approaches in the Social Sciences, pp. 181-204

Bonneuil, Noël [1997]; *Transformation of the French Demographic Landscape, 1806-1906* (Clarendon Press, Oxford)

Bongaarts, John [1975]; "Why High Birth Rates Are So Low," *Population and Development Review*, Vol. 1, No. 2, December, pp. 289-296.

Brown, John C. and Timothy W. Guinnane [2002]; "Fertility Transition in a Rural, Catholic Population: Bavaria, 1880-1910," *Population Studies*, Vol. 56, pp. 35-50

Brown, John C. and Timothy W. Guinnane [2007]; "Regions and Time in the European Fertility Transition: Problems in the Princeton Project's Statistical Methodology," *Economic History Review*, Vol. 60, No. 3, pp. 574-595

Caldwell, John C. [2004]; "Social Upheaval and Fertility Decline," *Journal of Family History*, Vol. 29, No. 4, October, pp. 382-406

Chesnais, Jean-Claude [1992]; *The Demographic Transition: Stages, Patterns, and Economic Implications* (Clarendon Press, Oxford)

Coale, Ansley and Susan C. Watkins (Eds.) [1986]; *The Decline of Fertility in Europe: the Revised Proceedings of a Conference on the Princeton European Fertility Project* (Princeton University Press, New Jersey)

Derosas, Renzo and Frans van Poppel (Eds.) [2006]; *Religion and the Decline of Fertility in the Western World* (Springer, Dordrecht – Netherlands)

Doepke, Matthias and Michèle Tertilt [2007]; "Women's Liberation: What Was in It for Men?," *MIMEO* (http://web.uvic.ca/econ/tertilt.pdf)

Edwards, Ward [1968]; "Conservatism in Human Information Processing," in B. Kleinmuntz [1968]; *Formal Representation of Human Judgement* (John Wiley & Sons, New York), pp. 17-52

Flandrin, Jean-Louis [1979]; *Families in Former Times: Kinship, Household and Sexuality in Early Modern France* (Cambridge University Press, Cambridge)

Flinn, Michael W. [1981]; *The European Demographic System, 1500-1820* (The Johns Hopkins University Press, Baltimore, Maryland)

Galor, Oded and David N. Weil [1999]; "From Malthusian Stagnation to Economic Growth," *American Economic Review*, Vol. 89, No. 2, May, pp. 150-154

Galor, Oded and David N. Weil [2000]; "Population, Technology, and Growth: From Malthusian Stagnation to the Demographic Transition and Beyond," *American Economic Review*, Vol. 90, No. 4, September, pp. 806-828

Gibson, Ralph [1989]; *A Social History of French Catholicism 1789-1914* (Routledge, London)

Gilbert, Nigel and Klaus G. Troitzsch [2005]; *Simulation for the Social Scientist – Second Edition* (Open University Press, Maidenhead)

Gilbert, Nigel [2008]; *Agent-Based Models* (Sage Publications, London)

Gille, H. [1949]; "The Demographic History of the Northern European Countries in the Eighteenth Century," *Population Studies*, Vol. 3, No. 1, June, pp. 3-65

Hajnal, John [1965]; "European Marriage Patterns in Perspective," in D. V. Glass and D. E. C. Eversley (Eds.) [1965]; *Population in History: Essays in Historical Demography* (Blackwell Publishers, Cambridge Mass.), pp. 101-143

Hedström, Peter [2005]; *Dissecting the Social. On the Principles of Analytical Sociology* (Cambridge University Press, Cambridge)

Henry, Louis [1961]; "Some Data on Natural Fertility," *Eugenics Quarterly*, Vol. 8, pp. 81-96

Henry, Louis [1972]; "Fécondité des mariages dans le quart sud-ouest de la France de 1720 à 1829," *Annales: Economies, sociétés, civilisations*, Vol. 27, No. 3 & No. 4-5, pp. 612-639 & pp. 977-1023

Henry, Louis [1978]; "Fécondité des mariages dans le quart sud-est de la France de 1670 à 1829," *Population (French Edition)*, Vol. 33, No. 4-5, pp. 855-883

Henry, Louis and Yves Blayo [1975]; "La population de la France de 1740 a 1860," *Population (French Edition)*, Vol. 30, pp. 71-122

Henry, Louis, and Jacques Houdaille [1973]; "Fécondité des mariages dans le quart nord-ouest de la France de 1670 à 1829," *Population (French Edition)*, Vol. 28, No. 4-5, pp. 873-924

Hoffman, Philip T., Gilles Postel-Vinay, and Jean-Laurent Rosenthal [2007]; "Is Trust an Ultimate Cause? Its Role in the Long Run Development of Financial Markets in France," *MIMEO* (http://international.ucla.edu/cms/files/hpvrtrustrev2.pdf)

Houdaille, Jacques [1976]; "Fécondité des mariages dans le quart nord-est de la France de 1670 à 1829," *Annales de Démographie Historique*, pp. 341-392

INED -Institut National d'Etudes Démographiques- [1977]; "Sixième rapport sur la situation démographique de la France," *Population*, Vol. 32, No. 2, March-April, pp. 255-338

Kirk, Dudley [1996]; "Demographic Transition Theory," *Population Studies*, Vol. 50, No. 3, November, pp. 361-387.

Kohler, Hans-Peter [2001]; *Fertility and Social Interaction: An Economic Perspective* (Oxford University Press, Oxford)

Knodel, John and Etienne van de Walle [1979]; "Lessons from the Past: Policy Implications of Historical Fertility Studies," *Population and Development Review*, Vol. 5, No. 2, pp. 217-245

Le Play, Frédéric [1874]; *La réforme sociale en France déduite de l'observation comparée des peuples Européens -5 édition, corrigée et refondue-* (Dentu, Paris)

Lesthaeghe, Ron [1980]; "On the Social Control of Human Reproduction", *Population and Development Review*, Vol. 6, No. 4, December, pp. 527-548

Mason, Karen O. [1997]; "Explaining Fertility Transitions," *Demography*, Vol. 34, No. 4, November, pp. 443-454

McLaren, Angus [1978]; "Abortion in France: Women and the Regulation of Family Size 1800-1914," *French Historical Studies*, Vol. 10, No. 3, Spring, pp. 461-485

McLaren, Angus [1990]; *A History of Contraception: From Antiquity to the Present Day* (Basil Blackwell, Oxford)

McQuillan, Kevin [1999]; "Religious Values and Fertility Decline: Catholics and Lutherans in Alsace, 1750-1870," in R. Leete (Ed.) [1999]; *Dynamics of Values in Fertility Change* (Oxford University Press, Oxford)

Montgomery, Mark R. and John B. Casterline [1993]; "The Diffusion of Fertility Control in Taiwan: Evidence from Pooled Cross-Section Time-Series Models," *Population Studies*, Vol. 47, No. 3, November, pp. 457-479

Montgomery, Mark R. and John B. Casterline [1996]; "Social Learning, Social Influence, and New Models of Fertility," *Population and Development Review*, Vol. 22, Supplement: Fertility in the United States: New Patterns, New Theories, pp. 151-175

Montgomery, Mark R., John B. Casterline and Frank Heiland [2001]; "Social Networks and the Diffusion of Fertility Control," *MIMEO* (http://www.demogr.mpg.de/Papers/workshops/010221_paper04.pdf)

Murphy, Tommy E. [2008]; "Old Habits Die Hard (Sometimes): What Can *Departement* Heterogeneity Tell Us About the French Fertility Decline?," *MIMEO* (http://www.nuffield.ox.ac.uk/users/murphy/files/Old_habits.pdf)

Pollak, Robert and Susan Cotts Watkins [1993]; "Cultural and Economic Approaches to Fertility: Proper Marriage or Mésalliance?," *Population and Development Review*, Vol. 19, No. 3, September, pp. 467-496

Rémond, René [1999]; *Religion and Society in Modern Europe* (Blackwell Publishers, Oxford)

Rosero-Bixby, Luis and John B. Casterline [1993]; "Modelling Diffusion Effects in Fertility Transition," *Population Studies*, Vol. 47, No. 1, March, pp. 147-167

Saito, Osamu [1996]; "Historical Demography: Achievements and Prospects," *Population Studies*, Vol. 50, No. 3, November, pp. 537-553

Service de la Statistique Général de France [1878]; *Annuaire Statistique de la France* (Imprimerie Nationale, Paris)

Tackett, Timothy [1986]; *Religion, Revolution, and Regional Culture in Eighteenth-Century France: The Ecclesiastical Oath of 1791* (Princeton University Press, Princeton)

Tackett, Timothy [2006]; "The French Revolution and religion to 1794," in S. J. Brown and T. Tackett [2006]; *The Cambridge History of Christianity – Volume VII: Enlightenment, Reawakening and Revolution 1660-1815* (Cambridge University Press, Cambridge), pp. 536-555

Tesfatsion, Leigh [2005]; "Agent-Based Computational Economics: A Constructive Approach to Economic Theory," in K. Judd and L. Tesfatsion (Eds.) [2005]; *Handbook of Computational Economics - Volume 2: Agent-Based Computational Economics* (Elsevier/North-Holland, Amsterdam), pp. 831-880

Van de Walle, Etienne [1974]; *The Female Population of France in the Nineteenth Century* (Princeton University Press, Princeton)

Van de Walle, Etienne [1976]; "Alone in Europe: The French fertility decline until 1850," in Tilly, Charles (Ed.) [1976]; *Historical Studies of Changing Fertility* (Princeton University Press, Princeton), pp. 257-288

Van de Walle, Etienne and Helmut V. Muhsam [1995]; "Fatal Secrets and the French Fertility Transition," *Population and Development Review*, Vol. 21, No. 2, pp. 261-279

Watkins, Susan C. [1991]; *From Provinces into Nations: Demographic Integration in Western Europe 1870-1960* (Princeton University Press, Princeton)

Weir, David R. [1983]; "Fertility Transition in Rural France, 1740-1829," PhD dissertation, Stanford University.

Weir, David R. [1994]; "New Estimates of Nuptiality and Marital Fertility in France, 1740-1911," *Population Studies*, Vol. 48, pp. 307-331

Wrigley, E. Anthony and Roger S. Schofield [1981]; *The Population History of England 1541-1871 – A Reconstruction* (Cambridge University Press, Cambridge)