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Projecting U.S. household changes with a new household model

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Abstract

Anticipating changes in number, size, and composition of households is an important element of many issues of social concern. To facilitate continued progress in these areas, an efficient household projection model with moderate data requirements, manageable complexity, explicit accounting for the effects of demographic events, and output that includes the most important household characteristics is needed. None of the existing modelling approaches meets all these needs. This study proposes a new type of headship rate model that projects changes in age- and size-specific headship rates by accounting for the effect of changes in population age structure, changes in the age structure of household heads, and the effect of demographic events. We compare model results to historical data on the last 100 years of experience in the United States, and to results from a projection over the next 100 years using the dynamic household model ProFamy. Results show that the new model is a substantial improvement over the commonly used constant headship rate approach. A simplified version of the model that does not require projecting the effect of changes in demographic events on headship rates appears to produce reasonably accurate projections of the composition of the population by household size and age of the household head.

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Projecting U.S. household changes with a new household model

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Motivation

Anticipating changes in the number, size, and composition of households is an important element of many issues of social concern including elderly support (Dalaker, 1999), housing policies (Holmberg 1987; King, 1999; Muller et al., 1999; Canada Depository Service Program, 1996; Scottish Executive, 2000), household savings and consumption patterns (Deaton and Paxson, 2000; Tsai et al., 2000; Gokhale et al., 1996) and environmental consequences (O'Neill et al., 2001; Liu et al., 2003; Perz, 2001; MacCracken et al., 1999; Van Diepen, 1995; O'Neill and Chen, 2002; Jiang, 1999; MacKeller et al., 1995; Fuernkranz-Prskawetz et al., 2001; Carlsson-Kanyama and Linden, 1999; Select Committee, 1998).

To facilitate continued progress in these areas, as well as to support household-related work in other fields, a method of producing household projections is needed that has several important characteristics. First, it should be relatively simple, with modest data requirements and low computational intensity, so that it is amenable for use in the types of large, integrated models often applied to interdisciplinary issues, and in the kinds of extensive sensitivity analysis such studies often require (Edmonds et al., 1995; Riahi and Roehrl, 2000; Babiker et al., 2001; Alcamo et al., 1998; Fisher et al., 2002; Webster et al., 2002; Nordhaus and Popp, 1997; Jiang and O'Neill, 2004). Second, the model should produce output on the household characteristics of interest. A minimal set would include total numbers of households, distributions by size, and distributions by age of the householder (O'Neill and Chen, 2002; Jiang, 1999; Prskawetz et al., 2001; Greening and Jeng, 1994; Perz, 2001). Third, the model should clearly identify links between demographic events and changes in household structures.

Several different types of household projection models have been developed over the past few decades (e.g. Wacther and Hammel et al., 1978; Van Imhof and Keilman, 1992; Zeng et al., 1998; Kuijsten and Vossen, 1988), including headship rate models, micro-simulation models, and dynamic macro-demographic models.

While each has particular strengths, none meets all three of these needs. Although the headship rate approach is a popular methodological choice because it is easy to apply and its data demands are modest. (e.g. US Bureau of the Census, 1996; Muller Canada Depository Service Program, 1996; King, 1999; Scottish Executive, 2000; Statistics New Zealand, 2003; Australian Bureau of Statistics, 2003), it suffers from three main limitations: (1) it typically assumes that headship rates will remain constant, when in fact they are likely to change due to changes in age structure and in behaviour; (2) it produces limited detail in projected household types; (3) it does not explicitly represent links between household headship rate changes and demographic events such as fertility, marriage, divorce, and mortality. Micro- and macro-dynamic models offer much more detailed projection results and also explicitly represent demographic processes. However, they have very large data requirements and need extensive efforts in preparing the input files for running the projection. They also often suffer the problems of inconsistencies in projecting the characteristics of population and households. Thus a gap in available tools exists: an efficient household projection model with moderate data requirements, manageable complexity, explicit representation of demographic trends and output that includes a moderate number of the most important household characteristics.

The goal of our study is (1) to develop a new model for age- and size-specific headship rates as a function of overall population changes and demographic events; (2) to test the validity and stability of the model, using the U.S. as a case study and considering both historical data as well as future simulations with a more sophisticated model (the macro-dynamic household model ProFamy); and (3) to identify key next steps in the development of an efficient household model.

Model specification

In our previous work (Jiang and O'Neill, 2004), we suggested a new household model which is based on the headship rate method but extends it in two ways: first, it defines headship rates not only by age of householder, but also by household size; second the size- and age-specific headship rates would be modelled explicitly as functions of demographic rates. The new model is theoretically grounded in the conceptual framework of the family or household life cycle and life course (Sorokin et al., 1931; Glick, 1947; Hohn, 1987; Willekens, 1988; Kapinus and Johnson, 2003), which provides sociological rationales for the observation that demographic events are not equally distributed over the life span, but are generally concentrated in relatively narrow periods of life. It has the benefits of being relatively simple, transparent and computationally efficient, with manageable data requirements. It also allows projection output to be generated for two key characteristics of interest – size and age of householders – and eliminates the "black box" treatment of demographic events inherent to the classical headship rate method, thereby potentially improving the credibility of results.

The necessity of explicitly considering changes in size-specific headship rates in addition to the more common focus on age-specific rates is illustrated by historical experience in the U.S. Figure 1 shows changes in age-specific headship rates for the total population as well as for households of specific sizes, calculated from PUMS data from the US censuses over the past 100 years. The figure demonstrates the significant changes that have taken place. It is particularly noteworthy that although changes in total age-specific headship rates were relatively moderate, changes in size-specific headship rates were pronounced. In general, rates for small (1- and 2-person) households increased while rates for large (5+) households decreased. Rates for households of size 3 and 4 increased in middle age groups but decreased in older age groups. These changes in the age- and size-specific rates can be qualitatively explained as responses to changes in specific demographic events over time. Based on current understanding and empirical data, we summarize the demographic events likely to have the key impacts on headship rates for households of various sizes and age groups in Table 1.

The changes in headship rates shown in Figure 1 result from not only the immediate effect of demographic rates, but also their lagged effects on the headship rates of the future population at older ages. For example, an increase in fertility will cause an immediate increase in the proportion of the population living in larger households with heads in the childbearing age groups. However, it will also have impacts on future headship rates: as this greater number of large households ages, future headship rates for large households at older ages will increase. Accordingly, we propose a method for specifying a model for age- and size-specific headship rates as a function of demographic rates in a manner that captures contemporaneous as well as lagged effects. To do this, we take advantage of the fact that lag effects are transmitted by propagation through the age structure of the population and of householders.

Let $H_s(a,t)$ be the number of households of size s, with householder aged a, at time t; F is the number of households formed, and D the number dissolved, per unit time due to demographic events, so we have

$$\frac{\partial H_s(a,t)}{\partial t} = -\frac{\partial H_s(a,t)}{\partial a} + F_s(a,t) - D_s(a,t) \quad (1)$$

This equation simply states that the time rate of change in the number of households within a given age category of householders (left hand side) is equal to the divergence of the householder age structure plus the net formation rate (formation minus dissolution) of households of a particular size due to fertility, mortality, migration, marriage, leaving home, divorce, etc. We can derive an expression for size- and age-specific headship rates by writing the number of households as the product of population size (P) and the headship rate (h), $H_s(a,t) = h_s(a,t)\ P(a,t)$, substituting this expression for H in eq. (1), taking the indicated derivatives, and rearranging terms:

$$\frac{\partial h_s(a,t)}{\partial t} = -\frac{\partial h_s(a,t)}{\partial a} + h_s(a,t)\left(\frac{\partial P(a,t)}{\partial t} + \frac{\partial P(a,t)}{\partial a}\right) \Big/ P(a,t) + \frac{f_s(a,t)}{P(a,t)} \qquad (2)$$

where $f_s(a,t)$ is the net household formation rate [$=F_s(a,t)-D_s(a,t)$]. Eq. (2) expresses the time rate of change in headship rates as being composed of three terms. The first two represent the change in headship rates due to the effect of the age structure of either householders or population. The first term indicates the effect on headship rates of the tendency for the number of households in a given age (and size) group to change as householders age (with population size held constant); the second term indicates the effect on headship rates of the tendency for the population size to change as cohorts age (with numbers of householders held constant). The third term represents the net effect of all demographic processes leading to either household formation or household dissolution.

Use of eq. (2) as a model for headship rates would proceed by (1) specifying $f_s(a,t)$ as a function of demographic events; (2) estimating parameters for this function; (3) solving eq. (2) numerically for $h_s(a,t)$ given initial conditions, an assumed population projection $P(a,t)$, and scenarios for any demographic rates used as determinants of the $f_s(a,t)$ term (e.g., including the fertility, mortality, and migration rates used to produce the population projection); and finally (4) multiplying the resulting $h_s(a,t)$ by $P(a,t)$ to obtain the number of households by type over time. The key strength of this model is the separation of the contemporaneous effects of demographic rates in $f_s(a,t)$ from the lagged effects of these rates which are propagated through the age structure in the first two terms, made possible by the specification of the model in terms of the time rate of change of headship rates, rather than in terms of the headship rates themselves.

Model validity test

The model represented by eq. (2) is relatively straightforward to implement with the exception of specifying the fs(a,t) term. Before considering how this might be done, we test a number of simplified versions of the model to judge how influential fs(a,t) may actually be to model outcomes. The test uses the model to attempt to reproduce either historical data, or projections from a more sophisticated model, on changes in population by household size and age. Results of this test can then inform how simple, or sophisticated, a model for fs(a,t) may need to be. To do this, we consider the following set of models, from simplest to most complete:

Model 1: Constant headship rates model

All size and age specific headship rates are held constant at their initial level for the duration of the projection period. This is equivalent to assuming that all terms on the right hand side of eq. (2) are equal to zero:

$$\frac{\partial h_{s(a,t)}}{\partial t} = 0 \tag{3a}$$

Model 2: Zero events model

In this model it is assumed that fs(a,t) = 0. That is, household headship rates change due to changes in the age structure of the population and of householders, but not due to demographic events:

$$\frac{\partial h_s(a,t)}{\partial t} = -\frac{\partial h_s(a,t)}{\partial a} + h_s(a,t)\left(\frac{\partial P(a,t)}{\partial t} + \frac{\partial P(a,t)}{\partial a}\right) \Big/ P(a,t) \tag{3b}$$

Model 3: Constant events model

This model assumes that fs(a,t) is fixed at its value in the base year of the projection, while also accounting for the effects of changes in population and householder age structure. It has the advantage of including some effect of demographic events on headship rates, but not requiring any model for projecting changes in those effects over time:

$$\frac{\partial h_s(a,t)}{\partial t} = -\frac{\partial h_s(a,t)}{\partial a} + h_s(a,t)\left(\frac{\partial P(a,t)}{\partial t} + \frac{\partial P(a,t)}{\partial a}\right) \Big/ P(a,t) + \frac{f_s(a,t_0)}{P(a,t_0)} \tag{3c}$$

where t_0 is the base year of the projection.

Model 4: Full model

This model uses eq. (2) directly without simplification. Of course, it requires either calculating or projecting fs(a,t) separately. In this section we consider models in which fs(a,t) is calculated from either the historical data or more sophisticated model output that we are trying to match. In this case, the model should differ from the outcomes to be matched due only to errors in the numerical approximation used to implement it.

We test the model against (1) historical experience in the U.S. over the period 1900-2000 as derived from PUMS data, and (2) US household projection output for 2000-2100 using the dynamic household model ProFamy (Zeng et al 2006), for a scenario in which all demographic rates are held constant at their initial values. For model 4, we calculated the fs(a,t) term as a residual using eq. (2), by calculating all the other terms from the historical data and the ProFamy projection output.

Comparison to ProFamy projection

We first consider results for the comparison to the ProFamy projection. This is an easier test, since the scenario we use is one in which demographic rates are held constant. Figures 2 and 3 show results measured in two different ways. In figure 2, we show the proportional difference in the number of households by size, which is also equal to the proportional difference in numbers of people in households by size.[1] This measure is useful if results for individual household sizes are important independent of the relative numbers of people living in one size household versus another. For example, it may be important to social service providers to be able to project the absolute numbers of people living in single person households over time, regardless of whether they make up a small or large share of the total population. However in other cases, what is important is the composition of the total population by size. For example, studies of the potential macro-economic effects of shifts in living arrangements need to know how the proportion (rather than the absolute size) of the population living in a particular household size or age group might change, since the effects of the population composition depend on these proportions, and not on absolute size. Therefore, Figure 3 expresses the same results in terms of the difference between the proportion living in households of a given size as projected by the ProFamy model versus one of the four models described above.

Figure 2 shows that the constant headship rate model does not do very well for most household sizes. While it projects the number of people living in 2 person households relatively accurately (less then 5% difference from the ProFamy projection at any time), it under-projects numbers living in larger households (size 3-7+) by up to 10-35% in the long run, and over-projects numbers living in 1-person households by up to 35%. The zero effect model does not provide much improvement: all household sizes are under-projected by 10-30% at some point over the projection horizon. In contrast, the constant effect model improves the outcome considerably. The population living in households of size 2-6 are within 5% of the ProFamy projection at all times, and the population in households of size 1 and 7+ are always within10% of the ProFamy projection. Comparison with the results from the

[1] Results for proportional difference in the numbers of households, and number of people living in those households, are not equal for the largest size category, 7+, because the household size is not constant over time in this category. However the effect is small.

full model indicates how much of this error is due to numerical approximation, and how much due to the simplification of keeping the demographic rates term constant over the projection period. The full model results differ from the ProFamy projection by no more than 5% for any household size, so roughly half the error in the constant effect model is likely due simply to the numerical approximation scheme.

Figure 3 shows a similar pattern for results using our alternative measure of model validity, although performance for all models is not as bad by this measure. The constant headship rate model over-projects the proportion of the total population living in households of size 1 and 2 by 3-4 percentage points, while under-projecting the proportion living in larger households by 1-2 percentage points. The zero effect model is some improvement, limiting differences with the ProFamy model to a maximum of about 1 percentage point. The constant effect model improves the situation even more, with the projected composition of the population accurate to within 0.5 percentage points of the ProFamy results, except for 1-person households which are only slightly more inaccurate. The full model results indicate again that a substantial fraction of the inaccuracy in the constant effect model is likely due simply to the approximation inherent in the numerical scheme for solving the model.

Thus on balance results indicate that the constant effect model produces results rather similar to the ProFamy model according to both measures: it is within 10% of the absolute population living in each household size, and within 0.5 percentage points of the projected share of the total population living in each household size. There is one further important consideration. In general, headship rate models suffer from the problem of inconsistency of implied total population size. That is, when applying size-specific headship rates to a projected population age structure, there is no guarantee that the number of people implied by the size specific household projection will be equal to the total number of people available in the projected population. Thus, some type of adjustment method is typically applied to correct for this problem. The results presented above are unadjusted. Table 2 summarizes the proportional differences in both total number of households and total population size implied by the four models, as compared to the ProFamy projection outcome. It shows that the constant headship rate model again does not fare well: it over-projects the number of households by up to 3%, and the implied total population by up to nearly 7%. The zero effect model does even worse, over-projecting both outcomes by up to nearly 12%. In contrast, the constant effect model is within 2% of the total number of households projected by ProFamy, and even more importantly is within a few tenths of a percent of the total projected population. Thus the constant effect model has another feature to recommend it: at least in this test case, it requires almost no adjustment to maintain consistency with the population projection, under the condition that all demographic events are kept constant for the whole projection period.

Historical comparison

Figures 4 and 5 present the same sort of results as Figures 2 and 3, but for a simulation of experience over the past 100 years, rather than for a projection of the future. This provides a tougher test of the model, since as shown in Figure 1 headship rates have undergone dramatic changes over the past century, with substantial changes in demographic rates. We focus our analysis on the constant headship rate model and the constant effects model.

As might be expected, the constant headship rate model performs very poorly in the long run, although it produces a relatively small error in projected total number of households in the first three decades. Using headship rates that were observed at the beginning of the century, it projects double the actual size of the population living in households of size 5+ by 1950, and triple the actual number in 2000. At the same time, it under-projects the numbers living in small (size 1 and 2) households by 50-75% by late in the century. Looked at in terms of population shares, performance is still very poor: the share living in 5+ households is overprojected by up to 30 percentage points, and the share living in sizes 1 and 2 is under-projected by 10 to 15 percentage points.

In contrast, the constant effect model performs substantially better. Projections of the number of people living in different household sizes are generally within 25% of actual experience, with the exception of a few time periods for 5+ households (and to a lesser degree 1-person households) where differences approach 50%. Projections of shares are accurate to within 3 or 4 percentage points, with the exception of a few time periods for 5+ households when projections are off by about 9 percentage points.

As shown in Table 3, the constant effects model also substantially reduces the problem of inconsistency with projected population totals. The constant headship rate model over-projections population by up to 20%, while the constant effect model remains within about 11% of the total population. It is possible that applying an adjustment method to the constant effect model could improve not only the match to total population, but also to outcomes for particular household sizes. An inspection of Table 3 and Figures 4 and 5 shows that the largest inaccuracies in the results for particular household sizes tend to occur when inconsistency with the total population size is largest. We suspect, therefore, that adjusting for inconsistency will improve the size-specific outcomes, but we do not explore that possibility here.

Modeling the effect of demographic events

Results of the comparison of alternative models to historical experience and a ProFamy projection of the future suggest that a model which includes a constant contemporaneous effect of demographic events on headship rates can perform well for a projection in which demographic rates are held constant. Performance is less good in comparison to historical experience, over which time demographic rates changed substantially, although the model performs far better than the constant headship rate approach. This suggests that there may indeed be situations in which it would be useful to develop a means of modeling changes in the fs(a,t) term over time, as a function of changes in demographic rates. We explore that possibility here.

To begin, we examine the form the fs(a,t) term has taken according to historical data and the ProFamy projection for the U.S. Figures 6 and 7 show these results, calculated as a residual using eq. (2) and either historical data or model output. The figures indicate that the shape of the term differs for each household size, but is relatively robust over time in both the historical data and projection output. The variation in the projection output is very small given the constant demographic rates assumption, while the variation over the history is larger due to the dynamics of demographic rates in various periods of time. The similarity in shape, however, suggests that this term may be amenable to modeling.

To specify models for the fs(a,t) terms, we propose a model of the general type

$$f_s(a,t) = \sum_{n=1}^{N} g_{s,n}(a, r_n(t), \beta_{s,n}) + \sum_{n=1}^{N} y_{s,n}(a, r_n(t), h(t), \beta_n) \qquad (4)$$

where the functions g (for each household size) depend on age, a demographic rate (r), and parameters (β) to be estimated for each of N demographic rates, as do the functions y, which represent possible interaction terms and therefore also depend on the household age structure and composition across types reflected in h(t). The observed shape of the $f_s(a,t)$ term for each household size (figs. 6 and 7) depends on the net effect of all demographic rates, and therefore it may be difficult to determine the appropriate functional forms of the functions $g_{s,n}$ in eq. (4). We have tested a means of developing functional forms based on model experiments that slightly perturb a single demographic rate and determine its marginal effect on the $f_s(a,t)$ term. For example, Fig. 8 shows the difference in the $f_s(a,t)$ term induced by a small perturbation to the fertility rate in the year 2000. It shows that a change in fertility has a very regular effect on the net household formation rate for each household size. For example, for smaller households (size 1 or 2), it decreases the headship rate (since increased fertility leads to more children and fewer small households). We have also tested the stability of this effect over time by repeating the perturbation experiment in 2050, and found nearly identical results (figure 8). The small difference most likely indicates interaction effects.

These preliminary results suggest that it may indeed be possible to model changes in the fs(a,t) term over time as a function of change in demographic rates, although further progress is left to future work.

Discussion and Conclusions

We have proposed a new household projection model based on projecting changes in age- and size-specific headship rates. The aim of such a model is to be able to project reasonably accurate outcomes for a small number of household types (here limited to the size of households and the age of the household head) in a simple and computationally efficient model with minimal data requirements. We find that a model that includes the effects of changes in the age structure of the population and of householders, and that holds the contemporaneous effect of demographic rates constant (i.e., a "constant effect model"), produces an excellent match to the outcome of a more sophisticated household projection model, at least for a scenario in which demographic rates do not change. It also produces a reasonable approximation of historical experience over the past 100 years, when demographic rates changed substantially. This is especially true for projections of the share of the population living in households of particular types; results for the absolute numbers of people living in each household size were less accurate. In all cases, however, the constant effect model is a substantial improvement over the common constant headship rate approach.

We have also suggested a means of projecting changes over time in the contemporaneous effect of changes in demographic rates, as a means of improving on the constant effect model. An initial analysis of historical data and ProFamy model output suggests that there are empirical regularities in the effects of demographic rates that can be exploited to model such changes, although further work is required to test the feasibility of this approach.

There are several caveats and areas that require further work. The performance of the alternative models should be evaluated according to additional metrics. For example, we have examined here the accuracy of projected numbers of people living in households of different sizes, but it would be valuable to examine outcomes for the population by age of the household head within each size category as well. We anticipate that the dynamic headship rate approach we propose here will outperform the constant headship rate model, but this test remains to be done. In addition, all headship rate models that include some measure of the size of a household will produce implied population sizes that are inconsistent with total population in the population projection to which the headship rates are applied. Although the constant effect model greatly reduces this problem, further work should explore how different adjustment methods may affect the accuracy of the model. We suspect that adjustments for total population consistency will improve results for composition by household size, but we have not yet carried out this test.

Finally, the dynamic headship rate approaches should be tested against a wider range of projections for the future. We have limited our analysis here to one projection which assumes constant demographic rates. Further work will explore performance relative to scenarios with changing rates. In addition, we plan to test the approach in other countries where demographic conditions differ from those in the U.S., particularly in developing country settings which face potentially much larger demographic changes, including trends away from living in extended families.

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Table 1. Demographic events of importance to a model of size-specific headship rates

HH Size	Key demographic events and parameters affecting headship rates		
	Early adulthood group	*Middle age group*	*Elderly age group*
1	Propensity of leaving home, Age and rate of marriage, divorce rate	marriage, remarriage and divorce rate, propensity of leaving home	Mortality, propensity of leaving home
2	Age and rate of marriage, age and rate of first birth, divorce rate	Propensity of leaving home, divorce rate, mortality	Mortality, propensity of leaving parental home
3	Fertility rate of first and second birth, divorce rate	Propensity of leaving home, divorce rate	Mortality, propensity of leaving home
4	Fertility rate of second and third birth, divorce rate	Fertility of second and third birth, propensity of leaving home	Mortality, propensity of leaving home

Table 2. Proportional differences in total households and total population size between the ProFamy projection outcome and various headship rate model outcomes.

	Total Households				Total Population			
	Constant headship	Zero effect	Constant effect	Full model	Constant headship	Zero effect	Constant effect	Full model
2000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2010	-0.026	-0.040	-0.009	-0.009	-0.011	-0.020	-0.002	-0.002
2020	-0.033	-0.064	-0.001	-0.001	-0.020	-0.039	-0.002	-0.001
2030	-0.029	-0.084	0.005	0.002	-0.028	-0.061	-0.002	-0.002
2040	-0.024	-0.103	0.007	0.002	-0.037	-0.084	-0.002	-0.003
2050	-0.016	-0.111	0.008	0.003	-0.043	-0.098	-0.002	-0.003
2060	-0.006	-0.115	0.010	0.004	-0.048	-0.110	-0.001	-0.002
2070	0.002	-0.109	0.016	0.015	-0.054	-0.113	-0.002	0.003
2080	0.012	-0.102	0.017	0.015	-0.058	-0.115	-0.002	0.002
2090	0.021	-0.093	0.018	0.016	-0.063	-0.117	-0.001	0.003
2100	0.030	-0.084	0.019	0.016	-0.068	-0.117	0.000	0.004

Table 3. Proportional differences in total households and total population size between historical data and two different headship rate model outcomes.

	Total Households		Total Population	
	Constant headship	Constant effect	Constant headship	Constant effect
1900	0.0000	0.0000	0.0000	0.0000
1910	0.0183	0.0286	0.0411	0.0395
1920	0.0161	0.0022	0.0586	0.0108
1930	0.0046	-0.0034	0.0795	0.0185
1940	0.0139	0.0171	0.1477	0.0634
1950	-0.0343	-0.0351	0.1499	0.0111
1960	-0.0973	-0.0619	0.0773	-0.0636
1970	-0.1629	-0.0524	0.0431	-0.0159
1980	-0.2155	-0.0295	0.0740	0.0824
1990	-0.1915	0.0354	0.1664	0.1187
2000	-0.1786	0.0173	0.2035	0.0425

Figure 1. Changes in US headship rates by age and size of household, 1900-2000.

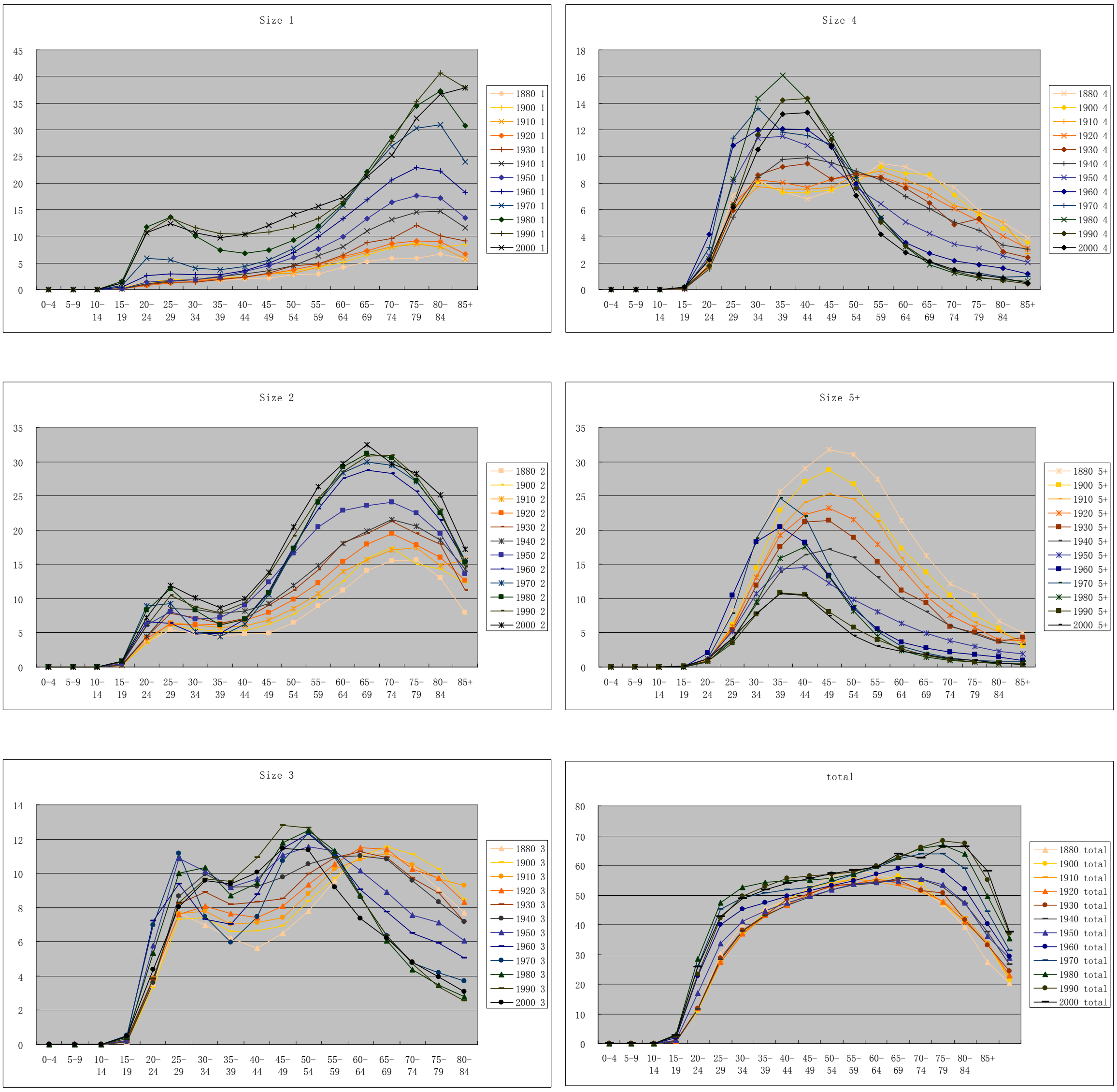
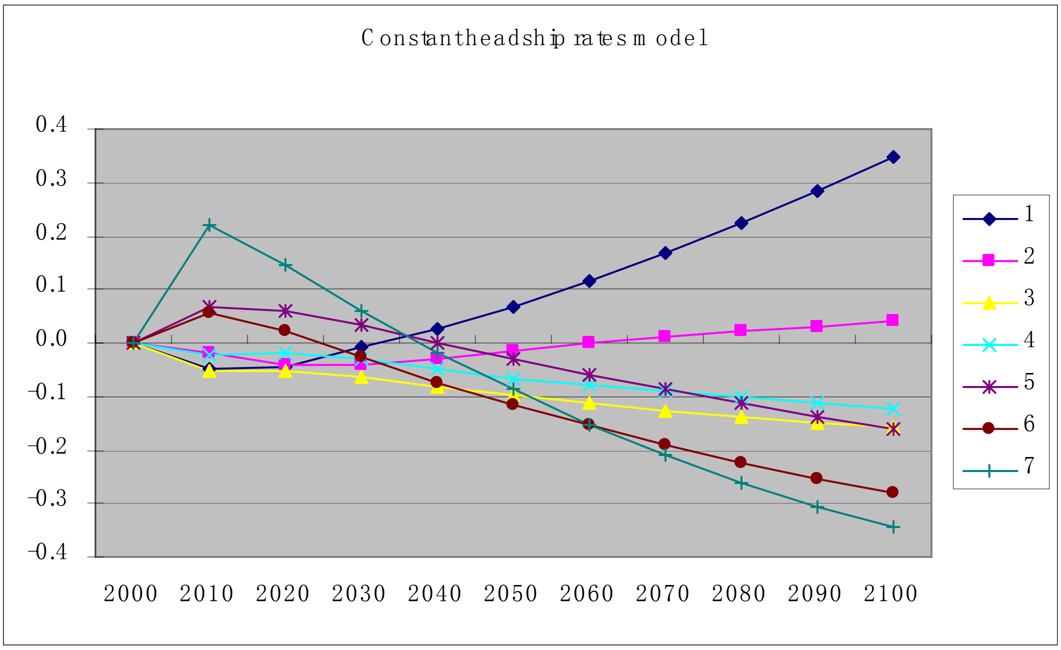
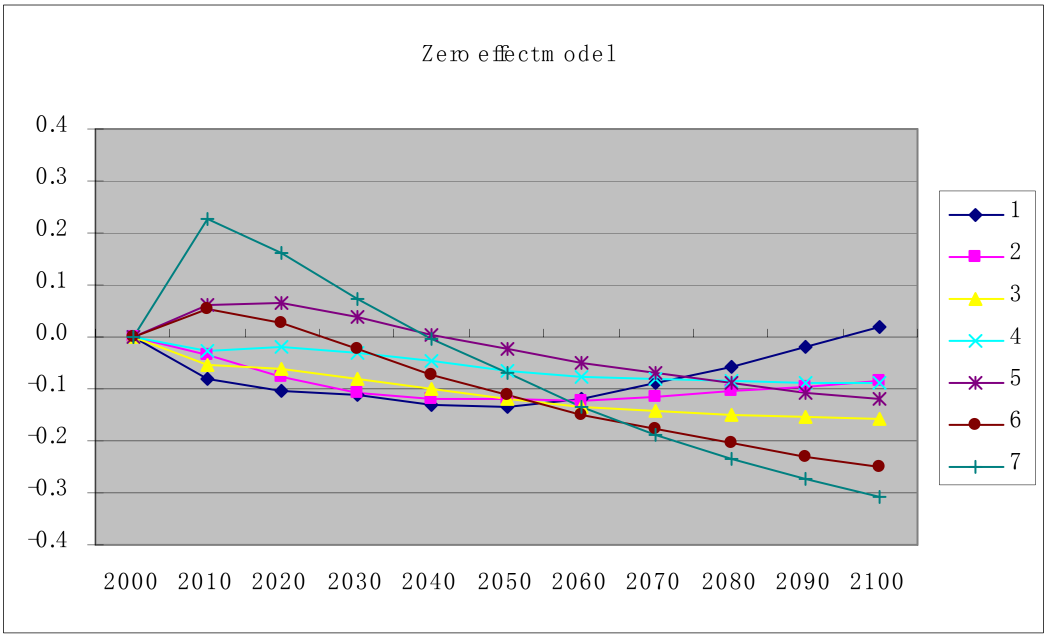


Figure 2. Proportional difference in population living in households of each size, for four models, relative to a ProFamy projection 2000-2100.

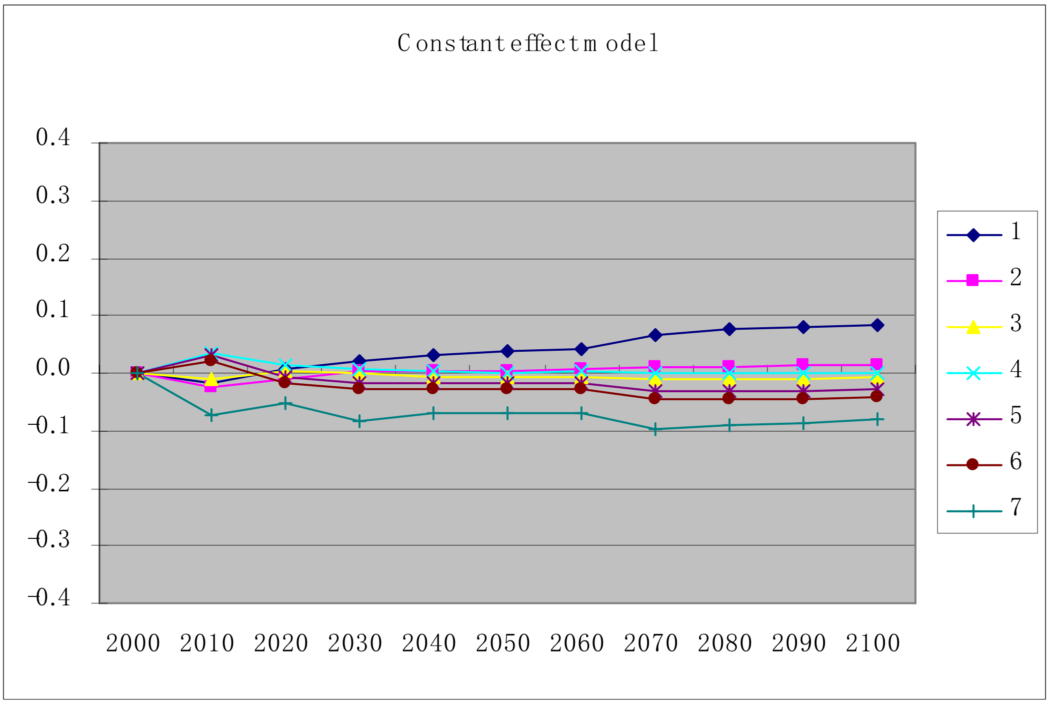
(a)



(b)



(c)


Constant effect model
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
1
2
3
4
5
6
7

(d)

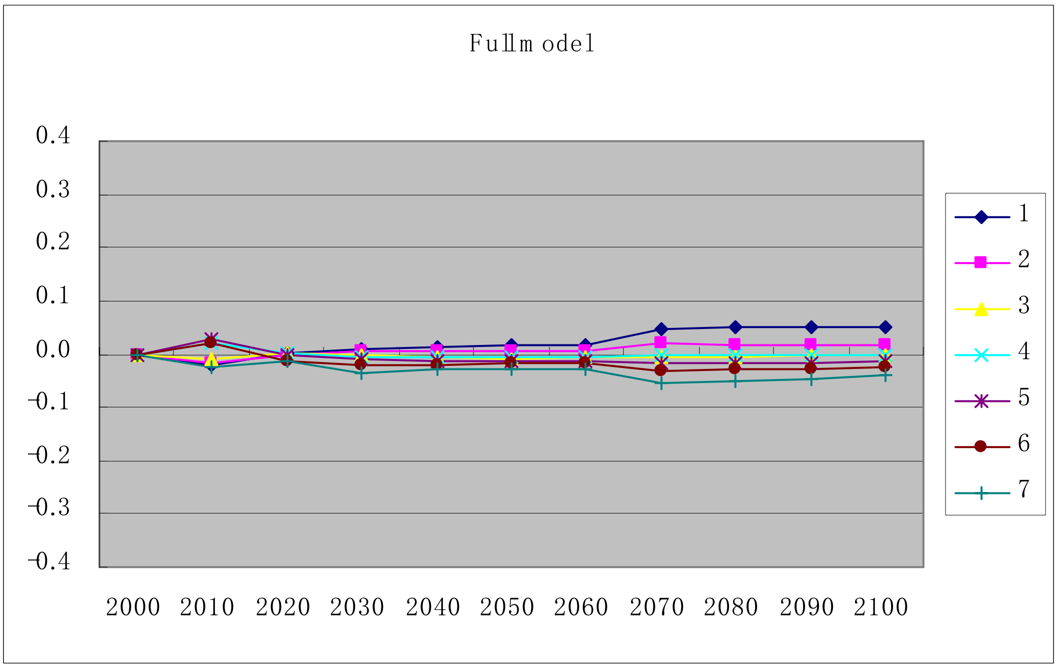
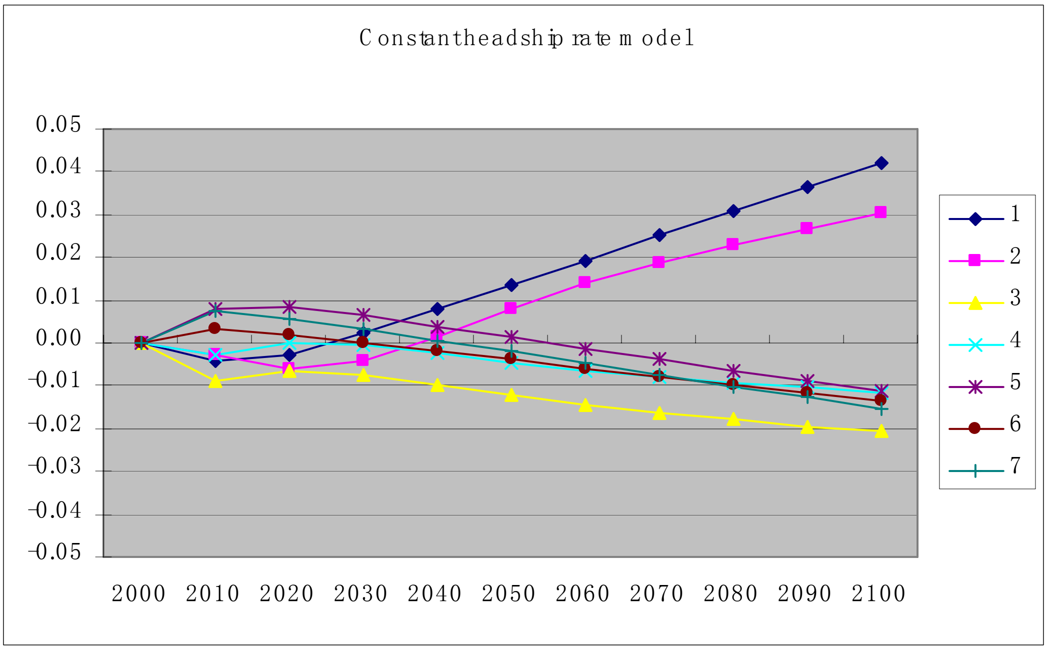
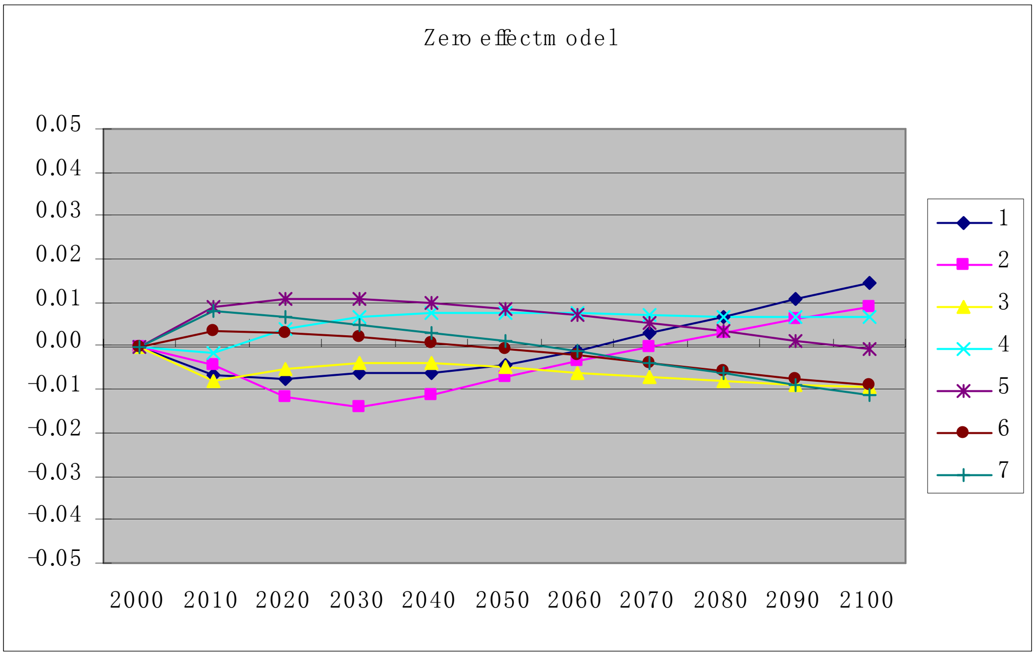

Full model
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
1
2
3
4
5
6
7

Figure 3. Difference in shares of total population by household size, for four models relative to a ProFamy projection 2000-2100.

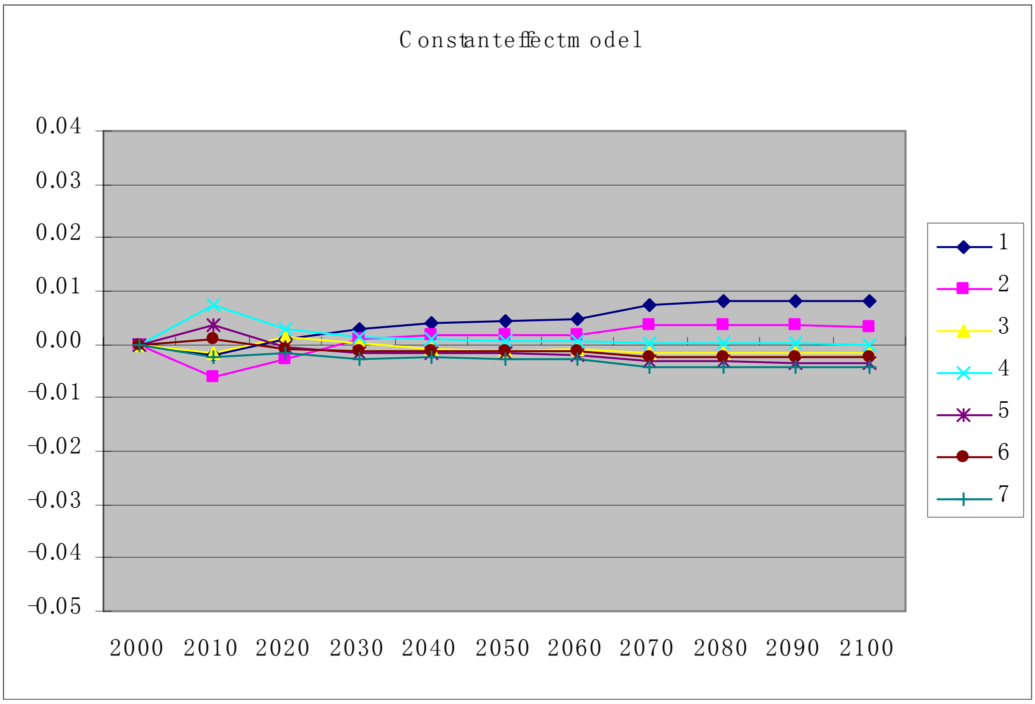
(a)



(b)



(c)


Constant effect model
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
1
2
3
4
5
6
7

(d)

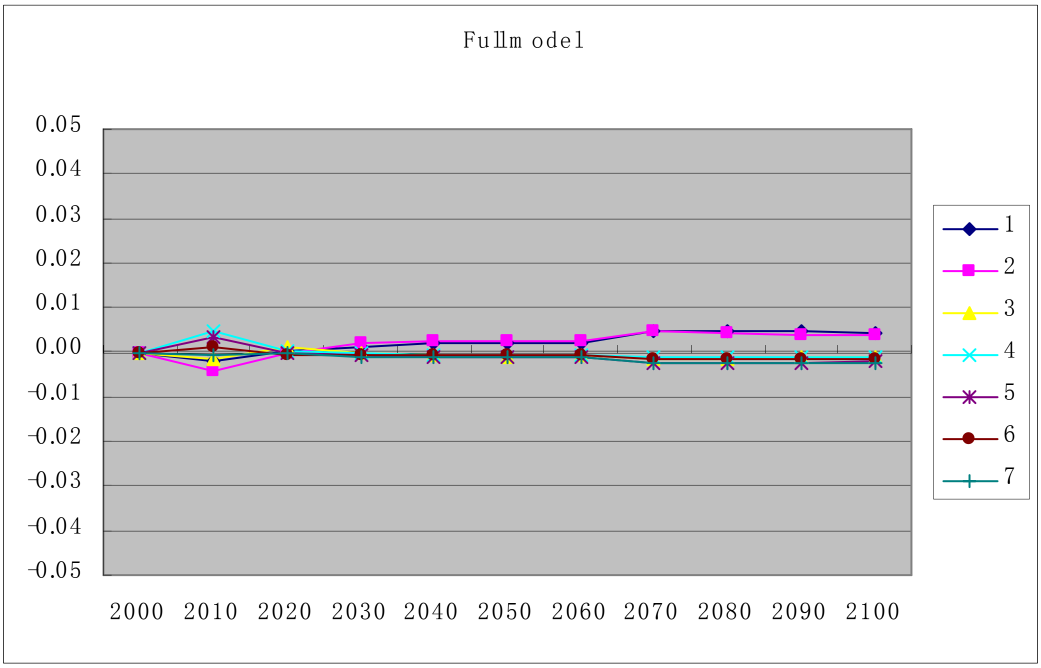
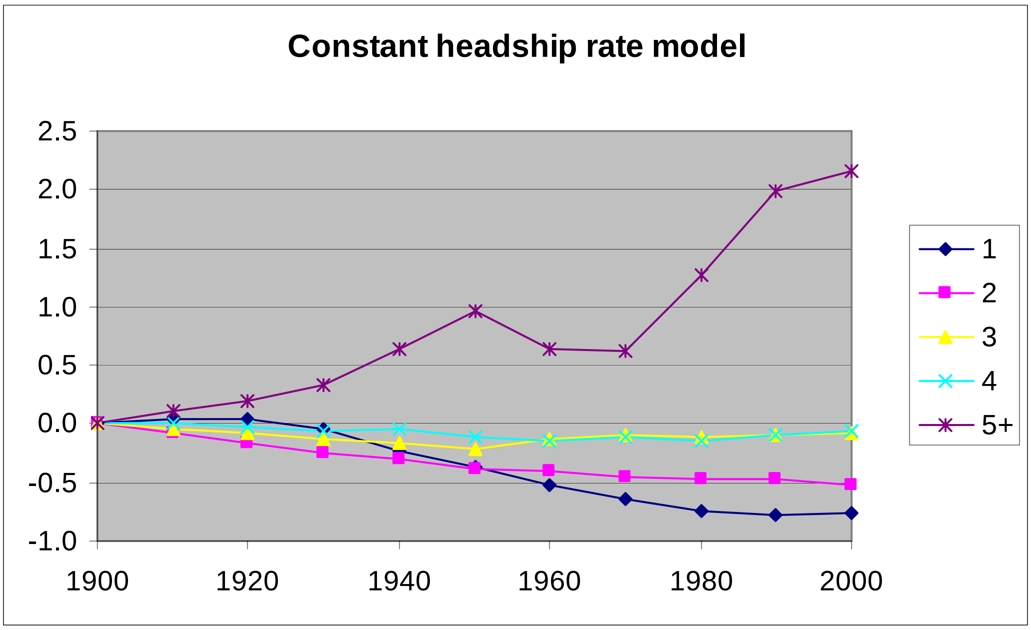

Full model
0.05
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
1
2
3
4
5
6
7

Figure 4. Proportional difference in population living in households of each size, for two models, relative to historical data, 1900-2000.

(a)



(b)

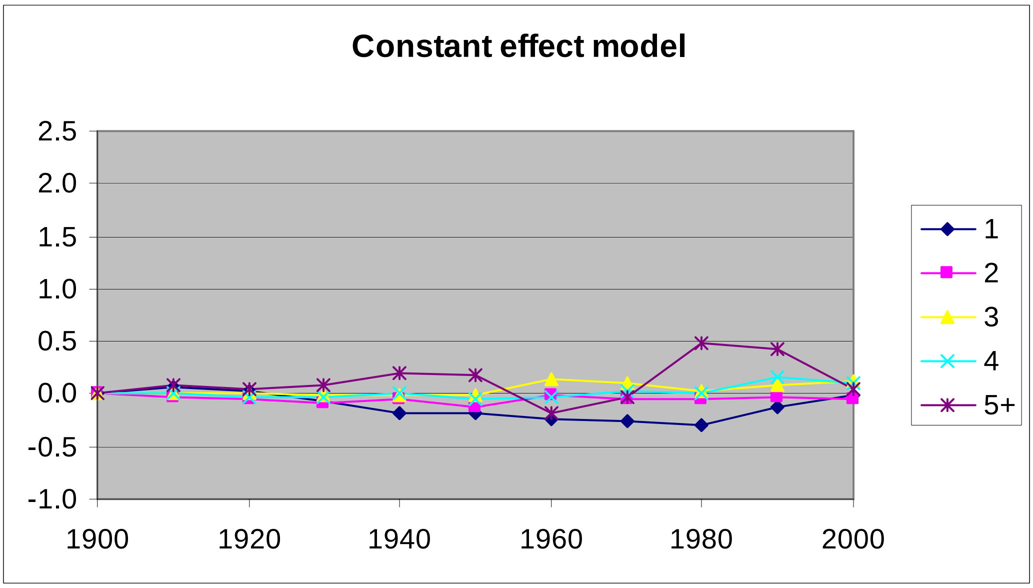
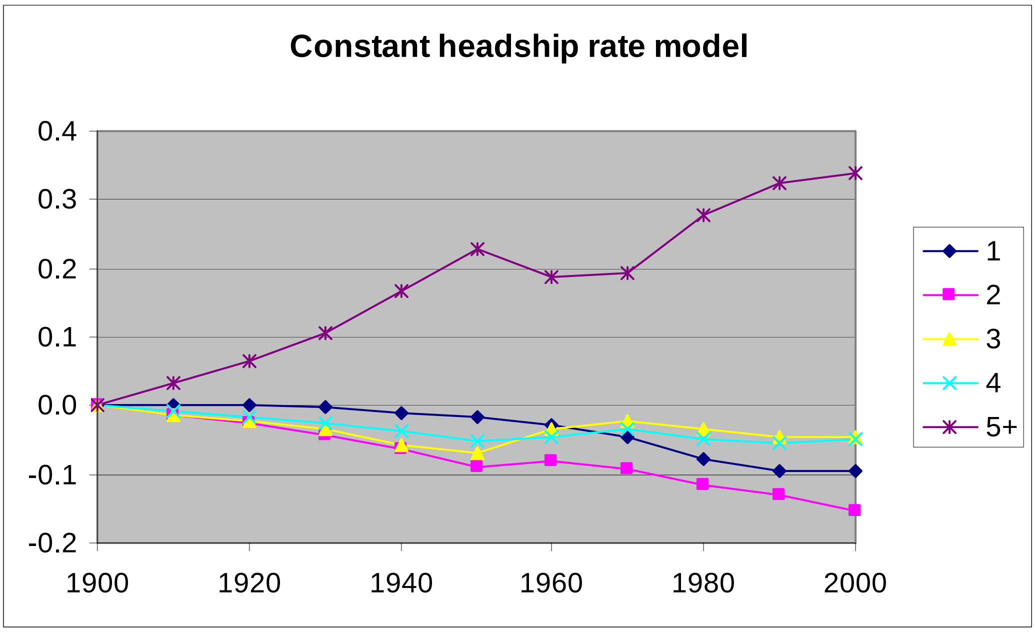


Figure 5. Difference in shares of total population by household size, for two models relative to historical data, 1900-2000.

(a)



(b)

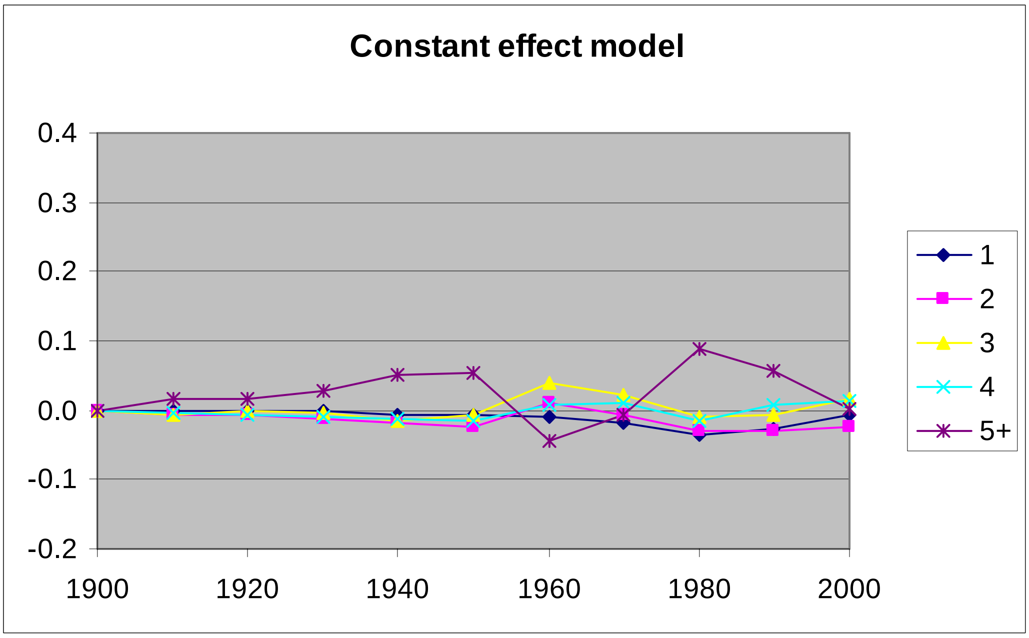


Figure 6. Contemporaneous effects of demographic events on headship rates in the period 1900-2000.

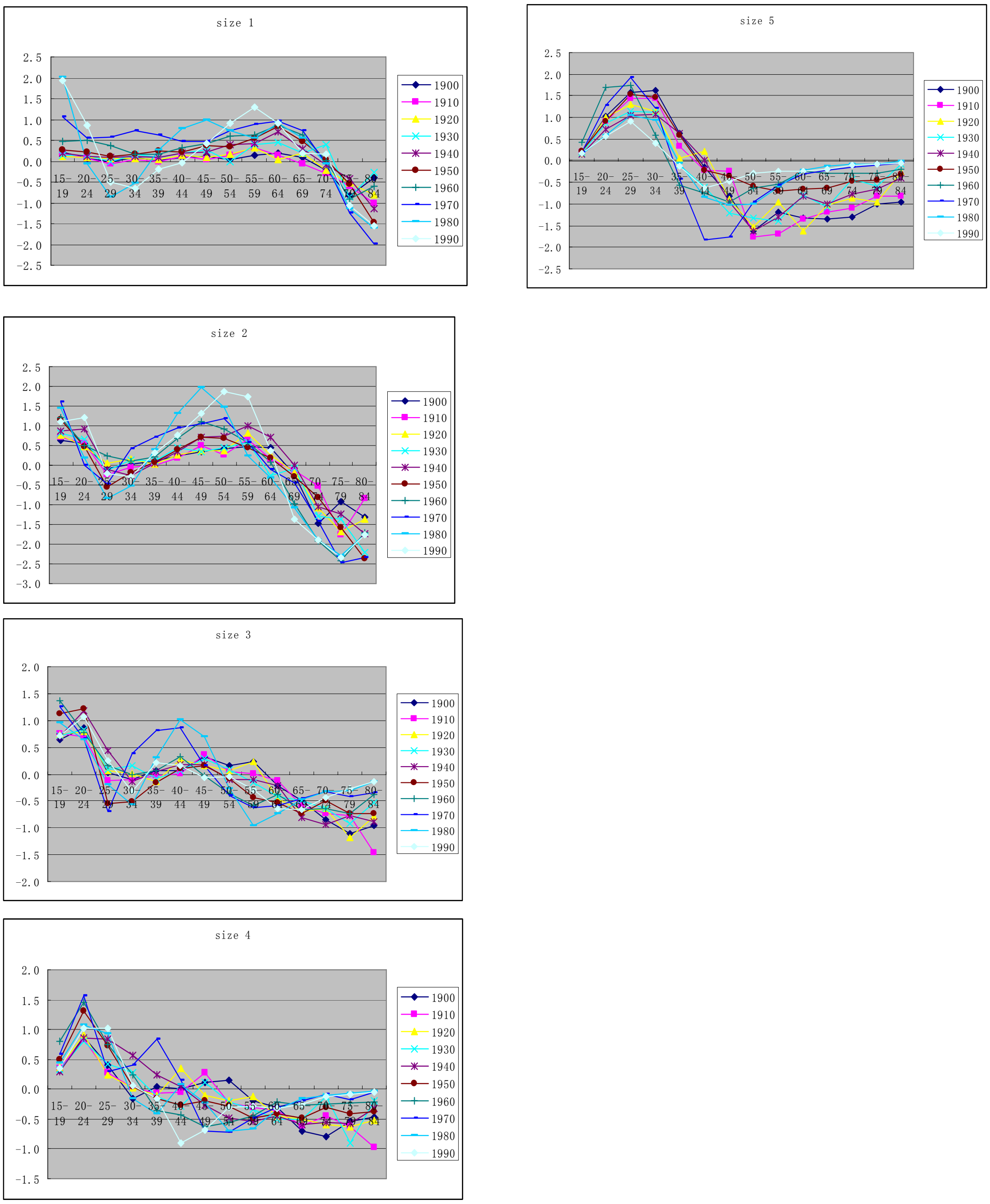


Figure 7. Contemporaneous effects of demographic rates on headship rates from ProFamy projection output.

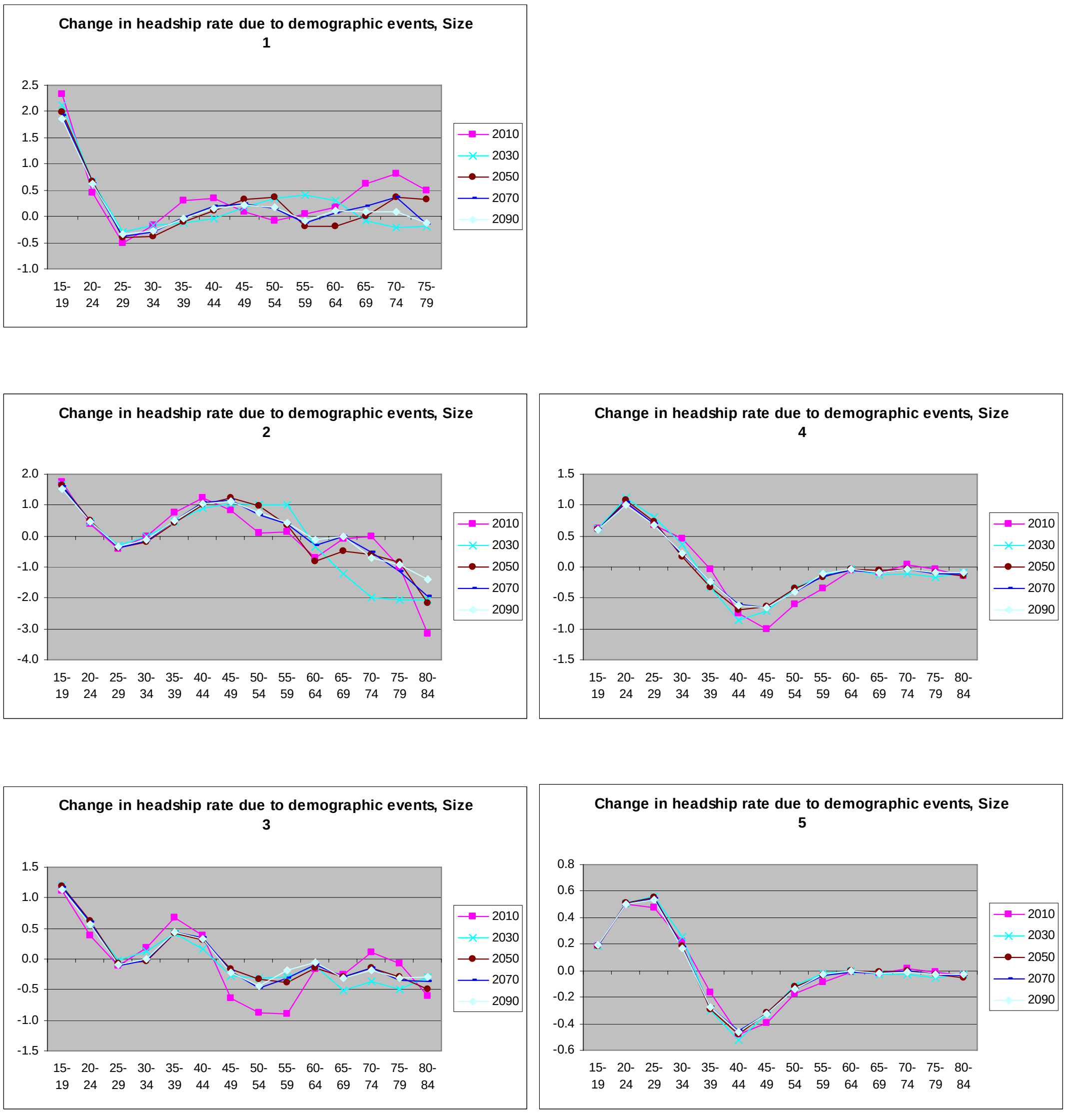


Figure 8. Change in the $f_s(a,t)$ term by a small perturbation to the fertility rate in 2000 and 2050.