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## CHAPTER 20

# Earth Systems: Engineering and Management<sup>†</sup>

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Imagine that we could let the world's economy continue to grow, bring the disadvantaged classes up from poverty, and not threaten the atmosphere or global ecosystems with unprecedented buildup of greenhouse gases (GHGs) and the climatic risks of such growth. Earth system engineering and management may just be such a panacea, some have suggested. But can we anticipate the costs or ever truly predict the consequences?

Few people would ask us to accept that a growing world economy based on greatly expanded per capita energy consumption would be free of environmental side effects. But many have claimed that the anticipated severalfold increase in GHGs—and associated sea level rises, intensified hurricanes, and drought and flood stresses—can be largely overcome by human ingenuity. Their optimistic vision depends greatly on what had been called geoengineering and has more recently been called earth system engineering, the deliberate manipulation of earth systems to manage the climatic consequences of human population and economic expansion.<sup>1</sup>

To others, the notion of geoengineering—injecting dust into the stratosphere, for example, to reflect some sunlight back to space and counteract global warming—is an irresponsible palliative. It evades the need for a real cure, such as curbing consumption by the rich and population growth by the poor and charging polluters for their use of the atmosphere as a free sewer.

In response, defenders of geoengineering retort that two-thirds of the world's people use a small fraction of the energy per capita of the rich. Cheap primary energy (mainly coal) is needed, they say, to build the economies of less developed countries and improve their well-being. The negative environmental side

effects of this will have to be tolerated or sidestepped by geoengineering if we are to have both a materialistic, growth-oriented world and an undisturbed climate.

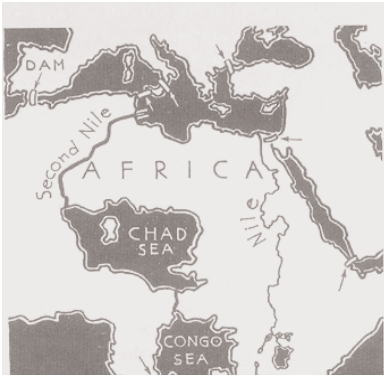
At times this debate takes on an ideological tenor. Claims that the imperative of development cannot be impeded by the prospect of global warming are greeted with the assertion that inadvertently damaging nature is bad enough, but deliberately attempting to manipulate the climate just to let our old habits prevail is a violation of stewardship and an ethical transgression against the natural world. These sets of opposing world views—anthropocentric expansion versus stewardship—are not new. They flared in the 1970s with Club of Rome debates over the limits to growth and matured with the publication of the Brundtland Commission's middle path, aiming to pursue sustainable development.<sup>2</sup> Today, they continue in arguments over whether nations must meet their emission reductions agreed in the Kyoto Protocol by domestic cuts—even if not cost-effective—or be permitted to buy their obligations elsewhere in the world at lower costs.

Let us return to the central question of what best characterizes earth system engineering. Is it a panacea for sustainable development, built with vision and ingenuity, or a palliative to avoid fundamental limits and maintain the privileged status quo for special interests? There is no easy answer to this question, but I believe that both sides have merit in parts of their arguments. I will try to sketch out some opportunities and pitfalls that might help to clarify the role of geoengineering and carbon management strategies in the climate policy debate.

## Historical Perspective

In Homer's *Odyssey*, Ulysses is the frequent beneficiary (or victim) of deliberate weather modification schemes perpetuated by various gods and goddesses. In Shakespeare's *The Tempest*, Prospero, a mortal (albeit one with magical powers), conjures up a tempest to strand on his mystical island a passing ship's crew. In literature and myth, only gods and magicians can control the elements. But in the twentieth century, serious proposals for the deliberate modification of weather or climate came from engineers, futurists, or those concerned with counteracting the inadvertent anthropogenic modification of the earth's climate.

About 1960, Rusin and Flit<sup>3</sup> from the former Soviet Union published a long essay titled *Man Versus Climate* in which they suggested "improving" our planet by, for instance, diverting rivers from the Arctic to the Russian wheat fields or from the Mediterranean to irrigate areas in Asian USSR. One of their ambitious projects was to create a "Siberian Sea" with water taken from the Caspian Sea and Aral Sea areas. Of course, flowery rhetoric with images of blooming arid zones stands in stark contrast to the ecological disaster that surrounds the Aral Sea today, where environmental degradation resulted from much less radical geoengineering projects.<sup>4</sup>

**FIGURE 20.1**

Some geoengineering projects, such as this plan for the irrigation of the Sahara by creating a “second Nile” to refill Lake Chad, have become part of geoengineering folklore. (Reproduced from ref. 3)

Other such proposals have become part of geoengineering folklore and include damming the Gulf Stream, the Bering Straits, or the Nile, or creating a Mediterranean drain back into central Africa, where a “second Nile” would refill Lake Chad, turning it into the “Chad Sea” after the Straits of Gibraltar were dammed (Fig. 20.1). But the potential side effects if these projects misfire—which is not unlikely, given the complexity of the highly nonlinear climate system—are rarely discussed.

In the early 1970s, Russian climatologist Mikhail Budyko<sup>5</sup> suggested that it was “incumbent on us to develop a plan for climate modification that will maintain existing climatic conditions.” What he endorsed was a stratospheric particle layer to reflect away enough sunlight to counteract global warming. But, wisely, he added that deliberate climate modification would be premature before the consequences could be calculated with confidence, a task for which the current simplified theories were inadequate.

William Kellogg and I looked at many such schemes in the 1970s and concluded then<sup>6</sup> that tampering blindly with the weather system would be the height of irresponsibility. Moreover, it would lead to disputes because any natural weather disaster occurring during deliberate climate modification experiments might well be blamed on the climate modifiers. We offered a modest proposal for “no-fault climate disaster insurance”: If a large segment of the world thought that the benefits of a proposed climate modification scheme would outweigh the risks, they should be willing to compensate those who subsequently lost their favored climate.

Ironically, perhaps, the term *geoengineering* seems to have been applied first to a scheme that is no longer called by that name. It was informally coined by Cesare Marchetti,<sup>7</sup> who outlined a proposal for tackling the problem of CO<sub>2</sub> in the atmosphere by a kind of extended “fuel cycle” for fossil fuels. Under this proposal, CO<sub>2</sub> would be collected at certain transformation points such as the smokestacks of principal fossil fuel-burning industrial centers. It would be dis-

posed of by injection into sinking thermohaline currents (say, the Mediterranean undercurrent entering the Atlantic at Gibraltar) that would carry and spread it into the deep ocean. Today, this kind of a plan is called industrial carbon sequestration, which is part of carbon management: controlling the amount of GHGs in the atmosphere. The term *geoengineering* has evolved to mean deliberate modifications to biogeochemical or energy flows in the climate system. This kind of tampering with natural processes, not surprisingly, inflames passionate debate.

Since Marchetti's article, perhaps the most ambitious attempt to justify and classify a range of geoengineering options was associated with a U.S. National Academy of Sciences (NAS) National Research Council panel on the policy implications of global warming.<sup>8</sup>

As a member of that panel, I can report that the very idea of including a chapter on geoengineering led to serious internal and external debates. Many participants (including me) were worried that even the thought that we could offset some aspects of inadvertent climate modification by deliberate modification schemes could be used as an excuse to continue polluting. Critics instead favored market incentives to reduce emissions or regulations for cleaner alternative technologies. But Robert Frosch countered as follows: What if a pattern of change currently thought unlikely but of high consequence actually started to unfold in the decades ahead? It would take decades to develop the technical and political tools to reverse the risks. We would simply have to practice geoengineering as the lesser evil.

Although skeptical about the viability of specific engineering proposals and the questionable symbolism of suggesting that we could sidestep real emission reductions, I nonetheless voted reluctantly with the majority of the NAS panelists, who agreed to allow a carefully worded chapter on the geoengineering options to remain in the report.

Extending Budyko's focus on the injection of aerosol particles (particles suspended in a gas) into the stratosphere, the geoengineering chapter of the report suggested that a 16-inch naval rifle fired vertically could propel a 1-ton shell consisting of dust particles up to an altitude of 20 kilometers. Given an aerosol lifetime in the stratosphere of 2 years, 10 megatons could be placed in the stratosphere 20 times during a 40-year period until 2030. Over this time the NAS authors estimated geoengineering costs to be about \$5 per ton of carbon (as CO<sub>2</sub>) mitigated. This cost is somewhat comparable to carbon taxes proposed by Nordhaus<sup>9</sup> for modest control of CO<sub>2</sub> emissions. But for a major mitigation of CO<sub>2</sub> emissions (for example, a 20 percent cut), Nordhaus's study suggests that the carbon taxes needed could be hundreds of dollars per ton carbon. (Conventional calculations of the costs of CO<sub>2</sub> mitigation through carbon taxes use economic models that are likely to overestimate the costs of mitigation because these models still ignore the effects of climate policies in inducing technological improvements.)<sup>10</sup>

But is it even possible to inject dust in the stratosphere, for example, in a

manner that would perfectly offset a given injection of GHGs in the atmosphere? Even though the 30 percent increase in CO<sub>2</sub>, 150 percent increase in methane, and addition of unnatural chemicals such as chlorofluorocarbons have spread fairly uniformly over every square meter of the earth since the industrial revolution, the patterns of heat trapped as a consequence are not uniform. The primary reason is the nonuniform distribution of other optically active constituents of the atmosphere, especially clouds.

Furthermore, humans add aerosols as well—not primarily the stratospheric kind, but mostly tropospheric sulphate aerosols resulting from the burning of coal and oil. These short-lived, lower-atmospheric aerosols are patchy in distribution and probably reflect sunlight back to space at the rate of up to 1 watt per square meter averaged over the Northern Hemisphere,<sup>11</sup> enough to offset perhaps one-fourth to one-half of the extra infrared heat associated with the enhanced greenhouse effect globally. And biomass burned also produces patchy distributions of aerosols, some of which actually warm the climate because they contain light-absorbing soot, as do some industrial aerosols, such as diesel engine exhaust.

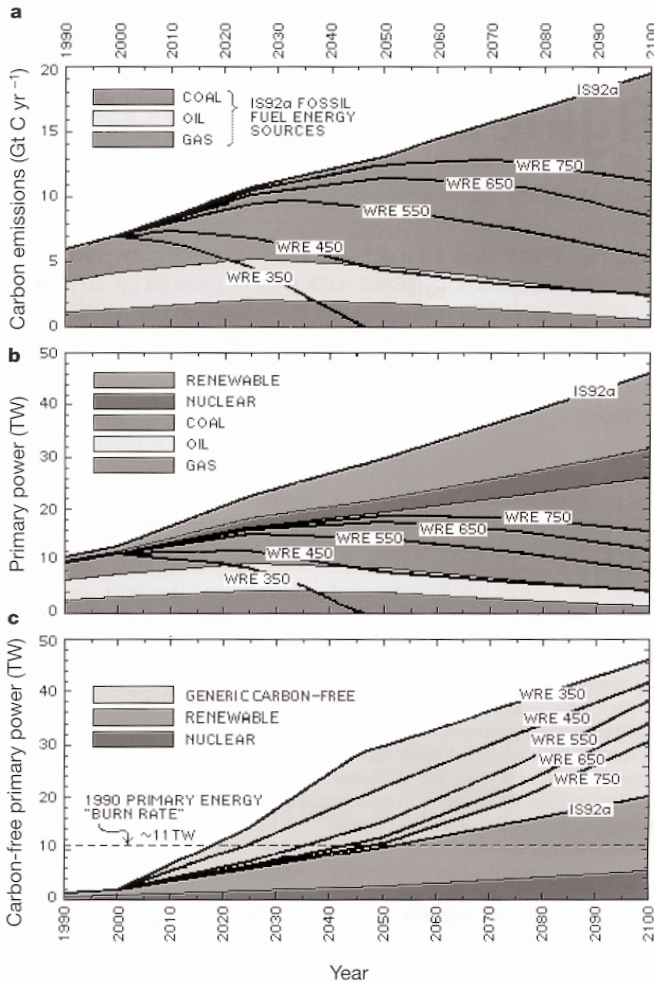
Because of the patchy nature of the greenhouse effect itself, even if we could engineer our stratospheric aerosol injections to balance on a hemispheric (or global) basis the amount of hemispherically (or globally) averaged heat trapped by human-contributed GHGs, we would still be left with some regions heated to excess and others left cooler. I am not saying that such anomalies arising from aerosol geoengineering would necessarily be worse than, say, an unabated 5–7°C warming. But this is why the strong caveats in the NAS report are reiterated by all responsible people who have addressed the question.

As a postscript to this question, a climatic model study at the Lawrence Livermore National Laboratory<sup>12</sup> attempted to simulate whether the zonal patterns of stratospheric aerosol cooling could offset the more patchy patterns of GHG heating. They concluded optimistically that within the sampling precision of the model—which is still quite noisy—the aerosol scheme might not generate major regional climatic anomalies relative to those of unabated climatic change. Although not definitive, such studies are needed to give confidence in the effectiveness of any geoengineering scheme. And without high confidence in the outcome, any implementation would be controversial and could even lead to overt conflicts.

## **Caretakers for a Century?**

No institutions currently have the authority to enforce responsible use of the global commons. There are some partially successful examples of nation-states willing to cede some national sovereignty to international authorities for the global good (for instance, the Montreal Protocol and its extensions to control ozone-depleting substances, the nuclear nonproliferation treaty, or the atmospheric nuclear test ban

treaty). The Kyoto Protocol, even if ratified (currently a questionable prospect), would address only a small fraction of the needed emission cuts if  $\text{CO}_2$  concentrations are to be stabilized below a doubling from preindustrial levels (much of the primary energy needed in 2050 will have to be mobilized with carbon emissions well below current standards, or huge efforts made to remove the excess)<sup>13</sup> (Fig. 20.2).



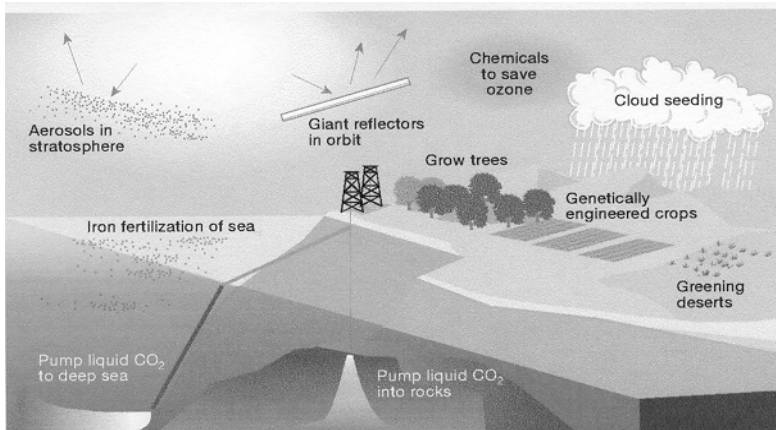
**FIGURE 20.2.** Fossil-fuel carbon emissions and primary power in the twenty-first century for various stabilization scenarios (IPCC scenario 1992a [dubbed “business as usual”], and stabilization of atmospheric  $\text{CO}_2$  at 750, 650, 550, 450, and 350 p.p.m.v.). a, carbon emissions; b, primary power; and c, carbon-free primary power (see ref. 13 for further explanation). Carbon-free primary power is total primary power less fossil-fuel carbon power, calculated on the basis of net  $\text{CO}_2$  emissions whether from sequestration or solar, nuclear or wind power. (Reproduced from ref. 13).

It would take a big increase in global-mindedness on the part of most nations to set up institutions to attempt to control climate and to compensate the losers should the interventions backfire (or even be perceived to have gone awry). Moreover, such an institution would need the resources and authority to make and monitor changes without interruption over a century or two—the time it will take the climate system to soak up the bulk of the GHGs we have injected. Thus, this is the time over which we would continuously need to inject measured amounts of dust in the stratosphere, iron in the oceans,<sup>14,15</sup> or sulfate aerosols into clouds to counteract the heat-trapping effects of long-lived constituents such as CO<sub>2</sub>. So the most difficult obstacle in the path of geoengineering may be questionable governance rather than technical uncertainties.<sup>16</sup>

## Varieties of Carbon Management

Two broad classes of carbon management can be distinguished. The first includes attempts to manipulate natural biogeochemical processes of carbon removal, or carbon sinks.<sup>17</sup> The second involves preventing carbon emissions into the atmosphere and instead disposing of carbon in stable reservoirs. David Keith (Box 20.1)

### BOX 20.1. Geoengineering



Geoengineering is planetary-scale environmental engineering, particularly engineering aimed at counteracting the undesired side effects of other human activities.<sup>1</sup> The term usually is applied to proposals for limiting the climatic impact of industrial CO<sub>2</sub> emissions by countervailing measures such as space-based solar

*(continues)*

shields. Scale and intent are both central to the common meaning of *geoengineering*, as the following examples demonstrate. The first is intent without scale: Ornamental gardening is the intentional manipulation of the environment to suit human desires, yet it is not geoengineering because neither the intended nor the realized effect is large-scale. The second is scale without intent: Anthropogenic CO<sub>2</sub> emissions will change global climate, yet they are not geoengineering because they are a side effect of the use of fossil fuels to provide energy services.

The distinction between geoengineering and more conventional responses to the CO<sub>2</sub> climate problem is fuzzy. *Geoengineering* has become a label for technologically overreaching proposals that are omitted from serious consideration in climate assessments. For example, few would object to applying the label to the first pair of examples that follow, but neither proposal rates serious consideration among climate policymakers. Conversely, the second pair receives serious consideration, but few would call them geoengineering.

## Geoengineering Proposals

### *Enhancing Oceanic Sinks*

Fertilizing the “biological pump” may enhance the flux of carbon into the oceans that maintains the disequilibrium in CO<sub>2</sub> concentration between the atmosphere and the deep ocean. Although use of nitrogen and phosphorus has been proposed, iron fertilization is the salient possibility because the ratio of iron addition to carbon fixation is very large (the Fe:C ratio is ~1:10<sup>4</sup>, whereas for N:C it is ~1:6).

Iron fertilization experiments have produced marked increases in oceanic productivity,<sup>2</sup> and surveys have shown that biological productivity is iron-limited over substantial areas.<sup>3</sup> Although enhancement of surface productivity is possible, increasing the carbon flux into the deep ocean is highly uncertain; models suggest that even if iron fertilization were used at the largest possible scale, the carbon flux would not exceed ~1 Gt C/yr<sup>-1</sup>. And problems abound because iron fertilization could produce anoxia in large regions of the deep ocean.

### *Shielding Some Sunlight*

Warming caused by anthropogenic GHGs can be countered by deploying systems in the stratosphere or in space that scatter sunlight away from the planet. Stratospheric scatters are much cheaper but entail risks to stratospheric chemistry; space-based systems offer an expensive but clean alteration of the solar “constant.”

Analysis has shown that it is possible to dramatically reduce the required mass and thus the cost of both scattering systems.<sup>4</sup> It had long been suggested that changes to the solar constant would compensate only poorly for the climatic effects of increased CO<sub>2</sub>, even if mean surface temperature were accurately controlled. But a recent climate model experiment indicates that reduction of solar input can compensate for increased CO<sub>2</sub> with remarkable fidelity.<sup>5</sup>

## Ambiguous Cases

### *Enhancing Terrestrial Sinks*

Given the substantial human control over the terrestrial biosphere, the large natural carbon fluxes between the atmosphere and the terrestrial biosphere provide a powerful lever for manipulating atmospheric CO<sub>2</sub>. A variety of methods have



been proposed to exploit this leverage, including reforestation and sequestration in agricultural soils via no-till methods or the genetic modification of cultivars to enhance lignin content, thereby increasing the amount of CO<sub>2</sub> stored in such plants.<sup>6</sup>

Is it geoengineering? Enhancement of terrestrial sinks has been seen as green and low-tech, in sharp contrast with geoengineering. The idea has garnered wide support in industry and among environmental organizations. Yet, if implemented at the scale needed to capture a significant fraction of emissions, terrestrial sequestration would resemble planetary-scale environmental engineering and may well entail high-tech methods such as genetic modification of crops. The divergent treatment of terrestrial and oceanic sinks illustrates the inconsistencies that pervade discussion of planetary engineering.

### *Sequestering CO<sub>2</sub>*

We may use fossil energy without CO<sub>2</sub> emissions by first capturing the carbon content of fossil fuels while generating carbon-free energy products such as electricity and hydrogen and then sequestering the resulting CO<sub>2</sub> in geological formations or in the ocean.<sup>7</sup>

Is it geoengineering? The term *geoengineering* was coined in the 1970s to describe the injection of power-plant CO<sub>2</sub> into the deep ocean. Despite this etymology, it is unclear whether capture and sequestration is rightly classified as geoengineering. It is certainly an end-of-pipe technical fix, but injection into geological reservoirs resembles conventional pollution-mitigation technologies more closely than it resembles geoengineering because it limits emission of CO<sub>2</sub> to the biosphere rather than compensating for emissions after they occur. Put simply, if geological sequestration is an end-of-pipe solution, then biological sequestration is beyond-the-pipe.

### **Commentary**

The post-war growth of the earth sciences has been fueled, in part, by a drive to quantify environmental insults to support arguments for their reduction. Paradoxically the knowledge gained is increasingly granting us leverage that we may use to deliberately engineer environmental processes on a planetary scale. The manipulation of solar flux using stratospheric scatterers is perhaps the best example of this leverage: We could reduce solar input by several percent—probably enough to initiate an ice age—at an annual cost of less than 0.01 percent of global economic output.<sup>1,4</sup> As remedies for the CO<sub>2</sub> climate problem, all proposed geoengineering schemes have serious flaws. Nevertheless, it is likely that this century will see serious debate about—and perhaps implementation of—deliberate planetary-scale engineering.

### **Notes**

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suggests that the dividing line between geoengineering and mitigation is when a technology acts by counterbalancing an anthropogenic forcing rather than reducing it.

Carbon management by manipulating biogeochemical cycles overlaps with geoengineering. Ideas include iron fertilization of the oceans to enhance uptake of carbon by the resulting blooms of phytoplankton, planting vast forests of fast-growing trees to sequester carbon,<sup>18</sup> or altering agricultural practices to increase carbon storage in soils.<sup>19</sup>

The prevention of carbon emissions that otherwise would have been injected directly into the atmosphere is not geoengineering. Briefly, it includes preserving primary forests that otherwise might have been cut down (which also helps to preserve biodiversity; Fig. 20.3); processing fuels such as coal or methane to increase the hydrogen content and remove carbon, then injecting the carbon into storage reservoirs; using less carbon-intensive energy supply systems; and improving energy efficiency. The last two of these, of course, are what has come to be called “mitigation,” usually favored by environmentalists. (The climate policy debate typically argues the costs of mitigation versus adaptation, although geoengineering has been mentioned as a third category from the outset.)<sup>20</sup>

One idea is to build on the chemical industry’s existing experience of industrial-scale carbon removal and sequestration. Nitrogen fertilizer, for example, is



**FIGURE 20.3.** Keeping carbon in forests provides a “double dividend”, as primary tropical forests contain good stores of CO<sub>2</sub> and also high biodiversity. But any carbon management scheme must take into account compensation for local people who lose their opportunity to convert the forest into economic product. In addition, monitoring is required to ensure that the carbon stays sequestered and that carbon “credits” are paid out to the donor to the project over time.

manufactured when carbon fuels such as natural gas or gasified coal are converted to secondary energy carriers such as hydrogen, although this is not done for the purpose of using the clean-burning hydrogen as a fuel but rather for chemical processing. And as carbon-intensive fuels such as coal are progressively converted to more hydrogen-based fuels such as methane, carbon dioxide is a byproduct that should be sequestered in a stable reservoir. The oil industry also has long experience with CO<sub>2</sub> sequestration through advanced oil recovery schemes. With one exception, these are not aimed at reducing atmospheric emissions of CO<sub>2</sub>. Nonetheless, this experience can be built upon to develop carbon management for climate purposes.

The feasibility of CO<sub>2</sub> sequestration below ground has already been explored at small scales. The Sleipner West offshore platform in the North Sea, operated by the Norwegian company Statoil, is an interesting experiment in which about 1 million tons of CO<sub>2</sub> annually is stripped out of the natural gas mixture brought out of the earth. The CO<sub>2</sub> is reinjected into an aquifer about 1,000 meters below the ocean surface. As the CO<sub>2</sub> spreads along this geological formation, eventually—perhaps over hundreds of years—it may leak out, but this slow reinjection back into the climate system will avoid the acute build up of CO<sub>2</sub> that would have occurred under normal circumstances. Most interesting, perhaps, is why this first-of-a-kind plant was built: Norway had instituted a tax on carbon emissions of around \$50 per ton, and it seems that CO<sub>2</sub> removal and sequestration might be cheaper than the tax.

This, of course, is the crux of the climate policy debate: How can we create incentives to put a price on carbon or other heat-trapping gases? Debate rages about whether to provide incentives directly by a carbon tax, indirectly via targets and timetables (as in the Kyoto Protocol), or via subsidies to enterprises willing to develop carbon management schemes. But without such incentives, the extent to which technological options will be explored is questionable.

Carbon management thinkers have also suggested that industrial efforts should not be limited to centralized sources such as power plants or oil platforms but must consider distributed applications such as transportation systems. Perhaps we will see the development of a few centralized plants to produce hydrogen fuel for zero-emission vehicles. To be cost-effective, such plants must be in areas with abundant resources of fossil fuels and adequate storage reservoirs for the waste carbon. However, some have questioned whether sequestered carbon will remain buried and thus whether carbon credits should be given unless it is proved that the storage is lasting. To eliminate endless debate I propose an inexpensive fix: to add into the injected CO<sub>2</sub> an inert chemical tracer unique to each sequestration site. Thus, the nondetection of this tracer over time would serve to certify that carbon credit is deserved for such sequestration projects.

## “Strong” or “Weak” Engineering

In 1992 at the Rio Earth Summit, the UN Framework Convention on Climate Change committed the nations of the world to avoid “dangerous anthropogenic interference with the climate system.” At that time the thinking was primarily about inadvertent modification. But now it seems that world leaders may have to extend their value judgment about what is harmful by including deliberate interference with the climate system.

Naturally, there is a philosophical debate about whether there is anything ethically wrong with such tinkering. On one hand, it is argued, we have progressed from hunting and gathering by increasingly large-scale manipulations of the natural environment. In fact, some environmental writers have despaired that an altered climate is already “The End of Nature.”<sup>21</sup> It has been argued<sup>22</sup> that earth system engineering and management is the approach “to rationally engineer and manage [the Earth] to provide the requisite functionality” and that this is not a logical transgression of naturalness because the earth is already an artifact of our manipulations. Of course, anything other than a preservation of current structure and function demands a definition of *improvement*, what constitutes an “improvement” over the natural, and this judgment will be very different across diverse cultures and over generations.

Moreover, there are still areas in the polar regions and deep tropical rain forest where there is, as Professor David Keith has observed, “essentially no visible human imprint; where the majority of species have evolved in situ . . . and where biochemical perturbations are small.” Such landscapes are not “artificial” simply because a slight global climatic change has already occurred. We should avoid disrupting them further rather than using “light perturbation” as an excuse to turn over the future of all nature to the value judgments of the planetary managers.<sup>23</sup>

Given our growing inadvertent impact on the planet, adaptation alone is likely to prove inadequate. But I would prefer to reduce slowly our economic dependence on carbon-emitting fuels rather than to try to counter the potential side effects with centuries of non-stop injecting sulfuric acid into the atmosphere or iron into the oceans. Laying stress instead on carbon management, with little manipulation of biogeochemical or energy fluxes in nature, is a much less risky prospect, despite remaining uncertainties about the longevity of deep-earth or deep-ocean carbon storage and the possible ecological consequences of localized injections of vast quantities of CO<sub>2</sub> in the oceans or the potential damper on global economic development. If preliminary studies prove reasonable, then the cost penalties for closing the industrial cycles by reinserting waste CO<sub>2</sub> back in the earth might be only a few tenths of a percent of current energy system

costs—something akin to \$50–\$100 per ton carbon. Such costs would have only a trivial impact on economic growth in the twenty-first century. The actual costs of various forms of carbon management will be crucial in determining how much climate change we and the unmanaged environment will have to adapt to in the decades ahead. But until national governments cooperate and provide incentives to both producers and users of climate-altering products, the potential for any carbon management enterprise will be limited and the likelihood of dangerous climatic changes increased.

To me, any stronger form of earth system engineering and management is a revision of Rusin and Flit's fantasy of 40 years ago to transform the earth system to achieve "improvements in climate." Those wanting to usurp the powers of ancient gods and conjurers should recall the ancient Greeks' warnings about human hubris embodied in the story of Prometheus.

## Acknowledgments

†Adapted (with permission) from Schneider, S. H., 2001. Earth systems engineering and management, *Nature*, 409: 417–421.

## Notes

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