

SINKS FOR ANTHROPOGENIC CARBON

Organic carbon buried in sediments as coal, natural gas, and oil over literally hundreds of millions of years is being consumed as a result of human activities and returned to the atmosphere as carbon dioxide (CO_2) on a time scale of a few centuries. The energy harvested from this transformation of fossil fuels supplies us with electricity, heat, trans-

portation, and industrial power. The clearing of forests for agricultural lands and the harvesting of wood, both of which remove carbon-bearing vegetation, have also added CO_2 to the atmosphere, in amounts equivalent to more than half of the fossil fuel source. The CO_2 added to the atmosphere because of man's activities, and the way it is currently distributed within the land, air, and sea, is depicted in the carbon cycle diagram shown in figure 1.

Because of anthropogenic emissions, atmospheric CO_2 has climbed to levels that are presently more than 30% higher than before the industrial revolution,^{1,2} as seen in figure 2. Indeed, geochemical measurements made on ancient ocean sediments suggest that atmospheric CO_2 levels over the past 20 million years were never as high as they are today.³

The increase in atmospheric CO_2 has drawn a great deal of attention because of the impact it has on the trapping of long wavelength radiation emitted from Earth's surface. More than half of the increase in the direct trapping that has occurred since preindustrial times is attributed to CO_2 , with the rest coming from other gases such as methane, nitrous oxide, and chlorofluorocarbons. The effect of this increased trapping on Earth's climate depends on a number of complex feedbacks. Nevertheless, the strong consensus of the scientific community is that the increased trapping will lead to global warming; it probably accounts for most of the 0.6 ± 0.2 °C warming that occurred during the last century.³ Humankind thus appears to be playing a significant role in altering Earth's climate.

Because CO_2 is nonreactive in the atmosphere, it has a relatively long residence time there. However, its growth rate is presently less than half of what would be expected if all the CO_2 released by fossil-fuel burning and land-use change remained in the atmosphere (figure 3). The growth

We have learned much about the workings of natural sinks like the oceans and terrestrial plants, but are just beginning to understand how their behavior might change as atmospheric CO_2 concentrations rise.

Jorge L. Sarmiento and Nicolas Gruber

rate is lower because the terrestrial biosphere (plants and soils) and the ocean are taking up a significant amount of anthropogenic CO_2 , that is, acting as "sinks." The scientific community has made much progress in establishing the relative role of these two major natural sinks on a global scale, and it appears that the missing carbon is about equally divided between them. However, scientists continue to debate aspects of the spatial distribution and mechanisms of these sinks. The future behavior of the sinks turns out to be highly sensitive to whatever mechanisms we assume. Thus, better understanding of their behaviors is key to predicting, and hopefully mitigating, the future impact of anthropogenic CO_2 . An important starting point for forecasting the future behavior is to understand its past.

Global carbon balance in the recent past

The most recent decade for which we have an estimate of all the carbon sources and sinks³ is the 1980s, during which the average fossil-fuel emissions were estimated at 5.4 ± 0.3 petagrams of carbon per year ($1 \text{ Pg} = 10^{15} \text{ g}$) and the atmospheric growth rate at $3.3 \pm 0.1 \text{ Pg C/yr}$. The difference of $2.1 \pm 0.3 \text{ Pg C/yr}$ must be taken up by the ocean and terrestrial biosphere. New developments using observations of oxygen and carbon isotopes in the atmosphere allow us to partition the sink between these two reservoirs, as described in box 1. The partitioning gives an average net oceanic uptake of $1.9 \pm 0.6 \text{ Pg C/yr}$ and a net land carbon uptake of only $0.2 \pm 0.7 \text{ Pg C/yr}$. However, there is an additional terrestrial source of CO_2 to the atmosphere, mainly due to deforestation in the tropics, estimated to be about 1.7 Pg C/yr . One can infer that the land must be taking up 1.9 Pg C/yr outside the areas affected by deforestation and hence appears to be as large a carbon sink as the oceans, as shown in figure 1. Note, however, that the uncertainty in the estimated terrestrial source is very large, with a reported range of $0.6\text{--}2.5 \text{ Pg C/yr}$. The uncertainty in the land sink, which is estimated by differencing all the other components of the carbon budget, is correspondingly large.

The carbon balance is not static in time. As seen in figure 3, the atmospheric growth rate varies by a large amount from year to year. Most of the interannual variability is correlated with the El Niño southern oscillation climate mode, with higher growth rates generally being associated with El Niño (warm climate) episodes. The cli-

JORGE L. SARMIENTO is a professor in the department of geosciences at Princeton University. NICOLAS GRUBER is an assistant professor in the department of atmospheric sciences and in the Institute of Geophysics and Planetary Physics at the University of California, Los Angeles.

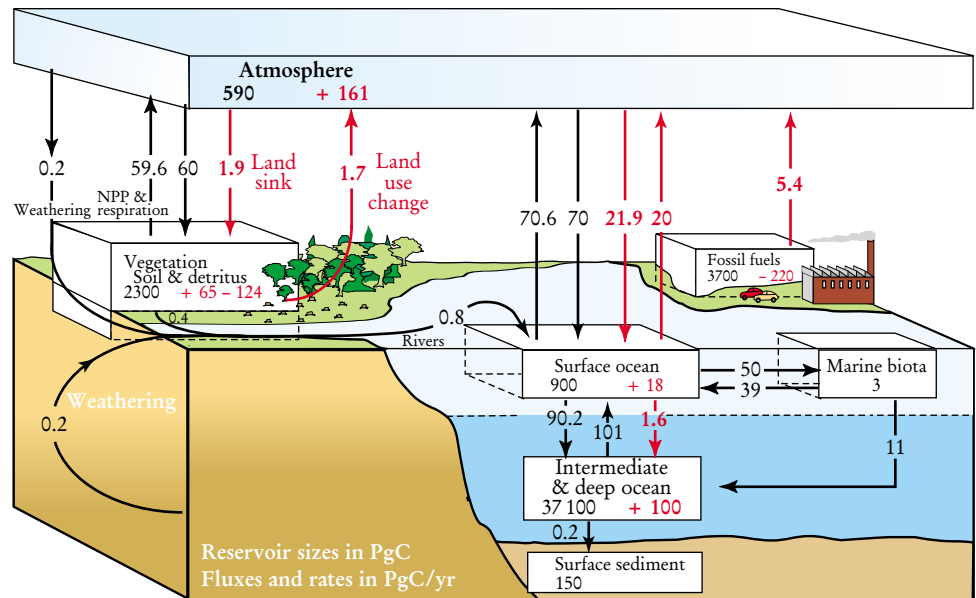


FIGURE 1. GLOBAL CARBON CYCLE. Arrows show the fluxes (in petagrams of carbon per year) between the atmosphere and its two primary sinks, the land and the ocean, averaged over the 1980s. Anthropogenic fluxes are in red; natural fluxes in black. The net flux between reservoirs is balanced for natural processes but not for the anthropogenic fluxes. Within the boxes, black numbers give the preindustrial sizes of the reservoirs and red numbers denote the changes resulting from human activities since preindustrial times. For the land sink, the first red number is an inferred terrestrial land sink whose origin is speculative; the second one is the decrease due to deforestation.¹⁶ Numbers are slight modifications of those published by the Intergovernmental Panel on Climate Change.³ NPP is net primary production.

mate cooling caused by the Mt. Pinatubo eruption in the early 1990s appears to have contributed to reduced atmospheric growth rates. The primary cause of the variability remains controversial, but is probably due mostly to the response of terrestrial vegetation to climate variability, with a smaller contribution due to the oceanic response.⁴

The total capacity of the oceans for taking up anthropogenic CO₂ is a function primarily of the solubility of CO₂ and the chemical buffering capacity of seawater. The chemical buffering stems from the reaction of CO₂ molecules with carbonate ions to produce bicarbonate ions. If a moderately sized pulse of CO₂ were added to the atmosphere today, about 85% of it would dissolve in the ocean, but the process would take more than 1000 years because of the sluggishness of vertical exchange between the surface and interior of the ocean. For example, the oldest ocean water in the world, which is found in the deep North Pacific, has been out of contact with the surface of the ocean for about 1000 years. Estimates of the oceanic concentration of anthropogenic carbon, shown in figure 4, demonstrate that, except in a few locations, carbon from human activities generally has not yet penetrated in significant amounts below a depth of about 1000 m. Surface waters carrying anthropogenic carbon descend into the abyssal ocean primarily in the North Atlantic and Southern Oceans, as part of the ocean's thermohaline circulation, the so-called "conveyor belt." From there, those waters spread, over the next centuries, throughout the entire deep ocean. Currently one can see a modest signal of the anthropogenic carbon in deep waters only in the Atlantic north of the equator.

Model simulations suggest that the Southern Ocean around the Antarctic (south of 35 °S) accounts for nearly half of the net air-sea flux of anthropogenic carbon. Another sixth of the total uptake occurs in the tropics (13 °S to 13 °N). Those are both regions with large surface areas, where upwelling (in the tropics and Southern Ocean) and deep vertical exchange (in the Southern Ocean) bring to the surface older, relatively uncontaminated deep water that has a high capacity for uptake of CO₂. From those regions, a large part of the absorbed CO₂ is transported laterally toward the subtropics, producing a relatively uniform distribution of anthropogenic carbon, as shown in figure 4. Dif-

ferent methods for estimating the uptake of anthropogenic CO₂ agree reasonably well with each other and with observational constraints in most regions except the Southern Ocean, where the relatively small-scale processes that destabilize the water column and lead to vertical overturning and formation of deep water are poorly understood and particularly difficult to model.

Understanding the land sink

The land sink for carbon is the subject of considerable controversy at present, concerning not only its magnitude but also its cause. For many years, researchers have believed that the dominant sink mechanism is the fertilizing effects of increased CO₂ concentrations in the atmosphere and the addition to soils of fixed nitrogen from fossil-fuel burning and agricultural fertilizers. This fertilization mechanism has been incorporated into most existing models of the terrestrial biosphere that are used to predict future concentrations of atmospheric CO₂. However, a recent analysis of long-term observations of the change in biomass and growth rates, made by the US Forest Service, suggests that such fertilization effects are much too small to explain more than a small fraction of the observed sink in the US.⁵ In addition, long-term experiments in which small forest patches and other land ecosystems have been exposed to elevated CO₂ levels for extended periods show a rapid decrease of the fertilization effect after an initial enhancement.⁶

What other mechanisms might then explain the existence of a large land sink? One of the few land regions of the world where the observational coverage and model analysis are sufficient for putting together a carbon budget is the coterminous US. A recent estimate of carbon uptake in this region⁷ shows that the largest sink is due to

regrowth in abandoned farmland and areas that had previously been logged.⁵ As shown in figure 5, a large fraction of the forests in the eastern US were cut down before 1920. As the use of agricultural land shifted westward over time, land in the east that had been used for agriculture was abandoned and started to recover its forests. Moreover, as the logging pressure has decreased in the east over time, there has been a large increase in secondary vegetation.

After regrowth in farmlands, the second most important sink mechanism identified by the study of carbon uptake in the US is the encroachment of woody growth into areas where fires have been suppressed, especially in the southwest, as seen in figure 5. The third largest mechanism is the growth of food and wood that is exported from the US before being consumed. But that is not a true sink because the CO₂ is returned to the atmosphere elsewhere in the world. Other sinks include storage of carbon in wood products and cropland soils, as well as in freshwater reservoirs, alluvium, and colluvium. Some carbon is taken up by weathering, such as the reaction of rock with CO₂ and water to form dissolved bicarbonate and calcium, but it is exported from the US by rivers.

What do we know about the land sink in the rest of the world? For the past decade, “inverse modeling”⁸ has been one of the primary tools to improve our understanding of the large-scale behavior of both the terrestrial and the oceanic sinks. Inverse models use information about how CO₂ is currently distributed in the atmosphere and knowledge of how the atmosphere transports CO₂ to infer the spatial distribution of carbon sources and sinks at Earth’s surface. From such models, as discussed in box 2, we have learned that more than half of the sink for anthropogenic carbon must be in the Northern Hemisphere. Furthermore, a majority of the Northern Hemisphere sink appears to be in the terrestrial biosphere.

While many attempts have been made to determine the location of this Northern Hemisphere land sink more precisely, the results show considerable variation among the various inversion models. Unfortunately, in situ verification of those estimates has proven to be extremely challenging. Despite the development of innovative new methods to measure in situ fluxes (as seen on the cover and as described at <http://www.as.harvard.edu/chemistry/hf>)

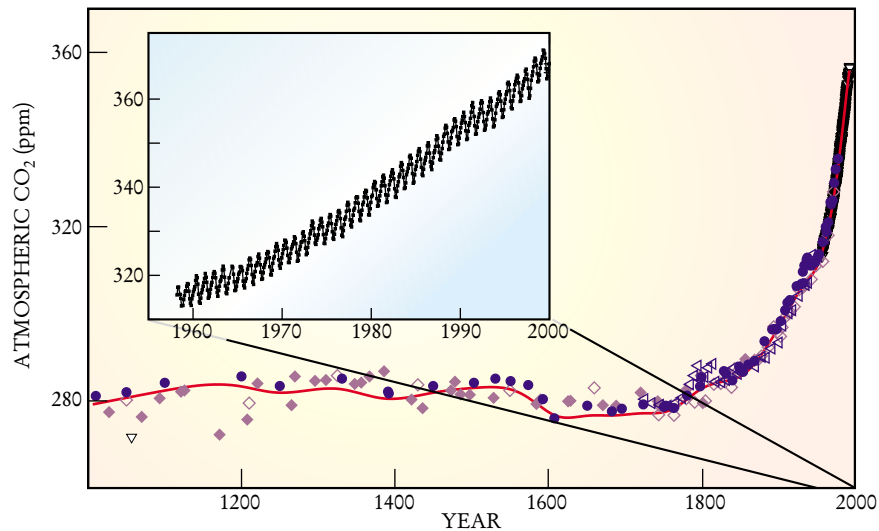


FIGURE 2. ATMOSPHERIC CARBON DIOXIDE LEVELS have increased by more than 30% since the industrial revolution started in the mid-18th century. Before then, atmospheric CO₂ had been at about 280 parts per million (ppm) for several millennia. Data before 1958 stem from measurements of air bubbles trapped in ice cores recovered from several sites in Antarctica.¹ The CO₂ data displayed in the inset were measured on air samples taken by Charles D. Keeling and collaborators at Mauna Loa, Hawaii.² The seasonal variations evident there reflect the seasonal breathing of the terrestrial biosphere in the Northern Hemisphere: CO₂ is removed by strong growth in spring and summer and returned by respiration and remineralization in the fall and winter.

and detailed distributions of atmospheric CO₂ from aircraft, it continues to be difficult to close the gap between lower in situ estimates and the large sinks inferred from the models. The estimate of the land sink in the coterminous US discussed previously gives a total carbon sink

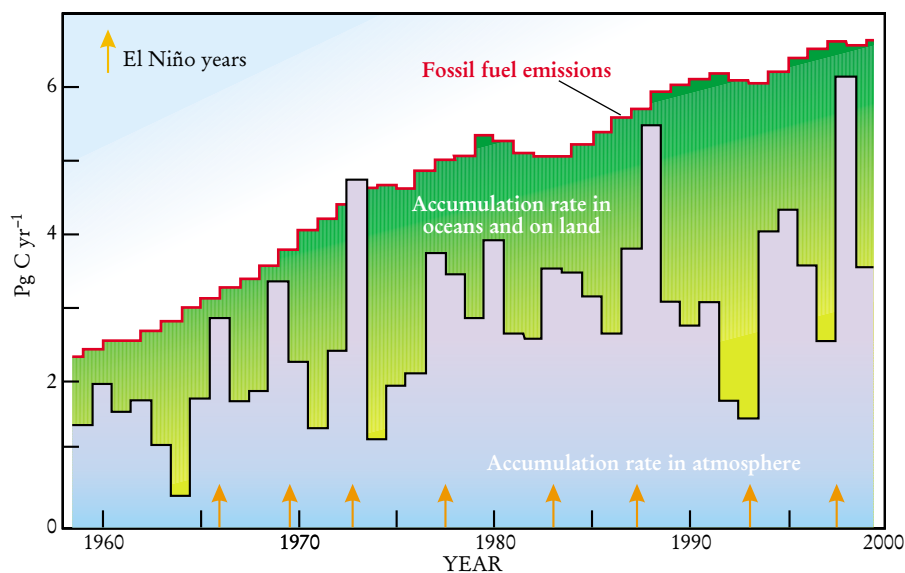


FIGURE 3. GROWTH RATE OF CARBON RESERVOIRS. Since 1958, the yearly accumulation rate of atmospheric carbon dioxide has grown, on average, from about 1 Pg C/yr to about 3.0 Pg C/yr (light blue area). Over the same period, fossil-fuel emissions¹⁷ (red line) have grown from about 2.5 Pg C/yr to about 6.5 Pg C/yr. Net uptake by the ocean or terrestrial biosphere (green region) must account for the difference. Note the large interannual variation in the annual atmospheric CO₂ growth rate.² Higher growth rates generally appear to be associated with El Niño episodes (orange arrows), the exception being the period following the eruption of Mt. Pinatubo in the early 1990s.

Box 1. Partitioning Carbon between Land and Ocean Sinks

To establish the redistribution of the anthropogenic carbon dioxide within the global carbon cycle, one ideally would measure the changes in the carbon inventory of all relevant reservoirs—atmosphere, ocean, and terrestrial biosphere—and then compare these changes with the total anthropogenic emissions. Unfortunately, the atmosphere is the only reservoir that is readily amenable to such an approach: It is relatively well mixed so that observations at a few key locations give a very accurate measure of its changes over time, as seen in figure 2. By contrast, mixing in the ocean is very slow, and the invasion of anthropogenic CO_2 there is masked by a substantial amount of natural background variability in the ocean's inorganic carbon system. Furthermore, very accurate measurements of dissolved inorganic carbon in the ocean have become available only over the past two decades, and are still insufficient to address changes over time. Measuring the carbon inventory changes in the terrestrial biosphere is even more difficult, given its inherent large spatial and temporal inhomogeneity. Therefore, up to now, researchers have had to rely primarily on indirect methods to determine the partitioning of anthropogenic CO_2 between the ocean and terrestrial biosphere.

Until the early 1990s, ocean models were the primary tool for investigating how the carbon was partitioned. The many indirect approaches that have been developed since then have led to a substantial improvement in the constraints available. Among the most powerful of these is the atmospheric oxygen method developed by Ralph Keeling of the Scripps Institution of Oceanography.¹³ Oxygen and CO_2 are exchanged in relatively fixed stoichiometric ratios during the burning of fossil fuels as well as during photosynthesis and respiration by plants, animals, and bacteria. By contrast, the exchange of CO_2 between the ocean and the atmosphere is independent of the exchange of oxygen between the two fluids. Therefore, only uptake of CO_2 by the terrestrial biosphere will leave an imprint on atmospheric oxygen. By measuring the changes in atmospheric oxygen and knowing the fossil-fuel emissions and the exact values of the stoichiometric ratios, one can separate the ocean uptake from that of the terrestrial biosphere.

Although the basic principle of the oxygen method is very elegant, it could not be implemented until the development of an instrument capable of measuring the resulting tiny changes in atmospheric oxygen. Ralph Keeling, while working as a graduate student at Harvard University, came up with an interferometric

technique that gave sufficient precision. More recently, the development of other methods based on mass spectrometry or the paramagnetic properties of oxygen has substantially decreased the complexities involved in measuring the subtle changes in atmospheric oxygen. The oxygen-based analysis of the carbon budget has been adopted by the Intergovernmental Panel on Climate Change (IPCC) as the primary means to determine the redistribution of anthropogenic CO_2 . Unfortunately, the method may have somewhat larger uncertainties than previously thought because it assumes no net exchange of oxygen between the ocean and atmosphere. By contrast, recent modeling and data-based studies are finding that such air-sea oxygen fluxes are fairly sensitive to temperature changes.

A second important method for determining the partitioning of anthropogenic CO_2 is based on measurements of the ratio of two isotopes, carbon-13 to carbon-12, in the atmosphere and ocean. Fossil-fuel CO_2 is slightly depleted in ^{13}C relative to ^{12}C , leading to a long-term decrease of the $^{13}\text{C}/^{12}\text{C}$ isotopic ratio of atmospheric CO_2 . As anthropogenic CO_2 is redistributed within the global carbon cycle, it brings with it this isotopic "color," which permits us to distinguish anthropogenic CO_2 from the natural CO_2 . Several variations of this basic concept have been developed and successfully applied, but they are currently limited by the scarcity of data, the exquisite precision and calibration required of the $^{13}\text{C}/^{12}\text{C}$ measurements, and the limited quantitative knowledge of the fractionation of ^{13}C relative to ^{12}C by land plants.

Despite the uncertainties associated with the different indirect methods for detecting the magnitude of the terrestrial and oceanic carbon sinks, it is encouraging to note that almost all of these methods have converged toward the values adopted by IPCC.³ We believe that the uncertainties will further decrease in the future because of the ongoing development of improved methods for estimating fluxes and inventories over land, and because a recently completed large-scale CO_2 survey of the ocean has given scientists, for the first time, an oceanwide high-quality data set of the oceanic CO_2 distribution that can serve as the basis for direct documentation of the cumulative increase in anthropogenic CO_2 in the ocean. Given enough time, we will be able to account for anthropogenic CO_2 in both the atmosphere and the ocean directly, and hence reduce the need to rely on indirect methods and likely reduce the uncertainties associated with the anthropogenic CO_2 budget.

that is on the low side but within the uncertainty of what is implied by atmospheric inversions. Although the US data suggest that the land sink there is driven primarily by land-use history and not fertilization by atmospheric CO_2 or atmospheric nitrogen deposition, it is not clear if the same findings hold true for other land regions. If they do, however, they have major implications about the future land sink: The global CO_2 uptake capacity from changes in land-use such as forest regrowth is much more modest than that predicted for fertilization.⁹

Predicting the future

The usual approach for evaluating the future trajectory of atmospheric CO_2 is to predict potential concentrations under each of several possible emissions scenarios. The emissions scenarios are beset with uncertainties: How will population changes, economic growth, technology developments, and so forth affect the amount of CO_2 emitted? And how likely is it that nations will agree to curb those emissions? Models for determining the resulting atmospheric

concentrations are further beset by uncertainties about the land and ocean sinks.

A common starting point for climate predictions is a scenario for anthropogenic emissions of CO_2 and other greenhouse gases known as IS92a; it was developed by the Intergovernmental Panel on Climate Change (IPCC) to represent "business-as-usual," with no intentional efforts to mitigate the greenhouse gas. This scenario estimates total fossil-fuel emissions between 2000 and 2100 of 1450 Pg C—a substantial fraction of the estimated remaining resource base of 3500 Pg C.¹⁰

To estimate how much of this CO_2 stays in the atmosphere, one must use models of the global carbon cycle. Until about the mid-1990s, most such models assumed that the climate remains stationary and that the land sink is primarily driven by CO_2 fertilization. Many such models project that about half of the CO_2 emissions will have accumulated in the atmosphere by the year 2100, and will lead to atmospheric CO_2 concentrations of around 700 parts per million (ppm). How the rest of the carbon is

partitioned between land and ocean varies widely with the model applied.³ In one particular simulation by the British Met Office's Hadley Centre,¹¹ 60% of the remaining CO₂, or 450 Pg C, ends up on land and the remaining 300 Pg C in the ocean.

Such predictions can change dramatically if one considers feedbacks due to global warming. In another run of their climate model, Hadley Centre researchers calculated that an increase of atmospheric CO₂ concentrations to 713 ppm by 2100 would cause global temperatures to rise by 4.0 °C, (5.5 °C over land) with an associated intensification of the hydrological cycle. In that simulation, the climate change is allowed to influence the terrestrial and oceanic carbon sinks but not the atmospheric concentrations, which remain fixed. As the climate warms, the land no longer absorbs carbon, but emits it; in other words, the land sink turns into a source, adding 60 Pg C to the atmosphere by 2100. At the same time, the oceanic sink becomes less effective, soaking up 250 Pg C, rather than 300 Pg C. The changed nature of the land sink in this model results first from the disappearance of the Amazonian rainforest due to increased dryness of soils and second from an increased rate of bacterial breakdown of organic carbon in soils due to increased soil temperatures. The oceans lose some solubility due to higher water temperatures, slowed vertical exchange, and changes in the way that biological processes redistribute carbon within the ocean. The com-

pared terrestrial and oceanic carbon sinks predicted by the Hadley model for 2100 are thus 190 Pg C rather than 750 Pg C, and this simulation is out of balance with the IS92a emissions by about 560 Pg C.

In a third simulation, Hadley Centre researchers put the excess 560 Pg C back into the atmosphere using a new fully coupled simulation of the carbon cycle and climate. Concentrations of atmospheric CO₂ climb to 980 ppm instead of 713 ppm, and the surface air temperature warming is 5.5 °C (8.0 °C on land). The greater warming induces the land to release even more carbon, but that release is counterbalanced by an increased oceanic absorption caused by the faster growth rate of atmospheric CO₂, as illustrated in the top panel of figure 6. All the additional CO₂ remains in the atmosphere.

The results are as uncertain as they are disconcerting. The bottom panel of Figure 6 shows the results of another simulation, done by the Institut Pierre Simon Laplace (IPSL), in France, which also predicts the impact of changing climate on the atmospheric carbon concentrations.¹² The IPSL model uses a newer emissions scenario, similar to the IS92a. The model's oceanic uptake is almost two times more effective than that of the Hadley model ocean, with most of the difference being in the difficult-to-simulate Southern Ocean. More important, however, the land uptake in the IPSL model is less than half as sensitive to temperature as the Hadley model, and does not

Box 2. Global Carbon Balance Predicted by Atmospheric Inverse Models

The spatial and temporal distribution of carbon dioxide sources and sinks produces small gradients in the observed distribution of its atmospheric concentration. Much of what we currently know about the spatiotemporal pattern of fluxes of CO₂ between the atmosphere and Earth's surface, in particular for land regions, comes from analysis of the observed distributions. In the inversion method, the land and ocean surfaces are first divided into a modest number of regions. Next, atmospheric transport models are used to estimate the concentration footprint that would result if a given region emitted a single unit flux of CO₂. The transport models are tested using tracers with known source-sink distributions. Various regression methods are then used to determine the weighted sum of footprints that best reproduces the observations. The weights represent the flux contributions from each region.

By far the largest signal in the annual mean atmospheric CO₂ distribution is the north-south gradient, which comes about because almost 90% of the global fossil-fuel emissions occur north of the tropics. The measured concentration gradient is about 3 parts per million (ppm) between the two poles. That's substantially smaller than the difference of about 5 ppm one would expect if the carbon sinks were evenly distributed around the world. This discrepancy implies the existence of strong sinks for atmospheric CO₂ in the Northern Hemisphere. Two contrary interpretations have been put forward to explain the nature of these Northern Hemisphere sinks.

One interpretation, put forward in 1989 by Charles D. Keeling of the Scripps Institution of Oceanography, working with Martin Heimann and colleagues,¹⁴ is that this apparent sink is not driven by anthropogenic processes, but to a large extent reflects part of the preindustrial (natural) carbon cycle in the ocean. They postulated that an amount of the order of 1 Pg C/yr of CO₂ is taken up in the northern North Atlantic and transported toward the Southern Ocean as part of a large-scale ocean circulation. As the waters upwell in the Southern Ocean, they tend to give this CO₂ back to the atmosphere. To force a return

transport pathway back to the Northern Hemisphere, the CO₂ must have built up to higher levels in the atmosphere in the Southern Hemisphere than the Northern Hemisphere in preindustrial times. This hypothesis seemed to be confirmed by an extrapolation of the interhemispheric CO₂ gradient back to a time when fossil-fuel emissions were zero.

Around the same time that Keeling and his colleagues made their proposal, an independent explanation for the reduced gradient was proposed by Pieter Tans of the National Oceanic and Atmospheric Administration in Boulder, Colorado, Inez Fung, now at the University of California, Berkeley, and Taro Takahashi of Columbia University's Lamont Doherty Earth Observatory.¹⁵ Using observations of the difference in the partial pressure of CO₂ between the atmosphere and the surface ocean in the North Atlantic and in a few other oceanic regions as additional constraints in their atmospheric inversions, they concluded that the apparent Northern Hemispheric sink cannot be attributed to the ocean and must be almost exclusively driven by the terrestrial biosphere.

These two strongly diverging views regarding the relative role of the oceans and terrestrial biosphere in the global carbon cycle dominated most of the carbon-cycle research discussions during the 1990s. Recently, a combined analysis of new oceanic and atmospheric observations has lent support to the view that this sink is primarily driven by the terrestrial biosphere, with a smaller contribution by the ocean. So far, there is little evidence for a strong interhemispheric transport of CO₂ by the oceans.

Atmospheric inversion studies have raised additional puzzles, which remain to be solved. One puzzle is posed by evidence indicating that the Southern Ocean is relatively neutral with respect to the atmospheric carbon budget, even though model simulations suggest it is a strong sink. As another puzzle, tropical lands also appear to be neutral, despite the large deforestation occurring there. Hopefully, extended inversion models now under development, when combined with improved observations, will provide insight into these puzzles.

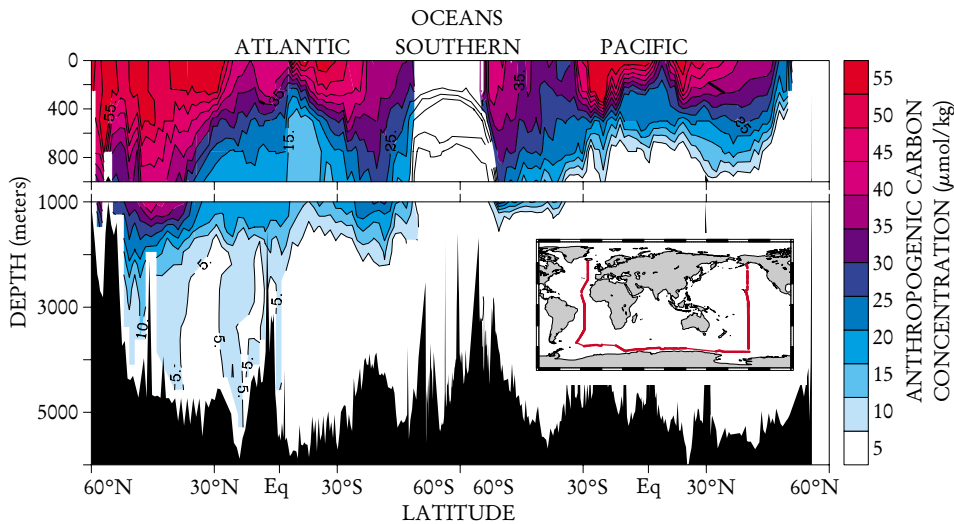


FIGURE 4. ANTHROPOGENIC CARBON CONCENTRATIONS IN THE OCEAN along the track shown as a red line in the inset.¹⁸ The black area represents the depth of the ocean floor. The anthropogenic carbon dioxide concentrations are separated from the natural background by using a recently developed analysis¹⁸ applied to high-precision measurements of dissolved inorganic carbon. Uncertainties in this separation technique are so large south of 60° S that they are shown there as contour lines only. Anthropogenic carbon has penetrated significantly below about 2000 meters of the water column only in the North Atlantic, where surface waters sink directly into the abyss.

allow the distribution of terrestrial vegetation to change. The IPSL model with global warming thus predicts an atmospheric CO₂ level in 2100 that only reaches 780 ppm, as contrasted with 980 ppm for the Hadley model, as shown in the lower panel of figure 6.

We scientists cannot hope to narrow the range between such simulations until we have a better understanding of the fundamental mechanisms that control the carbon sinks. The uncertainties that must be addressed include the magnitude of CO₂ uptake in the Southern

than estimated with models that did not include carbon–climate feedbacks and that did include fertilization as the main mechanism for the terrestrial carbon sink.

Some researchers have proposed enhancing the natural carbon sinks by, for example, reforestation, fertilizing with missing nutrients such as iron to stimulate the oceanic biological pump, and injecting CO₂ directly into the deep ocean. But the projected business-as-usual emissions of order 1450 Pg C over this century are far too large for the first two measures to alter significantly the final fate of CO₂. Deep ocean injection might reduce the future peak value of CO₂ in the atmosphere, but would not affect the final atmosphere–ocean equilibration. Moreover, it would require extremely large injections, with unknown technological challenges and environmental conse-

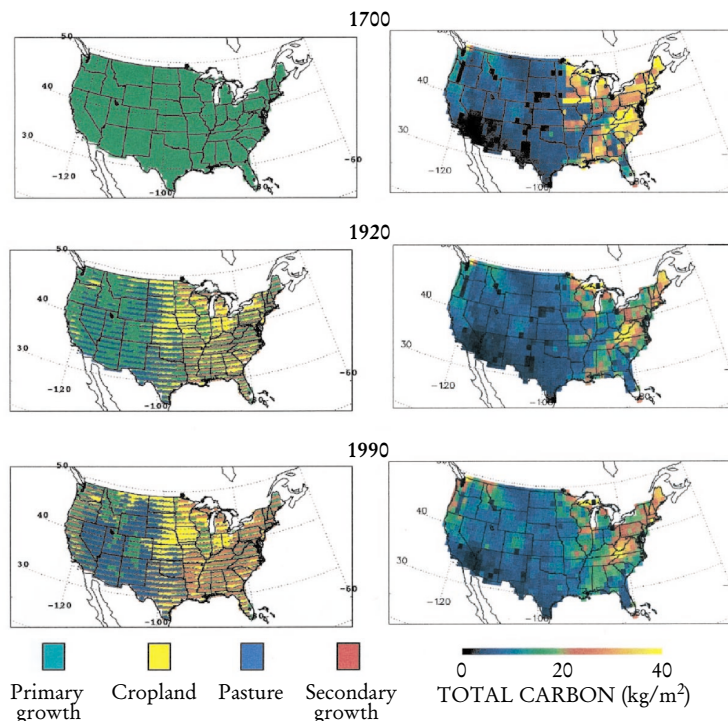


FIGURE 5. CHANGES IN LAND USE IN THE US and their impact on carbon stocks.⁹ As the eastern US was settled in the 18th and 19th centuries, primary vegetation (green) was converted to crops (yellow) and pastures (blue), as seen in the left panels. The impact of old growth logging is symbolized by a direct conversion from primary to secondary vegetation (orange). As the primary areas for cropland and pasture migrated west, some eastern and southern lands became abandoned and started to regrow secondary vegetation, a process that was nearly complete by the late 20th century. This sequence of land use changes had decimated the high carbon stocks contained in the eastern and southern forests by 1920, but by 1990, the stocks were slowly bouncing back (right panels). Carbon stocks have also increased in the southwestern US, thanks to fire suppression and other land management practices. (Adapted from ref. 9.)

Ocean and the worldwide impact of fertilization and land-use changes.

No magic bullets

Although we don't yet fully understand the global carbon cycle, it's safe to say there are no magic bullets in the carbon sinks to rescue the world from high atmospheric CO₂ levels any time in the next few centuries. Quite to the contrary, most of the feedbacks between the global carbon cycle and global warming seem to be positive—that is, global warming reduces the sink strengths. Furthermore, the land carbon sink, if it is due primarily to land-use changes, will likely saturate much earlier than if it were due largely to fertilization. Thus, the emission reduction and sequestration measures required to stabilize future atmospheric CO₂ at levels that will minimize impacts are likely to be more stringent

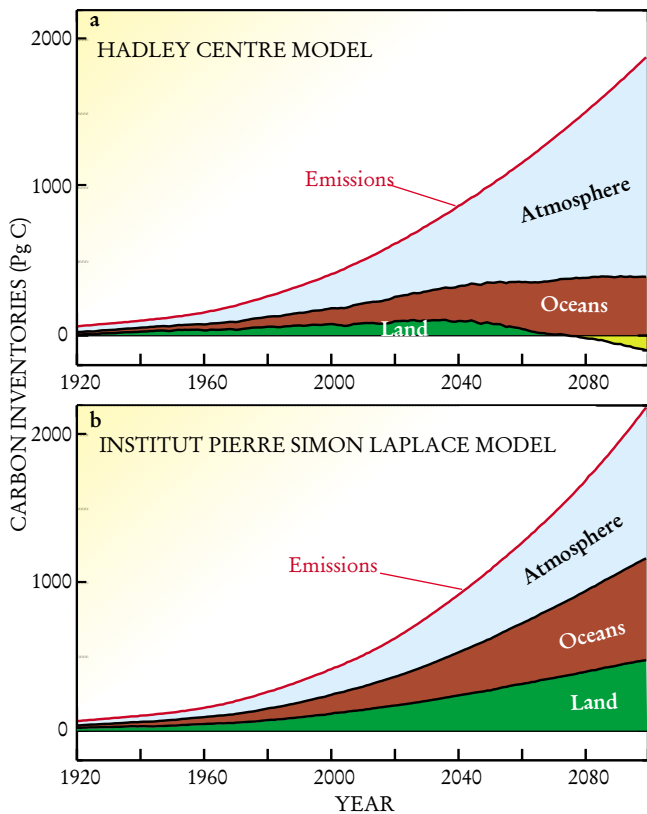


FIGURE 6. FUTURE DISTRIBUTION OF CARBON from fossil-fuel emissions, as estimated by (a) the Hadley Centre model¹¹ and (b) the Institut Pierre Simon Laplace¹² model. The two models differ strongly in their sensitivity to global warming. The primary difference is the land sink, which is far weaker in the Hadley model and actually becomes a source of carbon (yellow-green area) by the century's end.

quences. Geological sequestration is also being explored. Currently, the only method that can be guaranteed to mitigate the expected increases in atmospheric CO₂ is reduced fossil-energy utilization.

The past two decades have seen an improvement in our understanding of the global carbon cycle. We now know the history of atmospheric CO₂ for many hundreds of thousands of years. We have a good grasp of the partitioning of the present carbon sink between land and ocean, and strong constraints on the latitudinal distribution of those sinks. However, there is much need for improvement. On land, new findings call into question the fundamental mechanisms to which the historic terrestrial carbon sink had been ascribed. If the sink is primarily due to land-use changes, it will likely saturate much earlier than if due to CO₂ fertilization.

Regarding the oceans, we understand their chemistry and most of the fundamental mechanisms driving the ocean circulation and can develop sophisticated models of them. However, we have to settle for only a simplified representation of such important related processes as convective overturning and the formation and melting of sea ice, although progress is being made in these areas. We also face limitations in computer capabilities. Consequently, simulations of both the present uptake and response of the ocean to future warming using different models disagree substantially. The problem is particularly acute in the Southern Ocean around Antarctica, which we believe may account for 40–50% of present uptake of anthropogenic CO₂ and will continue to dominate the uptake in the future. In addition, we have only begun to understand how the cycling of carbon by organisms in the ocean will respond to climate and chemical changes.

The international scientific community is well aware of the problems we have identified and has developed long-term observational and modeling strategies for tackling

them. Those strategies include proposals for improved observational capabilities on land and in the ocean, with a particular focus on monitoring the changes that the carbon system will undergo in response to warming. Improved models of the coupled carbon–climate system are being developed at a number of locations around the world. Considerable additional progress can be expected over the next decade.

References

1. J. M. Barnola, *Tellus* **51B**, 151 (1999).
2. C. D. Keeling, T. P. Whorf, in *Trends: A Compendium of Data on Global Change*, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tennessee (2000). See <http://cdiac.esd.ornl.gov/ndps/ndp001.html>.
3. J. T. Houghton et al., eds., *Climate Change 2001: The Scientific Basis*, Cambridge U. Press, New York (2001). See <http://www.ipcc.ch>.
4. C. Le Quéré, J. Orr, P. Monfray, O. Aumont, *Global Biogeochem. Cycles* **14**, 1247 (2000).
5. J. P. Caspersen et al., *Science* **290**, 1148 (2000).
6. W. H. Schlesinger, J. Lichter, *Nature* **411**, 466 (2001).
7. S. W. Pacala et al., *Science* **292**, 2316 (2001).
8. K. R. Gurney et al., *Nature* **415**, 626 (2002).
9. G. C. Hurtt et al., *Proc. Natl. Acad. Sci. USA* **99**, 1389 (2002).
10. N. Nakicenovic et al. in *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change—Scientific-Technical Analysis*, R. T. Watson, M. C. Zinyowera, R. H. Moss, D. J. Dokken, eds., Cambridge U. Press, New York (1996), p. 75. See <http://www.ipcc.ch/pub/reports.htm>.
11. P. M. Cox, R. A. Betts, C. D. Jones, S. A. Spall, I. J. Totterdell, *Nature* **408**, 184 (2000).
12. P. Friedlingstein, J.-L. Dufresne, P. M. Cox, P. Rayner, *Tellus* (in press).
13. R. F. Keeling, S. R. Shertz, *Nature* **358**, 723 (1992).
14. C. D. Keeling, S. C. Piper, M. Heimann, in *Aspects of Climate Variability in the Pacific and the Western Americas: AGU Monograph 55*, D. H. Peterson, ed., American Geophysical Union, Washington DC (1989), p. 305.
15. P. P. Tans, I. Y. Fung, T. Takahashi, *Science* **247**, 1431 (1990).
16. R. A. Houghton, *Tellus* **51B**, 298 (1999).
17. G. Marland, T. A. Boden, R. J. Andres, in *Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center*, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tennessee, (2000). See <http://cdiac.esd.ornl.gov/authors/marland.html>.
18. N. Gruber, J. L. Sarmiento, in *The Sea*, A. R. Robinson, J. J. McCarthy, B. J. Rothschild, eds., Wiley, New York (2002), p. 337. ■