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Balancing Atmospheric Carbon Dioxide

Thomas J. Goreau

NOTE: This paper discusses the global sources and sinks of atmospheric carbon dioxide from both the oceans and land, and evaluates what steps are needed to bring them into balance to stabilize the concentration of the gas. It is shown that current projections of climate sensitivity to carbon dioxide in widely used models are far less than those shown by the climate record. When ocean and land sources and sinks are compared on the same basis, it is seen that the potential for human management of carbon dioxide removal on land is much greater than in the sea, and a mechanism of ensuring that carbon dioxide polluters pay the real cost of removal of carbon by planting trees is shown to be feasible and cost-effective. This paper was published in AMBIO, 1990, volume 19, pages 230-236.

ABSTRACT

Rising carbon dioxide and global temperatures are causing increasing worldwide concern, and pressure towards an international law of the atmosphere is rapidly escalating, yet widespread misconceptions about the greenhouse effect's inevitability, time scale, and causes have inhibited effective consensus and action. Observations from Antarctic ice cores, Amazonian rain forests, and Caribbean coral reefs suggest that the biological effects of climate change may be more severe than climate models predict. Efforts to limit emissions from fossil-fuel combustion alone are incapable of stabilizing levels of carbon dioxide in the atmosphere. Stabilizing atmospheric carbon dioxide requires coupled measures to balance sources and sinks of the gas, and will only be viable with large scale investments in increased sustainable productivity on degraded tropical soils, and in long-term research on renewable energy and biomass product development in the developing countries. A mechanism is outlined which directly links fossil-fuel combustion sources of carbon dioxide to removal via increasing biotic productivity and storage. A preliminary cost-benefit analysis suggests that such measures are very affordable, costing far less than inaction.

THE GREENHOUSE EFFECT AND CLIMATE CHANGE

Carbon dioxide and other greenhouse-gas levels are rising in the atmosphere (1, 2, see Fig. 1), along with global mean temperatures (3, 4) and sea level (5), but doubts about the reality of the greenhouse effect, uncertainty about the detecting of climate change, and fears over amelioration costs have prevented effective consensus on the need for action. The reality of the greenhouse effect is unquestionable (6, 7); without it the Earth would be 38°C colder, and the entire earth would be covered in ice (8). Short-term fluctuations in surface temperature are often confused with long term heat storage in the climate system. Variations in solar radiation, windborne dust, volcanic aerosols (9), heat transport by currents and winds, and sinking of polar waters into the deep sea, create spatial and temporal fluctuations of surface temperature.

The potential effects of global warming on soil moisture, agricultural production, sea level, etc., are well known (6, 7, 10, 11), and are not reviewed here. Climate models provide qualitative predictions with considerable uncertainty about short term rates of change, and require improved knowledge of polar ice flow and melting, cloud dynamics, biospheric metabolic rates, winds and ocean currents and present and future human activities. Most heat is absorbed and stored in the tropics, but it takes hundreds of years for deep oceans and polar ice caps to warm, and only then will increased heat storage be fully expressed at the surface. We cannot wait to detect such changes before initiating action because corrective measures would take decades to centuries to have an effect.

ATMOSPHERIC CARBON DIOXIDE INPUT- OUTPUT BALANCE

If the atmosphere is to be stabilized a balance must be sought between sources and sinks of CO2. Changes in atmospheric concentration are a sum of the rates of all processes adding CO2 minus all those removing it:

$$d(CO_2)/dt = C + D + R + S + O - P - I - B \qquad (1)$$

where the left hand side represents the rate of change of CO2 with time, C is fossil fuel combustion, D is deforestation and destruction of biomass and soil carbon, R is terrestrial plant respiration, S is respiration from soils and decomposers such as bacteria, fungi, and animals, O is the flux from oceans to atmosphere, P is terrestrial photosynthesis, I is the flux from atmosphere to oceans, and B is the burial of organic carbon and limestone carbon in sediments and soils. Major inputs and outputs of carbon (12) are shown in Figure 2.

Of these fluxes only the increase of CO2 and fossil fuel combustion are accurately known (12). Most of the other fluxes are uncertain due to insufficient measurements in the tropics. Gross rates of terrestrial photosynthesis and respiration may be considerably higher than the numbers cited (13). It has been suggested that rising CO2 should increase photosynthesis, but this assumes plant growth is limited by insufficient CO2. This can be true for highly fertilized greenhouse plants, but plants in nature are limited by nutrient deficiencies and unlikely to be stimulated by increased CO2.

Human activity adds CO2 from combustion and deforestation, decreases photosynthesis by deforestation and soil degradation, and increases carbon in sediments by erosion of soils and stimulating productivity with nutrients from soil erosion and untreated sewage, so around half the carbon from combustion accumulates in the atmosphere. To stabilize CO2, equation 1 shows that C + D + R + S + O must equal P + I + B. Since neither O nor I can be directly controlled, combustion and deforestation carbon releases (C+D) must be limited to the rate at which storage of carbon in biota, soils, and sediments can be increased (P + B - R - S).

Reduced combustion releases, up to 20 % or more in the next 30 years, through increased efficiency of energy use, have been proposed (14-21). Across-the-board reductions would preclude significant increases in energy use and severely hamper future development in developing countries, and such reductions would have only a trivial effect on CO2 increase unless land management practices are reversed so that the biota removes more carbon from the atmosphere than it adds, instead of exacerbating the problem as it now does (22-32). CO2 stabilization is primarily a biological problem, not a technological or geophysical one, because the bulk of carbon flows through biotic processes. Increased photosynthesis and carbon storage in vegetation, soils, and sediments is therefore needed along with emissions reductions to stabilize CO2 (22-32). This can be accomplished by halting destruction of highly productive ecosystems and increasing productivity of areas already degraded. Increased net biotic productivity (P- R in equation 1) by only a few percent worldwide, could absorb combustion, if managed to increase organic carbon and limestone in soil and sediment (22). The bulk of biomass and photosynthesis occurs in the tropics (12, 33), so productivity enhancement on degraded soils must be worldwide, but focused on sustainable tropical development, if it is to alleviate CO2 buildup (22). Preservation of tropical forests is essential not just for their species (23), but to preserve ecosystem metabolism, which buffers atmospheric composition (25). This will not be possible unless developing countries have the resources to vastly expand research and development efforts in renewable productivity, and raise living standards in rural areas (34).

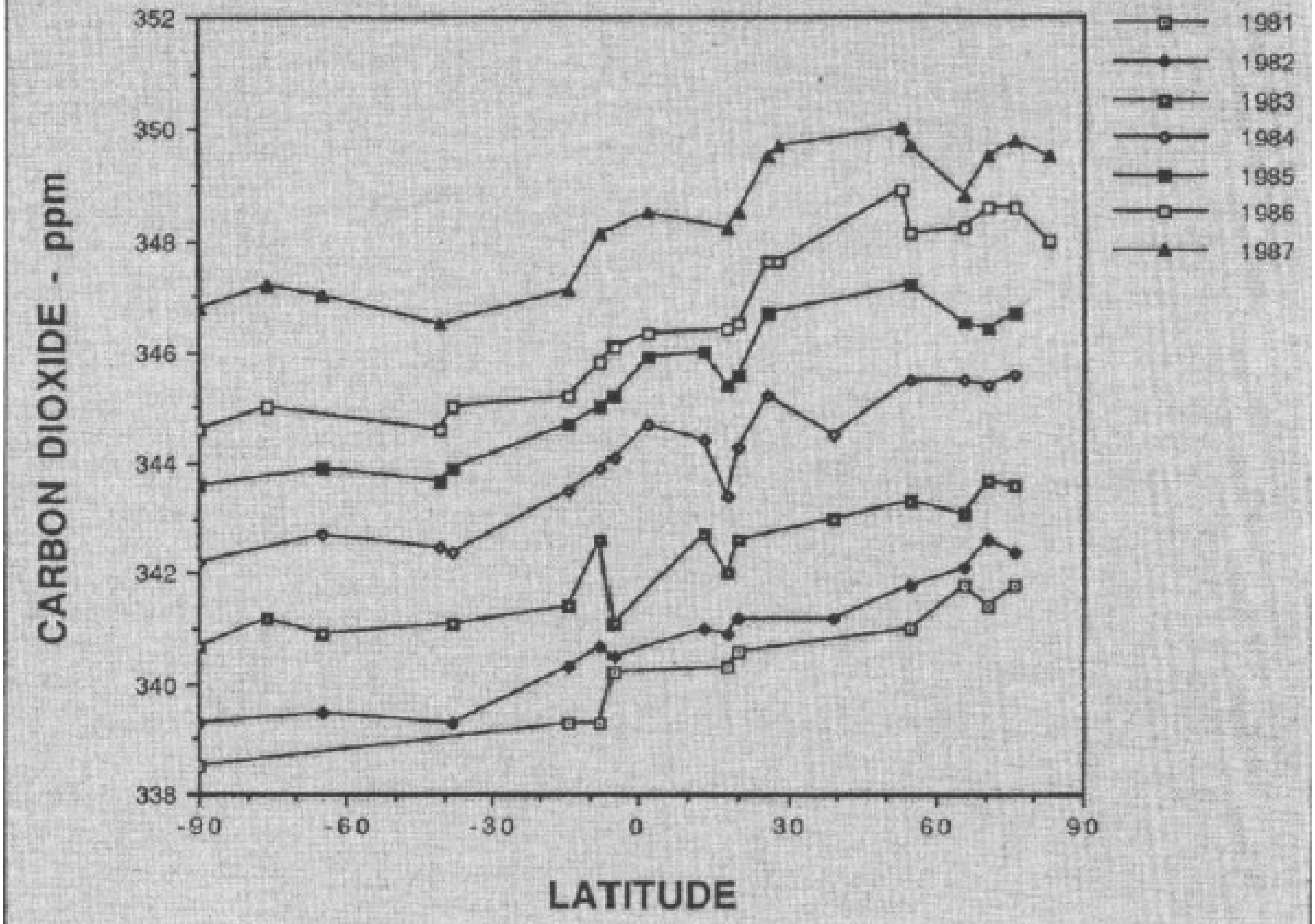
Sole reliance on CO2 source reductions poses a problem familiar to growing families whose only drain is blocking up, causing wastes to slowly rise. Supply-side measures mean producing less wastes while drain-side measures increase outflow by using a plunger or installing a bigger pipe. There are many reasons why the second approach is more likely to be chosen!

HAS THE GREENHOUSE EFFECT BEEN UNDERESTIMATED?

Global temperature increases of 3 to 5°C following doubling of CO2 are predicted from climate models (6, 7). Predictions are highly variable depending on how clouds are mathematically formulated. Models mostly assume that clouds amplify greenhouse effects by trapping heat (35), but recent direct satellite measurements suggest that increased clouds reduce climate change by reflecting more sunlight back to space (36, 37).

Current predictions seem to underestimate past observed climatic changes: CO2 is already 27% higher than 130000 years ago (38), when it was around 2 to 3°C warmer than today (39), sea levels were 6 meters higher (based on the wave cut notch of this age, near Discovery Bay, Jamaica, Fig. 3), and

Figure 1. CO_2 increases from 1981 to 1987 versus latitude, plotted from data in Tans et al. (87). The North Pole is at right, and the South Pole at the left. Concentrations are greatest in the Northern Hemisphere, where most fossil-fuel use and terrestrial biomass are found, but the increase is globally uniform.



hippopotamuses and crocodiles swam in tropical swamps near London, England (40). Current CO2 increases should have already committed us to at least as large a future change as those at that time, once atmosphere, oceans, and biosphere equilibrate.

The best single record of past changes in global climate is the 160 000 year record from Antarctic ice core (38, 39). CO_2 and temperature are highly correlated (41). Taking CO_2 and temperature values every 10 000 years (sufficiently for atmosphere, oceans, and ice caps to reach steady state), yields the linear regressions:

Change in Antarctic temperature (C) =
$-26.5 + 0.094 \times CO_2(\text{ppm})$,
$R = 0.86$, s.e. = 1.7C (2)

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CO_2(ppm) = 267.1 + 7.68 T (centigrade),
R = 0.86, s.e. = 15.6 ppm. (3)

This relationship explains about three fourths of the variance in temperature and CO2, but provides no clue to which are the controlling and dependent variables. CO2 is not the only greenhouse gas; indeed increased ocean evaporation and atmospheric humidity stores much more heat than CO2 does, implying that other factors correlated with temperature also covary with carbon dioxide.

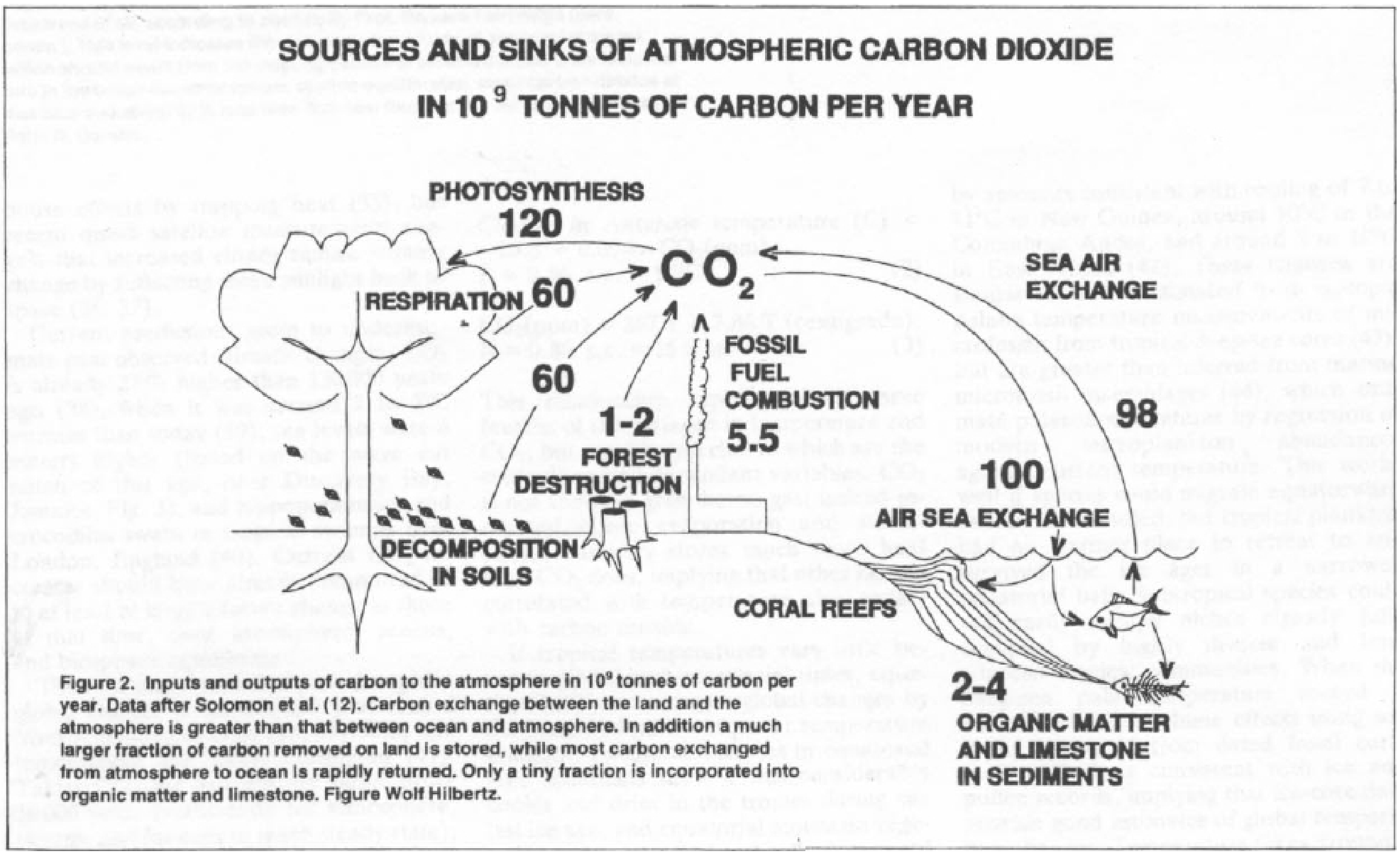

Figure 2. Inputs and outputs of carbon to the atmosphere in 10^9 tonnes of carbon per year. Data after Solomon et al. (12). Carbon exchange between the land and the atmosphere is greater than that between ocean and atmosphere. In addition a much larger fraction of carbon removed on land is stored, while most carbon exchanged from atmosphere to ocean is rapidly returned. Only a tiny fraction is incorporated into organic matter and limestone. Figure Wolf Hilbertz.

If tropical temperatures vary little between glacial and interglacial times, equation 2 will overestimate global changes by the increased pole to equator temperature gradient. Pollen abundances in equatorial lake sediments show it was considerably cooler and drier in the tropics during the last ice age, and equatorial mountain vegetation zones migrated vertically downward by amounts consistent with cooling of 7 to 11°C in New Guinea, around 10°C in the Colombian Andes, and around 9 to 10°C in East Africa (42). These changes are similar to those estimated from isotopic palaeo-temperature measurements of microfossils from tropical deep-sea cores (43), but are greater than inferred from marine microfossil assemblages (44), which estimate palaeotemperatures by regression of modern microplankton abundances against current temperature. This works well if species could migrate equatorward as the Earth cooled, but tropical plankton had no warmer place to retreat to and survived the ice ages in a narrowed equatorial belt. Subtropical species could not easily occupy niches already fully occupied by highly diverse and long adapted tropical communities. When the deep-sea palaeotemperature record is corrected for ice-volume effects using sea levels measured from dated fossil coral reefs (45), it is consistent with ice and pollen records, implying that ice-core data provide good estimates of global temperature changes. Temperature takes around a thousand years to come to steady state, the lag time caused by oceanic mixing (46).

Equation 2 predicts that temperatures increase by 0.094°C for each ppm rise of CO2. Doubling of CO2 from its present level is consequently predicted to increase temperature by 32.9°C, about eleven times greater than predicted by climate models. There are obvious risks in such extrapolation, and a concave downward relationship between temperature and CO2 is much more reasonable than a linear one,

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because CO2 absorbs less heat at high concentrations (47). The dot-dash curve in Figure 4 is based on calculations suggesting that 56 % as much heat is trapped per molecule at a concentration of 700 ppm as at present levels of 350 ppm. (48).

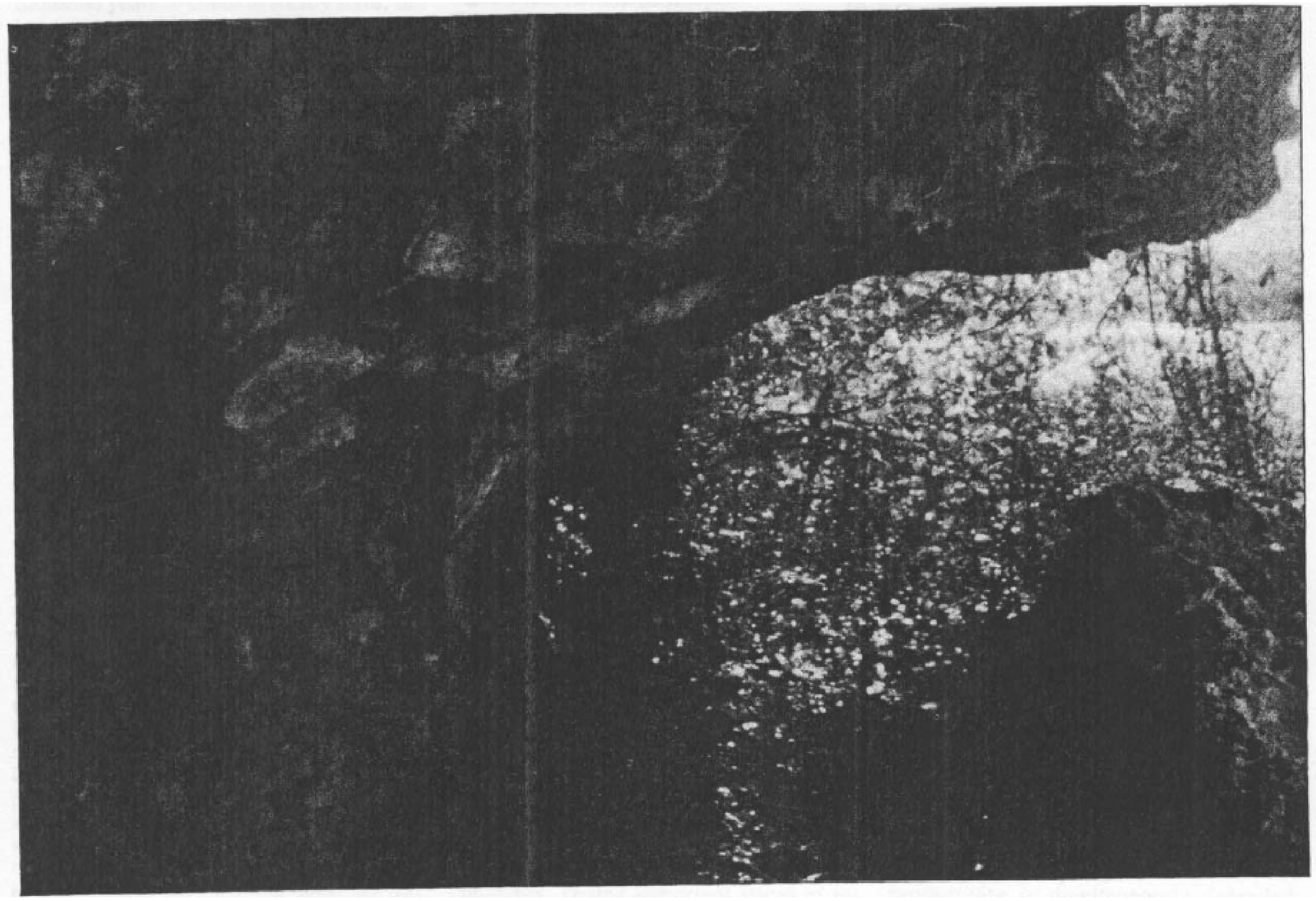

Figure 3. The wave cut notch near Dicovery Bay, Jamaica, 6 meters (20 feet) above present sea level, which formed 130 000 years ago, when temperatures were estimated to be 2 to 3 degrees centigrade warmer than today. Jamaica has not undergone significant uplift in the past 2 million years, and similar sea levels are found in areas as far apart as Florida, Eastern Australia, and the Seychelles in the Indian Ocean, but the sea-level notch in Jamaica is the best preserved of all, according to studies by Prof. Rhodes Fairbridge (pers. comm.). This level indicates the minimum magnitude of sea level changes which should result from the existing excess of carbon dioxide once temperature in the ocean-ice-atmosphere system equilibrates, since carbon dioxide at that time was about 27 % less than that now found in the atmosphere. Photo: Peter D. Goreau.

The empirical relationship suggests that strong positive climatic feedback mechanisms amplify the greenhouse effect severalfold. Very strong feedback is required to explain the temperature amplitude of glacial-interglacial cycles, which is much larger than that caused by changes in heat input to the surface as the Earth orbit around the sun slowly varies. Strong feedback between temperature and CO2 makes rising CO2 as much a result of temperature increase as a cause, and does not necessarily imply that an additional climatic forcing mechanism is needed beyond orbital variations, at least prior to human intervention in climatic cycles. Several positive feedback mechanisms are known, such as decreased CO2 solubility in warm waters, increased evaporation and humidity, and decreased reflectance following ice-cap melting (49, 50), but these are too small. Positive feedbacks are underestimated in climate models

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which contain geophysical feedback (49) but not biogeochemical feedbacks caused by changes in biotic metabolism (50). A likely cause of the discrepancy between predicted and observed temperature increases in the past is the exponential increase of respiration with temperature (51), which was not included in biogeochemical feedbacks analyzed by Lashof (50). Plant and algal respiration rises much more rapidly with temperature than photosynthesis (52, 53), and metabolism of bacteria and fungi also rises sharply (54), causing reduced net productivity of plants and increased decomposition of litter, soil, and sedimentary carbon. Tropical plants, unlike those in temperate zones, respire almost all the carbon they fix by photosynthesis (52), so tropicalization will make the biota less efficient at building biomass. Less carbon would be stored in polar tundra bogs because of increased decomposition (55). Global warming should therefore add CO2 to the atmosphere and make stabilization even more difficult.

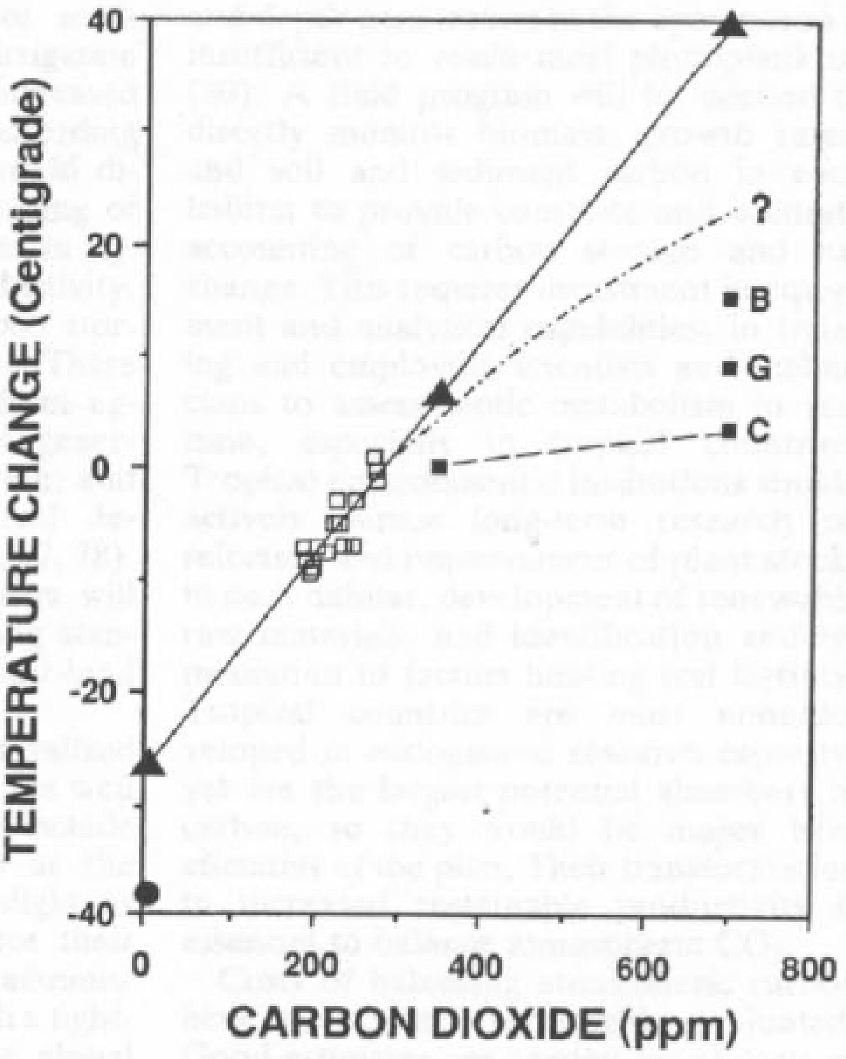

Figure 4. Antarctic ice temperature (centigrade difference from modern temperatures) versus atmospheric carbon dioxide (in parts per million) at 10 000-year intervals over the past 160 000 years (open squares). The straight line is the linear regression to the data. Upward pointing triangles indicate the values predicted from the regression at carbon dioxide concentrations of 0, present levels, and twice present levels. The filled square symbol at 350 ppm, which shows present day mean global temperature CO_2 concentrations, falls around 6 degrees centigrade below the regression line, indicating that global temperatures and current carbon dioxide levels have not yet reached their steady state values. The filled squares at 700 ppm show various predicted temperature increases due to CO_2 doubling. The dashed line indicates predicted 3 degree centigrade increase in global temperature for carbon dioxide doubling, using standard climate models (point C). For the global system to follow this trajectory, sensitivity of temperature to carbon dioxide would have to be 11 times less in the future than it has been over the past 160 000 years. Points marked G and B are based on a recent assessment of geophysical and biogeochemical feedbacks respectively (50), but do not include respiratory feedback mentioned in the text. The curved dot-dash line is a schematic fit to the ice-core data which estimates saturation of carbon dioxide feedback effects. The circular symbol shows the −38 degrees cooling of the Earth without atmosphere greenhouse gases (8). The regression line does not pass through it because without greenhouse gases the entire earth would be frozen, and the equator to pole temperature gradient would be reduced.

CARBON DIOXIDE EXCHANGE ECONOMICS

Many regard CO2 as a cost-free byproduct of civilization, removed for free by nature, although productive tropical forests are being replaced by degraded habitats (23), and temperate forest growth is declining from acid rain, ozone, and other pollutants (56). Discounting adverse effects of atmospheric pollutants to zero if they are sufficiently far in the future forces our descendants to pay the price with compounded

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interest of climate change, environmental degradation, species loss, and reduced sustainability, raising important issues of inter-generational equity (57).

CO2 is a "currency" common to energy, economic, and environmental transactions, whose inputs, outputs, and economic exchange values must be evaluated, requiring estimates of damage costs from reduced environmental productivity and removal costs of carbon dioxide and other pollutants, which we now fail to include in fuel prices. Mechanisms to raise funds for CO2 stabilization which ensure that external social costs of pollution are efficiently allocated include taxes, subsidies, and emissions fees (58-66). The "polluter pays" principle could be applied to all gaseous, liquid, or soils waste products with adverse environmental impacts, such as greenhouse gases, ozone modifiers, acid rain, etc. Only CO2 is discussed, but the same principle applies to all environmentally active byproducts. Technology exists to remove most other gases before, during, or after combustion, but no economic technology exists for CO2, methane, or nitrous oxide removal (67). Some approaches are punitive "carbon taxes" to reduce fossil-fuel consumption (58, 68), "pollution emission fees" set by overall pollution goals and costs (69-71), or "energy-growth taxes" on fossil fuels to pay for sufficient replanting to permanently remove the CO2 released (22, 32).

Fossil-fuel combustion adds new carbon to the atmosphere that has been and would remain buried underground for hundreds of millions of years. Deforestation and biomass burning also add CO2, but this carbon was withdrawn from the atmosphere by photosynthesis only a few years to decades before, and almost all of it would be naturally recycled to the atmosphere by decomposition. Biomass burning adds new CO2 only when the habitat's productivity is simultaneously degraded which is the general case, especially in tropical rainforests on poor soil (72, 73). Therefore, there should be no tax on CO2 emissions from biomass, wood, and renewable fuels, if managed sustainably. The small scale, remote location, and poverty of slash and burn farmers and biomass fuel users makes monitoring and enforcement impossible. Alternatives to forest burning which promote greater biological and economic productivity (74) without need for transient fertilization by ash should be promoted.

The effects of tropical deforestation extend well beyond addition of CO2 from burning and decomposition. Recycling of atmospheric carbon through the biota and soils is the major control of the lifetime of CO2 in the atmosphere: decreased productivity causes added CO2 to remain longer, reach higher levels in the atmosphere, and absorb more heat than would be the case without habitat degradation (22, 24, 25).

The oceans also play an important role in the global carbon cycle, but efforts to increase carbon storage should focus on terrestrial ecosystems rather than marine ones. Exchange of CO2 between atmosphere and oceans (O and I in equation 1) is controlled by winds and waves, factors beyond our control. Ocean warming reduces solubility of CO2, increases dissolution of deep-sea carbonate sediments, and increases thermal stratification, decreasing rates of cold, deep, CO2-rich water mass formation, and decreasing upwelling of nutrients which fuel marine productivity (75). These effects are positive feedbacks amplifying CO2 buildup in the atmosphere. On the other hand, productivity and carbon burial may become more concentrated around upwelling zones, and increasing carbon is buried in nearshore sediments, from erosion of soil organic matter and eutrophication of coastal ecosystems. Ocean fertilization to remove CO2 is unadvisable because most is promptly recycled to the atmosphere, and because it would increase oxygen depletion, causing massive kills of economically useful fish and invertebrates by hydrogen sulfide poisoning. It would be far preferable to sequester carbon in terrestrial soil, where it can act to retain water, soil minerals, and nutrients, further increasing productivity and carbon removal from the atmosphere.

Coral reefs, the most productive and species-rich marine ecosystems, are highly effective at permanently burying carbon as limestone, and must also be protected against ongoing destruction by human activities such as soil and freshwater runoff and excess nutrients from sewage. In 1987-1988 an unprecedented event, linked to unusually warm water temperatures, caused reef building corals worldwide to "bleach" from loss of their symbiotic algae. Bleached corals fail to grow (76). In 1989-1990 bleaching was focused on the North Coast of Jamaica, where temperatures were the highest recorded (76). Further bleaching and reef deterioration could reduce carbon burial and cause severe economic losses from destruction of reef fisheries, tourism, and shoreline protection from hurricanes and rising sea level. Water temperatures in the Caribbean are currently the highest ever at this time of year, and mass bleaching has set in, the earliest ever. In Jamaica, there has been no time to recover from the previous episode. It now seems that rising temperatures are already severely impacting many tropical marine ecosystems.

ALLOCATING CARBON DIOXIDE REMOVAL COSTS

CO2 is transported and mixed through the atmosphere (Fig. 1). Current annual combustion releases, 5.5 x 109 tonnes of carbon, could be accommodated by increasing global biological productivity by only several percent (Fig. 2). Many industrial countries are unable to absorb their own waste carbon by reforestation, and international transfer of funds from fuel burners to tree planters and soil nourishers will need to follow transboundary release and absorption of CO2. Tropical reforestation over some 2 to 8 million km2 (depending on productivity of plant species used, and climatic and soil suitability) could remove the current global buildup of carbon at a cost of around US$300-US$400 per hectare (32), around US$3-US$4 per tonne of carbon removed. Fossil-fuel combustion rates (Marland, pers. comm.) multiplied by unit costs of carbon removal (29-32) suggest per capita removal costs around US$15 or US$20 per person per year for the United States, around US$2 to US$3 per person per year in Brazil or Jamaica (whose combustion releases per capita are closer to the global mean), and less in India, China, and most of Africa and Asia.

Positive financial incentives for seedlings, fertilizer, terracing, and irrigation should be developed to promote increased carbon storage. Funds disbursed according to increases in carbon storage would directly reward reforestation, upgrading of soil organic matter, and increases in agriculture, pasture, and forest productivity. Countries rapidly increasing carbon storage would be primary beneficiaries. There would be many other benefits from agroforestry production, employment generation, soil and watershed protection, and building endogenous research and development capacity (22,29-32,34,77,78). Without them no replanting efforts will increase the productivity and living standards of small farmers on marginal land and be viable on the required scale.

Fossil-fuel mining is highly centralized and production and consumption are well quantified. It should be easy to include carbon removal costs in prices at the source. Prospects of cheating are slight, as few individuals mine and produce their own fossil fuels. Funds could be administered by an international body with a tightly mandated mission to evaluate global carbon flows and disburse funds for replanting and research in proportion to current and potential rates of carbon removal. While those fearing possible loss of sovereignty (expressed as the inalienable right to foul one's own nest), would prefer unilateral or bilateral measures, there is no assurance that uncoordinated approaches would achieve the necessary global balance. International mechanisms seem superior to national efforts, which are more likely to be diverted towards politically motivated expenditures.

The total funds required would have to be set at first by an initial goal of carbon removal and realistic cost assessments. Subsequently, it would be set by actual verified costs. The goal should not merely be to balance current fossil fuel CO2 inputs, but also to reduce the existing accumulated excess (32). As atmospheric CO2 is well mixed, plants cannot distinguish current fuel combustion carbon from that accumulated in the past. The tax rate on fossil fuels should be divided in a manner proportionate to cumulative emissions, assuring that responsibility is equitably distributed among nations in proportion to their total impact (18).

MONITORING AND RESEARCH NEEDS

Verification of carbon removal is essential to adequate management of global CO2. A worldwide monitoring program would be required, combining remote and ground sensing. Satellite multispectral radiometers provide objective measures of vegetation coverage (79), but cannot directly determine carbon in limestone, soils, and sediments, quantity of biomass per unit area, or rates of biomass carbon exchange. These vary markedly according to vegetation, soil, and water types, management practices, and weather conditions, and must be measured directly. Satellite measurements of "chlorophyll" have difficulty in distinguishing phytoplankton from suspended sediment in muddy coastal waters, and depth penetration in the open ocean is insufficient to reach most phytoplankton (80). A field program will be needed to directly monitor biomass, growth rates and soil and sediment carbon in each habitat to provide complete and accurate accounting of carbon storage and exchange. This requires investment in equipment and analytical capabilities, in training and employing scientists and technicians to assess biotic metabolism in real time, especially in tropical countries. Tropical environmental institutions should actively pursue long-term research on selection and improvement of plant stock; in each habitat, development of renewable raw materials, and identification and remediation of factors limiting soil fertility. Tropical countries are most underdeveloped in endogenous research capacity, yet are the largest potential absorbers of carbon, so they would be major beneficiaries of the plan. Their transformation to increased sustainable productivity is essential to balance atmospheric CO2.

Costs of balancing atmospheric carbon have never been thoroughly evaluated. Good estimates are needed for a) costs of planting, fertilizing, and growing biomas; including land, labor, fertilizer, and water costs; b) the fraction of carbon permanently incorporated (the fraction promptly returned to the atmosphere from burning and decomposition should not be counted); c) costs of research on selecting and improving plant species, identifying and remedying factors limiting productivity, and developing new products from renewable raw materials—the potential for substantial increases in biological and economic productivity are great if the problem is tackled in serious and coherent fashion; d) ancillary costs related to sustainability —environmental education, conservation, social, economic and fiscal incentives, land-reform, population control, pollution abatement, etc; and e) the time scale over which excess CO2 should be absorbed— several decades to a century, depending on success at increasing sinks and reducing sources—and the amount of excess which it is desirable to remove.

CARBON RECYCLING COSTS AND ENERGY PRICES

Proposals specifically targeted to stabilize atmospheric CO2 should be distinguished from taxing fossil fuels prohibitively to reduce use, offsetting only new sources of CO2, or taxation of fuels for expenditure; unrelated to environmental alteration caused by fossil fuels. If existing taxes were used to pay for specific costs of fuel burning, there could even be no increase in fuel prices to the consumer because carbon removal costs are a tiny fraction of current per capita fuel taxes, the bulk of consumer fuel prices in most countries. Governments are unlikely to take steps which reduce discretionary revenues, but adding real costs of carbon removal to existing prices would be only very slightly inflationary, even for the poorest users of coal and kerosene. Such consumers could be buffered against any decline in living standards (which would increase deforestation pressures by causing switches to fuel wood and charcoal), by subsidies from increased emissions fees for wealthy emitters, proportional to total past releases. In contrast, tax proposals which do not include carbon recycling would greatly increase energy prices and living costs (58, 68).

Recycling carbon from fossil fuels would not make non-fossil fuel energy sources or nuclear power significantly more competitive. France, which generates 75% of its electricity from nuclear power, has electricity prices higher than those of coal burning European countries, despite government subsidies and a debt by Electricite de France of nearly US$ 36 billion (81). However there are limits to land available for reforestation and to productivity increases, making the proposal an interim measure to bridge the period until truly renewable, economically competitive, energy sources are developed. Prices of photovoltaic cells should be greatly reduced once mass production begins (66, 82), and could provide a long-term balance between energy supply and the environment (83). Investments or start-up subsidies to lower solar energy cost (66) should be encouraged to substitute for future fossil-fuel use, especially in the sunny tropics. Without development of large scale non-fossil fuel energy supplies it may prove impossible to balance CO2 without unacceptable social costs by developing countries.

SOME COST COMPARISONS

"Market instrument" approaches to buying and selling pollution permits have advantages in economic efficiency over flat tax approaches when those who can reduce emissions most cheaply do so (61, 63, 65 69, 70), but selling of surplus unused pollution "rights" to inefficient polluters can leave total pollution unchanged (61, 84). Separate bureaucracies would be needed in each country to set overall emissions, derive damage costs, and oversee marketing of "pollution rights". It is unclear how such a mechanism could be integrated on the scale needed to achieve global CO2 balance.

If total research and development costs to stabilize CO2 equal direct reforestation costs, a decade-long, worldwide effort would cost around 15 to 30 billion dollars per year. These costs are poorly known, but are certainly less than:

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a) other costs of sustainable development, such as protecting cropland topsoil, raising energy efficiency, developing renewable energy, or slowing rates of population growth (77);

b) the costs of no action. Agro-ecosystem productivity losses due to decreased soil moisture in the United States alone are estimated at tens of billions of dollars (85). Up to US$ 6 billion would be needed in the Netherlands (10), and up to US$ 100 billion to protect the US East Coast shoreline alone against a meter of sea level rise (11);

c) cleaning up sulfur, nitrogen, and particulate emissions from fuels (for the US alone, 34 billion dollars in 1988, according to EPA figures). Sulfur cleanup costs around US$ 32 to US$ 74 per tonne of coal (67) (more per tonne of carbon), over an order of magnitude greater than carbon recycling costs,

d) global military expenditures (1.3 trillion dollars per year, so annual carbon dioxide removal costs could be paid by declaring peace for a few days),

e) the global debt (1.3 trillion dollars for developing countries alone. Only one tenth of this would cover most of the total reforestation and research costs).

In economic terms, then, it is far cheaper to recycle carbon than to adapt to climate change and continue our unsustainable path.

A FINAL OPPORTUNITY FOR SUSTAINABLE DEVELOPMENT

Stabilizing CO2 requires that all nations recognize that energy and environment are inextricably linked through exchange of CO2, and that climate change, sustainable development, and lack of tropical endogenous research capacity cannot be solved in isolation (22). Solutions will mandate placing common interests ahead of sectoral ones (86), a new maturity in notions of sovereignty over the environment (57), and rejection of values which place short-term profit over long-term environmental deterioration. An international mechanism is needed to set and evaluate goals, with the means to effect them. The United Nations system would be the logical home of such a body. Pressure toward a global treaty to protect the atmosphere is rapidly mounting, and will be a focus of the 1992 World Conference on Environment and Development in Brazil.

This generation and the next have the final opportunity to reverse the planet's degradation and save the remains of our natural heritage. It takes only a few year to degrade soil fertility, but generations to build it back. The task of restoring soil biomass and fertility is feasible if we dedicate the needed resources over several decades. A treaty to achieve atmospheric stabilization should explicitly link supply and demand of fossil fuels to the major sources and sinks of CO2. Sustainable development worldwide, but focused in the tropics, should be seen as the centerpiece of any serious effort to stabilize atmospheric and climate change. Our descendants will not forgive us if we fail to grow our way out of the crisis.

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