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Population Overshoot

by

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Motivation

Ehrlich and Holdren (1971) introduced the metaphor, I=PAT, to draw attention to the significance of the biosphere's carrying capacity for population ethics. The authors traced the *i*mpact of human activities on the Earth system to *p*opulation, *a*ffluence (read, per capita consumption of goods and services), and the character of *t*echnology in use (including institutions and social capital). Because our impact on the biosphere is proportional to the demands we make of it, and because those demands increase with our economic activity, we can assume our impact on the biosphere increases with economic activity. But it means that even though today's poorest societies can be expected in time to display fertility transitions, it is no reason to think that humanity's demands for the biosphere's goods and services will cease to exceed its ability to supply them (see below). That is why it is a mistake to ignore the Ehrlich-Holdren observation that the biosphere responds to the demands we make of it, not to changes in the demands we make of it (e.g. those that accompany declines in fertility rates), nor to changes in the rate of change in the demands we make of it (those that accompany declines in the rate of growth of the global population).[1]

Humanity's impact on the biosphere leaves traces. Studying biogeochemical signs in sediments and ice from the past several millennia, Waters et al. (2016) tracked the human-induced evolution of soil nitrogen and phosphorus from those deposits. The authors reported that the now-famous figure of the hockey stick that characterises time series of carbon concentration in the atmosphere are also displayed by time series of a wide class of global biogeochemical signatures. They display a flat trend over millenia until some 250 years ago, when they begin a slow increase, which continues until the middle of the 20th century, when they display a sharp and continuing rise. Waters et al. (2016) proposed that mid-20th Century should be regarded as the time we entered the Anthropocene.[2]

Their reading is consistent with macroeconomic statistics. World population in 1950 was about 2.5 billion and global output of final goods and services a bit over 8.7 trillion international dollars (at 2011 prices). The average person in the world was poor (annual income was only somewhat in excess of 3,500 international dollars). Since then the world has prospered beyond recognition. Life expectancy at birth in 1950 was 45, today it is a little over 70. World output of final goods and services is (at 2011 prices) above 110 trillion international dollars, meaning that at a population size of 7.5 billion, world income per capita is now more than 15,000 international dollars. A more than 12-fold increase in global output in a 65-year period helps to explain not only the stresses

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[1] The "PAT" in I = PAT may appear to be a product of P, A, and T, but it is not. There is no sense in which "technology" can multiple with the product of population and affluence. The equation should be read as a metaphor, nothing more.

2 The term "Anthropocine" was popularized by Crutzen and Stoermer (2000) to mark a new epoch of human domination of the Earth system. The Anthropocene Working Group has proposed that the immediate post-war years should be regarded as the start of the Anthropocene. See Vosen (2016).

that the biosphere has been subjected to in recent decades (MEA, 2005a-d), but it also hints at the possibility that humanity's demand for the biosphere's goods and services has for some time exceeded its ability to supply them on a sustainable basis.

That possibility has been given quantitative expression. In a review of the state of the biosphere, WWF (2008) reported that although the global demand for ecological goods and services in the 1960s was less than supply, it exceeded supply in the early years of the present century by 50 per cent. The figure is based on the idea of "global ecological footprint," which is the surface area of biologically productive land and sea needed to supply the resources we consume (food, fibres, wood, water) and to assimilate the waste we produce (materials, gases) on a sustainable basis. The Global Footprint Network (GFN) updates its estimates of the global ecological footprint on a regular basis. A footprint in excess of 1 means demand for ecological services exceeds their supply. By GFN's reckoning, maintaining the world's average living standard at the level reached some ten years ago (roughly 12,000 international dollars) would have required 1.5 Earths. It is now evident that the enormous gains humanity has enjoyed in the past 65 years has been at the expense of a diminished biosphere we are leaving behind for our descendants.[3]

What of future population? Figure 1, taken from UNPD (2017), shows world population projections by region from year 2015 to year 2100. The figure shows that, with the significant exceptions of Asia and Africa, population would appear to have stabilized in the rest of world when taken as an aggregate.[4] Asia's population is projected to grow from the current figure of approximately 4.1 billion to a bit over 5 billion in mid-century and then taper to a bit under 5 billion. In sharp contrast, Africa's population is projected to rise from its current 1 billion to 4 billion. Global population in 2100 is projected to be 11.2 billion. A global population of 11.2 billion would be expected to make vastly greater demands on the biosphere than today's population of 7.5 billion, and most certainly than a population of 2.5 billion (global population in 1950). And the reason the demands are most likely to be a lot greater is that with economic growth the per capita impact on the biosphere can be predicted to be larger.

In this chapter we offer one broad class of reasons for the overshoot in humanity's demand for the biosphere' goods and services relative to its ability to supply them on a sustainable basis. To put it figuratively, we are "eating into" the biosphere. The biosphere has the capacity to regenerate itself; which is why it is commonly modelled as a gigantic renewable natural resource. But if demand for its products exceeds its ability to supply them year to year, the socio-ecological system will eventually break. That is why environmental scientists today speak of tipping points separating distinct productivity regimes of the Earth system.

3 For pioneering work on the idea of ecological footprint, see Rees and Wackernagel (1994). Wakernagel, who founded the Global Footprint Network (www.footprintnetwork.org/public), was a lead author of WWF (2008).

4 Some countries have even experienced a population shrinkage in recent decades.

It is useful to decompose the factors making up our demands from the biosphere into population size and per capita demand, which is what Ehrlich and Holdren did in their paper. For the most part, though, we will keep technology aside and comment only at the end on the prospects of technology coming to humanity's aid in reducing the overshoot in global demand. In this chapter the focus is on demographic matters. Part I studies some important factors underlying what can only be called "population overshoot." We report on the way the desire for children has been estimated by demographers and argue that they overstate *informed* desire. The factors affecting expressed preferences for family size also point to "consumption overshoot" in countries that are today wealthy.[5] We package the factors under the familiar notion of "externalities." In Part II we make use of the estimate of humanity's current ecological footprint to ask how many people Earth can support at a reasonable standard of living. The data we use are cruder than are usual even in the social sciences. They are crude because the subject of our paper - the global population-consumption-environment nexus - has had very little quantitative airing among demographers and economists, and none from philosophers. Our aim here is to develop techniques of analysis that may prove useful when the study of socio-ecological processes becomes more common. Because the data are so crude, we do not even engage in exercises that uncover the sensitivity of our findings to the numerical assumptions on which they are built. The numbers we reach are meant to be illustrative, nothing more.

Part I

The Desire for Children

1 Rich and Poor: Consumption and Population

People have children for many reasons. The mix of motivations depends on the customs and institutions we inherit, as well as on our character and circumstances. That children are valuable in themselves is emotionally so compelling that it may seem too obvious to require acknowledgement, but social anthropologists have shown that children are not just valuable to us because of the innate desire we have to bear and rear them, but also because they represent the fulfilment of tradition and religious dictates, and because they are the clearest avenue open to self-transcendence. A common refrain, that our children are priceless, is an expression of how innately valuable they are to us.

Population in the Poor World

In places where formal institutions are underdeveloped, children also substitute for other assets, and are thus valuable also for the benefits they bring to their parents. This is most apparent in the poorest regions of the world. Children serve as security in old-age in places that have neither pension schemes nor adequate capital and land markets. They are also a source of labour in households possessing few labour saving devices. Children mind their siblings, tend domestic animals, pick berries and herbs, collect firewood, draw water, and help with cooking. (In South Asia children have been observed to work in household production from age six.) Children in poor

5 Our analysis borrows from Dasgupta and Dasgupta (2017).

countries are valued by their parents both as capital and as producer goods.

Those childhood activities are so unfamiliar today in the West that they direct us to study the mix of motivations governing procreation by contrasting rich regions from poor regions. There are notable exceptions, but broadly speaking fertility and mortality rates are high and health status and education attainments are low in poor countries, whereas the corresponding statistics in rich countries read the other way. Table 1, which presents a snap shot (roughly, the period 2014-'15), speaks to that by displaying data published by international organizations, where the two categories, "rich" and "poor", are defined in terms of GDP per capita. Countries have been known to make a transition from one category to the other (that's what economic development is usually taken to mean); moreover, the bulk of the world's population and a majority of the world's poorest people live in neither rich nor poor countries, and international statistics say there are enormously rich people in poor countries. It nevertheless pays to study sharp contrasts, as in Table 1.

Scholars have shown that differences in Table 1 between the rich and poor worlds are traceable to differences in institutions, beliefs, and social norms of behaviour. Kinship structure, marriage practices, and rules of inheritance vary across the world. The implied line of thinking says that causality shouldn't be traced to differences in income or wealth. It is not that fertility and mortality rates are high and health status and education attainments are low in poor regions *because* people there are poor, it is that very low incomes go hand in hand with those features of life. The variables are mutually determined over time.[6]

Table 1 is a snapshot. It says as compared to people in rich countries, those in societies that are poor receive far less basic education, have many more children, die a lot younger, enjoy fewer political and civil liberties, and suffer from greater failure in governance. There is no suggestion that poor societies will remain poor, nor that rich countries may not find their place reversed in the long run. Regional differences in fertility, education, and output per capita were slight until the start of the Early Modern era (roughly, 1500 CE). Global aggregates of earlier eras look much the same as their regional aggregates.[7] Figure 1 reveals that at least for population, regional aggregates will continue to diverge.

Caldwell (1982) drew on an idea that is suggested by Table 1, that the intergenerational transfer of wealth is from parents to children in rich countries but from children to parents in poor societies. The suggestion has been easier to confirm in rich countries, where the rate of investment in children's education has been found to be as high as 6-7 per cent of GDP (Haveman and Wolfe, 1995). Because a vast range of activities in poor societies are undertaken outside the institution of markets, it is especially hard to identify the direction in which resources there flow across the generations.

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6 Dasgupta (1993) contains a survey of these issues.

7 The classic on this is Maddison (2001), who provided estimates of expectancy of life at birth, population size, and output from 1 CE until year 1998 in various regions of the world.

Nevertheless, the Caldwell-hypothesis has been questioned for poor societies. Studies have found that even there the direction is from the old to the young (Lee, 2000, 2007). Further investigations may find hidden transfers from the young to the old in poor societies that confirm Caldwell's thesis, but as of now it would seem that throughout the world intergenerational resource transfers are made by the old to the young.

The Case of Africa

Taken as a region, sub-Saharan Africa has long been regarded as special, even among poor regions (Goody, 1976; Fortes, 1978; Bledsoe, 1994; Bongaarts and Casterline, 2013). Figure 1 confirms that the continent is an outlier in regard to population. In an early review of fertility intentions Cochrane and Farid (1989) noted that both the urban and rural, the educated and uneducated in sub-Saharan Africa have more, and want more, children than their counterparts in other less-developed regions. Even young women there expressed a desire for an average of 2.6 more children than women in the Middle East, 2.8 more than women in North Africa, and 3.6 to 3.7 more than women in Latin America and Asia. Updated versions of these figures are available, but it is worth considering the data from the mid-1980s because the income gap between Africa and the rest of the developing world was smaller at that time than it is now.

The idea of wealth-in-children has been developed by anthropologists to reflect the additional status and other social advantages that are conferred on women in some African societies by having children (Guyer and Eno Belinga, 1995). There is a formal resemblance here to Veblen's account of status in an entirely different context, which was conspicuous consumption in the Gilded Age in America (Veblen, 1925). In the context of wealth-in-children desired fertility is higher than it would have been otherwise because of the competition among households fuelled by the desire for status. It leads to a collective loss in well-being among those making fertility decisions.

Communal land tenure of the lineage social structure in sub-Saharan Africa has offered yet another inducement for men to procreate: a greater amount of land can be claimed by a larger family. In addition, conjugal bonds are frequently weak, so fathers often do not bear their fair share of costs of siring a child. Anthropologists have observed that the unit of African society is a woman and her children, rather than parents and their children. Frequently, there is no common budget for the man and woman. Descent in sub-Saharan Africa is, for the most part, patrilineal and residence is patrilocal (exceptions are the Akan of Ghana and the Chewa of Malawi). That depresses women's voice; and because women bear a disproportionate amount of the costs of reproduction, it raises fertility rate. Patrilineality, weak conjugal bonds, communal land tenure, and a strong kinship support system of children, taken together, have been a broad characteristic of the region. In principle they provide a powerful stimulus to fertility. Admittedly, patrilineality and patrilocality are features of the northern parts of the Indian sub-continent also. But conjugal bonds are substantially greater there. Moreover, as agricultural land is not communally held, large family sizes lead to fragmentation of land-holdings. In contrast, large families in sub-Saharan Africa are (or, at least were, until recently) rewarded by a greater share of land belonging to the lineage or clan.[8] Figure 1 and Table 1 tell us that the cost of the enormous increase in population that an extremely poor Africa is projected to experience in the coming decades will be an enormous burden on Africans themselves.

Consumption in the Rich World

In sharp contrast is the rich world. Table 1 reports that the 1.4 billion people living in the World Bank's list of high-income countries enjoy a per capita income of 41,000 (international) dollars. Total income therefore sums to 57 trillion dollars. Global income today is about 110 trillion international dollars. If, as a crude approximation we take consumption to be proportional to income, consumption in the richest 18% of the world's population (1.4 billion/7.5 billion) is more than 50% of world consumption (57 trillion/110 trillion). If economic development is to be sustainable, resource intensive consumption patterns in rich countries have to adjust substantially. In contrast, sub-Saharan Africa, a region inhabited by about 13% of the world's population, enjoys only 3% of the world's output of final goods and services. If population size and its increase is the significant social problem besetting the worlds' poorest region, it is high consumption in the world's rich countries that is currently responsible for a global ecological footprint well in excess of 1.

Positive and Normative Reasoning

Economists and historians have offered explanations for demographic trends (Rosenzweig and Stark, 1997) and the evolution of consumption tastes (Trentmann, 2016). They have commonly avoided moral theories in their studies. In contrast, philosophical discourses on population and consumption have been built on normative reasoning, directed at four questions: (1) What are the nature, ground, and limits of parental responsibility for existing children? (2) Does producing a child interfere with the rights of children the couple already have? (3) Do individuals have a duty not to have children who are likely to experience lives that will be bad for them? Do they have a duty to procreate if the children they create would likely to enjoy lives that will be good for them? (4) How should one value possible populations so as to decide which would be best?

One way to contrast the two disciplinary approaches is to say, in the case of population, that the economic demographer's task is to explain Table 1, while the aim in population ethics is to produce a normative theory that one could use to evaluate the behaviour patterns that give rise to Table 1 and prescribe better ones. Question (4), which stands in sharp contrast to those that demographers study, is at the heart of "population axiology," which attempts to uncover the ethics involved in what Parfit (1984: 356) called Different Numbers Choices. We do not pursue that line of enquiry here.[9]

2 Two Classes of Externalities

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8 The claim that households' access to natural resources increase with their size provides an inducement to procreate is proved formally in Dasgupta (2018).

9 The essays in the theoretical section of the Oxford Handbook explore population axiology. Dasgupta (2018) is a monograph-length treatment of the subject.

Processes driving the balance between population size and our demand for the biosphere's goods and services harbour *externalities*, which are the unaccounted for consequences for others of actions taken by one or more persons. The qualifier "unaccounted for" means that the consequences in question follow without prior engagement with those who are affected.

The way we have formulated the notion of externalities could appear odd, on grounds that our actions inevitably have consequences for future generations, who by the nature of things cannot engage with us. In fact future people engage with us constantly, albeit indirectly. Parents care about their children and know that they in turn will care about their children. By recursion, thoughtful parents take the well-being of their descendants into account when choosing the rates at which they save for their children and invest in them. Intergenerational engagement would be imperfect if parents choose without adequate concern for their children (e.g. if they discount the future well-being of their children at overly high rates). Externalities across the generations would be rampant in that case. We ignore that line of analysis here. Our aim is to study systematic reasons why choices made even by thoughtful parents do not reflect adequate engagement with *others*' descendants. As they are symptoms of institutional failure, externalities cannot be eliminated entirely, but can be reduced greatly by considered collective action. That is why reasoned reproductive decisions at the individual level can nevertheless result in collective failure.

One class of externalities arising from household consumption and reproduction decisions is traceable to open access resources: *the commons*. They have been much noted and studied by environmental economists (e.g. Baumol and Oates, 1975). The institutional failures that give rise to those externalities owe their origin to an absence of appropriate property rights to Nature's goods and services. By property rights we mean not only private rights, but communitarian and public rights too. One reason rights over the biosphere are difficult to define, let alone to enforce, is that Nature is constantly on the move (the wind blows, particulates diffuse, rivers flow, fish swim, birds and insects fly, and even earthworms are known to travel undetected). No one can contain the atmosphere they befoul. That means the price paid by someone for environmental services (that's the private cost) is less than the cost borne by all (that's the social cost). Modern patterns of consumption, relying as they do on long distance trade, are especially prone to being underpriced. That provides people with an incentive to consume too much. To cite a familiar example, in cases involving the global environment, such as the atmosphere as a sink for our carbon emissions, the damage an individual suffers from her own emissions is negligible even though the damage to all from the climate change that arises from everyone's emissions is large and positive. From the collective point of view there is excessive use of the atmosphere as a carbon sink.

The other category of externalities we study here has been less studied in the literature. Its source is the *social-embeddedness* of our preferences. Our desire for having children, for example, is in part influenced by the number of children others have. No doubt a single household cannot much influence others, but the aggregate effect of all households on one another is not negligible. We show that the social embeddedness of household preferences, the resulting behaviour can be called "conformist," can lead to high fertility even when the same preference structure sustains low fertility that households would prefer. Either situation - high fertility (allied to low educational attainment of children) or low fertility (allied to high educational attainment of children) - can sustain itself by its own bootstrap. Fertility transitions can be interpreted as moves from one equilibrium to the other.

Socially embedded preferences also influence consumption behaviour. Like reproductive behaviour, they take two forms. Our urge to compete with others (Veblen's "conspicuous consumption"; Veblen, 1925) is one form. (It's the counterpart to the "wealth-in-children" notion we noted earlier.) The other form arises from our desire to conform with others (Douglas and Isherwood, 1979). Both forms give rise to consumption externalities. We should conclude that the psychological cost to a person of a collective adjustment in consumption is likely to be much less than it would be if she were to adjust consumption unilaterally. The aggregate cost of collective adjustment could even be negative.

Externalities arising from our use of the commons and from the social-embeddedness of our preferences differ in their internal structures. The problem of choice in the use of open access resources resembles the well-known Prisoners' Dilemma. In contrast, socially embedded preferences give rise to Coordination Games. The latter class of externalities can be, and has been, turned by communities to their advantage by coordinating behaviour (e.g. through an appeal to social norms). The former class in contrast requires, at least over the global commons, more traditional policy measures such as environmental regulations.

3 Reproductive Rights

The 1994 International Conference on Population and Development reaffirmed the language of rights in the sphere of family planning and reproductive health. The widely noted publication that reported the Conference's conclusions stated:

"Reproductive rights ... rest on the recognition of the basic right of all couples and individuals to decide freely and responsibly the number, spacing, and timing of their children, and to have information and means to do so, and the right to attain the highest standards of sexual and reproductive health." (UNFPA, 1995: Ch. 7, Sect.3).

The qualifier, "responsibly", could be read as requiring couples to take into account the adverse environmental externalities their reproductive decisions may give rise to; but that probably would be a stretch. Certainly, writings affirming the UN declaration have interpreted the passage and its intent more narrowly. For example, the fundamental right of individuals "to decide freely and for themselves, whether, when, and how many children to have" is central to the vision and goals of *Family Planning 2020* (FP2020). It is also pivotal in the reproductive health indicators of the United Nations' Sustainable Development Goals.

It is useful to study the relationship between "externalities" and "rights." First, to insist that the rights of individuals and couples to decide freely the number of children they produce trump all competing interests is to play down the rights of all those (most especially, perhaps, future people) who suffer from the environmental externalities that accompany additions to the population.[10] Secondly, UNFPA's statement ignores the latent need among those who do not want family planning now but would want it if others among their peer group were using modern contraceptives.

That family planning services bring in their wake many benefits (health, education, income, women's empowerment) to those who make use of them has been documented repeatedly in recent years.[11] Our focus on externalities points to the fact that they bring benefits to others as well. Those additional benefits should be included in the design of social policies. Below we show that indicators currently in use by governments and NGOs of the value of family planning services underestimate it.

Policies for curbing adverse reproductive externalities can in principle take several forms. Education, especially female education, is one route; many argue it is the most effective route (Lutz et al., 2014). But that can take time, and female education is not the only factor driving fertility.[12] Another tool involves demonstrative persuasion, which can be attempted through community discussions on the need for behavioural change. The agency of persuasion could be the community, NGOs, or the state. A further tool is taxation, which permits people to choose as they wish, but at a price. Although taxation as a device for curbing environmental externalities is familiar in wealthy countries, it is not an available tool for reducing the demand for children in poor countries, where the poorest households are most often the ones that have the highest demand.

There are thus a variety of policy tools available for reducing fertility where fertility rates are above replacement levels. The tools differ in terms of the extent to which the right to self-determination is compromised. None are likely to prove uncontroversial. The issues remain unsettled.

4 Socially Embedded Preferences and Conformism

That children are a parental end (and not just a means toward other parental goals) provides a potentially powerful mechanism by which reasoned fertility decisions at the level of every household could lead to an unsatisfactory outcome from the perspectives of all households. It arises from the possibility that traditional practice is perpetuated by conformity. Reproductive decisions are not only a private matter; they are subject to social mores, which in turn are influenced by both family

10 Sen (1982) likens the emission of persistent pollutants to torturing future people. The clash between reproductive rights and adverse environmental externalities allied to new births is at its most striking under his reading.

11 See for example Koenig et al. (1992), Debpuur et al. (2002), Cleland et al. (2006), Tsui et al. (2010), Canning and Schultz (2012), Sonfield et al. (2013), and Bongaarts (2016), Miller and Babiarz (2016).

12 World Bank (2012) reported that in 2010 the proportion of people who completed primary education was, in India 96%, in Pakistan 67%, and in Bangladesh, 65%. Total fertility rates (TFRs) in those countries were 2.6, 3.4, and 2.2, respectively. It should also be noted that in Bangladesh non-governmental organizations at work on social matters have a far more extensive reach than in India and Pakistan. Reproductive behaviour is not mono-causal.

experiences and the cultural milieu. But social mores are shaped by the behaviour of all. There is circularity in this, which we can unravel by supposing that household preference structures are socially embedded. Behaviour is conformist when the family size each household desires is positively related to the average family size in the community (Dasgupta, 1993: Ch. 12).[13]

Whatever the basis of conformism, there would be practices encouraging high fertility that no household would unilaterally desire to break. Such practice could have had a rationale in the past, when mortality rates were high, population densities were low, natural resources were aplenty, the threat of extermination from outside attack was large, and mobility was restricted. But practices can survive even when their original purposes have disappeared. One reason they can survive is that if all others continue to follow the practice and aim at large family sizes, no conformist household would on its own wish to deviate from the practice; however, if all other households were to restrict their fertility rates, every household would wish to restrict its fertility rate as well. Conformism can thus be a reason for the existence of multiple social equilibria. A society could get embedded in a self-sustaining mode of behaviour characterized by high fertility and low educational attainment, even when there is another potentially self-sustaining mode of behaviour characterized by low fertility and high educational attainment and which is preferred by all.

Socially embedded preferences for children are drawn in Figure 2. The curve ABCDE is the representative household's desired number of children, plotted against the average number of children per household (the horizontal axis). The curve is upward sloping and intersects the 45^{o} line OF at three points: B, C, D. Each is a social equilibrium, at TFRs n_1, n_2, and n_3 respectively. To interpret ABCDE with concrete numbers, imagine that each household regards 5 to be the ideal number of children if all other households have 5 children (n_3 on the horizontal axis)); 4 to be the ideal number if all others have 4 (n_2); and 2 to be the ideal number if all others have 2 (n_1). Imagine now that each household prefers the outcome where all households have 2 children. It can nevertheless be that their society is stuck in a situation where each household has 5 children. It can get stuck because no household would have a reason to deviate from 5 if all other households have 5; which is another way of saying that 5 is a self-enforcing choice. It is easy to confirm that both 2 and 5 are stable equilibria, in that a small deviation from 2 (respectively, 5) would in time return to a situation where each

13 Douglas and Isherwood (1979) offered reasons for regarding consumption as an expression of social engagement. Taken literally, that would appear odd, but what authors were pointing to is that a meal taken alone is a different activity from a meal taken communally. Fads and fashion may be short-run expressions of social engagement, what Douglas and Isherwood showed is that our need to belong is deep and enduring and expresses itself in a wide variety of ways. We rely on one another for safety, consolation, information, companionship, and governance. Much of our actions are undertaken in a social setting, and all our actions are influenced in part by attention to others. In the text we apply that framework to reproductive decisions.

household chooses 2 (respectively, 5). It follows that 5 would be just as tenacious a TFR as 2.[14]

That does not mean society would be stuck at 5 forever. As always, people differ in the extent of their absorption of traditional practice. There would inevitably be those who, for one reason or another, experiment, take risks, and refrain from joining the crowd. They are the tradition breakers, and they often lead the way. Educated women are among the first to make the move toward smaller families.[15] A possibly even stronger pathway is the influence that newspapers, radio, television, and now the internet play in transmitting information about other life-styles. The idea here is that the media could be a vehicle by which conformism increasingly becomes based on the behaviour of a wider population than the local community (the peer group widens). And that disrupts behaviour.[16]

There have been a number of studies on fertility that point to choices that are guided in part by attention to others. In her highly original work on demographic change in Western Europe over the period 1870-1960, Watkins (1990) showed that differences in fertility and nuptiality within each country declined. She also found that in 1870, before the large-scale declines in marital fertility had begun in most areas of Western Europe, demographic behaviour differed considerably within countries. Differences among provinces within a country were high even while differences within provinces was low. Spatial behavioural clumps suggest the importance of the influence of local communities on behaviour. In 1960 differences within each country were considerably less than in 1870. Watkins explained this in terms of increases in the geographical reach national governments enjoyed over the 90 years in question. The growth of national languages could have been the medium through which reproductive behaviour was able to spread.

Watkins' was a historical study. Jensen and Oster (2009) in contrast have studied a natural experiment. They found that state level fertility rates declined in step following staggered introductions of cable TV in Indian states.[17]

It is a feature of historical studies of the diffusion of behaviour across space and time that they don't necessarily identify the fundamentals on which the diffusion process is built. They also differ from one another in terms of the transmission mechanism. The behavioural fundamentals (or "drivers", as some would call them) could be knowledge acquisition, they could be pure mimicry, they could be what Cleland and Wilson (1987) called "ideation", they could be the advent of modernity,

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14 Formally, we are studying Nash equilibria in a coordination game (Dasgupta, 1993). It can be shown that the social equilibrium in which each household has 4 children (n_2) is unstable. It would take us far afield to explain why, but see Dasgupta (2002) for the reason.

15 Farooq et al. (1987) is an early study that spoke to the phenomenon in West Africa. Lutz et al. (2014) is a collection of essays on the effect of education on fertility behaviour. Interactions among the elite and the general public can be a vehicle by which fertility behaviour among the poor changes.

16 The media are increasingly used to such end. For example, the Development Media International runs media campaigns aimed at changing behaviour.

17 For a wide ranging discussion of the role of societal norms on fertility behaviour, see Bongaarts and Watkins (1996).

they could be the desire to belong to one's (possibly expanding) group, they could be the force of celebrity culture, and so on. These fundamentals are not unrelated, but they are not the same. Regarding transmission mechanisms, it could be that people observe successful behaviour and copy it, it could be that the language in which newspapers are read spreads, it could be that people discuss and debate among themselves, and so forth.

The model in Figure 2 is built on the common structure of all such diffusion processes. Leaving aside the virtue of parsimony, studying the common structure offers the advantage that we are able to analyse the resting (i.e. equilibrium) points of a wide variety of diffusion processes without having to identify the processes themselves. Our model is analytical, not a historical narrative. It assumes that fertility preferences are socially embedded, but it doesn't specify the reasons households are influenced by the behaviour of others. Being analytical, the model is able to entertain counterfactuals. It allows us to ask how a household's behaviour would differ if the social parameters underlying the curve ABCDE were to be otherwise. That's a necessary exercise in policy analysis, because policies can be used to shift the curve ABCDE (therefore the equilibrium points n_1, n_2, and n_3) as well as influence the beliefs on the basis of which households act. The common structure also tells us that fertility transitions can be interpreted as disequilibrium phenomena (Dasgupta, 2002), where practices change slowly in response to gradual changes in the social environment, until a tipping point is reached from which society transits rapidly to a new stable equilibrium, say from high fertility to low fertility.

Socially embedded preference structures don't entail multiplicity of equilibria. We could have so drawn the curve ABCDE in Figure 2 that it intersects the 45^o line OF at a single point. We are interested in multiple equilibria because there is empirical evidence that societies support a multiplicity of stable fertility choices (e.g. n_1 and n_3). Historical studies of the diffusion of fertility behaviour point to that (Watkins, 1990). Fertility transitions are an expression of the phenomenon.

5 Unmet Need, Desired Family Size, and the UN's Sustainable Development Goals

UNFPA (1995) took it that family planning and reproductive health policies should address "unmet need", meaning that they should be made to serve women aged 15-49 who want to stop or delay child-bearing but are not using modern forms of contraception (Bradley et al., 2012; Alkema et al., 2013). Although the idea of "unmet need" could appear straightforward, it has in practice proved to be complex and has been interpreted in different ways over the years. It is currently measured using more than 15 survey questions, including questions on contraceptive use, fertility intentions, pregnancies, postpartum amenorreah, sexual activity, birth history, and menstruation. Women's reported fertility intentions are inferred from such questions as: "Now, I have some questions about the future. Would you like to have a(nother) child or would you prefer not to have (any more) children?" That is followed by a question on how long the women wants to wait should she have responded to the previous question that she does want a(nother) child.[18]

There are deep problems here. Unmet need as calculated from responses to survey questions is based on the respondent's expressed wants for children. The need for family planning is then inferred. But in matters of life and death resource needs assume an independent status, they even serve as the basis on which commodity rights are founded. A statement of the form "person A needs commodity X" can be regarded as tantamount to a challenge to imagine an alternative future in which A escapes harm without X (Wiggins, 1987: 22). Expressed wants or desires for children, which are used for calculating a woman's unmet need for family planning, may not adequately convey her true need for family planning, that is, for her own best interests. A poor woman, suffering from iron deficiency and living in a setting where she is more or less obliged to have sex, has a need for contraception for her own benefit that could remain undetected in her responses to questions on her expressed wants for children. To infer needs solely from wants is therefore to undervalue the significance of family planning. Moreover, none of the survey questions is conditioned on the behaviour of others. As we see below, that too is limiting.

Closely related is the notion of "ideal family size," which is obtained from answers to the following question: "If you could go back to the time when you did not have any children and could choose exactly the number of children to have in your whole life, how many would that be?"

There are dangers of biases in responses to the question at the basis of ideal family size, but the need for family planning programmes to have quantitative estimates of it is clear enough. Notice though that the questionnaire does not ask of someone what her desire would be if the prevailing fertility practices of others were different. In fact there is no mention of the prevailing fertility rate. As respondents are not invited to disclose their conditional desires, it is most likely they disclose their ideal family size on the assumption that fertility will remain at its prevailing rate. A direct way to discover socially embedded preferences would be to reconstruct the questionnaires by asking a series of conditional questions, which we collapse here for convenience into one:

"If you could go back to the time when you did not have any children and could choose exactly the number of children to have in your whole life, how many would that be, assuming everyone else in your community had n children over their whole life?"

The survey could pose the conditional question in an ascending order of n, say from 0 to 10 (thus 11 conditional questions in total). The example in Figure 2 imagines that the answers to $n = 2, 4$, and 5 are, respectively, 2, 4, and 5. It also imagines that answers to the questions in which $n = 0, 1, 3$, 6-10, respectively, differ from 0, 1, 3, 6-10; which is why the latter numbers are not social equilibria. No doubt responding to a string of conditional questions would tax respondents, but to not ask them is

18 Casterline and Sinding (2000) discuss ways in which the measure of unmet need can be used to inform family planning policies.

to misread fertility desires.[19]

Fabic et al. (2015) defined "total demand" for modern contraception to be the number of women who want to delay or limit child-bearing (i.e. the sum of contraceptive users and women with unmet need). The role of family planning, the authors argued, is to supply that demand. The suggestion is that the success of family planning should be measured by the ratio of family planning users to the total demand. The United Nations have adopted this measure in their Sustainable Development Goal 3.7.1. It is known as "demand for family planning met with modern contraceptive methods", or "demand satisfied" for short. Formally, if X is the number of women between 15-49 who are users of modern contraceptives, Y is the number of women with unmet need, and Z is total demand for modern contraception, then $Z = X+Y$ and the UN's "demand satisfied" is $X/Z = X/(X+Y)$.

Reproductive rights are at the heart of X/Z, which is its attraction. The indicator reflects voluntarism, rights and equity, informed choice, and the imperative of satisfying individuals' and couples' own choices with regard to the timing and number of children. But there are problems. The use of X/Z as the measure of success could create perverse incentives among programmes managers. A programme's performance would improve if more women were to declare that they want to get pregnant. So long as women want many children, Y (unmet need) remains small, and therefore Z (total demand) is only marginally greater than X (the number of modern contraceptive users). The country scores well in the indicator "demand satisfied" and appears not to need further family planning programming. The success could mask a situation where contraceptive use is low and stagnant and high fertility rates persist. This is demonstrated in Figure 3 which presents two examples. They have identical levels of demand for family planning met with modern contraceptive methods. However, the first example is characterised by higher use of modern methods. The second example is characterised by very low use of contraception and a significant proportion of women who are considered to have no need because of preferences for large families, and this example would likely have high fertility rates. Moreover, as we saw in Section 4, fertility preferences, which contribute to the measurement of Y, are themselves influenced by the behaviour of others. Y could therefore be small in a society that harbours another equilibrium in which Y is large.

The concept of reproductive rights, as currently framed, undervalues family planning. There are collective benefits to be enjoyed if members of a community are enabled to alter their fertility desires in a coordinated manner. Family planning can help to bring about changes in such social norms. Our analysis doesn't run against rights as a plank for family planning; it expands the sphere in which rights are acknowledged, protected, and promoted.[20]

19 Because people's preferences differ, we should expect the responses to differ but discover that each individual's preferred number of children is an increasing function of n. That would reveal socially embedded preferences.

20 Some moral philosophers would argue that the evaluation of family planning programmes should include the quality of lives that will not be lived on account of the

Part II

How Many People Can Earth Support in Comfort?

We have argued that the processes that have led to an overshoot in our demands on the biosphere are triggered by environmental and reproductive externalities. Below we present evidence which suggests that a global population of 11.2 billion (Fig. 1) at standards of living hoped for under the UN's Sustainable Development Goals would probably damage the biosphere to such an extent that the Goals would not be maintainable. Suppose then that by some miracle human society is able to eliminate the externalities. Suppose too that socio-economic inequalities are ironed out. Given current and prospective technological possibilities, what can we say about global population numbers that the biosphere can support sustainably at a comfortable living standard? In order to obtain sharp answers without technicalities, we confine ourselves to a world that is deterministic.

Economic possibilities are circumscribed by the biosphere. When thinking of the global economy, it is useful to regard the biosphere as a gigantic renewable natural resource. Fisheries are proto-typical examples of such resources. We observe next that human labour and ingenuity can be (and are!) applied to produced capital (machines and equipment) and the biosphere to produce output for consumption. That output is usually called GDP. However, other things equal, labour's contribution to output diminishes with increasing numbers. So, even though a larger population would produce more, there would be less to go round per person despite the larger output. Of course, other things are not equal: produced capital can be accumulated to counter the diminishing contribution of greater numbers of people to production. But produced capital is also subject to diminishing returns (accumulating tractors indefinitiely would not contribute to further agricultural production). Therefore, balances among the various factors of production should exist. In this paper we first select a standard of living that could be deemed to be comfortable. We then estimate the global population that could be supported by the biosphere at that living standard on a sustainable basis. But we first need an account of the biosphere in its role as a capital asset.

6 Ecosystem Services

The term "biosphere" is an all-encompassing construct. Although we will think of it as a gigantic renewable natural resource, it is in fact a mosaic of renewable natural resources. Agricultural land, forests, watersheds, fisheries, fresh water sources, estuaries, wetlands, the oceans, and the atmosphere are some of the interlocking constituents of the biosphere. We will refer to them generically as "ecosystems" and, so as to draw attention to populations of species in their habitats, we will speak of them also, more narrowly, as "biological communities."[21]

Ecosystems combine the abiotic environment with biological communities (plants, animals,

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programmes. Space forbids that we discuss those further considerations.

21 Tilman (1982) remains an excellent introduction to the processes by which competition among organisms for resources gives rise to the structure of biological communities.

fungi, and microorganisms) that form functional units. Individual actors in ecosystems include organisms that pollinate, decompose, filter, transport, re-distribute, scavenge, fix gases, and so on. Nearly all organisms that help to produce those services are hidden from view (a gram of soil may contain as many as 10 billion bacterial cells), which is why they are almost always missing from popular discourses on the environment. But their activities enable ecosystems to maintain a genetic library, preserve and regenerate soil, fix nitrogen and carbon, recycle nutrients, control floods, mitigate droughts, filter pollutants, assimilate waste, pollinate crops, operate the hydrological cycle, and maintain the gaseous composition of the atmosphere.

Ecosystems differ in composition and extent. They can be defined as ranging from the communities and interactions of organisms in your mouth or those in the canopy of a rain forest to all those in Earth's oceans. The processes governing them differ in complexity and speed. There are systems that turn over in minutes, there are others whose rhythmic time extends to hundreds of years. Some ecosystems are extensive ("biomes", such as the African Savannah), there are those that cover regions (river basins) and many involve clusters of villages (micro-watersheds), while others are confined to the level of a single village (the village pond). In each example there is an element of indivisibility. Divide an ecosystem into parts by creating barriers, and the sum of the productivity of the parts will typically be found to be lower than the productivity of the whole, other things equal (Sodhi, Brook, and Bradshaw, 2010). The mobility of biological populations is a reason (Section 2). Safe corridors, for example, enable migratory species to survive.

Ecosystems can regenerate but suffer deterioration (worse, exhaustion) when human expropriation exceeds the rates at which they are able to supply us with goods and services or when they are converted directly into produced capital. That is why ecosystems can be thought of as renewable natural resources. Population extinctions disrupt essential ecosystem services. In tropical forests dung beetles play an essential role in recycling nutrients. Excessive hunting of mammals in the forests has been found to be a cause of local elimination of dung dependent beetles (Brook, Sodhi, and Bradshaw, 2008). When subject to excessive stress, once flourishing ecosystems (e.g. biologically rich estuaries) flip into unproductive states (dead zones). The stress could be occasioned by an invasion of foreign species or substance (as in the above example), it could be owing to loss of population diversity, it could be triggered by the demise of a dominant species, and so on. Ehrlich and Ehrlich (1981) likened the pathways by which an ecosystem can be tipped out of a stable regime into an unproductive state to a flying aircraft from which rivets are removed, one at a time. The probability that it will crash increases very slowly at first, but then at some unspecifiable number rises sharply to 1.

Erosion of the biosphere usually goes unrecorded in official economic statistics because GDP does not record depreciation of capital assets. Destroy an open woodland so as to build a shopping mall, and the national accounts will record the increase in produced capital (the shopping mall is an investment), but not the disinvestment in what we may called "natural capital." The example is a commonplace. Even while industrial output increased by a multiple of 40 during the 20th century, the use of energy increased by a multiple of 16, methane-producing cattle population grew in pace with human population, fish catch increased by a multiple of 35 and carbon and sulphur dioxide emissions rose by more than 10. It has been estimated that 25-30 per cent of the 130 billion metric tons of carbon that are harnessed annually by terrestrial photosynthesis is appropriated for human use (Haberl et al., 2007). Although the rise in the concentration of atmospheric carbon receives much the greater public attention, MEA (2005a-d) reported that 15 of the 24 ecosystems the authors had reviewed world-wide were either degraded or are being exploited at unsustainable rates.

Current extinction rates of species in various orders have been estimated to be 10-1,000 times higher than their average rate (about 1 per million species per year) over the past several million years (Sodhi, Brook, and Bradshaw, 2009). The figures are reached from field studies of the decline in numbers of specific groups of mammals, insects, and birds, and from empirically drawn relationships between the number of species in an area and the size of the area. But the relationships are known to vary substantially among communities and habitats, which is why, as the range shows, there are great uncertainties in the estimates. Despite the uncertainties, the figures put the scale of humanity's presence on the Earth system in perspective.

The statistics we have just summarised for sketching humanity's recent doings differs sharply from the one that has been on offer in a string of recent books, in which intellectuals have re-drawn our attention to the remarkable gains in the standard of living humanity has enjoyed over the past century (Micklethwait and Wooldridge, 2000; Ridley, 2010; Pinker, 2018). The authors have collated data on growth in scientific knowledge and the accumulation of produced capital and human capital and argued that humanity has never had it so good. But with the exception of rising carbon concentration in the atmosphere, trends in the state of the biosphere accompanying those advances have gone unnoted by the authors. The problem is, global climate change is but one of a myriad of environmental problems we face today. And because it is amenable to technological solutions (innovating with cheap non-carbon sources of energy and, more speculatively, firing sulphur particulates into the stratosphere to reflect sunlight back to space; Pinker, 2018), it is not representative. Global climate change attracts attention among intellectuals and the reading public not only because it is a grave problem, but also because it is possible to imagine meeting it by using the familiar economics of commodity taxation, regulation, and resource pricing without having to forego growth in living standards in rich countries. The literature on the economics of climate change (e.g. Stern, 2006) has even encouraged the thought that with but little investment in clean energy sources (say 2% of world GDP) we can enjoy indefinite growth in the world's output of final goods and services (global GDP).

And that's a thought to be resisted. At least as grave a danger facing humanity is the unprecedented rate of species extinctions now taking place. Continued extinctions will damage the biosphere irreparably, and that cannot be prevented by technological fixes. Politics has intervened to prevent even the relatively small global investment that experts suggest is required to stall climate change. So we should expect the problem of species extinctions to remain off the table, at least until citizens take the matter seriously.[22]

7 The Biosphere as a Capital Stock

We assume that people apply their labour to produced capital (machines and equipment) and the biosphere's goods and services to produce an all-purpose commodity that can be consumed. Our idea is to choose a living standard deemed to be comfortable and identify the state of the biosphere that can sustain humanity at that standard on an indefinite basis.

Let Q be aggregate output of the consumption good and for the moment let K denote the biosphere, which is measured in, say, tons of biomass. If population size is N, we assume that

$$Q = K^{(1-\rho)}N^{\rho}, \qquad 0 \leq \rho < 1 \tag{1}$$

Equation (1) is widely used by economists to reflect production possibilities. The parameter ρ reflects the strength of the presence of labour in production. Notice that output is an unbounded function of population numbers, but the biosphere imposes a restraint on the rate at which output can expand with population. The latter is reflected in the condition $\rho < 1$. $(1-\rho)$ is a measure of the strength of the presence of K in production.

As of now we have little quantitative knowledge of the biosphere's dynamics. But we know that expanding our stock of produced capital would very likely to have environmental consequences. So, with both pairs of hands proverbially tied behind our backs we now regard K to be an aggregate measure of the biosphere and produced capital. Next, we stop K on its tracks and estimate $K^{(1-\rho)}$ (eq. (1)) on the basis of the global ecological footprint and the current size of the world economy. Stopping K on its tracks amounts to imposing a quota on what the human population is permitted to take from the biosphere. This is not an outlandish thought. Quotas are applied routinely to fisheries and forestry, and for access to potable water in dry regions. The recent international agreement to limit the rise in mean global temperature to 1.5^{o}C above what it was in pre-industrial times is tantamount to the use of quotas in emissions. That said, we realize that applying the idea on the biosphere as whole is a leap of faith in the ability, not to mention willingness, of international organizations to reduce the ecological footprint to a sustainable size. But we have found no other way to estimate the size of the global population Earth can support at reasonable comfort. Wilson (2016) has made an impassioned plea to leave half of Earth free of human encroachment.

The data being utterly crude, we confine ourselves to pen-on-paper computations. We assume that the value of the world's production of final good and services draws proportionately on ecosystem services at all levels.[23] World output is currently about 110 trillion international dollars. Using the

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22 The really hard problem in the political economy of global climate change involves using the latter's features to frame the way we should explore prospects of international agreements. Barrett (2003) and Barrett and Dannenberg (2012) are incisive studies on this.

23 This would be an incorrect assumption in non-stationary states, because it ignores differences among sectors

model of production in equation (1), we therefore have

$$K^{1-\rho}N^{\rho} = 110 \text{ trillion (international) dollars} \qquad (2)$$

We assume world population is 7.6 billion. For simplicity of calculations we assume that half the size of the global population (i.e., 3.8 billion) are engaged in production. (The global dependency ratio, that is, the ratio of the sum of the number of people below age 15 and above age 65 to the number of people between 15 and 65, is today about 1.6:1; so our assumption, that the dependency ratio is 1:1, is a reasonable approximation.) A huge empirical literature in economics suggests that as a rounded figure, $\rho = 0.5$ is not unreasonable.

Write $K^{1-\rho}$ as $\boldsymbol{K}$. Equation (2) then says

$$\boldsymbol{K} = 110\text{x}10^{12}/(3.8\text{x}10^{9})^{0.5} \text{ dollars per producer}^{0.5}$$

$$\approx 1.8 \text{ billion dollars per producer}^{0.5} \qquad (3)$$

To err on the conservative side of GFN's most recent estimate, we assume the current global ecological footprint is 1.5. That means if the biosphere and the stock of produced capital were stopped on their tracks, their sustainable value would be $\boldsymbol{K}/1.5$, which we denote by $\boldsymbol{K}^*$. Using equation (3),

$$\boldsymbol{K}^* = 1.2 \text{ billion dollars per producer}^{0.5} \qquad (4)$$

Having calibrated our model of global production, we now identify a living standard that could be deemed to be "comfortable."[24]

An analysis of one set of global surveys on happiness and their relationship with household incomes has revealed that in countries where per capita income is in excess of 20,000 dollars, additional income is not statistically related to greater reported happiness. Although the survey didn't work with international dollars (that is, the international rates of exchange corrected for differences in the purchasing powers of national currencies), we use 20,000 international dollars as our benchmark.[25] Using equations (1) and (4), and bearing in mind our demographic assumption that the

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in the value that labour adds to production of output.

24 Cohen (1995) reviewed studies that had estimated Earth's human carrying capacity. The range he reported was very wide (estimates, in billions, differed by nearly two orders of magnitude); but he didn't have at his disposal the ominous biogeochemical signatures that have been uncovered in recent years, nor the findings in MEA (2005a-d).

25 Layard (2011: 32-35) reports the finding and commends it. A number of explanations can be given for the finding, one being that what matters most to a household beyond a certain level of income is its income relative to the average income in its peer group. Veblen (1899,[1925]) based his theory of the leisure class on this particular psychology of consumption. Veblen's observation on human psychology found a telling expression in a remark attributed to a Garry Feldman of Stamford, Connecticut, one of the wealthiest towns in the USA: "I might be in the top one per cent, but I feel that I am in the bottom third of the people I know." (*The Guardian*, Saturday 16 February 2013)

Another explanation for happiness saturation bases itself on the idea that people are conformists even on styles of living. The problem isn't that either explanation is implausible (they are both all too believable), but that either dominates all other factors affecting the demand for goods and services beyond 20,000 international dollars. We work global workforce is half the size of the global population,

$$\boldsymbol{K}^*N^\rho/2N = 20{,}000 \qquad (5)$$

Solving for N in equation (5) yields $2N = 1.8$ billion. This was global population about a century ago (circa 1920); so we are not staring at a figure from the distant past.

The figure is revealing. The global population today is 7.6 billion and per capita consumption is a bit over 15,000 international dollars. Our estimate, with all the caveats we have stressed, says that if humanity were to find ways to husband the biosphere in a sustainable manner and to bring about economic equality, the population Earth could support at a living standard of 20,000 international dollars is 1.8 billion. It is a simple matter to conduct the exercise with alternative figures. We resist doing that.

Our decision to study how many people Earth can support in comfort in a *stationary state* was forced on us because of lack of data. We know that the biosphere can be thought to be a gigantic renewable natural resource, but we know next to nothing about the parameters that define its dynamics. So we have taken the desperate steps of freezing the biosphere and all other capital assets on their tracks and of calibrating the model by using estimates of our global ecological footprint. The idea that society can lock so complex an object as the Earth system on its tracks is wholly beyond belief, but it's the only move we have had available to us for finding a way through a horrible maze. The population figure we have reached (1.8 billion) on the basis of the calibration are not attainable, but we have presented them only to show how far off humanity is from where we should probably now be. Our aim has been to explore a mode of analysis, nothing more.

8 Technology and Institutions

When communities face exceptional resource stress (droughts and pests are only two causes), they can be expected to seek new practices and fashion new institutions. If migration to better locations is a possibility, communities can be expected to try that if all else fails. We shouldn't imagine people taking impending disasters lying down. Boserup (1965) collated evidence from agrarian societies to argue that resource stress generates societal responses that not only fend off disaster but can even lead to prosperity. Exceptional scarcities may raise exceptional "problems," but as the saying goes today, they offer exceptional "opportunities" as well. Boserup's work countered a widespread fear in the early 1960s that our capacity to produce food was being overtaken by growth in human numbers. She saw population growth as a spur to innovations. The Green Revolution that came soon after her publication matched her narrative. Population was dropped from public discourse even as Boserup came to be seen as a counterpoint to Malthus.

Boserup's case studies were about "organic economies" (Wrigley, 2004), where not only food but also raw materials are either animal or vegetable in origin. Inevitably, there was sample bias in her choice of examples. Societies that hadn't made the cut would have disappeared or moved to blend

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with that figure, even though we are not at all sanguine we understand the finding.

themselves among communities that survived; they would be absent from such records as those that Boserup studied. In a study of a modern-day society, Turner and Ali (1996) put together the contrasting concerns of Malthus and Boserup by demonstrating that in the face of rising population and a deteriorating resource base, small farmers in Bangladesh expanded production by intensifying agriculture practises (introducing multiple cropping and collectively strengthening drainage systems and flood and storm defences). The farmers haven't been able to thrive, they still live in poverty, but they staved off collapse (they haven't abandoned their villages *en masse* for cities), at least for now. Studies with a similar flavour for agricultural prospects in Africa have been summarised by Christiaensen (2017).

If Boserup is a counterpoint to Malthus, Jared Diamond is a natural counterpoint to Boserup. Techniques for reading archaeological records have improved since the 1960s. In a series of case studies drawn from early-to-middle second millennium CE, Diamond (2005) found that a number of societies that had deforested their land had been able to develop successful forest management practices and population measures, but that in contrast there were others, most notoriously Easter Island, that had failed to develop successful management practices, and had collapsed as a result. Diamond also found a common pattern in past collapses: Population growth that followed access to an abundant resource base made people intensify the means of food production (irrigation, terracing, double-cropping) and expand into marginal land. Growing populations led to a mining of the resource base; which in turn left communities vulnerable to climatic variations, as there was little room left for either mistakes or bad luck.

PNAS (2012) contains a Special Feature on historical collapses. Contributors reported twelve studies of past societies that had faced environmental stress. Seven were found to have suffered severe transformation, while five overcame them through changes in their practices. Butzer (2012) reported the ways in which a number of societies in 14th-18th centuries Western Europe displayed resilience by coping with environmental stresses through innovation and agricultural intensification. Like Diamond, he concluded that collapse is rarely abrupt.

That collapse is rarely abrupt suggests that socio-ecological systems are not brittle, but that on facing continual stress they become less resilient in withstanding shocks and surprises. In a study of European Neolithic societies that began some 9000 years ago, Downey, Randall Haas, and Shennan (2016) found that the introduction of agriculture spurred population growth, but societies in many cases experienced demographic instability and, ultimately, collapse. The authors also uncovered evidence of warning signs of eventual population collapse, reflected in decreasing resilience in socio-ecological systems. Scheffer (2016) has given further support to the thesis by reporting that there had been warning signs of reduced resilience prior to the great drought in the late 1270s that destroyed the communities that had built the iconic alcove sites of Mesa Verde.

Inevitably, these studies have been about societies with tight geographical boundaries. A community that failed because of population overshoot or bad resource-management practices no doubt destroyed their natural resource base, but it was their *local* resource base they destroyed; societies until modern times were incapable of affecting the Earth system as a whole. Matters are different today. Our presence is so dominant that the biosphere is no longer as modular as it was until recently. Disturbance in one location today gets transmitted to other parts in short order. Movements of people and trade in goods have created a transmission mechanism with a long and quick reach. The mechanism's medium has, however, remained the same. Nature is mobile: the wind blows, rivers flow, the oceans circulate, and birds and insects fly. We weaken the Antarctica ice sheet without ever going there; fish in the North Sea eat micro-plastic originating in markets in the Bahamas; phosphorus discharge from farms in Minnesota contribute to a deadening of the Gulf of Mexico; emissions of black carbon from kitchens in the Indian sub-continent affect the circulation patterns of the Monsoons; the Green Revolution's demand for water, fertilizers, and pesticides pollute the rivers and ground waters of the Indo-Gangetic Plain; and so on.

Economic historians of the Industrial Revolution point to the role institutions played in creating incentives for entrepreneurs to find ways to work round natural resource constraints. The rate at which we are able to reduce our dependence on natural resources has to exceed the growth rate of humanity's consumption level. Otherwise our ecological footprint will not decline. The footprint currently exceeds 1 and is continuing to increase. We can be sanguine about the character of technological advances and consumption patterns we correspondingly adopt only if we personally experience the scarcity value of the biosphere, that is, if we have to pay for its use. Understandably, entrepreneurs economize on the expensive factors of production, not the cheap ones. So long as the biosphere's goods and services remain under-priced, technological advances can be expected to be rapacious in their use. Moreover, technological advances that are patently good can have side-effects that are not benign. The tightening of links that bind the biosphere together has meant that economizing on the use of one resource is frequently at the expense of a greater reliance on some other resource (e.g. sinks for our waste products). The ability to use fossil-based energy at large scales has transformed lives for the better, but it has created the unintended consequence of global climate change. Bull-dozers and chain-saws enable people to deforest land at rates that would have been unimaginable 250 years ago, and modern fishing technology devastate large swathes of sea beds in a manner unthinkable in the past. If technological progress is our hope, it has either to come allied with elimination of environmental externalities or be directed by public investment in research and development (R&D).

The recent focus on global climate change has led us, even if imperceptively, to concentrate on technological solutions. But climate change is not paradigmatic of environmental problems. Contaminating the oceans with materials in all probability requires collective behavioural change in parallel with R&D that is moved by public concerns. Restoration and conservation measures are ways by which we can reduce the global ecological footprint. Creating safe zones for migratory species is another needed measure. Reducing waste is yet another. Advances in bio-technology would raise ecosystem productivity, but the advances would be successful only if they don't have large, unintended adverse consequences for the biosphere. Moreover, irreversible losses, arising say from biological extinctions, would act as constraints on the biosphere's ability to recover. Social moves toward consumption and production practices that make smaller demands on the biosphere would be a more direct approach to reducing our impact on the Earth system. A complementary approach involves investment in family planning as well as information programmes that shift fertility norms toward smaller families. That's the basis on which we have conducted our numerical exercise on how many people Earth can support in comfort.

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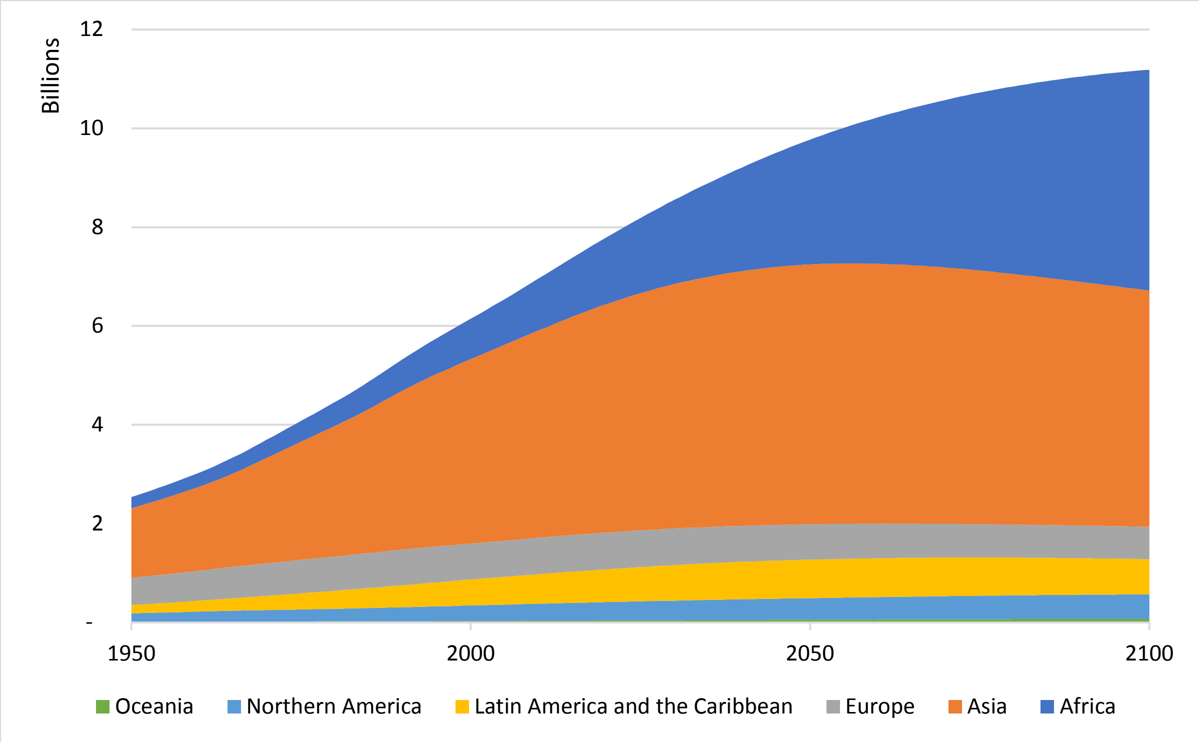
Figure 1. Total population by region, 1950-2100



Source: United Nations, Department of Economic and Social Affairs, Population Division (2017). World Population Prospects: The 2017 Revision

Table 1

Social Statistics from Rich and Poor Regions (Year 2014-15)

	Rich	poor
Population (millions)	1,420	620
GDP per capita (international dollars)	41,000	1,570
Total fertility rate*	1.7	4.9
Under-5 mortality rate (per 1000)	7	76
Life expectancy at birth (years)	80	60
Youth literacy	100	68
Civil liberties	high	low
Political liberties	high	low
Government corruption	low	high

Source: World Bank (2016), UNPD (2015), Freedom House (2017)

* Total fertility rate (TFR) is the number of births that a woman expects to have during her reproductive years. The number 2.1 is usually taken to be the TFR that, over the long run would lead to a stable population.

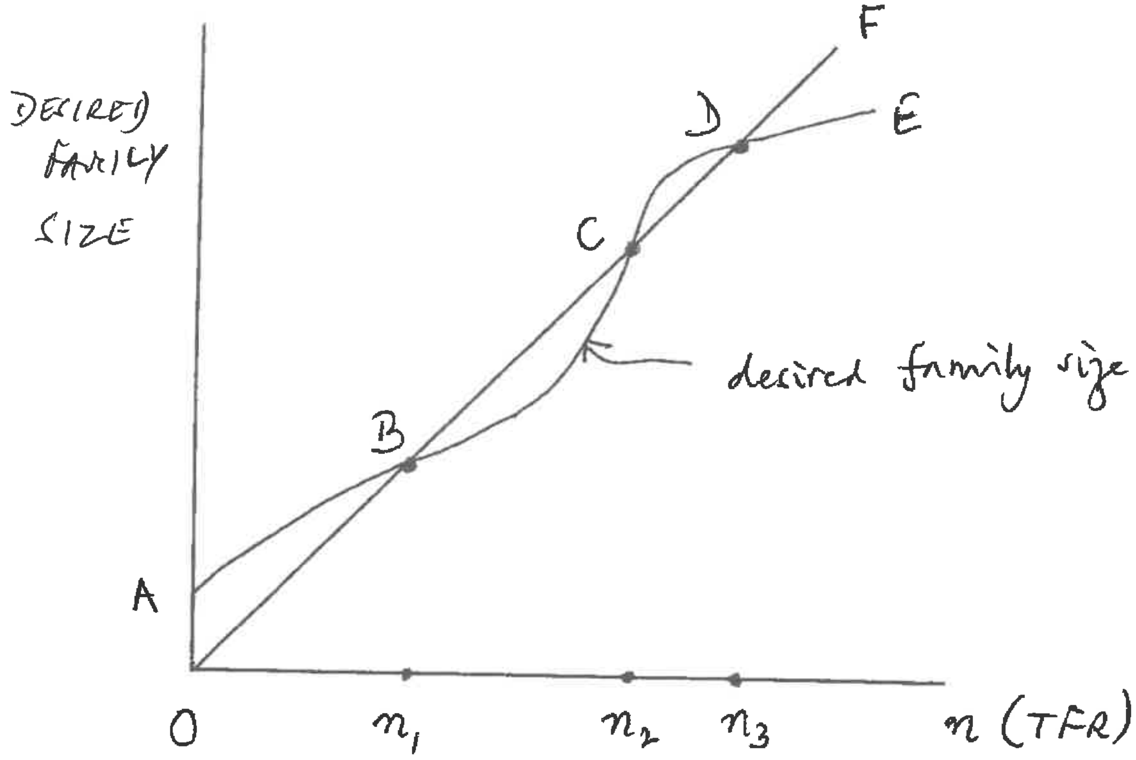


Figure 2

socially-embedded preferences

Figure 3. Two examples with identical levels of demand for family planning met with modern contraceptive methods