CORRECTED 29 AUGUST 2003; SEE LAST PAGE

overcome the unfavorable reaction to form a microtubule, but soon after formation, the microtubule is liberated. It will be of considerable interest to determine the molecular composition of the nucleating sites in *Arabidopsis* and the mechanism of microtubule release.

The new observations of microtubule behavior in plant cells, which lack a conventional centrosome, are remarkably similar to previous observations of animal cells treated to remove the centrosome. These cell fragments, or cytoplasts, contain fewer (and more disorganized) microtubules than the parental cells from which they were derived. In cytoplasts prepared from fibroblasts, microtubules with two free ends are observed, and these microtubules treadmill (*10*). Both in the plant cortex and the cytoplast, the apparent motion of the microtubule results from gain and loss of subunits at opposite ends; the lattice of the microtubule is stationary, presumably because of linkage to other elements of the cytoskeleton (see the figure, B). Interestingly, microtubule behavior in cytoplasts is cell type specific—microtubules in cytoplasts derived from epithelial cells have a static minus end and a plus end that shows dynamic instability (*10*). Minus-end capping complexes are likely to regulate microtubule behavior in these cells (see the figure, B).

In contrast to the tethered microtubules observed in the plant cortex, animal cells use motor-driven microtubule transport to establish and maintain noncentrosomal microtubule arrays in diverse cell types (see the figure, B) and to rearrange the microtubule array during cell locomotion (*11, 12*). This behavior is particularly striking in nerve axons, where microtubules are transported long distances by rapid but highly infrequent episodes of motility (*11*). In this case, the behavior is more like the proverbial hare, with bursts of activity followed by stasis or even reversal. The absence of cytoplasmic dynein from the *Arabidopsis* genome may partially explain the lack of microtubule transport, as well as the inability of microtubules in higher plant cells to organize their minus ends into tightly focused arrays.

Although the plus end of the microtubule has been the focus of much study, it is clear that a complete understanding of microtubule behavior will require an appreciation of what happens at the minus end as well. It will be particularly important to determine the mechanism by which microtubules are nucleated in vivo, and to learn which aspects of this process are conserved in diverse cells. A better understanding of microtubule nucleation may also shed light on the mechanism of release and on how cells regulate its frequency. For example, recent observations of motile fibroblasts have shown that microtubule release from the centrosome is more frequent than previously estimated and that this release contributes to cell motility (*13*). Clearly, much remains to be learned about how plant and animal cells generate microtubule arrays with distinct dynamic properties by regulating microtubule nucleation, release, and dynamic turnover.

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CLIMATE CHANGE

A Guide to CO_2 Sequestration

Klaus S. Lackner

Climate change concerns may soon force drastic reductions in CO_2 emissions. In response to this challenge, it may prove necessary to render fossil fuels environmentally acceptable by capturing and sequestering CO_2 until other inexpensive, clean, and plentiful technologies are available.

Today's fossil fuel resources exceed 5000 gigatons of carbon (GtC) (*1*), compared with world consumption of 6 GtC/year, assuring ample transition time. However, by 2050, the goal of stabilizing the atmospheric CO_2 concentration while maintaining healthy economic growth may require "carbon-neutral" energy in excess of today's total energy consumption (*2*). Lowering world CO_2 emissions to 2 GtC/year would shrink the per capita emission allowance of a projected world population of 10 billion people to 3% of today's per capita emission in the United States.

If sequestration is to achieve this goal, it must operate on a multiterawatt scale while sequestering almost all produced CO_2. It must also be safe, environmentally acceptable, and stable. For small stored quantities, storage time requirements can be minimal (*3*). But as storage space fills up, lifetime constraints due to aggregate leakage emissions would tighten, until storage times for the entire carbon stock would reach tens of thousands of years. If carbon emissions are reduced mainly through sequestration, then total carbon storage in the 21st century will likely exceed 600 GtC. Because leaking just 2 GtC/year could force future generations into carbon restriction or recapture programs, even initial storage times should be measured in centuries.

Storage time and capacity constraints render many sequestration methods—such as biomass sequestration and CO_2 utilization—irrelevant or marginal for balancing the carbon budget of the 21st century. Even the ocean's capacity for absorbing carbonic acid is limited relative to fossil carbon resources (*4*). Moreover, with natural ocean turnover times of centuries, storage times are comparatively short. Generally, sequestration in environmentally active carbon pools (such as the oceans) seems ill advised because it may trade one environmental problem for another.

Underground injection is probably the easiest route to sequestration. It is a proven technology suitable for large-scale sequestration (*5*). Injecting CO_2 into reservoirs in which it displaces and mobilizes oil or gas could create economic gains that partly offset sequestration costs. In Texas, this approach already consumes ~20 million tons/year of CO_2 at a price of \$10 to \$15 per ton of CO_2. However, this is not sequestration, because most of the CO_2 is extracted from underground wells.

Oil and gas sites have limited capacity (see the figure). Once they fill up, saline aquifers may be used, as demonstrated under the North Sea where the Norwegian energy company Statoil has sequestered CO_2 removed from natural gas (*6, 7*). Ubiquitous saline reservoirs imply huge storage capacities. However, because of uncertainties in storage lifetimes, seismic instability, and potential migration of buoyant CO_2, long-term integrity must be established for each site.

A more expensive but safer and more permanent method of CO_2 disposal is the neutralization of carbonic acid to form carbonates or bicarbonates (*4*). Neutralization-based sequestration accelerates natural weathering processes that are exothermic and thermodynamically favored, and results in stable products that are common in nature. Mineral deposits larger than fossil resources ensure essentially unlimited supplies of base ions (mainly magnesium and calcium, but also sodium and potassium).

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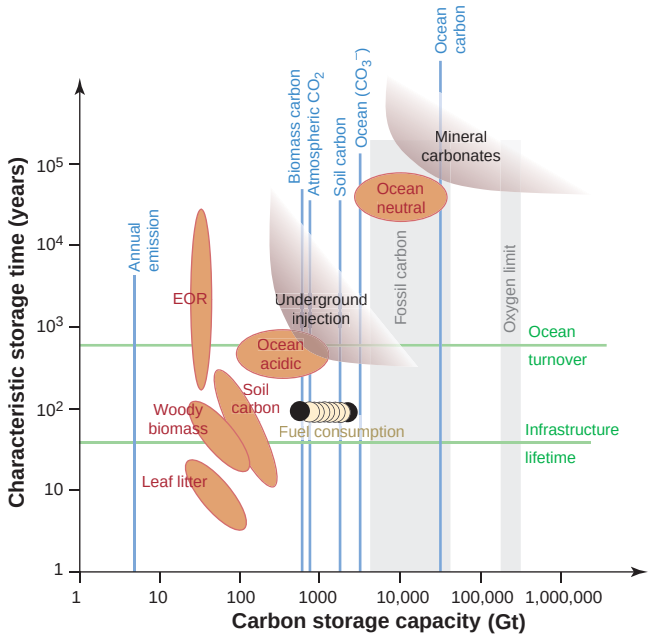
The least expensive way to neutralize CO_2 may be its injection into alkaline mineral strata. CO_2 would gradually dissolve into the pore water. Because it is acidic, it would leach mineral base from the rock, resulting in carbonates or bicarbonates that eliminate all concerns over long-term leakage. Neutralizing carbonic acid with carbonates as a base would create aqueous bicarbonate solutions. Unless injected underground, they would likely find their way into the ocean, which fortunately could accept far larger amounts of bicarbonates than of carbonic acid.

A better option than forming water-soluble bicarbonates would be the formation of insoluble carbonates that could be stored at the location of the mineral base, confining environmental impact to a specific site. To this end, serpentine or olivine rocks rich in magnesium silicates can be mined, crushed, milled, and reacted with CO_2. Estimated mining and mineral preparation costs of less than \$10 per ton of CO_2 seem acceptable, adding 0.5 to 1¢ to a kilowatt-hour of electricity.



Estimated storage capacities and times for various sequestration methods. The "fossil carbon" range includes at its upper end methane hydrates from the ocean floor. The "oxygen limit" is the amount of fossil carbon that would use up all oxygen available in air for its combustion. Carbon consumption for the 21st century ranges from 600 Gt (current consumption held constant) to 2400 Gt. "Ocean acidic" and "ocean neutral" are the ocean's uptake capacities for carbonic acid and neutralized carbonic acid, respectively. The upper limits of capacity or lifetime for underground injection and mineral carbonates are not well constrained. EOR stands for enhanced oil recovery.

Improved methods for accelerating carbonation are, however, still needed. The current best approach—carbonation of heat-treated peridotite or serpentine in an aqueous reaction—is too costly. Elimination of the energy-intensive heat treatment could render the process economically and energetically feasible. Above-ground mineral sequestration has the capacity of binding all CO_2 that could ever be generated and limiting the environmental impact, including terrain changes, to relatively confined areas.

Most sequestration methods require concentrated CO_2, which is best captured at large plants that generate clean, carbon-free energy carriers such as electricity and hydrogen. Retrofitting existing plants appears too expensive; new plants designed for CO_2 capture are more promising (*8*). Complete CO_2 capture opens the door to radically new power plant designs that eliminate all flue gas emissions, not only CO_2. Oxygen-blown gasification could approach this goal today. More advanced designs could even remove the efficiency penalty associated with CO_2 capture.

For example, sending gasification products of coal together with steam through a fluidized bed of lime would shift oxygen from water to carbon. Capture of CO_2 on lime would promote hydrogen production and provide necessary heat. Half of the hydrogen-rich output would be used to gasify coal; the other half would be oxidized in a high-temperature solid-oxide fuel cell. The water-rich spent fuel gas would be returned to the lime bed to repeat the cycle. Only excess water, ash, and impurities captured in various cleanup steps would leave the plant. Once the lime becomes fully carbonated limestone, CO_2 would be produced in a concentrated stream while the limestone is converted back to lime with waste heat from the fuel cell. Careful heat management could drive power plant efficiency to 70% (*9*) (for comparison, conventional coal-fired power plants are in the 30 to 35% range; modern gas-fired power plants can approach 50%).

CO_2 is three times as heavy as fuel and therefore cannot be stored in cars or airplanes. CO_2 from these sources will have to be released into the atmosphere and recaptured later. Currently, photosynthesis is the only practical form of air capture. Capture from air flowing over chemical sorbents—such as strong alkali solutions or activated carbon substrates—appears feasible but needs to be demonstrated (*10*). Wind is an efficient carrier of CO_2. The size of less than 1% that of capture apparatus would be windmills that displace equal CO_2 emissions, suggesting that they could be quite cheap to build (*11*). The additional cost of sorbent recycling should also be affordable (*12*).

Because the atmosphere mixes rapidly, extraction at any site, however remote, could compensate for emissions from anywhere else. By decoupling power generation from sequestration, air capture would allow the existing fossil fuel–based energy infrastructure to live out its useful life; it would open remote disposal sites and even allow for the eventual reduction of atmospheric CO_2 concentration.

Cost predictions for sequestration are uncertain, but \$30 per ton of CO_2 (equivalent to \$13 per barrel of oil or 25¢ per gallon of gas) appears achievable in the long term. Initially, niche markets (for example, in enhanced oil recovery) would keep disposal costs low, with capture at retrofitted power plants dominating costs. Over time, new power plant designs could reduce capture costs, but the costs of disposal would rise as cheap sites fill up and demands on permanence and safety tighten. Some applications—for example, in vehicles and airplanes—could accommodate the higher price of CO_2 capture from air, eliminating CO_2 transport and opening up remote disposal sites.

Today's urgent need for substantive CO_2 emission reductions could be satisfied more cheaply by available sequestration technology than by an immediate transition to nuclear, wind or solar energy. Further development of sequestration would assure plentiful, low-cost energy for the century, giving better alternatives ample time to mature.

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ERRATUM

post date 29 August 2003

PERSPECTIVES: "A guide to CO_2 sequestration" by K. S. Lackner (13 June 2003, p. 1677). Because of a last-minute typesetting error, the sixth sentence in the sixth paragraph on page 1678 (after "Wind is an efficient carrier of CO_2.") came out garbled. The intended wording was "Wind is an efficient carrier of CO_2. The size of capture apparatus would be less than 1% that of windmills that displace equal CO_2 emissions, suggesting that they could be quite cheap to build (*11*)." The intent of the sentence was to emphasize that air capture systems would be far smaller (not far larger) than wind mill systems that could displace an equal amount of CO_2.

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A Guide to CO_2 Sequestration
Klaus S. Lackner (June 13, 2003)
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Editor's Summary

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