SOCIAL INFLUENCE EFFECTS AND LONG-TERM FERTILITY DYNAMICS

LOOKING AT THE HISTORICAL FRENCH DECLINE WITH AN AGENT-BASED SIMULATION EXPERIMENT[♣]

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Preliminary paper - Please do not quote

This version: October 17, 2010

[♣] An earlier version of this paper appeared in the *Oxford Discussion Papers in Economic and Social History* series (No. 71, 2008) with the name "When Smaller Families Look Contagious: A Spatial Look at the French Fertility Decline using an Agent-Based Simulation Model". The current version owes much to the feedback we received from the referees of that series and from discussions in several seminars (Nuffield College, University of Copenhagen, European University Institute, Centro Dondena at Università Bocconi, UBC, Dalhousie University, and Paris School of Economics) and conferences (Economic History Society Meeting, World Congress of the International Institute of Sociology, World Congress of Cliometrics, the Conference of the European Social Simulation Association, and the Conference of the European Historical Economics Society). We thank the comment and advice of many people there, especially Marina Adshade, Bob Allen, Michael Biggs, Francesco Billari, Jérome Bordieu, Mauricio Drelichman, Giovanni Federico, Price Fishback, George Grantham, David Green, Knick Harley, Eliana La Ferrara, Matthias Messner, Scott Moser, Avner Offer, Cormac Ó Gráda, Gilles Postel-Viney, and Jacob Weisdorf. The usual disclaimer applies.

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Looking at the Historical French Decline with an Agent Based Simulation Experiment

Abstract

We build an agent-based simulation model that incorporates both historical data on population characteristics and spatial information on the geography of France to experimentally study the role of social influence in fertility decisions. We assess how different behavioural and social influence assumptions cause variations in macro dynamics and diffusion patterns. The analyses show that a combination of both endogenous and exogenous factors help to explain the way in which the diffusion took place, and suggest some of the mechanisms through which social influence was materialised.

Keywords Economic history, demographic history (Europe pre-1913), France, demographic economics, fertility, simulation experiments, agent-based models, diffusion, decision-making, social norms, social interactions, micro-macro behaviour.

JEL classification N33, J13, C15.

1. Introduction

Fertility transitions still generate both great interest and considerable controversy among social scientists. The systematic fall in birth rates represented a major demographic break in many regions around the world, and was arguably a crucial intermediate step for those enter modern economic growth [Galor, 2005]. Economic, social, and cultural factors have all been brought forward as potential drivers [see, e.g., van de Kaa, 1996; or Friedlander *et al.*, 1999], but no single explanation dominates, generating a persistent disagreement on the actual causes of the transition [Mason, 1997]. A consensus is now slowly emerging that a satisfactory explanation must incorporate *all* these elements [Durlauf and Walker, 2001: 115-116], but combing them in the context of a formal model that respects the main stylised facts observed has proved a difficult task.

We take up that challenge and suggest a way to integrate these various components in a single framework. This paper presents an agent-based simulation experiment that combines a behavioural model of fertility choices with the fragmentary historical information we have on the transition in France. By means of simulation, which has already been identified as a promising yet underexplored methodology in demography [e.g. Burch, 1996; Billari and Prskawetz, 2003], we offer new insights into how the French transition took place, and illuminate the generic behavioural principles affecting fertility. The model allows us to study demographic dynamics and interpret sparse empirical data in terms of a formal theoretical structure. At the same time, it lets us incorporate at least two components normally neglected in the historical fertility decline literature. On the one hand, the role of social influence in fertility decisions. As recent studies suggest [e.g. Kohler, 2000a, 2000b], decisions about family size are interdependent, with couples not wanting to depart too much from what other couples around them do; this sets up an endogenous process of social influence that our simulations model explicitly. On the other hand, we also discuss a particular mechanism through which the French revolution might have contributed to the fall, namely its impact on the functioning of the Catholic church. The onset of the decline coincided with the chain of events that followed the summer of 1789, and a growing body of research is actually pointing towards a regular connection between social upheavals and fertility decline [Binion, 2001; Caldwell, 2004; Bailey, 2009]. Building on these studies, and following Sutherland [2003: 345] hypothesis that dismantlement of the church was associated with the Ecclesiastical Oath of 1791 [Tackett, 1986], we model a heterogeneous, exogenous shock to population dynamics using the information on the extent of the Oath in different regions of France. In this way, our simulation connects with a recent line of research that sees the French Revolution as a natural experiment [Acemoglu et al 2009a, 2009b]. Whereas these studies pin down the effects of revolutionary institutions by using the fact that French armies invaded certain areas of Germany but not others, our paper delves into the idea that the institutional reforms associated with the Revolution had an uneven geographical impact the structure of the church within France, and this in the fertility rates.

Why France was the first country in Europe to experience a systematic fall in birth rates in the nineteenth century is still one of the most puzzling questions in demographic history, and as such we try to contribute to its understanding. But we also illuminate some of the behavioural mechanisms that underlie more general fertility dynamics. Our simulation experiment aims to identify the relative impact of factors that are normally neglected in standard approaches, such as social interaction and geographical diffusion. In this vein, we address several of the points raised by John Hobcraft in his plea to revise the research on demographic behaviour [Hobcraft, 2006]. Firstly, we put together concepts from several disciplines such as the standard family decision making process typical of economics and the role of social influence analysed by sociologists [Hobcraft, 2006: 155-156]. Secondly, we focus on how these factors feed on a dynamic processes, with a particular interest in the role of heuristics and social interaction [Hobcraft, 2006: 158, 169-172], all along using a model carefully defined in terms of demographic variables. Lastly, as opposed to other methodologies, agent-based simulations allow us to study the importance of context [Hobcraft, 2006: 172-173], connecting with the literature that focuses on *how*, rather than *why*, the fertility decline took place [e.g. Bocquet-Appel and Jakobi, 1998].

Far from imposing a specific view on the fertility transition, we explore to which extent different assumptions on social influence affect the dynamics of fertility throughout the transition. We are not able to prove that social influence effects were present during the French fertility decline, yet we can show that –given what we know about the demographic landscape of the time– different behavioural assumptions produce very different outcomes, with the assumption of no social influence being just one of those possible scenarios, and not necessarily the most likely. Simulation experiments allow us to explore a series of questions of interest by tweaking behavioural assumptions that are often treated as given, especially in the pre-transitional period where little data is available. For instance, we show it is not likely that couples were maximising family size, given what we know about the demographic characteristics of pre-transition France. We also show that some of the data we have available, when contrasted with the results of the experiment, is more consistent with a scenario where parents aim at surviving children and not fertility itself, as has already been suggested was a standard strategy in early modern Europe [e.g. Reher and Sanz-Gimeno, 2007: 705]. And finally, we highlight the explanatory relevance of social influence in the context of the French Revolution, which brought a dismantlement of the church associated to the fertility decline [Sutherland, 2003: 345] and boosted a change of norms, something we explicitly capture in our model.

2. SOCIAL INFLUENCE EFFECTS IN FERTILITY CHOICES

Following a period of relative neglect [Bongaarts and Watkins, 1996: 641], the study of social influence effects on reproductive behaviour has lately gained considerable attention in demography [e.g. Casterline, 2001; Kohler, 2001]. What comes as a surprise is how late this interest has risen given the long-standing tradition that the topic had in the European fertility decline debate [for a review, see Van de Kaa, 1996; Friedlander et al., 1999; or Guinnane, 2010]. Hypotheses linking social influence to the (first) demographic transition can be traced back to at least the late XIX century, when some authors attributed the fall in French birth rates to changes in the nature of social dynamics [Dumont, 1890: 130] or in the moral order of the society [Leroy-Beaulieu, 1896: 614]. These ideas gained support in the 1970s with the publication of the first results of the European Fertility Project [Coale and Watkins, 1986], which run counter to the predictions of the then dominant demographic transition theory: child mortality, urbanisation and industrialisation helped to explain some local differences in the decline, but not substantially; and countries that were different in terms of development had almost simultaneous transitions, and fertility patterns were strongly correlated with the distribution of various cultural traits (e.g. language). This evidence suggested that the diffusion of reproductive behaviour was influenced by social interactions [Knodel and van de Walle, 1979: 239], and that it was the spread of new ideas and not the change in material conditions what accounted for the decline [Cleland and Wilson, 1987: 27].

The importance of social influence to explain fertility has been, however, very controversial. While market-mediated social interaction is normally taken for granted, demographers and economists have been generally reluctant to consider peer effects, diffusion, or other form of non-market social effect. Economists in particular look at diffusion stories of the fertility decline with scepticism because they appear to be at odds with the idea of rational agents. The interpretation is that high fertility in the pre-transition period imply either the population's inability to control fertility or its unwillingness to do so on moral grounds [e.g. Brown and Guinnane, 2002: 40]. There are at least two reasons to think the European decline has nothing to do with the former. First, 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]. Second, the diffusion of contraceptive knowledge is expected to be relatively fast, but that does not match the timing of the fall. The diffusion of norms, however, appeals to longer-term shifts in attitudes and, as such, it could offer the crucial explanatory mechanism of this particular transition. The fact that many are still reluctant to look into this aspect of social interaction as a plausible argument has arguably to do with the pervasiveness of the taxonomy associated with Gösta Carlsson. According to that seminal paper, explanations of the decline either invoke adjustment to new (typically economic) conditions, or diffusion/innovation of a new behaviour [Carlsson, 1966: 149-151]. Most authors in the debate have placed themselves on opposite sides of this dichotomy, and it is difficult to see in their writings any room for potential coexistence of these hypotheses [e.g. Cleland and Wilson, 1987; Brown and Guinnane, 2002].

Yet, some do not really see these alternative arguments as substitutes but as complements [e.g. Pollak and Watkins, 1993]. Most decisions about family behaviour are heavily embedded in tradition and more often than not they reflect some degree of path-dependence. To the extent that people tend to be conservative and avoid change [Edwards, 1968], changing long-rooted assumptions and, with them, individual preferences for a different family size, could take some time. Even though fertility control might begin to make sense economically, the uncertainty on how that strategy (which implied breaking a long-established norm) would impact on those pursuing it could make them reluctant to do so. This does not underscore the relevance of economic factors, but it highlights the importance of taking social effects into account, particularly as they interact with economic conditions. Following an increasing interest in the study of social influence effects in fertility [Mason, 1997; Rosero-Bixby and Casterline, 1993; Montgomery and Casterline, 1993, 1996; Montgomery *et al.*, 2001], recent works are beginning to shape formal models rooted in micro-foundations where social interaction affects rational, utility maximising couples that face the possibility of adopting low fertility [e.g. Kohler, 2001, Durlauf and Walker, 2001]. According to these models, fertility choices are seen as coordination problems: the benefits of choosing low or high fertility are dependent on the fertility choices of others. Agents face a value function that has more or less the following shape:

$$(1) \qquad V\left(n\left(f_i\right), Z_i, F_i^e, \varepsilon_i\left(f_i\right)\right) = u\left(n\left(f_i\right), Z_i; \boldsymbol{\alpha}\right) - \frac{J}{2}\left(f_i - F_i^e\right)^2 + \varepsilon_i\left(f_i\right)$$

Each agent *i* is characterised by a vector Z_i of personal attributes (including tastes, values, environmental factors, etc.) and chooses a fertility strategy f_i (typically f_c –contraception– or f_{nc} –no contraception–) taking in consideration her expectations F_i^e of what the rest of the population are doing in terms of fertility. The terms $\boldsymbol{\alpha}$ and J are parameters. The right hand side of this equation is divided in three parts: the personal utility that agents obtain from choosing a particular strategy that produces $n\left(f_i\right)$ children, the cost faced if she deviate from the average behaviour of the other agents, and some external personal shock $\varepsilon_i\left(f_i\right)$, also dependent of the fertility strategy chosen. There are various reasons that motivate the introduction of the second (cost) term, the most straightforward being simple social pressure. Another is the uncertainty associated to infrequent events. Although an important choice, forming a family is a relatively infrequent event in a lifetime, and people rely on the experience and judgment of others to make their own evaluation; from the point of view of the agent, a deviation from the norm can have negative consequences, hence the cost accounted by the function. Kohler [2000a] has shown that the presence of this sort of component in potential parents' value function can lead to very particular birth rate dynamics, allowing to explain a series of empirical puzzles associated with the presence of multiple equilibria, high fertility 'traps' or the timing of some transitions [e.g. Kohler, 2000b, 2001].

This formalisation can illustrate another (equally controversial) type of non-market social effect: religion. The role of religious influence on fertility choice is a recurrent theme in the literature [e.g. Derosas and van Poppel, 2006], yet it is rarely treated in a formal way. Although linked to the concept of social influence, the effect of religion is plausibly different in nature. One way of thinking about the interaction of religion and fertility, in a similar way as Botticini and Eckstein have done for the Jew and education [Botticini and Eckstein: 2007: 893-894] following Iannacone [1992], is by assuming that the utility of the individual is affected directly, through a subcomponent of Z_i, assigning a positive or negative impact to a particular fertility strategy choice. If belonging to a religious group imposes certain norms of behaviour in terms of fertility, and those contrast with the strategy the individual wants to pursue, she will face a cost. Let's say $x(f_i)$ is the reward the individual receives from her religious institution for choosing a particular strategy. We can modify the value function above such that:

(2) $$V\left(n\left(f_i\right), Z_i, F_i^e, \varepsilon_i\left(f_i\right)\right) = u\left(n\left(f_i\right), Z_i, x\left(f_i\right); \boldsymbol{\alpha}\right) - \frac{J}{2}\left(f_i - F_i^e\right)^2 + \varepsilon_i\left(f_i\right)$$

For a religious person $\partial u / \partial x > 0$ and, plausibly, for a non religious person $\partial u / \partial x = 0$. If the religious institution condemns in any way contraception, we should have that $x\left(f_c\right) \leq 0 < x\left(f_{nc}\right)$: that is, when religious ideals are enforced, controlling fertility results in a disutility. Making some assumptions on the functional form, we could rewrite the equation above as:

(3) $$V\left(f_i, Z_i, x\left(f_i\right), F_i^e, \varepsilon_i\left(f_i\right)\right) = u\left(n\left(f_i\right), Z_i\right) + x\left(f_i\right) - \frac{J}{2}\left(f_i - F_i^e\right)^2 + \varepsilon_i\left(f_i\right)$$

Our modified version of the standard social influence model including the effect of religion summarises good part of the discussion on the roles of non-economic factors in fertility. If we take equation (3) to be a reasonable approximation to the way an agent chooses her family size, it is easy to see why economic modernisation does not necessarily result (at least immediately) in a fall of birth rates. Although a secular change in the fundamentals, here conveyed by the component Z_i, might lead the individual to favour an alternative fertility strategy (e.g., an increase in the opportunity costs of mothers leading to some degree of active contraception), as long as the other components of the payoff function remain stable there will be a threshold under which the fertility strategy will not change. Any improvement in utility stemming from the fertility choice reaction to different economic conditions should offset both the religious *and* social cost to lead to a new fertility strategy. Once this threshold is surpassed, an endogenous mechanism is triggered: the expectations on the behaviour of other agents $\left(F_i^e\right)$ begin to change and this leads to self-enforcing dynamics towards a new generalised fertility strategy. At the same time, non-economic modernisation taking the form of a relaxation in religious norms (a decrease in $x(f_i)$) or a weakening of social ties (a fall in J) can make the value function more sensitive to changes in the fundamentals.

The complex nature of this sort of models generate a series of challenges for the empirical analysis, especially regarding their econometric implementation [Durlauf and Walker, 2001: 131-133]. In this paper we pursue an alternative strategy: we build an agent-based simulation in which every agents follow a behavioural rule inspired in equation (3) and assess the impact of alternative parametric values in that rule. In order to provide an empirical reference point, the simulation model incorporates a series of features of the geography and demographic history of France in the eighteenth and nineteenth centuries and replicates its fertility decline. In the following section we discuss why the French makes an interesting case study, and how we connect the stylised fact we know about it to the agent-based model.

3. Modelling French demographic history

The peculiarities of the French fertility decline make it a canonical case for the study of demographic transitions in which social effects might have played a role. On the one hand, the early arrival of the decline does not seem to be triggered (at least at first sight) by any major economic change. Its timing coincides with the advent of the Revolution, although the actual mechanisms driving such connection are still not clear [Weir, 1983]. Figure 1 shows how the French case stands with respect to the rest of Europe.

[Figure 1 about here]

How fertility rates behaved within France is also of particular interest. Systematic historical information covering different geographical areas for the whole country is available at the *département* level [van de Walle, 1974; Coale and Watkins, 1986; Bonneuil, 1997]. Figure 2 plots the Princeton I_g index of marital fertility for some selected dates in the nineteenth century; they give an account of the proportion of births with respect to the maximum biologically attainable given the age structure of married women. This fertility measure is of particular interest because, by focusing on the group at higher risk of procreating, it reflects more clearly the impact of fertility control.

[Figure 2 about here]

All throughout the period there are two distinct zones of low fertility: the valley of the Seine (the Bassin Parisien) and the region of Aquitaine (the Bassin Aquitaine, in the south-west); over time, these two areas spread to the detriment of two 'islands' of high fertility: the region of Bretagne in the north-west and the Massif Central in the centre-south-east. 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 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, 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, as seen in Figure 1 England arrived quite late to the fertility transition. Figure 3 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 or follower in the decline. Changes in fertility seem to be pretty homogeneous across the country and at best it is hard to say at any time that there is heterogeneity among counties. If there was a process of diffusion taking place in England, it was indeed at much faster pace.

[Figure 3 about here]

Both the presence of clustering and the spatial evolution of rates depicted by Figure 2 points towards diffusion as an appealing way of describing what happened in France [Bocquet-Appel and Jakobi, 1998: 190], but it is certainly not the only plausible way to understand the evidence. One of the problems is that data limitations do not allow assessing whether what we see is the beginning of the story or a process 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 4 we plot a time series of the mean and the coefficient of variation across *départements* for the time since we have some data available.

[Figure 4 about here]

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. 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; but the results presented below suggest that even if that is the case, something else was also diffusing throughout the nineteenth century that was correlated with fertility.

The Simulation Experiment

Our model is an attempt to formalise the rules of behaviour that underlay those geographical patterns, echoing the theoretical discussion above about the impact of social interaction on fertility choices. As such, our model explicitly focuses on some aspects of the process and disregards others. Its main experimental aim is to analyse the correspondence between behavioural assumptions at the individual level and the diffusion of fertility rates over space and time. Our simulation treats the evolution of family size as the dependent variable and the demographic and geographical constraints, calibrated empirically, as controls; the explanatory factors are the rules that determine how agents influence each other, what in the equations above was conveyed by the term $\left(f_i - F_i^e\right)^2$. The model also evaluates 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. With this structure we are explicitly addressing Hobcrafts suggestion of integrating in mid-level theories [Hobcrafts, 2006: 155].

A detailed description of the simulation model appears in the appendix, but here we summarise its main concepts. The simulation covers the historical period between 1740 (the first moment for which we have information covering the whole of France) and 1900 (when the transition is well underway), and it is connected to empirical data in at least two levels: in the initial demographic set-up, by defining how many agents of each demographic group populate the *départements*; and in part of its dynamics, by defining how likely it is for an agent to die at different stages of its life and with no offspring at all. Its main characteristic is that agents interact in a geography that reproduces the demographic reality of France during this period, as assessed by available data. Fertility decisions agents make are affected not only by this reality but also by the local knowledge they have of what other agents around them do. All of these factors affect their decisions by means of a behavioural rule in which agents not only consider their own willingness to have children but also the desired offspring of their neighbours. When agent *i* reaches reproductive age (that is, becomes 'mature') at time *t*, she establishes her desired number of offspring ($y_{i,t}$) by considering her own inclination to have children (z_i), how likely is that the child will survive (adjusting by the level of child mortality *d*), and the average desired number of offspring that other fertile agents around them were inclined to have in *t* -1:

$$(4) \qquad y_{i,t} = \alpha z_i \left(1+d\right) + \left(1-\alpha\right) \frac{1}{m} \sum_{j=1}^{m} y_{j,t-1}$$

The degree of social influence is then captured by α. This parameter determines the relative weight agents give to their own preferences with respect to the behaviour of those around them, hence allowing us to test how much population patterns depend on this sort of social effect. The larger the value of α, the more she cares about her inclination, and the less about that of her neighbours. Since individuals most likely look at the closest generation to them, the behavioural rule makes agents take as reference the behaviour of agents $j = 1,\ldots,m$, which are all those in the vicinity that were fertile in the previous period. And here 'vicinity' takes a very specific meaning. In our model geographical proximity is defined in terms of the grid that underlies the simulated map of France, where each cell accounts for about 100 km^2, and the 'neighbourhood' is defined by the cell where the agent lives and the eight cells immediately surrounding it, as illustrated in Figure 5.

[Figure 5 about here]

The way the transition is modelled in our simulations rests on two main assumptions that stem from the theoretical model described above. First, the majority of agents in the economy are relatively close to the threshold separating the old and new fertility order, but not yet there; that is, fundamentals are such that *non-religious agents* in *isolation* (i.e., with $x(f_i) = (J/2)(f_i - F_i^e)^2 = 0$) would adjust their fertility to a new level. In the context of a modernising society with many factors encouraging individuals to have smaller families [e.g. Galor and Weil, 1999], this is probably not a costly simplification. And second, agents have two alternative strategies: to follow the fertility behaviour conventional in the *ancién regime* (labelled with the superscript ar), or to modernise (labelled with the superscript mo), which they exercise by picking a fertility level from two alternative random distributions: $Z^{ar} \sim \log N(\mu^{ar}, \sigma)$ or $Z^{mo} \sim \log N(\mu^{mo}, \sigma)$, where $\mu^{ar} > \mu^{mo}$.

This latter modelling choice of using distributions has the purpose of reflecting the heterogeneity inherent to individuals that are affected by different vectors Z_i or some occasional shock $\varepsilon_i(f_i)$. By describing fertility choices as a continuum we are somewhat relaxing one of the assumptions often made in the literature that the choice takes place in a binary decision space of 'contraception' or 'no-contraception' [e.g. Kohler, 2001] to have different *degrees* of contraception. We do recognise that the use of random distribution keeps utility maximisation as a black box, but developing a model that also looks into that aspect of the dynamic is beyond the scope of this work. On a practical side, making agents assess factors such as income or education levels, though technically possible, would have demanded an additional level of discretion at the moment of deciding parameters and functional forms for the interaction of diverse covariates and increased computational costs considerably. On a more significant matter, this modelling choice allows to focus our attention on what happens when agents decide their fertility levels in a simultaneous and interdependent manner, without the confounding effects of other variables.

At the beginning of the simulations all agents draw their inclination to have children z_i from Z^{ar}. After a certain moment, however, a certain amount of them switch to draw their desired z_i from Z^{mo}, and then this behaviour spreads other agents both vertically (mothers to daughters) and horizontally (from agent to agent). We explain in detail why and how this switch is done in Section 5, after we discuss the population dynamics of pre-transitional France in the next section.

4. SOCIAL INFLUENCE IN PRE-TRANSITIONAL FRANCE

Most of the evidence on pre-transitional Europe [e.g. Flinn, 1981] suggests fertility levels were more or less stable over time, and France does not seem distinct in that respect [Henry, 1972, 1978; Henry and Houdaille, 1973; Houdaille, 1976]. For the case of France it is also well established now that signs of a downturn became evident only after 1790 [Weir, 1983]. These two stylised facts render plausible the assumption that before the transition all individuals were drawing their fertility levels from a single, stable distribution. Bearing in mind the simulation model described in the previous section, we can then focus on this pre-transitional period and study which parametric configurations allow us to reproduce empirical patterns of population growth and fertility levels. This means basically finding the values of μ^{ar} that are consistent with the macro-behaviour of population dynamics under different values of α, the social influence parameter.

Assuming σ to be 0.45, which is more or less the average value for empirical populations as estimated from age-specific fertility tables [Flinn, 1981], we began by generating sets simulations starting in 1740 and up 1790 for different values of μ^{ar}: from 1.0 (equivalent to 2 children per family in actual data) to 3.0 (equivalent to 6 children), with increments of 0.05; and for different values of α: from 0.2 (virtually complete social influence) to 1 (no social influence at all). We assessed how these different parametric combinations affected the evolution of population levels by plotting the average of 100 simulations against the empirical data. Figure 6 shows our results.

[Figure 6 about here]

At least a couple of things are worth mentioning from the figure. The first is that several parametric combinations $\left(\mu^{ar},\alpha\right)$ lead to good fits of the population trend, where alternative degrees of social influence are consistent with different levels of μ^{ar}. Simulations where α was smaller required lower means to sustain the same population levels. This is probably a consequence of having less agents aiming at lower values of the distribution and, since there is an upper limit to the amount of children an agent can have in her lifetime, this generates a tendency to have on average larger families. In general, for every α_i there is a μ_i^{ar} that allows us to track population growth well, and the match we obtain from an optimal pair $\left(\mu_i^{ar}, \alpha_i\right)$ is comparable to that of any other pair as assessed by alternative goodness of fit measures. At this stage we lack elements to favour one parametric combination over other, but it is clear from these experiments that a simple assumption on social interaction can have substantial consequences for the dynamics of the system.

The second result of interest is that, for every degree of social influence, there is a level of μ^{ar} for which population can grow too much. This outcome is not trivial. It basically says that a population with the demographic characteristics of the French one in the eighteenth *could have grown more*. Since by construction the model does not allow agents to have more children than what is plausible given basic biological limitations (like fecundity and mortality rates, and age structure of the population) and some social considerations (effective marriage rates), the fact that there are values of μ^{ar} for which population growth is considerably higher than the empirical one implies that families in fact were probably not maximising the number of offspring. In effect, the graphs suggest that a mean of around 3 children per family (the empirical equivalent of $\mu^{ar} \simeq 1.5$) is enough to replicate the population growth of France during the period.

When turning to fertility, we face a couple of obstacles at the moment of assessing the performance of the model. One has to do with making the results of the experiments –generated in a discrete, sequential process– comparable to empirical data. For computational reasons, the simulation establishes an order of events: starting from some initial population first some people die, then the rest grow older, and finally a subset of them has children (see appendix for details). Since the number of agents is measured at the end of each of these (5-years) periods, the number of births *at that moment* is probably smaller than in a more 'continuous' world because all fertile agents that could have died in the last five years did so in the previous step. Although this effect is balanced by the dynamics of the whole system in the long run, in the short run (when we take the measure) we have a downward bias in the *measurement* of births. This will translate in fertility rates that are too low, especially those that take as reference a large proportion of the population. Given this limitation that future research on alternative simulation models can solve, we take figures on fertility with caution, paying more attention to their relative value (over time or space), than to their actual level.

When looking into the results, effectively the model produces –under the various $\left(\mu_i^{ar}, \alpha_i\right)$ pairs–somewhat lower fertility rates than those coming from the empirical estimations available, yet with the same stable trend. Our estimates of crude birth rates in the simulation are in the order of 30 to 31 per 1000, whereas the empirical average for the second part of the eighteenth century is about 39 [INED, 1977: 332-333]. The margin is not so large if we take other measures, such as the Princeton indices. For the period 1740-1790, for example, studies suggest for the whole of France average I_f values of around 0.41 [Weir, 1994: 330-331], whereas those we get are about 12% smaller (in the order of 0.36), a difference smaller than discrepancies within alternative empirical estimates of the Princeton indexes for the early nineteenth century [e.g. Weir, 1994 versus Bonnueil, 1997].

The second obstacle we face is the scarcity of regional level information to compare our results with. Beyond the estimates for the whole country mentioned above, data before 1800 are partial and scattered, so there is no direct way to assess whether simulated fertility rates for the different *départements* across France do in fact reflect actual rates in the pre-transition period. Yet there are a series of alternatives to see if they are going in the right direction. One possibility is to compare them with the estimates for the INED sample [Weir, 1983: 189, 194]. Since these values correspond to specific villages, one cannot really take the I_g values to be representative of that of the *départements* they were in, but they could provide a first (yet noisy) indicator of the simulations' performance. We find, for various $\left(\mu_i^{ar}, \alpha_i\right)$ combinations, a positive correlation of around 0.37 between Weir's estimates for the villages in the 1690-1769 period and our values for the respective *départements* in the 1740-1790 simulated interval, which is reassuring. We can also compare the results of the simulation with the earliest fertility figures available for all French *départements*, the I_f values calculated by Bonneuil [1997] for the period 1806-1811. By this time the decline had already started in some places, yet regional differences were probably dominated by the pre-transitional dynamics. With respect to these figures, we also find a positive, and stronger association to our results. Correlations were between .50 and .59, where pairs with high levels of α performed marginally better.

This later evidence must be taken with care but, overall, it suggests the model is able to replicate some of the stylised facts of France's demographic history during the *ancien regime*. The model, however, could be used to study a series of alternative scenarios and, before moving into the analysis of the transition, we carry out an additional exercise to illustrate this point. In the construction of the behavioural rule we made the assumption that parents take into account the level of child mortality in the area at the moment of deciding their family size. This is in effect a hypothesis about pre-transitional demographic behaviour that has been around for some time, most recently championed by Reher and Sanz-Gimeno [2007], but that is still somewhat contested in the literature [van de Kaa, 1996: 405-409]. Now, does a model that uses a behavioural rule where parents *do not* take into account child mortality equally good? The answer our model provide is 'no'. To assess this, we replicated all the experiments above, but with the following alternative behavioural rule:

$$(4') \qquad y_{i,t} = \alpha z_i + (1-\alpha)\frac{1}{m}\sum_{j=1}^{m} y_{j,t-1}$$

With regards to the evolution of population, the results are very similar, and Figure 7 shows two examples of this. As expected, the values of μ^{ar} that provide a good fit are higher: agents must aim to a mean close to 2 (equivalent of 4 children in the real world) to maintain the empirical population growth rate. There is somewhat more volatility in the series but, besides that, the results at macro level are not substantially different for this alternative behavioural rule. Regarding fertility, however, the results were not nearly as good. There was absolutely no relationship between our estimates at local level and those of the INED sample or the early nineteenth century *départements* figures: correlations were significantly lower in every case, and close to zero in most of them. We can read this evidence as suggesting parents were indeed looking at surviving children when deciding the size of their families, and some of the pre-transition differences in fertility rates can be explained simply by differences in infant mortality.

[Figure 7 about here]

5. Revolution, Religion and Social Influence in the Transition

As expected, running simulations that maintained pre-1790 parameters for every 'optimal' $\left(\mu_i^{ar}, \alpha_i\right)$ pair always over-estimated population growth for the nineteenth century. At least some agent must have switched to draw their fertility decision from another distribution. In this section we consider a series of experiment that explore possible causes driving such a decline. In particular, we 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 the support to the Revolution. 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) addresses the empirical 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]. At the same time, this connects with the theoretical suggestion of Kohler [2000a] that fertility choice can be partly understood as a coordination problem that induces multiple equilibria, which implies that sometimes shocks can make agents update their expectations to coordinate in a new equilibrium, and the ever-present idea in the literature that the French Revolution probably had something to do with the decline.

Recent studies suggest social upheavals have in general a profound effect on the evolution of birth rates [e.g. Caldwell, 2004; Bailey, 2009], yet the specific connection between the Revolution of 1789 and the French fertility decline has been apparent for some time [Spengler, 1938: 163-174; Flandrin, 1979: 238]. Timing itself makes it a good candidate, as the first signs of reductions in birth rates appear after 1790 [Weir, 1983: 39], but at least two types of theoretical arguments support the hypothesis. One type is linked to an ideational shift associated with the rise of a more egalitarian and democratic society following the Revolution [Dumont, 1890; Leroy-Beaulieu, 1913], where individuals now realise they can decide in aspects of their lives that were historically taken as given [Binion, 2001]. The other stresses institutional aspects of the new order, like modifications in inheritance laws [Le Play, 1874] or the revolutionaries' promotion of agricultural capitalism [Weir, 1983: 280]. In either case, there are reasons to believe the Catholic church played a key role in the changes.

There is extensive evidence suggesting a connection between religion and fertility behaviour [e.g. Derosas and van Poppel, 2006]. Up to the early nineteenth century Catholicism, which held a particular code with respect to family behaviour, remained as the main norm-setter in France and had a strong attitude against contraception [Flandrin, 1979: 194-196; Gibson, 1989: 185-186]. Regarding 'ideational shift' stories, the Revolution shook the Church to its very foundations enabling "at least some French men and women to break free from old constraints" [Gibson, 1989: 244-245], allowing them to reach a new ideal normative equilibrium in terms of fertility behaviour.

But the National Assembly interfered in the regular functioning of the Church in a more literal way by suddenly curtailing its liberties, along with its resources, and shaking its whole apparatus with the purge of its members. Towards the end of 1790 the revolutionaries imposed a clerical oath of allegiance to the new Constitution that split the clergy into jurors (*constitutionnel*) or non-jurors (*réfractaire*), fuelling confrontations within the clergy and at different levels of society. The nature and consequences of the oath are rather complex [see Tackett, 1986], but some authors have ventured the idea that the relaxation of clerical discipline in 'constitutional' regions can partly explain the rapid spread of birth control in those areas where the Church was now lacking a considerable amount of raw material to sustain clerical authority and administer sacraments. Most notably Sutherland pointed out that this contributed to put an end to a quasi-universal religious practice in France and, in particular, perhaps limited the potential ways in which local priest could influence birth control practices, facilitating the rise of 'anomalies' in sexual behaviour such as contraceptive practices, illegitimacy, and bridal pregnancies [Sutherland, 2003: 345]. Of course, arguments not primarily religious are consistent with this story. Given the extent of the influence of the Church it is not unlikely to think that 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. In either case, it is worth noting this argument has an interesting political economy corollary. If the revolutionary government had the typical pro-natalistic interest of modern states, its success in taking to pieces (at least partly) the church's structure might have been Pyrrhic, as it dismantled the institution that was helping to sustain high levels of fertility.

One way of interpreting Sutherland 's hypothesis in terms of our theoretical model is that in oath-taking areas the Revolution reduced the costs of not following the prevalent norms (i.e. those mandated by the church) via a drop in $x(f_i)$ for some of the agents. If fundamentals were such that those agents were close to the threshold to change their fertility strategy, which for early modern France is a plausible assumption, they will decided to become modern. Since the proportion of priests taking the oath varied substantially throughout the country, we use this variation to model spatial differences in this attitudinal shift. We do so in the most straightforward way: if in a *département* 25% of the priest swore the oath, then a quarter of the agents in that same *département* will now draw their personal fertility inclination (z_i) from a distribution that has a mean of μ^{mo} instead of μ^{ar}.

This is a shock that takes place only once, randomly affecting agents of all ages. Those that are young will take this into consideration when choosing their family size. Fertility of those that are mature will not be affected, because they already made their choice when becoming mature, but they will pass this trait to their offspring with probability 1. In terms of the literature on cultural transmission [e.g. Cavalli-Sforza and Feldman, 1981; Bisin and Verdier, 2001], this means that the direct vertical socialisation (that is, the one coming from the family) [Cavalli-Sforza and Feldman, 1981: 78-84] is perfect and daughters behave exactly like their mothers. But the simulation model includes as well a dynamic for oblique or horizontal socialisation (that is, the one coming from the society at large) [Cavalli-Sforza and Feldman, 1981: 130-133]. Theoretically, there are more than one reason for this to happen. On the one hand, there is indeed a role played by the expectation of behaviour of other agents as described above (through the component F_i^e). On the other hand, however, one could also think that by having shown that a low fertility strategy was possible (economically viable, and possibly even desirable) modern families reduce the uncertainty of traditional families that now are less afraid to modernise (which, among other ways, can be interpreted as the religious reward $x\left(f_i\right)$ becoming less relevant). The way we model this is by making agents decide before they enter the fertile age whether they want to continue being traditional or to become modern (we do not consider the possibility of turning traditional if you are modern), a decision that is contingent on the number of agents around them that are modern. Agents that were not affected by the initial shock will look at their surroundings (own cell and eight adjacent cells) and decide to become modern if a proportion of neighbours equal to or larger than a threshold γ are modern. This parameter γ , then, provides the second experimental space.

[Figure 8 about here]

We run several simulations for all alternative $\left(\mu_i^{ar},\alpha_i\right)$ combinations and results were in general comparable. Figure 8 illustrates some of them, corresponding to the initial combination $\left(\mu_i^{ar},\alpha_i\right)=\left(1.5,0.7\right)$. The first thing to notice is that we need relative small falls from μ^{ar} to μ^{mo} to replicate the evolution of population. In general, depending on the assumption on γ a decline of less than 20% in the average desired family size is enough to achieve the empirical population growth rates. Another feature of interest is that the dynamics of the system are quite sensitive to γ, with high values requiring a more important fall in the mean of the distribution. As in the previous section, in this case we can also find a series of combinations $\left(\mu_i^{ar}, \mu_i^{mo}, \alpha_i, \gamma_i\right)$ that maximise goodness of fit for the evolution of population. Figure 9 studies how the alternative parametric trade-offs affect simulated fertility trends when holding constant the mean of Z^{ar} and one of the parameters, while moving the other parameter and choosing μ^{mo} to minimise departure from the population trend.

[Figure 9 about here]

Again, the matching of the level is not perfect, but we do get the change in trend more or less in the right moment. Interestingly enough, the best results in both panels come from parametric combinations where social effects were present but not total. In panel (a), for example, a steep and persistent decline is achieved with intermediate levels of interaction ($\alpha = 0.7$), and not so much when it is too large ($\alpha = 0.4$) or absent ($\alpha = 1.0$). It is more difficult to read the results in panel (b), but certainly the worst are those for which $\gamma = 0$. In either case, the model does not perform as well in the later period. Partly this has to do with the fact things could be further changing (e.g. the new mean μ^{mo} could be going down all throughout the century), and we are considering a once-and-for-all shock to the system. On the other hand, this is partly consequence of the roughness of I_f as a measure of fertility. As we can see in Figure 10, since I_g incorporates the fact that people is marrying earlier in the later period, its tracking of the fertility decline is much better.

[Figure 10 about here]

But in these sets of experiments we can pay a closer look at the performance of the simulation vis-à-vis the actual data at *départements* level. Figures 11 and 12, for example, look at some areas that were laggards and leaders in the decline. The most important fact is that the model indeed shows persistence in areas of high fertility and a downward trend in those of low fertility. The simulations track better the sluggish area of the Massif Central than Brittany, and different factors might explain the difference. For example, Brittany was relatively richer and, on top of that, appears to have been largely undertaxed [Jones, 1988: 36] so, ceteris paribus, parents had more disposable income to spend on children. If children were indeed normal goods, it is not unlikely to think families in Brittany were motivated ex-ante to draw fertility from a distribution with higher mean.

[Figure 11 and 12 about here]

As Figure 12 shows, the simulation overstates the levels of fertility for the leaders, although it picks the general downward trend. A few characteristics of the model could explain this problem. On the one hand, it assumes homogeneity across all individuals in terms of social influence (that is, α remains 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.

[Figure 13 about here]

Finally, Figure 13 shows the performance of the model in other *départements* that were not leaders nor laggards in the decline and, reassuringly, trends were followed more or less well. How well is not easy to say, but we can address here the question of whether a different shock could have done as well. To look into that, we run a set of experiments with the same parameters, and with a shock that on average transformed the same proportion of agents into modern types, but that was completely random across the territory of France (i.e. not correlated with the oath-taking). As we did in our previous exercises, we used squared errors as a basic goodness of fit indicator. For the whole period, the oath-correlated shock did only slightly better, being on average 17.3% away from the true value, than the random shock (17.5%). Since these numbers are dominated by the later period, when we the general tracking of the fertility was not as good, we look into the period only up to 1856. There the oath-correlated shock does comparatively better, 16.4% versus 17.0%. Differences are small, but consistently favouring the oath-correlated shock.

6. CONCLUSION

In this paper we explored a plausible argument that can explain the dynamics of the fertility decline in France combining elements from economics and sociology. It is by no means the only possible story, but it is consistent with some the data we have available under a simple, yet theoretically-founded model of fertility behaviour. 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 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 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 partial 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. 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.

This paper reinforces the idea in recent literature [e.g. Billari and Prskawetz, 2005; Hobcraft, 2006: 176] that agent-based simulation provides a fruitful avenue to explore mechanism in a way that was previously prohibitive. Further, the model developed here could be extended to integrate micro decisions and macro behaviour. By being well defined geographically, it could use alternative contextual variables, and the fact that models heterogeneous individuals with 'long lives' allow us to look into variations in the life-course, bargaining dynamics between partners, or other variables of interest.

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APPENDIX

Agents in the model described in this paper 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), or the actual dynamic of the couples jointly determining the fertility they are aiming at [Miller *et al.,* 2004]. Nevertheless, we allowed them to live for fifteen periods to facilitate comparison with demographic data, that usually comes in five-year ranges. Agents are classified into different groups of 'age': newborns, young1 to young3, mature1 to mature5, and old1 to old6 (that is, the maximum of fifteen time periods they are allowed to live). They have two attributes associated to their age: the probability of death, a rate that is determined empirically; and fertility, which results from rules of the model. Only agents classified as mature are able to create new agents and therefore reproduce the population, following the behavioural rules discussed in the text.

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, each grid representing more or less 100 square kilometres (i.e. a 10x10 km area), and a total of 5308 cells. The simulation starts with roughly 100,000 agents that 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 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]. As can be seen in panel (a) in Figure A1, the correspondence between model and actual data is nearly perfect; only for the oldest population there are some substantial differences because, for simplicity, we only allow agents to live until they are 75. We are making the assumption that age pyramids were more or less same throughout France, which is probably not the case but is not a major drawback for the purposes of the model. 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 Panel (b) of Figure A1 shows how this was done.

[Figure A1 about here]

According to this initial set-up, not all agents will eventually have children. It is more or less agreed that Europe was characterised by a particular marriage pattern, where women married late and some did not marry at all [Hajnal, 1965]. We follow here the estimates of Henry and Houdaille [1979: 421] for the mean age of marriage for ten different regions within France at five different times in the period 1740-1900. To translate mean ages of marriages into proportion of women married by age-group we had to make the rough assumption that everyone that is ever to be married will do so by the time they are mature3 (i.e. age 30-34) and mature2 had smaller, yet constant rate. Hence, differences in age of marriage translates in different proportions of agents married in the stage of mature1. In Figure A2 we show how the averages of our departmental levels relate to the empirical estimates available for the whole of France.

[Figure A2 about here]

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

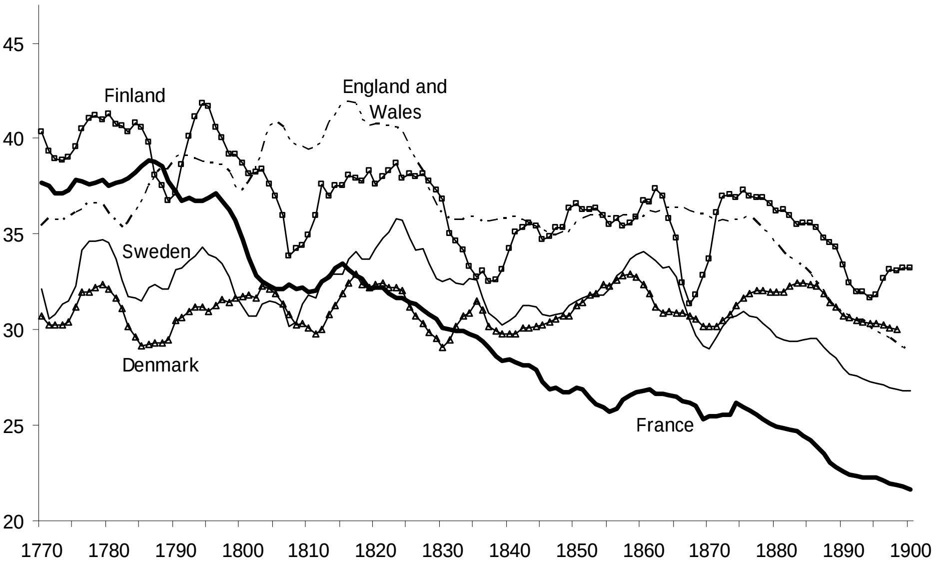
[Henry, 1961: 85] as upper-bounds and impede procreation of 15% of mature4 and 30% of mature5 (that might be married or not). With these data we obtain a series of expected proportions of agents in the risk of having children. Following this rule, mature agents can generate new agents until they reach 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. Mortality rates were estimated by Bonnieul [1997] for all age ranges every five years throughout the nineteenth century and for every *département*. 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.

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 (4). 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, depicted in Figure A3, is repeated 36 times, at which point the simulation stops.

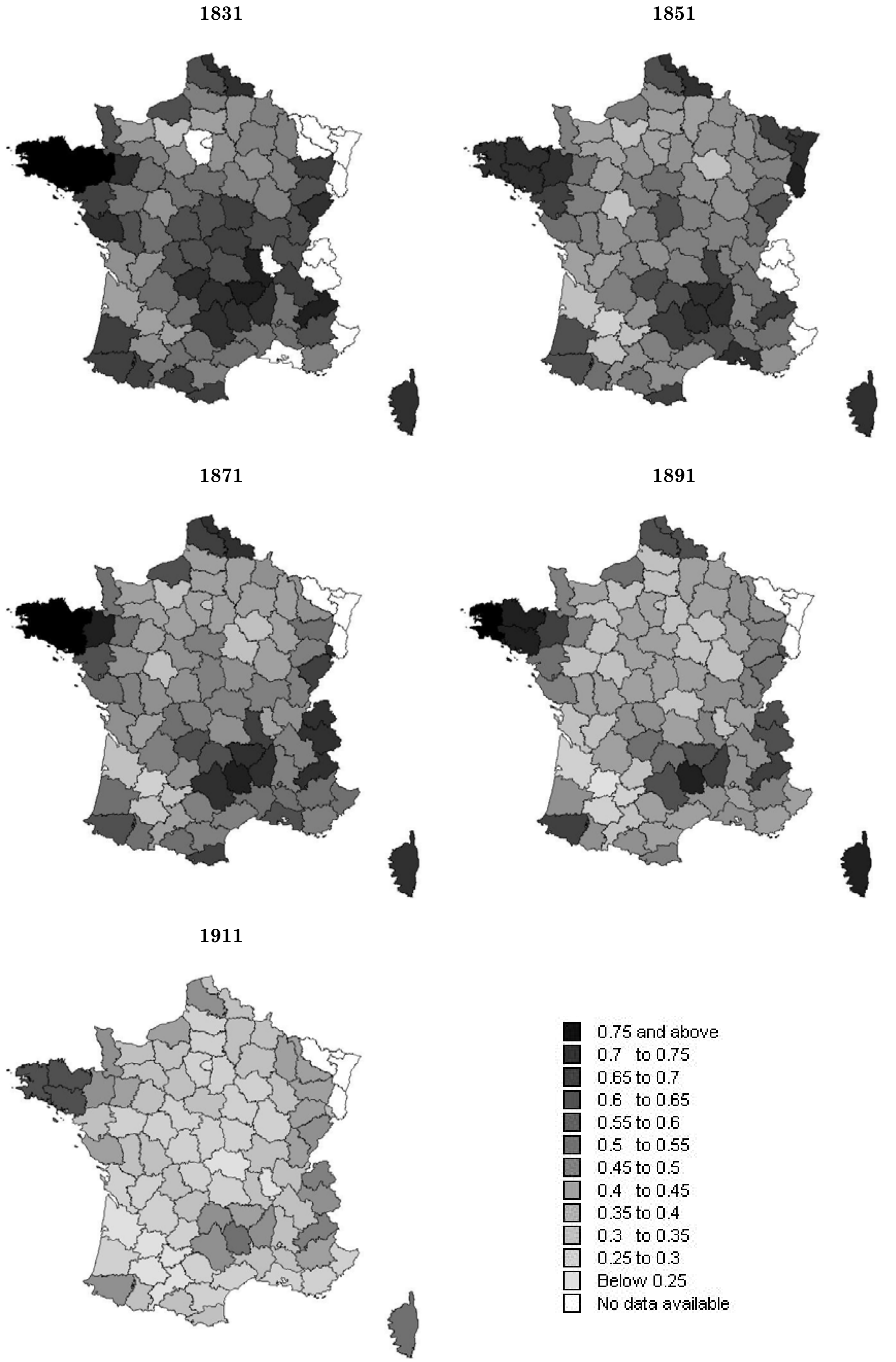
[Figure A3 about here]

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



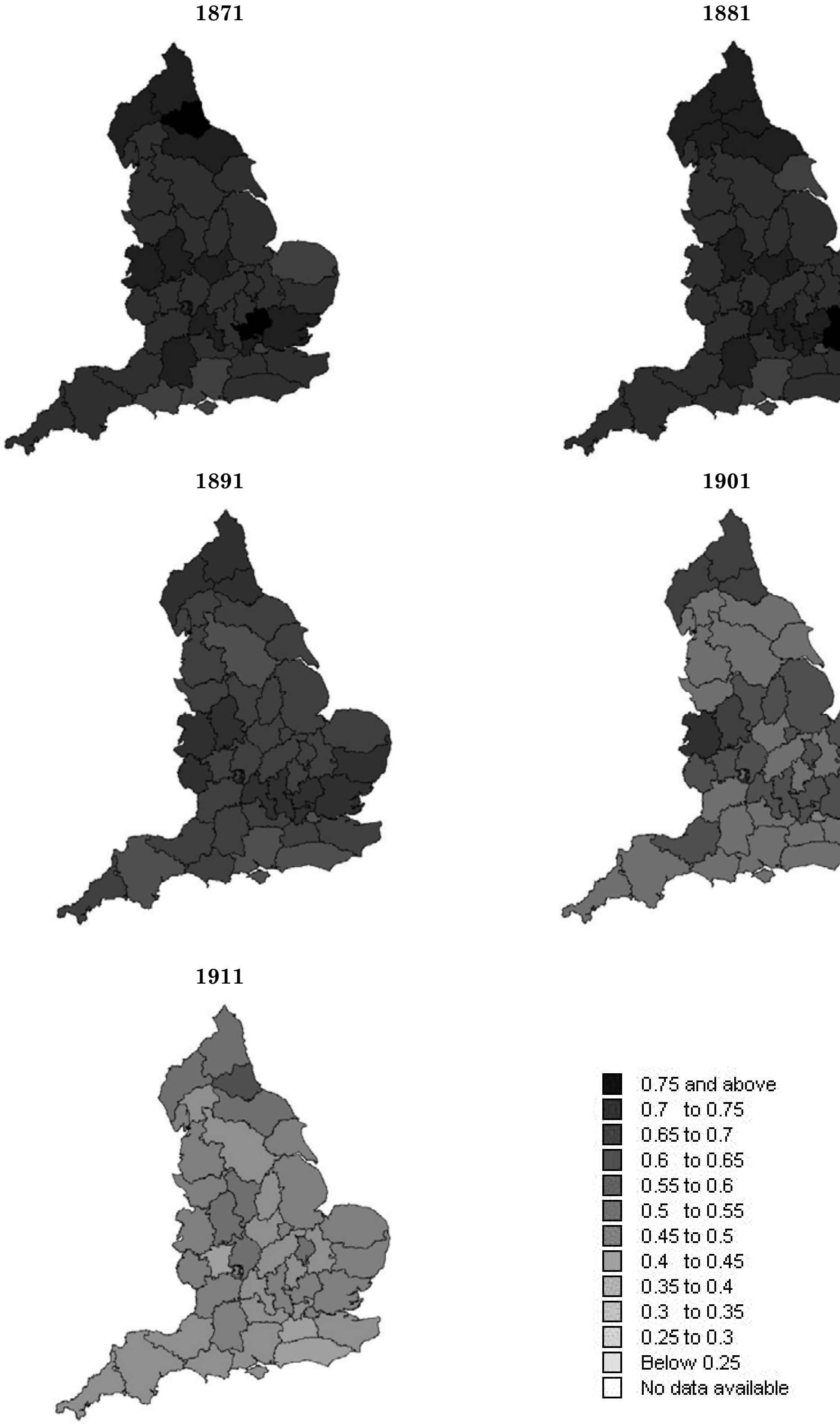
Sources: For France, INED [1977: 332-333]; Wrigley and Schofield [1981: 531-535] for England and Wales; for Sweden, Denmark, and Finland, Gille [1949: 63] and Chesnais [1992: 518-541]. Values are 5-year averages, centred in the year.

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



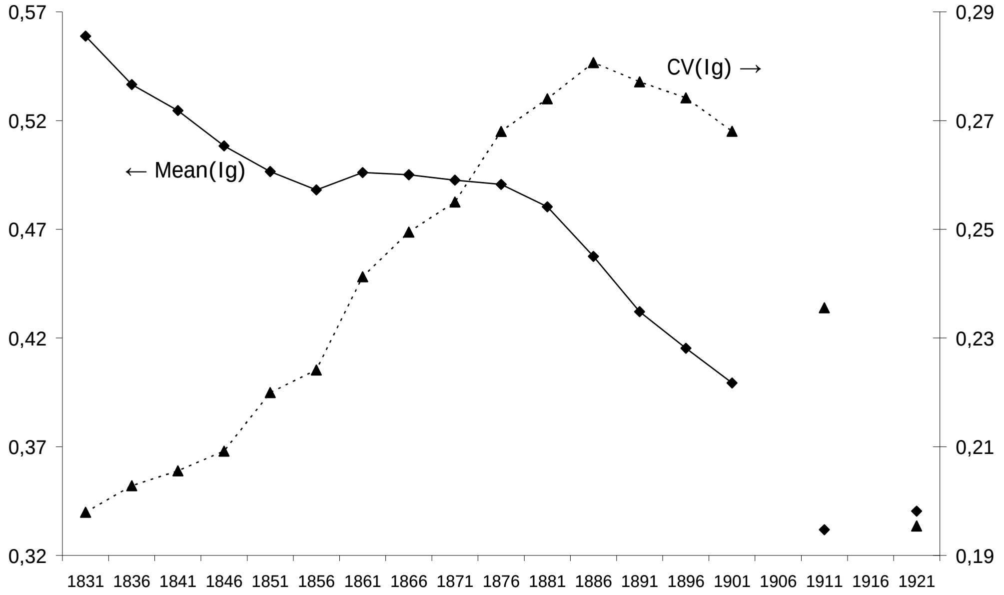
Sources: Maps are ours, constructed using data from Coale and Watkins [1986: 94-107].

Figure 3. **Marital fertility index (Ig) in England for each county, 1871-1911**



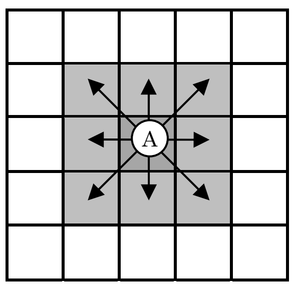
Sources: Maps are ours, constructed using data from Coale and Watkins [1986: 88-93].

Figure 4. **Mean and coefficient of variation of marital fertility (Ig) within departments, 1831-1921**

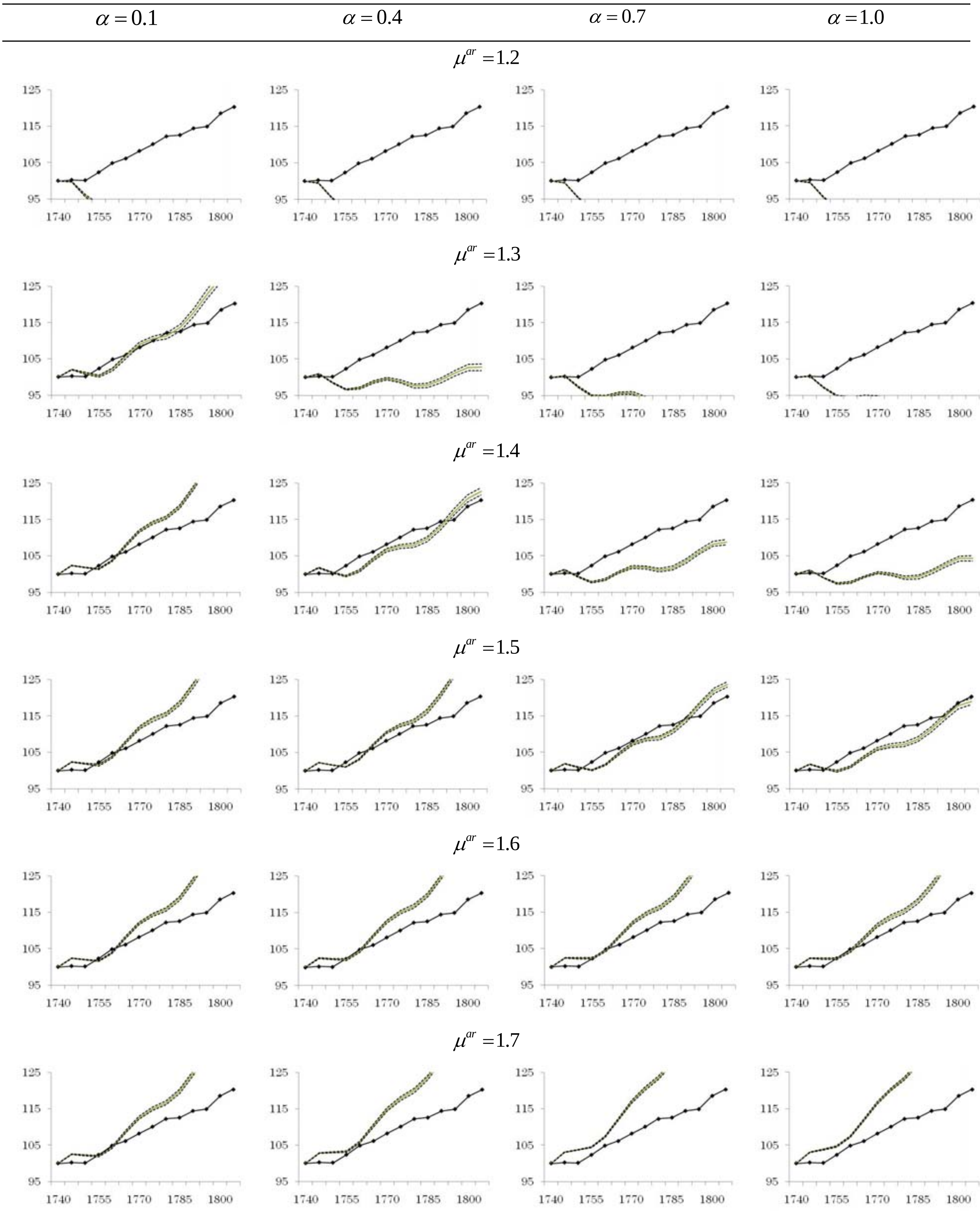


Sources: Our calculations, using data in Coale and Watkins [1986: 94-107]. Arrows indicate axis of reference.

Figure 5. **Agent's neighbours in the grid**

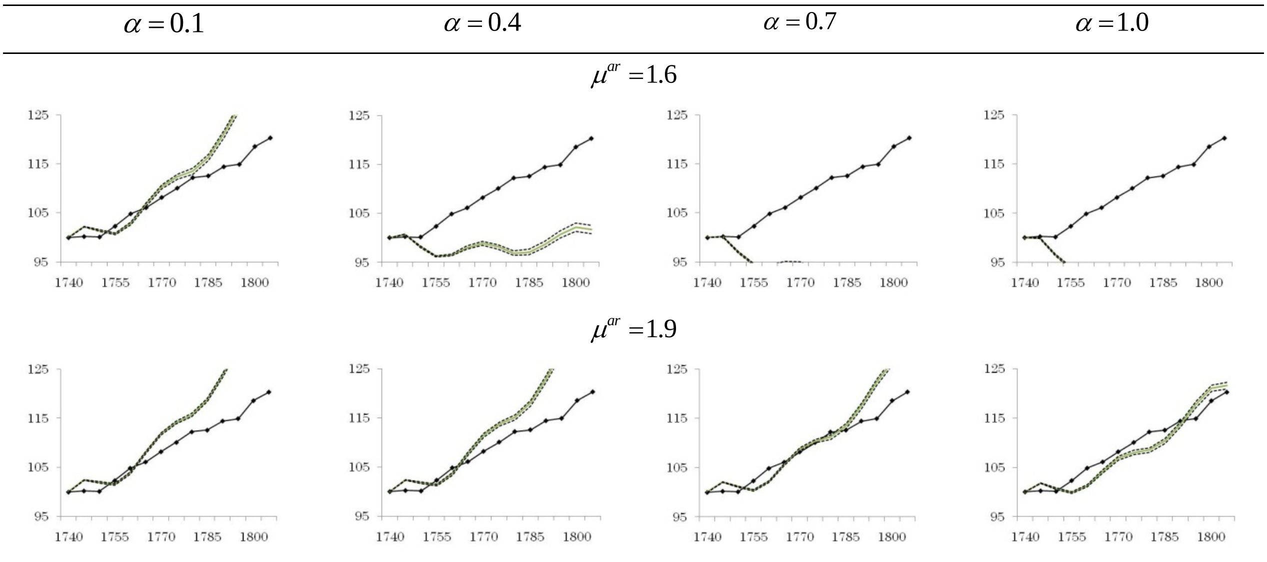


<u>Figure 6.</u> Actual and simulated levels of population for different pairs of (μ^{ar}, α)



<u>Notes</u>: Dotted lines indicate actual values and smooth lines correspond to average of 100 simulations. Actual and simulated populations are set equal to 100 in 1740. Actual population is from INED [1977: 332-333] and INSEE [1961: 36].

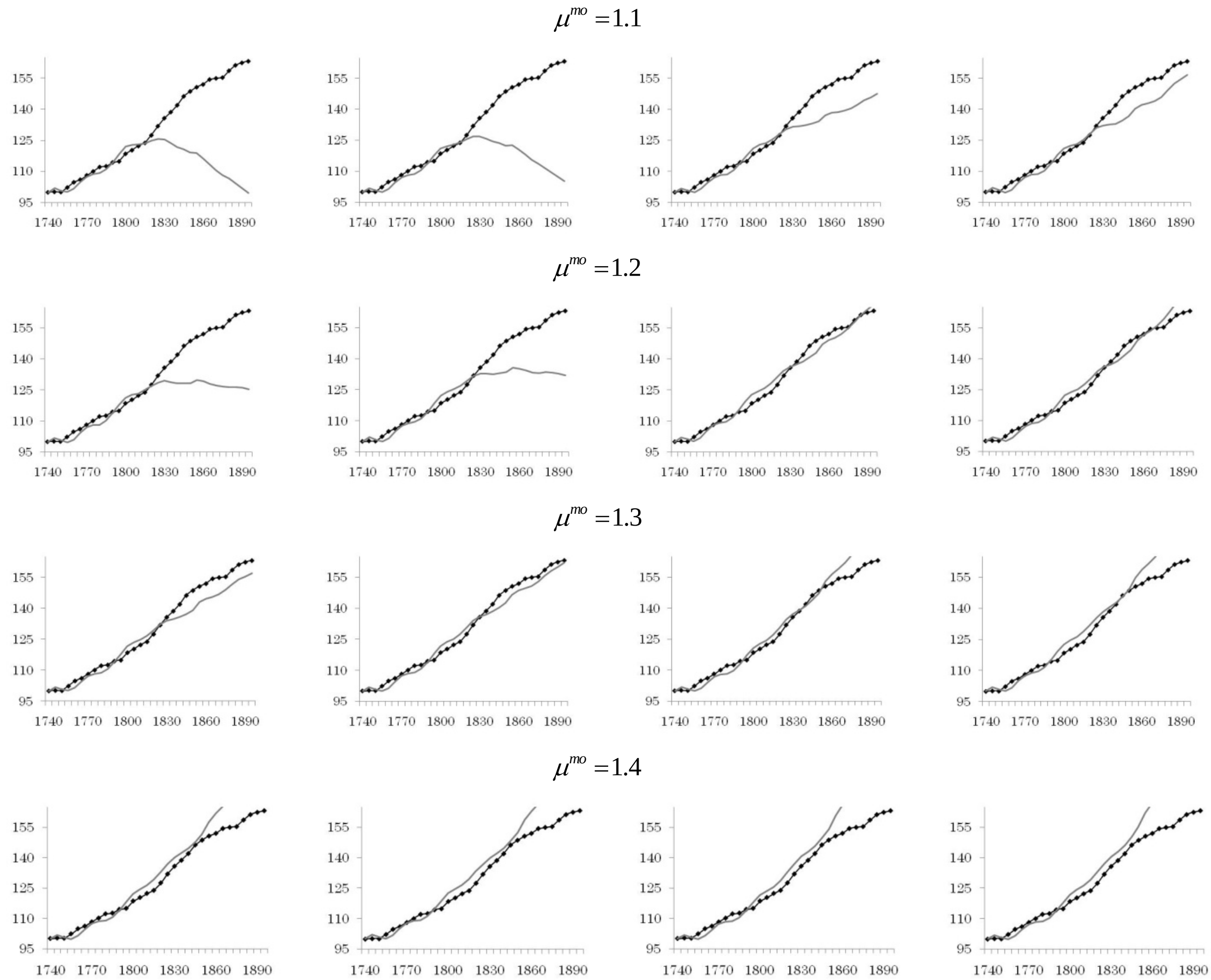
Figure 7. **Actual and simulated levels of population for different pairs of $\left(\mu^{ar}, \alpha\right)$ when the decision rule ignores child mortality levels**



Notes: Dotted lines indicate actual values, smooth lines correspond to average of 100 simulations, and dashed lines 95% confidence intervals. Actual and simulated populations are set equal to 100 in 1740. Actual population is from INED [1977: 332-333] and INSEE [1961: 36].

Figure 8. **Actual and simulated levels of population for different pairs of (μ^{mo}, γ), when $(\mu^{ar}, \alpha) = (1.5, 0.7)$**

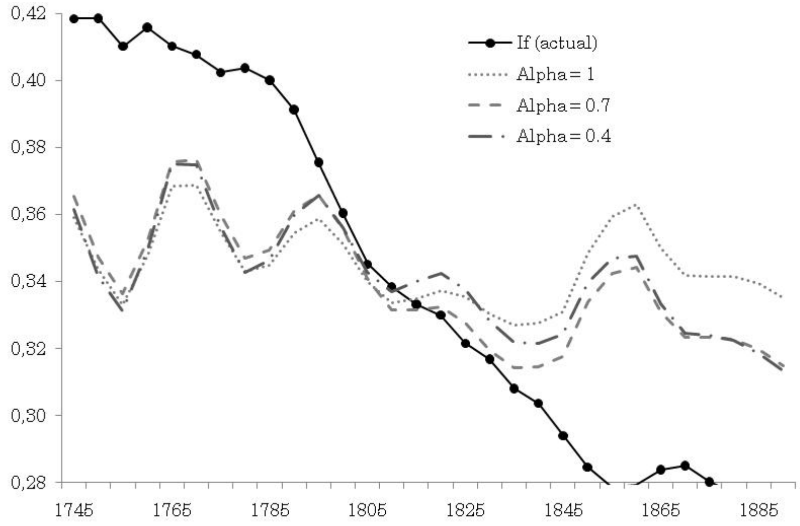
$\gamma = 0.0$	$\gamma = 0.3$	$\gamma = 0.7$	$\gamma = 1.0$



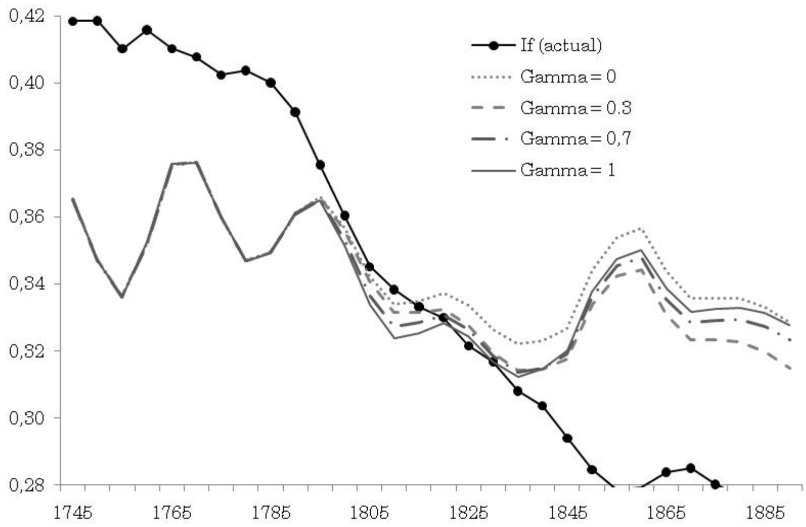
Notes: Dotted lines indicate actual values, smooth lines correspond to average of 100 simulations, and dashed lines 95% confidence intervals. Actual and simulated populations are set equal to 100 in 1740. Actual population is from INED [1977: 332-333] and INSEE [1961: 36].

Figure 9. **Actual and simulated overall fertility (I_f) and marital fertility (I_g) at macro level when μ^{ar} = 1.50, 1740-1900**

(a) Changing α (with $\gamma = 0.3$)



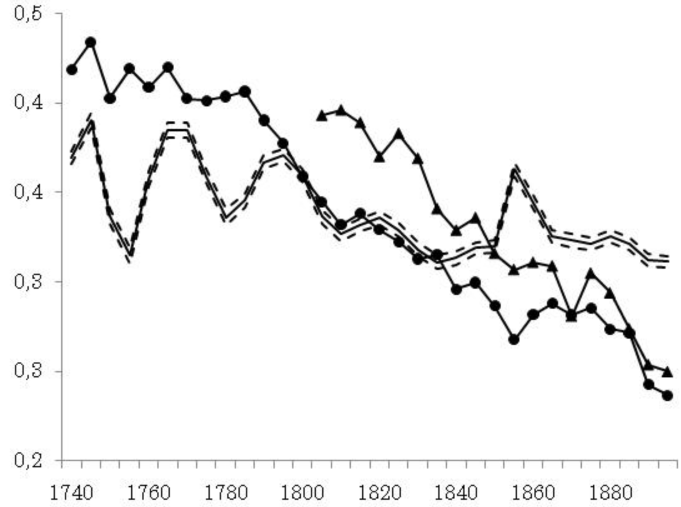
(b) Changing γ (with $\alpha = 0.7$)



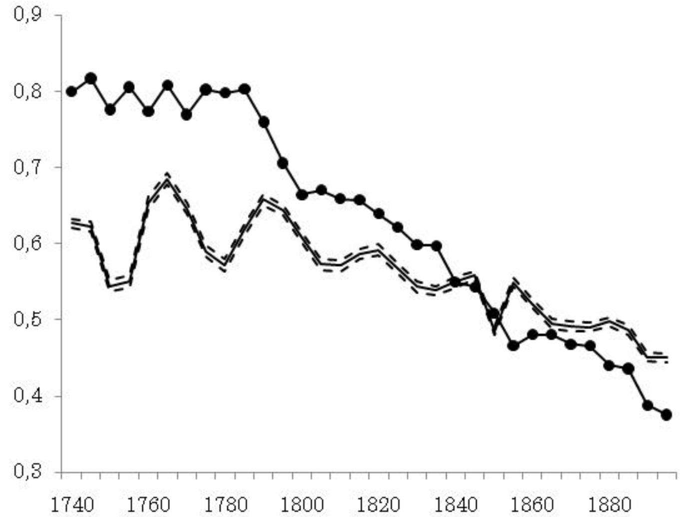
Sources: Dotted lines indicate actual values and smooth lines correspond to average of 100 simulations. Overall fertility 1740-1900 as estimated by Weir [1994: 330-331]. Simulations hold constant μ^{ar} and one parameter (either γ or α), while changing the other (either α or γ) for the value of μ^{mo} that maximised the goodness of fit for the evolution of population.

Figure 10. Actual and simulated fertility at macro level when ($\mu^{ar}, \mu^{mo}, \alpha, \gamma$) = (1.50, 1.3, 0.7, 0.3), 1740-1900

(a) Overall ferility (I_f)

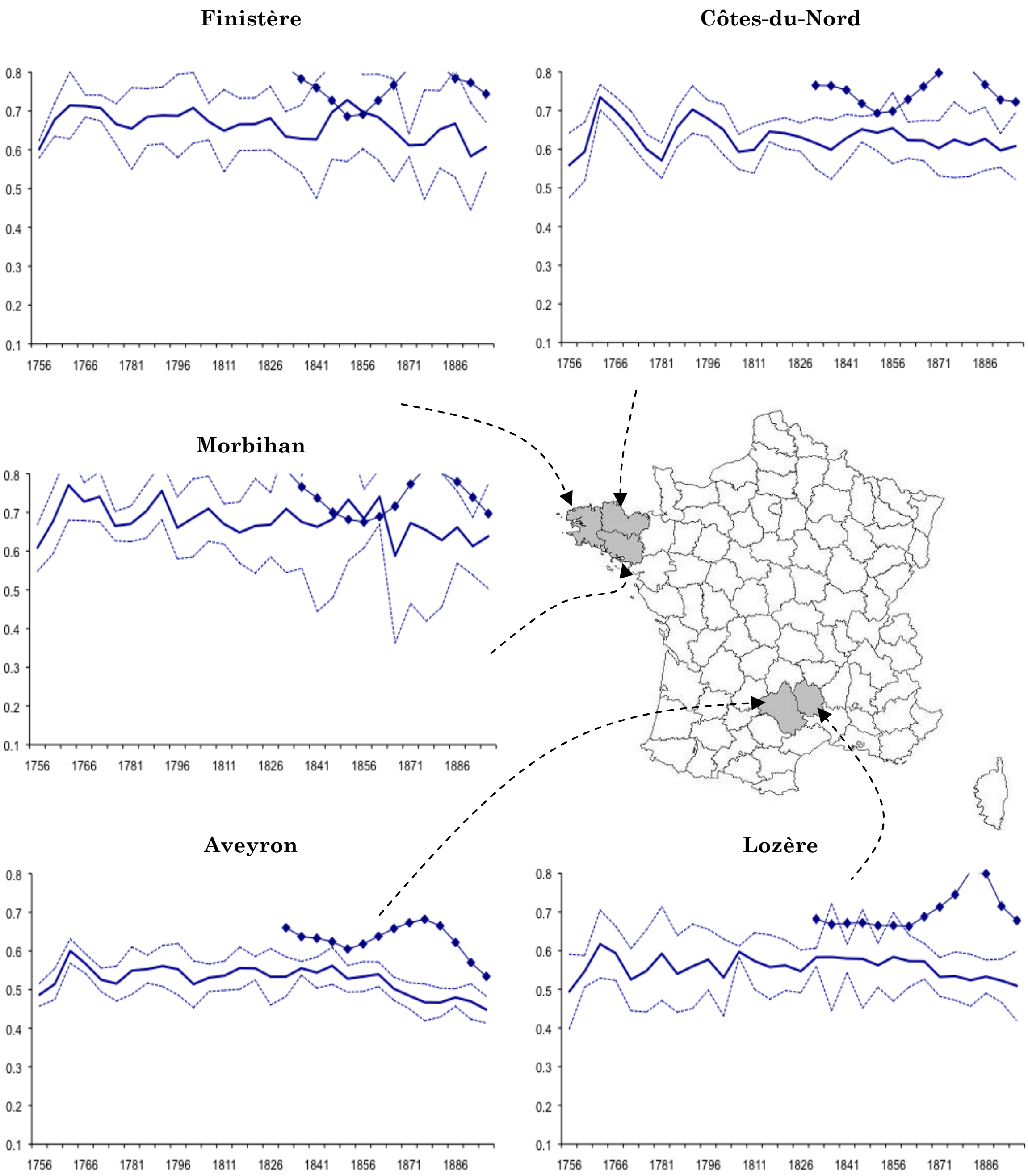


(b) Marital fertility (I_g)



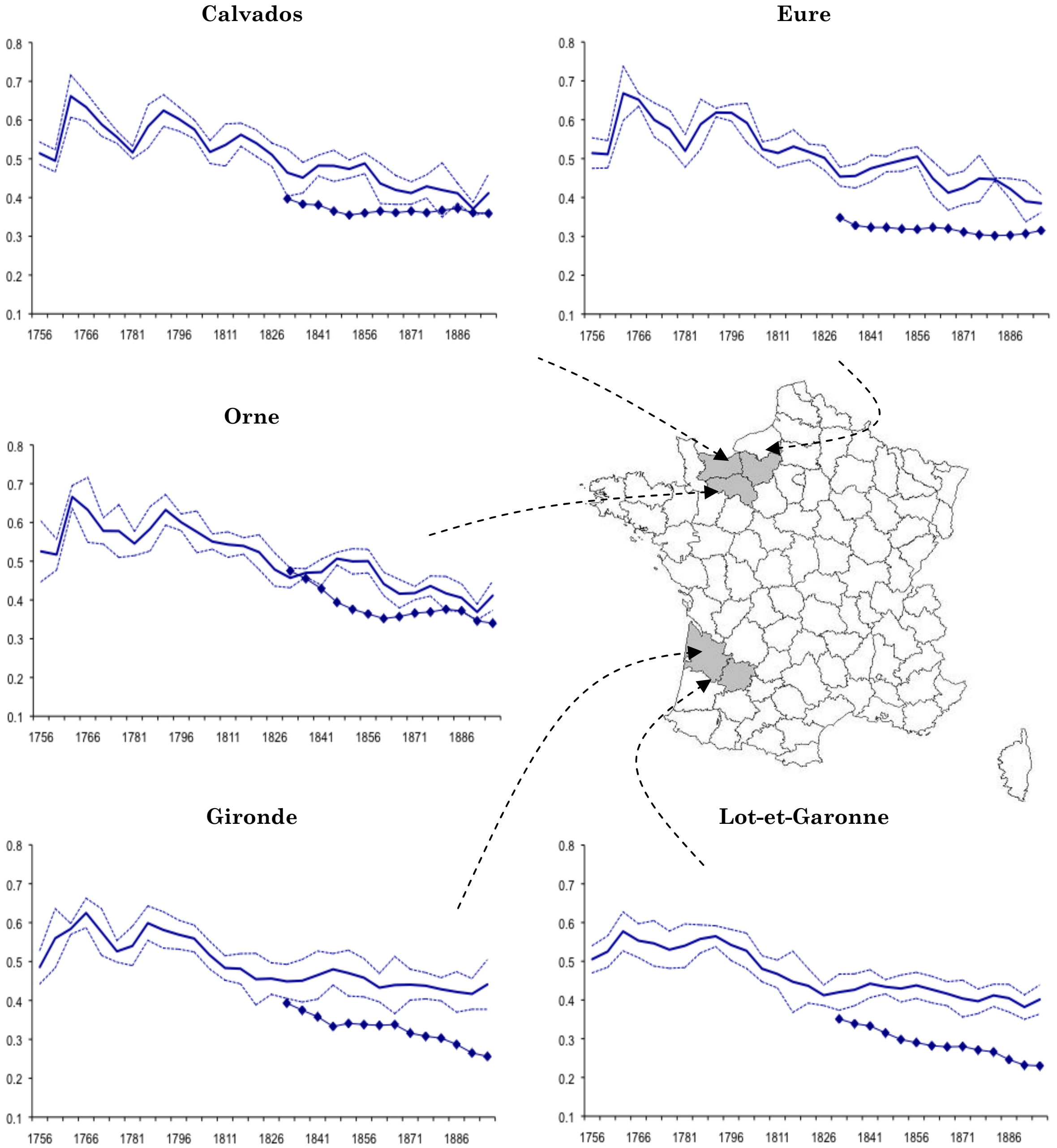
Sources: Dotted lines indicate actual values and smooth lines correspond to average of 100 simulations (dashed lines indicate 95% confidence interval). Marital and overall fertility 1740-1900 (indicated with dots) as estimated by Weir [1994: 330-331], and shorter series of overall fertility 1806-1901 (indicated with triangles) as estimated by Bonneuil [1997: 197-205]

Figure 11. **Actual and simulated marital fertility levels when ($\mu^{ar}, \mu^{mo}, \alpha, \gamma$) = (1.50, 1.3, 0.7, 0.3), lagging *départements*, 1740-1900**



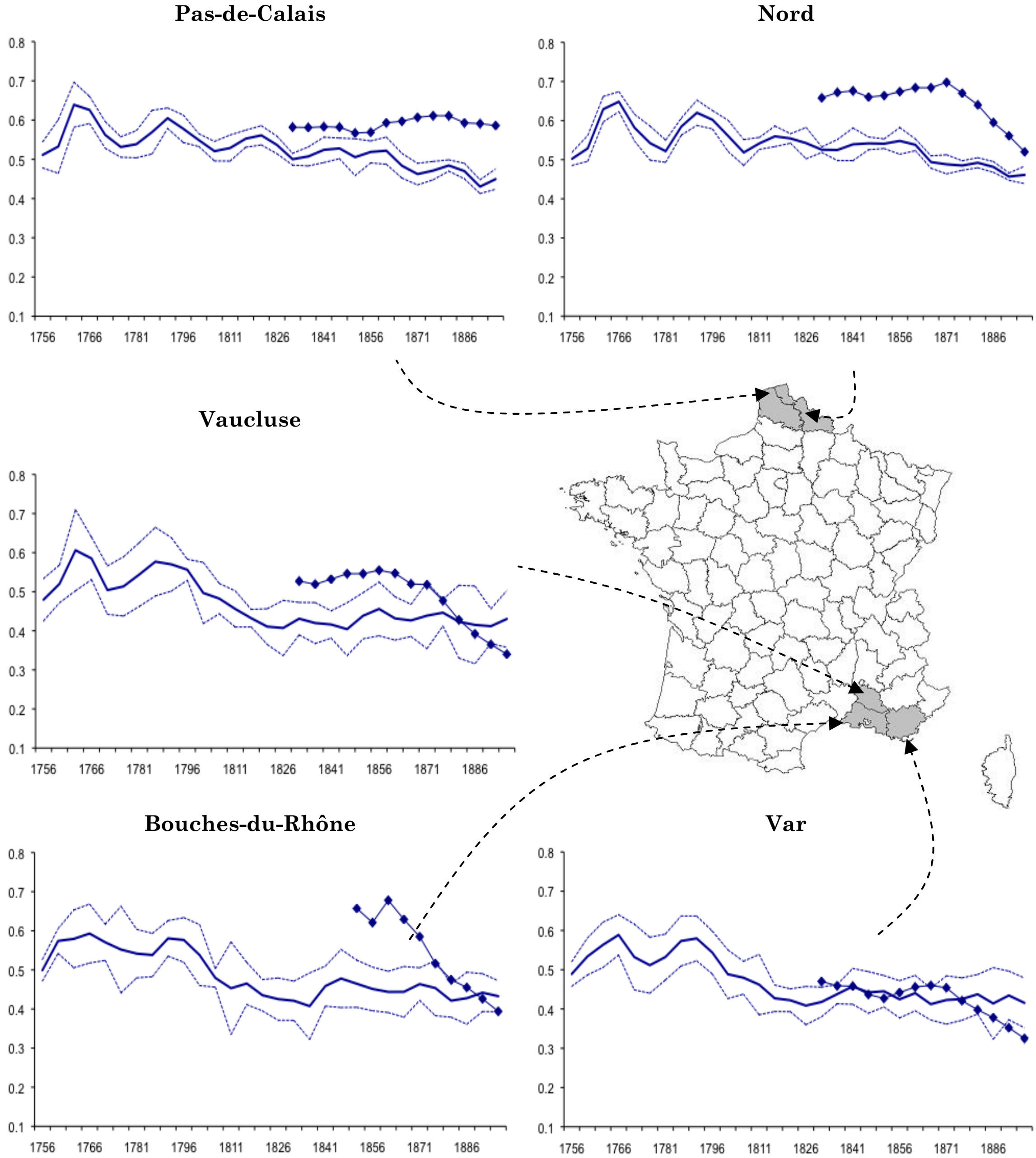
Notes: Dotted lines indicate actual values starting in 1831 [van de Walle, 1974], whereas smooth lines correspond to simulation starting in 1741. Both finish in 1896.

Figure 12. **Actual and simulated marital fertility levels when ($\mu^{ar}, \mu^{mo}, \alpha, \gamma$) = (1.50, 1.3, 0.7, 0.3), leading *départements*, 1740-1900**



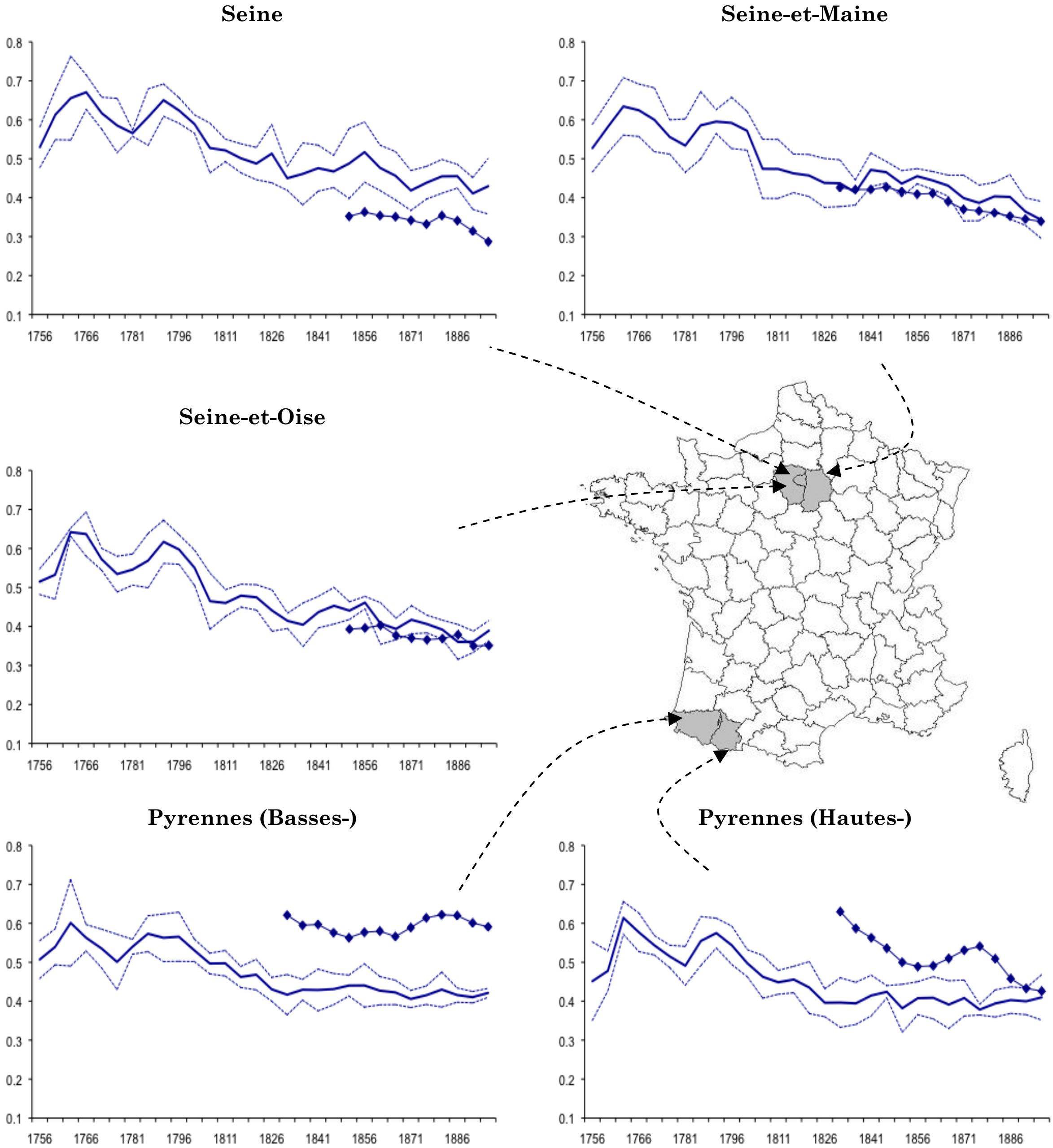
Notes: Dotted lines indicate actual values starting in 1831 [van de Walle, 1974], whereas smooth lines correspond to simulation starting in 1741. Both finish in 1896.

Figure 13. **Actual and simulated marital fertility levels when ($\mu^{ar}, \mu^{mo}, \alpha, \gamma$) = (1.50, 1.3, 0.7, 0.3), other *départements*, 1740-1900**



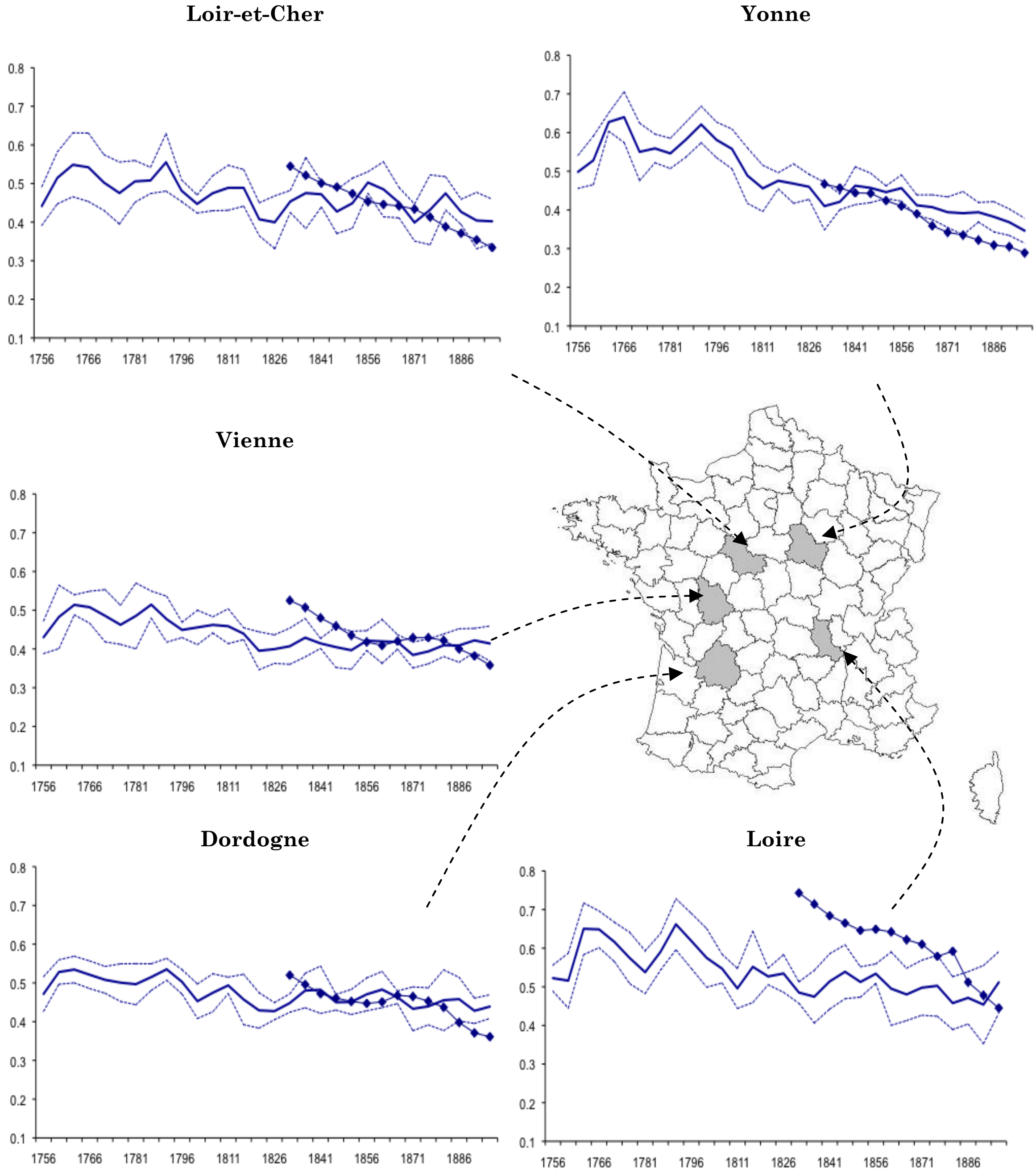
Notes: Dotted lines indicate actual values starting in 1831 [van de Walle, 1974], whereas smooth lines correspond to simulation starting in 1741. Both finish in 1896.

Figure 13 (cont.) **Actual and simulated marital fertility levels when $(\mu^{ar}, \mu^{mo}, \alpha, \gamma)$ = (1.50, 1.3, 0.7, 0.3), other *départements*, 1740-1900**



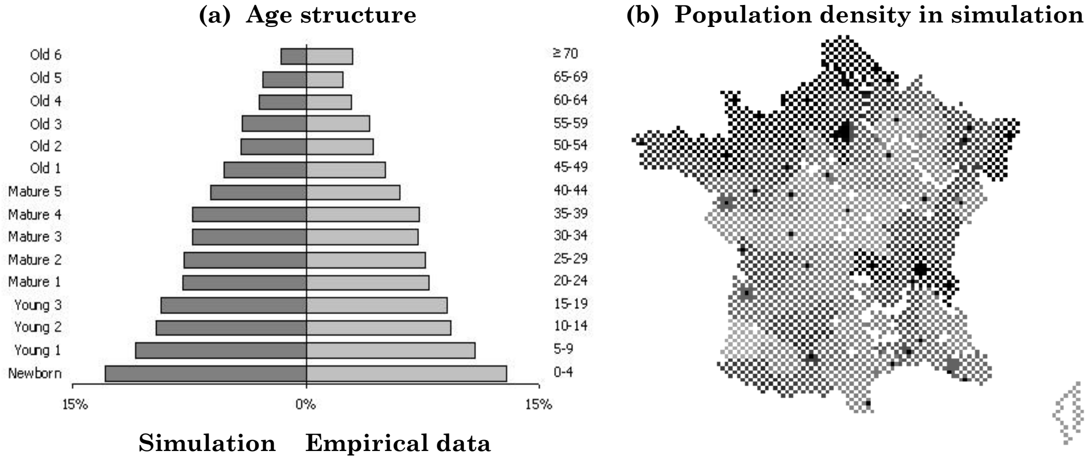
Notes: Dotted lines indicate actual values starting in 1831 [van de Walle, 1974], whereas smooth lines correspond to simulation starting in 1741. Both finish in 1896.

<u>Figure 13 (cont.)</u> **Actual and simulated marital fertility levels when ($\mu^{ar}, \mu^{mo}, \alpha, \gamma$) = (1.50, 1.3, 0.7, 0.3), other *départements*, 1740-1900**



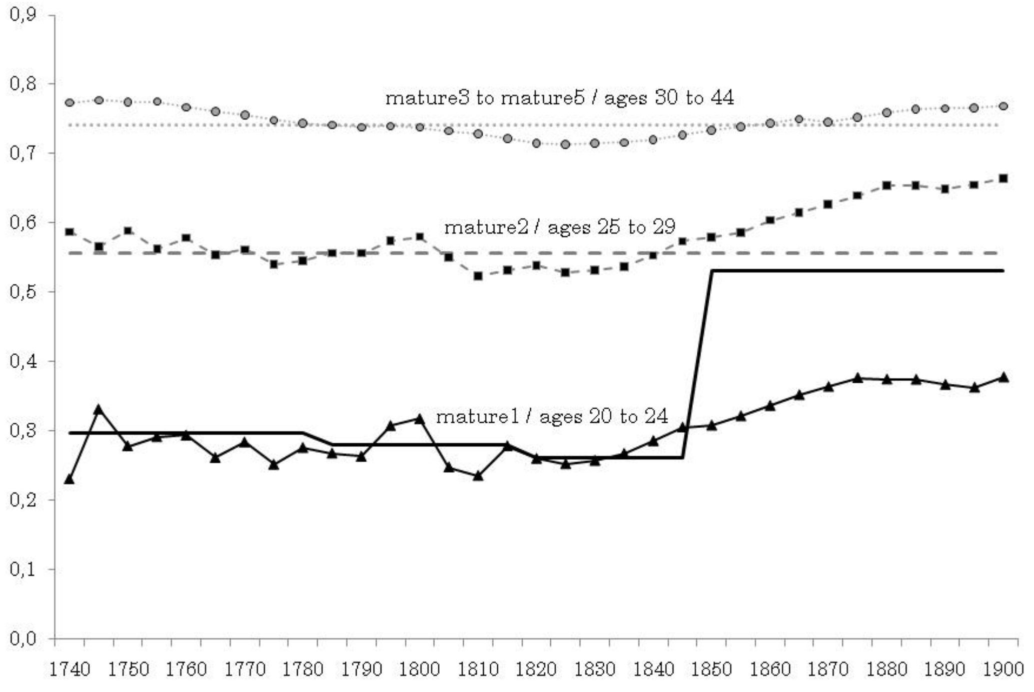
<u>Notes</u>: Dotted lines indicate actual values starting in 1831 [van de Walle, 1974], whereas smooth lines correspond to simulation starting in 1741. Both finish in 1896.

Figure A1. Demographic features of the simulation



Notes: Panel (a): 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]. Panel (b): Population density as simulated in the model; darker patches are more populated.

Figure A2. Proportions 'married' in the simulation model and real data



Notes: Dotted lines indicate actual values and smooth lines simulation.

Figure A3. Simulation dynamics