How Many People Can the World Support?

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New Scientist, No. 415, 285-287, 1964

The world population is now about 3,000 million and is increasing at a rate corresponding to a doubling in 37 years. In view of the increasing importance attached to the immediate effects of the rapid growth in human numbers, it is of interest to examine ultimate technical limits to this growth. Traditionally, these limits have usually been regarded as fixed by possible food supplies. Although, in practice, at least in historical times, the actual limiting factor has more often been disease.

Diseases are now nearly, and will soon be entirely, eliminated as effective controllers of population growth but it is not at all clear that difficulties in food production will take their place. It is true that there is a limit to the improvement of agricultural output by application of existing scientific knowledge, but by the time this limit is reached other methods of food-production will have been devised. In this article I shall explore the possibility that the real limits are physical rather than biological.

I shall assume throughout an effective degree of world cooperation in the application of food technology, etc. This is quite evidently essential if the maximum world population is to be reached. There are of course many ways of not reaching the maximum, but none of these will be discussed here.

In order to give a time scale, it is supposed that the rate of increase of population remains constant at the present value -- that is to say, doubling every 37 years. In fact the rate is itself accelerating, so that, in the absence of limitations, this time scale will be too long.

Stage 1: up to 400,000 million in 260 years' time

Using existing crop plants and methods it may not be practicable to produce adequate food for more than four doublings of the world population, though the complete elimination of all land wildlife, the agricultural use of roofs over cities and roads, the elimination of meat-eating and the efficient harvesting of sea food might allow two or three further doublings -- say seven in all. That would give us, with the present doubling time of 37 years, 260 years to develop less conventional methods, and would allow the population of the world to increase to about 130 times its present size, or about 400,000 million.

Stage 2: up to 3 million million in 370 years' time

The area of ice-free sea is some three times that of land. Photosynthesis by single-celled marine organisms may be more efficient than that of the best land plants. If organisms could be found capable of the theoretical maximum efficiency (8 percent of total solar radiation, according to A. A. Niciporovic) we should gain a factor of three in yield. We could then double our numbers a further three more times if all the wildlife in the sea, too, was removed and replaced by the most useful organisms growing under controlled conditions, with the optimum concentration of carbonates, nitrates and minerals. (Of course a reserve of specimens of potentially useful species could be preserved, perhaps in a dormant state.) Again, for maximum efficiency we must harvest and consume directly the primary photosynthesis organisms, rather than allow the loss of efficiency involved in the food chains leading to such secondary organisms as zooplankton or fish.

By this stage, we should have had ten doublings, which at the present rate would take some 370 years, with a final world population of 3 million million. Since the world's surface (land and sea) is 500 million million square meters, each person would have a little over 160 square meters for his maintenance-about a thirtieth of an acre-which does not seem unreasonable by more than a factor of two, so long as no important human activity other than food production takes place on the surface.

No serious shortages of important elements need be envisaged so far, though extensive mining operations for phosphates might be needed, and we have not yet approached any real limit.

Stage 3: up to 15 million million in 450 years' time

At first sight, it seems that a very big leap forward could be taken if we use sources of power other than sunlight for photosynthesis. The solar power received at the earth's surface is only about 1 kilowatt per square meter at the equator at midday, and the average value over the day and night sides of the globe is a quarter of this. Over half of it is in the regions of the spectrum of no use for photosynthesis.

About one kilowatt-year per square meter could be produced by the complete fission of the uranium and thorium in about 3 cm depth of the Earth's crust or by fusion of the deuterium in about 3 mm depth of seawater, so that adequate power should be available for some time. It is, however, difficult to see how the overall thermal efficiency from fuel to the light actually used for photosynthesis could be even as good as the ratio of useful to non-useful solar radiation (about 40 percent).

It would, therefore, be better to use large satellite reflectors in orbit to give extra sunlight to the poles and to the night side of the Earth. A large number of mirrors could be maintained in quasi-stable orbits about 1½ million kilometers outside the Earth's orbit, any deviations being controlled by movable "sails" using the pressure of sunlight. To double our total radiation income would require a total area of about 100 million square kilometers of mirror which, in aluminum a tenth of a micron thick, would weigh about 30 million tons. With plenty of people to design and make the equipment it should not be difficult by the time it would be required, and it would bring the whole Earth to equatorial conditions, melting the polar ice and allowing one further doubling of population.

A second doubling of radiation income would give the whole Earth midday equatorial conditions round the clock, which would be exceedingly difficult to cope with without serious overheating. The overall efficiency of local power sources for photosynthesis is likely to be less than that of sunlight, so that no real gain in ultimate population size can be expected from their use, without an even more serious overheating of the entire globe.

If, however, the mirrors outside the Earth's orbit were made of selectively reflecting material, reflecting only the most useful part of the spectrum, and if a further satellite filter were used, inside the Earth's orbit, to deflect the useless 60 percent of direct solar radiation, a further gain of a factor of 2½ should easily be possible without creating thermally impossible conditions, at the cost only of perhaps a 10-100 times increase of weight of mirror plus filter -- not difficult for the larger population with an extra 50 years of technical development. We should then have attained a world population of 15 million million about 450 years from now.

Stage 4: up to 1,000 million million in 680 years' time

A considerably larger gain is in principle obtainable if the essential bulk foods: fats, carbohydrates, amino acids and so on, could be directly synthesized. Biological methods might still be permitted for a few special trace compounds. The direct rate of energy production resulting from the conversion of our food into our waste products is only about 100 watts per person and, if high-temperature energy from nuclear fuel (or sunlight) could be efficiently used, waste products could in principle be changed back into food compounds with the absorption of little more energy. Cadavers could be homogenized and would not, at least for physical reasons, need to be chemically treated at all. The fresh mineral material which would have to be processed to allow for population growth would be much less than 1 percent of the turnover, and its energy requirements can be neglected.

If we suppose that the overall efficiency could not be increased beyond 50 percent, a further 100 watts per person would be dissipated as heat in the process of feeding him. We have some hundreds of years to work up the efficiency to this value, so at least this ought to be possible. Some further power would be needed for light, operation of circulation machinery, communications etc., but 50 watts per person should suffice.

As we have seen, the long-term average heat income of the Earth's surface is at present about 250 watts per square meter, and this could be doubled without raising the temperature above the normal equatorial value. (The initial rate of rise would be low till the polar ice had gone, which might take 100 years.) We thus have 500 watts per head, could support 1,000 million million people altogether. The population density would he two per square meter, averaged over the entire land and sea surface of the Earth.

Stage 4a: up to 12,000 million million in 800 years' time. Dead end

Above two people per square meter, severe refrigeration problems occur. If the oceans were used as a heat sink, their mean temperature would have to rise about 1 °C per year to absorb 500 watts per square meter. This would be all right for the doubling time of 37 years, at the end of which we should have four people per square meter. Half another doubling time could be gained if efficient heat pumps (which, for reasons of thermal efficiency, would require primary energy sources of very high temperature) could be used to bring the ocean to the boil.

Two more doublings would be permitted if the oceans were converted into steam, though that would create an atmospheric pressure comparable with the mean ocean bottom pressure at present. Since the resulting steam blanket would also be effectively opaque to all radiation, no further heat sink could be organized and this procedure would therefore seem to lead to a dead end.

Stage 5: S: up to 60,000 million million in 890 years' time

A preferable scheme would be the opposite one of roofing in the ocean to stop evaporation (this would, in any case, probably have been done long before, for housing) and hermetically sealing the outer surface of the planet. All of the atmosphere not required for ventilation of the living spaces could then be pumped into compression tanks, for which no great strength would be needed if they were located on ocean bottoms. Heat pumps could then be used to transfer heat to the solid outer skin, from which, in the absence of air, it would be radiated directly into space. The energy radiated from a black body goes up as T^4, where T is the absolute temperature (°K), but for a fixed rate of heat extraction from the living space, at a fixed temperature (say, 30°C or 303°K), the heat-power radiated must for thermodynamic reasons be proportional to T even if the refrigeration equipment is perfectly efficient (see any good textbook on the principles of refrigeration). Hence the rate of heat extraction will go up no faster than T^3 where T is the outer surface temperature.

All the same, this gives more promising results than would the use of the ocean as a temporary heat sink. An outer skin temperature of 300°C would give a heat extraction of 3 kW per square meter and 1,000°C would give an extraction ten times greater. If heat removal were the sole limitation, then we could manage about 120 persons per square meter for an outer skin temperature of 1,000°C which represents nearly six further doublings of population after the end of Stage 4, with a world population of 60,000 million million in 890 years' time. 1,000°C may be a rather modest figure for the technology of A.D. 2854 and the population could, as far as heat is concerned, be able to double again for each rise of absolute skin temperature of $2^{1/3}$ or 26 percent. The difficulties in raising it much further while keeping all thermodynamic efficiencies high would, however, seem to be formidable. A rise to 2,000°C would give us less than three further doublings.

We seem, therefore, to have found one possible absolute limit to human population, due to the heat problem, which at the present rate would be reached 800-1,000 years from now, with a world population of between 10^{16} and 10^{18}.

I have not considered emigration to other planets because it seems to me unlikely that our technical capacity to do so will catch up with the population expansion. To keep world-population level we would have to be sending out 60 million people per annum now. It is so much cheaper to feed them here that this will not be done.

If, however, it were possible to export population on the scale required it would not make a great difference. Venus is much the same size as the Earth, so (assuming that it has all the raw materials needed) an extra 37 years would bring it to the same population density as the Earth. Mercury, Mars and the Moon together give half the same area, so that Venus and the Earth together would take them up to the same population density in a further 10 years. The moons of Jupiter and Saturn could give us another 2 years or so. It is not clear that normal human beings could live on Jupiter and Saturn themselves and impound their extensive atmospheres, and the outer planets would take a long time to reach; if all these extraordinary problems could be solved, nearly 200 years might be gained.

Other possible limitations than heat will doubtless have occurred to readers, but these do not seem to be absolute. The most obvious is perhaps the housing problem for 120 persons per square meter. We can safely assume, however, that in 900 years' time the construction of continuous 2000-story buildings over land and sea alike should be quite easy. That would give 7½ square meters of floor space for each person in 1,000 stories (though wiring, piping, ducting and lifts would take up to half of that) and leave the other 1,000 stories for the food-producing and refrigerating machinery. It is clear that, even at much lower population densities, very little horizontal circulation of persons, heat or supplies could be tolerated and each area of a few kilometers square, with a population about equal to the present world population, would have to be nearly self-sufficient. Food would all be piped in liquid form and, of course, clothes would be unnecessary.

Raw materials should not be a problem. The whole of the oceans and at least the top 10 kilometers of the Earth's crust would be available, giving a wide choice of building, plumbing and machine-building materials. Even with 8 tons of people per square meter (reckoning 15 people to the ton) all the necessary elements of life could be obtained; some from air and sea (C, H, O, N, Na, Cl, Ca, K and some trace elements) and some from the top 100 meters of solid crust (Fe, S, P, I and remaining trace elements). Only after a further hundredfold increase in population would it be needful to go below the top 10 km of crust for some elements (N, S, P, I). Such an increase would need an outer skin temperature of 5,000° C (comparable with the surface of the Sun) to radiate away the body heat, which would seem to be well beyond the possible limits.

A question of obvious importance which is not easy to answer is whether people could in fact live the nearly sessile lives, with food and air piped in and wastes piped out, which would be essential. Occasional vertical and random horizontal low speed vehicular or moving-belt travel over a few hundred meters would be permissible, however, so that each individual could choose his friends out of some ten million people, giving adequate social variety, and of course communication by video-phone would be possible with anyone on the planet. One could expect some ten million Shakespeares and rather more Beatles to be alive at any one time, that a good range of television entertainment should be available. Little heat-producing exercise could be tolerated. The extrapolation from present life of a car-owning, flat-dwelling office-worker to such an existence might well be less than from that of the Neolithic hunter to that of the aforesaid office-worker. Much more should be known about social conditioning in a few hundred years' time and, though it is difficult to be quite certain, one could expect most people to be able to live and reproduce in tile conditions considered.

Many readers will doubtless feel that something unconsidered must turn up to prevent us from reaching the limiting conditions I have supposed. One point of this study is however to suggest that, apart from the ultimate problem of heat, we are now, or soon will be, able to cope with anything that might turn up. Anything which limits population growth in the future will, therefore, be something that we can avoid if we wish. It would be perfectly possible to choose not to eliminate some major killing disease or to neglect the world food problem and let famine do its work, but this would have to be a positive decision; it can no longer happen by mistake.

Consequently all methods of limitation of population growth will, from now on, be artificial in the sense that they are consciously planned for, whether or not the plan is carried out by individuals for themselves. We are, collectively, free to choose at what population density we want to call a halt, somewhere between the 0.000 006 per square meter of the present and the 120 per square meter of the heat limit; if we do not choose, eventually we shall reach that limit.