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Global Biogeochemical Restoration to Stabilize CO$_2$ at Safe Levels in Time to Avoid Severe Climate Change Impacts to Earth's Life Support Systems: Implications for the United Nations Framework Convention on Climate Change

Thomas J. Goreau

CONTENTS

Introduction

This chapter focuses on (1) why and how policymakers have severely underestimated the long-term impacts of climate change, (2) how the carbon management mechanisms they have developed are flawed and counterproductive, (3) how they could be corrected, (4) where the carbon can be most cost-effectively stored, (5) how quickly that could be done, and (6) the practical and policy actions needed to get there.

Atmospheric carbon dioxide (CO_2) concentrations are currently at levels the Earth has not experienced for around 25 million years (Pagani et al., 2005; Zhang et al., 2013), a time when there were no polar ice caps and temperatures and sea levels were much higher than today, and CO_2 is headed much higher. Humanity faces unpalatable short- versus long-term trade-offs between reducing emissions of CO_2 versus short-lived climate pollutants to minimize future global warming impacts (Shoemaker et al., 2013). Supply-side approaches amount to reshuffling Titanic deck chairs if they overlook demand-side solutions. CO_2 cannot be reduced to safe levels in time to avoid serious long-term impacts unless the other side of atmospheric CO_2 balance is included by increasing sinks while simultaneously decreasing sources (Goreau, 1987, 1990, 1995).

Down to Earth underground solutions to global warming (Figure 2.1) have been ignored by policy makers' exclusive focus on source reductions and geoengineering. They need to look at the other side of the carbon coin, implementing solutions that can work in time to make a difference by removing carbon from the atmosphere, where it does the most harm, and putting it in the soil, where it does the most good. The answer lies at our feet.

Reducing emissions is of course essential, but without greatly increasing carbon sinks at the same time, it alone is not adequate to do the job (Goreau, 1995). Increasing sinks is not an excuse to avoid emissions reductions but is the *sine qua non* for making emissions reductions work effectively and fast enough to prevent severe climate change impacts.

The excess CO_2 in the atmosphere largely came from fossil fuel combustion and from soil and vegetation carbon loss. Soil holds around four times more carbon than the atmosphere or vegetation and could hold more again (Lal, 2004; Lehmann and Joseph, 2009; Woolf et al., 2010). The dynamic time response spectrum of CO_2 sources and sinks shows the fastest way to decrease CO_2 is to increase photosynthesis and biomass storage in tropical soil carbon, which could resolve the problem in decades, but CO_2 source reductions alone will take centuries to millennia to have an effect, so impacts will be far worse (Goreau, 1995).

Transferring carbon from atmosphere to soil would also greatly increase soil productivity, biomass, and groundwater resources, while increasing rainfall and reducing temperature through increased evapotranspiration. Effective methods to greatly increase soil carbon by intensifying natural biogeochemical recycling work in all ecosystems, agricultural land, degraded land, pastures, and forests. Not only is there 2–4 times more carbon in soil than in the atmosphere or vegetation, this article shows that the
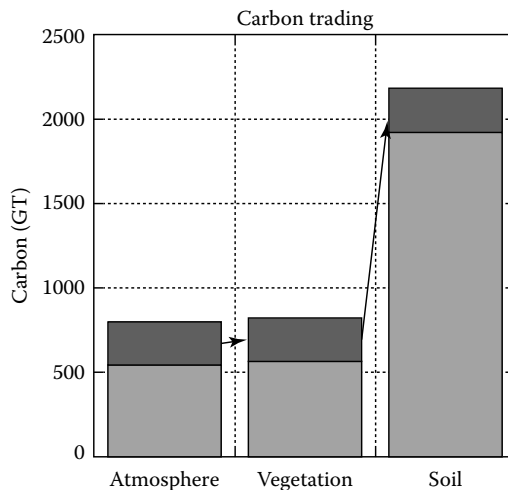
FIGURE 2.1 Carbon contents of atmosphere, vegetation, and soil, showing transfer of the anthropogenic excess, shown in light gray. In the left column, dark gray represents the preindustrial CO_2 level, and the current value is the dark gray plus light gray column. To get transfer of all the excess to the current biosphere (dark gray, middle column) would be an equally large increase, but if that is transferred to the current soil carbon (dark gray, right column), the proportional increase is small. Soil carbon estimates to a depth of 2.3 m are based on Shangguan et al. (2014). Note that this is an underestimate because it does not include carbon in deeper soil horizons. Also note that wetland carbon and marine mangrove and sea grass carbon may also be equivalent in magnitude to soil, but current estimates are too poor to show.

soil is the only place we can store the excess CO_2 quickly enough to prevent severe future impacts from global warming. The *Down to Earth* solution to global warming, putting it in the ground, will save money in the long run and provide many additional benefits to humanity.

Without restoring global soil fertility, and the biogeochemical planetary life-support systems only healthy growing plants can provide, it will be not possible to stabilize CO_2 at safe levels and avert the worst impacts of runaway global warming and sea level rise; that is the bad news (Pimentel and Pimentel, 1996; Flannery, 2005; Lovelock, 2006; Romm, 2007; Ehrlich and Ehrlich, 2013). The good news is that this can *still* be done in time to avoid the worst, but not all, of the impacts, in a way that minimizes costs and maximizes benefits, if we act right away. To understand how, we must begin with the entire global carbon cycle and descend to the atomic-scale details of how carbon works in soils, oceans, and plants, before returning again to the global scale.

CO_2 as Planetary Currency

CO_2 is central to the physics, chemistry, biology, geology, and climate of our planet, quite apart from being both food for plants and the largest waste product of our energy and food (for just a small part of the important literature, see Woodwell et al., 1978; Holland, 1984; Solomon et al., 1985; Post et al., 1990; Schlesinger, 1990; Gerlach, 1991; Jenkinson et al., 1991; Sundquist, 1993; Greenland, 1995; Berner, 2003, 2004, 2006; Houghton, 2003; Retallack, 2003; Sundquist and Visser, 2003; Royer et al., 2004, 2007; Beerling and Berner, 2005; Pagani et al., 2009). CO_2 is the major greenhouse gas (GHG) causing global warming, confirmed again by the latest Intergovernmental Panel on Climate Change (IPCC) report (Hegerl and Stott, 2014). CO_2 therefore serves as the most fundamental natural *currency* unit of the major planetary biological, environmental, energy, and ecological life-support services (Daily, 1997). We have not learned how to assign a monetary value to most of these benefits or the costs from their degradation. Until we do, we cannot assign a realistic price for the carbon these processes produce or consume as $XCO_2 = Y\$$. The obvious idea of CO_2 as a universal environmental currency has come independently to almost everyone who has thought about the issue, so many it is impossible to know who was first or who should be credited. It is made yet again very clearly in the Foreword of this book by John Todd. It is simply an idea whose time has come, whether or not we call payment for carbon services a *tax*, a *fee*, a *surcharge*, or some other euphemism.

We pay directly for the costs of fossil fuel extraction, processing, distribution, and profits in order to produce that CO_2, but we completely ignore the many real indirect costs such as global climate change, simply foisting them off on future generations. Like a profligate heir squandering an inherited family fortune created through no work of his/her own on wasteful personal gratification, we are condemning our descendants to beggary and servitude if we do not clean up our act and stop fouling our own nest. But instead of paying to undo the environmental damages of fossil fuels, we effectively subsidize it, making it artificially cheap. If we paid those costs in the fossil fuel energy price, renewable energy would not need subsidies to compete. A recent estimate of the real costs of fossil fuel CO_2 emissions puts the minimum cost at \$125/ton of CO_2 and could be a lot higher (van den Bergh and Botzen, 2014).

Failure to set a carbon price in a way that accurately reflects *all* costs of these complex and interlinked services, whenever and wherever they take place, guarantees a failure of market mechanisms to address the complex and intertwined issues. These are the economists' *externalities*, which society is left to pay (Stern, 2006; Dasgupta and Ehrlich, 2013). This failure is evident in the collapse of the European carbon market price, which was doomed at its very conception because the EU began by giving away CO_2 pollution permits free to the biggest polluters, devaluing its price, and because, for political reasons, they gave away permits to emit more CO_2 than polluters could actually produce, thereby ensuring carbon price collapse. With pollution permits so cheap as to be practically free, there was little incentive to clean up. While the Europeans tried to set up a carbon market, and blew it, other rich countries simply refused to require any carbon accounting and trading. The poorest countries are most vulnerable to climate hazards (Ehrlich et al., 2012), none more so than the low-lying developing states, so they pay the disproportionate cost of market failures from which they derive no benefit. This is clearly no way to effectively regulate GHG emissions.

Global Carbon Cycle

A complete and holistic understanding of the complete global biogeochemical CO_2 cycle is essential for any solution that solves the CO_2 waste problem by taking it from the atmosphere, where it does the most harm, and putting it in the soil, where does the most good (Figure 2.2).

Global warming over the last century and a half is only the very start of much larger future change to come unless we quickly restore global ecosystems to recycle CO_2 into permanent storage and stabilize CO_2 and our planet's critical life-support systems. Large-scale restoration of degraded habitats is the most important option for CO_2 sequestration: so little intact wild habitats now remain that strict conservation of them is incapable of storing the carbon needed. Without large-scale restoration of habitats that are already damaged or degraded, the requisite amount of carbon cannot be stored. Every degraded habitat, forests, pastures, marshes, swamps, mangroves, sea grasses, coral reefs, and even deserts, needs to be involved. The areas are vast and the home to the bulk of species biodiversity (Figure 2.3).

Tragically, restoration of ecosystems in general, and of their soil carbon in particular, is completely missing from the United Nations Framework Convention on Climate Change (UNFCCC) negotiations. UNFCCC's continued failure to grapple with the real issues and solutions guarantees continued runaway climate change. Soil carbon simply is not on the list of accepted carbon sinks in the UNFCCC negotiations, even though it has around four times more carbon than the atmosphere (Figure 2.1). This fundamental error makes the rest of their carbon accounting basically irrelevant.

Unfortunately, the entire CO_2 discussion is bedeviled by selective and misleading analysis since very few scientists, much less decision makers, have the full grasp of the *entire* carbon cycle system essential for scientifically sound policy. The polemics of the CO_2 issue are full of selective or false arguments that usually consider only one process at a time, not the entire interlinked cycle. Confusion is caused by

FIGURE 2.2 Major fluxes in the global carbon dioxide cycle. (After Goreau, T.J., *Ambio*, 19, 230, 1990, drawing by Dr. Peter Goreau, adapted by T. Goreau.) Of these fluxes, only fossil fuel inputs are accurately quantified because coal, oil, and natural gas commerce is well measured. The others have uncertainties that will slightly affect the quantitative details of the discussion in the following, but not the fundamental features. This figure, while capturing the essence of the entire cycle, does so by simplifying smaller or slower subcycles that affect atmospheric CO_2 more slowly. This chapter shows that only increasing CO_2 transfer from atmosphere to biomass and soil carbon can reduce CO_2 levels fast enough to solve the problem in time.

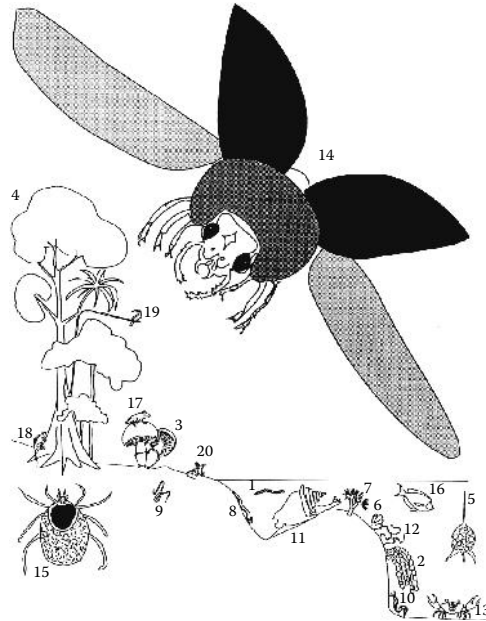**FIGURE 2.3** Global biodiversity with each major class of organism shown in a size proportional to the number of species. (Figure by Dr. Peter. D. Goreau.).

mistaking gross carbon sources and sinks with net ones, and even confusing sources with sinks. Global policy is being made with fundamental errors of incomplete and partial accounting of GHG sources and sinks that ignores or confuses the major global carbon flows.

Unless we start large-scale global restoration efforts to increase atmospheric carbon sinks *now*, they will come too late to prevent catastrophic overshoot, of CO$_2$, temperature, and sea level (Hansen et al., 2007, 2008, 2010; Rogelj et al., 2011, 2013; Matthews and Solomon, 2013; Stocker, 2013). The global restoration profession must lead in urging world leaders to start immediate massive restoration efforts in all degraded ecosystems. These must simultaneously maximize biodiversity, biogeochemical function, nutrient recycling, and natural carbon sequestration, and so cannot be based on monocultures (single species plantations). The sooner they are started, the less they will cost, the shorter they will be needed, and the greater the ecological, environmental, and economic benefits to humanity and the other species we share the planet with.

CO$_2$ Futures

If we burn all the oil, natural gas, and coal we can extract from the ground, we will increase atmospheric CO$_2$ from 5 to 10 times, but in about 100 years, we will have used up most of the available oil and gas, and in about 300 years, the coal too. No matter which fossil fuel *business as usual* scenario we adopt, a century, perhaps three, of vastly increasing atmospheric CO$_2$ lies ahead (Figure 2.2) unless we switch to non-fossil-fuel energy resources. We would have to eliminate almost all fossil fuel use to bring CO$_2$ back down to safe levels, and that would take centuries.

We have not yet felt the vast bulk of the temperature and sea level response that will hit us, because most of the effects that today's level of CO$_2$ will cause lie far in the future. Technologies needed to stabilize CO$_2$ at safe levels, including sustainable biomass energy and biochar to sequester carbon (increasing soil carbon, fertility, water-holding capacity, and forest and agricultural productivity) discussed in this book, are mature and well known (Green Disc, 2014) but, due to the lack of support at policy and funding levels, are not being used on the scale needed as cost-effective problem-solving tools.
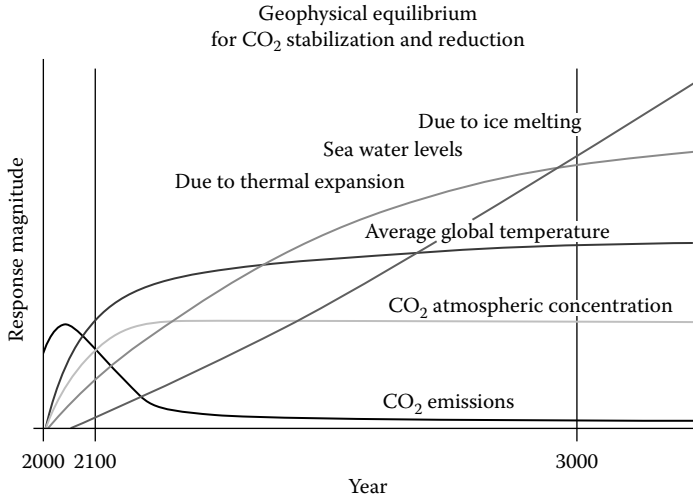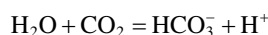
FIGURE 2.4 Time scale of CO_2 temperature and sea level responses to fossil fuel emissions. (Adapted from Climate Change, Synthesis Report. A contribution of working groups I, II and III to the third assessment report of the Intergovernmental Panel on Climate Change, Figure SPM-5, 2001, Cambridge University Press.)

It takes about 1000 years for excess atmospheric CO_2 to dissolve and mix into the deep ocean, so the CO_2 concentration in the atmosphere will stabilize on the time scale of ocean mixing, in a few thousand years. The same is true of temperature (Figure 2.2). Right now we feel only a small part of the heat increase of the planet as sensible temperature, because the excess planetary heat is flowing into the largest heat sink, the deep sea (Levitus et al., 2012), and being used to melt ice (which does not change the temperature, even as it adds heat to the system). These last two important effects are not included in the IPCC (Figure 2.4). Until the deep sea warms up, and all the ice is melted, we would not feel the full effect of global warming of atmospheric and land surface temperature (SST), and that will take thousands of years.

After a thousand years, CO_2, temperature, and sea level rise from thermal expansion of seawater will start to level off, but sea level rise from ice melting will continue to increase for thousands of more years. Sea level rise will not level off until all the ice melts, which will raise sea level by up to 50 or more meters after several thousand years. We do not really know how long because that depends on just how quickly the glaciers flow, and as is well known, they move at a glacial pace, you can outwalk them. There is clear evidence that at the end of the last Ice Age (10,000–18,000 years ago), there were times of very rapid sea level rise, possibly with surges (Hanebuth et al., 2000; Overpeck et al., 2006; Rohling et al., 2008). During that time, changes in sea level were likely due to catastrophic surges of melting ice suddenly sliding into the sea, because instead of glacial ice being frozen to the rocks beneath them, the bottom of the ice was lubricated by a layer of melt water, as they are increasingly now in Greenland and Antarctica. No one can predict when such surges in sea level will take place due to glacial melt (especially due to climate change), but large and sudden sea level rises are not just possibilities, but certain based on our current trajectory. This unpredictable surge and melt pattern will make stable life along coastal shorelines impossible when melting accelerates.

Increased atmospheric CO_2 and temperatures will remain in the atmosphere until the carbon dioxide is removed through a chemical reaction with rocks, called weathering. High CO_2, temperature, and sea level is expected to persist on a time scale in the range of tens to hundreds of thousands of years unless rock weathering is greatly accelerated above natural levels (Norris et al., 2013). That can be induced with the methods described using rock powders in many chapters in this book. Increased biological soil carbon sinks also greatly increase rock weathering carbon sinks.

The weathering time scale is determined by the time it takes atmospheric CO_2 dissolved in rainwater to react with minerals in rocks and soils, being converted into dissolved bicarbonate and acid (which dissolves more minerals):

$$H_2O + CO_2 = HCO_3^- + H^+$$

The bicarbonate then is washed by rivers into the ocean and builds up in the deep sea until it is ultimately precipitated as limestone and finally buried deep in marine sedimentary rocks, which takes hundreds of thousands of years:

$$2HCO_3^- + Ca^{++} = CaCO_3 + H_2O + CO_2$$
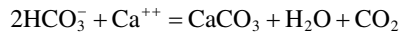
About half the marine carbon involved in limestone production is buried and the other half is released back to the atmosphere (Stumm and Morgan, 1996).

Using fossil fuels now will therefore cause environmental impacts to everyone, everywhere, for perhaps around a million years or so. These long-term impacts are largely *not* included in the IPCC climate change models because IPCC was mandated for political reasons to use models to predict impacts for 20, 50, or 100 year horizons, and so they miss almost all of climate responses to increasing CO$_2$ that take thousands of years to develop. The IPCC was ordered by UNFCCC to make projections only over short time periods that coincidentally ignore almost all of the anticipated damage. In effect, they were instructed to come up with a totally irrelevant *answer* to the wrong question, which is of little use for serious scientifically sound long-term planning.

One leading thinker on these issues states pithily: "I don't believe that humans can destroy the earth's capacity for renewal. I do believe that full recovery from our abuse will come in geologic time (millions of years), not human time (200,000 years), certainly not agricultural time (10,000 years). We want to stay here, but we want all the other species embedded in the same ecosphere within their ecosystem to stay with us too" (Jackson, 2010).

Climate Change Sensitivity: IPCC Models Underestimate Reality

All components of the earth atmosphere/ocean/biosphere/soil/ice system are affected by complicated positive and negative feedbacks (interactions that increase and reduce their impacts) linked to exchange of CO$_2$ and by the responses to the temperature changes that CO$_2$ causes. The climate change prediction models are far too simple to describe the many known feedback mechanisms accurately in quantitative terms, even if they give qualitative insight into them. We can gain the best insight into the long-term responses of the climate system from actual real-world data: the paleoclimatological records preserved in ice, sediments, corals, tree rings, and permafrost.

Changes from Ice Age to interglacial conditions have been clearly controlled for millions of years by small changes of the earth orbit, as explained by Milankovitch theory (eccentricity, obliquity, and inclination), that affect the amount and timing of sunlight and heat reaching different parts of the earth. These cycles are completely and accurately predictable from physics and explain the timing of long-term climate change with extreme precision (except blips caused by unpredictable massive volcanic eruptions or asteroid impacts). The amplitude of these changes in solar warming input is only enough to explain long-term temperature changes of around 0.1°C from Ice Age to interglacial orbital configurations, while the actual changes at the earth's surface between Ice Age and interglacial conditions are around 5°C–10°C. This means that the earth climate system contains very large positive feedbacks that amplify these small input heat changes about 50–100 times.

Unfortunately, the bulk of these feedback mechanisms that we know exist in the system are not well enough known to accurately include in climate change models, not even the most mathematically sophisticated models running on the largest and most expensive computers in the world (Soden and Held, 2006; Torn and Harte, 2006; Hansen et al., 2007). Those feedbacks that are well known, like the fact that dark open seawater absorbs much more heat than water covered with shiny reflective white ice (ice–albedo feedback) or the fact that increased temperature causes more evaporation of water into the atmosphere that absorbs more heat (water vapor feedback), are readily described and modeled, but only around a quarter or a third of the positive feedbacks that we

know the system actually has is included in the models; the rest cannot be described well enough to model accurately yet (Stocker et al., 2013).

For example, respiration rates are strongly affected by the facts that the land is warming faster than the ocean (Seneviratne et al., 2014), nighttime temperatures are rising faster than daytime temperatures (Karl et al., 1991; Peng et al., 2013), and tropical sea surface winter temperatures are rising faster than summer temperatures (Goreau et al., 1993). As a result night and winter respiration are increasing faster than day and summer photosynthesis (Wan et al., 2009; Xia et al., 2009, 2014), acting as another positive feedback not in the models. These changes act to decrease net primary production and increase the amplitude of seasonal atmospheric CO_2 variations, especially in boreal climates (Graven et al., 2013). Furthermore, these feedbacks are highly nonlinear, so they do not simply add up (Zickfeld et al., 2011) and are very hard to model accurately. The crucial result of this neglect of feedbacks is that even the best climate models underestimate long-term impacts by perhaps around a factor of 3 or 4. IPCC was mandated by the UN to use climate change models, not real-world paleoclimate data, to predict future changes, so IPCC predictions, being based on incomplete models, are intrinsically guaranteed to underestimate real long-term impacts. How much is estimated from the paleoclimate data further in this chapter?

Some people have proposed that negative feedbacks will stabilize CO_2 and prevent further temperature rise, although there is no evidence for this in the fossil record. Fossil fuel industry lobbyists like to call CO_2 *plant food* and suggest that the more we add to the atmosphere, the faster the plants will grow and that there is no need for concern. For greenhouse plants that are saturated with fertilizers, adding CO_2 to greenhouse air can cause faster growth. But this does not happen in nature because plant growth under real conditions is always limited by lack of nutrients, water, or light, not by insufficient CO_2. That can only happen under artificially manipulated conditions. When CO_2 is added to forest air, there is no increase in plant growth or litter production (Bader et al., 2013). Plants take up all the CO_2 they need, as determined by nutrient levels in the soil, and once they have taken up what they can use, they shut their stomata, the holes in the leaves through which CO_2 enters. This reduces the amount of water lost by transpiration, so it makes plants use water more efficiently and increases the amount of water, CO_2, and dissolved inorganic carbon (bicarbonate) stored in the soil, increasing chemical weathering (Bader et al., 2013). However, there is a possible negative consequence of increased CO_2, because increased soil microbial nitrification can inhibit mycorrhizal fungi that feed plant roots, increase the amount of nitrogen loss from soil as nitrate that pollutes streams, and increase soil nitrogen limitation and soil acidification (Bader et al., 2013).

Underestimation of positive feedbacks is far from the most serious flaw in IPCC model projections. What really reduces their projections to serious underestimates is the fact that IPCC was ordered to make predictions of climate change over 10, 20, 50, at most 100 year periods. This time frame was set by political convenience and has no relationship to the real time scale of the phenomena being modeled. All future impacts longer than a century are effectively discounted to zero. Since the responses take thousands of years, 90% or so of the responses are not included in the models as a result. Consequently, IPCC's mandate was to come up with the wrong answer to an irrelevant question, and not to the questions we really need to answer: what are the long-term impacts of climate change and how long will they last? Policymakers who use IPCC projections are therefore dealing with quasi-irrelevant and arbitrary estimates of impacts, not those based on long-term effects. Policy based on bad science cannot work.

The real-world long-term sensitivity of temperature and sea level to CO_2 can be accurately determined from the long-term data in Antarctic ice cores, deep-sea sediments, and corals, and they tell a very different story than the models. Immediately after the first IPCC projections (Houghton et al., 1990) were made, the first paper contrasting the climate sensitivity of IPCC projections versus the climate record revealed fundamental flaws in IPCC's climate sensitivity estimates, which were much lower than the climate data indicated (Goreau, 1990). Table 2.1 from a briefing to delegations from the Association of Small Island States to the United Nations Conference on Sustainable Development in Rio de Janeiro in 1992, reveals the differences clearly. These are not small errors in the IPCC estimated climate change sensitivities, they are up to ten, a hundred, and a thousand times too low for the sensitivity of temperature to CO_2, of sea level to temperature, and of sea level to CO_2, respectively (Figure 2.5a through c).

TABLE 2.1

Table of Sensitivities Based on Changes in Global CO$_2$, Temperature, and Sea Level, Comparing IPCC Model Projections with Actual Data

Factor	IPCC Projections	Ice Age–Interglacial
CO$_2$ (ppm)	350	100
Temperature (°C)	1–4	5–10
Sea level (m)	0.1–0.5	100–150

Source: After Goreau, T.J., *Nat. Resour. Forum*, 2, 5, 1992.

Notes: Briefing to association of small island states delegations at the United Nations Conference on Sustainable Development, Rio de Janeiro, 1992.
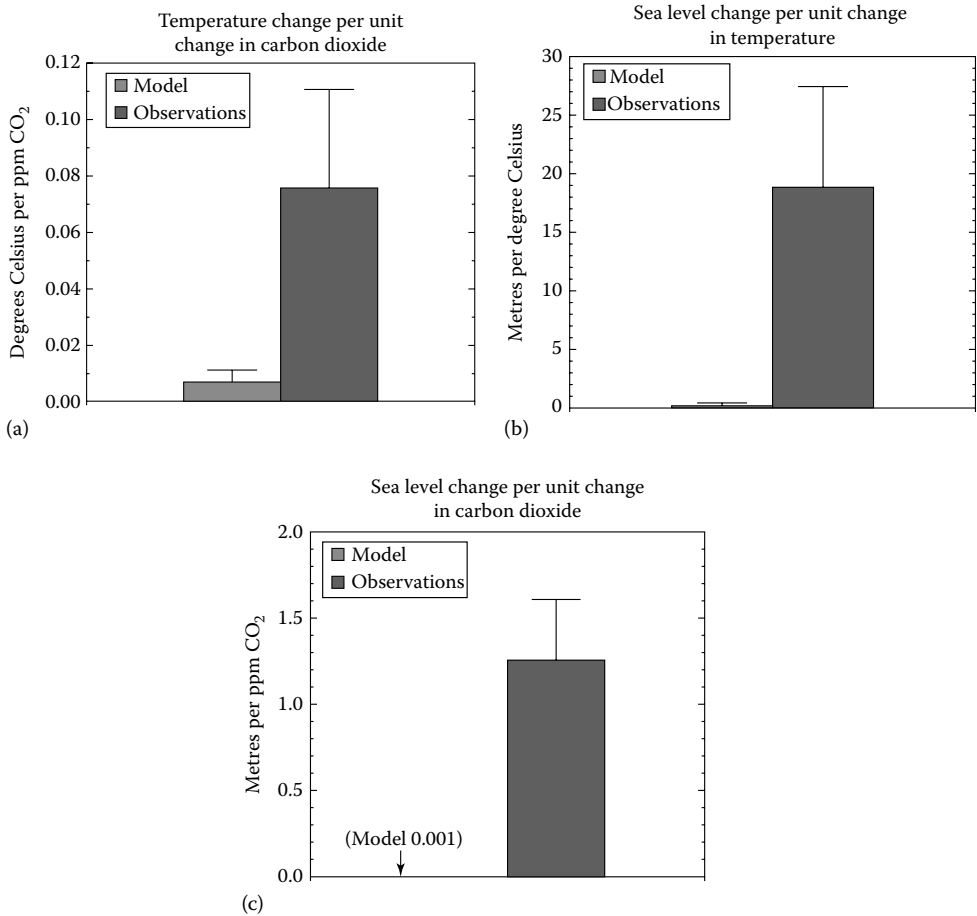
FIGURE 2.5 (a–c) IPCC model projections for sensitivity of temperature, sea level, and CO$_2$ to each other compared to real climate data throughout the last 800,000 years, based on data from Table 2.1.

By using the Antarctic ice core records of temperature and CO$_2$, and the deep-sea stable isotope records of sea level, supplemented by fossil coral samples, we can calculate the real sensitivities of global temperature and sea level over the last 800,000 years. The data show that temperature is many times more sensitive to CO$_2$ than the values assumed in the IPCC models. Nor do the IPCC models give the right value of temperature for the current level of CO$_2$, indicating that the first IPCC models seriously underestimate global temperature response to CO$_2$ (Goreau, 1990; Figure 2.6).

FIGURE 2.6   Global temperature versus CO_2. (After Goreau, T.J., *Ambio*, 19, 230, 1990.)

Straight black line is the line of best fit of the data based on values 10,000 years apart, the central triangle is for the atmospheric CO_2 in 1990, the top ri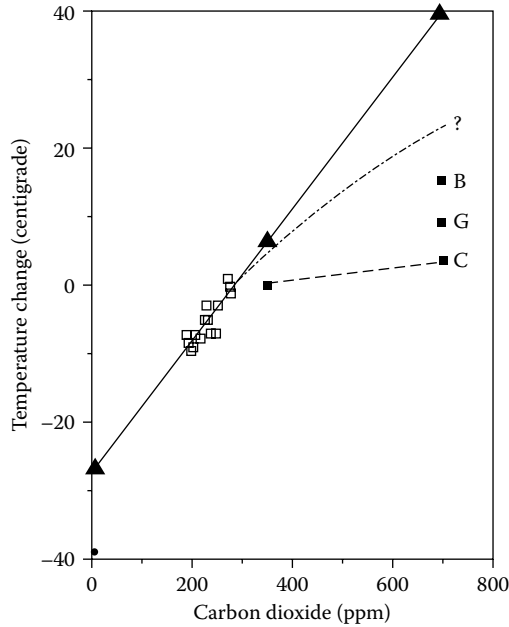ght triangle is the linear regression value for 700 ppm, the bottom left triangle is the regression temperature for no CO_2 in the atmosphere, and the straight dashed line (C) is the IPCC projection for increase of CO_2 from 350 to 700 ppm. The IPCC projection (dashed line) is seen to greatly underestimate the changes. B and G are increased model estimates of geophysical and biogeochemical feedbacks (Lashof, 1989), but it is clear that even these are insufficient to reflect the real feedbacks in the system. The real value is likely much higher due to unknown feedbacks, and most likely curved as in the dashed dot line to the (question mark), but it should also curve down to the circle at the zero axis, which is the temperature of the earth with no CO_2. This curvature results from saturation of the CO_2 thermal infrared absorption lines with increasing CO_2 concentration (Goody and Yung, 1989). At the time this data was plotted, only the ice core data from the first Ice Age cycle (160,000) years had been analyzed. Much more data over the last 800,000 years that has accumulated since then; the results are basically identical to the first estimates in this figure.

Since 1990, IPCC models have greatly increased in complexity, but with only minor increases in model-predicted sensitivity of CO_2 to temperature. There has also been a huge increase in ice core temperature and CO_2 data, providing a much larger database for calculating climate sensitivity. Recent determinations of real-world climate sensitivity using 800,000 years of data are in (Rohling et al., 2009; Grant et al., 2012; Skinner, 2012; Hansen et al., 2013). The long-term equilibrium sea level for today's CO_2 levels is 23 m (75 ft) above today's sea level, and equilibrium temperature is around 16°C (27°F) above today's value (Figure 2.7) (Rohling et al., 2009). Both will be higher if CO_2 rises above the present level. Eventually, the sea level rise will stop because there is no more ice to melt and runaway warming is now racing toward that point when the Arctic Ocean was 19°C warmer than today (Ballantyne et al., 2010) and when CO_2 is thought to be around 390 ppm, below the current value of 400 ppm, and rising.

Rohling was not aware of the earlier work shown in Figure 2.5, and he plotted his curve the other way (CO_2 vs. temperature rather than temperature vs. CO_2 in Goreau (1990)), but when the graphs are flipped and scaled to overlay the axes, the results are essentially identical, confirming that IPCC models seriously underestimate how global temperature and sea level responds to CO_2.
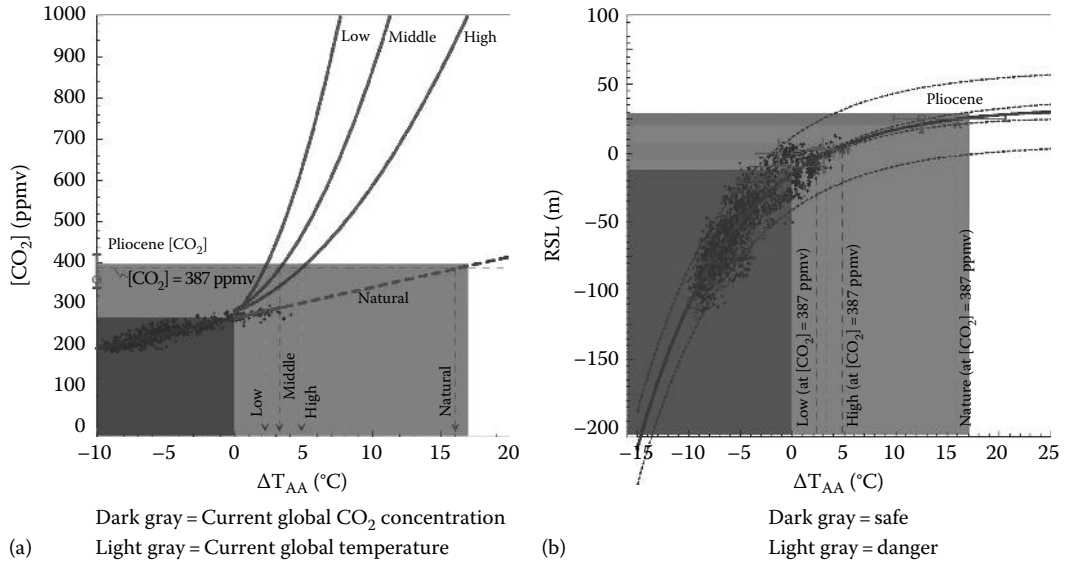
FIGURE 2.7 Identifying safe CO$_2$ limits from temperature and sea level responses. (a) Global CO$_2$ versus global mean temperature over the last 800,000 years, (b) global sea level changes versus mean temperature over the last 800,000 years. (Data from Rohling, E.J. et al., *Nat. Geosci.*, 1, 38, 2008.)

What Is the Safe Level of CO$_2$?

When CO$_2$ was around 280–290 ppm 125,000 years ago (Luthi et al., 2008), it was 1°C–2°C warmer than today and the sea level was 7 m higher than today. This suggests the safe level of CO$_2$ to avoid dangerous changes in sea level that will imperil billions of people living in coastal areas should be distinctly lower than 290 ppm. But there is an important caveat, because too low CO$_2$ values can trigger an ice age. The safe level of CO$_2$ today is higher than it was 125,000 years ago because at that time the Earth's orbital configuration was in a full interglacial (warm) mode, whereas now, if humans were not interfering with the system, the current orbital configuration would be moving toward an Ice Age. Slightly higher CO$_2$ levels are needed to compensate for the difference in the orbital characteristics at different times. The new ice age that would be expected from the current orbital configurations without human interference is now likely impossible because the huge excess CO$_2$ that we have now put in the atmosphere prevents it. Ruddiman (2005) convincingly claims that the earth would have already started an Ice Age about 5000 years ago if it were not for the massive CO$_2$ inputs from deforestation for agriculture that turned the natural decline in CO$_2$ levels (and temperature) into a dramatic increase starting about 8000 years ago (and accelerating further due to the industrial revolution). As a result, the safe level under today's conditions is likely around 270 ppm or so. Unless we can get to those levels very quickly, the long-term climate change forecast is far more alarming than any policymaker grasps.

The widely discussed *goals* for CO$_2$ discussed in the UNFCCC negotiations are dangerously higher than the safe levels. Some countries call for levels of 450 or more ppm, and the most conservative goals are 350 ppm (Hansen et al., 2008). Only Micronesia has called for a preindustrial CO$_2$ goal (i.e., around 280 ppm) at UNFCCC, but their call was ignored by the other small island developing states, which accepted 350 ppm as being a better target than 450 ppm. A level of 350 ppm amounts to a death sentence for all coral reefs and low-lying coastal areas, so low-lying island nations that support such goals are effectively agreeing to a suicide pact. The safe level should be based on the science of how the climate system responds to CO$_2$, and not politically convenient, arbitrary, and fictional goals.
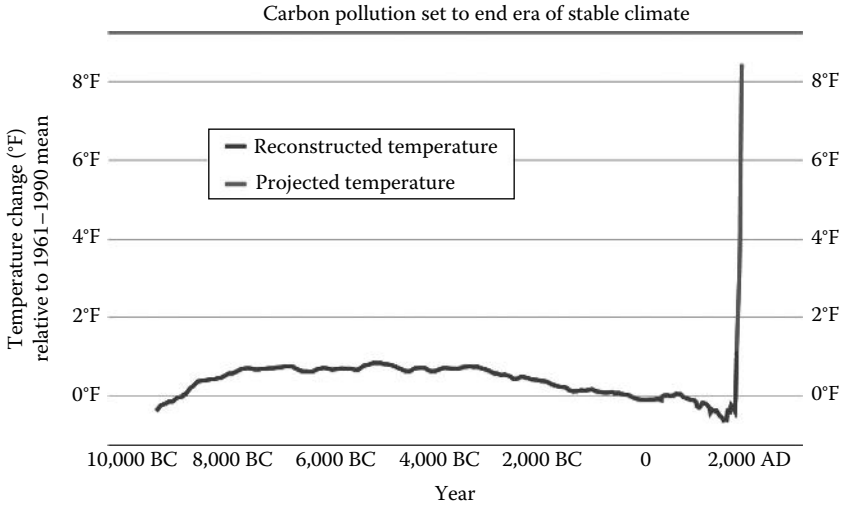
FIGURE 2.8   11,300 years of temperature.

Figure 2.7 shows how to determine the safe level of CO_2 that avoids serious change to current conditions using the data by Rohling and colleagues 2008.

We can use Rohling's graphs to determine the *safe* levels of CO_2 that do not cause dangerous increases in temperature and sea level—dark gray is safe and light gray is dangerous—with regard to change from today's conditions (Figure 2.7). These graphs suggest that the warming *in the pipeline* due to the current levels of CO_2, even if all production of fossil fuel CO_2 were completely stopped, is far higher than IPCC projections. We are already completely beyond the CO_2 range of the last 3 million years. We are headed directly for temperatures similar to the Pliocene, before the ice ages began, when the Arctic was up to 19°C warmer (Ballantyne et al., 2010; Brigham-Grette et al., 2013) and sea levels were round 25 m higher (Fagan, 2013). The graphs show that current CO_2 level corresponds to a long-term increase of temperature of around 17°C and of sea level by more than 23 m, based on climate changes over the last several million years. This will result in increases that are beyond our experience and the capability of most to adapt (Figure 2.8), and averting it requires a safe level of CO_2 around 270 ppm.

The reconstructed line shows global average temperature from global long-term climate records over the last 11,300 years since climate and sea level stabilized at the start of the current interglacial period (Marcott et al., 2013). The projected line is the mean IPCC estimate based on CO_2 increases, which is argued here to be a serious underestimate, so it should be even steeper than shown.

Limitations of Climate Prediction Models

All climate models agree that it will get warmer as CO_2 increases because they all contain the same fundamental physical laws, especially Lambert's law, which says that if we increase the concentration of a gas that absorbs heat, the gas will get hotter. This fundamental physical law is inviolable and allows no exceptions, just as the law of gravity means we can drop a billion apples, and every single one will fall down. All climate models come to precisely the same qualitative conclusion, but since they differ slightly in mathematical assumptions in the models redistributing that heat, they give slightly different predictions for how hot it will get and how long it will take to reach that level.

A fundamental weakness is the model's treatment of heat flow to the deep sea, which is by far the major heat sink in the earth climate system. Until the deep sea warms up fully, the surface ocean, atmosphere, and land surface will not reach their maximum temperatures, so the response contains an intrinsic thousand-year time lag. Most climate change models do not include realistic ocean models due to the fundamentally different space scales over which ocean and atmosphere processes operate.
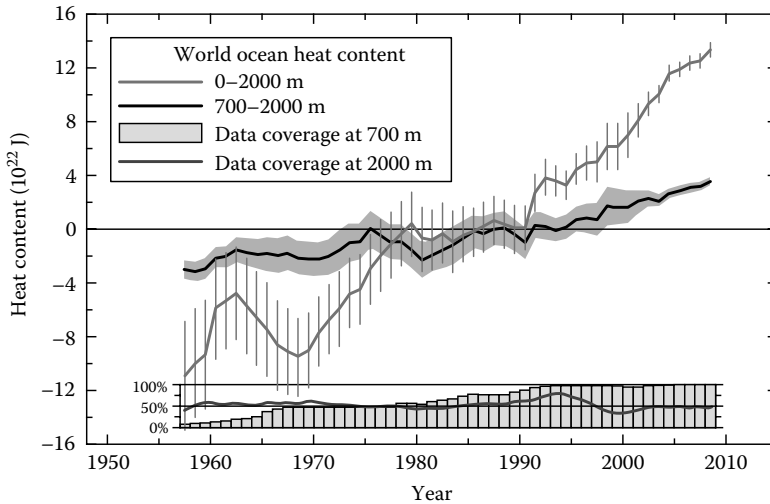
FIGURE 2.9 Heat content of the oceans. (From Levitus, S. et al., *Geophys. Res. Lett.*, 39, L10603, 2012.)

The increased global heat caused by the greenhouse effect is very real and fully measureable, but most is flowing rapidly into the deep sea, not accumulating at the surface. The increase in total heat in the earth system is increasing linearly and inexorably (Figure 2.9), even though we are not yet feeling it as SST. Despite many incorrect claims that global warming has stopped, in fact, there has been no slowdown in global warming (Levitus et al., 2000, 2001, 2005, 2012; Antonov et al., 2005; Hansen et al., 2010; Meehl et al., 2011; Balmaseda et al., 2013; Guemas et al., 2013; Otto et al., 2013; Rosenthal et al., 2013; World Meteorological Organization, 2013), precisely as expected from the physical effects of CO_2 increases.

A large part of the apparent slowdown of SST rise in this period was due to increased upwelling of cold water in the Southern and Eastern Tropical Pacific (Kosaka and Xie, 2013) caused by global-warming-induced increases in wind speed in the Southeast Pacific (England et al., 2014). The East Pacific has been in an unusually prolonged La Niña phase since 1998. The last La Niña was so strong that the global sea level rise was temporarily cancelled and ocean levels actually fell (Boening et al., 2012). This was due to record rainfall in Australia and South America, and much in Australia originated from evaporation of seawater that fell in inland drainage basins where it could not run back to the sea (Fasullo et al., 2013). After this ponded water evaporated, global sea level rise again accelerated to record levels. When the next El Niño hits, an upward jump in global SST and sea level will follow.

Any slowdown in the rate at which heat is flowing to the deep ocean will result in a dramatic jump in sea SSTs. There is clear evidence that during the warmest part of the last interglacial, when temperatures were about a degree warmer than now, a period that is the best model for the conditions we are soon headed for, the rate at which deep ocean water formed underwent sudden and prolonged shutdowns for century long periods (Galaasen et al., 2014). If that were to happen now, a sharp rise in SST would be expected.

Another process slowing the temperature increase is that melting of ice adds heat to the system without raising the temperature. Once the ice is gone, the temperature increase will jump dramatically upward. This effect has been neglected in climate models to date.

A further factor is all the pollution we put in the atmosphere causing smog that reflects sunlight. Dirty fossil fuels with high sulfur content add sulfuric acid to the atmosphere, which forms aerosols that cool the earth by reflecting sunlight. When we burn fossil fuels this cooling effect lasts days to weeks until the sulfuric acid rains out (Smil, 2001), but the warming effect of the CO_2 that accompanies it lasts for centuries. One would have to add exponentially increasing sulfuric acid pollution just to stay in place and keep balancing the temperature effect of the original CO_2 input with sulfuric acid aerosols, as proponents of geoengineering propose. Even if we were to shoot sulfuric acid by rockets into the upper atmosphere, it might last only a year or so before raining out, causing acid rain damage to forests and agriculture, and

one needs to keep adding more and more to mask the warming of the CO_2, while adding more CO_2 to do so. This is a race that can never be won. Incredibly, the fossil fuel industry pays lavishly for research on such schemes that cannot possibly work even if they were technically feasible and affordable, but some academics and politicians treat this as a serious option, most likely to get funding from oil and coal companies.

Even if the models all agree on the fact that it will get hotter, they do not agree on what will happen to rainfall. Some models predict increases, others decreases, and others no change. They do not even agree with each other qualitatively due to the models being far too primitive to predict the real-world distribution and effects of clouds. One can look up at the complex pattern of clouds in the sky and realize no model is complicated enough to realistically describe what we see every day above our heads.

Qualitatively, the warmer it gets, the more evaporation will take place, so atmospheric moisture and rain will dramatically increase on a global average. Real-world measurements show strong global increases of atmospheric moisture and average rainfall with a water cycle increase of around 8%/°C (Durack et al., 2012) or 16%–24% if temperature rises 2°C–3°C. Tropical extreme rainfall events get up to 6%–14% more frequent per °C of temperature increase (O'Gorman, 2012). Water vapor in the air over the tropical ocean increases about 7%/°C (Held and Soden, 2006). Changes in surface ocean salinity show wet areas are getting wetter while dry areas are getting drier (Boyer et al., 2005). Periods in the geological past with much higher CO_2 and temperature had much higher rainfall and erosion, especially before plants evolved and began to stabilize and build soil (Beerling and Berner, 2005; Beerling, 2007; Gibling and Davies, 2012). What is clear is that global warming will make climate much wetter along coasts near sources of moisture, while inland areas in the centers of large continents will get drier because soil moisture evaporation increases strongly with temperature, but the rain falls out in the mountains before it reaches the continental interiors. The result is that wet areas will get wetter and dry areas drier, as data shows it is actually happening (Jung et al., 2010).

Analysis of global rainfall data from 1979 to 2010 (Chou et al., 2013) shows that wet seasons are getting wetter (0.94 mm/day/century), dry seasons are getting drier (−0.53 mm/day/century), and the annual range is increasing even more (1.47 mm/day/century), just as expected from fundamental physical principles. The largest variations of rainfall were over the oceans, rather than land, while for temperature, the opposite was true. This results from the fact that the ocean is all water, while only small parts of the land are covered with water that can evaporate, and since water has much higher thermal capacity, it changes temperature more slowly than land does.

On land, most areas got wetter in the rainy season, in particular the Sahel, Southern Africa, Northern Australia, Northwest India, Pakistan, the Amazon, and the Southern Caribbean. However, some areas got *less* rain in the wet season, in particular, the Near East, the Mediterranean, North China, East Africa, Central Brazil, Southern Australia, the northern Caribbean, the Coral Triangle (Indonesia, Philippines, New Guinea, the global center of marine species diversity, the Amazon and Congo of the ocean), the central Andes, and the Western and Southern United States. This has enormous implications for agriculture in those places and alarming ones for some of the world's major food producing areas that are getting less rain in the growing season. Another interesting trend is the large increase in wet season (summer) rain in the Arctic regions, which will further melt ice.

While dry season rainfall decreased most over the oceans, South America, India, Pakistan, the Caribbean, and the Western and Southern United States were especially affected, leading to increased droughts. Polar regions also got drier in the dry season, meaning less snowfall, leading to reduction in snow and ice thickness. An unusual exception is the Coral Triangle, which became slightly wetter in the dry season, probably from increased ocean evaporation.

The seasonal range shows increased seasonal ranges in rainfall over most of the oceans, which will cause water availability for aquifers to decrease in the dry season and increased droughts, with more runoff and erosion of soil onto coral reefs in the rainy season. The Coral Triangle is an unusual exception where the range decreases slightly.

So even if the models are essentially useless to predict future trends, the measured current rainfall trends, which are our best guide to future trends, are cause for serious concern regarding disruption to worldwide agriculture and ecosystems from rainfall changes, as the latest IPCC states.

How High Can the Sea Level Go?

There is no limit to how high temperature can go if CO$_2$ reaches above the levels of the distant geological past before the ice ages began around 3 million years ago, when periods of high CO$_2$ resulted in temperatures up to 15°C or 20°C higher than today (Ballantyne et al., 2010). One recent study from such a period of high CO$_2$ around 55 million years ago found SSTs as high as 74°C, or 165°F! On the other hand, there is a real limit as to how high sea level can rise, which is limited by the total amount of ice in the continental ice caps (mainly Antarctica, plus a much smaller contribution from Greenland) and mountain glaciers (mainly in the Himalayas, the Andes, and Alaska). Once that is all melted, sea level cannot rise further. The data suggest that at essentially all the ice will eventually melt at a global atmospheric CO$_2$ concentration of about 400 ppm, what we *already* have at time of writing this chapter.

Rohling et al. (2009) calculated the sensitivity of sea level to CO$_2$ (Figure 2.7). This indicates that the equilibrium level of today's CO$_2$ level is 23 m above today's level (75 ft), and if CO$_2$ increases further, it will be significantly higher. Projected increases in CO$_2$ expected in the coming decades of this century could lead to equilibrium sea levels 50 m or more above today's levels and even higher (80–100 m) if runaway ice cap melting takes place. These are vastly beyond the levels that IPCC model projections present, of 5–10 cm, with extremes of 1 m sea level rise from more recent IPCC models. The geological record represents the entire long-term system response, not the short-term initial transient response in IPCC models. As was pointed out earlier, it takes thousands of years before the responses are fully developed. But they do represent the real long-term changes to which we have committed future generations, a situation that would flood billions of people from their homes in coastal areas, perhaps half the human population. These changes will be vastly greater than the feeble sea level changes IPCC projects, which people falsely think can be adapted to by building 1 m high sea walls, not realizing that is but a temporary fix, and they will need to build higher walls every generation, for hundreds of generations.

The logical fallacy of relying on IPCC projections as a guide to future changes is like someone kicking a football, measuring how far the ball has moved in one tenth of a second, and then thinking that is how far the ball will go! This is precisely the thinking that currently guides global climate change policy, based on IPCC projections for time scales that miss almost all of the inevitable response, giving the wrong answer to the wrong question.

Seeing the Past, Present, and Future

The sensitivity of sea level to CO$_2$ and temperature is clearly visible to those who know how to read the landscapes left on coastlines all around the world from the last time in earth history when sea levels, and temperatures, were higher than today. That happened at the last interglacial epoch 120,000–130,000 years ago, when the configuration of the earth's orbit, amplified by natural internal climate feedback factors, caused some of the highest temperatures in the last 3 million years (van de Berg et al., 2011). At that time, global temperatures were around 1°C–2°C warmer than today, and sea levels were about 7 m higher than they are now due to the melting of polar ice caps (Rohling et al., 2008; Kopp et al., 2009; Dutton and Lambeck, 2012). Yet at that time, CO$_2$ levels were around 280 parts per million (ppm). The current CO$_2$ value at time of writing is more than 40% higher than those values. And, unlike now, the feedbacks that affected CO$_2$ then were purely natural, since the human race was only recently evolved, very small in number, confined to southern and eastern Africa, and had not developed the technology to cut down and burn the forests on a large scale and significantly change CO$_2$.

We can see the precise sea level from those days perfectly preserved at a handful of places, probably no place better than on the North Coast of Jamaica. Stable sea levels create a sea level notch in limestone rocks, and Jamaica has ideal conditions for its formation and preservation, although one can find examples in other places, such as Bonaire and Barbuda. Jamaica has been tectonically stable in the last 130,000 years, and the same level is found at sites all around the island and correspond closely to those in Bonaire and Barbuda, so it is the result of global sea level changes, not of local vertical tectonic movements caused by earthquakes or uplift.

FIGURE 2.10   Fossil sea level notch at Discovery Bay, Jamaica. (Photographed by T.J. Goreau.)

Figure 2.10 was photographed inside the sea level notch at Discovery Bay, Jamaica, looking outward with today's ocean, some 7 m lower, clearly visible in the background. Inside the sea level notch, one sees large masses of rock (visible at right) that fell from the limestone cliff above into the mouth of the notch. Fossil corals and encrusting marine organisms are found below the notch itself, but not above, and also on the fallen rocks below this level, showing that the rock fell from the cliff into seawater at the time that the notch formed and was colonized by marine organisms below the high water mark (Goreau, 1990).

Discovery Bay, Jamaica, is a place where one can see the past and the present, and if you know what to look for, you can see our future as well. At the same time that sea level formed this notch in Jamaican limestone cliffs, hippopotamuses and crocodiles lived in subtropical swamps where London, England, now stands, their fossils are in the British Museum of Natural History. Since conditions at that time represented CO_2 levels of around 280 ppm, and we are already at 400 ppm, it is clear that what happened at that time is a considerable underestimate of what is going to happen from today's CO_2 levels, even if all fossil fuel use stops overnight.

A geological cross section of the North Coast of Jamaica shows the fossil and recent sea level notches, and the coral reefs that grew in front of them. Figure 2.11 shows these formations, mapped by the author when he was 14. Much higher up the cliff, around 50 m or so high, are the traces of several fossil sea level notches that probably date from the Pliocene period, before the ice ages started, when CO_2 levels were a bit less than the 400 ppm they now are and the Arctic was up to 19°C warmer (Ballantyne et al., 2010; Brigham-Grette et al., 2013)! That is where our current course of action will inevitably lead us if we do not quickly reduce CO_2 levels.

The Jamaican fossil reef from 125,000 years ago has two distinct layers. The lower layer has the corals in position of growth, then there is a thin sharp layer of mud about a centimeter thick, and above that, all the corals are broken and lying on their sides. These coral reefs appear to have died from excessively high temperatures (Kiessling et al., 2012) and then been devastated by huge waves, from hurricanes stronger than any we have experienced (another well-founded prediction for global warming according to Emanuel, 1987), or tsunamis. This sharp boundary is found all around Jamaica and can also be seen at other sites all around the Caribbean that the author has looked at, suggesting the latter. Given that we are already at the maximum temperature that corals can tolerate (Goreau and Hayes, 1994, 2005) and
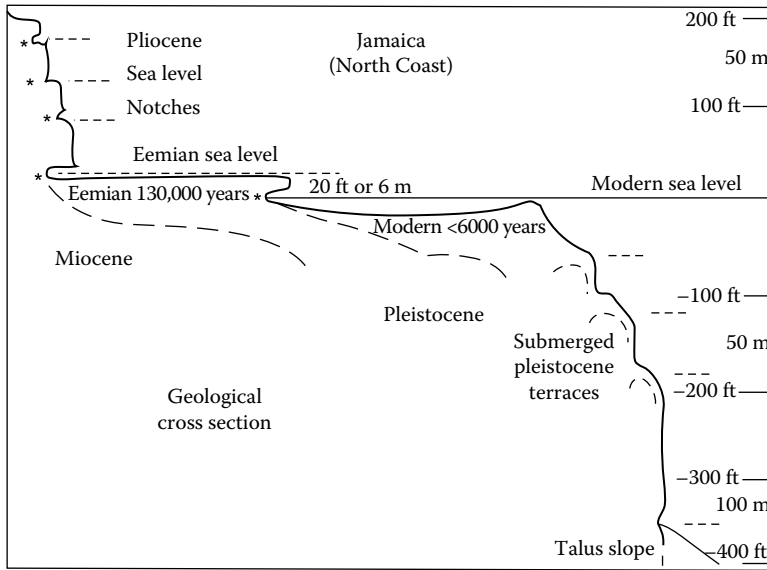
FIGURE 2.11 Geological cross section of North Jamaica. (After Goreau, T.J., 1965.)

that the temperatures at that time were above that lethal threshold, then it is likely that these reefs had already been killed by high temperatures (Kiessling et al., 2012; O'Leary et al., 2013) before they were physically damaged, and it was the dead coral skeletons that were flattened.

At present, we are at CO_2 levels much higher than in those days but we have not yet felt the response of the latest increase (Figure 2.12).

Time history of atmospheric carbon dioxide from 800,000 years ago until January, 2012

FIGURE 2.12 CO_2 changes measured in Antarctic ice cores over the last 800,000 years. CO_2 levels at the last interglacial, when the elevated sea level notches formed, were around 270 ppm, much less than the current value of 400 ppm. (After NASA, http://www.youtube.com/watch?v=vA7tfz3k_9A&feature=player_embedded#at=203.)

FIGURE 2.13 Long-term sea level changes (2000 years) for various global warming scenarios. (After Levermann, A. et al., *Proc. Natl. Acad. Sci.*, 2013.)

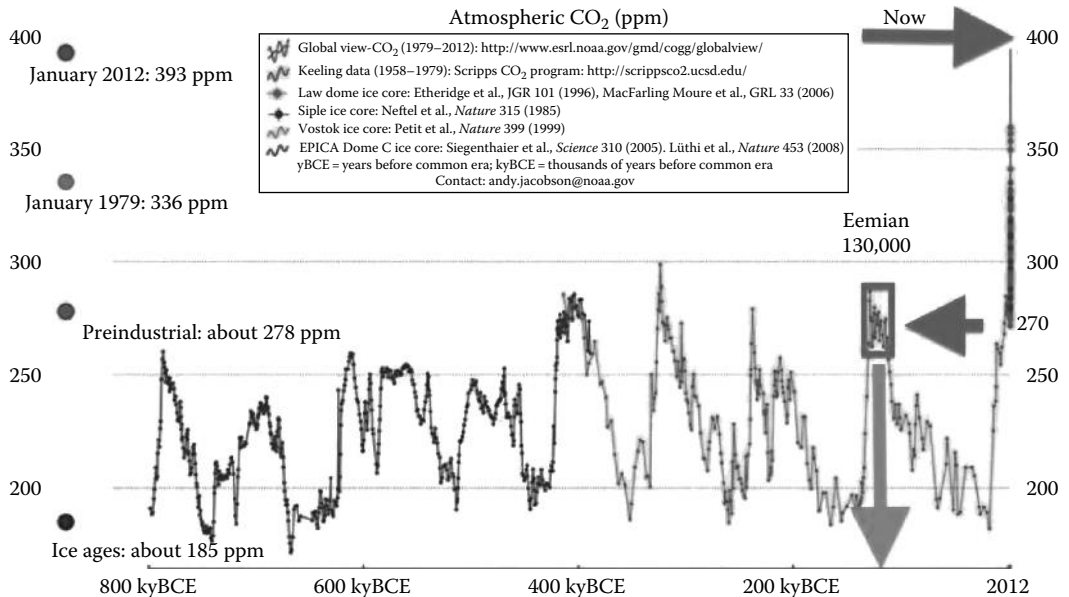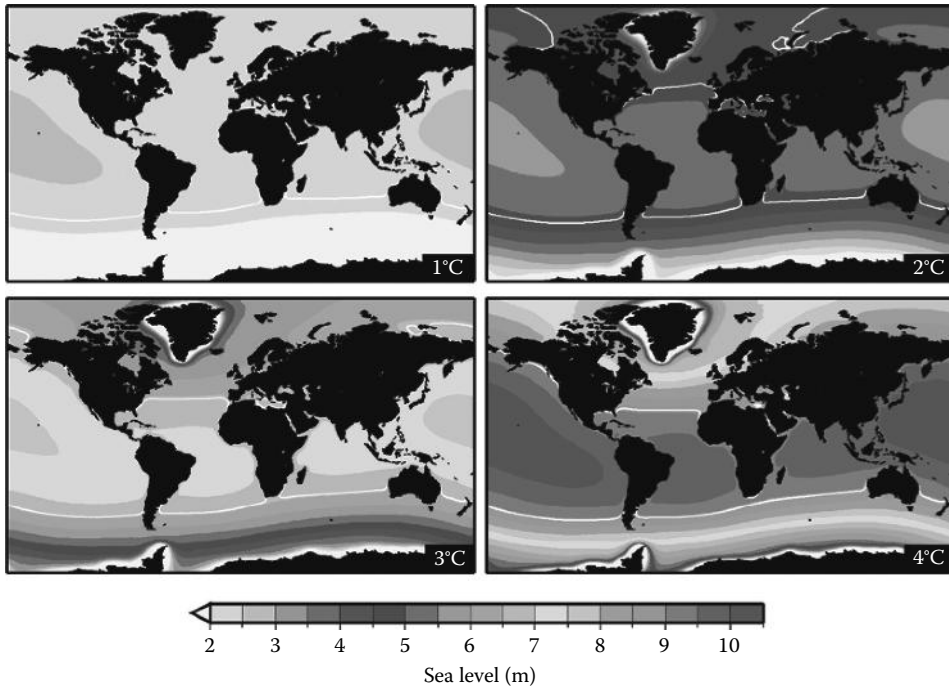Long-term sea level rise estimates based on paleoclimate data (Levermann et al., 2013) are in accord with much higher climate change sensitivity than IPCC model projections (Figure 2.13).

The Other Half of the Global Carbon Dioxide Problem

Almost all discussions of CO_2 stabilization focus only on emissions reductions. We show in the following that such supply-side *solutions* cannot possibly work in time and miss the most important opportunities to remove excess CO_2:

The rate of change of atmospheric carbon dioxide is associated with changes in its major sources and sinks, which are biotic, not industrial. The literature focuses on comparing quantities of carbon in different pools rather than fluxes between them, which are poorly known, except for combustion. This emphasizes large pools, which slowly exchange with the atmosphere (fossil fuels, soil humus, the deep ocean, limestones, volcanic gases) over smaller ones, which exchange much more rapidly (the tropical biota). Hence it artificially obscures the other key to the atmospheric CO_2 problem, which is to protect the metabolism of the tropical biota, the primary determinant of atmospheric composition.

Current land 'development' practices that ignore changes in community ecophysiology have a large hidden price tag. They diminish the capacity of the biosphere to modulate atmospheric CO_2, which increases the magnitude and duration of climatic alteration (Goreau and de Mello, 1987, 1988; Goreau, 1992) beyond those forecast by conventional climate models.

There are two real limiting options. First, destruction of the biota and conversion of productive ecosystems to degraded secondary habitats increases combustion-derived atmospheric CO_2, which dissolves in the ocean on a 103 (thousand) year time scale, and becomes incorporated into marine sedimentary carbonates and organic matter on a 105 (hundred thousand) year time scale. Avoidance of the worst risks of the Greenhouse Effect will require global limits and national quotas on combustion.

The second, missing option is to conserve the remaining undisturbed habitats that cycle carbon rapidly (like tropical rain forests and coral reefs) and to undertake pan-tropical replanting and fertilization to restore

productivity to degraded areas. Atmospheric CO_2 is held down by rapidly recycling through the biota, and the ultimate fate of most added carbon is soil and sediment organic carbon, further enhancing soil productivity.

To escape the Greenhouse Problem by renewable resource-based land management is much the cheapest option in the long run, and has many advantages. Solutions equitable to all countries demand cooperation. The price of fossil fuel should include its long-term environmental costs as an added "energy-growth" tax, which transfers income from fuel burners to environmentally sound tropical development. The sooner such a course is adopted, the greater the benefit and the lower the cost (Goreau, 1987).

The key question then is what time scales are involved in the trajectories of CO_2, temperature, and sea level in both of these scenarios, and if the impacts can still be meaningfully reduced in the rapidly shrinking window of time remaining. Had the world acted in 1987 when that paper was published, much of what will happen could have been averted, and the longer we wait, the more difficult and expensive it will be to accomplish. To understand the time responses, we need to look more closely at the dynamic time scales with which each major carbon pool interacts with atmospheric CO_2, including all their sources and sinks.

Carbon Cycle Response Times: Dynamic Time Scales of CO_2 Sources and Sinks

Every process that produces or consumes CO_2 results in a flux of CO_2 molecules between the atmosphere and each other carbon pool that interchanges with it (Goreau, 1992). We can define a matrix of time scales that define how long each process takes to significantly change atmospheric CO_2 and combine these time constants into the complete spectrum of all of the source and sink time constants, which then allows us to determine how quickly the atmosphere will respond to changes in fluxes (Goreau, 1995). It is crucial to use gross fluxes, not net fluxes, which are the difference of two separate processes with different time constants, but one can treat any combination of source and sink fluxes. These fluxes are shown in Table 2.2 (Goreau, 1995) and their time scales in Figure 2.14. We can use these figures to estimate the

TABLE 2.2

Major Atmosphere CO_2 Exchange Fluxes and Time Constants

Process	Flux (%/Year)	Time (Years)
Sources		
Ocean–atmosphere	12.99	7.7
Plant respiration	7.81	12.8
Decomposition	7.81	12.8
Fossil fuel combustion	0.714	140
Deforestation	0.338	295.8
Volcanism	0.012	8,500
Sinks		
Photosynthesis (land)	−15.625	−6.4
Atmosphere–ocean	−12.99	−7.7
Sedimentary burial	−0.39	−256.4
Soil formation	−0.052	−1,925
Weathering	−0.01	−10,000
Net balance		
All sources	29.674	3.37
All sinks	−29.067	−3.44
Net change	0.607	165

Source: After Goreau, T.J., Tropical ecophysiology, climate change, and the global carbon cycle, in J. Pernetta, R. Leemans, D. Elder, and S. Humphrey (Eds.), *Impacts of Climate Change on Ecosystems and Species*: *Environmental Context*, International Union for the Conservation of Nature, Gland, Switzerland, pp. 65–79, 1995.

Major atmospheric CO_2 sources and sinks:
Sizes and replacement times

FIGURE 2.14 Time response spectra of all major sources and sinks of atmospheric CO_2, showing the percentage of CO_2 replaced each year and the length of time each source or sink takes to cycle CO_2 to or from the atmosphere. (After Goreau, T.J., Tropical ecophysiology, climate change, and the global carbon cycle, in J. Pernetta, R. Leemans, D. Elder, and S. Humphrey, Eds., *Impacts of Climate Change on Ecosystems and Species*: *Environmental Context*, International Union for the Conservation of Natu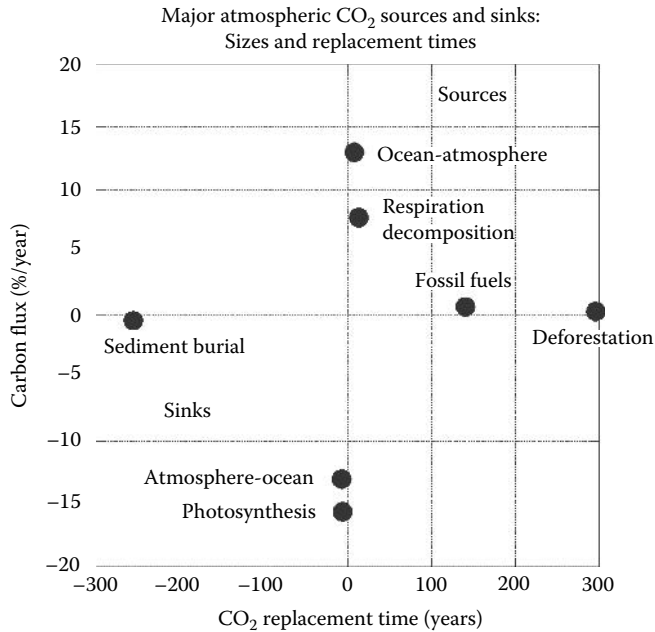re, Gland, Switzerland, pp. 65–79, 1995.) Note that only a few processes can act on a time scale of less than a century (other smaller and slower acting sources and sinks are not shown on this scale). Also note that respiration and decomposition are shown as equal. In reality, only fossil fuel sources are well known; the others have a fair range of estimates and will be refined in the future when better numbers are available. However, this will not result in important changes in the conclusions. In particular, as discussed further on, a large part of decomposition is actually underground plant respiration, so respiration is in reality larger and decomposition smaller. Photosynthesis is the only major source or sink that can be readily modified by human activity. Fossil fuels are too small a global source to be able to change CO_2 much on a time scale of a century even if all fossil fuel sources were eliminated immediately.

response time scales of various CO_2 source and sink options. For example, all sources acting together or all sinks acting together will process atmospheric CO_2 in about 3 years, but since sources outweigh sinks by only a small amount, the current rate that the net of all sources and sinks would change CO_2 by the same amount is around 165 years. Here, we focus on the *fast carbon cycle* and ignore the *slow carbon cycle* exchanges that take much longer to affect CO_2, such as with ocean bicarbonate, which takes 200,000 years to turn over, or sedimentary organic matter and limestone, which affect CO_2 over many millions of years (Holland, 1984; Walker, 1986; Berner, 2004).

These atmospheric CO_2 response spectra allow one to see at a glance which processes are the most effective. We now use these data to systematically examine the rate at which various supply and demand-side measures act to affect atmospheric CO_2:

1. Source side reductions only: We cannot practically reduce the rate at which CO_2 is released to the atmosphere by the oceans and by respiration and decomposition, so our only leverage on the supply side is on fossil fuel combustion and reducing emissions from deforestation and land degradation. Even if we *completely stop* these sources right now (or had 100% carbon capture and sequestration [CCS] of all fossil fuel CO_2, which is impossible technically as well as unaffordable if it were), it would take about 140 years for the atmosphere excess to respond by decreasing by half if no other sources and sinks changed. If we reduce emissions by only 50%,

it will take twice as long. Stopping deforestation will take several times longer to have an impact. It is clear that supply-side measures alone will be very slow at best, centuries to thousands of years, and cannot possibly act quickly enough to avert the worst damage.

2. Sink side increases only: We cannot practically change the rates at which CO$_2$ is transferred from atmosphere to the ocean any more than we can change the converse flux, because we cannot control the wind and waves. Photosynthesis recycles all of atmospheric CO$_2$ in only about 7 years. Almost all of it is returned in short order via respiration and decomposition, so the strategy that is needed is to increase photosynthesis (which is limited not by CO$_2$ but by nutrients, which is a key point of this book). Even more important is to find ways to store that photosynthetic carbon so it does not go right back to the atmosphere. What we can do though is to convert photosynthetic carbon into forms of carbon, like biochar, that are very slow to be oxidized or decomposed. If we could turn half of photosynthesis carbon into biochar, we could remove most of the excess CO$_2$ in the atmosphere in around 15 years. Figure 2.14 shows that this is the fastest (and very likely the cheapest) method for getting rid of the excess CO$_2$. The more biochar we make, the more root biomass, fungi, and soil organic matter we grow, storing even more carbon, and the faster we can avert the worst consequences of runaway warming and the more cost effective the investment will be. By accelerating the rate of rock mineral weathering by plant roots pumping CO$_2$ into the soil, we also add an additional CO$_2$ sink. While that is likely smaller than what we can do with biochar, the chapters in this book show that combining these two carbon sinks in the right ratio maximizes the increase in soil fertility and photosynthesis, further speeding up the removal of excess CO$_2$, and has the capacity to take up the excess CO$_2$.

3. Combined strategies: By combining source reductions with sink increases, we can accelerate the transformation and avert more damage to the global environment and economy. We can stabilize CO$_2$ at safe levels in the minimum possible time only by combined strategies. It is therefore important to reduce fossil fuel sources as quickly as we can, since relying on increased sinks alone will be slower and more damaging in the long run. Combining processes is much faster (Goreau, 1995), but it must be noted that time constants are not additive, they add the same way as parallel electrical resistances, the inverse of the net time constant of several processes acting together is the sum of the inverse time constants of all the process (Goreau, 1995).

Polluter Pays: Carbon Taxes and Fees

The only practical way to avert the consequences of the existing CO$_2$ excess is to reduce CO$_2$ quickly enough to reduce the impacts, and this must now be done very quickly, within a few decades, if we are to avert the most dire and drastic consequences. Had the world community acted seriously when UNFCCC was signed in 1992, the problem could already be well on the way to solution, but instead the problem was ignored and allowed to get worse, and these systematic failures to act have made solutions far more difficult and expensive. The window of opportunity is constantly shrinking and will soon close.

All economic experts agree that prices of products should include all their real costs and that *the polluter pays principle* is the fundamental basis of waste management. Any other strategy saddles other people with the costs of benefits they do not obtain, what economists call *externalities* (DasGupta, 2002; Stern, 2006). A realistic price must include all the real costs, and we have failed to do so: recent estimates place the real costs of fossil fuel CO$_2$ emissions at a minimum of $125/ton, possibly higher (van den Bergh and Botzen, 2014). If fossil fuels and nuclear power paid for the real costs of the energy they produce, renewable energy would be far cheaper and no subsidy would be needed to compete, but the fossil fuel and nuclear industry are massively subsidized directly and indirectly through giveaways and tax breaks totaling trillions of dollars (Trucost, 2013). On top of this, most of the value of the oil companies is now in underground carbon reserves that cannot be burned, creating an enormous financial bubble of overstated assets (Carbon Tracker, 2013).

If polluters do not clean up their own mess, they leave it indirectly to public taxation to pay the cleanup as a public service. The more directly this carbon transfer is done, the cheaper and the faster the result. Transaction costs are minimized and efficiency increased by eliminating fund skimming by intermediaries who do not actually solve the problem, passing the problem on to the next level while taking a cut of the funds for themselves. There is great pressure to control such funds by politicians and government bureaucracies in order to pay for the deficits they create through unproductive expenditure. The desire to intercept tax revenues for other purposes prevents interactions in which the *polluter pays* up front as directly as possible to the person who cleans up their mess (if they are incapable of doing so themselves).

The polluter should pay up front at the time they purchase fossil fuels, and not saddle future generations with the costs of a previous generation's gratification. Apart from being inequitable and unjust, any other approach results in more expensive and complicated *ad hoc* arrangements, which are usually inadequate to resolve the problems created. The simplest way is a direct carbon tax paid by the purchaser in proportion to the carbon content, which is easily verifiable at the source. There is no guarantee that any *post hoc* market mechanism will settle on the correct price for pollution and plenty of empirical evidence that it does not. Figure 2.15 shows the European carbon trading price. Since then, the price has collapsed further as the result of the failure of the EU to reform the carbon trading system, even though it is the centerpiece of their global climate change strategy. It is clear this strategy has failed politically, economically, and environmentally, and a much more serious strategy is needed.

At present, the world subsidizes fossil fuels to the rate of 500 billion dollars/year (Whitely, 2013), or about \$15/ton of CO_2 emitted. This subsidy to pollute far exceeds the \$3/ton EU carbon tax, so that the current structure of carbon trading rewards pollution. If this perverse subsidy rewarding polluters were instead spent on actually absorbing carbon, most of the costs of CO_2 stabilization might be met.

There are two major options by which a carbon tax can be administered. One is as direct as possible a transfer from carbon fuel purchasers to those who verifiably absorb their carbon. That way, the polluter directly pays for the removal of his/her pollution, and this is precisely the sense in which a carbon tax was originally proposed (Goreau, 1987, 1990; Myers and Goreau, 1991), not as a tax that would disappear into general tax revenue and be spent on unrelated problems.

Unfortunately, the term carbon tax was later used on a much larger scale by economists to convey a diametrically opposite concept, trivializing the term as originally intended and making it ineffective at
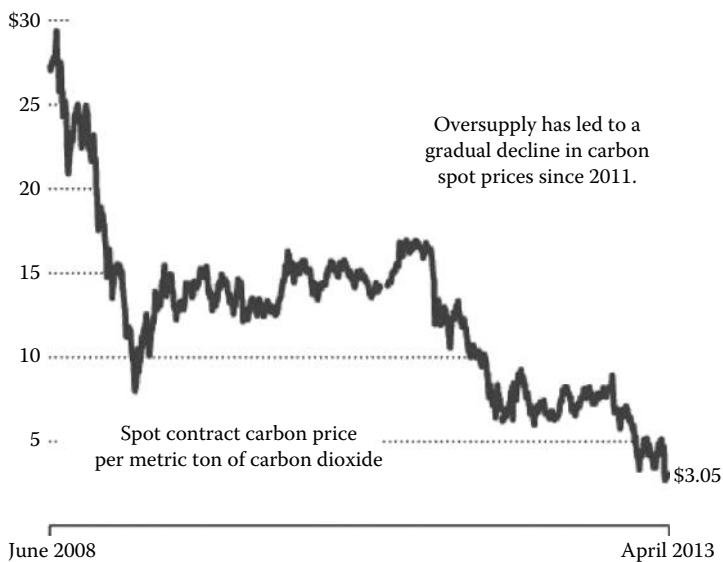

FIGURE 2.15   EU carbon price. (From Thomson Reuters.)

solving the problem. Economists seeking market mechanisms ask: how much do we need to tax *goods* and *bads* (products with negative societal consequences) so the increase in price reduces their consumption and the damage they cause? Obviously real *goods* that only provide positive benefits should be encouraged as much as possible, and any tax on them reduces their benefit value, which is why many economists believe that true *goods* should not be taxed, only *bads* that reduce the capacity of society to use its resources to best effect, saying "tax bads, not goods" (Stiglitz, 2006).

However, energy use is not what economists call *elastic*, that is to say that an increase in price results in a proportional decrease in consumption. You can raise fossil fuel prices in Los Angeles 10 fold, and people will still need to drive, so large increases in prices are needed for small decreases in consumption. The result would be small contribution to real pollution reduction, while increasing energy prices so much that all users would suffer brutal declines in living standards as most of their money goes to buy petroleum. This is the most expensive and ineffective solution.

But the problem is worse than that, because carbon taxes as proposed by economists and politicians are designed to go into general government revenue, they would be spent without solving the problem by directly absorbing the CO$_2$. The economists' and politicians' current concept of a carbon tax is an expensive boondoggle that impoverishes people without solving the problem and prevents direct solutions transferring the CO$_2$ to where it will provide the greatest benefit to society.

Equally destructive is the economists' habit of *discounting the future*, making severe impacts count less and less the further in the future they occur. Either the discount rate for CO$_2$ pollution should be zero or the discount rate should be small and last long enough to extend its duration the entire time length of the impacts in order to be meaningfully calculated (Stern, 2006; van den Bergh and Botzen, 2014).

Where Can We Store Excess CO$_2$: Geoengineering

There are two options: (1) to enhance natural sinks and storage mechanisms (geotherapy) or (2) to create artificial ones (geoengineering). We discuss geoengineering first, because it gets all the attention and press. It is important that these diametrically opposed concepts not be confused, because they are different in all respects. Geoengineering sinks usually involve (1) chemicals to absorb CO$_2$, (2) pumping CO$_2$ someplace where it would not come back (CCS), or creating shields to reflect sunlight from reaching the earth's surface, whether clouds, aerosols, smoke, or mirrors (The Royal Society, 2009). Chemical absorbents are costly and relatively inefficient, although some good new ones may be developed. But it is unlikely that these can make much difference to the atmosphere as a whole at an affordable cost, so they are largely confined to trying to strip CO$_2$ out of the exhausts of major power plants (Rau et al., 2007; Rau, 2008, 2009, 2011). In this case, they reduce some of the new CO$_2$ inputs, but cannot remove the excess CO$_2$ already in the atmosphere like plants do.

CCS, in order to be effective, must extract a very small amount of CO$_2$ from power plant exhaust gases (typically no more than a few percent of the total gas) from a vastly greater amount of nitrogen and oxygen, purify it, compress it, and pump it large distances to a hole in the ground or the deep sea, where it is hoped that it will never leak back. If concentrated CO$_2$ is pumped into the deep ocean, it will immediately bubble to the surface, and high-pressure pumping into underground layers, such as done in fracking, fractures overlying confining layers. These conditions make this option very unlikely to be efficient (proper testing has not yet occurred due to prohibitive testing costs) or cost effective, a source of earthquakes, and a threat to overlying aquifers. Concentrating CO$_2$ and shooting it out into space would be prohibitively expensive, even if all rocket launches actually succeeded, more so when they do not.

CCS has been widely touted by fossil fuel producers to be the answer that will allow us to keep burning fossil fuels as if there were no tomorrow without paying an environmental price, and CCS research is lavishly funded by the fossil fuel industry. All claims that CCS could be feasible and affordable have been clearly rejected by serious investigators, who suggest that the real costs would be

something like around $1000/ton (House et al., 2011; Michel, 2013; Scott et al., 2012). The CCS cost could be more expensive than the benefits from burning the fossil fuel, while also consuming additional fossil fuels for CO_2 extraction, concentration, and transportation. Almost all CCS projects that have been started have been abandoned as uneconomic (House et al., 2011; Scott et al., 2012; Michel, 2013). Even if they could affordably capture *all* of the CO_2 emissions from large stationary sources like big power plants, the inability to trap smaller household cooking, heating, and transportation fossil fuel emissions would cause the net impact on global atmosphere CO_2 to be at best a small and slow source reduction (Michel, 2013).

Another popular high-tech *solution*, nuclear power, is also less effective than it seems. Nuclear power does in fact have a large carbon footprint from power plant manufacture and fuel processing. Nuclear power is intrinsically inefficient because it can only be used to make electricity and bombs, and electrical transmission line losses require thousands of nuclear power plants spaced every few hundred kilometers apart. It makes no thermodynamic sense to use power sources with potential energy of millions of degrees only to heat up water by a few tens of degrees to boil water for electrical power plants, since this wastes almost all of the energy potential. Even if there were no safety and terrorism issues, and no problems of storing nuclear wastes safely for a quarter of a million years afterward, the costs of nuclear power do not include the costs of decommissioning power plants, which are passed on to the taxpayers later. It can cost hundreds of billions of dollars to shut down nuclear power plants. If these real costs were included in the electricity price, nuclear power would not be cost competitive, but instead, taxpayers heavily subsidize them. Furthermore, the total amount of the uranium resource is limited and would not last much longer than petroleum, for about a human generation or so. Somewhat more power could be obtained using thorium, and even more making plutonium from uranium and thorium, but this would require breeder reactors every few hundred kilometers making plutonium and shipping it in large quantities to plutonium power plants. Plutonium is perhaps the most toxic substance known; a teaspoonful in a reservoir could kill a city of millions and an open invitation to mad terrorists and mad generals to build bombs. The precautionary principle tells us that this is a future worth avoiding.

Several geoengineering approaches have been proposed to use the oceans to get rid of CO_2 and heat. One proposal involves building huge pumps to pump cold deep ocean bottom water to the surface, in order to mix atmospheric CO_2 down into deep water (Lovelock and Rapley, 2007). The proponents unfortunately do not realize that deep water has much higher CO_2 content than surface water. Ocean bottom water forms in polar regions since CO_2 is far more soluble in cold water than warm water, and in addition, bottom water has much more added CO_2 from decomposition of organic matter in deep waters and sediments. The net effect of this proposal would be to greatly increase the rate at which CO_2 is added to the atmosphere, the opposite result of what they claim.

Another geoengineering fix is to fertilize the oceans in the hope that plankton will grow, take up CO_2 from the surface, and sink to the bottom without decomposing. In fact, almost all the organic matter plankton biomass produced is rapidly returned as CO_2 within days to weeks as the plankton respire, are eaten, or die and rot, and most of this recycling takes place in surface waters. Most of the rest is decomposed on its fall down to the deep sea, on the bottom mud, or inside the sediments. Only a very tiny fraction of the carbon, typically one tenth of one percent, are preserved, so in fact, the net sink would be very small indeed (Betts and Holland, 1991). The only way to bury carbon without it rapidly rotting is to turn the entire ocean into an anoxic *dead zone* devoid of oxygen. This is indeed the condition that was present when much of our oil supply formed around a hundred million years ago, when the water was very hot due to high atmospheric CO_2, with the result that very little oxygen could dissolve in hot water, and was rapidly consumed by bacteria. To make the ocean an effective carbon sink by turning it into a dead zone would kill the fish, almost all marine life, and toxic hydrogen sulfide produced by bacteria would give the ocean a rotten egg stink. Adding nutrients to warm surface waters would cause massive algae blooms that would kill coral reefs, the most nutrient-sensitive ecosystem (De Georges et al., 2010). Ocean fertilization hardly seems a sensible or well-thought-out proposal because the negative effects would greatly outweigh the benefits. All geoengineering proposals seem to involve unproven technology, whose effectiveness is questionable, whose costs have been greatly understated, and whose side effects may be serious and unpredictable.

Where Can We Store Excess CO$_2$: Geotherapy

For enhancing natural carbon sinks, there are two major options, sea and land.

Despite the many suggestions that the ocean absorbs CO_2, there are at least three independent lines of evidence that suggest that the ocean is a net source, not a sink of atmospheric CO_2, because more organic carbon is decomposed in the ocean than is produced or imported:

1. The amount of organic carbon entering the ocean from marine primary productivity and from rivers and coastal wetlands exceeds the amount of organic carbon being buried in marine sediments (Hedges, 1992; Smith and McKenzie, 1993; Berner, 2004).

2. The concentration of CO_2 in the surface ocean exceeds that in the atmosphere, except in polar waters (Takahashi et al., 2002), so the net flow of CO_2 must be from ocean to atmosphere. Tropical waters in particular are large sources of CO_2 to the atmosphere because CO_2 solubility decreases as temperature increases, so global warming acts to increase atmospheric CO_2. CO_2 is much more soluble in cold water, and so the effects of ocean acidification will be felt first in cold and deep waters and only last in hot tropical waters like coral reefs. Coral reefs are already at their upper temperature limit (Goreau and Hayes, 1994; Goreau et al., 2005; 2012), and the most vulnerable of all ecosystems to global warming (Mora et al., 2013a), and they will the first ecosystem to be severely impacted in coming decades when mean temperatures exceed the extreme hottest years of the past record (Mora et al., 2013b). Corals will die from further temperature increases decades to centuries before ocean acidification begins to dissolve their dead skeletons, making the long-term acidification effects from increased CO_2 a straw man threat to coral reefs compared to the much more immediate effects of the rising temperature CO_2 causes. Controlling CO_2 in time to prevent coral reef extinction from global warming will automatically take care of the global acidification problem, but controlling CO_2 in time to avert ocean acidification will ensure that coral reefs will die from high temperatures. For coral reefs, the focus on acidification effects instead of the high-temperature effects is a dangerously irresponsible red herring that acts as a deliberate delaying tactic and will produce disastrous policy based on bad science. As global warming proceeds, CO_2 solubility decreases so warming waters release CO_2 to the atmosphere, a positive feedback. As surface water warms and the surface layer becomes too thick for nutrient upwelling to reach the surface, the phytoplankton concentration and productivity decreases (Boyce et al., 2010), so less CO_2 is removed to marine organic matter, yet another positive feedback.

3. The concentration of oxygen in the surface coastal waters is almost everywhere less than the atmosphere, although in low-productivity open ocean areas, it is near to equilibrium with the atmosphere (Levitus, 1982), so the net flow of oxygen is from the atmosphere to the ocean. I have made hundreds of measurements of oxygen in tropical coral reefs, sea grasses, and coastal zones, and the concentrations were almost everywhere about 90% of atmospheric values (being higher only over dense shallow sea grass beds in full sunlight). As the ocean has more respiration than photosynthesis, it is inefficient at storing carbon, unless a major part is converted into anoxic *dead zones*. Tropical waters are especially low in oxygen because high temperature reduces its solubility, so global warming amplifies oxygen depletion. The long-term consequence of increased CO_2 will be to increase anoxia that could cause severe ocean dead zones lasting around 100,000 years (Shaffer et al., 2009), similar to the worldwide ocean anoxic events during high temperatures in the Cretaceous, 80–120 million years ago (Wilson and Norris, 2001), and other times in the geological past. Eventually, the increased carbon storage in these zones acts to reduce the amount of CO_2 in the atmosphere, but that is on a geological time scale, not a human one, so it would be foolish to wait for it.

This leaves the land as the only feasible prospect, to which we now turn. There are at least three land sinks, biomass, soil, and rock weathering, which by themselves could be easily managed to absorb excess CO_2 and can do so even faster in combination. The intensity of the carbon cycle per unit area on land

is more than three times as great as the ocean, because roughly equal gross fluxes of CO_2 from the atmosphere take place on land and sea (Figure 2.1 and Table 2.2) but the ocean has more area than land. Land photosynthesis is far more efficient at storing carbon because plant biomass lasts much longer than marine biomass, being stored as biomass carbon for years to centuries before it is returned to the atmosphere from land, versus only days to weeks from the ocean. The amount of organic carbon stored in soils is around 2–4 times higher than the atmosphere or biomass and that also lasts for centuries, unless we cause it to erode and decompose due to bad management. There is good reason to believe that soil carbon estimates are too low for several reasons: poor estimates for wetlands, especially in the tropics and Arctic, and the fact that soil carbon assays usually include only shallow soil due the difficulty of digging and so miss large amounts of carbon in deeper layers (Jobbagy and Jackson, 2000; Harper and Tibbett, 2013; Scharlemann et al., 2014; Shangguan et al., 2014). Thus, soil storage is the most sensible option, not the ocean, or outer space, or deep underground.

How Long Can We Store Carbon in Soil?

We have treated our soil like dirt, and let it degrade and be eroded (Carter and Dale, 1974; Hyams, 1976; Nye and Greenland, 1965; Brady, 1990; Hillel, 1991; Lal et al., 1995; Richards, 2003; Diamond, 2005; Montgomery, 2007), even though restoring soil fertility is the key to our sustainable future. Cultivation of soils is estimated to have released 150×10^9 tons of soil organic carbon (SOC) to the atmosphere as CO_2, and it is only in the 1960s that fossil fuel emissions exceeded net soil CO_2 sources (Bohn, 1978). Reversing this loss and managing soils so there is only a modest increase (roughly 10%) of global soil carbon over current levels could reestablish atmospheric CO_2 at preindustrial levels (Aniwaer and Goreau, 2009) in as little as a few decades (Goreau, 1995). As some of the examples given further on in this chapter show, many people have achieved much higher rates of carbon sequestration per unit area than is needed on a global scale, done so in a large variety of habitats, and it is likely that this could be improved with sound scientific carbon management.

SOC is composed of a huge range of compounds, some of which are very rapidly consumed by bacteria, fungi, and soil invertebrates, and those that are so resistant to decomposition that they last centuries (Pauli, 1967; Alexander, 1977; Brady, 1990; Schmidt et al., 2011; Huang et al., 2012a,b). Managing soil to increase SOC can create enormous sinks if managed properly (Lal, 2004; Post et al., 2012). SOC can be made even more effective by producing biochar. Biochar consists of a wide range of compounds, depending on the composition of the starting material and the physical conditions (temperature and pressure) under which it is made. The key feature is that a major part of it is largely pure elemental carbon rather than organic carbon (carbon combined with oxygen, hydrogen, nitrogen, sulfur, phosphorus, and other trace elements), and the composition ranges between these two extremes depending on age and conditions of formation. *Terra preta* (black earth) soils in the Amazon are among the most fertile soils known and contain up to 35% black carbon (Glaser et al., 2000). Char materials are extremely abundant in grassland soils, where they make up to 40%–50% of SOC (Mao et al., 2012).

Elemental carbon, and organic carbon that approaches it in composition, is extremely resistant to chemical and biological destruction, practically indestructible (Lehmann and Joseph, 2009; Ladygina and Rineau, 2013). However, fine particles can be windblown as black carbon in the atmosphere, where it can cause complicated effects acting to increase global warming (Bond et al., 2013). Research on elemental *black carbon* found that it was globally distributed, and an excellent tracer of the distribution of fires, both natural and man-made, faithfully documenting their history worldwide, carbon transport by soil erosion, water, or wind (Goldberg, 1985; Suman et al., 1997). These studies allowed the frequency of natural and human-caused fires to be determined and directions of ancient winds to be mapped from their distribution. The geological record suggests that black carbon, once formed, is virtually indestructible, or it would not serve as good a tracer for sources and transport mechanisms as long as it does.

Recent research shows that large portions, in some cases or most, of the long-lived *recalcitrant* carbon in soil are in fact biochar from forest and grass fires. In some cases, this may have been deliberate management to clear land or increase productivity, repeated use of the same sites for hunter campfires for thousands of years, or inadvertent results of use of fire to manage grassland for wild game, or for

livestock, which is widespread. Large parts of Australia, South America, and Africa are deliberately burned each year. Such fires are the most inefficient way to produce biochar, because almost all the carbon is converted to CO$_2$ and only a percent or so winds up as biochar. The use of biochar made in kilns instead of traditional burning could therefore increase soil carbon inputs by around 50-fold over traditional open air burning and rapidly build up carbon-rich soil.

Because biochar is such an efficient absorber of water and nutrients and because biochar is densely intergrown by fungi symbiotic with plant roots, mature biochar greatly stimulates nutrient and water uptake by plants, causing much more rapid growth (Glaser et al., 2002; Steiner, 2006; Warnock et al., 2007). At the same time, it increases the release of CO$_2$ from root metabolism, while decreasing the release of the powerful GHG nitrous oxide (Stewart et al., 2013). But these intricate symbiotic soil interconnections involving fungi are damaged or destroyed by chemical fertilizers and by fungicides (Stamets, 2005).

There is much controversy over how long biochar lasts in soils, largely due to use of materials of varying properties and formation conditions. While there is some evidence for loss of char from soils with time, especially of lower-molecular-weight volatile compounds, in most cases, these are very low (Ladygina and Rineau, 2013). Where they are appreciable, it is likely that these studies refer to very low-grade char that is much lower in total carbon and contains large amounts of organic carbon molecules that can be easily broken down by bacteria and fungi. Low-temperature chars have a much lower elemental carbon content, and hence degrade much faster, than high-temperature chars (Lehmann and Joseph, 2009; Bates, 2010; Taylor, 2010). Char contains a mixture of compounds from small to large. The smaller-size materials can be readily transported as colloidal suspensions in water and be transported via rivers to the sea or blown by the wind.

Ocean sediment carbon contains about 10%–30% black elemental carbon (Masiello and Druffel, 1998). Much of this is derived from erosion of black carbon in soils (Dittmar et al., 2012). Recent measurements have mischaracterized this fine charcoal fraction transported via rivers into the ocean as *soluble black carbon* that makes up 10.6% of river organic carbon (Jaffe et al., 2013). But rather than being soluble, these are largely insoluble microscopic or nanocolloidal particles that are so small they pass through the small holes in filters. These materials are a major source of marine *dissolved* organic carbon (DOC), which is highly resistant to decomposition, is evenly mixed throughout the ocean, and lasts thousands of years. This DOC contains a *black carbon* component that is much older, about 18,000 years old and therefore very resistant to decomposition (Ziolkowski and Druffel, 2010), subject only to photooxidation in surface waters (Stubbins et al., 2012). Unfortunately, the data of Jaffe et al. have been widely misinterpreted to mean that soil biochar is *soluble* and washes away. In fact, this transportable component hardly decomposes, and from the point of view of atmospheric carbon sinks, it hardly matters whether it is stored in soil or in the ocean as long as it does not rapidly get oxidized back to CO$_2$.

Several lines of geological evidence suggest that biochar has a very long lifetime, practically infinite for all practical purposes, and provides accurate historical records of past fires (Goldberg, 1985; Suman et al., 1997). The art of making *terra preta do indio* (black earth of the Indians, in Portuguese) by Amazonian Indians in pre-Columbian times was lost following genocide by European diseases some 500 years ago, but *terra preta* deposits remain for thousands of kilometers along the banks of the Amazon River and its major tributaries (Sombroek, 1966, 1984; Sombroek et al., 2003). The demise of mammoths and mastodons in North America 12,800 years ago is marked by a layer of charcoal across North America and Europe that are associated with forest fires triggered by a small asteroid impact (Wittke et al., 2013). The settlement of Australia by the Aboriginals some 40–50,000 years ago is marked by a dramatic increase in soil charcoal in lake sediments well above the natural background from wild fires (Kershaw et al., 2002), indicating that systematic burning of the land for wildlife began shortly after the large megafauna were hunted to extinction, triggering major vegetation changes (Lopes dos Santos et al., 2013). All these lines of evidence related to human-caused fire suggest charcoal can last in soils for up to 50,000 years, but even older evidence can be found.

The charcoal layer from worldwide forest fires that followed the asteroid impact that killed the dinosaurs 65 million years ago is perfectly preserved (Wohlbach et al., 1990; Kruge et al., 1994). One of my students once brought this material to my laboratory to look at in the microscope and we were amazed that we could see clearly every plant cell in the charcoal ash. Similar charcoal layers mark the

Permian extinction event 250 million years ago, although those fires are thought to have been caused by massive lava eruptions (Grasby et al., 2011). The oldest known perfectly preserved charcoal known goes back to nearly the evolution of the first forests, some 420 million years ago, and becoming more common after 350 million years ago (Scott and Glasspool, 2006; Scott, 2009). This suggests a lifetime of elemental carbon charcoal in soils of at least 400 million years and indicates that elemental carbon has a lifetime that is infinite for all our practical carbon storage needs and far longer than any other form of carbon.

How Much CO_2 Can We Store: Carbon Sequestration Capacity

Many different soil and biomass sinks are capable of storing enough carbon by themselves, and in combination, to absorb all the excess CO_2 above safe levels, and stabilize climate change.

The first and most obvious is biomass. Massive and accelerating increase of CO_2 from fossil fuel combustion over the last 150 years, since the industrial revolution, caused the famous so-called *hockey stick* curve of temperature increase (Mann et al., 2008), which has been fully confirmed in all of its details as it has been greatly extended in length (Marcott et al., 2013). However, a major part of the excess atmospheric CO_2 to date comes from the much slower destruction of the great forests of Asia, Europe, and North America since the start of agriculture 10,000 years ago, with South America, Africa, and Southeast Asia coming to the fore only after the forest vanished in northern temperate zones and from erosion and decomposition of soil carbon following deforestation (Bohn, 1978; Houghton, 2003; Lal, 2004; Ruddiman, 2005; Perlin, 2005; Lal, 2011). The amount of forest left is constantly decreasing, while the fossil fuel output is rising exponentially, so land degradation is now a minor and diminishing global source of atmospheric CO_2. It has been obvious to anyone who looks at forests and deforested areas that if the latter could be reforested, vast amounts of carbon could be stored, and if the forests were to be fully restored, most of the existing excess could be absorbed. If the fertility of the soil were to be restored or further enhanced by using rock powders and biochar, then we propose that *all* of the excess could be taken up, the core point of this entire book.

The obvious concept of large-scale ecosystem reforestation to store carbon has occurred independently to many. As an example, we look at one of the first such estimates. Myers and Goreau (1991) looked only at the areas of deforested, badly degraded land in the tropics that had been abandoned and useless after deforestation because of the lack of productivity and that had been overrun by invasive weeds. They asked:

1. Is there enough land available to absorb global fossil fuel CO_2 production using the productivity of typical tropical replanted forests?
2. If the polluter were to pay a carbon tax used directly for the replanting, what would it cost them using typical tropical reforestation costs?

They found that

1. There was more than enough tropical land that had been abandoned and become economically useless after deforestation. In fact, there was enough in Brazil alone.
2. The real costs for tropical tree planting came to about $2–3/ton of carbon, so average cost per capita for global citizens to remove their own excess carbon through tropical reforestation would be about $2–3/year or for highly fossil-fuel-intensive countries like the United States, about $10–15/person/year (Myers and Goreau, 1991).

A fossil fuel carbon tax earmarked for tree planting would be very affordable, even in very poor countries, and could solve the CO_2 pollution problem at real cost without being inflationary. This is in sharp contrast to the economists' concept of a punitive carbon tax to drive prices up and decrease consumption of fossil fuels, and hence emissions, to the needed level, which would be ruinously expensive for the

consumer. This distinction highlights the fundamental differences between CO_2 demand-side measures like reforestation versus supply-side measures like punitive carbon taxes. The key is for the tax to reflect only the real costs of planting, administration, and verification and that it is not diverted by politicians as discretionary revenue for projects that do not directly solve the CO_2 problem.

Many other independent estimates have been made of reforestation carbon sink costs, but most have been based on reforestation costs in North America and Europe, where there is much less degraded land available, and planting costs are much higher, so they result in cost estimates several times higher than Myers and Goreau. But even so, they are quite affordable, being around 10 times less than CCS estimated costs. On a complete global scale, the real cost will vary from place to place depending on land availability and labor and tree nursery costs, so the Myers and Goreau estimates, which are for poor tropical countries, are a lower end estimate, while those from North America and Europe are an upper end estimate, and the true global average is somewhere in between.

There are vast opportunities to increase soil carbon everywhere (Figures 2.16 to 2.18), as living roots, as fungi, as soil organic matter, and as biochar, and we must do so as fast as we can, everywhere to preserve a sustainable future and grow our way out of the climate change crisis.

It is clear that the greatest benefit at the least cost will be obtained by focusing on the tropics because the growth rates of the trees are much higher (Purseglove, 1968; 1972), and the labor costs lower, so tropical restoration should be the first priority. On the other hand, despite their slower growth, cold boreal zone forests like those of Siberia and Canada grow more slowly but are more efficient carbon sinks, since the cold greatly reduces respiration, so they hold onto their carbon much longer. Boreal zone forest replanting is a key part of the solution along with equatorial zone forests because cold forests are more efficient sinks, but hot forests are more effective at recycling CO_2 and reducing its lifetime in the atmosphere (Figure 2.19). Vast areas of our planet are in need of reforestation to conserve soil and water, quite apart from their role as carbon sinks. Global warming, because it reduces carbon storage efficiency, makes it harder to store carbon as living biomass.

Cold forests store about 70% of photosynthesis carbon as living biomass, but hot forests store only 20%. Much less efficient carbon storage in tropical soils is due to the very high rates of CO_2 released
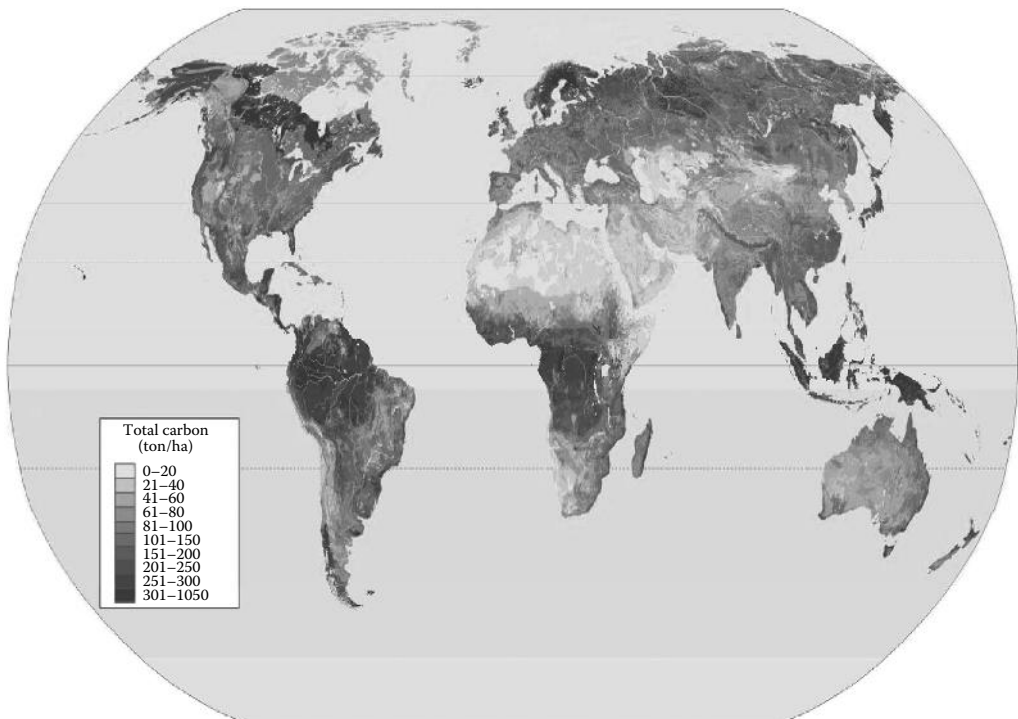

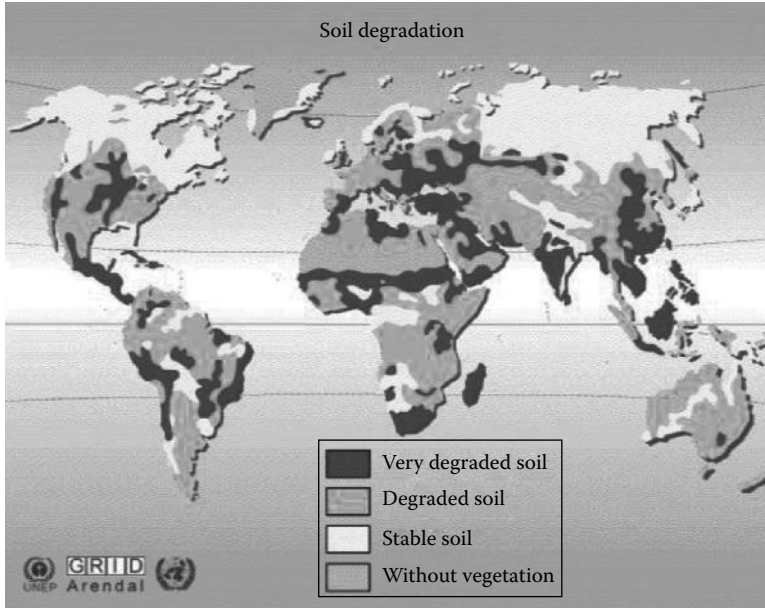**FIGURE 2.16** Soil organic carbon. (UNEP/WCMC 2008.)
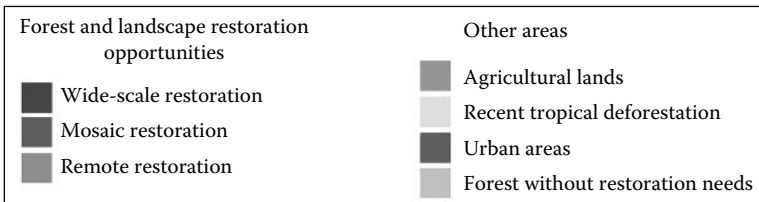
FIGURE 2.17   World map of degraded soils.

FIGURE 2.18   Forest opportunities cover much of the planet.

Forest photosynthesis, respiration, net production,
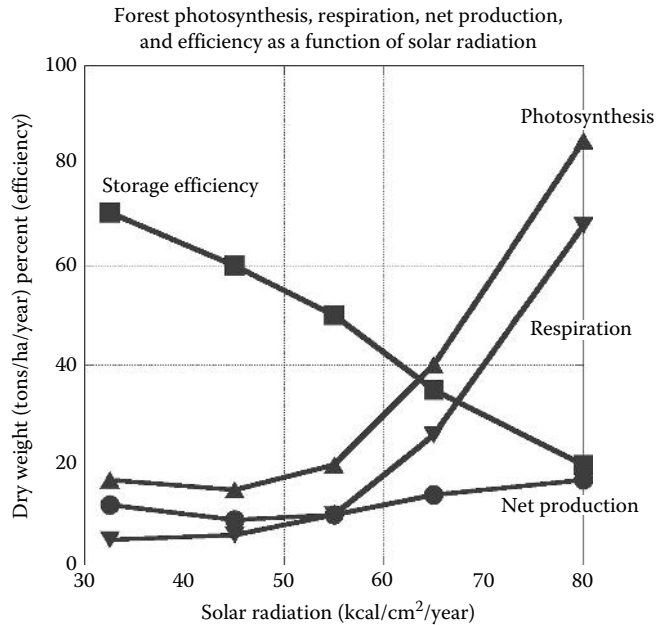and efficiency as a function of solar radiation

FIGURE 2.19 Gross photosynthesis (upward triangles), respiration (downward triangles), net production (filled circles), and net ecosystem efficiency (P-R)/P as a function of solar radiation. Equatorial forests are at the right, boreal forests at the left. Note that photosynthesis (gross production) and respiration increase sharply with sunlight due to the increased temperature, but net production is relatively constant. (Data from Jordan, C.F., Productivity of tropical rain forest ecosystems and the implications for their use as future wood and energy sources, in F. Golley, Ed., *Tropical Rain Forest Ecosystems: Structure and Function*, Elsevier, Amsterdam, the Netherlands, pp. 117–135, 1983; Larcher, W., *Physiological Plant Ecology*, Springer Verlag, Berlin, Germany, 1980; graphed in Goreau, T.J., Tropical ecophysiology, climate change, and the global carbon cycle, in J. Pernetta, R. Leemans, D. Elder, and S. Humphrey, Eds., *Impacts of Climate Change on Ecosystems and Species: Environmental Context*, International Union for the Conservation of Nature, Gland, Switzerland, pp. 65–79, 1995.)

from soils due the increased respiration and decomposition caused by higher temperatures, which will increase further with global warming (Lloyd and Taylor, 1994; Kirschbaum, 1995, 2000, 2006; Meir et al., 1996; Boone et al., 1998; Schlesinger and Andrews, 2000; Fang and Moncrieff, 2001). Cold forests are more efficient carbon sinks, but hot forest carbon cycling regulates atmospheric CO_2 lifetimes by rapid recycling. Both ecosystems are crucial for global climate management, but for different reasons. There are huge areas of both in need of restoration for soil and water conservation reasons alone (Figure 2.18). The possibility of restoration should never be an excuse for not conserving all primary forests, since they are more species rich and big old trees store carbon at the greatest rate (Stephenson et al., 2014).

The transformation from barren soil to forests provides amazing benefits. In the early 1800s, all of the forests in the mountains above Rio de Janeiro were cut down to plant coffee, the soil washed away, and bare rock mountains remained (those famous bare peaks overlooking the city had forests to their very top when Pedro Cabral *discovered* them for Portugal in 1504). As a result of deforestation, the year-round forest springs and streams dried up and the city was without water in the dry season. There was no doubt that the cutting of the forest had destroyed their water supply, and so the city systematically replanted the hill slopes where soil remained at the base of the mountains. A handful of slaves, employed by the city, spent their careers climbing up into the few forests that remained because they had been too steep to cut down and plant coffee, and these green heroes carefully transplanted tree seedlings, trying to maximize biological diversity (IBDF, 1991). When the trees came back, so did the water supply (Bandeira, 1994). This forest, the Floresta da Tijuca Park, is the beautiful green forest that overlooks Rio de Janeiro (Figure 2.20), and it is entirely artificial, although few people are now aware of that. In the 2012 Rio+20 UN Conference on Sustainable Development, the official brochure to delegates incorrectly described it

FIGURE 2.20 Floresta da Tijuca was planted by hand, and restored the water supply to Rio de Janeiro. (Photo by Alberto Peterson.)

as *natural forest*, implying it had been successfully conserved, when in fact it had been totally destroyed and successfully restored. Around a hundred and fifty years after replanting, William de Mello of the Universidade Federal Fluminense and I measured the CO_2 emissions from the soils of the Tijuca Forest, and we found that it had completely recovered its biogeochemical function in terms of GHG cycling by comparing our data with that from virgin Amazonian jungles (de Mello and Goreau, 1998).

Millions of individuals and thousands of groups have similarly learned on their own how to restore barren areas back to lush and complex ecosystems, storing carbon, nutrients, and water. Moreover, these unsung heroes have done so in every single ecosystem, habitat, climate zone, and soil type. Their work proves that mature technology exists to restore all our ecosystems if we chose to apply it on the scale needed. It is impossible to begin to list all these groups, but here, we give one example, in the same Brazilian Coastal Rainforest habitat as Floresta Tijuca, the Minas Gerais family farm of the famous photographer Sebastião Salgado. The family that herded their cattle said that 40 years ago, there had not been a single stick of shade to hide from the sun, but after the barren site was systematically replanted with trees, a forest now stands, and springs and rivers have returned to the formerly barren landscape. For before and after photographs, see http://www.institutoterra.us/about/history_land.html.

Panama is an unusual example of how deforestation can be turned into massive reforestation through suitable policy. Twenty or thirty years ago, the banks regarded forests as economically worthless and would only give bank loans to people who had first cut down all their trees to *make worthless land valuable*. Now, the banks pursue the opposite strategy, they would not give money to people who deforest, but they will give loans to replant degraded land. A systematic national policy of large-scale tree nurseries make tree seedlings cheap and widely available, and all over Panama, one sees massive forests arising where the land had been previously covered with useless weeds. The major problem is that almost all of the seedlings being planted are Asian teak, *Tectona grandis*, the most valuable tropical hardwood, so biodiversity does not increase as it should. But the Panamanian example does show how quickly effective policy can reverse the situation, even if they could be improved by variety.

Even more carbon can be stored in soils if we manage them to increase carbon content, and this can be done in pasture and agricultural habitat as well as forests. Soil holds around four times more carbon than the atmosphere or the biosphere, even though we have already lost around half of the soil carbon from areas deforested for agriculture or pastureland (Lal, 2004). It is easy to manage the soil to build up organic matter instead of destroying it (Kimble et al., 2007; Magdof and van Es, 2009), and there are enormous benefits in increased agricultural and forest and livestock production and soil water retention.

There are many paths to doing so. One major key is to build up soil root biomass and the biomass of root-associated symbiotic fungi, a major source of soil carbon (Clemmensen et al., 2013), especially by the use of perennial plants instead of annual crops that die and have to be replanted every year, which have much less root biomass, fungi, and SOC (Jackson, 2010). By managing succession of species in ecosystems, large increases in soil carbon storage and biomass can result (Wolkovich et al., 2010). It takes clever thinking to manage livestock so that they increase plant growth and soil carbon, fertilizing them with manure and then leaving them alone until they recover and preventing overgrazing that has the opposite effects, but such methods have been developed and work very well (Savory, 2009; see Chapter 9) although there is not yet enough data on the large increases of soil root and carbon that result. *Carbon farmers* do the same with soil, managing their fields so the SOC content is increasing instead of decreasing, which has the added benefit of increasing their agricultural productivity at lower cost (Lal et al., 1995).

These methods, applicable in all human-managed environments, are reported to be capable of sequestering from a few to several tens of tons per hectare per year and a maximum of over 30 tons/ha/year measured. If managed responsibly, pastures alone, agriculture alone, or reforestation alone could absorb much of the CO_2 increase. But there are even more opportunities, such as biochar, which greatly increases carbon storage and its storage lifetime, as well as soil water-holding capacity, with many additional benefits. Of course biochar should not be produced from plantations that compete with food production land, and the biochar should be made from agricultural wastes returned to the soil on the land from which they came to increase future production or be made from weedy biomass on land that is being restored to more economically productive and biodiverse habitats. Those possibilities are immense in every single ecological habitat type. The goal should be to be able to produce enough biochar by restoring weedy and degraded areas to greatly increase the quantity and quality of their productivity, while having a surplus of biochar to apply to agricultural and pasture soils where the produce carbon is exported. With a strategy that combines all of these approaches in all habitats, there should be no difficulty to meet the global goals to absorb all the excess.

How much carbon would we need to add to soil to do the job needed? If we focus not merely on removing the year by year CO_2 increase but on the much larger task of removing all the excess CO_2 above safe levels already in the atmosphere and get back to preindustrial levels, then global soil carbon content would need to rise from the current average value by around 10% (Aniwaer and Goreau, 2009). This is doable (Woolf et al., 2010; Chapter 3), although the increases would be greater in some places than others. Figure 2.1 shows the atmospheric, biomass, and soil carbon pools and the amount of changes needed to stabilize CO_2 at safe levels.

Additional and very important opportunities also occur in wetlands, which are major carbon stores because waterlogged conditions promote bacterial decomposition that consumes the oxygen from the water, greatly reducing decomposition rates. Wetland peats are vast carbon stores, around half or more of all soils, and instead of increasing these sinks, we are destroying them, draining them, and allowing the soil to oxidize to CO_2 (Moore et al., 2013), so the soil vanishes and atmospheric CO_2 increases, as well as methane. The Everglades have lost up to 5–10 m of soil in some locations since the soil carbon has been drained, dried, and decomposed for agriculture (Stephens and Speor, 1970). Global-warming-caused melting of frozen Arctic peats in Siberian and Canadian wetlands and submerged peats will cause huge new sources of CO_2 and methane to go into the atmosphere from buried peats in the Arctic Ocean where the overlying ice has melted away (Shakhova et al., 2010). This is another positive feedback increasing global warming, especially when added to the huge melting permafrost peat sources. There is an urgent need to not only stop wetland destruction but to restore them. This can be done by managing water flow to retain water rather than drain it and needs to be part of a global carbon strategy. This will of course at the same time provide additional water reservoirs. Since wetland peat soils can be nearly half carbon, wetland restoration is the most effective way to store soil carbon.

Besides freshwater wetlands, enormous carbon possibilities exist in marine wetlands, mangroves, and salt marshes (so-called blue carbon). Here too, these ecosystems are being cut down and their huge peat carbon deposits being destroyed for *development*, further accelerating global warming as the peat carbon oxidizes. The potential carbon stores of marine wetlands alone, if sensibly managed, could probably store a significant amount of the global excess (Mitra et al., 2005) if we were

growing wetlands instead of destroying them. The same applies to marine coastal forests, mangroves, salt marshes, etc., which store huge amounts of peat that are being oxidized following drainage. Restoration of these ecosystems could provide huge carbon storage benefits (Nelleman et al., 2008; Fourqurean et al., 2012). Wetlands can be intense sources of the major GHGs CO_2, CH_4, and N_2O, but each gas shows a different environmental pattern in their changes (Goreau and de Mello, 2002, 2007) so maximizing carbon storage in wetlands may also involve complex trade-offs with GHG emissions. Wetlands show elevated GHG emissions compared to dry soil, but it is likely that the increased burial of soil peat carbon in these habitats is greater than the increased flux, since a much smaller portion of the carbon is decomposed; however, detailed studies of soil carbon storage with regard to GHG fluxes still remain to be done.

An additional important advantage of increasing soil carbon storage is preventing loss of nitrogen and phosphorus. Nitrogen loss from soil is a major source of both air and water pollution. Soil-derived atmospheric N_2O is a major GHG and regulator of the stratosphere ozone layer (Goreau, 1982), NH_3 causes aerosol smog pollution, NO and HONO also produce ozone pollution in the lower atmosphere, and acid rain, while ammonium, nitrate, nitrite, and phosphate leached from soils, contaminate ground waters, rivers, lakes, and the ocean. By overfertilizing the water, they cause severe harmful algae blooms that kill coral reefs and fisheries, cause red tides, and create dead zones (Sutton et al., 2013). Storing the nutrients in the soil will not only make the soil more fertile, it will prevent air and water pollution now causing severe consequences worldwide. Biochar is an ideal medium to adsorb these nutrients, retain them in the soil, and prevent water pollution (see Chapter 32).

In summary, there are more than enough places where the carbon could be stored cost effectively, with enormous direct economic benefits, while preventing the costs of runaway global climate change. To solve the CO_2 problem, we need to systematically restore plant productivity, soil carbon storage, and the integrated global biogeochemical ecosystem functioning of all major habitats that have been damaged. It is not simply enough to pay a corporation to cut down other people's forests, convert it to biochar, dump it all on their land, and then demand carbon credits. Without global-scale restoration, it is simply impossible to store enough carbon to meet the global needs, so large-scale restoration of destroyed, degraded, and damaged ecosystems is the *sine qua non* for stabilizing climate at safe levels. The methods to do so already exist. All that is lacking is the will on the part of policy makers and funding agencies to solve global problems on a global scale.

How Fast Can We Store CO_2: Carbon Sequestration Rates

There is clear evidence that with good management, soil carbon can readily be increased by tons, of carbon per hectare per year, and to tens of tons in best cases (Lal et al., 1995; Lenton, 2010; Lal, 2011; Stockman, 2011; Powell and Lenton, 2012; Kang and Banga, 2013; Schwartz, 2013; Soil Carbon Sequestration Conference, 2013; Ohlson, 2014; see Chapter 33). It should be noted that most of these estimates consider only opportunities from conventional crop agriculture or pasture and ignore the vast opportunities for forestry and restoration of unused degraded lands.

Restoration of the vast areas of land that has been deforested, degraded, abandoned, and overrun by weeds offers enormous opportunities to increase both biomass and soil carbon (Figures 2.17 and 2.18). This would turn useless land into economically and biologically productive carbon sinks.

Biochar can be applied at rates of up to hundreds of tons of carbon per hectare per year, but in fact, this is much more than is needed for benefits to plants, cannot be supplied from in situ carbon biomass carbon resources, and would require import of carbon from elsewhere sustainably (see Chapter 13). Such carbon transportation could defeat the purpose of increasing carbon stocks everywhere.

Scientifically sound soil carbon management should be based on accelerating natural processes that build soil carbon. The semiarid Loess Plateau grassland soils of northern China are some of the most fertile in the world but are rapidly depleted and eroded by conventional farming methods. When these soils are abandoned due to loss of fertility and are allowed to recover, the SOC doubles from around 3% after abandonment to about 6% in 20–30 years, with an increase soil nitrogen, water-holding capacity, and total microbial populations (Xiao et al., 2013). A natural succession

in soil microbial communities and the biochemistry of the soil takes place during which soil CO$_2$ metabolism remains fairly constant, so there is a decline in soil respiration per unit of microbial biomass, making them less efficient as they approach steady state (Xiao et al., 2013). If this process were increased by adding soil carbon in both metabolizable forms (such as crop litter) and recalcitrant forms (such as biochar), the potential to significantly increase soil carbon in a few decades could very likely be further enhanced.

There is therefore no technical or economic barrier to solve the excess CO$_2$ problem in timely fashion, and there are incalculable economic and environmental benefits that will reward current and future generations. The problem is only lack of understanding and lack of will by policymakers and funding agencies to solve the problem as fast as possible so as to minimize the costs and maximize the benefits. They have frittered away decades asleep at the wheel since the problem and solutions were understood, and there is now very little time left for serious action before the inevitable crash.

Managing Soil Carbon Sinks

Reversing soil loss and soil carbon loss is the art of maximizing plant growth and biomass, underground root biomass, symbiotic soil fungi, and bacteria that live with roots and provide them with nutrients (Malavolta, et al., 1962), as well as the soil organisms that recycle them (Darwin, 1881; Pauli, 1967; Brady 1990) while storing a major part of SOC and biochar carbon. The tools that will greatly amplify these *carbon farming* methods will include selection of perennial crops so annual roots do not die and need to regrow each year. The use of biochar combined with rock dust can store soil carbon in virtual perpetuity, while accelerating soil CO$_2$ reactions to form bicarbonate (which eventually will neutralize ocean acidification) by weathering rocks to provide plant root nutrients that are inadequate in most soils (Brady, 1990).

To understand this process better, we need to understand the dynamics of CO$_2$ in soil. If the major source of CO$_2$ in soils was from the atmosphere, and its major sink was weathering, then CO$_2$ concentrations in soil would be less than in the atmosphere. In fact, it is typically from 10 to up to a hundred times higher. Figure 2.21 shows the rate at which CO$_2$ flows out of soils in just minutes into chambers placed at the soil surface in a temperate mountain hardwood forest (Goreau, 1982), much higher rates are found in tropical forests. Plants greatly increase soil CO$_2$ through root respiration, which serves to increase the rate of chemical weathering and nutrient release from soil minerals.

Amazonian Soil Metabolism and the Lifetime of CO$_2$

It is generally assumed that soil CO$_2$ is largely derived from the microbial decomposition of dead organic matter provided by leaf litter falling from plants to the ground. But measurements of CO$_2$ emissions from soils to the atmosphere in virgin Amazonian jungles that had just been clear-cut, and left to dry in preparation for burning and conversion to cattle pasture, showed otherwise. If decomposition of dead organic matter were the source of soil CO$_2$, the flux out of the soil surface would greatly increase after the living forest was chopped down and turned into dead organic matter. Instead, the release of CO$_2$ rapidly fell immediately after felling, and bare soils had only about 25% as high CO$_2$ release (Figure 2.22 after data in Goreau and de Mello, 1987, 1988). It is important to note that this site was not burned; the measurements were made in sites where the biomass was left to dry prior to burning.

This indicates that around 75% of CO$_2$ in soil comes from the respiration of living plant roots and the respiration of fungi, bacteria, and soil invertebrates directly feeding from living root organic carbon or from metabolizable carbon compounds that are released from roots. The data shows that forest metabolism above- and belowground is more symbiotically integrated, and larger amounts of carbon are flowing through tropical forest soils than had been realized. In Figure 2.2, most of what is labeled belowground *decomposition* is therefore actually metabolism of living plants and plant-dependent organisms. If we restored tropical rain forests instead of destroying them, forests would reduce the atmospheric lifetime and warming impacts of CO$_2$. The master planters of Floresta da Tijuca showed it can be done.
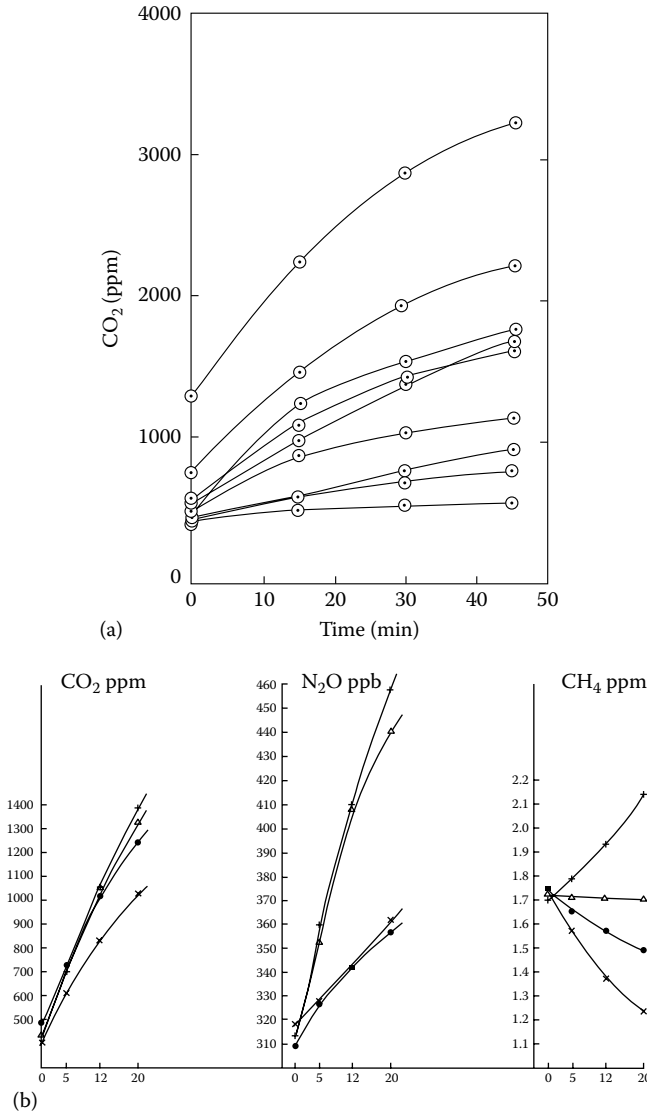
FIGURE 2.21   (a) CO_2 concentrations in chambers above the soil, showing soil levels are up to 10 times higher than atmospheric. These are measurements made at different seasons and locations at the Hubbard Brook Experimental Forest in the White Mountains National Park, New Hampshire, United States. All chambers started out with higher than atmospheric CO_2 concentrations (at that time around 350 ppm). (From Goreau, T.J., Biogeochemistry of nitrous oxide, PhD thesis, Harvard University, Cambridge, MA, 1982.) (b) Changes in greenhouse gas concentrations over Amazonian forest soils (Goreau & De Mello, 1987). The site that released methane was next to a termites nest.

We also looked at pastures that had been burned and seeded to grass, both before and after cattle started to graze it. It was also found that after the cut-down forest was burned, only the leaves and fine twigs were turned into CO_2 and a black surface layer of charcoal, but the fires burned quickly and did not burn the vast majority of tree trunks and branches. These lay superficially charred on the ground after the fire had passed and the ground was seeded to grass. But within a few years, the charred wood biomass vanished entirely because it was completely consumed by termites that built their nests over it. Measurements of the gases emitted from Amazonian termite nests showed very high methane-to-carbon dioxide ratios (Goreau and de Mello, 1987). This methane is produced by symbiotic bacteria, living in the guts of the termites, and the amount produced after deforestation is so large that it acts to amplify global
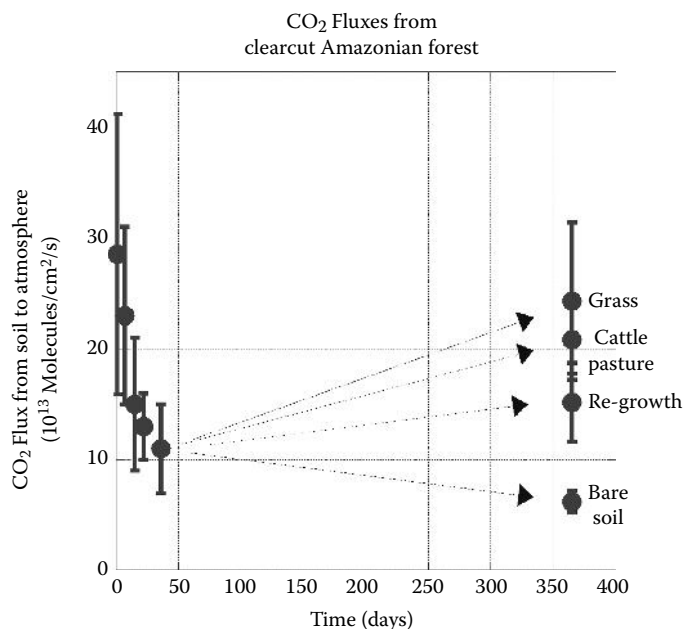
FIGURE 2.22 CO_2 fluxes (means plus or minus standard deviations) from clear-cut Amazonian forest soils versus time. (After Goreau, T.J. and de Mello, W.Z., Effects of deforestation on sources and sinks of atmospheric carbon dioxide, nitrous oxide, and methane from Central Amazonian soils and biota during the dry season: A preliminary study, in D. Athie, T.E. Lovejoy, and P. de M. Oyens, Eds., *Proceedings of the Workshop on Biogeochemistry of Tropical Rain Forests*: *Problems for Research*, Centro de Energia Nuclear na Agricultura and World Wildlife Fund, Piricicaba, Sao Paulo, Brazil, pp. 51–66, 1987.) Fluxes were measured in multiple replicate plots in undisturbed rainforest and at various times after the forest had been clear-cut. The cut trees and vegetation simply lay where they fell and were left to dry as was so it could be burned at the end of the dry season with seeding of grass at the start of the next rainy season. The data at the left follow the decrease in CO_2 emissions with time. The data at the right are comparisons with plots cut and cleared the previous year; one had grass with no cattle, one had grass being actively grazed, one was regenerating in place with no burning (due to early rains), and the fourth was weeded once and left bare (nothing more grew there after the first weeding). The arrows show the trajectory of CO_2 fluxes for various land management for various forms of ecosystem recovery. This should be a curve, not a straight line, but there are no more data available to refine it. More data are needed to follow the changes in such plots, but it is clear that the deforested ecosystems all cycle CO_2 at lower rates than intact forest.

warming because methane is a much stronger GHG than CO_2. We also compared sites that were regenerating after clear-cutting without burning, due to the rainy season coming before they could light it. Methane release was also found from cow manure (Goreau and de Mello, 1987; Steinfeld et al., 2006).

Since most CO_2 emitted from soils comes from the respiration of the living biota, and not decomposition of dead organic matter, CO_2 is being recycled back to the atmosphere much faster than had been realized. Tropical forests with very rapid CO_2 cycling rates act to control the lifetime of CO_2 in the atmosphere. If rapid CO_2 recycling ecosystems are replaced with land uses that recycle CO_2 much more slowly, the lifetime of CO_2 in the atmosphere will increase, and each molecule of CO_2 will absorb heat longer and produce more global warming per molecule (Goreau and de Mello, 1988; Goreau, 1990), another major positive feedback mechanism not included in global climate change models. Since respiration of plant roots controls CO_2 concentrations in soils, it controls the rate at which minerals are released by weathering, and hence the magnitude of weathering carbon sinks.

Much of this mineral weathering and nutrient uptake is performed by mycorrhizae, fungi that are symbiotic with the plant roots. Mycorrhizae are fed organic carbon by the roots, while providing them nutrients in exchange (Taylor et al., 2009) and can make up a major part of soil carbon (Rillig et al., 2001; van der Heijden et al., 2008; Maser et al., 2010). Healthy growing plants are the key to increase weathering sinks, but deforestation and conversion to annual crop greatly reduces the rate at which such nutrients are released to soil. Restoring plant growth restores the carbon sink, but

deforestation reduces the weathering carbon sink and therefore acts as yet another positive feedback mechanism for global warming not in the models.

Mycorrhizae types greatly influence soil bacterial activity (Averill and Finzi, 2011; Waring et al., 2013) and influence soil carbon storage by affecting the efficiency with which nitrogen is recycled in soils (Averill et al., 2014). The type of mycorrhizae most common in tree roots is unable to take up nitrogen, which is processed in the soil, but the type more common in swamp plants and nitrogen-poor environments is able to take up nitrogen directly and therefore short-circuits the bacterial nitrogen cycle, reducing loss of nitrogen to groundwater and to the atmosphere. Habitats dominated by the latter group of mycorrhizae store much more soil carbon for the same amount of nitrogen (Averill et al., 2014).

The effects of these differences are very clear in the two major Amazonian soil types, yellow clay soils and white sand soils. Trees on the yellow soils that cover most of the Amazon Basin have mycorrhizae that are efficient in taking up phosphorus but not nitrogen, and such tropical forest soil biomes are the largest single source of atmospheric nitrous oxide, a potent GHG and ozone layer regulator (Goreau and de Mello, 1987, 1988). No litter builds up on the soil surface in these forests because it is immediately removed by termites and broken down by symbiotic fungi underground. On the other hand, the few percent of the Amazon Basin with white sand soils has a stunted tree vegetation of different species adapted to extreme nutrient scarcity. Surprisingly, there is thick surface leaf litter layer, and the roots of the plants do not grow down into the sand, but they grow *up* into the leaf litter, where their symbiotic mycorrhizae are extremely efficient at taking up nitrogen. The bacterial nitrogen cycle is so efficiently short-circuited that there is no release of nitrous oxide from the soil (Goreau and de Mello, 1988). These areas, despite extremely low productivity, are so efficient at storing carbon that the rivers draining them have black waters, stained by DOC compounds leached out of the soil, and these small areas are the major source of organic matter exported in the Amazon River.

## Soil Carbon, Water, and Temperature Cycles under Extreme Conditions

The Amazon soil GHG study also revealed important interactions between the soil carbon and the soil water cycle. Around 85% of global water that is evaporated to the atmosphere from soils goes via transpiration through plants rather than direct evaporation (Jasechko et al., 2013). Plants dominate water and heat flow to the atmosphere in all except plant-free deserts, even though evaporation greatly accelerates with increased temperature. We compared GHG emissions from virgin Amazonian jungle with a nearby site where the forest had been completely cut down 1 year before, but due to early rains, they could not burn the biomass, so it was overgrown by weeds; the ranchers could not convert it to pasture and lost their deforestation investment. We made measurements of temperature and GHG emissions at both sites around the clock.

In the forest site, the temperature range between the afternoon maximum and early morning minimum was about 1.5°C, and it was always delightful in the equatorial forest even at the warmest time of day. The nearby clear-cut plot was much hotter, and the daily temperature range was nearly 10 times higher, and nearly 15°C (Figure 2.23a, Goreau and de Mello, 1987). During the short Amazon dry season, the forest soil was moist and the ground vegetation was green and succulent. But in the nearby clear-cut, the soil was bare, dry, and baked to a concrete-like hardness, and the vegetation was brown. In the city of Manaus, center of a 50 km deforested area, the grass was brown and dying, as if in severe drought.

Where the forest is intact, the ground and air are cooled by shading and by evapotranspiration of moisture through the tree leaves, but clear-cut areas lack these cooling mechanisms, making them much hotter. Degradation of the carbon cycle causes perturbation of the water and heat cycles that act to greatly increase temperatures and reduce water soil water availability. Every increase in soil roots, fungi, soil organic matter, and biochar increases soil's water-holding capacity and stabilizes temperatures. The increased evapotranspiration of the vegetation cools the ground while it increases rainfall. It was noted in Brazil as far back as the 1600s that where the forest was cut to grow sugar cane, the land became much hotter and the small streams dried up. After Honduras was rapidly deforested, air temperatures rose very rapidly, around 10 times faster than global warming. Much local heating has
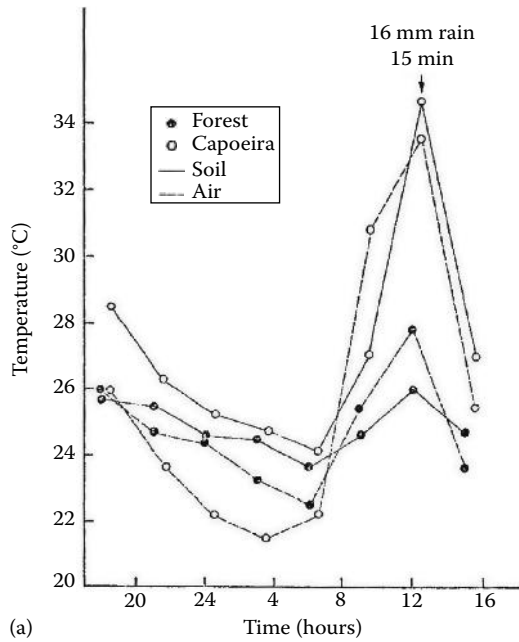
(a)
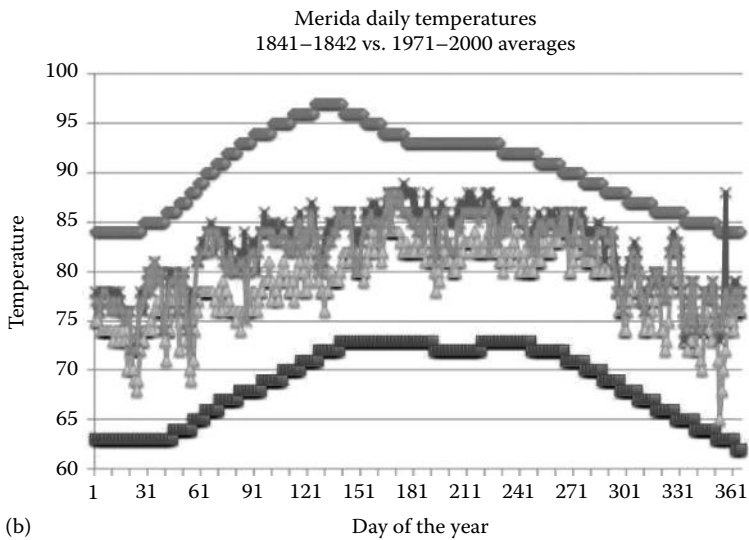
(b)

FIGURE 2.23 (a) Daily temperature cycles in virgin Amazonian rainforest versus in a nearby clear cut patch. (After Goreau, T.J. and de Mello, W.Z., Effects of deforestation on sources and sinks of atmospheric carbon dioxide, nitrous oxide, and methane from Central Amazonian soils and biota during the dry season: A preliminary study, in D. Athie, T.E. Lovejoy, and P. de M. Oyens, Eds., *Proceedings of the Workshop on Biogeochemistry of Tropical Rain Forests: Problems for Research*, Centro de Energia Nuclear na Agricultura and World Wildlife Fund, Piricicaba, Sao Paulo, Brazil, pp. 51–66, 1985.) (b) Merida, Yucatan, temperature changes over 170 years. Daily measurements from 1841 to 1842 at 6 AM, 12 noon, and 6 PM are graphed from data tables in Stephens (1843). The average 1970–2000 maxima (top light gray) and minima (bottom dark gray) are from URL.

been caused by loss of the evapotranspiration cooling mechanism that living vegetation provides, and restoration of the forests would in turn help cool the climate.

Increased soil carbon storage brings huge further benefits in terms of cooling off the temperature while increasing our water resources, quite apart from biological production benefits. As the result of greater soil moisture, the growing season lasts longer, and groundwater is recharged, restoring springs

and rivers. Wetland habitats urgently need to be restored because the large amounts of organic peat they build up are the most important carbon storage ecosystems in the world per unit area. Recreating them will not only be the most effective carbon storage possible; it will also stabilize our water resources and reduce erosion at the source, turning brown land green and turning brown water blue.

Temperature extremes are becoming worse with time. This is dramatically shown in daily temperatures measured at 6 AM, noon, and 6 PM in Merida, Yucatan, in 1841–1842 (Stephens, 1843), when compared to the average maxima and minima from 1971 to 2000 (Figure 2.23b). The surrounding area was forested in 1841, but deforested by 1970. Not only does the daily temperature range seem to have increased greatly as the result of losing the cooling and regulation of temperature by forest transpiration, but the peak of the hot season now comes suddenly 3 months earlier.

Turning the UNFCCC into an Effective Tool

To solve the problem, the UNFCC must take the lead. In 1989, I was Senior Scientific Affairs Officer for climate change and biodiversity at the United Nations Centre for Science and Technology for Development and helped review the first draft version of the UNFCCC. We tried to make sure that the draft treaty was both scientifically sound and complete, so it could serve as a strategy to effective action to halt climate change and degradation. As an internal UN technical expert, I helped ensure inclusion of the essential elements in the first draft: (1) complete global accounting of *all* GHG sources and also of *all* of their sinks; (2) a formal stated goal to protect Earth's most high-temperature-sensitive ecosystems, especially the most fragile and threatened of all, coral reefs; (3) monitoring of the most temperature-sensitive ecosystems to determine if they were being pushed beyond their limits; and (4) trigger mechanisms to reduce GHG emissions if such harm was shown.

Every one of these crucial elements of an effective and sound treaty in the initial drafts was eliminated or watered down in the political horse trading of governments interested in minimizing their moral responsibilities and financial liabilities to the planet as a whole and to future generations in particular. These failures, selective and incomplete accounting, confusion of gross and net fluxes, failure to include the 70% of the planet covered by oceans, lack of a clear goal to protect climatically sensitive ecosystems, failure to monitor ecosystem performance and health, and lack of corrective mechanisms, turned the treaty into being incapable of solving the problem. Had their accountant or finance ministers done such an incompetent job with their money, they would be immediately fired or shot, depending on their country.

A couple of typical examples of the tricky and scientifically unsound way the treaty was gutted are important, because few people understand how governments of the world acted in these crucial negotiations:

1. In the very last moments of the last negotiating session before approval of the draft treaty at the UN General Assembly in 1989 (actually, after those moments, because they were mandated to finish Friday night at midnight, and when it was clear that they were not going to make it, having wasted so much time with meaningless posturing and ritual phrases, they stopped the clock at few minutes before midnight, and it was actually around 2 AM the next day when they finally passed the resolution), the US delegation suddenly called for all countries to get credit for photosynthesis on their land, knowing that photosynthesis absorbs much more CO_2 than fossil fuel emissions, but completely ignoring respiration and decomposition that returns essentially all of it back to the atmosphere! The result of this dishonest accounting would be that almost all countries except totally barren deserts could falsely claim to be CO_2 sinks entitled to credits.

2. A movement by Indonesia and other coral reef countries tried to claim that coral reefs are a sink of atmospheric CO_2, when in fact they are a small source, only about 1% as much as fossil fuels. The use of electrolysis to grow coral reefs (Goreau, 2012a,b; 2014) or precipitate limestone from the ocean (Rau, 2011) has been coupled to mistaken claims that limestone is CO_2 sink.

Although limestone deposition is a carbon sink from the ocean, in fact limestone deposition releases an equal amount of CO_2 to the atmosphere to maintain charge and pH balance, so it is actually a source of atmospheric CO_2 and not an atmosphere CO_2 sink at all (Stumm and Morgan, 1996). To place this into perspective, about half of the limestone burial in the sea took place in coral reefs (Milliman, 1974, 1993), before global warming killed most corals, and at that time, the global source of CO_2 from coral reefs was only about 1% as much as we release every year from fossil fuel combustion (Ware et al., 1991), showing how human activity has overwhelmed the natural carbon balance.

Instead of effective proposals to solve the problem, governments have refused to think globally and are simply protecting the interests of their politicians and energy industry. Even in the poorest countries, the energy industry pays politicians' election campaigns, pocket money, and slush funds and writes national energy policy. The result is a blizzard of smoke screen proposals that do little or nothing to solve the problem but can be claimed to be a symbolic step in the right direction (sometimes falsely) for PR purposes. These slick proposals are developed by high-paid technical consultants and cunningly misnamed to make it appear that they do the opposite of their likely effects. They amount to stratagems to continue burning fossil fuels as if there were no tomorrow, while tossing a bit of money to people in poor countries so that they do not also destroy their forests the way the rich countries did, in effect forgoing the same *development* strategy of destroying and capitalizing their natural resources. This is widely viewed by developing countries as a trick to keep them poor.

Examples are the current *carbon trading markets* and the so-called clean development mechanism (CDM) by which rich countries pay poor countries to absorb their carbon pollution. CDM is not clean because it does not decrease gross pollution and is most unlikely to result in real development of poor countries, but it can be claimed to be a mechanism. Another is reducing emissions from deforestation and forest degradation (REDD), in which rich countries pay poor countries not to cut their trees down. Since much of the forests are in the lands of indigenous peoples, this has directly motivated governments to act to seize control of forests from their native inhabitants, so governments can pocket the carbon credits that would result. The indigenous peoples of Panama, where most of the forest is on indigenous lands, have rejected REDD (http://www.redd-monitor. org/2012/08/30/coonapip-panamas-indigenous-peoples-coordinating-body-denounces-un-redd/) as a trick that will not prevent pollution, and that will be used by their own national government to steal their lands and REDD carbon credits. Many other indigenous forest people, in South America, Africa, and Asia, for example, the native forest people of Malaysian Borneo and Indonesian Kalimantan, feel the same way.

The worst of these proposals, CCS, envisions pumping CO_2 from power plants into the deep sea or the ground, in the hope that it never comes back. This is the favorite of the energy industry and of all countries that produce, or consume, fossil fuels, because it means no change in business as usual. At every UN climate change meeting, the oil-producing and coal-producing countries demand that more money be spent on CCS, even though CCS has no hope of being affordable or adequate to solve the problem even if it were technically feasible.

At present, UNFCCC is incapable as serving as an effective global problem-solving strategy because it relies on scientifically unsound accounting, goals, and models. It needs to be reformed with honest and complete accounting of all GHGs; meaningful goals to stabilize climate at safe levels that prevent extinction of our most productive, diverse, and temperature-sensitive ecosystems; and a mechanism that allows CO_2 emitters to directly pay for their CO_2 absorption, focused on verifiable and real removal and storage, without the funds being diverted by unproductive middlemen who do not solve the problem. UNFCCC's flaws can easily be remedied and turned into an effective problem-solving tool if (1) soil is recognized as a carbon sink; (2) there is complete accounting of *all* GHG sources and sinks; (3) the goal of the convention is stated to protect earth's most climatically sensitive ecosystems; (4) international and funding agencies fund large-scale increases in soil carbon, in all forms, by all methods, in all habitats; and (5) restoration of degraded habitats to regulate climate becomes a key strategy in reversing global warming.

Conclusions

Atmospheric CO_2, sea level, temperature, water, soil, agriculture, forestry, and fisheries cannot be stabilized at safe levels without restoring the integrated biogeochemical functioning of global ecosystems that we have degraded and destroyed in many places. Soil is the only place where carbon can be quickly and affordably stored, with many additional benefits. The fundamental solution is simple: manage the carbon cycle to store carbon in soil (Figure 2.24) instead of using it up (Figure 2.25a through c).

In Figure 2.25a, the carbon is in balance in that photosynthesis carbon is returned directly to the atmosphere by aboveground respiration and by underground respiration and soil decomposition of litter fall. There is no net storage of carbon in soil once the ecosystem is mature. In Figure 2.25b, photosynthesis is low because of soil exhaustion (unless chemical fertilizers are added, which acts to increase decomposition of soil carbon even faster), and respiration is also lower (although likely with a higher respiration/photosynthesis ratio and lower carbon storage efficiency than (Figure 2.25a) caused by higher heat stress). Decomposition is greatly reduced because litter fall of crops, biomass, wood, fuels, and meat of grazing animals are removed from the ecosystem, resulting in increased emissions of CO_2 where they are consumed, reducing soil carbon cycling at the site and greatly increasing decomposition of SOC, which declines rapidly at first (Nye and Greenland, 1965). In Figure 2.25c, the system is managed to maximize soil fertility using biochar, rock dust, and compost increasing photosynthesis, respiration, and litter fall carbon to the soil. SOC increases, and the addition of biochar made from local weeds stabilize it in the soil.

All biomes, ecosystems, and countries can and should, indeed must, be involved, marine as well as terrestrial (Goreau and Trench, 2012; Goreau et al., 2009; Goreau 2010). Millions of individual soil carbon restorationists, working on their own in every ecosystem and every part of the world have taken barren severely degraded sites and restored them to stunning productivity, enriching biomass, soils, and water supplies by paying careful attention to retaining and recycling essential nutrients. Soil can store excess atmospheric CO_2 in a time scale of decades and avert damage that would otherwise continue for thousands of years. The ecosystem service benefits of increased biodiversity, productivity, food, water, and soil resources additional to climate stabilization far outweigh the costs of reversing runaway climate change and are dwarfed by the costs we will have to pay if we do not. If we seriously break our critical biogeochemical life-support systems, we may not be able to repair them (Figure 2.26).

FIGURE 2.24 Brazilian archaeologists, led by Dr. Eduardo Goes Neves (at left), look down on a freshly excavated pit in Amazonian Terra Preta black earth soils. The soils contain high levels of biochar, fish bones, and broken pottery, which sticks out of the sides. (Photograph by James Richardson.)
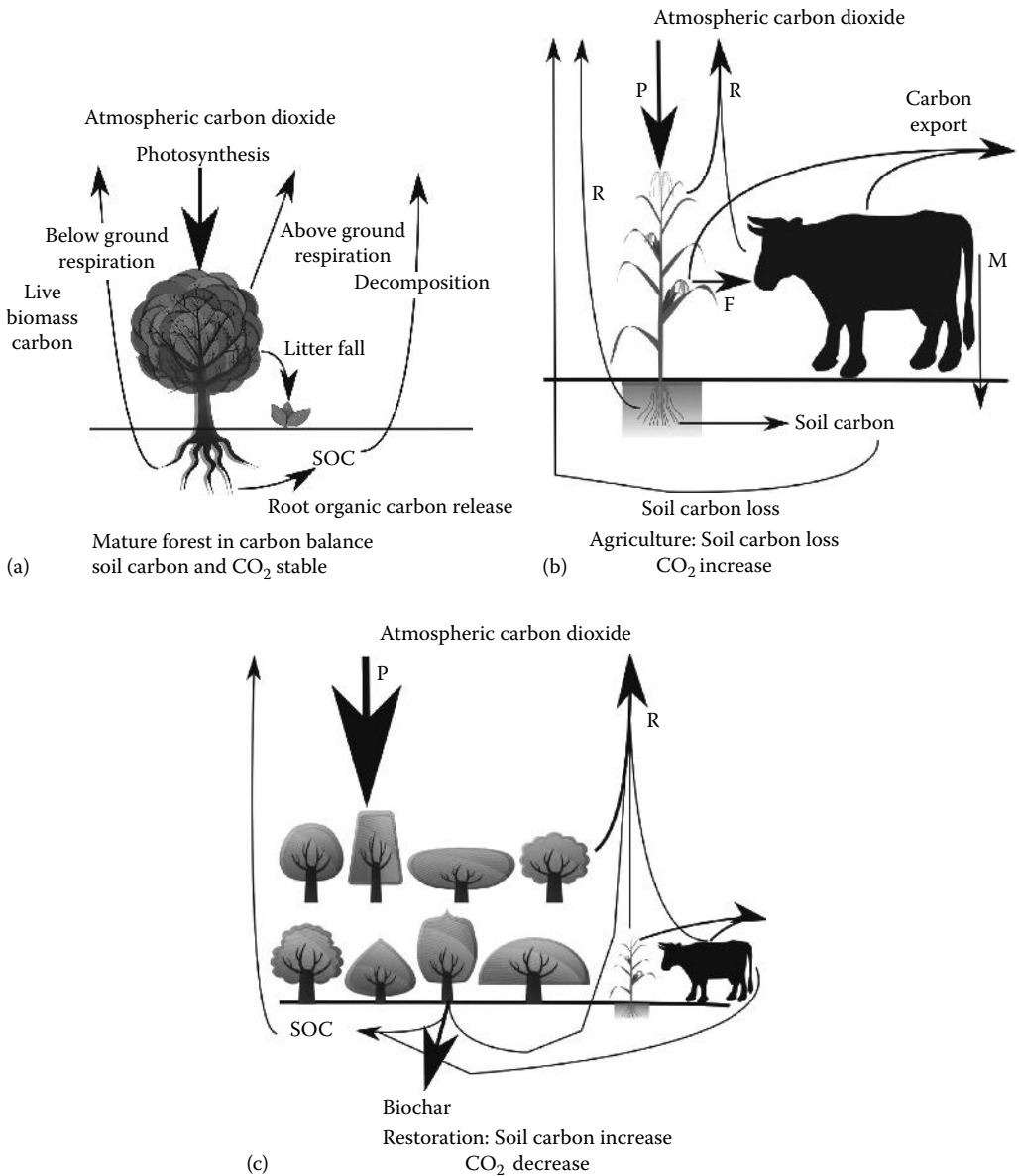
FIGURE 2.25 The carbon cycle in (a) undisturbed forest, (b) conventional agriculture and pasture, and (c) restored ecosystems managed to store carbon.

The tools to solve the problem are already at our disposal, as described in this book, if we choose to use them. All countries should use them including the developed countries that have historically produced most of the CO$_2$ excess. At the same time, it is crucial that the world's largest CO$_2$ polluter changes toward a carbon neutral or negative path. This is indeed possible if China steps aside from following the old dirty *brown* Western path of development and switches to leading a *green* low-carbon energy revolution. There are hopeful signs in this regard (Liu et al., 2013), and it is urgent that they be rapidly implemented and applied to the other developing countries so that sustainable development can be achieved without runaway climate change.
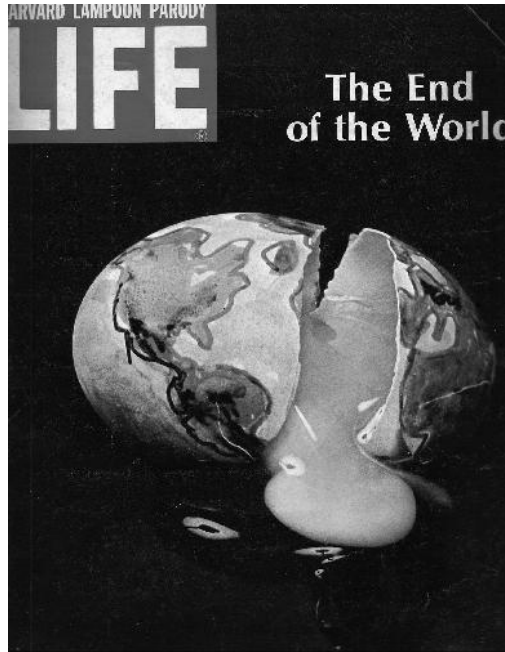
FIGURE 2.26   Prevention is cheaper than cure. "All the king's horses and all the king's men couldn't put Humpty Dumpty together again." (From Harvard Lampoon, 1968.)

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