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Maternal nutritional status and offspring childlessness: Evidence from the late-nineteenth to early-twentieth centuries in a group of Italian populations

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The role of maternal nutrition in affecting offspring fertility, through alteration of foetal programming, has been demonstrated in animal-based experiments. However, results from human populations appear inconsistent and sometimes contradictory, likely because they have been based on single famine events. In this paper, we adopt a different approach. We combine official annual time series of daily nutrient availability with a sample of women's reproductive histories from the 1961 Italian Census to investigate the role of maternal nutritional status in pregnancy on offspring childlessness. The analysis therefore covers cohorts of females born between 1861 and 1939. Our results show a negative association between calorie availability in pregnancy and the odds of offspring childlessness, whereas no association is found between protein availability and offspring childlessness. The consequences of poor calorie intake were aggravated during the summer, likely due to the participation of pregnant women in physically demanding work.

Keywords: infertility; foetal programming; nutrition; time series; individual data; Italy

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Introduction

The role of early-life conditions in adult outcomes, such as subsequent diseases and health problems, has been widely investigated in recent years. Many studies from different research areas (demographic, biology, genetics, etc.) have demonstrated to what extent such conditions may interfere with many aspects of a healthy adult life (Elo and Preston 1992; Finch and Crimmins 2004; Bengtsson and Broström 2009; Kuzawa and Quinn 2009; Case and Paxson 2010). Pathologies such as cardiovascular and respiratory diseases (Bengtsson and Lindström 2003; Sjoholm et al. 2018), diabetes (Craig et al. 2019), and neuropsychiatric disorders (Factor-Litvak and Susser 2004) have been associated with adverse conditions in early life.

More recently, the origins of many diseases later in life have been traced back to the conditions experienced during the foetal stage (Barker 2001). In particular, early-life nutrition is one of the elements that may affect subsequent development in later life (Fernandez-Twinn and Ozanne 2010; Vickers 2014; Langley-Evans 2015). It has been demonstrated that maternal nutritional imbalance and metabolic disturbances during pregnancy are potentially able to induce changes in foetal development that produce an altered adult phenotype, a phenomenon known as 'foetal programming' (Barker 1990). This process is mediated by epigenetic modifications, that is, profound changes in gene expression according to environmental conditions.

This sort of predisposition 'represents an important risk factor for non-communicable diseases of adulthood' (Langley-Evans 2015, p. 2). In particular, there is growing epidemiological and experimental evidence indicating that it may also affect the reproductive system (Ibanez et al. 2007, 2011; Franks and Berga 2012; Chadio and Kotsampasi 2014; Chan et al. 2015; Block and El-Osta 2017). These studies have highlighted a large spectrum of consequences on the reproductive system, and these are likely to affect the final number of offspring.

This paper deals with the most extreme of the possible reproductive outcomes, namely primary sterility. In particular, our intention is to investigate the relationship between maternal nutritional conditions during pregnancy and offspring infertility in adulthood. We study this association based on women's reproductive histories from a set of Italian communities recorded in the 1961 Italian General Population Census. The retrospective nature of the analysis allows us to check whether the risk of infertility among the birth cohorts born between the second half of the nineteenth century and the first half of the twentieth century increased during periods associated with a shortage of nutrients available to mothers during pregnancy.

The role of foetal nutrition in reproduction

It is now well known that disease risk is well established before birth. The complex interplay between genes transmitted from parents to progeny and the foetal environment experienced during pregnancy determines the chances that some diseases may intervene later in life. Various organs and their associated functions are formed and 'programmed' during the embryonic and foetal stages, thereby determining the future metabolic response in adulthood. Any stress during that particularly delicate phase may therefore induce developmental adaptation in the foetus, resulting in a permanent change in metabolic response.

Maternal malnutrition is one of the most important and powerful stressors that may affect foetal programming (Cooper et al. 1996; Barker 2001; Chan et al. 2015; Kwon and Kim 2017; Marciniak et al. 2017). Just before and during pregnancy, the nutritional energy needs of the mother change, as she must ensure a correct intake of nutrients for both herself and the foetus. Women whose energy intake is insufficient, limited, or with little variety may present problems not only in reproducing successfully but also in ensuring correct foetal growth. A shortage of resources during pregnancy or even changes in the intrauterine supply of nutrients may alter foetal programming, thereby inducing foetal adaptations which may result in increased risk of and susceptibility to specific diseases.

Several pathologies and complications of the reproductive system occurring later in life are known to or thought to originate in alterations in foetal nutritional status. When the foetus does not receive adequate quantities of nutrients or enough oxygen, its development may be hampered, leading to a condition called 'small for gestational age' (SGA), which characterizes infants of very low birthweight. This foetal growth problem is known to be associated with various reproductive alterations during the lifetime, including retarded ovarian development, advanced menarche, early menopause, and even infertility (de Bruin et al. 1998; Díaz-García et al. 2011). Other important causes of infertility, such as endometriosis (Kobayashi et al. 2014) and polycystic ovary syndrome (Van Weissenbruch 2007; Gur et al. 2015; Barsky et al. 2021), are now believed to be associated with foetal nutritional stress. Both these diseases have a genetic basis, but some scholars have also highlighted the possible influence of epigenetic modifications that occur in utero during growth and development.

Experimental and observational data on animals have highlighted the impact of a deficit of specific macro- and micronutrients on foetal programming. Inadequate availability of proteins in utero has been associated with altered reproductive functions, accelerated reproductive ageing, and accelerated gonadal development in offspring (Guzman et al. 2006; Zambrano et al. 2014). Shortening of the reproductive lifespan has also been observed in the case of maternal exposure to calorie restrictions during pregnancy and lactation. This effect seems to be triggered by early follicle loss and/or diminished ovarian reserve. Other studies have found that low maternal calorie intake is associated with a delay in the onset of puberty (see Chan et al. 2015 for a review). Various studies have highlighted the potential role of micronutrients, such as vitamin B12 (Pepper and Black 2011), melatonin (Davis 1997), folate (Radziejewska and Chmurzynska 2019), and selenium (Hofstee et al. 2019), which are thought to play a role in foetal development and metabolism, as well as in growth of organs, such as ovaries.

The influence of in-utero nutritional conditions on reproduction and reproductive outcomes later in life has also been investigated in demographic studies on historical populations. The findings, however, are not always consistent, and studies have reached very different conclusions. Women exposed in utero to the Dutch famine of 1944–45, for example, did not show differential fertility compared with those not exposed (Lumey and Stein 1997), but women exposed to the same famine during childhood were found to be less fertile (Elias et al. 2005). Another study by Yarde et al. (2013) supported these conclusions but also highlighted that maternal exposure to the Dutch famine induced early menopause in offspring. This evidence of the association between foetal exposure to nutritional restriction and early menopause is supported by other studies (Cresswell et al. 1997; Mishra et al. 2009; Crawford 2019) and might be a precondition for lower fertility under specific circumstances. The study by Painter et al. (2008) on the same data set even reported higher early fertility among the exposed. Conversely, some studies on the Chinese famine of 1959–61 provide evidence of a negative association between acute in-utero nutritional stress and reproductive outcomes. In particular, Song (2013) found that women conceived in that period experienced a higher sterility rate than controls, while Zhang et al. (2020) discovered that they also presented an increased risk of stillbirth.

Many scholars have considered month of birth as a proxy for maternal nutritional status and its effects on diseases later in life (Moore et al. 1997; Doblhammer and Vaupel 2001; Ueda et al. 2013). A study by Jongbloet et al. (2007) showed that the cycle of oocyte maturation is characterized by seasonal preovulatory release of overripe ovum (SPrOO), which could be responsible for the higher rates of subfecundity and infertility among women born in late winter to early spring (SPrOO hypothesis). This seasonal interval corresponds to the period from autumn to early winter in the fifth month of gestation. In contrast, late winter to summer would be the most favourable mid-gestation period for reducing the risk of childlessness in adulthood. The weather conditions associated with the month of birth—or with specific stages of gestation—are another element that has been found to affect foetal programming. In particular, this may occur through insufficient intake of vitamin D and/or melatonin, which is associated not only with diet but also with weather conditions (Cyprian et al. 2019; Olcese 2020). Melatonin is a neurohormone that affects the circadian rhythm and also the reproductive mechanisms of many mammals. It is produced during the night, and when the days get shorter and darker, the pineal gland secretes a higher amount of melatonin. Vitamin D has been found to participate in the regulation of reproductive physiology (Luk et al. 2012). It is synthesized by human skin when exposed to UV radiation and is therefore strictly connected with the presence of sunlight and thus with the longer and sunnier summer days. Finally, there is evidence of large seasonal differentials in food availability and agricultural work and, therefore, in nutritional energy balance (Watson and McDonald 2007), especially in rural populations. In Southern Europe, for instance, farmers harvested in summer, which was, therefore, a season of considerable physical stress and low availability of food stocks at home. Women had to contribute to farm work even during the first stages of pregnancy, and this would have greatly increased their energy requirements.

Data and method

The data used in this study come from the 1961 Census returns of a group of Italian communities. These data have formerly been exploited in other studies (Breschi et al. 2013, 2016). Raw data from the 1961 Italian Census returns are not available, nor can they be consulted in any form. Since the Italian Institute of Statistics published analyses only at the aggregate level, the only way to collect the original 1961 data is to turn to the municipal archives where the original census returns are kept in paper form. The populations studied here form the sole collection of digitalized individual data from that census; thus, they do not represent a random sample in strictly statistical terms. However, the populations include communities from different areas of Italy, spanning Friuli in the north (Lauco and Turriaco), central Italy (Novellara, in Emilia, and Casalguidi, in Tuscany), southern Italy (Massa Lubrense, in Campania), and Sardinia, for which we analyse both strictly rural and urban communities (Breschi et al. 2016). Despite the geographical localization of the different communities, the sample is skewed towards Sardinia, whose population of married women is over-represented, accounting for 57.2 per cent of the total sample of married women studied here (Table 1). In any case, the communities we study encompassed different socio-economic structures, environmental conditions, and demographic and household patterns. Some communities (e.g. Lauco and some Sardinian communities) were still living on subsistence agriculture and pastoralism at the time of the census, while others had achieved the transformation from an agricultural to an industrial economy (e.g. Turriaco) or had coupled such an industrialization process with the transformation of agriculture into a modern and more dynamic sector (e.g. Novellara and Casalguidi). As for the southern populations, Massa Lubrense's economy was still based on agricultural and sea-related activities, while Sardinia is represented here by both its various urban facets (Alghero, Macomer, and Porto Torres) and its rural territory (10 small communities spread all over the region). In 1961, workers in the agricultural sector accounted for over 38 per cent of the overall

Table 1 Childlessness among married women in a sample of Italian communities, 1961

Population	*N* married women	Childlessness (percentage)	Agricultural sector (percentage)[1]
Lauco	327	8.5	31.6
Turriaco	519	7.5	13.1
Novellara	2,322	6.2	45.2
Casalguidi	1,062	5.5	34.4
Massa Lubrense	1,304	5.1	49.1
Sardinia (Urban)	4,845	5.9	24.6
Sardinia (Rural)	2,551	6.4	66.1
Overall	12,930	6.1	38.7

[1]Figures refer to the share of active population employed in the agricultural sector.
Source: Italian 1961 Census (women's reproductive histories).

population in the areas sampled here (see Table 1), and it likely accounted for much more in the period 1861–1939 when our cohorts were born. This is an appropriate context in which to test our hypothesis, as women living in rural areas were likely at high risk of suffering from a combination of hard work, malnutrition, and low social position within the household.

As for fertility, Italy had completed its demographic transition within the first half of the twentieth century. Consequently, all the populations analysed in this study showed a general reduction in fertility over time triggered by some form of voluntary birth control, although this was much more marked and rapid in the more industrialized communities of northern and central Italy than in the southern regions and the Sardinian communities. Considering only women in first marriages, the General Fertility Rate fell from values of 350 children per 1,000 married woman before 1916 in all the populations analysed to 130 children in the northern and central communities (−62.8 per cent) and 230 in the southern ones (−34.3 per cent) between 1946 and 1960.

The peculiarity of the 1961 Italian Census is that it includes a section dedicated to the reproductive history of each ever-married woman. Each return reports the name and surname of the woman, her birthdate, dates of current marriage and eventual widowhood, marital status at marriage, and number of children ever borne, as well as the number stillborn. For each child (stillbirths included) the year of birth is provided. The complete date of birth is available only for those children still recorded among the family members (for more details on the data source, see Breschi et al. 2013, 2016). Other information available from the family data include spouse's occupation and educational attainment, total number of household members, residence (address), and some housing characteristics.

Data on macronutrients are drawn from official statistics from the Italian Institute of Statistics (ISTAT 1958). They provide annual estimates of the daily mean availability of macronutrients per person. In particular, the tables report annual figures for proteins, fats, and carbohydrates in grams (g), as well as the number of calories (excluding those derived from the consumption of alcohol) for the period 1861–1955. Unfortunately, ISTAT did not publish data at the regional or provincial level. However, the market integration process was already at an advanced stage in late-nineteenth-century Italy, which led to there being only small differences in food prices between regions on the eve of the First World War. This process of convergence was particularly fast for wheat, but all food products showed some degree of convergence, which was 'brought about mainly by the progress in maritime transportation' (Federico 2007, p. 312).

Clearly, the historical data used in this study lack any medical information, so what we investigate is childlessness rather than primary infertility, although we implement some controls in the models to try to disentangle involuntary (biological) from voluntary childlessness.

The sample we use in this analysis is, first, limited to women married once, to avoid possible bias due to incorrect attribution of children in the case of a woman's multiple marriages. The second selection criterion is based on marriage duration: in particular, we include all women whose marriage had lasted at least seven years. Accordingly, age at first marriage in this group is limited to a maximum of 38 years, which implies that the models include women born between 1861 and 1939. Seven years is the interval usually adopted to individuate infertile women from secondary data (Larsen 2000; Liu et al. 2005; Gurunath et al. 2010), with the drawback of not properly addressing the postponement of the first child that is typical of populations controlling their fertility. Here, we not only drop from the analysis unions that were too short, but we are also able to take into consideration a firstborn whose birth occurred after seven years of marriage, thereby allowing for the inclusion of couples who had postponed their first child. Some considerations on the model design and the resulting robustness of results are provided in the Appendix, where we present a sensitivity analysis.

All the analyses are based only on live births. All the models are estimated using Stata 14.

We model the odds of being childless (sterile) as a function of the daily mean availability of proteins or, alternatively, calories, and also season at mid-gestation (fifth month of gestation). First, we estimate a multilevel mixed-effects generalized linear model with a binomial distribution and a logit link to take into account the hierarchical nature of the data, where women are nested within populations. Seven geographical clusters are defined (see Table 1), with the Sardinian populations grouped into two clusters: urban and rural communities. This last choice is motivated by both the small size of the rural Sardinian communities and their stronger identity. In this way, we are able to adjust for the co-dependence pattern among married women from the same population. However, a simple likelihood ratio (LR) test proved that this kind of model did not provide statistically different results to a simple logistic model (Hosmer and Lemeshow 2000). Therefore, we ultimately estimate this latter model using the Huber–White estimator of variance, which is robust to various kinds of model misspecifications (Huber 1967; White 1980).

When dealing with a logistic model with many categorical variables, some of them with more than two levels, the Wald test usually used to estimate the *p*-values of each contrast is known to have major shortcomings (Hauck and Donner 1977; Væth 1985). This is why we do not present such *p*-values but only the *p*-values for the joint significance of each variable estimated using a likelihood ratio test.

Two models are run, to assess the impact of either proteins or calories on the odds of experiencing childlessness. Given that nutritional stress to the foetus may occur at different stages of the gestation period, from conception to the last trimester of pregnancy, a good theoretical compromise is to evaluate the mother's nutritional status at mid-gestation, let's say at the fifth month of gestation, just when the nutritional requirements of pregnant women become more demanding. While the season is easily assessed by simply shifting back the month of birth by four months, the determination of the availability of proteins and calories is more difficult. Monthly figures for macronutrients are unavailable, but we have access to annual figures. Thus, we use the only possible estimation method: taking either nutrient availability in the year of birth in cases where pregnancy occurred within a single calendar year or the nutrient availability average for two consecutive years in cases where pregnancy covered two calendar years.

Context

A brief overview of childlessness in the sample population

Estimates of marital childlessness are scarce for the period considered here, especially for Italy. Some partial evidence is available from the 1996 Italian Fertility and Family Survey, in which permanent childlessness for women born in the late 1940s was estimated to be around 5.5 per cent (Tanturri and Mencarini 2008). This is definitely in line with Werner's (1986) estimates of biological infecundity for developed populations, which spanned 3–5 per cent. These figures appear to support the idea that voluntary childlessness was unusual among those birth cohorts. Other indications come from Dykstra (2009), who collected and elaborated historical data on childlessness for four European countries. Her paper presented the data disaggregated by marital status, showing a general decline in childlessness over time, from generally above 15 per cent for women born in 1900 to between 8 and 12 per cent for the 1920–24 birth cohort.

Although the criteria on which the samples of married women are constructed differ from one another, overall childlessness in our entire sample of married Italian women shows a declining trend similar to that illustrated in Dykstra's study for the four European countries (Figure 1). The higher levels among older generations are usually explained by the 'grand historical events' (Hareven 1982, p. 8) that women born at the turn of the twentieth century had to endure, forcing them to postpone marriage to older ages and/or to face physical separation from their husbands for long periods, especially during conflicts.

Once the data set is disaggregated to the community level, childlessness shows homogeneity across the Italian populations, with an overall figure of 6.1 per cent of women (Table 1). The main exception is Lauco, whose childlessness was the highest in our sample. We guess that this may have been

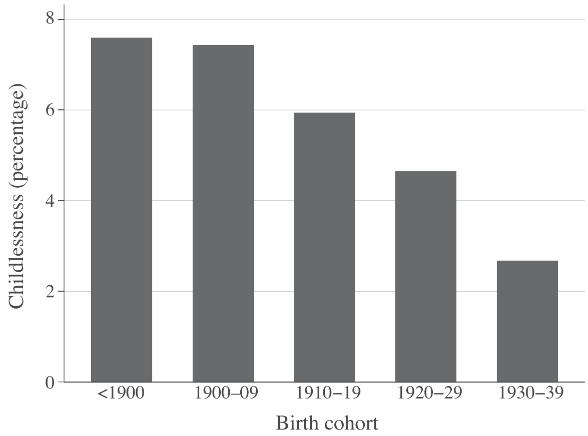

Figure 1 Childlessness by birth cohort, women in Italy
Source: Italian 1961 Census.

caused by either the strong impact of the First World War in that area (in 1917–18 the whole Friuli region was occupied by the Austrian army, with dramatic consequences on the population) or the high level of men's seasonal migration, which was not only capable of reducing fertility but also of channelling the spread of sexually transmitted diseases (Saggurti et al. 2012; Wei et al. 2014).

Availability of nutrients over time: Proteins and calories

To appreciate the nutritional status of pregnant women over time, we assess the evolution of protein and calorie availability. We have already described and emphasized the key role of these two macronutrients during pregnancy on the reproductive health of offspring. Figure 2 illustrates the official figures for mean proteins (in grams; left-hand panel) and number of calories (right-hand panel) per person per day between 1861 and 1955, based on the data published by ISTAT.

The nutritional indicators display high correlation (rho = 0.910, $p < 0.001$) and high consistency over time with only a few changes. One of these is the higher levels of macronutrient availability between 1900 and 1940 when contrasted with the levels before 1900. This change is more marked for proteins than it is for calories, with increases of +17.5 per cent and +11.9 per cent, respectively. The other important feature of the macronutrient trends is the existence of two deep troughs. The first occurred on the occasion of the agrarian crisis that hit the country in the last 20 years of the nineteenth century. It was the consequence of the process of structural transformation in Italian agriculture towards being more capitalistic, which had led to a marked proletarianization and pauperization of the rural classes. In this context of poverty and social

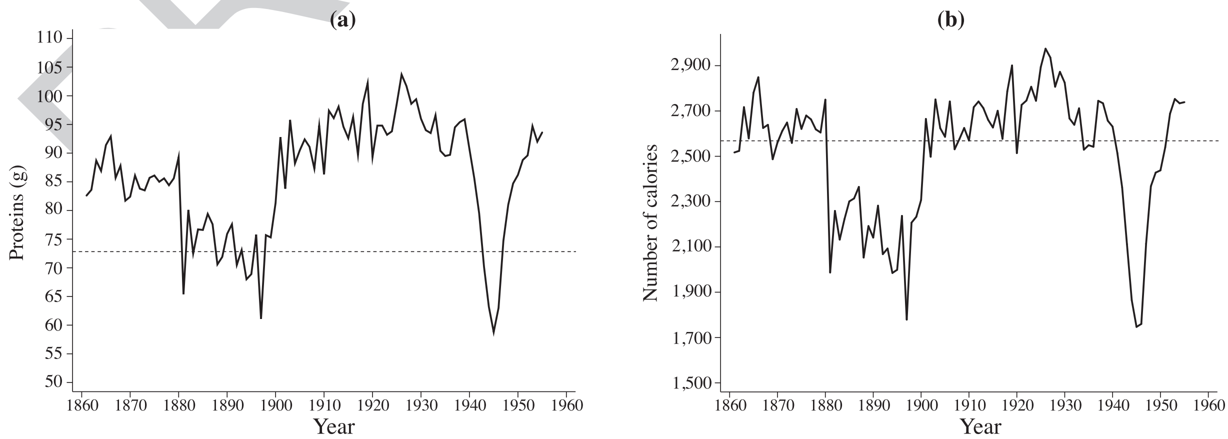

Figure 2 Daily availability per person of: (a) protein; and (b) calories, Italy 1861–1955
Note: Horizontal dashed lines represent the recommended values.
Source: Data from ISTAT (1958).

instability, the concurrent arrival of foreign products had triggered a generalized drop in prices, which had made the economic situation even worse. Furthermore, such dramatic conditions were worsened at the turn of the twentieth century by the spread of the phylloxera louse, which was responsible for the destruction of thousands of hectares of vineyards. As a consequence, the diet of rural families became poorer and less and less varied, with maize becoming the main and sometimes only food of the poorest social groups. This caused real nutritional problems, such as the spread of pellagra in many areas of Italy, northern Italy in particular (Livi Bacci 1986; Ginnaio 2011).

This is well illustrated by the time series of proteins and calories, which show that between 1878 and 1895, the mean daily availability of proteins dropped from 84.4 g per person to 68.9 g (−18.4 per cent) and the number of calories from 2,619 to 1,999 (−23.7 per cent).

The second trough is clearly associated with the consequences of the Second World War. In that period the decline was even more marked, characterized by overall drops of 38.4 and 36.1 per cent for proteins and calories, respectively, between 1938 and 1945.

Such levels, however, must be analysed in light of the nutrient requirements of pregnant women, which normally vary according to gestation: lower at the beginning, higher at the end. Recent studies have set the estimated average daily protein requirement during pregnancy at 1.22 g and 1.52 g per kilogram in early (11–20 weeks) and late (31–38 weeks) gestation, respectively (Stephens et al. 2015). Assuming a mean weight of 60 kg for adult women of reproductive age in that period (Danubio et al. 2005), pregnant women should have been consuming a minimum of 73.2 g or 91.2 g of proteins in the second and third trimesters of gestation, respectively. As for calorie intake, the European Food Safety Authority affirms that the total number of calories needed by pregnant women is about 2,560 and 2,800, in the second and third trimesters of gestation, respectively (EFSA 2013). More specifically, for women aged 30–39, EFSA recommends an intake of between 2,000 and 2,600 calories, which should be supplemented by a further 260 calories for pregnant women in the second trimester. Our cut-off is therefore determined using the midpoint of this interval plus 260, namely 2,560 calories. In that respect, some of the birth cohorts born before 1900 suffered from insufficient maternal intake of proteins and calories in the last trimester of gestation. Such generations were concentrated mainly during the agrarian crisis of the last 20 years of the nineteenth century, but some generations born before the start of that crisis also suffered from some maternal food shortage. This evidence may also help to explain the higher childlessness of the cohorts born before 1910, as highlighted in Figure 1. The nutritional situation subsequently improved only partially in the early-twentieth century but worsened again between 1934 and 1936, well before the expected crisis associated with the Second World War. The effects of that conflict on mothers' intake of both macronutrients then extended until 1951. It is clear from this evidence that our method is able to capture years or periods of limited food availability that are not necessarily associated with well-known historical famines.

The relationship between mothers' nutritional status and offspring fertility

The results from the logistic regression models of the odds of being childless according to macronutrient availability are shown in Tables 2 and 3 (for proteins and calories, respectively). The tables report the odds ratios for all variables, including controls. Proteins and calories are used as proxies for nutritional status due to their key role in the growth of the foetus and foetal programming. We treat them as dichotomous variables indicating whether or not a specific year was characterized by insufficient availability of macronutrients for pregnant women according to the standard nutritional requirements described in the previous section. Because of their high degree of collinearity, the proteins and calories are included in separate models. The season at the fifth month of gestation is included both to capture the seasonal effects on the mother's energy balance associated with periods of harder physical work and to test the SPrOO hypothesis. This is a categorical variable that contrasts winter (December, January, February) with spring (March, April, May), summer (June, July, August), and autumn (September, October, November).

The model also includes some control variables: age at first marriage, educational attainment, housing facilities, and the First World War. These are all categorical variables except age at first marriage. Age at marriage is included to control for the beginning of exposure to the risk of having a baby. Women's educational attainment and housing facilities capture the influence of socio-economic factors on fertility, which should also allow us to capture, at least partly, the effects of voluntary

Table 2 Logistic regression of the odds of offspring childlessness according to protein availability and season of gestation: married women in a sample of Italian communities, 1961

Variables	Percentage	Odds ratio	*p*-value[1]
Availability of proteins at mid-gestation	–	–	*0.438*
Sufficient	86.0	1.000	–
Insufficient	14.0	1.083	–
Season at the fifth month of gestation	–	–	*0.010*
Winter	22.4	1.000	–
Spring	24.6	1.045	–
Summer	24.7	0.789	–
Autumn	28.3	1.115	–
Age at first marriage	23.5	1.115	*<0.001*
Educational attainment	–	–	*0.039*
No education / illiterate	38.3	1.024	–
Primary education	58.2	1.000	–
Secondary or higher education	3.3	1.666	–
Unknown	0.2	1.608	–
Housing quality	–	–	*0.007*
Poor	27.8	1.000	–
Medium	67.1	1.237	–
High	5.1	1.704	–
Population	–	–	*0.020*
Casalguidi	8.3	1.000	–
Lauco	2.6	1.504	–
Novellara	18.1	0.951	–
Turriaco	4.1	1.142	–
Massa Lubrense	10.0	0.678	–
Rural Sardinia	19.6	1.084	–
Urban Sardinia	37.4	1.028	–
First World War period	–	–	*0.120*
No	92.1	1.000	–
Yes	7.9	0.790	–
N		13,124	
Log-likelihood		–2,802.9	
Wald chi^2		233.2	
p-value		<0.001	

[1]The *p*-values in italic come from likelihood ratio tests of the joint significance of each variable.
Source: Authors' analysis based on data from Italian 1961 Census (women's reproductive histories) and ISTAT (1958).

birth control on childlessness. Previous research has shown that the adoption of reproductive behaviours aimed at controlling and regulating couples' fertility was, in fact, closely associated with both socio-economic status and, more importantly, women's education (Caldwell 1982; Becker 1991; Cleland 2002; Breschi et al. 2013; Caltabiano and Dalla Zuanna 2015). Women's education can also be considered a proxy for early-life maternal socio-economic status. In fact, at the turn of the twentieth century, only well-off young women could obtain any educational qualification. Operatively, the educational attainment variable contrasts women with primary education (reference category) with the illiterate and those without any education, on the one hand, and those with a higher level of education, on the other hand. This kind of categorization is necessary because of the very low level of schooling of Italian women in that period. Compulsory education was first introduced in Italy in 1877, when five-year-old children were obliged to attend primary school up to age eight; this was then extended to age 12 in 1911 and age 14 in 1923. As for housing facilities, we classify houses into three categories according to the presence of running water, a toilet, a bath, electricity, gas, and heating. High-quality houses had five or six facilities and medium ones three or four facilities, while poor-quality houses (reference category) had just one or two. We consider housing characteristics to be more stable than occupation over time. This consideration relies on the fact that changes in housing quality might not occur in all cases of moving house but only when moving to a house with different characteristics (Breschi et al. 2013). Daily farm labourers who moved to the city to work in factories likely changed their occupation

Table 3 Logistic regression of the odds of offspring childlessness according to calorie availability and season of gestation: married women in a sample of Italian communities, 1961

Variables	Percentage	Odds ratio	*p*-value[1]
Availability of calories at mid-gestation	–	–	*0.010*
Sufficient	86.0	1.000	–
Insufficient	14.0	1.243	–
Season at the fifth month of gestation	–	–	*0.008*
Winter	22.4	1.000	–
Spring	24.6	1.042	–
Summer	24.7	0.783	–
Autumn	28.3	1.113	–
Age at first marriage	23.5	1.113	*<0.001*
Educational attainment	–	–	*0.031*
No education / illiterate	38.3	0.985	–
Primary education	58.2	1.000	–
Secondary or higher education	3.3	1.677	–
Unknown	0.2	1.559	–
Housing quality	–	–	*0.007*
Poor	27.8	1.000	–
Medium	67.1	1.233	–
High	5.1	1.701	–
Population	–	–	*0.024*
Casalguidi	8.3	1.000	–
Lauco	2.6	1.459	–
Novellara	18.1	0.953	–
Turriaco	4.1	1.153	–
Massa Lubrense	10.0	0.684	–
Rural Sardinia	19.6	1.097	–
Urban Sardinia	37.4	1.035	–
First World War period	–	–	*0.257*
No	92.1	1.000	–
Yes	7.9	0.840	–
N		13,124	
Log-likelihood		–2,799.8	
Wald chi^2		242.5	
p-value		<0.001	

[1]The *p*-values in italic come from likelihood ratio tests of the joint significance of each variable.
Source: As for Table 2.

but were less likely to change the quality of their housing. In any case, housing facilities are more indicative of women's socio-economic status than their profession is (Manfredini and Breschi 2008), as more than 75 per cent of married women were reported as 'housewife' or 'retired' in the 1961 Census returns analysed here. Finally, a dichotomous variable concerning the First World War is included as a key context variable, as the war potentially affected women's reproductive histories through its impact on married life, food availability, and health status.

The estimates from the two basic models presented in Tables 2 and 3 show different patterns for the two macronutrients studied. Maternal availability of proteins does not appear to affect the odds of experiencing childlessness for offspring significantly, although the odds ratio for insufficient supply is positive (1.083). Conversely, maternal availability of calories does appear to modify the odds of childlessness in later life significantly (p = 0.010), as pregnant women with insufficient calorie supply are about 24 per cent significantly more likely to bear offspring with infertility problems (childlessness) than women with the correct intake of calories at mid-gestation. These results provide evidence that the long-term consequences of nutritional problems in pregnancy were associated more with global calorie intake than with the quality of the diet.

As for seasonality at mid-gestation, it is significantly associated with the odds of childlessness, as shown by the joint significance of that variable in both models (for the proteins model, LR = 11.36,

p = 0.010; for the calories model, LR = 11.85, p = 0.008). In this context, summer appears to be associated with the largest change in the odds of childlessness in adulthood in both models (about −22 per cent). This result was not necessarily expected because the summer season is characterized, as outlined earlier, by elements that may have conflicting effects on the reproductive system later in life. The lower odds for the summer season seem, in this case, to provide partial evidence of the protective role associated with the seasonal cycle of the maturing oocyte (SPrOO hypothesis). We cannot even exclude the possibility that some protective effects associated with the higher level of vitamin D production might also be at play.

As for the control variables, they work in the expected directions in both models. On the one hand, the odds of childlessness appear to increase significantly with age at first marriage for obvious physiological reasons; on the other they show a positive association with socio-economic indicators (housing quality and women's education): the wealthier and more educated the woman, the higher her odds of being sterile. In our view, this was a consequence of deliberate choice among wealthy and educated women, who were forerunners in effectively controlling their fertility. Finally, there is evidence of significant geographical differentials, but these do not imply the existence of a North–South divide. The two extremes relate to the population of Massa Lubrense, characterized by 32 per cent lower odds of childlessness compared with the Tuscan village of Casalguidi (reference category), and Lauco, which presents 45–50 per cent higher odds for reasons previously discussed.

A clearer picture of the roles of nutrients and seasonality can be gained from the results of an interaction model. Such a model allows us to analyse the interplay between these two factors to appreciate whether they are somehow intertwined. Thus, we estimate two interaction models, for proteins and calories, respectively, both controlling for the same covariates. Before getting into more in-depth analysis of the results, a likelihood ratio test was applied to check for a statistically significant improvement in model fit after the introduction of the interaction terms. This test returned LR = 0.50, p = 0.919 for the proteins model and LR = 6.61, p = 0.085 for the calories model. Since only the latter model showed a significant improvement in model fit (at $p < 0.100$), we present and discuss the results only for the interaction between seasonality and calorie availability (Table 4).

The output of the interaction model shown in Table 4 is not easy to interpret. Let's call *b1* the effect of the season at mid-gestation, *b2* the effect of nutrient availability, and *b3* the interaction term. We can interpret *b1* as the odds ratio of being childless in later life for any season with respect to winter (reference category) in times of sufficient nutrient availability. Likewise, *b2* is the odds ratio comparing sufficient vs insufficient nutrient availability in winter. Finally, *b3* represents how much the effect

Table 4 Logistic regression of the odds of offspring childlessness including interactions between calorie availability and season of gestation: married women in a sample of Italian communities, 1961

Variables	Odds ratio
Availability of calories at mid-gestation (ref. = *Sufficient*)	1.000
Insufficient	0.928
Season at the fifth month of gestation (ref. = *Winter*)	1.000
Spring	0.979
Summer	0.632
Autumn	0.984
Insufficient × Spring	1.223
Insufficient × Summer	1.799
Insufficient × Autumn	1.445
N	13,124
Log-likelihood	−2,796.5
Wald chi2	248.0
p-value	<0.001
Likelihood ratio test	6.61
p-value	0.085

Notes: Age at first marriage, educational attainment, housing quality, population, and First World War are also included as control variables. Ref. is the reference category.
Source: As for Table 2.

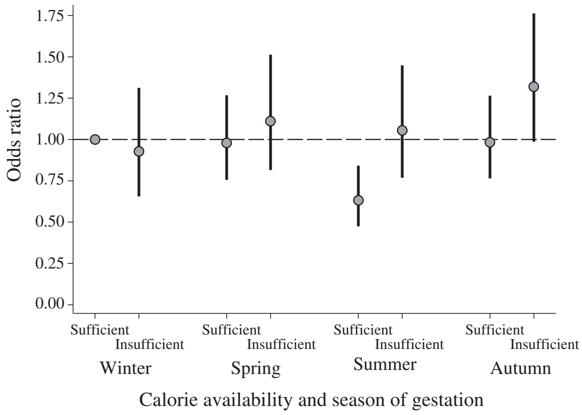

Figure 3 Interaction model between calorie availability and gestation seasonality in Italy after reparameterization of odds ratios
Note: Vertical bars show 95 per cent confidence intervals.
Source: Authors' analysis based on data from Italian 1961 Census and ISTAT (1958).

of the season changes when insufficient nutrient availability is considered instead of sufficient availability. That said, the results clearly show the modification of the seasonal effect by calorie availability. Experiencing mid-gestation in summer is associated with 37 per cent lower odds of offspring childlessness compared with winter, when the supply of calories is sufficient. In contrast, the effects of summer on offspring childlessness increase by 80 per cent in times of insufficient calorie supply. A similar pattern is also found for autumn, when a scarce intake of calories produces a 45 per cent increase in the odds of childlessness of offspring compared with periods of sufficient intake.

Finally, we carry out a reparameterization of the interaction terms to adjust them to a single reference category, namely winter with sufficient nutrient availability. This requires a recalculation of the odds ratios for the interaction terms as $b1 \times b2 \times b3$ (Figure 3). Figure 3 shows how the summer period, which is usually extremely favourable for normal foetal development compared with winter, is associated, in the case of insufficient calorie supply, with as high a risk of childlessness in later life as the winter season. A noticeable increase in risk during years with scarce calorie availability is also detectable in autumn, when the odds of childlessness for offspring rise by about 32 per cent compared with winters with sufficient availability of calories. No doubt even autumn demanded hard physical work in the fields, due especially to the grape harvest (in almost every region considered here) and olive harvest (in Sardinia, Tuscany, and Campania).

The models presented here use a dependent dichotomous variable based on live births to determine childlessness. However, the distinction between a live birth and a stillbirth was not necessarily clear for non-medical people of that period and, given that census family sheets were self-compiled, the numbers of live vs stillbirths reported in the reproductive histories of women are not completely reliable (Breschi and Pozzi 2013). For consistency reasons, we re-estimated the same models using a dichotomous dependent childlessness variable based on total births (including stillbirths) rather than live births only. The models (not presented here for the sake of space) showed consistent results with the findings already described.

Discussion and concluding remarks

The role of maternal nutritional status in pregnancy on the reproductive system of offspring has been tackled only rarely in historical demography. The lack of reliable data is surely one of the most compelling reasons for this dearth of studies. Some scholars have, therefore, preferred to focus on specific historical moments characterized by well-known phases of food shortage, food crisis, or famine, such as the Dutch famine of 1944–45 or the Chinese famine of 1959–61. The results, however, have not provided any clear-cut evidence of the relationship between maternal malnutrition and offspring fertility.

In this study, we used women's reproductive histories from the Italian Census of 1961 and official statistics on the mean daily availability of macronutrients per person to try to shed some light not simply on this relationship but on the possible extreme consequence that mothers' nutritional status may have on the reproductive system of offspring, namely infertility. The data used in this study allowed us to investigate childlessness rather than real infertility, but we have proved that voluntary childlessness was quite uncommon in Italy during that period, making us confident that married women without children were so because they were biologically unable to conceive or bring to term a live birth.

The results have provided clear evidence of the effect of nutritional stress in mid-pregnancy in increasing the odds of offspring childlessness (infertility) in adulthood; in particular, limited availability of calories was associated with significantly higher odds of offspring having no children. Conversely, no association was found for protein availability.

In the light of this outcome, we can guess that foetal programming at mid-gestation was much more sensitive to calorie intake than it was to the quality and variety of the diet. Therefore, years with scarce calorie availability (at least below the standard requirements for pregnant women) might have affected foetal development to such a point that the reproduction system of offspring was severely impaired and damaged. These nutritional conditions may then have been aggravated by the specific seasonal conditions experienced by mothers. In particular, the significant increase in the odds of offspring childlessness for mothers who experienced mid-gestation during summer (but also autumn) proves that pregnant women were involved, in that season, in energy-consuming work alongside possibly raising previous children. This implies that in rural families, the help and participation of women in agricultural work, even when pregnant, was deemed a necessary contribution to the meagre family income.

The mixed evidence concerning the two macronutrients studied here allows us to stress another important point. The negative association between maternal calorie availability and the odds of offspring childlessness related to foetal stress presents elements that could fit with the theory of 'maternal depletion syndrome' (Jelliffe and Maddocks 1964). In the light of this theory, the delicate equilibrium between nutrient intake and energy expenditure may be broken by repeated childbearing, the need to work during and immediately after pregnancy, and, most of all, poor nutrition leading to poor maternal health, if not death (Scalone 2014; Manfredini et al. 2020). Unfortunately, no information is available on childless women's birth order within their sibling set, which makes it impossible to know whether individuals' mothers experienced repeated childbearing. Any conclusion about the possible connections between maternal depletion syndrome and the relationship between a mother's poor nutritional status and offspring childlessness would be premature at this stage. However, according to the results from our study, it is possible that maternal depletion status, usually triggered by low calorie intake and the resultant low energy balance during periods of hard physical work, may also induce deep stress in the foetus, leading to developmental problems and altering foetal programming.

Some limitations related to data robustness and the geographic representativeness of this study should be considered, although, in our opinion, they do not seriously undermine the conclusions. First, nutritional data from official statistics are daily averages at the national level. However, every single community is likely to have experienced different levels of calorie and protein availability over time, according to its economic, environmental, and social specificities. Even if it is conceivable that life quality and well-being were higher in the northern areas than in the southern ones (which were more economically and socially backward in 1881, i.e. in the period characterized by the most remarkable drop in nutrient availability according to Vecchi and Coppola [2003]), the share of malnourished families was similar in both northern and southern Italy. Another study (Manfredini and Breschi 2020) highlighted that in the period 1861–1955, the maternal mortality rate was lower (or, in any case, not higher) in the southern regions than the northern ones despite the backwardness of the former. In addition, our analysis was based largely on Sardinian communities, and this might signify a representativeness bias.

Second, nutrient availability may differ by sex. It is well known that the best and most energy-rich food was reserved for men, especially in rural families, so women's calorie intake might have been lower than reported in official statistics, thereby making the consequences on foetal programming even worse. Moreover, nutritional differentials may arise in relation to the position within the household. It is well known, for example, that the household head's wife had a privileged position within the rural family, especially over other female members (Barbagli 2013).

A further limitation of this study was the absence of any information on husbands. Childlessness can be a consequence of genetic and/or physiological problems in men and the introduction of any proxy that could control for that effect would further refine the results.

In conclusion, notwithstanding our promising results, much more research is needed to better understand the complex mechanisms linking poor maternal nutritional conditions with offspring reproductive histories, especially in historical contexts of poor data quality and unsatisfactory representativeness of samples.

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Appendix: Sensitivity analysis

In the paper, we presented a model where women were defined as infertile if they had not given birth for seven years after marriage, unless they had subsequently had a first birth (after postponement or for any other reason). This poses some concern for the women married in the late 1950s, who were observed for a shorter time compared with earlier marriage cohorts. We therefore check the robustness of results by estimating a model that includes only women aged 45+ years at the 1961 Census. This allows us to consider only women observed for their entire reproductive period. The results of this model are shown in Table A1, and they are consistent with those presented in the paper on a larger sample of women.

Table A1 Logistic regression of the odds of offspring childlessness according to calorie/protein availability and season of gestation: married women aged 45+ in 1961

	Odds ratio	*p*-value
Model with proteins		
Availability of proteins at mid-gestation	–	*0.860*
Sufficient (ref.)	1.000	–
Insufficient	1.019	–
Season at the fifth month of gestation	–	*0.016*
Winter (ref.)	1.000	–
Spring	1.033	–
Summer	0.794	–
Autumn	1.253	–
Log-likelihood	−2,005.9	
Wald chi^2	159.8	
p-value	<0.001	
Model with calories		
Availability of calories at mid-gestation	–	*0.087*
Sufficient (ref.)	1.000	–
Insufficient	1.167	–
Season at the fifth month of gestation	–	*0.015*
Winter (ref.)	1.000	–
Spring	1.030	–
Summer	0.791	–
Autumn	1.249	–
Log-likelihood	−2,004.5	
Wald chi^2	163.6	
p-value	<0.001	
N	8,433	

Notes: The models also control for age at first marriage, house quality, educational attainment, population, and the First World War. Ref. is the reference category.
Source: Authors' analysis based on data from Italian 1961 Census and ISTAT (1958).

A second issue concerns the youngest and oldest birth cohorts included in the model. These cohorts might have been subject to quite strong selection effects. Thus, we re-estimate the model excluding the tails of the birth cohort distribution (Table A2). More precisely, we exclude the 15 youngest and oldest yearly cohorts, therefore limiting the analysis to women born between 1876 and 1924. The sample investigated shrinks by almost 20 per cent, but the results once again appear to be definitely consistent with those presented in the paper.

Table A2 Logistic regression of the odds of offspring childlessness according to calorie/protein availability and season of gestation: married women born 1876–1924

	Odds ratio	*p*-value
Model with proteins		
Availability of proteins at mid-gestation	–	*0.736*
Sufficient (ref.)	1.000	–
Insufficient	1.036	–
Season at the fifth month of gestation	–	*0.011*
Winter (ref.)	1.000	–
Spring	0.997	–
Summer	0.784	–
Autumn	1.139	–
Log-likelihood	−2,475.9	
Wald chi^2	194.3	
p-value	<0.001	
Model with calories		
Availability of calories at mid-gestation	–	*0.035*
Sufficient (ref.)	1.000	–
Insufficient	1.200	–
Season at the fifth month of gestation	–	*0.010*
Winter (ref.)	1.000	–
Spring	0.995	–
Summer	0.780	–
Autumn	1.137	–
Log-likelihood	−2,473.7	
Wald chi2	197.5	
p-value	<0.001	
N	10,418	

Notes: Both models also control for age at first marriage, house quality, educational attainment, population, and the First World War. Ref. is the reference category.
Source: As for Table A1.