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Sustainable welfare and optimum population size

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Abstract This paper is an attempt to estimate the level of sustainable welfare, namely a level of consumption that can be enjoyed by all future generations. Based on available measures of the ecological footprint and biocapacity and assuming an acceptable level of per capita consumption, we estimate the maximum level of world population, which will allow that level of consumption without damaging the natural productive capacity of the earth. Also based on a criterion of the ability of each country to feed its people, we estimate the maximum size of population for the fifty most populated countries. It turns out that a few countries are underpopulated (Argentina, Canada, Russia, etc.), but most are overpopulated (China, India, Japan, etc.). We conclude by emphasizing the need for an ecumenical effort to educate and inform people about the need to reduce world population.

Keywords Population · Sustainable welfare · Ecological footprint · Biocapacity

1 Introduction

Sustainable growth defined as a positive rate of increase of gross world product (GWP) or of per capita consumption for an infinite or very long period is impossible. This is because economic growth cannot exceed the limits imposed by the “earth ecosystem which is finite, non growing and materially closed” (Daly and Townsend 1993). Resources are limited,

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and some of them cannot increase by investment or by new technologies. For instance, land, water, and fossil fuel are limited resources (Pimentel et al. 2010). Copper and other metals, potassium, and phosphorous are also limited. Recycling may delay exhaustion of a non-reproducible resource but can never increase it. It can only decrease it because some of the initial quantity of the resource may be lost in every recycling round. Every time a metal is used, some of it is lost. Some resources are substitutable. Furniture can be made from wood or from aluminum. The price system may provide the motive for the use of one or the other, but it cannot increase the upper limits of either. More forests may be created, but more land is required and land is limited.

New technologies may improve the use of resources. Better irrigation systems may increase crops that need irrigation, but cannot increase the quantity of water. Some people even hold the untenable view that "resources are not; they become" implying that technologies may lift the limits imposed on production by finite resources (De Gregori 1987). Certainly, the possibilities of technological advances should not be underestimated, but the fact remains that resources are finite with limited possibilities of substitution. Nothing can be substituted for water or for soil. Some authors (Hopwood et al. 2005; Rees 1992) attribute to Robert Solow an argument that "…the world can, in effect, get along without natural resources, so exhaustion is just an event, not a catastrophe." This is a misinterpretation of Solow who actually writes "If it is very easy to substitute other factors for natural resources, then there is in principle no "problem." The world can, in effect, get along without natural resources, … If on the other hand, real output per unit of resource is effectively bounded—cannot exceed some upper limit of production *which is in turn not too far from where we are now*—then catastrophe is unavoidable. In between there is a wide range of cases in which the problem is real" (Solow 1974, p. 11, emphasis added). Arguably, Solow does not suggest that the world can get along without natural resources. Actually, for the emphasized quote, he seems to believe that not much further substitution is possible.

The fact that resources are limited, and with limited substitutability, means that world production, and thus sustainable development, in any of its countless definitions (Cole 1999, p. 90) is limited. This, in turn, raises crucial questions with respect to the size of world population and the level of consumption per capita that people can enjoy.

In this paper, (a) we estimate the relationship between the world population and per capita product for a sustainable level of gross world product, (b) we suggest that sustainable development as a goal should be abandoned and instead direct our attention to sustainable welfare, and (c) we estimate, for several countries, the required population reduction necessary to achieve sustainable welfare.

2 Population and growth

The views about the relationship between population and growth can be roughly classified as pessimistic or optimistic. Pessimists are usually characterized as Malthusians (or neo-Malthusians), i.e., they support the view, as summarized by Boserup (1996), that increasing population will ultimately result in food shortages because of diminishing returns and using land of inferior quality. Technology introduced to alleviate the effects of reduced productivity of land will damage the environment. Also, increasing population will ultimately result in damaging the environment in the form of pollution. Food shortages and pollution will increase mortality rates and thus reduce population growth. Thus, unless measures for population control are taken, the population will readjust itself to a smaller size, but this will cause human suffering and pain.

Optimists in general believe that there is no need to cause alarm about the future of society because of overpopulation. It is argued (Boserup 1975) that population pressure will lead to needed adaptations in the existing agricultural systems and that research on improvements of crops, animals, and methods of fertilization will accelerate the pace of scientific progress.

The statistical data of the last 50 years seem to support the optimistic viewpoint. During the period 1960–2013, the rate of growth of per capita world gross output was higher than the rate of growth of population, with the exception of 4 years of severe economic recession (1975, 1982, 1991, and 2009). Thus, the per capita output was increasing throughout this period.

However, there are arguments that support the pessimistic viewpoint. First, although per capita world output was increasing, the existing trends of world output and population show that the growth rate of gross output is declining much faster than that of population. Therefore, if the existing trends continue, the growth rate of the population will eventually exceed that of world output, and per capita output could begin to decline. Figure 1 shows the growth rates of population (POP_{gr}) and world output (GWP_{gr}) and their linear trends. It appears that the two growth rates will be equal in 2037.[1] At that year, both rates will be 0.68. After that year, per capita output will decline.

The second argument supporting the pessimist viewpoint is that the growth of per capita world product has become possible, partly due to the overuse of resources and the destruction of natural capital. Since 1975, the gap between the ecological footprint and biocapacity is widening (see next section).

Of course, the role of technology, embodied or disembodied, cannot be ignored. However, there is no guarantee that new technologies, including better systems of resource management, can always be found. Overall, the present situation is far from providing reasons for optimism.

The world population is expected to rise in the next decades. According to a recent study from the International Institute for Applied Systems Analysis (Lutz et al. 2014a, b), the world population is likely to peak at 9.4 billion around 2070 and then decline to about 9 billion by the end of the century. According to a United Nations study (Gerland et al. 2014), the world population can be expected to grow to 9.6 billion in 2050 and to 10.9 billion in 2100. Despite their differences, both studies predict a thirty percent increase in world population in the next forty to 50 years. The prospect of such an increase makes one

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[1] The growth rate regressions against time ($t = 1, 2, \ldots, 53$) give the following results:

$$\begin{aligned} GWP_{gr} &= \underset{12.4}{5.068} - \underset{4.47}{0.057}\,t \quad \bar{R}^2 = 0.28 \quad \text{obs} = 53 \\ POP_{gr} &= \underset{53.1}{2.143} - \underset{14.7}{0.019}\,t \quad \bar{R}^2 = 0.81 \quad \text{obs} = 53\,. \end{aligned}$$

The linear trends in Fig. 1 are based on these regressions. For the data used in these estimations, see Table 3.

We have also estimated the same regressions using five year moving averages to avoid the effects of outlying observations. The resulting regression equations are practically the same, and the two growth rates will be equal (0.68) in 2038.

$$\begin{aligned} GWP_{gr} &= \underset{22.4}{5.089} - \underset{8.12}{0.059}\,t \quad \bar{R}^2 = 0.57 \quad \text{obs} = 49 \\ POP_{gr} &= \underset{96.4}{2.222} - \underset{28.3}{0.021}\,t \quad \bar{R}^2 = 0.94 \quad \text{obs} = 49\,. \end{aligned}$$

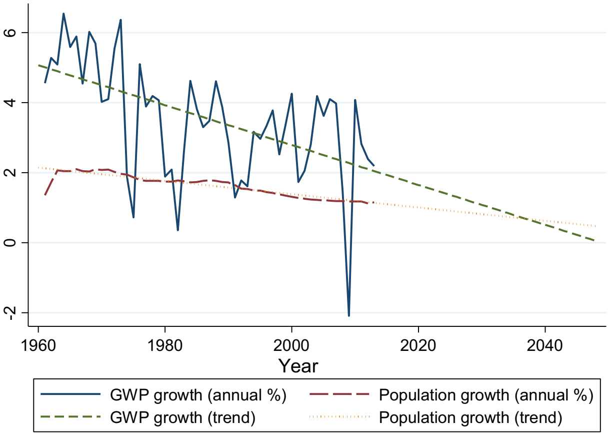

Fig. 1 Growth rate of world population, growth rate of gross world product, and their linear trends. *Data sources*: Population growth (annual %): World Bank Indicators (Indicator code: SP.POP.GROW). GDP growth (annual %): World Bank Indicators (Indicator code: NY.GDP.MKTP.KD.ZG)

wonder whether the resources of our planet can sustain another two billion people. It seems that the pessimistic view becomes more credible.

3 The ecological deficit

The ecological footprint (EF), a term coined by Rees (1992), is a measure of the consumption of renewable resources (crops, animal products, fish, and timber), consumption of energy, and the use of built-up areas in standardized units of biologically productive area. Biocapacity (B) is an aggregate measure of the production of various ecosystems and represents the biosphere's regenerative capacity (Schaefer et al. 2006). The ecological footprint (EF)–biocapacity (B) accounting provides a measure of the ecological deficit defined as the difference $\mathrm{EF} - B$ or as the ratio $L = \mathrm{EF}/\mathrm{B}$. If $L < 1$ biocapacity exceeds the ecological footprint (thus, there is an ecological reserve), and if $L > 1$ the ecological footprint exceeds biocapacity (thus, the Earth has an ecological shortage). In the global context, an ecological deficit implies that the world production is made possible by overusing and depleting the natural capital.

From Fig. 2, it can be seen that during the period 1961–2009, the ratio L has increased dramatically.[2] In the beginning of this period, the world had a substantial ecological reserve, which disappeared after 10 years. In 1971 and perhaps a few years later, the world was in ecological balance, i.e., $L \approx 1$. This is the desired situation in terms of resource use. Since then L follows an upward trend. During the last few years, L is around 1.5, indicating that the demand for resources exceeds the available supply by 50 %.

From the values of L and the corresponding values of GWP per capita and population, it appears that the ecological deficit was zero at about 1976 ($L = 1$) and the corresponding pair was: gross world product per capita = \$5618, population = 4.15 bn. If we wish to keep the ecological deficit at zero level, this pair is in fact one point in the trade-off

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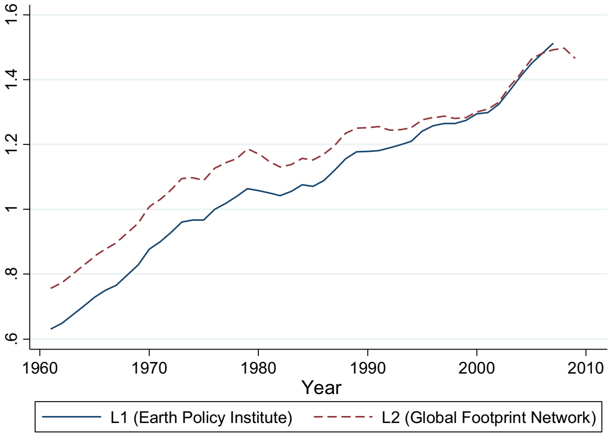
[2] Actually two series for L are given in Fig. 2. The first, L_1, is compiled by the Earth Policy Institute and the second, L_2, by the Global Footprint Network. The two series present some small differences in the yearly values, but they show a similar trend. For our regressions, we use the series given by the Earth Policy Institute.

Fig. 2 Ecological footprint to biocapacity ratio, 1960–2010. *Sources* L_1, Earth Policy Institute (2010); L_2, Global Footprint Network (2013)



between population size and product per capita. It follows that if population increases above that size the per capita product must decrease to keep $L = 1$.

In an attempt to determine how L changes as a result of changes in per capita product and in population, we have regressed the rate of change of L on the rates of change of the two variables. This regression is obtained, if we state, similarly to the impact equation of Ehrlich and Holdren (1971, 1972), that ecological deficit = technology × population × product per capita (i.e., L = TPC), and differentiate with respect to time and divide both sides by L. Since technology cannot be measured as a specific variable, $\Delta T/T$ becomes the constant term in the regression equation. The resulting regression equation is as follows:[3]

$$\frac{\Delta L_1}{L_1} = \underset{(2.84)}{-0.0257} + \underset{(7.17)}{0.8276}\left(\frac{\Delta GWPpc}{GWPpc}\right) + \underset{(3.05)}{1.5584}\left(\frac{\Delta Pop}{Pop}\right)$$

$$\overline{R^2} = 0.57 \quad \text{obs} = 46$$

From the above regression, it appears that a certain percent change in population affects the percent change in L twice as much as the same percent change in per capita product. By letting $\frac{\Delta L_1}{L_1} = 0$, the trade-off between percent changes in population and per capita product is $\frac{\Delta GWPpc}{GWPpc} = 0.031 - 1.88\frac{\Delta Pop}{Pop}$. According to this trade-off for a one percent increase in population, a 1.88 percent reduction in per capita GWP is necessary if L is to remain constant. It is interesting to note that the constant term is negative and significant which indicates that the role of technology in the period covered by the data has been positive, i.e., it reduces the value of the ecological deficit L. In other words, the technological changes introduced in the production of commodities have been resource saving.

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[3] Similar results are received if L_2 is used instead of L_1. The relation between L_1 and L_2 is given by $L_1 = 0.94\, L_2$ with $R^2 = 0.997$, see Fig. 2.

4 The optimum size of population

The actual size of population is estimated to a satisfactory degree. It was 6.884 bn in 2010 (World Bank 2014), and it is now (July 2015) estimated[4] to be 7.326 bn. The maximum size of the population is difficult to define and to estimate in a way that would be generally accepted. The same is true for the optimum size.

However, the classical economic theory has well-defined concepts for both, maximum and optimum, sizes of population. The maximum size is where the declining product per head is equal to the subsistence wage as it is determined by material needs, habits, and customs. In other words, when the average product of labor is just enough to "feed" the laborer, the optimum size is where per capita product is at its maximum. Figure 3 shows maximum population at point P_1 and optimum population at point P_2. Below P_3 there is underpopulation, and above P_1 there is overpopulation.

The question of the optimal population size has been discussed in the context of population ethics in which maximum total utility is the criterion by which populations of different sizes are compared. The use of that criterion leads to what is now known as the Repugnant Conclusion (Parfit 1984), namely that a very large population where individuals have a very low positive quality of life is better than a smaller population where individuals have a very high positive quality of life. In Parfit's words "for any possible population of at least ten billion people, all with a very high quality of life, there must be some much larger imaginable population whose existence, *if other things are equal*, would be better even though its members have lives that are barely worth living" (emphasis added). There have been several attempts to deal effectively with the Repugnant Conclusion, but none has been found satisfactory (Arrhenius 2000; Arrhenius et al. 2014). In fact, it is asserted that "what we seem to have found … is an impossibility theorem for the existence of an acceptable welfarist theory" (Arrhenius 2000, p. 264).

The difficulties of the welfarist axiologies regarding the population size should not prevent one from discussing the optimal size of population. First, we do not all need to be utilitarians of the total utility version. Second, the Repugnant Conclusion is based on the "other things being equal" assumption. If there are resource (or income) constraints, the mere addition of people violates this assumption. Adding people to a population may initially have positive effects if it promotes cooperation and the development of useful things that could not otherwise be developed. But after a point, adding people will increase the demand of scarce resources and will result in less resources available to the original population and the ceteris paribus assumption is violated.

In considering questions of optimal population, the Aristotelian (1932) idea of "best life" is more helpful. This is a life in which the individual has enough material wealth by which he/she can live with comfort and generosity but not luxuriously and wastefully. Aristotelian eudemonia (happiness) means acting with virtue, and this requires external goods, i.e., material wealth. Since resources are limited, the concept of "best life" puts a limit to the size of population. However, instead of discussing optimal levels of population, Aristotle gives limits within which the "best life" can be achieved. The lower limit of population size is that which is necessary for self-sufficiency, for the purpose of living a good life after the manner of a political community. The upper limit is that at which problems of public administration and of political democratic processes begin to appear. If

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[4] Worldometers (2015).

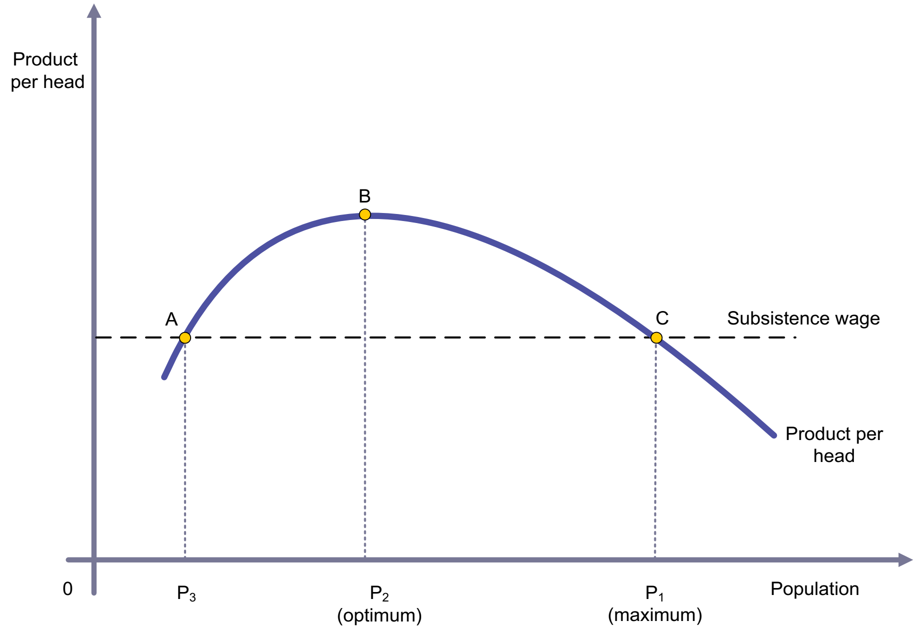

Fig. 3 Population–product per head relationship

population exceeds the upper limit, birth control is suggested to reduce the population size (Aristotle 1932).

The Aristotelian brief discussion can be found in many modern phraseologies. For example, Daily et al. (1994) state: "an optimum population size should be small enough to guarantee the minimal physical ingredients of a decent life to everyone." This means all have access to food, education, health care, sanitary living conditions, and economic opportunities. It also means that the social sphere and the democratic political processes are secure from problems generated by high population densities.

Similar are the ideas of Mill (1970, pp. 115–116) concerning overpopulation. According to him, the population size should be within a lower limit above which "all the advantages both of cooperation and of social intercourse" can be attained and an upper limit where solitude and natural beauty can be secured. For, as Mill poetically states, "solitude in the presence of natural beauty and grandeur, is the cradle of thoughts and aspirations which are not only good for the individual but which society could ill do without."

Many other views have been expressed on population size.[5] The estimates of the optimum population size are many, and they differ substantially. Most estimates are in the range of 4–16 billion people with a median of about 10 billion (Cohen 1995, 2005; United Nations 2001, p. 31). In 1994, Daily et al. (1994) made an estimate of the optimum population size on the basis of the amount of energy "at which ecosystems and resources seemed to be holding their own" and a per capita energy consumption. Assuming an amount of world energy of 6 TW (1 TW = 10^{12} W), which provides for a 50 % error, and a per capita consumption of 3 kW, they arrived at an estimate of 2 billion people as an optimum population size. The same year, Pimentel et al. (1994) based on the estimate that

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[5] For a review and a categorization of ideas on population, see Panayotou (2000).

0.5 hectares (ha) per capita is needed for supply of food and assuming a program of soil conservation estimated that a world population of 3 billion people could be sustained. Recently, Pimentel et al. (2010) estimated that under certain reasonable assumptions regarding land inputs, a European standard of living for everyone, and sustainable use of natural resources, the Earth has a carrying capacity of 2 billion people. Even allowing for a 100 % margin of error, the estimates stated above clearly show that the present population size of 7.1 billion exceeds by far the carrying capacity of our planet.

The optimum population size is impossible to estimate with an acceptable degree of accuracy. However, the maximum size of population can be determined if an objective criterion can be found, as, for example, those used in the works by Daily and Pimentel mentioned above. As an objective criterion, we use the unitary value of the ecological footprint—biocapacity ratio. If $L = \mathrm{EF/B}$ is equal to unity, world production can go on without depleting the natural capital of the Earth (Lianos 2013). If the maximum product is determined, the optimum population can also be determined by choosing the level of product per capita that is accepted as best. In other words, the optimum population size depends on the resources of the Earth and on material and ethical considerations regarding the needs of individuals, i.e., what Aristotle called “best life.”

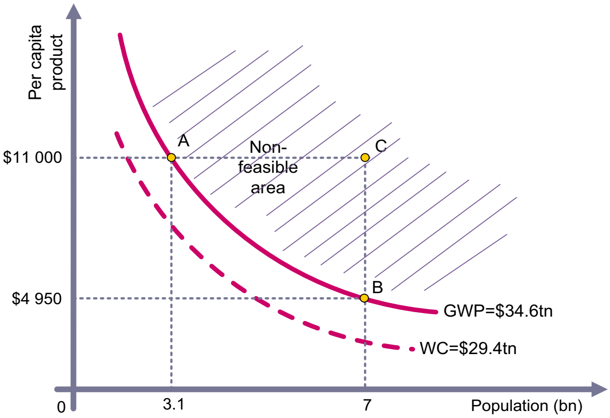
The value of L is uniquely related to production. If gross world product (GWP) is zero, the ecological footprint (EF) is zero and the EF/B is also zero. Thus, we estimated a regression equation of L on GWP using L_1 and L_2. The results were almost identical; we present below only the regression with L_1.

$$L_1 = \underset{(26.91)}{0.02887}\, GWP \quad \overline{R^2} = 0.94 \quad \text{obs} = 47$$

Now, if we set $L_1 = 1$, GWP for this value of L is GWP $=$ 34,638 billion dollars. This is the maximum world product the production of which would leave the natural capital of the Earth intact.

The gross world product is by definition equal to product per capita multiplied by the number of people, i.e., $\mathrm{GWP} = \frac{\mathrm{GWP}}{\mathrm{Pop}} \times \mathrm{Pop}$. If GWP takes the maximum value that corresponds to $L = 1$, then $34{,}638 = \frac{\mathrm{GWP}}{\mathrm{Pop}} \times \mathrm{Pop}$ is a rectangular hyperbola, which presents the world budget constraint shown in Fig. 4. It is actually the frontier that shows

Fig. 4 Population–per capita product frontier



the choices we can have if we wish to preserve the natural capital of our planet. If we wish to enjoy a per capita product of $11,000 per year, close to the average European, then the world population must be reduced to 3.1 billion as shown by point A. With greater population, the level of $11,000 will be untenable in the long run. If we wish to keep population at 7 billion, per capita product must be reduced to $4950 (point B). It follows that the current situation, which is shown at point C, cannot be sustained in the long run. It is clear that the world is overpopulated. The pressure on the resources is evident in several ways: material, social, and political.

5 Sustainable welfare

By sustainable welfare, we mean a situation where a certain level of consumption can be enjoyed by all future generations. This level of consumption depends on the state of technology, the availability of resources, and the size of population. The requirement that this level must be enjoyed by all future generations introduces the constraint that the natural and the material capital remain intact. This means that part of production should be devoted to investment for the purpose of replacing worn out material capital and to the conservation of natural capital. Obviously, for given technology and given available resources there is a trade-off between the level of sustainable welfare and the size of world population.

In the context of social systems theory, it is argued that there is a trade-off between the complexity of a system and its sustainability. According to Valentinov (2014, p. 19), “complex systems may increase their sustainability in a given environment by devising mechanisms for binding themselves to constrain and control the unfolding of their complexity.” If reducing complexity implies resource saving without sacrificing the benefits of technology, then it will also raise the level of sustainable welfare.

The depreciation rate of material capital stock is found to be between 6 and 13 percent (Nadiri and Prucha 1996). If we assume that 15 % of gross product is required for replacement of material capital (depreciation) *and* for the preservation of natural capital, then the sustainable world production that is available for consumption is ($29.442 trillion (= $34.638 × 0.85) and the corresponding consumption constraint is the dotted line WC in Fig. 4. Actually, the line WC shows the maximum sustainable consumption per person for various levels of population size. Therefore, the level of welfare that we can enjoy as a global community depends on our choice of how many people we want on our planet.

It follows from the above that the present situation of 7 billion people with $11,000 income per capita and about $9000 per capita consumption is not a choice. Given that the Earth cannot provide anything more than what it already has, the only choice we have is to reduce the size of population. Otherwise, the prospects of humanity are bleak (Pimentel 2012; Schade and Pimentel 2010). Technically, one can argue that the level of consumption per capita can also decrease so that more people can live at that (lower) consumption level. This, however, seems to be impossible to happen voluntarily, but it could happen under the pressure of overpopulation, the depletion of natural capital, and the exhaustion of resources.

6 Population size for sustainable welfare by country

If we accept that a per capita consumption of about \$9000 is sufficient for a comfortable level (with a corresponding per capita product of \$11,000), this level of consumption can be sustained forever if the world population does not exceed 3 billion people. With a larger population according to the previous calculations, the economic footprint exceeds biocapacity. It is interesting that a similar view regarding the sustainability of welfare in relation to the size of population was expressed, although in a different context, by Keynes.[6] In 1930, when the world population was 2.1 billion, much lower than the level corresponding to the critical value of $L = 1$ for year 1971, Keynes (1963) wrote "I draw the conclusion that, assuming no important wars and no important increase in population, the economic problem may be solved, or be at least within sight of solution, within a 100 years. This means that the economic problem is not—if we look into the future—the permanent problem of the human race." Keynes did not foresee that the world population will increase at a high rate. Actually, he expected the population to stabilize or decline.

The reduction in population should take place in every country according to some criterion. A simple, reasonable, and objective criterion is the proportion of cultivated land (i.e., arable land plus land with permanent crops) of each country. Clearly, this is not the perfect criterion because it leaves out other resources (oceans, wind, solar energy, human capital, etc.), but as a first approximation it is a good way to measure the ability of each country to feed its people.

In Table 1, we present the relevant data for the fifty most populous countries plus Australia and Kazakhstan, which are two of the largest countries. The first column presents the cultivated land in thousands of square kilometers. Column 2 gives the cultivated land of each country as a percent of total (world) cultivated land. Column 3 gives population in millions for 2010. Column 4 gives the population size each country should have if total world population was to be three billion, and its share should be determined by the same percentage as its percentage of cultivated land. Column 5 gives the number of times the actual population exceeds desired population. The last column gives the required reduction in population for each country.

According to Table 1 (Column 8), there are only eight countries that their population is below the desired level, i.e., Australia, Canada, Russia, Ukraine, Kazakhstan, Argentina, Sudan, and USA. In relative terms (Column 7), the most overpopulated countries (according to the criterion adopted here) are as follows: Korean Republic, Japan, Egypt, Bangladesh, Yemen, Colombia, China, Nepal, and UK, followed by Venezuela, Vietnam, Philippines, Pakistan, and India. In absolute terms (Column 1), the most heavily populated countries are by far China and India. These two countries are home to 37 % of the world's population, while their combined arable land and cropland is 19 % of the total. In these two countries, the required population reduction is 1.9 billion.

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[6] Grounds for concern on overpopulation are raised by many researchers in the field of ecological economics. For an overview, see Alcott (2012), who argues that curbing population growth should be actively included in policy agendas of all countries.

Table 1 Required population change, by country

	Column number	1	2	3	4 = (2) + (3)	5	6 = [(5) × 3,100,000,000]/100	7 = (1)/(6)	8 = (6) − (1)
	Country name	Population, total, 2010 (million)	Permanent cropland, 2010 (000 sq.km)	Arable land, 2010 (000 sq. km)	Permanent cropland +arable land, 2010 (000 sq.km)	% of world P + A (000 sq.km)	Desired population (million)	Population (2010)/ desired population (million)	Required population change (million)
	World	6883.5	1537.3	13,884.0	15,421.3	100.00	3100.0	2.2	−3783.5
1	China	1337.7	146.2	1113.5	1259.7	8.17	253.2	5.3	−1084.5
2	India	1205.6	121.0	1575.1	1696.1	11.00	341.0	3.5	−864.7
3	USA	309.3	26.0	1598.3	1624.3	10.53	326.5	0.9	17.2
4	Indonesia	240.7	200.0	236.0	436.0	2.83	87.6	2.7	−153.0
5	Brazil	195.2	71.0	703.2	774.2	5.02	155.6	1.3	−39.6
6	Pakistan	173.1	8.5	205.5	214.0	1.39	43.0	4.0	−130.1
7	Nigeria	159.7	32.0	360.0	392.0	2.54	78.8	2.0	−80.9
8	Bangladesh	151.1	9.0	77.4	86.4	0.56	17.4	8.7	−133.8
9	Russian Federation	142.4	17.8	1200.0	1217.8	7.90	244.8	0.6	102.4
10	Japan	127.5	3.1	42.8	45.9	0.30	9.2	13.8	−118.2
11	Mexico	117.9	26.8	253.1	279.8	1.81	56.3	2.1	−61.6
12	Philippines	93.4	51.0	54.0	105.0	0.68	21.1	4.4	−72.3
13	Ethiopia	87.1	10.4	139.5	149.9	0.97	30.1	2.9	−57.0
14	Vietnam	86.9	36.9	64.4	101.3	0.66	20.4	4.3	−66.6
15	Germany	81.8	2.0	118.5	120.5	0.78	24.2	3.4	−57.6
16	Egypt, Arab Rep.	78.1	8.0	28.7	36.7	0.24	7.4	10.6	−70.7
17	Iran, Islamic Rep.	74.5	18.4	173.7	192.1	1.25	38.6	1.9	−35.8

Table 1 continued

	Column number	1	2	3	4 = (2) + (3)	5	6 = [(5) × 3,100,000,000]/100	7 = (1)/(6)	8 = (6) − (1)
	Country name	Population, total, 2010 (million)	Permanent cropland, 2010 (000 sq.km)	Arable land, 2010 (000 sq. km)	Permanent cropland +arable land, 2010 (000 sq.km)	% of world P + A (000 sq.km)	Desired population (million)	Population (2010)/ desired population (million)	Required population change (million)
18	Turkey	72.1	30.1	213.8	244.0	1.58	49.0	1.5	−23.1
19	Thailand	66.4	45.0	157.6	202.6	1.31	40.7	1.6	−25.7
20	France	65.0	10.3	183.7	194.0	1.26	39.0	1.7	−26.0
21	UK	62.8	0.5	59.7	60.2	0.39	12.1	5.2	−50.7
22	Congo, Dem. Rep.	62.2	7.6	68.0	75.6	0.49	15.2	4.1	−47.0
23	Italy	59.3	25.9	70.4	96.2	0.62	19.3	3.1	−39.9
24	Myanmar	51.9	14.1	108.1	122.2	0.79	24.6	2.1	−27.4
25	South Africa	50.9	4.3	125.3	129.6	0.84	26.1	2.0	−24.8
26	Korea, Rep.	49.4	2.1	15.1	17.2	0.11	3.4	14.3	−46.0
27	Spain	46.6	46.9	125.3	172.2	1.12	34.6	1.3	−12.0
28	Colombia	46.4	15.9	17.6	33.5	0.22	6.7	6.9	−39.7
29	Ukraine	45.9	9.0	324.8	333.7	2.16	67.1	0.7	21.2
30	Tanzania	45.0	17.0	116.0	133.0	0.86	26.7	1.7	−18.2
31	Kenya	40.9	6.5	55.0	61.5	0.40	12.4	3.3	−28.5
32	Argentina	40.4	10.0	372.2	382.2	2.48	76.8	0.5	36.4
33	Poland	38.2	4.0	109.2	113.2	0.73	22.8	1.7	−15.4
34	Algeria	37.1	9.1	75.0	84.1	0.55	16.9	2.2	−20.2
35	Sudan	35.7	1.6	188.6	190.2	1.23	38.2	0.9	2.6
36	Canada	34.0	50.2	434.0	484.2	3.14	97.3	0.3	63.3
37	Uganda	34.0	22.0	67.5	89.5	0.58	18.0	1.9	−16.0

Table 1 continued

	Column number	1	2	3	4 = (2) + (3)	5	6 = [(5) × 3,100,000,000]/100	7 = (1)/(6)	8 = (6) − (1)
	Country name	Population, total, 2010 (million)	Permanent cropland, 2010 (000 sq.km)	Arable land, 2010 (000 sq. km)	Permanent cropland +arable land, 2010 (000 sq.km)	% of world P + A (000 sq.km)	Desired population (million)	Population (2010)/ desired population (million)	Required population change (million)
38	Morocco	31.6	11.6	78.3	89.9	0.58	18.1	1.8	−13.6
39	Iraq	31.0	2.1	40.0	42.1	0.27	8.5	3.7	−22.5
40	Peru	29.3	8.2	36.5	44.7	0.29	9.0	3.3	−20.3
41	Venezuela, RB	29.0	6.5	26.0	32.5	0.21	6.5	4.4	−22.5
42	Uzbekistan	28.6	3.6	43.0	46.6	0.30	9.4	3.1	−19.2
43	Afghanistan	28.4	1.2	77.9	79.1	0.51	15.9	1.8	−12.5
44	Malaysia	28.3	57.9	18.0	75.9	0.49	15.2	1.9	−13.0
45	Saudi Arabia	27.3	2.5	31.1	33.6	0.22	6.7	4.0	−20.5
46	Nepal	26.8	1.2	23.6	24.7	0.16	5.0	5.4	−21.9
47	Korea, Dem. Rep.	24.5	2.1	23.0	25.1	0.16	5.0	4.9	−19.5
48	Ghana	24.3	28.0	47.0	75.0	0.49	15.1	1.6	−9.2
49	Mozambique	24.0	2.0	52.0	54.0	0.35	10.9	2.2	−13.1
50	Yemen, Rep.	22.8	2.9	12.9	15.8	0.10	3.2	7.2	−19.6
51	Australia	22.0	4.0	425.7	429.7	2.79	86.4	0.3	64.3
52	Kazakhstan	16.3	0.8	235.9	236.7	1.53	47.6	0.3	31.2

Data sources: (1) World Bank, World Development Indicators “Total Population.” Indicator Code SP.POP.TOTL. (2) Permanent cropland (000 sq. km) calculated as “Permanent cropland (% of land area)” x “Land area (sq. km)”/1000. Indicator codes AG.LND.CROP.ZS and AG.LND.TOTL.K2. (3) Arable land (000 sq. km) calculated as “Arable land (% of land area)” x “Land area (sq. km)”/1000. Indicator codes AG.LND.ARBL.ZS and AG.LND.TOTL.K2

7 Discussion

7.1 Avoiding the catastrophe

Nature has laws, but no volition nor feelings for us. No love, no hate. We humans have reason and thus assume responsibility for our own well-being as well as for that of the future generations. If we choose to ignore the constraints of nature and of the limited size of our planet, sooner or later, we will simply suffer from hunger, wars, lack of space,[7] etc.

According to some writers, the situation is already far from being acceptable and worse, developments such as "a painful population crash" (Schade and Pimentel 2010) and "increased social and political instability in many parts of the world" (Pimentel 2012) are likely to happen, or "the present obese scale of the human economy means the rights of people today conflict with those of people tomorrow" (Alcott 2012). It is hard to shake the feeling that this is already happening. Local wars and regional conflicts as well as international conflicts and tensions are undoubtedly strongly related to social pressures originating from limited resources. Under these circumstances, and taking into consideration that resources are used at a level that exceeds by 50 % the level which corresponds to sustainability, there seems to be no strong argument against policies to reduce the size of the world population. Some scientists seem totally pessimistic; virologist Frank Fenner, for example, suggested that the human race will be extinct within 100 years because of population explosion and "unbridled consumption" (reported by Firth 2010).

Thus, it is interesting to ask: why people do not voluntarily reduce the size of their families? This is the question that we should focus on if we are to design policies for reducing or stabilizing the size of world population within the limits of a sustainable world economy. Following is a short list of some of the factors that prevent the size of population from being reduced: (1) having children is the result of a natural and irresistibly pleasant process; (2) many people do not know how to use or do not have access to contraceptive devices or methods;[8] (3) for many families in the developing countries, children are an important labor force and security for old age; (4) there are religious and/or moral convictions against not having children and against contraception; (5) large populations may be part of desired military power for some countries; (6) increasing population is profitable for international capital because it provides wider markets for the products and increasing labor force at relatively low wages; and (7) the majority of people in the world are not adequately informed about the dangers of overpopulation.

Individuals have been known to learn from their experiences and to have the ability to adjust so that they can avoid dangers that threaten their welfare and take advantage of circumstances that improve the condition of their existence. However, the fallacy of composition alerts us to the fact that what is true for the individual is not necessarily true for all individuals taken together. Rational behavior for the individual is not necessarily rational for society as a whole. If a fire breaks out in a crowded amphitheater, it is rational for everyone to run to the door as fast as possible, but then the way out gets blocked. In this case, it would be better to have someone coordinate the evacuation of the amphitheater. It should also be noted that the effects of overpopulation in one country are not limited within

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[7] This is already evident in many regions of the world. The same is true for wild animals whose habitat is continuously shrinking, see, e.g., Stein, Adams and Kutner (2000).

[8] It is reported that nearly 40 % (80 million) of pregnancies every year are unintended, see Singh et al. (2009, p. 52), and Engelman (2010).

its boundaries. What happens in one country affects other countries as well through the existing physical, economic, and political linkages among countries.

Therefore, a central world authority is required for the solution of the overpopulation problem. Individual national policies may have some effects in the sense of reducing the population pressure in a country, but the world needs a worldwide effort, which may neutralize individual reactions. Isolated attempts by countries may have effects, but they cannot change the existing situation in any appreciable extent. For example, China's one-child policy has reduced the rate of population growth from 1.330 million in 2010 to 1.343 in 2012, an increase of (only) 13 million, while in the same period the population of India has increased from 1.173 million to 1.205, an increase of 32 million. What is needed is a deafening worldwide alarm that will force people to realize the real threat of overpopulation and the imminent catastrophic consequences, some of which we can already observe.

The most vital role in the attempt to reduce world population should be played by the United Nations, the organized Churches,[9] non-governmental organizations, and possibly other groups. One can think of something similar to the Kyoto Protocol for the reduction in emissions of greenhouse gases and the Montreal Protocol for the reduction in chlorofluorocarbons (CFCs) and other substances. Establishing a central authority to deal with the problem of overpopulation involves risks of high operational costs, bureaucracy, abuse of power, etc. However, the extent of the problem is such that taking the risk is justified.

Information, moral suasion, and the power of economic incentives may be used to convince people worldwide to reduce their desire for a large family size. We are not suggesting that it is easy to initiate such an effort or that it will have noticeable effects, but we will never know if we do not try. Also, we do not suggest that a process of population reduction will be harmless. There is no doubt that a declining population will have a negative impact on economic growth. Aggregate demand for all categories of output, capital and consumption goods will decline, and therefore, total product will decline. Also, the population pyramid will change by becoming thinner in the base, thus making it difficult to support the older groups of people. The extent of these problems depends on how quickly population declines and on the kind of government policies that will be undertaken. But in any event, a declining population will result in unemployment, perhaps severe, for some time. As Keynes, who in 1937 predicted stabilization or decline of population, said, when the devil of overpopulation is chained up the devil of unemployment is liable to break loose. Obviously, the drastic intervention of government to mitigate the negative effects would be necessary. In the long run, the economy will stabilize and—with a given population, given technology, and given resources—will reach equilibrium at a desired standard of living.

In addition to the overall effects of the reduction in population, the difference in the required reduction among countries with different production possibilities and comparative advantages and different consumption habits will facilitate slow but important changes in the international division of labor, in the flows of international trade, etc.

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[9] Most organized churches seem to share a myopic view on this matter. For example, in his May 2015 Encyclical letter (Vatican 2015), Pope Francis writes "Since everything is interrelated, concern for the protection of nature is also incompatible with the justification of abortion" and "demographic growth is fully compatible with an integral and shared development; to blame population growth instead of extreme and selective consumerism on the part of some, is one way of refusing to face the issues."

Table 2 Resource requirements for the production of plant and animal protein

Type of output	Resource requirements[a]			
	Land (ha)	Water (l)	Nitrogen (kg)	Phosphorus (kg)
1 kg of digested protein from pig meat[b]	0.0240	11,345	17.9	11.7
1 kg of digested protein from peas[c]	0.0013	185	8.9	6.9

[a] Compiled from data in Aiking et al. (2006), p. 28. Nitrogen and phosphorus are net figures (input minus output)

[b] Crops expended: 22 kg of tapioca and 27 kg of soybeans

[c] Crops expended: 6.5 kg of peas

7.2 Technology and consumption patterns

In the estimation of the optimum population size, technology and consumption patterns have been held constant for convenience. The importance of technological change should not be underestimated. Resource-saving technical change would increase the level of consumption that can be enjoyed by a certain number of people. The effect of such technology would be seen as a shift of both curves shown in Fig. 2. However, it should be noted that technical changes in one area may cause expenses in other areas, i.e., produce negative externalities, thus reducing or eliminating the benefit from technical change. For example, genetically modified crops may increase product per land, but they may also cause genetic contamination of other crops; more intensive agriculture can lead to contamination of ground, air, and water due to heavier use of herbicides. Technical change in rearing animals (as is seen in concentrated animal feeding operations) may create the need for more antibiotics, which may be present in meat and dairy, and also pollute soil and groundwater. In general, as technology improves our standard of living, our sustainable welfare level could be rising without damaging our long-run production possibilities as long as population is held constant.

Regarding consumption patterns, two main issues should be raised. First, there is a wealthy class of individuals who live a scandalously luxurious life which is offensive to the masses of poor people. This is not only a question of huge disparities in the distribution of incomes but also a question of a wasteful lifestyle. Second, we often choose to satisfy our needs with consumption goods that have high resource requirements.

In the case of food, for example, calories and micronutrients may come from plant or animal sources. It is established that calories and micronutrients from plant sources require considerably fewer resources (land, water, nitrogen, phosphorus, energy, etc.) to produce than their animal-derived analogs, see Pimentel et al. (2004), Hoekstra and Chapagain (2007), and Eshel and Martin (2006), among others. These studies converge in that the substitution of animal-derived foods with plant-derived ones results in substantial resource savings. For example, Aiking et al. (2006) calculate that the land footprint of animal protein is 18 times larger (0.024 ha/0.0013 ha) than its plant-based equivalent. Also, the water footprint of animal foods is much higher than their plant equivalents, as given in Table 2.[10] Different studies on the water requirements of products reach similar results. Ercin et al. (2012), for example, estimate that the production of beef burgers requires 15 times the amount of water than is required to produce equivalent soy burgers.

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[10] This program was called "Protein Foods, Environment, Technology and Society" (PROFETAS). Its aim was to develop meat alternatives with low energy, land, and other input requirements.

Baroni et al. (2007) reach similar conclusions by analyzing weekly diets. They compare diets of similar macronutrient value but with different levels of animal-derived foods (typical Italian, omnivorous, vegetarian, vegan). They find that the vegan (plant only) diet imposes the least harm on the environment and public health and has the least use of water and other resources. The vegan diet with organically grown foods is found even more efficient.

It is interesting to note that food processing (heating, grinding, milling, cutting, drying, cooking, combining, packaging) requires additional resources while the nutritional content (calories, vitamins, minerals, etc.) of food remains, at best, the same. Therefore, calories from processed foods will most probably have a larger footprint than calories from less processed (e.g., raw and whole) foods (Pimentel and Pimentel 2008; Pimentel et al. 2008).

The above and other studies show that calories from animal sources embody large quantities of resources. On the other hand, in the body of medical research, there seems to emerge a consensus that a plant-based diet is a healthier alternative to the current pattern. The current draft USDA (2015) Dietary Guidelines (p. 7, lines 257–260) state: “the major findings regarding sustainable diets were that a diet higher in plant-based foods, such as vegetables, fruits, whole grains, legumes, nuts, and seeds, and lower in calories and animal based foods is more health promoting and is associated with less environmental impact than is the current U.S. diet.” Similar recommendation has been made in the past by medical researchers and bodies (see McMichael et al. 2007; Campbell and Campbell 2008; American Dietetic Association 2009; Harvard School of Public Health 2011), highlighting that the incidence of diseases such as coronary artery disease, ischemic heart disease, type II diabetes, some cancers (mainly colorectal, breast, prostate), and others, will be greatly reduced with the population-wide substitution of animal calories by plant calories. Given the above, the substitution of some animal calories with plant calories in the sustainable welfare-level scenario (e.g., in the ways suggested in Pseiridis 2012) would free up a considerable amount of arable land, energy, water, minerals, and other resources (those used for food production and those used to treat diet-related diseases), thus allowing for a higher level of sustainable welfare.

Of course, neither we suggest a stoic way of life nor do we wish to interfere with personal tastes. But the point should be made that we have developed consumption habits that are wasteful, unhealthy, detrimental to other people and non-human species, and often insulting to human dignity. Changes in our consumption patterns in the direction implied here will raise the level of sustainable welfare at any given level of population.

8 Conclusions

In this paper, we have attempted to estimate the optimum size of the world population. According to our estimates, the optimum size that corresponds to a situation that would allow sustainable welfare at the level of the average European citizen of today is approximately 3.1 billion people. Therefore, the Earth, with 7.3 billion presently, is heavily overpopulated. However, not all countries are overpopulated. According to the criterion we have adopted, i.e., the size of arable land and permanent cropland, most countries are overpopulated, some are underpopulated, and a few have the right population size. Russia, Australia, Canada, Kazakhstan, Argentina, Ukraine, Sudan, and USA are underpopulated. Korean Republic, Japan, Egypt, Bangladesh, China, and India are some of the heavily overpopulated countries.

It seems clear that the size of the population will not decline if left to individual family decisions, at least not before the catastrophic effects of overpopulation become clear and are understood by the general population. Also, it seems that individual countries are either unable and/or unwilling to devise policies that would lead to the needed dramatic reduction in population. It seems imperative that a strong international authority should be instituted and invested with sufficient powers to implement policies that would contribute to the reduction in world population. At the same time, efforts to reduce the per capita consumption of resources will also be useful in achieving a sustainable level of welfare.

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Appendix

See Table 3.

Table 3 Population growth, GWP growth, ecological footprint to biocapacity (*L*), 1960–2013

Years	GWP growth (annual %)	Population growth (annual %)	*L*
1961	4.6	1.4	1.72
1962	5.3	1.7	2.07
1963	5.1	2.1	2.05
1964	6.5	2.0	2.05
1965	5.6	2.0	2.10
1966	5.9	2.1	2.05
1967	4.5	2.0	2.03
1968	6.0	2.0	2.11
1969	5.7	2.1	2.08
1970	4.0	2.1	2.09
1971	4.1	2.1	2.03
1972	5.5	2.0	1.96
1973	6.4	2.0	1.94
1974	1.9	1.9	1.87
1975	0.7	1.9	1.79
1976	5.1	1.8	1.76
1977	3.9	1.8	1.76
1978	4.2	1.8	1.77
1979	4.1	1.8	1.75
1980	1.9	1.7	1.75
1981	2.1	1.7	1.78
1982	0.4	1.8	1.76
1983	2.6	1.8	1.72
1984	4.6	1.7	1.73
1985	3.8	1.7	1.76
1986	3.3	1.8	1.78
1987	3.5	1.8	1.76

Table 3 continued

Years	GWP growth (annual %)	Population growth (annual %)	*L*
1988	4.6	1.8	1.73
1989	3.9	1.7	1.72
1990	2.9	1.7	1.64
1991	1.3	1.6	1.54
1992	1.8	1.5	1.54
1993	1.6	1.5	1.49
1994	3.2	1.5	1.49
1995	3.0	1.5	1.44
1996	3.3	1.4	1.42
1997	3.8	1.4	1.38
1998	2.5	1.4	1.35
1999	3.4	1.3	1.31
2000	4.3	1.3	1.28
2001	1.7	1.3	1.26
2002	2.1	1.3	1.23
2003	2.8	1.2	1.22
2004	4.2	1.2	1.21
2005	3.6	1.2	1.20
2006	4.1	1.2	1.18
2007	4.0	1.2	1.19
2008	1.5	1.2	–
2009	−2.1	1.2	–
2010	4.1	1.2	–
2011	2.8	1.2	–
2012	2.4	1.1	–
2013	2.2	1.2	–

Sources: *L*, Earth Policy Institute; Population growth, World Bank Indicators (code SP.POP.GROW); GDP growth, World Bank Indicators (code NY.GDP.MKTP.KD.ZG)

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