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FORUM

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LETTERS

The Future of Fusion

Jan Beyea's contribution to the fusion discussion (January 1990) seems to me to present a plank in the environmentalist platform rather than to give a penetrating analysis of actual public attitudes. While environmentalists do have strong allies in the media, in academia, and in the leadership of influential lay organizations, the public has been known to go in a different direction when it at last senses that its own interests are not being served by the orthodoxy.

Many years ago the head of the local labor union said to me "Let's face it, there's no industrial hazard that can't be eliminated by a dollar an hour wage increase!". Nowadays this observation would be considered too crass to be openly expressed. Nevertheless, the stacks of unsold radon detector kits gathering dust in hardware stores suggest the continued willingness of members of the public to discount even widely publicized hypothetical hazards. We are constantly warned of the need to protect "Spaceship Earth." But the public may come to realize that, on a perilous journey, the agonizing decisions must be based on more objective analyses of the comparative risks of alternative courses of action and more attention to technological constraints than has been customary in the environmental movement.

With respect to fusion power, the real issue seems to me to be whether or not fusion power plants can be as safe and economical as the advanced fission plants that are being designed by U.S. vendors for off-shore use. I don't know whether or not Beyea and friends would consider these plants to be "melt-down-free." But, having the ability to perform my own risk assessments, I would rather my grandchildren live near an advanced LWR than in one of the sealed up homes prescribed by proponents of energy conservation.

It will admittedly be more difficult for fusion power plants to compete with advanced LWR's than with a duplicate interstate highway system covered with expensive PV devices, installed and maintained by an army of workers whose enthusiasm for solar energy is not guaranteed to lead to unprecedented restraint at the bargaining table. If fusion scientists and engineers are willing to accept the greater challenge, they deserve our continuing support. On the other hand, I question the wisdom of devoting major societal resources to the pursuit of standards of safety that are far more rigorous than those utilized by members of the public in making their own "real life" decisions.

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The January issue carried four articles that dealt with the "Future of Fusion." These articles, and others on this subject that I have seen elsewhere, make no mention of what I feel is the reality that will prevent nuclear fusion from having a major impact on our national energy scene for several decades. By "fusion" I mean fusion that might be achieved by the traditional mechanisms that are being explored in mega-machines that heat plasmas or that implode pellets. The "reality" to which I refer is the complexity of commercial power systems that might evolve from those experiments.

Most of the proposals that I have seen for commercial fusion power would use the fusion process as a source of heat which would convert water into steam which would drive turbines which would then drive electric generators. The primary commercial product of the

fusion systems would be power for the nation's electrical grid.

We have had over one hundred years of experience with the production of electricity from steam plants that burn fossil fuels. The dependability and reliability of these steam plants is one of the marvels of the age in which we live. In my memory I can't recall one of these plants exploding. Their concept is simple, their design and engineering are superb, and their output has reshaped our society. Our society now requires absolute dependability of our electricity as to voltage, frequency, and capacity and outages of electrical power have a severe economic impact on all who are affected. Fortunately outages are rare. This is the game in which any new source of electric power must compete. Increasing complexity of a system is a major adverse factor in the ability of the system to compete. Nuclear fission power plants are one or two orders of magnitude more complicated than the fossil fuel plants with which they must compete. It is a credit to all involved that nuclear fission electric plants have done remarkably well in spite of their inherent complexity. But there have been disasters, and the political problems surrounding the disposal of the waste from these plants remains unsolved. It may well be that today's nuclear fission power plants are about as complex as can be managed by humans where the requirements of reliability are so stringent, and where the societal costs of even occasional catastrophic failure are so high.

It seems reasonable to predict that nuclear fusion power plants will be one or two orders of magnitude more complex even than nuclear fission plants. As a consequence, the probability seems low that they could supply reliable 60 Hz power 24 hours a day for years at a time.

I don't recommend that we stop our research on nuclear fusion. However, the combination of the inflexibility of our high performance requirements for electric power systems and the almost certain complexity of possible nuclear fusion power plants, leads me to make an observation and a prediction.

Observation: It would be unwise for energy planners to count on any schedule of proposed or predicted availability of commercial quantities of electric power that is generated by nuclear fusion.

Prediction: Children born today will not live to see ten percent of our national energy consumption being supplied by terrestrial nuclear fusion power plants.

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Global Warming Causes: Population or Lifestyle?

Recently two quite different prestigious sources have commented on the causes of global warming, but with quite different root causes:

1. The University of California held a workshop on global climate change during the summer of 1989. The workshop combined the strengths of the nine UC campuses and the three DOE labs under UC management (Lawrence-Berkeley, Lawrence-Livermore, Los Alamos). They concluded that "Population growth is the single most important force driving global environmental changes" (from *Global Climate Change Newsletter 1*, #4, p. 9, Nov 1989).

2. The Pope also has spoken out on the global ecological crisis, but on the other hand the Pope stated that "The seriousness of the

ecological crisis lays bare the depth of man's moral crisis." He appealed to modern society to take a "serious look at its life style" in a world given to "instant gratification and consumerism." He called for "simplicity, moderation, discipline as well as a spirit of sacrifice" as ingredients of a healthier global society (*Los Angeles Times*, 6 Dec 1989, p. A6).

The juxtaposition of these two studies is most interesting. Is the cause of the global greenhouse population growth or lifestyle? Why does one study name population growth (and not lifestyle) and the other study name lifestyle (and not population)? Is one correct and the other wrong, are they both correct, are they both wrong, or are they both partly correct and partly wrong?

As an old adage has it, "we stand where we sit." The University and DOE scientists feel that conservation by denial is impossible politically, so they refrain from attacking the superfluous use of energy. They conclude that we should (1) use energy more efficiently, and (2) use fuels that produce less CO₂. On the other hand, the Pope attacks the superfluous use of carbon fuels, but does not wish to support birth control. Thus he too is silent on one part of the problem, population growth.

In fact, annual global carbon dioxide production (C) can be written as

$$d(\text{CO}_2)/dt = C = PE/h + N.$$

where P is the global population of about 5 billion people, and E is annual average per capita consumption of energy. The product of P and E is presently about 100 million barrels of oil/day, or 200 quads (1 quad = 10¹⁵ Btu) of energy/year. The symbol h represents the average amount of usable energy produced per unit energy. The value of h for a particular process varies between almost zero (house fire) to almost infinity (fission, photovoltaics, fusion). Improved end-use efficiency can help a great deal; for example, new refrigerators are now using one third as much energy as before the oil embargo, increasing h by a factor of three. At present, E divided by the average

value of h is about 5 giga-tonnes per year of carbon. The last term, N, is the net production of CO₂ by natural causes.

The logarithmic derivative of this equation gives us the fractional rate of increase of C:

$$(dC/dt)/C = (dP/dt)/P + (dE/dt)/E - (dh/dt)/h$$

For simplicity, we have ignored man's impacts on the natural production of carbon, by assuming that $dN/dt = 0$. Actually man's impacts should not be ignored since the cutting and burning of trees can be large, and increased global warming can release methane, a very effective greenhouse gas, from the tundra. The fractional increase in population, $(dP/dt)/P$, is the large term at about 1.8% per year. However, the large use of energy by the industrialized states is clearly part of the problem since the world is aspiring to attain our life style.

Thus, it looks like both reports are partially correct. UC/DOE favors the first term, the fractional growth of population $(dP/dt)/P$, as the most important term in the equation. On the other hand, the Pope considers the second term, the excess consumption of fossil fuels $(dE/dt)/E$, as the most important term. On the other hand, the energy conservers, the nuclear power advocates, and the photovoltaic fans all agree that the diminished use of fossil fuel through either end-use efficiency or alternate, nonfossil power sources is the most important.

I congratulate the two groups for pointing out the two leading terms as the main cause of global warming. I agree that a global population increase of 1.8% per year is large, but I also recall that our life-style got us into trouble in the first place. We are all part of the problem as well as part of the potential solution: I confess to contributing to $(dP/dt)/P$ by having three children, and to $(dE/dt)/E$ by visiting our son in Paris this coming summer at his new job.

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ARTICLES

The Case for Civil Defense in Nuclear War Education

Robert Ehrlich and Jane Orient

[A copy of the original lengthier version of this article, including 48 footnotes, can be obtained from the first author.]

A majority of educators teaching courses on nuclear war and peace profess to believe in the importance of presenting both sides of controversial issues. Yet the pro side of the civil defense issue is seldom presented without the ridicule often used by its detractors. In fact, many nuclear war courses do not include *any* significant amount of material about civil defense. This may be because most educators feel very strongly that nuclear war is unsurvivable, or perhaps that thoughts of nuclear war survivability are an obstacle to peace. This article argues that civil defense advocates should be allowed to make their own case, so that students can decide for themselves whether or not the idea deserves to be ridiculed.

This essay defends the proposition that civil defense measures (shelters, food and medicine stockpiles, evacuation plans, and most importantly, education about protective measures) could save many millions of lives in the event of a nuclear war. We stress the word "could" because skeptics can always come up with some condition under which any given protective measure will fail to work.

For example, consider the idea of evacuating "high risk" areas prior to an attack — a particularly controversial civil defense measure. Evacuation of "high risk" areas would be futile in the event of an attack without warning, even though most observers believe that such a "bolt-out-of-the-blue" attack would be highly unlikely. Likewise, skeptics can point to the extreme difficulty in evacuating particular

cities such as New York even given several days notice, but New York is far from typical in terms of its ease of evacuation. Skeptics also note that an attacker can simply retarget fleeing populations, but this would only be an effective tactic if the attack occurred relatively soon after the start of the evacuation, and before the population dispersed. Finally, skeptics note that even if evacuation "succeeded," no place in the nation is safe given the lethal levels of fallout radiation, "nuclear winter," or other such global threats to life. A detailed rebuttal will be given later. For now we reemphasize that the issue of how well city evacuations would work is undecidable, short of an actual nuclear war. Circumstances under which it *could* save many lives include (a) most likely nuclear war initiation scenarios, (b) most cities, (c) most strategies of an attacker, and (d) most realistic estimates of seriousness of the long-term threats to life (fallout and "nuclear winter").

For most Americans, civil defense is an issue of very low saliency. If reminded in a poll that the Soviet Union spends far more on civil defense than the U.S., most Americans favor increasing U.S. expenditures. However, it is not an issue about which most citizens are particularly concerned, especially now that the perceived risk of nuclear war seems to have diminished greatly. Those few civil defense enthusiasts that do exist are regularly derided as kooks or Dr.

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Strangelove types who actually would relish the prospects of a nuclear war. Some psychiatrists believe that "denial," the unconscious suppression of unpleasant facts, is a motivation for believing that nuclear war could be survivable. We believe, however, that the reverse is more likely the case, and that the term "denial" better fits the belief in nuclear war *unsurvivability*. For many Americans the thought of experiencing the kind of unpleasant hand-to-mouth existence prevalent in 90 percent of the Third World today, a realistic prospect for survivors, is simply unimaginable. It is more comforting to imagine one's instantaneous annihilation in a nuclear war. In reality, of course, far more people would suffer slow, painful deaths, especially those who died from radiation sickness—deaths that could be prevented by taking precautions, some of a relatively simple nature.

For example, fallout radiation (present on dust particles) can simply be washed off food without the food being contaminated afterwards, and contaminated water can easily be decontaminated by simply filtering it through an earthen filter. Another simple protective measure unknown to many civil defense skeptics who think in terms of special purpose fallout shelters is the simple expedient of survivors staying in their own home basements for a week or two following a nuclear war. This measure wouldn't work for everyone: those without home basements, those not at home when the attack occurs, those whose homes burn down, etc. But for those living in perhaps 75 percent of the nation's land area, a ten to twenty-fold reduction in the radiation level (as a below ground basement provides) is enough to make survival possible. Of course some areas of the country would become "radioactive wastelands" in the sense that a very long time would be required before radiation levels decayed to safe levels. In those very "hot" areas, survivors would need shelters with a protection factor much higher than 10 or 20, and shelter stays longer than a week or two would be required. But such areas occupy a relatively small percentage of the nation's land area.

Civil defense critics often portray the situation otherwise by speaking of the vast land area that can be "contaminated" by a single nuclear explosion. In making this claim, they are either using the word "contaminated" to refer to any amount of radioactivity, however small (in which case everyone on earth is contaminated right now), or else they are referring to the present day peacetime radiation standards used by the government for limits on radiation exposure. These limits are 5 rems in one year for occupational exposure or 0.5 rems in one year for the general public. Such peacetime exposure limits are extremely stringent in terms of the health risks (primarily excess cancer deaths) faced by people exposed. The health risks faced by people receiving a given dose of radiation are reasonably well-known (at least for high doses), based on studies of the survivors of the Hiroshima and Nagasaki bombings. For example, the rate of increase in cancer deaths (most 20 or more years later) was found to be about 8 percent for every 100 rads a survivor received.

In discussing the dangers of fallout from nuclear weapons, people often mention the islands in the Pacific that remain "uninhabitable" as a result of U.S. nuclear testing, despite a radiologic clean-up operation. In fact, the radiation on the Marshall Islands is somewhat higher than it was before the testing. But it is still not very high. The Northern Marshall Islands Radiological Survey conducted in 1978 showed that on most of the islands the annual dose due to fallout was about 0.006 rems from all exposure pathways, including food, or about 4 percent of the average annual external background dose in the U.S. On Bikini Island, one of the most heavily contaminated areas, the maximum annual dose to those eating locally grown food was less than 2 rems.

One other greatly-feared effect of radiation on humans and animals is genetic mutations. Studies on the survivors of the Hiroshima and Nagasaki bombings have, however, shown no evidence for an increase in the 10 percent spontaneous rate of genetic defects among survivors' offspring. This does not mean that no increase occurred, only that it was too small to be seen given the size of the group studied. Extrapolations from studies with mice indicate that a small increase would probably be expected, but certainly nothing like the popular misconception, shared by many nuclear war educators, of radiation

producing a new breed of "monsters" among nuclear war survivors—a favorite theme of science fiction and editorial cartoons.

Radiation is only one of numerous threats to human survival in nuclear war. Other immediate or early sources of casualties would include blast, thermal radiation, and fires. Later, people might perish from starvation, disease, climate change ("nuclear winter"), or other factors. Yet none of these factors, singly or in combination, has been shown to pose such an overwhelming threat that all protective measures would necessarily be useless.

Consider, for example, the "duck-and-cover" drills of schoolchildren in the 1950's, which are still taught to all Soviet citizens today. Although widely ridiculed, such simple action could save many people outside the lethal blast area who might otherwise be severely injured from flying glass or from the intense thermal radiation which could cause severe burns or temporary blindness.

Obviously, inside the lethal blast zone, measures to protect lives would need to be much more elaborate (blast shelters), but it should be noted that the cumulative U.S. area subject to such lethal blast damage (over 5 psi) is probably less than 5 percent (and for the U.S.S.R. it is probably less than 1 percent). These figures will probably surprise most people who may have heard the widely repeated assertion that we and the Soviets have enough nuclear weapons to kill each other 10 or more times over. Other variations on this theme are that the world's arsenals equal one million Hiroshimas, or three tons of TNT per person on Earth, or our favorite: a hand grenade for every square foot of the Earth's surface.

If these latter "statistics" are true how is it possible that less than 5 percent of the U.S. (or 1 percent of the Soviet) land area would probably be subject to lethal blast damage in an all-out nuclear war? The early calculations of deaths per megaton were based on a "cookie cutter" model. Each nuclear detonation is assumed to result in lethal blast damage inside a circle of specific radius. One then imagines nonoverlapping circles to be placed over the areas of greatest population density. In this way, it was estimated that perhaps 400 one-megaton weapons could kill about 25% of the population. This 25% fatality level was considered by strategists in the 1960's to represent a level of damage that no nation would tolerate—the "assured destruction" level. "Assured destruction" does *not* mean that everyone would be killed with 400 megatons. Moreover, the present U.S. megatonnage of ten times this amount would not kill everyone either, even in the simplified "cookie cutter" model. The reason is that a point of diminishing returns is reached fairly quickly after the major population areas are targeted, and each additional megaton used would kill fewer and fewer people; the major urban areas of the nation occupy no more than 2 percent of the U.S. land area, and no more than 0.2 percent of the Soviet land area.

In fact, on a worldwide basis all the weapons in all the world's arsenals would subject less than 1 percent of Earth's land area to lethal blast pressures. Thus, the "overkill" statistic about being able to kill each other ten times over is at best a metaphorical use of numbers that has no relation to actual casualties, and at worst a deliberate attempt to mislead people into believing nuclear war survival is impossible. That statistic (as well as all the others: 3 tons of TNT per person, one million Hiroshimas, etc.) have as little bearing on the actual estimate of casualties as the observation that the explosive power in the world's nuclear arsenals is comparable to that released in one very large volcanic explosion.

The fact that only a relatively small percentage of the nation's land area would be subject to lethal blast damage makes evacuations of cities prior to nuclear attack a conceivable strategy. This, of course, is not nearly as effective a strategy as having in-place blast shelters that can be occupied on short notice, but for a nation that doesn't wish to pay the expense (estimated at 60 billion dollars or \$250 per blast shelter occupant) it is the next best possibility. Obviously, an evacuation of cities would pose extraordinary problems for people residing in the "host" areas. And even outside the "high risk" areas, there still would be many other hazards, especially fallout.

Often, the ability of people to survive the short-term effects of nuclear weapons is portrayed as "meaningless" in view of the long-

term environmental effects. One example of such predicted effects is the depletion of the ozone layer which supposedly has been linked to various human activities. The primary human hazard of a depleted ozone layer would be an increase in skin cancers due to ultraviolet radiation. Calculations by the National Academy of Sciences estimate the rate of increase following a nuclear war to be about 10 percent for Northern Hemisphere survivors — roughly one tenth the increase in danger faced by someone who today chose to move from Minnesota to sunny Texas!

The long-term consequence of nuclear war that has received the widest publicity as being possibly serious enough to bring about mankind's demise has been "nuclear winter," originally proposed in 1983. More recent studies by Thompson and Schneider, however, using more sophisticated models than the 1983 study, show that the duration and magnitude of the maximum expected temperature declines (about 200 degree-days of cooling rather than 22,000), might justify the term "nuclear autumn" better than nuclear winter. Moreover, the magnitude of the climatic effect is highly dependent on factors under the control of the initiator of the nuclear war (the choice of weapons, their altitude of detonation, the targets, and the time of year). Any attacker seriously concerned that nuclear winter is a remote possibility need only choose his weapons and tactics accordingly to avoid "nuclear winter's retaliation." For example, calculations of the maximum temperature depression averaged over northern hemisphere mid-latitudes yield 15 °C for a war in the summer but only a few degrees for a wintertime war. The idea of a "threshold" for nuclear winter if one percent of the world's arsenal is used, or that any attacker would suffer as badly as his victim because of nuclear winter, are additional myths created by those who see in these positions further justifications for their long-held views on nuclear disarmament.

Given the present (and probable future) uncertainties in nuclear winter calculations it would be foolhardy to claim that worldwide climatic changes following a nuclear attack would certainly be negligible, only that they almost certainly would not be catastrophic. As S. L. Thompson and S. H. Schneider note: "On scientific grounds the global apocalyptic conclusions of the initial nuclear winter hypothesis can now be relegated to a vanishingly low level of probability" ("Nuclear Winter Reappraised," *Foreign Affairs*, Volume 64, 1986, pp. 981-1005). Of course, even with climatic changes of less than catastrophic dimensions, large numbers of people might suffer starvation from the disruption of domestic agriculture and food imports from other countries. But then the civil defense measure of prior food storage could partly ameliorate such suffering in the event of a nuclear war (or other natural and man-made hazards prevalent in many parts of the world.)

Disinterest in civil defense is not a global phenomenon. The Soviet Union, for example, spends over 20 times as much as the U.S. does on civil defense every year. Despite assertions about the unsurvivability of nuclear war made by Mikhail Gorbachev in his 1987 book, there is no sign of slackening in Soviet civil defense efforts. Soviet civil defense is often dismissed as a sham by many Americans and by selected Soviet officials by pointing to specific problem areas, using ridicule, or by citing the response to the Chernobyl accident and the Armenian earthquake. In fact, while considerable problems were encountered in the Chernobyl and Armenian earthquake disasters, Soviet civil defense also had some notable successes. Moreover, those who regard Soviet civil defense as a sham rarely cite specific details about the program, including the existence of more than 20,000 blast shelters to protect up to 175,000 party leaders, the blast doors in every subway system in the land (present in cities of one million or more population), the more than 100,000 full-time and 20 million part-time civil defense personnel, and the civil defense classes that are required of all Soviet citizens. Although the Soviet civil defense system would probably fall short in many respects if actually put to the test, CIA estimates of its effectiveness suggest that Soviet casualties in an all-out nuclear war that occurred following a week of heightened tension during which preparations could be made would probably be "in the low tens of millions," namely about 10 percent of the population.

At the same time that many deride civil defense as being incapable of coping with an all-out attack by the Soviet Union, there is a growing perception that better U.S.-Soviet relations make such an attack less likely, perhaps even the least likely, of potential nuclear threats. If that is the case, civil defense deserves reconsideration even by Doomsday theorists. The proliferation of nuclear weapons (and worse, long-range delivery systems) to Third World nations, or even to terrorist groups, poses a growing though clearly nonapocalyptic threat. Civil defense could also make a considerable difference in coping with the aftermath of the accidental launch of a few weapons.

This article cannot answer every one of the literally endless stream of arguments advanced to "prove" that nuclear war would be unsurvivable: firestorms, mass epidemics, societal collapse, insects inheriting the earth, just to name a few. Rather, it has addressed some of the commonly stated arguments in order to illustrate a general approach, to highlight some of the factual material that should be considered in reaching a conclusion, and to suggest specific sources of additional information.

If civil defense advocates are correct, then decisions about this issue could affect the lives of many millions of people in the event that nuclear weapons are ever used. Thus, a serious consideration of this viewpoint is worthy of inclusion in all courses related to nuclear war and peace.

Trees Can Sequester Carbon, Or Die And Amplify Global Warming: Possible Positive Feedback Between Rising Temperature, Stressed Forests, and CO₂

Arthur H. Rosenfeld and Daniel B. Botkin

Global facts: good news and bad

Forest biomass plays an important role in the global carbon cycle. Forests store billions of tonnes of carbon in plants and soil. This is why there is currently so much discussion about planting trees to sequester a significant fraction of the carbon added to the atmosphere by human activity. The idea of forestation to offset carbon emissions was first proposed by Dyson and Marland (1, 2). To assess the viability of massive tree planting, we need to understand how planting trees and deforestation relate to the current global carbon release.

We will make a rough estimate of how much carbon could be sequestered by planting trees, and how much carbon could be released by deforestation or global warming. For the purpose of the discussion we make the following assumptions concerning the order of magni-

tude of various quantities and rates, some of which, unfortunately, are poorly known:

1. World combustion of fossil fuel produces about 5 Gt of carbon (as CO₂) each year:

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Fossil Fuel Rate = 5 Gt/year.

(1)

Figure 1 gives the Mauna Loa (Hawaii) data on the buildup of atmospheric CO₂. We will use it to give a simplified carbon accounting. We also need to know that the atmosphere contains about 700 Gt of carbon (as CO₂). This gives us the right-hand scale of Figure 1. We see that the average concentration of carbon in the atmosphere is now rising about 15 Gt every 5 years or 3 Gt/yr. This is 60% of the fossil fuel rate in Eq. 1. The remaining 40% is apparently removed by the oceans (Bert Bolin, University of Stockholm).

2. We know that for the last 160,000 years there has been an astounding correlation between temperature and atmospheric CO₂ and methane concentration (Figure 2).

3. Living biomass, mainly trees, contains about 500 billion tonnes (Gt) of carbon, comparable with the 700 Gt of carbon as CO₂ in the atmosphere. In the soil there are an estimated 2000-4000 Gt of carbon.

4. The carbon turnover rate from the 500 Gt of living biomass is on the order of 1%/year, i.e. each year about 5 Gt of carbon are sequestered by photosynthesis, and another 5 Gt are returned to the atmosphere by respiration of living biomass and by decaying biomass.

5. If we deforest 1% of the world's 4 billion hectares (Gha), we will promptly (within a few years) add 5 Gt of carbon to the atmosphere.

6. If we add an additional 1% to our forests, which will eventually sequester 5 Gt (but only over 100 years), we will have net sequestering for 100 years, but only at 1% of 5 Gt/year. In other words, in terms of delaying the greenhouse threat for 20 years while we develop non-fossil sources of energy, we have the problem that dead trees decay in a short time span compared to 20 years, but young trees grow in a long time span compared to 20 years. Thus, for a 20 year time-horizon, we must plant 5 ha to offset the carbon released by deforesting 1 ha. Thus, it is better to save 1 ha of forest than to plant 1 ha. This is an important consideration in dealing with nations which need incentives to slow their deforestation.

7. Returning to point 5, that 1% dead and decayed forest biomass represents 5 Gt of carbon, we now cite a serious danger. If global warming takes place too fast for forests to adapt to changes in temperature and humidity, it is conceivable that an additional 1% of the forests could die per year. This would be very damaging positive

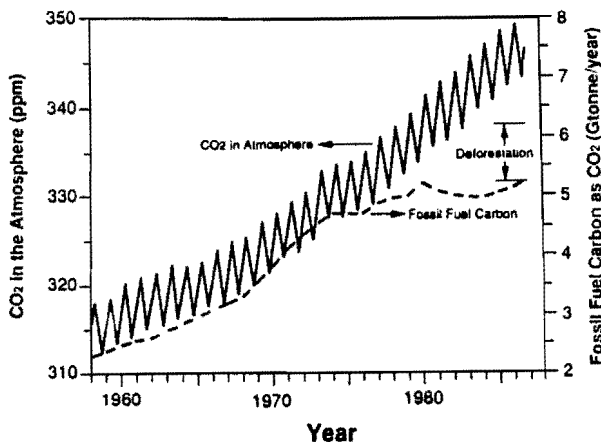


Figure 1. Carbon Dioxide Concentration in the Atmosphere and Fossil Fuel Carbon Emissions, 1958 to 1987. The figure shows monthly concentrations of atmospheric CO₂ at the Mauna Loa Observatory, Hawaii. The yearly oscillation is explained mainly by the annual cycle of photosynthesis and respiration of plants in the northern hemisphere. The slowly increasing concentration of atmospheric CO₂ at Mauna Loa since the 1950s is primarily caused by carbon emissions from fossil-fuel combustion (dashed line). The current annual rate of fossil fuel emissions is about 5 gigatonnes (Gt). Also shown is the estimated 1 Gt of carbon emissions from deforestation. Source: Charles D. Keeling, Mauna Loa, Hawaii.

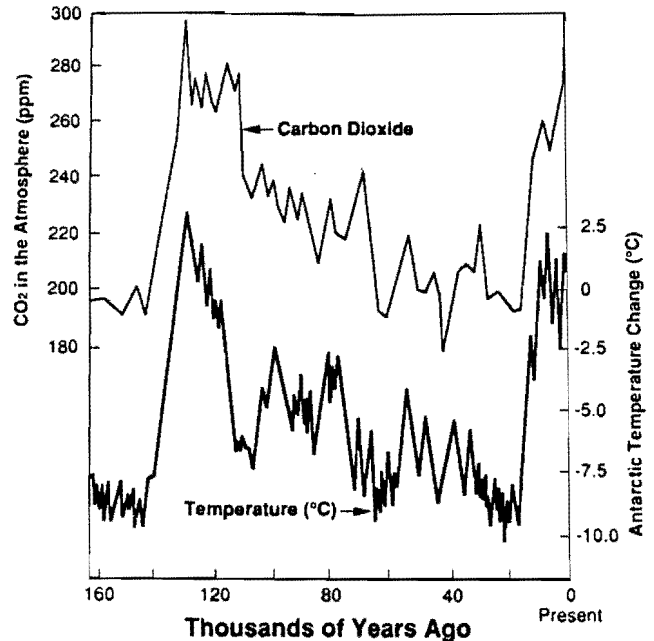


Figure 2. Inferred Atmospheric CO₂ Concentration and Temperature Change from 160,000 Years Ago to the Present. CO₂ and temperature are very closely correlated over the past 160,000 years. The long-term record, based on evidence from Antarctica, shows how atmospheric CO₂ and local temperature rose nearly in step as an ice age ended about 130,000 years ago, fell almost in step at the beginning of a new glacial period, and rose again as the ice retreated about 20,000 years ago. Source: Stephen H. Schneider, *Scientific American*, September 1989—from Claude Lorius et al., Laboratory of Glaciology and Geophysics of the Environment near Grenoble.

feedback.

How fast will forests have to migrate if fossil fuel combustion continues to rise by 1.5%/year? At this rate the carbon dioxide concentration in the atmosphere will double in about 50-70 years. Climatologists are in general agreement that a doubling of CO₂ and an equivalent increase in other trace gases will warm the earth's average surface temperature by 3-5°C. About a dozen research groups around the world have developed computer models to help predict how global climate will be affected by increasing greenhouse gas emissions, and Figure 3 shows the results of one of these models (3).

If greenhouse gases double by 2050, Figure 3 shows an average warming of 3.5°C. In the summer, for temperature latitudes, average temperatures change by about 1°C for every 200 km north-south latitude change. If Figure 3 is correct and average temperatures rise 3.5°C, then this would be equivalent to moving summer temperate zones 600-700 km north over 60 years. If the temperature increase is linear, the move would have to be about 10 km/year. Unfortunately, Figure 3 is more nearly quadratic—the slope starts at zero, and then increases linearly (e.g. $T = t^2$, $dT/dt = 2t$)—so that by 2050 the rate of change might be closer to 20 km/year. If the predicted global temperature increase is correct, then forests will have to migrate at a rate of 200 km per decade, by 2050. This could result in massive forest destruction. (During the last period of glacial retreat, forests had to migrate at a rate of only about 0.2 km/decade.) So a "business as usual" approach over the next 60 years is a severe threat to unmanaged forests or wilderness areas. We will discuss this quantitatively below. Massive human intervention to "help" the forests migrate north might be possible. Unfortunately, without being able to predict how rainfall patterns will change with temperature, it is doubtful that such a huge and unprecedented project would ever even get started.

8. An additional danger is that as the atmosphere heats up, biomass will decay at an accelerated rate, releasing additional carbon into the atmosphere. Aerobic decay yields carbon dioxide, and anaerobic decay yields methane, an even more serious greenhouse gas. An area

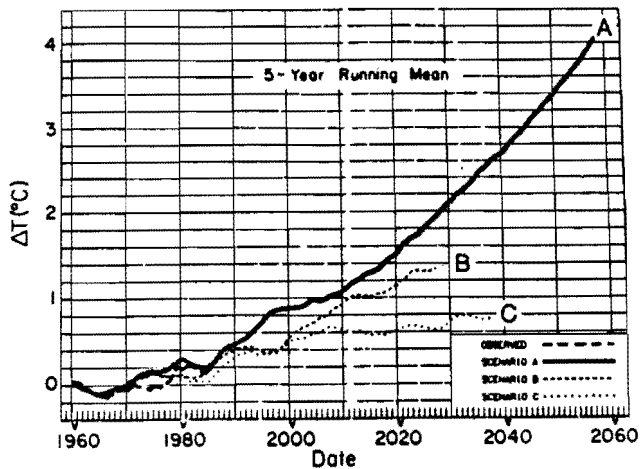


Figure 3. Five-year Running Mean Global Surface Air Temperature Computed for Scenarios A, B, C, 1960-2060. Scenario A—exponential trace gas growth, 1.5%/year; Scenario B—reduced linear growth of trace gases; Scenario C—rapid curtailment of trace gases, no increase after the year 2000.

of concern is the arctic and antarctic boreal forests and tundra where soils are believed to contain 2-5 times more carbon per unit than soils closer to the equator (4). Arctic and antarctic soils have higher concentrations of carbon because of the greater rate of vegetative growth that occurs during the warm, long days of summer relative to the slower rate of decay that occurs during the cold, short days of fall and winter. Increasing temperatures from global warming could increase the decay rate in the soil and release billions of tonnes of carbon into the atmosphere that are now stored in the soils of arctic and antarctic boreal forests and tundra.

Photosynthesis: the good news

Next we note the oscillations in Figure 1, and remember that Hawaii is in the Northern Hemisphere, along with most of the land and vegetation. For simplicity, in the rest of this note we will assume that all the biomass in vegetation is in forests, and that all of it is in the Northern Hemisphere. The dips of the annual oscillation correspond to summer, when warmth and sunlight cause growth, increasing the rate of photosynthesis, and pulling CO_2 from the atmosphere faster than respiration and decomposition put it back. Then, each winter, the balance switches to excess decomposition and CO_2 release. We note that the summer pull-down is about 12 Gt. Only a part of this is yearly net incremental growth in the long-term storage of biomass of typical trees, the rest is leaves and twigs which fall off or are eaten, and small roots which slough off. To a first approximation we assume that,

$$\text{Growth of trees, northern hemisphere} = 5 \text{ Gt/year} \quad (2)$$

This doesn't mean that the forests are sequestering an extra 5 Gt/year of carbon, but that carbon stored in new organic matter in forests is approximately 5 Gt/year. This increase offsets carbon release from decay. We would only get a net sequestering of carbon if we plant new trees or allow now unforested areas to become forested. Ecologists believe that the mass of carbon in vegetation is comparable with, but less than the 700 Gt of carbon in the atmosphere. Our estimate is 500 Gt, and for simplicity, we assume that all of it is forests, so that

$$\text{Forest biomass} = 500 \text{ Gt} \quad (3)$$

By comparing Eq. (1) and Eq. (2) we see that if we wanted to plant enough forest to offset 100% of current annual fossil fuel combustion, we would have to double the forested area of the world, i.e. add 5 times the U.S. land area.

Deforestation: the bad news

We return to point 6. Remember that 4 Gha of forest contain 500 Gt of carbon, so each hectare contains 125 tons of carbon. Suppose that we kill or clear one hectare. Then the trees will burn or decay within a few years. This is a short time compared to the time necessary for the world to switch to renewable sources of energy, and hence to the time scale of the CO_2 threat. For bookkeeping purposes, let's call this decay time one year. Then we see the bad news:

$$1 \text{ dead ha/year} = 125 \text{ tonnes of carbon released/year} \quad (4)$$

Since trees take 100 years to sequester this 125 tonne/ha

$$1 \text{ newly planted ha/year} = 1.25 \text{ t carbon bound/year} \quad (5)$$

In summer, it takes 100 years of growth to offset the damage of clearing the same area of forest.

Worse than that, suppose we let the temperature rise too fast, so that forests cannot migrate fast enough to keep up with the changing climate (or cannot adapt). Then maybe 1% of the forest would start dying each year. But 1%/year of 500 Gt of biomass corresponds to 5 Gt/year, which in turn corresponds to our fossil fuel rate in Eq. 1. If this were to happen we would double the rate of CO_2 release, and introduce a damaging and potentially irreversible positive feedback. We are playing with fire.

Fortunately, current estimates of human-induced deforestation is only 0.2%/year, which corresponds to 20% of the current fossil fuel rate.

Tree planting or tree farming to sequester carbon

We can now see that it's impractical to plant trees fast enough to offset deforestation—we'd have to plant 800 Mha (1/5 of the world's forests) one time to offset killing 8 M ha/year. So let's assume that the developed world can induce the developing world to slow deforestation. Then we have a chance, and tree planting can become a useful tool.

In the industrialized countries, before the first oil crisis, energy use grew at the same rate as the Gross World Product, about 3.5%/year. After the first oil crisis, from 1973 to 1986, the industrialized countries held their energy use constant while their economies grew 2.5%/year. For a 13-year period the industrialized world proved that it could keep energy use constant and maintain economic growth. With the proper political leadership, we could reduce energy intensity in industrial countries by 50%, using existing technology, and still maintain the same quality of life—i.e. comfortable, well-lighted buildings, comfortable and safe automobiles, etc. If we reduce energy intensity by 50% over the next 20 years this is equivalent to a 2.5%/year improvement in energy efficiency. If economic growth continues at 3.5%/year however, a 2.5%/year improvement in efficiency translates into a 1%/year increase in energy use. Suppose this increase came from fossil fuel. This means just to keep world carbon emissions constant, we would have to plant enough trees to offset 1% of the 5 Gt/year fossil fuel rate.

According to Eq. 2, growing trees sequester 5 Gt/year, so we only have to add 1% annually to world forests. This would require planting 40 Mha/year of forests. This doesn't solve the problem, but it gives us an estimate of a reasonable use of trees to help keep carbon emissions constant to reduce the impact of global warming.

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