The New York Review of Books
May 29, 1997

Review

Reaching the Limit

By Bill McKibben

How Many People Can the Earth Support?
by Joel E. Cohen
Norton, 532 pp., $14.95 (paper)

The Carrying Capacity Briefing Book
by the Carrying Capacity Network
2,600 pp. (two volumes) pp., $43.00 (2000 P Street NW, Suite 240, Washington, D.C. 20036)

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1.

Fertility rates are falling fast enough in most parts of the world that it is at least possible that a child born today will be living when human population reaches its peak. The United Nations regularly estimates a high, low, and "middle series" projection for population growth—the most recent "middle series" shows our numbers, currently about 5.8 billion, essentially stabilizing at 10.4 billion sometime late in the next century. A recently completed series of computer models prepared by the International Institute for Applied Systems Analysis in Austria predicts with 60 percent confidence that the planet's population will not double again, most likely topping out at just over 11 billion.

This outcome is not certain. As Carl Haub, demographer at the Population Reference Bureau in Washington, D.C., points out, if you exclude China women in the world's developing countries now average four children apiece, down from six a generation ago; to stabilize the population, that number must drop to two. If we stalled at current fertility rates, the population would reach the absurd size of 700 billion by the year 2150. Other than extrapolation from historical experience, there is no strong reason to believe that the rate will continue to drop quickly. If the two-child target is missed by even a small margin we will continue to grow forever; for instance, if each of the world's women has 2.5 children, the population would reach an only slightly less absurd 28 billion by 2150.

One reason the outcome is so difficult to predict is that no one knows precisely why fertility fell in the past. What evidence there is supports a tangle of interwoven and occasionally contradictory explanations, ranging from increased economic development to better education to more widespread availability of birth control. Other data seem to show, though, that in some places birth rates fall fastest when times are hard.

Still, whatever the reason, for those of us who grew up with the vague and dark impression that the world's population would increase infinitely, at an ever steeper rate, until our great-grandchildren stood

shoulder to shoulder on their assigned square meter of the planet's surface, the news of this downward trend must seem reassuring. According to the UN the number of people added to the planet in 1995 was about 81 million, down from 86 million annually in the late 1980s. So maybe the tide has turned. Perhaps this is a special moment in history—the trend in human numbers since Adam and Eve, or Lucy, has been generally up, rising more steeply in this century, but now it may eventually reach a plateau.

Of course, there is another way of looking at this. By many measures—food supply, environmental disruption, species extinction—the earth already strains to support six billion people. We are apparently altering the planet's very climate, for instance, by burning fossil fuels and forests. And now we are poised to nearly *double* the earth's population. You could argue that the camel has six billion straws on its back and we're about to dump five billion more on top of them. Perhaps this is a special moment in history in an altogether different way—the moment when we run out of margin.

To puzzle out this issue, we must consider the controversial topic of "carrying capacity," a subject that most academic demographers never go near. According to Joel Cohen, the director of Rockefeller University's Laboratory of Populations, none of the more than two hundred symposia at recent meetings of the Population Association of America dealt with the subject. It is the quintessential back-of-the-envelope discipline, often left to zealots: "Demographers fear to tread where ecologists rush in," Cohen writes. Happily, Cohen is an exception to the rule—both a respected demographer and a fine writer and historian, he has tackled directly the central question posed in his title, *How Many People Can the Earth Support?*

The book begins with a clear description of the history of human population—in particular the extremely slow growth in numbers that has marked our evolution as a species. For most of the history of human civilization—from 8000 BC until roughly 1750 AD—it took between 1,400 and 3,000 years for the globe's population to double. As the period of "local agriculture" gave way to the era of "global agriculture," which lasted from about 1750 until World War II, the pace speeded up—world population size began to double in little over a century.

During the "public health" era that began after the war, as modern medical practices spread to the Third World, there was a further acceleration: global population size doubled in only thirty-six years. This was the period when the fertility rate stayed high, but vaccinations and cleaner water meant that infant mortality declined and life expectancy soared. Now, in what seems to be the start of the era of falling fertility rates, doubling time has slowed slightly to forty years or more.

Those statistics make it clear just how weird, demographically, the last few decades have been. If the world's population had increased by the same number each year throughout its history as it increased in 1994, then, thinking backward from the current total, the population would have to have started from zero in 1932 and Adam and Eve could have voted for FDR. Alternately, if there had been only one couple 12,000 years ago, at the end of the last Ice Age, and they had multiplied at the current rate of 1.6 percent a year, the world's population would be 5.3×10^{82}. "Finding matter to construct this number of people would be a problem," Cohen writes, "because the number of charged particles in the entire known universe is approximately 10^{80}, or 100 times smaller."

Fertility rates, for the variety of reasons I have mentioned, did finally begin to fall—sometime between 1965 and 1970, the world's population growth rate peaked at about 2 percent annually and began to decline. But of course that did not mean that the world's population was, or is, anywhere near

peaking—only now is the total number of people added each year beginning to decline slightly, and even so we're gaining a population the size of Mexico annually, of India each decade. Even if fertility rates continue to fall steadily we are, at best, decades away from any hope of stabilizing the size of the total population. And of course if we are interested in the real world, we need to figure out what it means to be a human being, beyond an integer on a statistical table. Even though population has been growing rapidly, our demands on the globe have been growing much faster.

Take, for example, energy use—one measure of our ability to alter the planet. Though global averages are fairly useless when people on some continents walk and those on others drive Ford Explorers, the numbers are still startling. The per capita use of inanimate energy (everything from waterwheels to fossil fuels to fusion reactors) climbed from less than 1 megawatt-hour per person in 1800 to 19 megawatt hours per person today. Not only are there many more of us than ever before, but our appetites are much, much larger. Which leads directly, of course, to questions of carrying capacity. How many of us, living at what level, can the planet support?

This question is not a new one. Cohen cites alarmed predictions about population from ancient Babylonian tablets, Chinese scrolls, and even the early Christian leader Tertullian. But the modern story begins in 1798, when Thomas Malthus, the English cleric, published his warning that population growth, being geometrical, would inevitably outstrip growth in food production. Malthus was actually answering the Marquis de Condorcet, an Enlightenment optimist who was convinced, as Cohen puts it, that the human mind was "capable of removing all obstacles to progress." In particular, he thought that new technology would support more people, and that more education would cause birth rates to fall. Their debate has continued for two centuries now; at the moment, the Malthusian position is held most prominently by Paul Ehrlich, the Stanford professor responsible for *The Population Bomb*, while Condorcet—whose point about increased education reducing fertility is now widely accepted—has found a champion for his hope of technological progress in Julian Simon, who believes that people are "the ultimate resource" and that any talk of impending catastrophe is claptrap.

So far, obviously, the argument has gone to Condorcet. Malthus wildly underestimated the ability of human beings to transform the landscape so as to increase the production of food, and also perhaps their ability to someday control their numbers. Everyone now agrees that Malthus was wrong—wrong for eighteenth-century Europe; and wrong for the subsequent centuries of world history, when the increase in food production has outstripped even the growth in population. Wrong even in recent decades—it was only a generation ago that Ehrlich predicted extremely widespread famine for the 1970s. Malthus's sense of inevitability was flawed; clearly we are now starting to control our numbers.

But are we starting to control them soon enough to prove Malthus wrong in the long run? Very few people who study this question believe that there is no meaningful limit to the number of people the planet can support. They may disagree about whether it will be food that will limit human numbers, or water, or environmental degradation; but for most who examine the possible limit there is a point at which Malthus would be proved a prophet. For us the question becomes: Will it be before we double the population once more and then reach a plateau?

Cohen devotes the heart of his book to examining the search for that answer. He analyzes in great detail eight different attempts to estimate carrying capacity, beginning with an 1891 paper by an Englishman

who calculated six billion and a 1925 German effort that reckoned eight billion. A somewhat bizarre 1967 analysis that posited photosynthesis as the limiting factor concluded the earth might support a trillion people, although if each person insisted on having a third of a football field's worth of land, the number would drop to 79 billion. This "highly abstract" exercise, as Cohen calls it, was followed shortly by the analyses of a Stanford geneticist who figured a billion humans could subsist at American levels of affluence, a Harvard oceanographer who suggested in 1970 that there might be food for 40 billion people, a Brown University researcher who thought 5.9 billion vegetarians might be viable, and an Australian economist, Colin Clark, who first guessed 28 billion and then a decade later changed his mind to 157 billion, mainly because he revised his estimates of the amount of arable land and the number of people each hectare could support.

Cohen discusses each of these attempts at length, and gives glancing attention to fifty-eight additional efforts over four centuries. By the time he is finished, one is no longer wondering why demographers, as opposed to soil scientists or agronomists or environmentalists, avoid such calculations. The variables in the calculations are so enormous that anyone who makes them takes a big risk.

And yet Cohen to his immense credit does not entirely dismiss or disdain the effort to arrive at such estimates. Among other things, he offers his own effort to discover whether the availability of fresh water might be a limiting factor in the size of human populations. It is instructive in showing the complexity of such calculations. There is quite a lot of water, he reports—enough to cover the entire earth to a depth of 2.75 kilometers. Of that, however, only between 2 and 5 percent is fresh, and of that 70 percent is fairly inaccessible—locked up in glaciers, snow fields, or aquifers more than a kilometer deep. Still, somewhere between 90,000 and 119,000 cubic kilometers of fresh water fall each year as rain over land. Much of that simply evaporates, but there remain perhaps 41,000 cubic kilometers annually to replenish aquifers or return to the ocean as runoff.

That's far more than we use annually. Unfortunately, most of it rushes back to the ocean during spring flooding, when dam managers have no choice but to open the floodgates or be overwhelmed. Therefore,

> the world's *available* renewable fresh water lies somewhere between the 9,000 cubic kilometers per year of stable underground flow in inhabited regions and the 14,000 cubic kilometers per year if the stable underground flow in uninhabited regions is included.

That still should be plenty—we used only about 3,240 cubic kilometers per year in 1987. Unfortunately, and obviously, that water is not distributed evenly around the globe. Many people have too little, and many regions face acute water shortages that may begin to impose limits on development and food production.

Cohen goes through long and fascinating calculations—what percentage of irrigation water reaches crop roots in Pakistan's Indus Basin, how much water is needed to grow wheat as opposed to cucumbers, what are the leakage rates from municipal water supply systems, etc. He then begins to estimate carrying capacity. Depending on efficiency and choice of diet, he estimates that if you could capture every bit of rainfall and use it for irrigation, you could support somewhere between 4.9 billion and 137.5 billion people. "The assumptions required to obtain these figures are numerous and doubtful," he warns, and he goes on to point out exactly how the calculations change as living standards change. If you want to eat more meat, for instance, and hence require more grain to be grown to feed animals, then the numbers drop precipitously.

Cohen also tries to connect water supply with other constraints—the stage of a country's economic development, the amount of energy it takes to pump water, the amount that is needed to cool electric power utilities using different technologies, the sensitivity of irrigated soils to salinization. He even suggests possible new sources of water—vast floating plastic sheets, for instance, that might capture the fresh water falling over the oceans. His conclusions from all this work are modest: the biggest current problems derive from distribution of water between wet and dry regions, not total amounts of rainfall. If the population continues to grow, present water shortages could "become more severe in many regions." Relatively easy "improvements in recycling, pricing, and the efficiency of delivering and using water could postpone water shortages."

What is interesting here is how difficult it is to make such estimates, and how close we are coming to the neighborhood, at least, of certain limits. Every single one of the estimates of carrying capacity that Cohen presents—a total of sixty-six—can be picked apart and second-guessed. Many are probably less robust than Cohen's own admittedly preliminary examination of water supplies. Still, taken together, they may yield some important data for our question: Is the next, and seemingly last, doubling of our population the one that will bring us right up to certain limits, or will we end up safely beneath whatever ceiling nature has established? Summing up all the studies, Cohen notes that his long collection of guesses centers on a narrow range of future population estimates: the median low value is 7.7 billion people, and the median high value is 12 billion people. Interestingly, the UN projections for expected population in 2050 range from 7.8 billion to 12.5 billion. In other words,

> The human population of the Earth now travels in the zone where a substantial fraction of scholars have estimated upper limits on human population size…. The possibility must be considered seriously that the number of people on the Earth has reached, or will reach within half a century, the maximum number the Earth can support in modes of life that we and our children and their children will choose to want.

Cohen does not, of course, announce a number to answer the question in the title of his book, and this is entirely appropriate in a book that shows how dependent on our choices any such number must be. It is contribution enough to point out that, as he puts it in the title of one chapter, we are "Entering the Zone" where the world may well begin to pinch.

2.

Still, it is a little frustrating not to be told one way or the other. If we're safe it would be nice to know so that we could go on to other, smaller, worries. If however in our lifetimes we may actually run up against some of the limits to carrying capacity, then we are potentially in an emergency situation—an emergency that dwarfs even the other approaching emergencies that we have begun to pay attention to, such as the impending shortfalls in the Social Security system. Even the chance that we may be approaching such limits should perhaps yield more alarm than what we now hear. It is true that there are activists who worry about overpopulation (for a variety of reasons, from its depressing effect on developing economies to the burdens it places on women), and there are others who worry about the environment (from the conservation of species to the elimination of health hazards). But few are obsessed with the connections between these issues—with the largest questions of how near we're getting to the limits.

An exception is the Carrying Capacity Network, which issued in January a two-volume, 2,600-page compendium of articles and studies on the issue. The group, whose board of advisers include well-known environmentalists such as former Senator Gaylord Nelson, the biodiversity expert Thomas Lovejoy, the

longtime Sierra Club activist Edgar Wayburn, and several biologists and demographers, operates from a small Washington office. Their letterhead includes this definition: "Carrying capacity refers to the number of individuals that can be supported without degrading the natural, cultural and social environment, i.e., without reducing the ability of the environment to sustain the desired quality of life over the long term." The general conclusion of the enormous *Briefing Book* (I could hardly carry it) is that this number has either already been reached or soon will be.

Although many of the papers in the *Briefing Book* are global in their calculations, their authors particularly concerned with American carrying capacity, an obsession that can be justified for two reasons. One is that, as Cohen points out, it often makes more sense to figure carrying capacity locally (the amount of water that falls in Algeria doesn't make much difference to agriculture in Indiana); the other is that Americans, by virtue of their demands on the planet, are special cases.

Though many of the most important papers in the book are buried amid op-ed articles, philosophical speculations, and simply strange side issues (for instance, a Tom Wolfe interview conducted in the 1960s with a psychoanalyst who believed crowding was making New Yorkers insane), a few basic themes emerge. The first is the power of rapid population growth to change the face of any region or indeed the entire world. What seems abundance may be, a single doubling of the population later, scarcity—and doubling can happen extremely quickly. China's economy is growing at 10 percent a year, for instance, which means it doubles in size about every seven years. Even at our more modest 3 percent growth rates, the size of the American economy will double in just twenty-three years, with all the implications involved for fuel use and other environmental problems. The more pessimistic of the writers included in the *Briefing Book* believe we may have already "overshot" both the planet's and the nation's carrying capacity, eroding our land and burning our fuel in an effort to keep alive more people than the planet can support over the long run.

As William Catton, one adherent of this view, writes in a long study of the population crash on Easter Island, "there is an important difference between the maximum load that can exist briefly versus the load that can be supported indefinitely." For instance, the soil that could have permanently supported, say, three billion people could be so damaged in the attempt to support six billion that eventually only one billion might be able to survive. (Shortages of fuel wood in much of the third world now leave many peasant farmers no choice but to remove and burn the crop residues left in their fields after harvest, greatly accelerating erosion; a paper by the Cornell scientist David Pimentel indicates that this practice may have become extremely widespread in recent decades.) The ecologist Garrett Hardin, famous for his theory of "The Tragedy of the Commons," puts the same concern this way:

> Because transgression is so serious a matter, the conservative approach is to stay well below the best estimate of carrying capacity. Such policy may well be viewed by profit-motivated people as a waste of resources, but this complaint has no more legitimacy than complaints against an engineer's conservative estimate of the carrying capacity of a bridge.

In theory that seems inarguable. But are we anywhere near the maximum load that the planet can carry? The authors of the *Briefing Book* cite several reasons to think so. The first is that we will eventually run out of certain crucial resources, especially fuel. Another involves necessities like food and water, whose production we might not be able to increase fast enough to keep pace with population growth.

Energy first. Consider the case of the United States. At the advent of the first oil crisis in 1973, of course, it was common wisdom that that we were sucking the planet dry of fossil fuel, and soon would be freezing in the dark. Instead, energy prices have fallen so dramatically that filling your tank now costs less in real terms than it did in the 1960s; now the common wisdom is that everyone can buy a GMC Suburban. But should we? The most comprehensive excerpt on this topic is from a book called *Beyond Oil* by a team of academic researchers.[1] Examining domestic oil resources, they found that oil production had peaked in the late 1970s and is now sharply declining—following very closely the slope predicted in the 1950s by an oil company geologist named M.K. Hubbert. In their estimate, "by the year 2020 domestic oil supplies will be effectively depleted." ("Effective depletion" occurs when you use more energy bringing up the remaining oil than you would get by burning it.)

Even if you didn't worry about American dependence on foreign oil, the world's supply is apparently following a similar curve, albeit one that lasts a few decades longer. Supplies of natural gas last somewhat longer, and of course the world has lots of coal—but along with coal come many other problems, chief among them its devastating effect on global warming. Is it possible, the authors ask, that they are exaggerating the situation, and that rising prices will spur explorers to find vast new reserves? Perhaps not. Consider the US example:

> More large oil discoveries in the lower forty-eight states are highly unlikely because there is not enough room between existing drill holes to contain them. As of 1975 there was one production or exploratory well for every 1.6 square kilometers of sedimentary rock, the only kind to contain oil, in the continental United States.

What is most useful about the authors' analysis is not the dates for which they predict depletion; these are likely to be wrong, in keeping with Cohen's dictum that "the future is unlike the past because it hasn't happened yet," and his "Law of Information: 97.6 percent of all statistics are made up." Instead, it's that they've considered the economic difficulties of simply gliding on to some other energy source, especially if careful planning is not undertaken now. What the world enjoyed during the last century was a worldwide bonanza of *cheap* energy; the amount of energy it took to extract more energy was so low that we were able to transform almost every human activity (transportation, agriculture, industry). That's why minerals have gotten cheaper even as they've gotten scarcer—the cost of energy is so low that it's covered up the fact that you now need far more of increasingly low-grade ore to produce the iron to make a girder.

Unfortunately the same principle works in reverse, and as energy becomes scarcer the effects could ripple through the economy. In particular, trying to maintain the same standards of living will likely mean that less and less money will be available for the potentially difficult transition to more efficient and renewable forms of energy. (It's not like running out of white wine and switching to red. One paper cited here, for instance, estimates that 20 percent of the American land surface might have to be covered with photovoltaic panels if we were to produce from solar power half our current energy consumption.)

It's true that we come up with new technologies all the time that could reduce the amount of energy we use; it's also true that we're doing a poor job both here and abroad of switching to such technologies, and in some respects (those Ford Explorers) we're going backward. Because we face an eventual reduction in cheap energy, the authors suggest that Americans, at least, may soon face "a long period of decline in per capita material wealth." The clear implication is that developing the rest of the planet to the point where it can match anything close to our current US standard of living is a pipe dream.

Reduced energy availability could conceivably reduce our standard of living, but that may be fairly far away, and it may not limit carrying capacity in and of itself. In fact, *not* running out of fossil fuel, because it exacerbates global warming, may turn out to be more fundamentally troublesome, for it could hurt efforts to increase the world's food supply. The growth in world food production long outpaced population growth—the amount of grain produced each year per capita increased from fewer than 250 kilograms in 1959 to nearly 350 in the mid-1980s, despite the enormous growth in populations. During this period immense amounts of new land came into production, far more of that land was irrigated than ever before, fertilizer was applied in ever-increasing amounts, and the Green Revolution led to large gains in yield. Malthus was therefore wrong. During the 1990s, however, world grain production has increased less quickly, and therefore the amount of grain grown per capita has actually shrunk considerably—nearly 10 percent between 1984 and 1996.

The grain would stretch much farther if we ate less meat, but quickly developing countries like China are in fact eating more meat. There is little land left to expand onto, and applying more fertilizer no longer increases harvests much—indeed, fertilizer use is now dropping. Meanwhile, the world's fisheries have hit the upper limits of sustainable harvest—since 1989, the fish catch per capita has fallen 9 percent.[2] We will not, of course, deplete food supplies; unlike oil, you can grow another crop each year. But if we double the size of the population, that crop will have to stretch further and further each year, and there is no evident reason (other than "so far it's always worked out") to think that that will happen.

There are several reasons to think that perhaps it won't—our current situation is in fact quite different from the past—and that Malthus could still turn out to be prophetic, though by forces he couldn't have imagined. New technologies have in the past altered the world in any number of creative ways; but now we have begun to alter the planet in damaging ways as well, introducing one more set of obstacles to sustainability. For instance, it now seems likely that global warming will make the job of farmers far more difficult. The very warm summers of recent years have done their part in reducing grain stocks—1988's record heat, for instance, dramatically reduced corn and soybean yields. New data indicate that warming has led to large increases in severe storms across the grain belts, and hint at reductions in soil moisture. In fact, very few of the estimates of carrying capacity cited by Cohen take into account the possibility that we will degrade the planet's support systems below their theoretical maximums.[3] And now, just when we need everything to work extremely well, we are eroding croplands, salinating irrigated fields, and changing the very temperature of the planet. Such changes make any calculation of carrying capacity more difficult than before—even the previously stable variables, such as temperature, must be refashioned as a series of ranges—and almost certainly more gloomy.

A good deal of the *Briefing Book* is devoted to ways of fending off the crisis its authors see as looming, and their solutions tend to be more radical than those supplied by other environmentalists or family planning advocates. They are especially concerned with correcting problems in the US. And rightly so—as Ehrlich argues in an article titled "The Most Overpopulated Nation," our large population and huge per capita consumption mean that we do "several hundred" times the damage to, say, global climate, of a nation like Bangladesh, where family planning efforts are a high international priority.

Not only that:unlike European nations and Japan, which have reached stable population sizes, ours is continuing to grow. New census estimates suggest that we may be approaching 400 million Americans by the middle of the next century. The Carrying Capacity Network is especially keen to limit immigration, arguing that it converts foreigners into wasteful Americans and that it may offer a relief valve for nations

that would otherwise be forced to lower their fertility.

The evidence for the latter claim is ambiguous, and at any event the debate about immigration is the *Briefing Book*'s low point. Here the collected articles and papers sometimes des-cend into one-sided criticisms of the alleged effects of immigration on "national character," which are so far removed from any discussion of carrying capacity that they confuse the issue, at the very least.

Internationally, many of the authors adhere to what Garrett Hardin famously termed "lifeboat ethics." They tend to oppose large-scale foreign aid, believing (much like this country's welfare reformers) that people should make their choices about childbearing and other basic issues without being influenced by the prospect that they will get help from outside sources. It's a grim prescription for what they see as a grim future, and it is too bad that their diagnosis, unlike some of their prescriptions, can't be easily discounted.

But they cannot. As a species we seem nearly certain to try nearly doubling our population one more time. The inhabitants of the rich nations continue to demand unnecessary economic growth as well. Both of these trends take us ever further out into unknown territory. We plunge ahead, even though, as Cohen makes clear in his history of carrying-capacity estimates, the reports from the few scouts who have gone out to take a look are not particularly promising. Perhaps they are just weak-kneed, like the scouts Moses sent to the Promised Land who came back with the report that it was inhabited by fearsome giants. On the other hand, it's possible that we live reasonably close to the Promised Land right now, and are venturing somewhere else altogether. In fact, one could plausibly rewrite the opening sentence of this article to read: The limit of the earth's carrying capacity may be so rapidly reached, and in the process its systems so impaired, that it is at least possible that a child born today will live to see the peak of human population.

Notes

[1] John Gever et al., *Beyond Oil: The Threat to Food and Fuel in the Coming Decade* (University Press of Colorado, 1991).

[2] These statistics are from Lester Brown, *State of the World 1997: A Worldwatch Institute Report on Progress Toward a Sustainable Society* (Norton, 1997), p. 23ff.

[3] An exception are estimates cited in the famous "Limits to Growth" report of the early 1970s, most recently updated by Donella Meadows as *Beyond the Limits* (Chelsea Green, 1992.) These "systems models" calculations, heavily dependent on the assumptions built into the computer programs, show that we are tending to overshoot the planet's carrying capacity and may pay a price in long-term declines of both maximum population and living standard. Cohen points out the problems with the systems approach, but adds: "Without placing faith in the conclusions from the modeling, I confess sympathy with many of the recommendations made in 1992 by Meadows et al."

Letters

June 26, 1997: David F. Durham, THE FIFTH HORSEMAN

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Reaching the Limit. Sebastien NovA. Album Odysseus [Album]. Reaching the Limit Lyrics. [Instrumental]. More on Genius. "Reaching the Limit" Track Info. Countries claiming to have reached the limit of what they can do really mean that they have reached the limit of what they can do on their own. patents-wipo.Â lowered than the first value has reached a limit value; and a third value indicating the charge state when the battery power discharged from the battery (B) when the charge state exceeds the first value has reached the limit value. Giga-fren. Reaching the limit. ArticlePDF Available. August 2018. eLife Sciences 7. DOI: 10.7554/eLife.39804. Benedetta Bolognesi. Ben Lehner.Â in high enough amounts to reach the burden. limit. This was because the genes that encoded. these enzymes contained sequences that were. not optimal for protein production. Another 19 enzymes could be expressed until. they formed close to 15% of the total protein.