Chapter 3
Modelling the Dynamics of Demography in the Dutch Roman *Limes* Zone: A Revised Model

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Abstract In this chapter, a simulation model for better understanding the population dynamics of the *limes* zone is presented, building on our earlier study on the possible effects of recruitment of soldiers for the Roman army (Verhagen et al., Modelling the dynamics of demography in the Dutch limes zone. In: Multi-, inter- and transdisciplinary research in landscape archaeology. Proceedings of LAC 2014 Conference, Rome, 19–20 September 2014. Vrije Universiteit Amsterdam, Amsterdam. https://doi.org/10.5463/lac.2014.62, 2016a). In this earlier study, a number of questions were raised concerning the realism of using estimates from historical demographical sources for understanding the population dynamics of the region. In the current paper, the available data sets, approaches and hypotheses regarding fertility and mortality in the Roman period are re-assessed, together with the available archaeological evidence on the population dynamics of the region. A revised model is then presented that allows for more refined experimenting with various demographic scenarios, showing that a much larger number of parameters can be responsible for changes in population growth than is often assumed in archaeological studies. In particular, marriage strategies would seem to play an important role in regulating the number of births. The model remains a work in progress that can be further refined and linked to models of settlement and land use development.

Keywords Roman demography · Simulation modelling · Population dynamics · Fertility · Mortality

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3.1 Introduction: Demographic Modelling in the Roman Period

3.1.1 Available Data Sets

In order to better understand population growth dynamics, base data on mortality, fertility and migration are needed. For the periods before the introduction of parish records in Europe from the fifteenth century onwards, however, this information is almost completely lacking. This has led palaeo-demographers to employ datasets from the recent past instead. These datasets, collected from the 1950s onwards for modern population studies, can be used to study premodern populations as long as we are aware of the difficulties of obtaining reliable data on ancient population structures (see Chap. 2, Séguy).

In palaeo-demographic studies, it has often been assumed that prehistoric populations were stable, i.e. that the fertility and mortality patterns did not change over time and that net migration was zero (Lotka 1934, 1939). Under these conditions, a population will grow at a constant rate. Furthermore, it has often been assumed that population growth rates in premodern times were close to zero, following Acsádi and Nemeskéri (1970). This is partly because of the Malthusian principle that populations will not grow beyond carrying capacity but also because all the available evidence seems to point to very low growth rates throughout the premodern period of at most 0.2% per year. Even in cases where higher population growth is observed, like at the onset of the Neolithic, the growth pattern seems to quickly stabilize to near-equilibrium again (Bocquet-Appel 2008). Nevertheless, this does not mean that short-term population growth patterns need to be very stable (Séguy and Buchet 2013).

The generally low population growth rates observed in the past can mostly be attributed to devastatingly high (infant) mortality, but were also the consequence of (conscious) birth control. Most studies, however, have focused on mortality since it can be estimated with relative ease from the age structure of a population. If we can reconstruct a population's age structure, then we can also estimate its mortality very precisely.

The empirical data on mortality for the Roman period stem from epigraphic evidence on tombstones, skeletal material and a limited number of written sources, in particular census records from Egypt (Frier 1982; Parkin 1992; Bagnall and Frier 1994). On fertility and migration there is hardly any data at all. However, the available information is usually thought to support the assumption that the average life span in the Roman period was approximately 25 years and that Roman mortality patterns were very close to those of modern non-industrialised societies. The use of demographic data from 'non-industrialised' societies (Séguy and Buchet 2013) has therefore become a widely accepted approach to obtain demographic estimates for the Roman period (e.g. Parkin 1992; Bagnall and Frier 1994; Woods 2007; Hin 2013).

Life tables (Box 3.1) present the relationship between mortality and population age structure and have, therefore, been used extensively for Roman demographic studies. Since they only provide population age structure, but not growth rates, we also need to estimate birth rates in order to understand population dynamics in the Roman period. Henry (1961) and Coale and Trussell (1974, 1978) presented *natural fertility* schedules on the basis of historical demographic data that approach the situation when there is no form of birth control (Boxes 3.2 and 3.3).

Using these figures, the net reproduction rate (*NRR*) under the often used Model West 3 Female life table equals 2.1, corresponding to an annual growth rate (r) of 2.8% for the whole of the childbearing period of females. This is substantially higher than what can be inferred from historical and archaeological data (Wrigley and Schofield 1981; Bagnall and Frier 1994). Therefore, natural fertility rates do not reflect the true patterns of fertility in premodern times, and methods of birth control must have been applied extensively in the past, unless mortality really was much higher than is assumed.

Box 3.1 Life tables

A life table is a table of survivorship of people in an age group, usually starting with a population of 10,000 or 100,000 at age 0. Depending on the *mortality rate* per age group (usually denoted as $\boldsymbol{q_x}$), the number of people in subsequent age groups will decline by a figure $\boldsymbol{d_x}$ until reaching 0 at the maximum age. The number of survivors at age x is denoted $\boldsymbol{l_x}$, although this is also used sometimes to indicate the proportion of survivors, or survivorship, $\boldsymbol{l_x/l_0}$.

Usually, the age groups are presented as 5-year cohorts, with the exception of the first life year that is often included separately, since infant mortality is high in non-industrialised societies. In the case of cohort life tables, l_x refers to survivorship at the end age of the age group, not to the start. Note, however, that mortality rates for an age cohort are often given as ${}_{\mathrm{n}}\mathrm{q}_{\mathrm{x-n}}$, with n denoting the number of years in the age cohort.

From life tables, a number of additional statistics can be obtained, including the *life expectancy* ($\boldsymbol{e_x}$) at a specific age.

Model life tables were first constructed on the basis of census data by the United Nations (1955) as idealised representations of the population age structure in various parts of the world. The more detailed model life tables published by Coale and Demeny (1966) are frequently used in palaeo-demographic studies since they include tables for life expectancies at birth ($\boldsymbol{e_0}$) that are supposed to reflect pre-industrial mortality regimes. The often cited *Model West 3 Female* life table, for example, is based on reliable historical census data from predominantly Western countries for females with $e_0 = 25$ years.

Box 3.2 Natural and true fertility

The concept of *natural fertility* was introduced by Henry (1961) to refer to the situation in which a population will make no conscious effort to limit the number of children born, such as was the case in many pre-industrial societies. Since Henry only studied historical data of fertility among married couples, the concept is also referred to as *marital fertility*. Natural fertility is only dependent on the physiological factors that influence *fecundity* during the reproductive period of females, usually taken as the age interval between 15 and 50 years. From his analysis, Henry concluded that natural fertility was remarkably similar throughout the cases studied.

True fertility on the other hand, refers to a situation where birth control is applied. This can be a highly variable figure, depending on the socio-cultural and historical context.

A *fertility schedule* (either natural or true) lists the *age-specific fertility rate (ASFR)* or the average number of births per female per age group; $\boldsymbol{m_x}$ then denotes the average number of daughters born.

Note that fertility schedules are always based on the assumption that a female survives all her childbearing years from age 15 to 50.

Box 3.3 Reproduction and growth rates

The *gross reproduction rate* (*GRR;* Kuczynski 1935) is a hypothetical figure denoting the number of daughters born to a woman that survives all her childbearing years from age 15 to 50, and it is calculated as the sum of m_x over all age groups. The *total fertility rate* (*TFR*) then is the number of children, male and female, born to this same woman.

The *net reproduction rate* (*NRR;* Kuczynski 1935) is equal to *GRR*, corrected for mortality of the females. It is also known as the *reproductive rate* (R_0). If *NRR* is larger than one, then the population will grow; if it is lower, it will decline.

NRR can be easily calculated on the basis of a life table and a fertility schedule, and equates to $\boldsymbol{\Sigma\ l_x/m_x}$. When using age cohorts, however, the value of l_x should be calculated based on the survivorship at the mid-point of the age group; so, at $x - 0.5n$ (see Caswell 2001:24–25).

The annual population *growth rate* ($\boldsymbol{r}$) is slightly more difficult to calculate and equals $\mathbf{ln}(\boldsymbol{NRR})/\boldsymbol{t}$, where $\boldsymbol{t}$ is the average length in years of a generation and equates to $\boldsymbol{(\Sigma\ x\ l_x/m_x)/NRR}$. When working with age cohorts this becomes $(\Sigma\ (x - 0.5n)\ l_{x-0.5n}/m_x)/NRR$.

3.1.2 Birth Control in the Roman Period

Bocquet-Appel (2008) states that regulating the birth interval was the most important factor influencing fertility in most prehistoric societies through post-partum abstinence and/or an extended lactation period. Extension of the lactation period was a well-known strategy of birth control in the Roman period (Bagnall and Frier 1994), and one that could have been applied quite easily—although it should be noted that in the upper classes, wet-nursing was common (Caldwell 2004). Bagnall and Frier (1994) also suggest that family size may have been effectively limited by 'stopping behaviour', meaning that once the desired number of children was born, couples no longer had intercourse. In the Roman Empire, divorce was quite common and therefore also constituted an effective way of reducing the duration of the childbearing period.

However, there are a number of other socio-cultural factors that can influence birth rates, in particular, where it concerns the rules around marriage. Increasing the (first) marriage age (or better said, the age at which females become sexually active) has a substantial reducing effect on birth rate. It is also known from historical data that the proportion of never-married females could be substantial (Wrigley and Schofield 1981), but there is little evidence for this in the Roman period. In the case of the Dutch *limes*, this would seem an unrealistic assumption anyway because of the male surplus created by the influx of immigrants (see Chap. 2, Séguy).

When raising the female first marriage age from 20 to 25 years under the Model West 3 Female life table, for example, the number of births will be reduced by about 23%, NRR will go down from 1.7 to 1.2 and r from 1.7% to 0.5%. Marrying of females to older males will also have an effect on population growth, especially if females are not allowed to remarry, since the average duration of the union will then be shorter because of the higher mortality among males (Caldwell 2004). The net effect however under the Model West 3 Female life table of females marrying a 5-year older male is only a 0.2–0.4% reduction in r.

Contraception, abortion and infanticide may have played a role as well in regulating the number of births. Evidence for contraception and abortion in the Roman period, however, is limited, and its effectiveness can be doubted (Caldwell 2004). Infanticide, though often suggested, seems not to have been practiced very widely, although 'exposure' of new-born children was quite common (Caldwell 2004), which could either mean the death of the child, or, more probably, its adoption as a foundling.

All in all, a number of effective strategies were available to premodern societies to limit the number of births, although their actual application will have been highly tied to social and possibly religious norms. For this reason, modelling ancient birth rates remains challenging, since it will be hard to identify the precise causes for reduced or increased birth rates. In an earlier study (Verhagen et al. 2016a), we demonstrated that removing a sufficiently large number of males from the marriage pool because of army recruitment will in the end lead to population collapse, since the number of unmarried females will then become too large. The figures presented there were compared to a base scenario of natural fertility. However, since the population in the Dutch *limes* zone does not show signs of substantial growth before the arrival of the Romans, its inhabitants may already have applied one or more of the birth control strategies mentioned. This also implies that there was at least a theoretical opportunity to increase the number of births per female and thus to provide the Roman army with more men by ‘breeding soldiers’.

3.1.3 Mortality Crises in the Roman Period

A factor usually not addressed in ancient population modelling studies is the influence of mortality crises on population size and structure. This is probably because these can be poorly linked to modern-day equivalents. However, the ancient world was full of diseases, famine and warfare that could wipe out substantial portions of the population over a short period of time (see also Chap. 2, Séguy and Chap. 6, Jongman). Quantitative data on these aspects is scarce, however, especially where it concerns the effects of famine. Furthermore, ancient written sources often seem to exaggerate the effects of these crises.

3.1.3.1 Epidemics

Some estimates are available of the effects of epidemics in the Roman period, in particular those of the Antonine Plague that struck the Empire in the years between 165 and 189 CE with outbreaks of varying severity. Littman and Littmann (1973) estimated that 7–10% of the population died during the major outbreaks and suggested that contemporary reports of 25% to one-third of the population are unlikely. Duncan-Jones (1996) indicates that epidemics were a common occurrence but that the Antonine ‘plague’ (presumably smallpox) was likely an especially devastating case since it was so often mentioned in later sources and at the same time led to a decrease in written sources in general (see also Chap. 6, Jongman). The available quantitative evidence is mainly from Egypt and Rome. Egyptian sources would seem to point to a mortality of over one-third of the population. These effects could however be (very) localised, and the spread of the plague is thought to have occurred mainly through the main communication arteries and the army. A side effect of epidemics was also an increased animal mortality, leading to a reduction in the availability of animals for both food consumption and agricultural work.

3.1.3.2 Warfare

Where it concerns warfare, Rosenstein (2004) provides detailed figures of soldier mortality in the Roman Republican army in the period 200–168 BCE. Combat losses would amount to 2.6% of the soldiers per year. During major battles, however, these figures would be much higher (around 5.6%), especially in the case of defeats, although it is noted that mortality rates were not as high as in the nineteenth-century mass warfare. In major documented battles, some 15–30% of the soldiers would die, but these are exceptional events.[1] In the study region, the only major battles were fought during the Batavian revolt (69–70 CE), but of course the recruited Batavian soldiers were also involved in other military campaigns, especially in the conquest of Britain (43–66 CE).

Estimates on the loss of civilian life during wartime are unavailable, although it should be borne in mind that the killing of civilians was relatively rare and mainly affected non-Roman enemies, like in the case of Julius Caesar's campaign against the Eburones. However, prolonged military campaigns might have had a negative effect on the availability of food, as well as carry diseases with them and lead to an exodus of population fleeing from the advancing armies.

3.2 The Settlement Evidence

As part of our research, we have collected and evaluated all the publicly available information on Roman period settlements in the Dutch *limes* (Verhagen et al. 2016b) in order to analyse patterns of settlement distribution in the region through time. Of course, all settlement inventories can be criticised for their level of detail and accuracy, and ours is no exception. The main problems associated with large-scale settlement databases are found in their uneven geographic and temporal representation, and in their lack of detail on the number of inhabitants of individual settlements that can be inferred from the number of house plans, cemetery sizes and other indicators. The problem of estimating population sizes on the basis of settlement inventories has been discussed in various studies on the Dutch *limes* (Bloemers 1978; Willems 1986; Vossen 2003; Buijtendorp 2010; Van Lanen et al. 2018) and has led to a large range of estimates (see Chap. 1, Verhagen, Joyce & Groenhuijzen). However, reliable information on the development of rural settlements throughout the Roman period is limited to a few studies (e.g. Hessing and Steenbeek 1990; Jansen and Fokkens 1999; Van Londen 2006; Heeren 2009; Vos 2009) and has not been fully synthesised. A study like the one presented by Nüsslein in Chap. 5 could therefore be very useful to better understand the development trajectories of settlements beyond the major studied ones, but so far this has not been undertaken.

The general trends, however, can be easily identified. First of all, as was already pointed out in Chap. 1 (Verhagen, Joyce and Groenhuijzen), the growth in settlement numbers during the Early and Middle Roman period is well attested, although the exact growth rate remains open to debate. From our own data, we estimated an approximate 70% increase in rural settlement numbers in the period between 25 CE and 150 CE. Also, there is sufficient evidence that many existing settlements grew in size, so the actual increase in population will have been more than that. For this

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[1] https://www.quora.com/How-has-mortality-rate-per-battle-changed-throughout-history

reason, Van Lanen et al. (2018) postulated a population increase of more than 260% from the Early Roman to the Middle Roman period. These are clear indications of a population growth increase that goes well beyond the supposed maximum of 0.2% per year for pre-industrial societies, and it is in sync with observed larger trends in the Roman empire (see Chap. 6, Jongman). The rural population growth is most probably linked to increased economic productivity and urbanisation, following the arrival of a substantial Roman military and civilian population (possibly in the order of 20–30%).

Natural population growth (without immigration) needs to come from a decrease in mortality, an increase in fertility, or a combination of the two. Jongman points out that economic growth must have led to higher living standards and thus to a higher life expectancy and the possibility to raise more children, but the fact remains that we have no reliable evidence for this. Cremation burial evidence from the cemetery of Tiel-Passewaaij (Heeren 2009, 81–93) does not reveal significant changes in life expectancy from the mid-first century until the third century CE even when evidence for pathologies decreases somewhat. For the whole cemetery, the life expectancy of the buried individuals was estimated at 29.4 years, which is clearly higher than the usually assumed life expectancy for the Roman period, but it is assumed that the high infant mortality is not reflected correctly in the burial evidence. Furthermore, an increase in the site's population in the Early Roman B and Middle Roman A periods is evident with a demographic peak suggested for the period 90–120 CE.

An open question remains on how the economic growth and urbanisation in the Roman empire may have influenced the local population dynamics. On the one hand, immigrants will have moved into the region, possibly bringing spouses with them, but it is conceivable that they sought and found local marriage partners as well. On the other hand, there also was a strong pressure on the inhabitants to supply the Roman army with soldiers, leading to (temporary) emigration of men from the region. There is, however, ample evidence for family life of soldiers and the maintenance of contacts with the homeland in the form of army diplomas and military finds in rural settlements. It is therefore assumed that the legal ban on marriage for soldiers only applied to Roman citizens and was probably not enforced. Saller and Shaw (1984) point out that the phenomenon of *dilectus* (family separation) is well known from historical evidence and was much resented. This led Van Driel-Murray (2008) to hypothesise that a large proportion of the females was left behind in the rural settlements. She suggested that extended leave would have allowed soldiers to maintain families in their homeland, but as Heeren (2009, 251–252) points out, it is also plausible that women accompanied their men. Also, spouses from different corners of the empire may have been taken back to the homeland after the service term.

The evidence from the Tiel-Passewaaij cemetery suggests that, at least for this site, there was only a small surplus of females in the period between 40–150 AD, although no statistical test was performed on the data set. This relative lack of a female surplus is attributed to the practice of Batavian soldiers to take local spouses with them to their place of deployment. Emigration could therefore have affected the population size as a whole, but may not have had a significant effect on the biological reproductive capacity of the ones left behind. However, emigration would then suppose an even stronger natural population growth than can be deduced from the settlement and cemetery evidence alone.

The available settlement data then suggest a strong population decline starting in the Middle Roman B period, again following general trends in the Roman empire. The number of rural settlements in the area decreases by at least 40% from the Middle Roman B to the Late Roman A period, but the situation may have been much more serious than that, given the almost complete disappearance of indicators for occupation from excavated settlements in the period 275–300 CE (Heeren 2015; De Bruin 2017), coupled to clear evidence for incoming new settlers in the late fourth century. Van Lanen et al. (2018) assume a reduction to about 20% of the population size in the Late Roman period. An almost complete depopulation of the area in the late third century therefore seems plausible, possibly forced by the Roman authorities but certainly triggered by the abandonment of the forts and the disappearance of the urban settlements. Several authors have suggested that the population decline may already have started by the end of the second century and have linked this to the compound effects of diseases, economic downturn and raids by Germanic tribes (De Jonge 2006; Vos 2009). While these all seem plausible explanations, a good understanding of the effects of these events on the local population is lacking, since the decline does not seem to be equally severe for all settlements and micro-regions. Again, the evidence from the Tiel-Passewaaij cemetery does not indicate any changes in life expectancy, but shows a clear reduction in population size from approximately 150 CE onwards (Heeren 2009, 81–93).

3.3 Towards a Dynamical Model of Human Reproduction

In our earlier study (Verhagen et al. 2016a), we presented a preliminary demographic simulation model to understand the possible effects of recruitment on population growth in the Dutch *limes* region, prompted by the long-standing debate on the problem for the local population to sustain the Roman army with men without jeopardizing agricultural production capacity (Bloemers 1978; Willems 1986; Vossen 2003; Van Driel-Murray 2008). This model, written in NetLogo 5.1.0 (Wilensky 1999; http://modelingcommons.org/browse/one_model/4678), was kept as simple as possible in order to come to grips with the main factors influencing population growth. It only allowed for experimentation with the mortality regime and recruitment rate, and the resulting scenarios pointed to a potentially precarious balance between recruitment rate and viability of the population over the longer term.

The main problem with the model was that it was difficult to judge the realism of its outcomes, partly because of the simplification of the factors involved and the small modelled population size, but also because of the lack of any reliable data or well-defined hypotheses on marriage strategies, mortality regimes, recruitment rates and actual population size. This is all the more relevant since relatively small changes in fertility and mortality can lead to large differences in outcomes, provided the time period considered is long enough.

For the current paper, the original model was therefore extended to address the following questions:

1. What is the effect of marriage strategies on population growth?
2. What is the effect of birth control strategies?
3. What is the effect of mortality crises on long-term population viability?

The extended model was written in NetLogo 6.0.4 and can be accessed at http://modelingcommons.org/browse/one_model/5764.

3.3.1 Marriage Strategies

In the original model, high annual population growth rates of 0.95–2.15% were obtained, depending on the mortality regime chosen. This high growth rate was achieved because almost all females in the model would get first married at age 18, remarriage was allowed, and no birth control options were included. The males were not allowed to get married under the age of 26. These marriage rules were assumed to be broadly valid for the Roman period (Verhagen et al. 2016a). By contrast, however, the census data from Egypt (Bagnall and Frier 1994) point to different patterns, with only 60% of females married at age 20 and no remarriage allowed.

The new model therefore allows to experiment with more scenarios by manipulating the allowed age difference between spouses, adding an option to prevent remarriage, and by introducing a 'first marriage probability' factor for females, reflecting the fact that they would not all be first married at the same age and following the 'standard schedule of the risk of first marriage' described by Coale (1971). Coale's model departs from two basic parameters: the allowed first age of marriage and the time span it takes for all females to become first married:

$$r(a) = (0.174k)e^{-4.411e^{-\left(\frac{0.309}{k}\right)(a-a_0)}}$$

where

a = age of female

$r(a)$ = risk of getting married at age a

a_0 = allowed first age of marriage

k = time span reduction factor; the lower the k, the shorter the time span until all females will be married and thus the higher the number of births

A separate option for non-marriage of females has not been added in this stage since it is not supposed to be a realistic assumption for the Roman period, but it can easily be implemented as an extra option. In practice, this was already experimented with: when modelling the effects of recruitment (Verhagen et al. 2016a), the number of unmarried females increased with increasing recruitment rates, leading to long-term negative effects on population growth.

Lastly, the original model had no limitation to the number of available marriage partners. Interaction between any member of the population was allowed. In reality, the rural population lived in settlements with only one or a few households (see also Chap. 7, Joyce), potentially limiting the number of available partners because of distance and/or kinship relations. We have, however, not aimed to model these more complex effects in this stage.

3.3.2 Birth Control

The original model only had one fertility schedule based on the natural fertility regime as defined by Coale and Trussell (1978). As discussed in Sect. 3.1.2, this schedule is not realistic for most pre-industrial societies. The census data from Egypt, for example, points to an average gap of 45 months between the birth of children (Bagnall and Frier 1994). Experimenting with the fertility schedule in the model can now be achieved in two ways: either by setting a fertility reduction factor that will lead to a lower number of births in general (simulating a longer birth spacing), and/or by allowing for stopping behaviour after a certain number of children is born and surviving, as suggested by Bagnall and Frier (1994).

3.3.3 Mortality Crises

Lastly, a ‘mortality crisis’ option was introduced in the model, with the possibility to explore two parameters: frequency and severity. Severity is modelled by adding a mortality multiplier, and frequency by specifying a return period of the mortality crisis.

In practice, mortality will have fluctuated from year to year, selective diseases might have targeted the elderly and or young disproportionately, and diseases, famine and warfare may have varied geographically as well. More specific mortality crisis scenarios should therefore be included in the model, but for the moment these have not been implemented.

3.4 Results

3.4.1 Marriage Strategies

While many combinations of marriage strategies can be explored in the new model setup, the major effects on population growth are found when manipulating the first marriage probabilities. The revised model runs suggest that the most effective strategy for increasing population growth is reducing the first marriage age and time span for females. The effects of changing the marriage age difference and allowing remarriage are limited compared to this.

The models were run with the 'Woods South 25' high mortality schedule and a natural fertility regime (Table 3.1). Under these conditions, applying very long first marriage time spans will lead to population decline, especially when combined with higher first marriage ages. Coale (1971) compared data from early twentieth-century Taiwan with those from Sweden, with *k* values of, respectively, 0.48 and 0.89. Even applying the 'Taiwanese' model already leads to a low mean population growth of only 0.2% if the first marriage age is set at 18 years with no minimum age difference between spouses; the 'Swedish' scenario is not viable. However, lowering the first marriage age to 15 dramatically increases the number of births, with a mean population growth of 1.2% for the 'Taiwanese' model.

3.4.2 Birth Control

Applying birth control is highly effective to reduce population growth. A reduction of the natural fertility rate to 80% is already sufficient to reduce population growth from 0.9% to 0.1% in a scenario with $a_0 = 15$ years and $k = 0.5$ (Table 3.2).

Table 3.1 Effects of first marriage age (a_0; columns) and first marriage time span (k; rows) on annual population growth

	15 years	18 years
0.1	1.9%	1.3%
0.3	1.5%	0.7%
0.5	1.2%	0.2%
0.7	0.7%	−0.3%
0.9	0.0%	−0.9%

Averages based on 100 model runs over 100 years per scenario with 'Woods South 25' mortality schedule and natural fertility

Table 3.2 Effects of fertility reduction (left) and stopping behaviour (right) on annual population growth

Fertility reduction factor		Stopping behaviour	
1.0	0.9%	8	0.9%
0.9	0.5%	7	0.9%
0.8	0.1%	6	0.8%
0.7	−0.5%	5	0.8%
0.6	−1.2%	4	0.5%

Averages based on 100 model runs over 100 years per scenario with 'Woods South 25' mortality schedule, natural fertility regime and first marriage span with $a_0 = 15$ years and $k = 0.5$

Manipulating stopping behaviour will only have a major effect on population growth when the limit on the number of children is substantially below the average number of children born under the natural fertility regime. When set at seven or eight children there is no discernible difference, but setting the stopping behaviour at four surviving children reduces population growth from 0.9% to 0.5%.

Averages based on 100 model runs over 100 years per scenario with 'Woods South 25' mortality schedule, natural fertility regime and first marriage span with $a_0 = 15$ years and $k = 0.5$

3.4.3 Mortality Crises

Annual average mortality rates based on the 'Woods South 25' high mortality schedule (Woods 2007) are in the order of 4%. Adding a mortality multiplier to the model results in clear temporary population declines, but the return rate is a very important factor for determining whether mortality crises will have a long-term effect. For example, when departing from the same scenario as above (natural fertility regime and first marriage span with $a_0 = 15$ years and $k = 0.5$), a 50% increase in mortality will not have a significant long-term effect on population growth when the return rate is only 20 years: average population growth will then decrease from 0.9% to 0.8% (Table 3.3). With faster return rates, however, it will quickly start to have a larger negative effect. For higher mortality rates, this is even more evident. A fivefold increase (so from 4% to 20%) will clearly reduce population growth with longer return rates as well, but it is important to note that even severe mortality crises will not be sufficient to bring the population in decline when they occur in isolation. It is only when the crises return more regularly that the long-term survival of the population will be in danger.

Table 3.3 Effects of mortality crises on annual population growth for different mortality multipliers (rows) and return rates (columns)

	20 years	10 years	5 years	2 years
1.5	0.8%	0.7%	0.5%	0.1%
2	0.7%	0.5%	0.2%	−0.8%
3	0.5%	0.1%	−0.9%	−2.4
4	0.3%	−0.3%	−1.9	X
5	0.1%	−0.6%	−2.2	X

Averages based on 100 model runs over 100 years per scenario with 'Woods South 25' mortality schedule, natural fertility regime and first marriage span with $a_0 = 15$ years and $k = 0.5$. X = populations did not survive over model run

3.5 Conclusions

The model runs demonstrate that relatively small changes in some of the parameters used may greatly influence long-term population dynamics. These results are not all completely new or surprising, but the advantage of modelling population dynamics in the NetLogo environment is the ease of manipulation of scenarios to help us understand the contribution of various factors to population growth and decline that are suggested in historical and archaeological studies.

Of course, we do not know whether the *limes* population was aware of the modelled effects and adapted their reproductive behaviour accordingly. However, while mortality patterns were largely outside the influence of conscious human behaviour in the Roman period, marriage and birth control strategies could be effectively manipulated to regulate reproduction. In practice, a combination of strategies may have been consciously or unconsciously applied that would increase population growth, driven by the Roman demand for armed forces and the improved economic prospects in the first half of the Roman period. For example, restrictions on early marriage might have been more relaxed in times of economic prosperity, when it would be easier for couples to achieve economic independence. Stopping behaviour, while not the most effective birth control strategy at the macro-level, may have been very effective at the household level to make sure that the number of children would not exceed the settlements' carrying capacity.

The models also suggest that mortality crises in themselves are not sufficient to cause long-term population decline, but when the return rate increases their negative effects will be clearly felt. This confirms the assumption that diseases like the Antonine Plague, which returned at irregular intervals, must have kept a prolonged pressure on the population (see Chap. 2, Séguy). This may have been exacerbated by the effects of economic decline (see Chap. 6, Jongman) which may have led to changes in marriage and birth control strategies as well. In the end, however, the strong depopulation of the area in the Late Roman period may have been the consequence of (forced) emigration rather than of internal population dynamics.

The models presented in this paper remain a work in progress. The main difficulty is to set up a dynamical model that does not become too complex to handle while still producing meaningful results. While general conclusions on the causes and effects of changes in reproductive behaviour can be obtained relatively easily with the current models, fully understanding the interplay of various factors for the *limes* zone and judging the realism of the modelled outcomes is a much more difficult task. Especially the rules for finding marriage partners, based on socio-economic status, distance and/or kinship would seem a fertile ground for further experimentation, but this would also involve finding realistic approximations of marriage probabilities that are not based on the generalised model that has been used now. Also, questions about the limitations to the growth of rural settlements into settlements with multiple households are currently not addressed, nor were the questions of rural-urban relationships and the effects of migration included in the model. For this, we would also need to couple the demographic model to socio-economic simulation models such as the ROMFARMS model developed by Jamie Joyce (Chap. 7) or land use simulation models (De Kleijn et al. 2018).

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