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Interactions between CO_2 Stabilization Pathways and Requirements for a Sustainable Earth System

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Efforts to stabilize the atmospheric CO_2 concentration take place within a fully coupled Earth system in which there are major interactions between the carbon cycle, the physical climate, and human activities. Hence it is necessary to consider atmospheric CO_2 mitigation in the context of the Earth system as a whole, and its long-term sustainability.

"Sustainability" and "sustainable development" have been defined in a number of ways. The Brundtland Report (World Commission on Environment and Development 1987) defined sustainable development as "development that meets the needs of the present, without compromising the ability of future generations to meet their own needs." In practice, definitions of sustainable development hinge on several key issues: what has to be sustained, what has to be developed, for how long, and with what tradeoffs. It is necessary to consider economic, social, and environmental dimensions and to accommodate the different perspectives of each dimension as well as the interrelations between them. For the purposes of this chapter, we will follow the consensus of the United Nations Commission on Sustainable Development (1996), which identified the major challenges for global sustainable development as (1) combating poverty; (2) protecting the quality and supply of freshwater resources; (3) combating desertification and drought; (4) combating deforestation; (5) promoting sustainable agriculture and rural development; and (6) conserving biological diversity. To this list may be added the goal of the 1992 UN Framework Convention on Climate Change (UNFCCC) of preventing dangerous anthropogenic interference in the climate system, implying the need to stabilize the atmospheric concentrations of greenhouse gases and CO_2 in particular.

This chapter examines the challenge of achieving CO_2 stabilization in the context of the requirements for a sustainable Earth system, broadly defined as above. We have three objectives, each the topic of a major section. First, we sketch a systems framework for analyzing CO_2 stabilization pathways within the full range of carbon-climate-human interactions. Second, we identify the wider economic, environmental, and sociocultural implications of a large number of carbon management options in order to provide information about these implications for the systems analysis. Third, we consider a particular important case (land-based mitigation) in more detail. An overall synthesis concludes the chapter.

A Systems Analysis

The Carbon Cycle and the Stabilization Challenge

We begin with the familiar aggregate atmospheric CO_2 budget, written in the form

$$\frac{dC_A}{dt} = M\frac{dc_A}{dt}\; F_{Land} \underbrace{+ F_{Ocean} + F_{Foss}}_{\text{Indirect human influence}} + \underbrace{(F_{LULUC}) + F_{Seq} + F_{Disp}}_{\text{Direct human influence}}$$

where C_A is the mass of CO_2 in the atmosphere. The fluxes on the right-hand side, which change C_A, include the land-air and ocean-air fluxes (F_{Land}, F_{Ocean}); industrial (mainly fossil fuel) emissions (F_{Foss}); fluxes from land use and land use change (F_{LULUC}) excluding managed sequestration; managed terrestrial and ocean biological carbon sequestration (F_{Seq}); and engineered disposal of CO_2 in land or ocean reservoirs (F_{Disp}). Fluxes from the atmosphere (uptake to land and ocean pools) are negative. All these fluxes are influenced by human activities, in the sense that they are different from what they would have been without human intervention in the carbon cycle. We can, however, distinguish different levels of human influence. Some fluxes are linked with identifiable human actions as proximate causes: for instance, fossil-fuel burning, land clearing, or managed CO_2 sequestration. Others are influenced by human actions only through changes in the Earth system, such as rising atmospheric CO_2, rising average temperatures, changes in precipitation patterns, and changes in nutrient cycles. The distinction is not absolute, but it is important because the directly human-influenced fluxes are candidates for carbon management. Therefore we identify some fluxes in equation (1) (F_{Foss}, F_{LULUC}, F_{Seq}, F_{Disp}) as "directly influenced" by human activities and others (F_{Land}, F_{Ocean}) as "indirectly influenced," with the fluxes in former group being actually or potentially directly manageable.

Most of the fluxes in equation (1) depend on the atmospheric CO_2 concentration. These dependencies (often called "feedbacks") are both direct and indirect. The direct feedbacks occur through physical and biological mechanisms like CO_2 fertilization of carbon uptake into terrestrial and marine pools, while the indirect feedbacks occur through climate properties like temperature, light, precipitation, and ocean circulation, which influence the fluxes. Climate, in turn, is responding to a range of "climate forcings," including CO_2 and non-CO_2 greenhouse forcing, solar variability, and volcanogenic aerosols. The result is that the fluxes in equation (1) depend on the atmospheric CO_2 level (C_A) both directly through physics and biology and indirectly through climate. Through this dual set of dependencies, the behavior of the fluxes in response to rising C_A can potentially change drastically as C_A itself rises; for example, negative (stabilizing) feedbacks can be replaced by positive (destabilizing) feedbacks through mechanisms like a shift in the land-air flux toward CO_2 emission as respiration increases with warming, or a substantial change in the oceanic thermohaline circulation. Such possible changes in system behavior, or "vulnerabilities" in the carbon-climate-human system, are associated with nonlinearities or thresholds in the relationships between fluxes (F), atmospheric CO_2 (C_A), and climate (see Gruber et al., Chapter 3, this volume, for more discussion of vulnerabilities). Their significance here is that they have major implications for efforts to stabilize atmospheric CO_2.

At present, the largest of the directly human-influenced fluxes in equation (1) is the fossil-fuel emission (F_{Foss}). This can be expressed[1] as a product of five driving factors:

$$F_{Foss} = P \underbrace{\left(\frac{G}{P}\right)}_{g} \underbrace{\left(\frac{E_{Pri}}{G}\right)}_{e} \underbrace{\left(\frac{E_{Foss}}{E_{Pri}}\right)}_{f} \underbrace{\left(\frac{F_{Foss}}{E_{Foss}}\right)}_{i} = Pgefi$$

where P is population, G is gross world economic product, E_{Pri} is global primary energy,[2] and E_{Foss} is the primary energy generated from fossil fuels. Key ratios among these variables are the per capita gross economic product ($g = G/P$), primary energy per unit economic product ($e = E_{Pri}/G$), fraction of primary energy from fossil fuel ($f = E_{Foss}/E_{Pri}$), and carbon intensity of energy generation from fossil fuel ($I = F_{Foss}/E_{Foss}$). We note that $ge = E_{Pri}/P$ is the per capita primary energy. The sum of the directly human-influenced fluxes in equation (1) now becomes

$$\begin{aligned} F_{DHI} &= F_{Foss} + F_{LULUC} + F_{Seq} + F_{Disp} \\ &= F_{Foss} + F_{LULUC} + F_{Seq} + F_{Disp} \end{aligned}$$

Table 6.1 gives current global average values for quantities in equations (3) and (1). Of course, these averages mask huge regional differences (Romero Lankao, Chapter 19, this volume).

Table 6.1. Current (1990–1999) global average values for terms in the global carbon budget and the quantities *P, ge, f, i*

Quantity	*Description*	*Value*	*Unit*	*Reference*
dc_A/dt	Growth rate of atmospheric CO_2	+3.3	PgC y^{-1}	IPCC (2001a)
F_{Nat}	Natural C flux to atmosphere	–4.7	PgC y^{-1}	IPCC (2001a)
$= F_{Ocean}$	= ocean-air flux	–1.7		
$+F_{Land}$	+ land-air flux	–3.0		
F_{DHI}	Direct-human-induced C flux to atmosphere	+8.0	PgC y^{-1}	IPCC (2001a)
$= F_{Foss}$	= industrial (mainly fossil fuel) emission	+6.4		
$+F_{LULUC}$	+ disturbance flux from land use change	+1.7		
$+F_{Seq}$	+ managed terrestrial C sequestration	–0.1		
$+F_{Disp}$	+ engineered disposal of CO_2	–0.0		
E_{Pri}	Primary energy	12 3.8×10^{14}	TW MJ y^{-1}	Hoffert et al. (2002)
P	Population	6.0×10^9	Humans	
$ge = E_{Pri}/P$	Per capita primary energy	2.0 6.3×10^4	kW $human^{-1}$ MJ y^{-1} $human^{-1}$	Calculated using $ge = E_{Pri}/P$
f	Fraction of energy from fossil fuel	0.85	—	Hoffert et al. (2002)
i	Carbon intensity of energy generation from fossil fuel	19.9	gC MJ^{-1}	Calculated using $F_{Foss} = Pgefi$

Of the eight quantities (P, g, e, f, i, F_{LULUC}, F_{Seq}, F_{Disp}) determining the directly human-influenced fluxes through equation (3), six are associated with strategies for carbon mitigation:

- *e:* energy conservation and efficiency (while maintaining economic well-being, *g*);
- *f:* use of non-fossil-fuel energy sources;
- *i:* more carbon-efficient energy generation from fossil fuels;
- F_{LULUC}: reduction of carbon emissions from land disturbance;
- F_{Seq}: managed sequestration of carbon in terrestrial or oceanic biological sinks; and
- F_{Disp}: engineered disposal of CO_2 in geological or oceanic repositories.

The other two quantities (*P* and *g*) are not regarded here as carbon mitigation strategies. That is, we do not consider options for reducing fossil-fuel emissions by lowering population (*P*) or economic well-being (*g*). Nakicenovic (Chapter 11, this volume) discusses trends in both variables.

We turn now to the stabilization challenge. A stabilization trajectory for direct-human-induced emissions, $F_{Stab}(t)$, is a (non-unique) trajectory for the directly human-influenced carbon flux, $F_{DHI}(t) = F_{Foss} + F_{LULUC} + F_{Seq} + F_{Disp}$, such that the atmospheric CO_2 level (C_A) is eventually stabilized ($dC_A/dt = 0$) at a given target level (Wigley et al.

1996; Houghton et al. 2001, Figures 3.13 and 9.16). Examples are shown in Figure 6.1. Stabilization trajectories are determined by the feedbacks between the fluxes in equation (1), particularly F_{Land} and F_{Ocean}, and the atmospheric CO_2 level (C_A). Stabilization trajectories have several important features: first, $F_{Stab}(t)$ increases initially and then peaks and declines to near zero in the far future (and for low stabilization CO_2 targets F_{Stab} can actually become negative). Second, the lower the stabilization CO_2 target, the sooner and lower is the allowed emissions peak. Third, short-term trajectories of $F_{Stab}(t)$ (over the next decade) do not depend much on the selected stabilization CO_2 target. Fourth, it is crucial to note the implications of the vulnerabilities associated with possible positive feedbacks in the relationships between CO_2, fluxes, and climate. These vulnerabilities add considerable uncertainty to stabilization trajectories, especially when the stabilization CO_2 target is high. The higher the target, the greater is the magnitude of likely climate change and the greater the probability of carbon-climate feedbacks becoming important. In extreme cases, positive feedbacks could prevent stabilization from being achieved at all.

A quite different picture emerges from consideration of the direct-human-induced C flux F_{DHI} (equation (3)), especially its fossil-fuel component. At present, fossil fuels represent about 85 percent of the 12 TW of primary energy generated by human societies (Table 6.1). Future human energy demand will increase substantially (though far from uniformly across regions and scenarios), in response to both increasing population (P) and increasing globally averaged per capita energy use ($E_{Pri}/P = ge$) associated with globally rising standards of living. If a significant fraction of this demand is met from fossil fuels, the trajectory for F_{DHI} is likely to be far from that required for stabilization. Emissions scenarios (Nakicenovic et al. 2000; Edmonds et al., Chapter 4, this volume; Nakicenovic, Chapter 11, this volume) give an internally consistent set of assumptions for the time trajectories of the quantities P, g, e, f, i, F_{LULUC}, F_{Seq}, and F_{Disp}, which influence F_{DHI}. Under most (though not all) scenarios, $F_{DHI}(t)$ substantially exceeds the human-induced C flux required for stabilization, $F_{Stab}(t)$. The difference $F_{DHI}(t) - F_{Stab}(t)$ is called the carbon gap.

To give an idea of the relationship between stabilization requirements and possible trajectories of the terms in equation (3), Figure 6.1 shows how these terms evolve over the next century from their current values (Table 6.1) under simple growth assumptions for three cases (see Figure 6.1 caption). Case 1 approximates the well-known IS92a scenario (Houghton et al. 1996) and includes no mitigation through F_{LULUC}, F_{Seq}, and F_{Disp} except for a decreasing land disturbance emission. It does include some "default" or "business-as-usual" mitigation through negative values for the growth rates of f and i, as is commonly done in baseline scenarios (Edmonds et al., Chapter 4, this volume). Case 2 includes major mitigation through F_{LULUC}, F_{Seq}, and F_{Disp} but is otherwise the same as Case 1. Case 3 includes major mitigation in all terms (e, f, i, F_{LULUC}, F_{Seq}, F_{Disp}) and produces a trajectory for F_{DHI} that approximates a stabilization trajectory. This figure shows that major mitigation through sequestration and disposal (Case 2) cannot

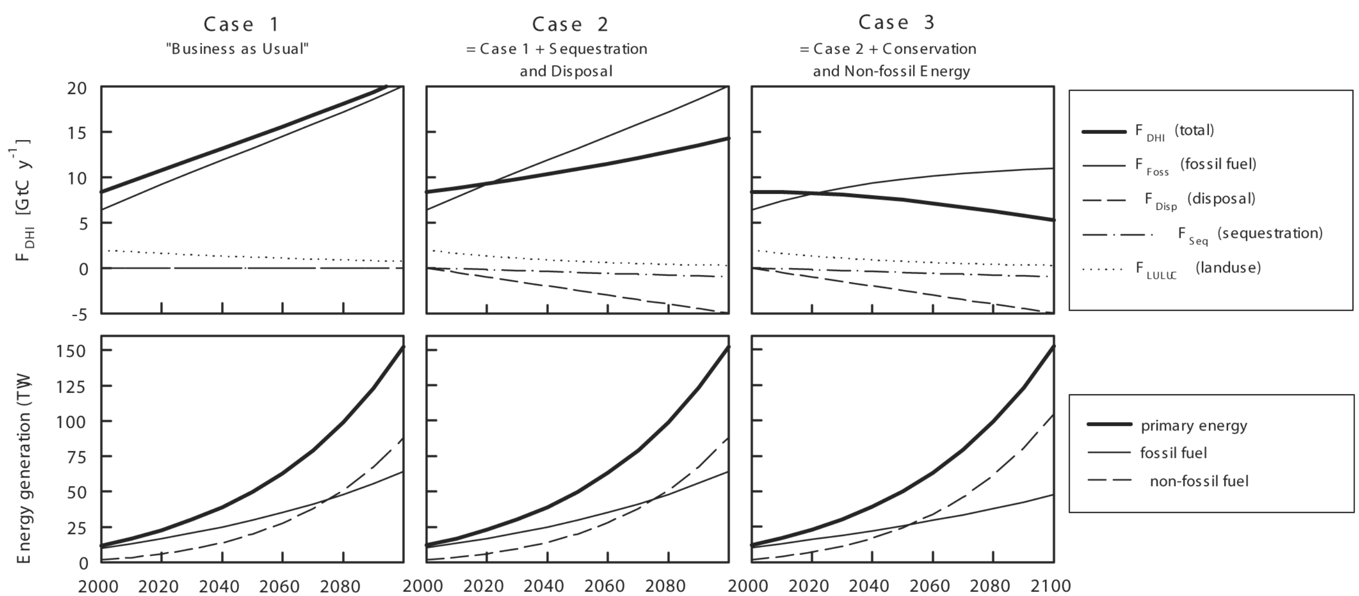

Figure 6.1. Evolution of the terms in equation (3) over the next century from their current values (Table 6.1), under simple growth assumptions: per capita primary energy *ge* grows geometrically; *f*, *i* and F_{LULUC} decline geometrically; and F_{Seq} and F_{Disp} grow linearly. Assumed rates for each term are shown in the inset table. Three cases are shown: Case 1 approximates the IS92a scenario (IPCC SAR 1995) and includes no land-based mitigation except for a decreasing land disturbance emission. Case 2 includes major mitigation through F_{LULUC}, F_{Seq}, and F_{Disp} but is otherwise the same as Case 1. Case 3 includes major mitigation in the energy-sector terms *f* and *i* in addition to F_{LULUC}, F_{Seq}, F_{Disp} (which are as in Case 2), and produces a trajectory for the direct-human-induced flux F_{DHI}, which approximates a stabilization trajectory at a target CO_2 level of around 500 ppm. The top panel compares the direct-human-induced emission flux F_{DHI} for all three cases; the middle three panels show the carbon fluxes contributing to F_{DHI} for each case; the lower three panels show the primary energy and its contributions from fossil-fuel and non-fossil-fuel sources. The conclusion is that major mitigation through sequestration and disposal (Case 2) cannot achieve stabilization unless there is also major mitigation in the energy sector (Case 3).

achieve stabilization unless there is also major mitigation in the energy sector (Case 3). Our intention here is not to construct self-consistent scenarios like those described in Edmonds et al. (Chapter 4, this volume), but only to indicate the orders of magnitude of the terms in equation (3), their trends under simple constraining assumptions, and how those trends relate to stabilization requirements.

Trajectories of the Carbon-Climate-Human System as Emergent Properties

It might seem that closing the carbon gap is simply a matter of managing the future values of the quantities P, g, e, f, i, F_{LULUC}, F_{Seq}, and F_{Disp}, which determine the total direct-human-induced flux $F_{DHI}(t)$, so that its trajectory conforms with a stabilization trajectory $F_{Stab}(t)$. Of course, the real world is not like this "command and control" or "rational" decision-making model (Keely and Scoones 1999). All these quantities are internal variables in a coupled carbon-climate-human system and are constrained by numerous interactions with other variables. The future trajectory of the system, and of each of its components, is an emergent property—that is, a property of component interactions rather than the result of external control.

To explore these constraints and interactions, we consider the multiple effects of a portfolio of mitigation options or technologies. These options may include any of those listed after equation (3), together with abatement of non-CO_2 greenhouse gas emissions from agriculture and other sectors. The effect of any one mitigation technology can be described by its technical potential (T) and its uptake proportion (u), where T is the maximum mitigation or carbon equivalent avoided emission (in tCeq per year) that can be achieved by the technology, subject only to biophysical constraints such as resource availability; and u is a number between 0 and 1 determining how much of the technical potential is actually utilized, subject to additional economic, environmental, and sociocultural factors. The achieved mitigation from a portfolio of options will then be $u_1 T_1 + u_2 T_2 + \ldots$, where the subscripts refer to different technologies.

A range of constraints and driving factors influence the uptake of a mitigation technology, and the effort devoted to maximizing its technical potential. Briefly (pending more detailed discussion in the next subsection), these include:

- *climate factors:* the need to avoid dangerous anthropogenic interference in the climate system by minimizing CO_2 and other greenhouse gas emissions (the direct purpose of mitigation);
- *economic factors*, including the competitiveness of energy options, the material and energy intensities of economic growth, access to markets, and industrialization pathways;
- non-greenhouse *environmental factors*, including the provision and maintenance of ecosystem services such as clean air, clean water, and biodiversity; and

- *social, cultural, and institutional factors,* including consumption patterns, lifestyles, class structures, incentives, policy climates, and demographics at scales from local to global.

To account for these influences, we consider "utility functions" or "benefit functions" U_{Clim}, U_{Econ}, U_{Env}, and U_{Soc} that quantify the effects of the portfolio of mitigation options in climate, economic, environmental, and sociocultural spheres. These functions may be either positive (net benefits) or negative (net costs). They reflect all aspects of societal well-being and are not confined to measurement in economic terms. They depend on the uptake proportions of the various mitigation options: thus, $U_{Econ} = U_{Econ}(u_k)$ (where the subscript *k* distinguishes the various technologies) and similarly for U_{Env} and U_{Soc}. A major part of the climate utility U_{Clim} is clearly the total achieved mitigation $u_1T_1 + u_2T_2 + \ldots$, though there may be climate costs as well, for instance through adverse effects of land use change on regional climates (Betts et al. 2000) or increased N_2O emissions from higher fertilizer use.

It is possible to consider the overall utility or net benefit from the portfolio of mitigation options, U_{Total}, accounting for benefits and costs in all spheres. This is a combination of the utilities U_{Clim}, U_{Econ}, U_{Env}, and U_{Soc}. There is a substantial literature from the discipline of welfare economics on the formulation and properties of such overall utility measures (see, for example, Brock et al. 2002). Here it suffices to assume that U_{Total} is the weighted sum

$$U_{Total} = w_{Clim}U_{Clim}(u_k) + w_{Econ}U_{Econ}(u_k) + w_{Soc}U_{Soc}(u_k) + w_{Env}U_{Env}(u_k),$$

where the weight factors *w* describe the relative importance that a society gives to each component of the overall utility of the portfolio of options. The uptake proportions u_k can now be formally specified as the quantities $u_k(t)$, which maximize the overall utility, integrated over some time period, subject to several basic constraints: that energy supply meets demand and that requirements are met for other basic resources such as water, food, and land. It is also possible to regard the technical potentials T_k as variable to maximize U_{Total}, to the extent that the technical potentials are influenced by societal choices such as investment in research and development. Thus, both u_k and T_k emerge as "control variables" in a constrained optimization.

This is merely an indicative analysis rather than a quantitative recipe. Even so, several features emerge. First, major variables determining the outcome are the weights *w*, which express the economic, environmental, sociocultural, and policy priorities emerging from societal institutions and structures. These weights are key "levers" influencing future trajectories of the energy system and more generally the carbon-climate-human system.

Second, diverse societies have different institutions, structures, and priorities. The analysis and the outcomes are therefore both regionally specific. A major point of intersection between regions is that they all share the atmosphere as a global commons and hence all pay a climate-change cost as a result of global fossil-fuel emissions. Even so, climate-change impacts and hence the nature of this cost are different among regions.

Third, the existence of benefits as well as costs is of great significance. Here are two examples: (1) a switch to clean fuels or renewables is likely to have benefits for regional air quality, and (2) more efficient transport systems in cities usually confer net social and urban-environment benefits. Such benefits in the non-greenhouse aspects of the overall utility are crucial in adding to the likelihood that real greenhouse mitigation will occur through changes in energy use.

Fourth, there are synergisms between different constraints (or different components of the overall utility in equation (4)). For example, if the technology for a massive switch to biofuels were available at reasonable cost, consequences would include declines in the availability of land for agriculture, biodiversity, and carbon stocks in forest ecosystems. This point is expanded later.

Finally, the uptake of mitigation options is constrained by technological and institutional inertia or contingent history: for example, it is not usually practical to change technologies at a rate faster than the turnover time of the infrastructure (see Caldeira et al., Chapter 5, this volume).

Diversity of Influences on Carbon Mitigation Strategies

We now consider in more detail the diverse factors affecting the uptake of a particular carbon mitigation strategy. Figure 6.2 is a graphical representation of the factors influencing the difference between the technical potential of a particular mitigation strategy and the actual, achieved mitigation. The horizontal axis is the mitigation potential, measured by the total amount of carbon-equivalent greenhouse forcing avoided (in tCeq per year, for example), and the vertical axis is the price of carbon (in dollars per tCeq), a measure of the weight ascribed to carbon mitigation relative to other goals. The maximum mitigation that can be achieved by a strategy is its technical mitigation potential, based solely on biophysical estimates of the amount of carbon that may be sequestered or greenhouse gas emissions avoided, without regard to other environmental or human constraints. This amount is not dependent on the price of carbon and hence is a straight line. There is also a minimum mitigation achieved by baseline or business-as-usual technological development (as reflected, for example, in the family of scenarios appearing in the Intergovernmental Panel on Climate Change [IPCC] *Special Report on Emissions Scenarios* [SRES]; Nakicenovic et al. 2000), which already include assumed mitigation such as through shifts toward non-fossil fuels). This baseline mitigation is likewise independent of the price of carbon. Between these limits, the actual, achieved mitigation is a price-dependent curve. It is less (often very much less) than the technical potential, because of a range of economic, environmental, and social drivers and constraints. In more detail than before, these include the following:

- *Economics:* Economic factors include (1) access to markets for carbon-relevant products; (2) the nature of those markets; (3) the influence of pathways of industrialization and urbanization on existing and new carbon-relevant economic sectors; (4) the

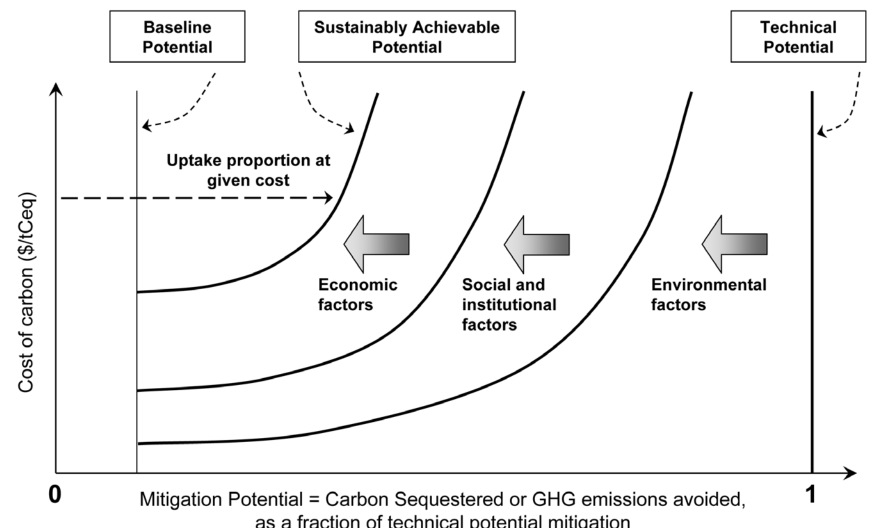

Figure 6.2. Effects of economic, environmental and social-institutional factors on the mitigation potential of a carbon management strategy. The technical potential (independent of cost) is reduced a combination of economic factors (markets, trade, economic structures, urbanization, industrialization); environmental factors (need for land, water and other resources, waste disposal, property rights); and social and institutional factors (class structure, politics and formal policies, informal rules, lifestyles, attitudes, behaviour). The end result is a sustainably achievable mitigation potential for the carbon management strategy being considered. This depends on the cost of carbon, which is a measure of the weight ascribed to carbon mitigation relative to other goals. The uptake proportion for the strategy is the ratio of the sustainably achievable potential to the technical potential. The Figure also shows a baseline potential, representing the extent to which the carbon management strategy is deployed in a "business as usual" scenario.

existence or absence of crisis-prone economic conditions; and (5) the indebtedness of many countries, especially in the developing world. Economic markets play an important role in governing access to resources and, used intelligently by governments, can provide important incentives to switch to lower-carbon energy portfolios.

- *Environmental requirements for other resources:* The need for resources to supply essentials, such as food, timber, and water, can reduce the estimated technical potential.
- *Environmental constraints:* Mitigation activities can incur environmental costs such as waste disposal and ecological impacts.
- *Social factors:* Differences in social factors between countries and between urban and rural locations exert strong influences on mitigation outcomes. On a personal level, class structure and lifestyles are often related on one hand to increasing consumption and use of carbon-relevant commodities as cultural symbols, such as cars, mobility, and

travel to exotic places (Lebel, Chapter 20, this volume). On the other hand, lifestyles are linked to poverty and lack of access, for instance, to technical alternatives. On a public level, societal values and attitudes determine the level of support for carbon management strategies, through education and societal self-image (such as frontier, pro-modernization, pro-conservation).

- *Institutional factors:* Institutions determine the structure of incentives influencing any management option, both in terms of taxes, credits, subsidies, sectoral strategies, property rights regimes, and other formal components and in terms of the policy climate or informal policies within which management strategies are designed and implemented. Examples of policy climate include the level of performance, the presence or absence of corruption, and the extent and nature of powerful vested interests. To illustrate the last point, significant constraints can arise within both public and private sectors that affect the speed of technology deployment and the choices of alternative systems. Owners of existing energy technologies can use their considerable financial and technological influence to block the development or deployment of alternative systems. Similarly, government regulators may use their powers to control the flow of investment in mitigation technology or its application in their country in order to protect perceived national interests.
- *Institutional and timing aspects of technology transfer:* Some features of technology transfer systems, like the patenting system, do not allow all countries and sectors to gain access to the best available technology rapidly or at all. The timing of technology transfer is an issue, as many technological paradigms need 50–70 years to be completely established (Nakicenovic, Chapter 11, and Romero Lankao, Chapter 19, both this volume).
- *Demography:* The density, growth, migration patterns, and distribution of the population can form another constraint, especially in countries with high levels of social segregation. For instance, in regions with a high concentration of land in few hands, population pressure on land can pose an obstacle to a reforestation strategy.

Some of these constraints are price dependent, implying that a higher carbon price would increase the viability of the carbon management strategy. Hence, in general, the relationship between the sustainable mitigation potential and the price of carbon is a curve in Figure 6.2.

After considering these factors, the remaining amount of mitigated carbon emission or sequestration is the sustainably achievable potential at a given price of carbon. In the schematic analysis of the previous subsection, the price of carbon is a measure of the relative weights (w) between the climate cost and other components of the overall cost in equation (4), and the uptake proportion (u) is the ratio of the sustainably achievable potential to the technical potential. Figure 6.2 again emphasizes the importance of the weighting between carbon mitigation and other societal goals in determining the uptake of mitigation technologies and hence mitigation outcomes.

Implications of Carbon Management Options

A large portfolio of carbon management options is needed to give flexibility in designing a practical pathway for achieving stabilization of atmospheric CO_2 (Caldeira et al., Chapter 5, this volume). As already emphasized, all carbon management options bring both positive and negative environmental, economic, and sociocultural impacts, in addition to greenhouse mitigation. In designing carbon management strategies it is necessary to take advantage of beneficial synergies between mitigation and other impacts.

Our discussion of the wider implications of mitigation is intended to supplement the more technically oriented contributions of Caldeira et al. (Chapter 5) and the engineering-oriented review of Hoffert et al. (2002), by providing some analysis of collateral effects. We consider four classes of impact corresponding to the four terms in equation (4): climate change and greenhouse, economic, environmental, and sociocultural. The technical options are organized into five categories identifiable with the six mitigation-oriented terms in equation (3): conservation and efficiency (combining the factors *e* and *i* into one category), non-fossil-fuel energy sources (factor *f*), land-based options including disturbance reduction and biological sequestration (terms F_{LULUC} and F_{Seq}), biological sequestration in oceans (term F_{Seq}), and engineered CO_2 disposal (term F_{Disp}). We restrict discussion to options that are currently technically feasible, at least at moderate scales, omitting (for example) nuclear fusion and spaceborne solar power. Also, although the focus is on carbon mitigation toward CO_2 stabilization, we include discussion of other greenhouse gases where these are closely related to carbon mitigation options, for example in land use.

The results of our analysis are summarized in Table 6.2, where we have somewhat subjectively estimated the collateral costs and benefits for each strategy in each impact class as minor, moderate, or major.

Conservation and Efficiency

A number of changes in technology, policy, and human behavior will reduce energy demands, with benefits or at most small costs for economic productivity. These influence the factor *e* (primary energy per unit economic product) in equation (3). Examples include:

- *more efficient appliances* (light-emitting diodes, low-power computers, . . .);
- *more efficient indoor environments* (passive lighting, heating, cooling, insulation . . .);
- *urban microclimate design* to minimize energy demand in extreme weather conditions (for example, using trees to lessen both heating and cooling demands);
- *better urban planning* (improving public transport, shortening travel distances, . . .);
- *shifts toward diets* that require less energy inputs (shifting diets toward vegetarianism).

Technological changes that will reduce the carbon intensity of fossil-fuel energy generation (factor *i* in equation (3)) include

Table 6.2. Assessment of positive and negative climate, economic, environmental, and sociocultural impacts associated with mitigation strategies

	Impact			
Mitigation strategy	*Climate change and greenhouse*	*Economic*	*Environ-mental*	*Socio-cultural*
Conservation and efficiency				
More efficient appliances				
More efficient indoor environments				
More efficient automotive transport	(+++)	(++) and (-)	(+++) and (-)	(++) and (-)
Better urban travel planning				
Urban microclimate design				
Better use of fossil fuels				
Cogeneration				
Changes to diets				
Non-fossil-fuel energy sources				
Hydropower	(++) and (-)	(+) and (-)	(++) and (- -)	Developed: (-) Developing: (- - -)
Solar power	(+++)	(-)	(+++) and (-)	Δ
Wind power	(++)	(+) and (-)	(+++) and (-)	(+) and (-)
Bioenergy	(+++) and (- -)	(+) and (-)	(+++) and (- -)	(+) and (- -)
Geothermal power	(+)	Δ	(++) and (-)	Δ
Nuclear energy	(+++)	(++) and (- -)	(++) and (- - -)	(- - -)
Land-based options				
Afforestation, reforestation, and land restoration	(++) and (-)	Incentives needed	(++) and (-)	(++) and (- -)
Reduction of net deforestation	(+++)	Incentives needed	(++)	(++) and (- -)
Forest management and fire suppression	(+) and (-)	(+) and (-)	(++) and (-)	Δ
Changing agricultural management	(++)	(++) and (-)	(++) and (- -)	Δ
Non-CO_2 mitigation from land biosphere	(++)	(++) and (-)	(++) and (-)	Δ
Bioengineering solutions (- -)		Δ	(++) and (- -)	(+) and (- - -)
Biological sequestration in the oceans				
Ocean fertilization	(++) and (- -)	Δ	(- -)	(- - -)
CO_2 disposal on land and oceans				
C separation with ocean storage	(+++) and (- -)	Δ	(- -)	(- - -)
C separation with geological storage	(+++) and (- -)	Δ	(- -)	(-)

Note: Symbols (+), (++), and (+++) indicate minor, moderate, and major positive impacts (benefits); likewise, (-), (- -), and (- - -) indicate minor, moderate, and major negative impacts (costs). Where distinct benefits and costs occur, these are indicated separately. Impacts in the climate change and greenhouse area refer to technical potential, indicated as minor (< 0.3 PgC y^{-1}), moderate (0.3 to 1 PgC y^{-1}), and major (> 1 PgC y^{-1}). A question mark indicates that insufficient information is available to make a judgment.

- *more efficient automotive transport* (hybrid vehicles that electrically recover lost mechanical energy, use of smaller cars rather than sports utility vehicles in cities, . . .);
- *better use of fossil fuels* (natural gas, highly efficient coal combustion); and
- *cogeneration* (recovery and use of low-grade heat from electric power stations, usually with smaller and more distributed power stations).

The technical potential for gains in energy efficiency from these options are large, in many cases from tens to hundreds of percentage points on a sectoral basis, and in most cases the technology is readily deployable (Hoffert et al. 2002; Edmonds et al., Chapter 4, this volume). As a group, these options have significant environmental and sociocultural benefits, including lower urban air pollution, more efficient urban transport networks, more congenial and livable cities, and improvements to population health. Some involve changes to lifestyles (such as reducing car sizes) that may be seen as sociocultural drawbacks. They also involve some transfers of economic power (for instance, away from oil suppliers), although many oil companies, particularly in Europe, are turning this change to advantage by repositioning themselves as energy service providers, including renewables and conservation.

Because of the magnitude and generally rapid uptake time of these mitigation options, and also recognizing the significant collateral benefits and minimal costs, many future scenarios include significant continuing mitigation from this area. Although scenarios vary widely, it is common to assume improvements in energy efficiency in the order of 1 percent per year while maintaining economic growth of 2–3 percent per year (Edmonds et al., Chapter 4, this volume; Figure 6.1). A key question is whether these uptake rates can be improved.

Non-Fossil-Fuel Energy Sources

These options reduce f (the fraction of primary energy from fossil fuel) in equation (3).

Hydropower

At present about 19 percent of the world's electricity is produced from hydropower (McCarthy et al. 2001). Although this source is reaching saturation in developed countries, continued deployment is likely in many developing countries. Hydropower is a renewable energy source with important benefits, such as flood control and regulation of river flows for agricultural, industrial, and urban use. From the power-engineering viewpoint, hydropower is fast to start in peak electricity consumption periods and can store surplus energy from other sources during low consumption periods, thus increasing overall system efficiency. There can, however, also be a range of negative sociocultural, environmental, economic, and ancillary greenhouse-gas consequences. During dam construction and first filling, few or many (up to millions) of people are displaced from their homes, often leading to impoverishment (World Commission on Dams 2000). Dams alter downstream nutrient cycling patterns, ecosystems, and food-web structures, reduce biodiversity in rivers, affect the viability of fishing industries, and accumulate sediment. WBGU (2003) suggests that at least 20 percent of global rivers should remain undammed. From the greenhouse-gas perspective, the global production of greenhouse gases from hydropower systems is relatively low, but lakes in vegetated areas can incur significant methane production in anoxic sediments (McCarthy et al. 2001).

Solar Power

The solar option has low sociocultural and environmental impacts compared with many other energy systems. Available energy densities are moderate, about 15 W per square meter (m^{-2}) for electric power (Hoffert et al. 2002), so that current global electricity consumption could be met from a square less than 400 kilometers on a side (WBGU 2003). The resource is most concentrated in subtropical semiarid to arid areas, implying development opportunities in these areas, which are largely in the developing world. Extensive decentralization is also possible and is very efficient in some sectors (such as solar hot water), leading to substantial social benefits and microeconomic opportunities. On the cost side, large-scale solar energy deployment may involve significant land use changes with consequences for ecosystems; water supply may be an issue in arid regions; energy transport over large distances and across national borders is both a technical and an institutional hurdle; and environmental issues can arise in the production and disposal of photovoltaic cells (silica crystal with traces of heavy metals).

Wind Power

Like solar energy, wind power is considered a clean energy. Its technology is rapidly deployable to many suitable regions around the world, making it the world's fastest growing energy source at present. Its energy density is comparable to solar, but areas for deployment are more restricted. Wind power has very limited negative effects on the environment. The largest concern is probably the visual impact of large-scale wind farms with turbines up to 200 meters tall on mountain ridges or in coastal regions with aesthetic and cultural values. Wind turbines, especially older models, can be noisy. A controversial impact is that on bird communities through killings by turbine blades.

Bioenergy

An important option is the substitution of biofuels for fossil fuels, both for transport and for electricity generation from biofuels alone or with fossil fuels in co-fired plants. Biofuels have minimal net carbon emissions because atmospheric CO_2 is continuously recycled. The technical potential is large: up to 500 megahectares (Mha) of land (around 3 percent of the global land area) could be made available for biofuel crop production by 2100 (Watson et al. 2000b). This amount would produce in the range of 150–300 EJ y^{-1} and displace 2–5 petagrams (Pg) C y^{-1} of carbon emissions. Biofuel production offers many ancillary benefits: with good design, soil erosion can be reduced and water quality improved through increased vegetation cover. From a national viewpoint, dependence on imported oil can be reduced, rural investment increased, work opportunities created, and agricultural products diversified. There are few negative impacts when biomass sources are by-products (organic waste and residues) from agriculture and forestry, though transport infrastructure is an issue because of low energy densities (0.3–0.6 W m^{-2}). The large-scale production of dedicated biofuels can, however, have negative impacts, including competition for other land uses, primarily food production; soil sustainability (extraction of residues should not exceed 30 percent of total production to maintain soil fertility); poor resilience of monocultural plantations; and the implications for biodiversity and amenity (Watson et al. 2000b). The full greenhouse gas balance of biofuel production also needs to account for significant emissions from mechanization, transport, use of fertilizers, and conversion to usable energy. Taking into account some of these constraints, especially competition for other land uses, Cannell (2003) estimated the range 0.2–1 PgC y^{-1} to be a more conservative achievable mitigation capacity for C substitution using biofuels. This amount is about 15 percent of the potential mitigation described earlier. Other estimates are even lower (WBGU 2003).

Geothermal Power

Geothermal power is a niche option with small mitigation potential but significant environmental benefits where available because of the clean energy yield. There are some environmental concerns over the depletion of geothermal resources.

Nuclear Power

Nuclear energy is a non-fossil-fuel source with significant mitigation potential. Environmental concerns include waste and plant (old reactor) disposal and the potential for accidents. There is also a major sociocultural or political issue with weapons proliferation, especially where breeder reactors are used to create additional fissile material. This issue is too large to be explored here. It is notable that the UNFCCC Conference of Parties (COP 7 and 8) has agreed not to include nuclear power in the Kyoto Protocol flexible mechanisms.

Terrestrial Biological Sequestration and Disturbance Reduction

In equation (3), these options reduce emissions from F_{LULUC} and promote CO_2 uptake in the land component of F_{Seq}.

Reforestation, Afforestation, and Land Restoration

The potential global carbon sequestration due to increased forest extension and other land uses is in the order of 1 PgC y^{-1} by 2010 (Watson et al. 2000b). In the past few decades major plantation has occurred in many countries, often where previous deforestation took place. During the 1990s alone, the global area of plantations increased by

3.1 Mha y^{-1} (Braatz 2001). Regionally, reforestation and afforestation in China during the past two decades is contributing 80 percent of the total current Chinese carbon sink (Fang et al. 2001), and the return of abandoned farmland to native vegetation is estimated to be responsible for 98 percent of the current sink in the eastern United States (Caspersen et al. 2000).

If done with proper regard for the ecology and history of human land use in a region, expansion of forest area usually brings a number of collateral benefits: preservation of biodiversity, decreased soil erosion and siltation, decreased salinization, and watershed protection with associated water supply and flooding regulation. These benefits will most likely come with little adverse effect on agricultural production, employment, economic well-being, and cultural and aesthetic values in countries with agricultural surpluses such as Europe and the United States. In developing countries, however, which are usually dependent on exports of raw materials and confronted with high levels of social segregation, diverting land for reforestation may have negative consequences if it is not adapted to the local environment, land use patterns, and institutional settings. In these regions, land for afforestation is usually created by logging primary forest (Schulze et al. 2003). This practice affects vulnerable communities such as small-holding farmers (Silva 1997). There are also some environmental concerns: reduction of runoff during dry periods (due to increased soil infiltration and transpiration) may have impacts downstream, for instance in farmlands and wetlands. In boreal regions, changes in albedo due to darker forest canopies may lead to positive climate forcing and regional warming (Betts 2000; Betts et al. 2000). Taking into account a set of institutional and socioeconomic constraints only, Cannell (2003) estimated that only 10–25 percent of the potential C sequestration could realistically be achieved by 2100.

Managing Wood Products

Managing wood products is an important part of a terrestrial sequestration strategy. It involves recycling paper, making use of long-lasting wood products that can substitute for high fossil-carbon-content materials, and other steps to increase the residence time of carbon sequestered as utilized wood.

Reduction of Net Deforestation and Emissions from Land Use

Deforestation over the past 200 years has contributed 30 percent of the present anthropogenic increase of atmospheric CO_2. Current estimates of emissions from deforestation are 1.6 PgC y^{-1}, or about 20–25 percent of total anthropogenic emissions (Houghton et al. 2001). Therefore, reduction of deforestation has large carbon mitigation potential: a 3 to 10 percent reduction of deforestation in non–Annex I (developing) countries by 2010 would result in 0.053–0.177 PgC y^{-1} carbon mitigation, equivalent to 1 to 3.5 percent of Annex I base-year emissions (Watson et al. 2000b). The environmental benefits of slowing down deforestation are numerous, including most of the benefits mentioned for reforestation, with maximum value for biodiversity conservation in pristine forests, particularly in the tropics. Although ending forest deforestation is a laudable goal, it has, however, proved difficult or impossible to implement in many regions unless there are tangible socioeconomic incentives and the other drivers of deforestation (such as markets and policy climate) are specifically addressed. This is especially so in developing countries, where most deforestation occurs (Lambin et al. 2001). Another unintended outcome of rewarding the preservation of carbon stocks in forests could be a more relaxed emphasis on reduction of energy emissions, the most important pathway for long-term CO_2 stabilization (Figure 6.1).

Forest Management and Fire Suppression

Changes in forest management could increase carbon stocks with an estimated global mitigation of 0.175 PgC y^{-1} (Watson et al. 2000b). One management activity being suggested is fire suppression. Fire is a natural factor for large forest areas of the globe, and therefore an important component of the global carbon cycle. Fire is a major short-term source of atmospheric carbon, but it adds to a small longer-term sink (<0.1 PgC y^{-1}) through forest regrowth and the transfer of carbon from fast to inert pools including charcoal (Watson et al. 2000b; Czimczik et al. 2003). For instance, in the immense extent of tropical savanna and woodland (2.45 gigahectares [Gha]; Schlesinger 1997), a 20 percent fire suppression would result in carbon storage of 1.4 tC ha^{-1} y^{-1} with associated mitigation of 0.7 PgC y^{-1}. Tilman et al. (2000) estimated that additional fire suppression in Siberian boreal forest and tropical savanna and woodland might conceivably decrease the rate of accumulation of atmospheric CO_2 by 1.3 PgC y^{-1}, or about 40 percent. The biggest problem with fire suppression, however, is that these estimated rates of carbon storage are not sustainable in the long term and that potential catastrophic fires in high biomass density stands could negate the entire mitigation project apart from some sequestration in charcoal.

Changing Agricultural Management

Changes in agricultural management can restore large quantities of soil carbon lost since the onset of agriculture. The global potential for this strategy is estimated at 40–90 PgC. Estimates of potential soil C sequestration vary between 0.3–0.5 PgC y^{-1} (Smith, Chapter 28, this volume) and 0.9 PgC y^{-1} (Lal 2003), which in the best case would restore most of the lost carbon within 50 to 100 years. A large number of "stock-enhancing" practices bring environmental benefits: reduced erosion and pollution of underground and surface water, maintenance of biodiversity, and increased soil fertility (Smith, Chapter 28). However, the frequently proposed "win-win" hypothesis, according to which strategies aimed at increasing carbon accumulation will always bring other environmental benefits, needs to be verified on a case-by-case basis and with reference to sustainable development goals assigned to a region. For instance, increasing soil C stocks also leads to increasing soil organic nitrogen, which provides a source of mineralizable N, and therefore potential for increased N_2O emissions, further enhanced by the use of nitrogen fertilizer (Robertson, Chapter 29, this volume). Also, activities such as the use of fertilizer and irrigation have an associated carbon cost that often exceeds the carbon benefit (Schlesinger 1999). Other management options such as zero or reduced tillage may reduce the carbon cost of production (owing to less on-farm diesel use, despite a carbon cost associated with the extra herbicide required), but the extra use of herbicide and pesticides may create further negative environmental impacts. Taking into account a number of environmental and socioeconomic constraints, Freibauer et al. (2003) estimated that only 10 percent of the potential mitigation in the agricultural sector in Europe by 2020 is realistically achievable.

Non-CO_2 Mitigation from Land Biosphere

In the livestock sector, methane and N_2O emissions can be reduced by better housing and manure management. Methane emissions from enteric fermentation can be reduced by engineering ruminant gut flora or by use of hormones, but in some countries there are societal and legislative constraints on these technologies. N_2O emissions from agriculture can be lessened by reducing N fertilization. This decline could be achieved without loss of productivity by better timing, spatial placement (precision farming), and selection of fertilizers (Smith et al. 1996). The total anthropogenic flux of N_2O is 8.1 teragrams (Tg) N_2O-N y^{-1}, equivalent to 1.0 PgC_{equiv} y^{-1}. More than 80 percent of this amount is from agriculture; most of the rest is from the industrial production of adipic and nitric acids and can be abated with available technology.

Bioengineering Solutions

Genetically modified organisms (GMOs) were initially developed to increase food production, but also have possibilities for increasing biomass production through disease- and pest-resistant genes that promote higher productivity. This potential has possible implications for increasing both carbon sequestration and biofuel production. GMOs have still largely unknown ecological consequences, however. Major known hazards are increased weediness of GM plants, genetic drift of new genes to surrounding vegetation, development of pest resistance, and development of new viruses (Barrett 1997). Given the large uncertainty surrounding the ecological consequences of GMOs, this technology is banned in many countries.

A comment applicable to all of the options described involving terrestrial biological sequestration and disturbance reduction is that there are timescales associated with both biological sequestration and disturbance. In general, carbon losses to the atmosphere by land disturbance occur partly through delayed emissions long after the disturbance event (one to two decades). Gains from reforestation are quite slow, with similar time frames needed to rebuild carbon stocks. It follows that even if F_{LULUC} were to stop, emissions from disturbed ecosystems would still continue for some time. On the other hand, if reforestation programs are to make a major contribution to closing the carbon gap, they must be implemented early enough to see their effect on stabilizing CO_2.

Biological Sequestration in the Oceans

In equation (3), this option promotes CO_2 uptake in the ocean component of F_{Seq}.

Ocean Fertilization

The efficiency and duration of carbon storage by ocean fertilization remain poorly defined and strongly depend on the oceanic region and fertilizer (iron, nitrogen, phosphorus) used (Bakker, Chapter 26, this volume). The maximum potential of iron fertilization has been estimated as 1 PgC yr^{-1} by continuous fertilization of all oceanic waters south of 30°S (Valparaiso, Cape Town, Perth) for 100 years (Sarmiento and Orr 1991). This model study, however, probably strongly overestimates the potential for carbon storage by its assumption of complete nutrient depletion (Bakker, Chapter 26). Furthermore, roughly half of the stored carbon would be rapidly released to the atmosphere upon termination of the fertilization. Verification of actual C sequestration remains an issue.

Enhanced algal growth upon ocean fertilization of the surface oceans will decrease oxygen levels and may create anoxic (near-zero oxygen) conditions at intermediate depths (Fuhrman and Capone 1991; Sarmiento and Orr 1991), which will promote production of N_2O and methane. The release of these potent greenhouse gases to the atmosphere will partly offset or even outweigh the reduction in radiative forcing by atmospheric CO_2 mitigation, especially for the equatorial Pacific Ocean (Jin and Gruber 2002; Jin et al. 2002; Bakker, Chapter 26). Increases in biological production may also result in the release of dimethyl sulphide (DMS) (Turner et al. 1996) and halocarbons (Chuck 2002) to the atmosphere, which will create powerful feedbacks on atmospheric chemistry and global climate.

Large-scale iron fertilization will profoundly change oceanic ecosystems, ocean biogeochemistry, and the composition of oceanic sediments (Watson et al. 2000a; Ducklow et al. 2003; Bakker, Chapter 26). A shift toward larger algal species was observed in iron fertilization experiments (Coale et al. 1996; Boyd et al. 2000). A comparison to mariculture and coastal seas suggests that harmful algal blooms may occur in intensively managed systems (Bakker, Chapter 26). Fertilization might affect fish stocks, and thence fisheries and other economic sectors.

The public is very concerned about large-scale fertilization manipulations of the surface ocean for carbon storage. International law with respect to fertilization is ambiguous.

Engineered CO_2 Disposal on Land and Oceans

In equation (3), these options promote CO_2 uptake through F_{Disp}.

Carbon Separation with Ocean Storage by Deep Ocean Injection

The addition of pure liquid CO_2 in the deep ocean has potential for being a low-impact and highly effective mitigation option (Brewer, Chapter 27, this volume). There is still, however, little understanding of the potential effects of the instability of CO_2

deposits in the deep ocean and of the negative effects of the formation of CO_2-clathrates and a substantial lowering of pH on deep ocean biota. If numerous sequestration sites were concentrated in specific, rare deep ocean habitats, this practice could endanger biodiversity at these locations, but it seems likely the effects would be local. Further away a moderate pH decrease might be of similar magnitude as that expected from rising atmospheric CO_2 levels. In light of how little is known, deep ocean disposal may have unexpected effects on marine chemistry and ecosystems. Public opinion is skeptical about the technique. The London Convention (the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972) is often cited as a treaty that could prohibit such a strategy.

Carbon Separation with Geological Storage in Sediments and Rocks

Given adequate technologies to capture CO_2, largely from industrial processes, CO_2 can be disposed of in exhausted oil and gas wells and in saline aquifers. This method is a relatively clean solution provided there are not CO_2 escapes, dissolution of host rock, sterilization of mineral resources, and unforeseen effects on groundwater (Metz et al. 2001, Section 3.8.4.4). At this stage, there are still large uncertainties regarding these possible environmental impacts, but it remains a promising option.

Illustrative Case: Constraints on Land-Based Options

In this section we consider, as an illustrative case, the inclusion of land management as part of a portfolio of mitigation strategies to close the carbon gap defined earlier. Future scenarios such as the A1, A2, B1 and B2 scenario families (see Nakicenovic et al. 2000 and Figure 6.3) allocate different amounts of land for carbon mitigation strategies (such as cropland for biofuels), while also allowing for an increase in agricultural land to meet the food demands of a growing population. Globally, in 1990, 11 percent of the land surface (1,500 Mha) was under cropland. By 2100, cropland area is projected to increase to about 15 percent (A1), 17 percent (A2), 9–10 percent (B1), 16 percent (B2), and up to 24 percent under some A1 variants (Nakicenovic et al. 2000).

To illustrate the interactions between opportunities and constraints in carbon management, this section examines how each SRES scenario is likely to place pressure on land for food production as different amounts of land are allocated for carbon mitigation. It then asks two questions: (a) Are the areas of land required for mitigation realistic? (b) Under realistic environmental and sociocultural constraints on land use, what is the sustainably achievable potential for land-based options under each SRES scenario?

Scenarios

The scenarios used are the six SRES marker scenarios, taken from four scenario families, A1, A2, B1, and B2. The main characteristics of each scenario family are summarized in Figure 6.3, which shows how the scenarios fall on two axes: one examining glob-

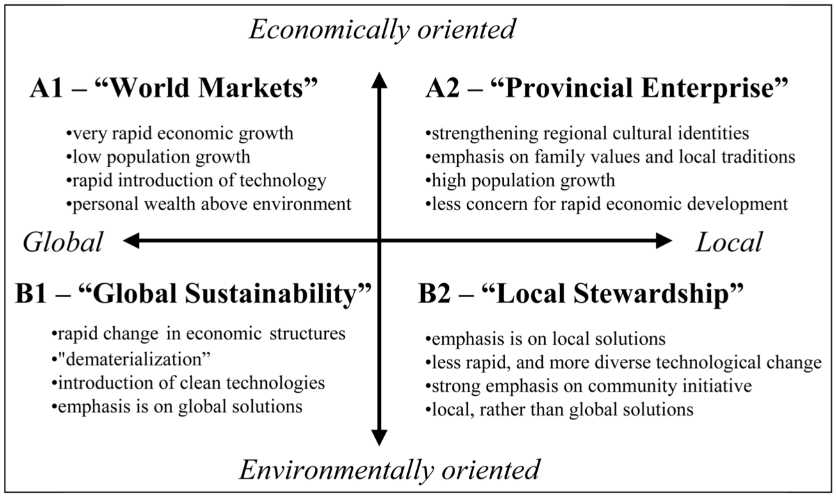

Figure 6.3. Characteristics of the main SRES marker scenario families (adapted from Smith and Powlson 2003)

alization versus regionalization and the other examining relative societal emphases on economic versus environmental considerations. Three variations of the A1 scenario (globalized, economically oriented) are considered here: A1FI (fossil fuels are used intensively), A1T (alternative technologies largely replace fossil fuels), and A1B (a balance between fossil fuels and alternative technologies). Further details are given in Edmonds et al. (Chapter 4, this volume); see also WBGU (2003). Key scenario parameters are given in Table 6.3.

Population Effects on Food Demand

We calculated 2100 food demand (assumed proportional to population growth) and the increase in productivity for each scenario (Table 6.3b). The area under crops in 1990 represents slightly over a third of the land that is theoretically estimated to be suitable for crop production. Although this estimated area may be optimistic (since some land is not well suited to permanent cropping, and other land will be removed from production by degradation), there is evidence that additional food can be generated sustainably to match population growth. This is supported by the fact that from 1961 to 1997, when human population doubled, agricultural land increased by only 11 percent. Nevertheless, the higher the food demand, the greater the pressure placed on land for agriculture, and less land may be available for other purposes, including carbon mitigation. This increased food demand could be met either by using more land for agriculture or by increasing cropping intensity and per-area productivity. Increased productivity can be obtained either (1) by increased fertilization and irrigation, subject to water availability, with associated carbon costs (Schlesinger 1999) and increased N_2O emissions (Robertson, Chapter 29, this volume); or (2) by technological improvement through breeding or biotechnology.

The A1FI, A1B, A1T, and B1 scenarios require an increase in productivity of 0.3–0.4 percent y^{-1} whereas the A2 and B2 scenarios require 0.9–1.1 percent y^{-1}. All these increases are in the range considered achievable within integrated assessment models; 1.5 percent y^{-1} is assumed by Edmonds (personal communication, 2003). Although there is a limit to how much agricultural productivity can be increased, with yield increases slowing during the past two decades (Amthor 1998; Tilman et al. 2002), there is still capacity. The Food and Agriculture Organization of the United Nations (FAO) projects global aggregate crop production to grow at 1.4 percent y^{-1} to 2030, down from 2.1 percent y^{-1} over 1970–2000. Cereal yield growth, the mainstay of crop production growth, is projected to be 1.0 percent y^{-1} in developing countries, compared with 2.5 percent y^{-1} for 1961–1999 (Bruinsma 2003). We note also that future impacts of climate change on crop yields can be quite large. Leemans et al. (2002) estimate the effect of CO_2 fertilization on crop and biofuel yield and hence on land use demand, suggesting a 15 percent increase in the land use demand without CO_2 fertilization.

Increased intensity of cropping can lead to land degradation through salinization and erosion. Despite these environmental risks, irrigation is expected to play an important role in agricultural production growth in developing countries, where an estimated 40 Mha could come under irrigation, an expansion of 33 percent more than the land currently irrigated. Scenarios A2 and B2 require increased productivity close to potential growth rates, sustained until 2100.

In summary, scenarios with slow technology development and low per capita gross domestic product (GDP) will be less able to deliver food requirements on the existing land area and are likely to increase pressure on the land resource.

Impact of Each Scenario on Possibilities for Meeting Food Demand

There are a number of logical qualitative trends for assessing whether food demand can be met by increased per-area productivity or by placing more land into production. Implications of possible trends in per capita GDP are:

- If per capita GDP is high, then (1) demand for more meat (protein) in the diet is high in developing countries, tending to increase pressure on land for food; and (2) there is capital available for increasing productivity, tending to decrease pressure on land for food.
- If per capita GDP is low, then the opposite trends ensue: (1) there is less protein in diet, decreasing pressure on land for food; and (2) less capital is available for increasing productivity, increasing pressure on land for food.

Table 6.3a. Scenario drivers taken from the SRES scenarios

Scenario	*Total carbon gap ($PgC\ y^{-1}$) in 2100 at stabilization target of 450 ppm*	*Population in 2100 (billion)*	*World GDP in 2100 (10^{12} 1990 US$)*	*Per capita GDP in 2100 (10^3 1990 US$)*	*Income ratio in 2100 of Annex I to non–Annex I*[a]	*Technology*
1990	—	5.3	21	3.9	16.1	—
A1FI	25	7.0–7.1	522–550	73.5–78.6	1.5–1.6	Rapid introduction of technology
A1B	10	7.0–7.7	340–536	44.2–76.6	1.5–1.7	Rapid introduction of technology
A1T	1	7.0	519–550	74.1–78.6	1.6–1.7	Rapid introduction of technology
A2	25	12.0–15.1	197–249	13.0–20.8	2.7–6.3	Relatively (to A1) slower introduction of technology
B1	1	6.9–7.1	328–350	46.2–50.7	1.4–1.9	Rapid introduction of technology
B2	10	10.3–10.4	199–255	19.1–24.8	2.0–3.6	Less (relative to A1) rapid, and more diverse technological change

Source: (Nakicenovic et al. 2000; Table SPM-1a and story-line text) and total carbon gap from Chapter 4, this volume

[a] Annex I = developed or industrialized nations; non–Annex I = developing countries.

Table 6.3b. Increase in food demand under each scenario

Scenario	*Increase in fooddemand relative to 1990*	*Long-term average increase in per-year productivity required to meet food demand*[a]
A1FI	32–34%	0.3%
A1B	32–45%	0.3–0.4%
A1T	32–34%	0.3%
A2 126–284%	1.1%	
B1 30–34%	0.3%	
B2 94–96%	0.9%	

[a] calculated by % change by 2100 divided by 110 (years since 1990).

Table 6.3c. Impacts of scenarios on the pressure on land for food production. + = more pressure on land for food, - = less pressure on land for food (relative to 1990)

Scenario	*Per capita GDP impact on potential increase in productivity – pressureon land resource*	*Per capita GDP impact on change in diet – pressure on land resource*	*Technology – pressure on land resource*	*Carbon gap*
A1FI	+	+++	- - -	Small
A1B	+	+++	- - -	Moderate
A1T	+	+++	- - -	Small
A2	+++	+	-	Large
B1	++	++	- - -	Small
B2	+++	+	-	Large

Trends in technological development will be equally critical and can be summarized thus:

- If technology development and *effective* dissemination are high, there is more capacity to increase production, tending to decrease pressure on land for food, and vice versa.

A caveat is needed concerning thresholds. Since even the lowest change in per capita GDP by 2100 (A2) is more than three times greater than 1990 per capita GDP, this may already exceed the thresholds that lead to changes in food consumption patterns, thereby creating increased pressure on the land resource (Bruinsma 2003). Similarly, technology may cross a threshold allowing increases in productivity to be met with technological advances. Where these thresholds lie, or whether they exist at all, is unknown. Such threshold effects are not considered in this analysis.

To apply these trend indicators to estimate net pressure on land resources, we first use the A1FI scenario (global free market with intensive fossil-fuel use) as an example. Here food demand, driven by population growth, increases by 34 percent by 2100 (Table 6.3b). Per capita GDP is high, meaning that there is likely to be more demand for meat in the diet (pressure on land resource = +++), but also that capital will be available to increase per-area productivity (average of 0.3 percent per year required; pressure on land resource = +). Rapid introduction of new technologies means that technological advances, leading to higher per-area productivity, are favored to help meet the increased demand (pressure on land resource = —-). The first row in Table 6.3c shows the net consequences of these factors.

Applying the same reasoning, Table 6.3c shows how the parameters associated with each SRES marker scenario affect net pressure on land for food production. The highly regional scenarios A2 and B2 present the greatest pressure on land, since both have high food demand, low per capita GDP, and slow technological development and dissemination (hence low capacity to feed their high populations). Hence, scenarios A2 and B2 offer the least land for closing the carbon gap by using land-based options or for meeting other human needs.

Scenarios A1FI, A1B, A1T, and B1 present the lowest pressure on land for food production, because of relatively low population growth, high per capita GDP (leading to better ability to increase per-area productivity, even though diet would include more meat), and a high rate of technological development and dissemination. These scenarios also have the lowest, and therefore most realistically achievable, increases in productivity to meet increased food demand. Scenarios A1FI, A1B, A1T, and B1 are the most likely to offer land for helping to close the carbon gap and for providing land for other human needs.

The magnitude of the carbon gap for each SRES scenario has implications for the land available to close the gap. As shown in Table 6.3a, for a stabilization level of 450 parts per million (ppm), scenarios A1FI and A2 have the largest carbon gap by 2100 (25

PgC y^{-1}), A1T and B1 have the smallest gap (1 PgC y^{-1}), and A1B and B2 are intermediate (10 PgC y^{-1}). There would be little land available for carbon sequestration and biofuel cropping to help close these gaps for A2 and B2. Scenarios A1T and B1, however, have the smallest carbon gaps and are also the most likely to have land available for gap closure by land-based options. Scenarios A1FI and A1B are also more likely than A2 and B2 to have land available for gap closure, but the gap is 10–25 times larger than for A1T and B1. Hence, carbon sequestration and biofuel cropping may form part of the portfolio to close the carbon gap for A1FI or A1B, but the gap is much larger. Although the income ratio between developed and developing countries (Table 6.3a) decreases significantly in all scenarios between 1990 (16.1) and 2100 (1.5–6.3), scenarios A2 and B2 are the most likely to show regionally different impacts on land pressure, with low incomes in developing countries lessening the ability to meet food demand by improved management or technology.

In conclusion, this analysis suggests that given the constraints on land required for food production, land-based methods (biofuel cropping and carbon sequestration) for carbon gap closure show a sustainably achievable mitigation potential only under SRES scenarios A1T and B1. Under all other scenarios, land-based methods do not show a potential for contributing significantly to carbon gap closure.

Concluding Summary

We have examined the challenge of achieving CO_2 stabilization in the context of a sustainable Earth system, by outlining a systems framework and then identifying the wider implications of carbon management options in economic, environmental, and sociocultural terms.

The systems analysis begins from the familiar global atmospheric carbon budget, and the stabilization requirement that direct-human-induced CO_2 emissions are low enough to allow land-air and ocean-air carbon fluxes to buffer atmospheric CO_2 at a constant future level. A range of strategies is available to keep net emissions within this constraint: (1) conservation of energy at end-use points, (2) use of non-fossil-fuel energy sources, (3) more carbon-efficient use of fossil fuels; (4) reduction of carbon emissions from land disturbance; (5) sequestration of carbon in terrestrial or oceanic biological sinks; and (6) engineered disposal of CO_2 in geological or oceanic repositories. Each strategy also has a range of impacts (benefits and costs), broadly in four classes: climatic, economic, environmental, and sociocultural.

The success of a suite of carbon mitigation strategies will be determined not only by the technical potential of each strategy (the amount of carbon emission that can be avoided, based on biophysical considerations alone), but also by the uptake rates of the various strategies. These rates are determined by the overall benefit-cost outcomes of the entire suite of strategies, judged not only against carbon-mitigation, but also against economic, environmental, and sociocultural criteria. Thus, the uptake rates (and the trajectories of all parts of the carbon-climate-human system) are emergent properties of the system, resulting from interactions among system components, rather than being imposable properties of isolated components. This situation has several important consequences: First, it is important to maintain a broad suite of mitigation options. Next, successful carbon mitigation depends on exploiting beneficial synergies between mitigation and other (economic, environmental, and sociocultural) goals. Third, societal choices play a major role in determining the relative weightings between these goals and thus the overall outcome.

An order-of-magnitude comparison of likely achievable mitigation potentials (Figure 6.1) shows that major mitigation through sequestration and disposal cannot achieve stabilization unless there is also major mitigation in the energy sector, which has a larger overall impact.

We have assessed a wide range of carbon management options for their economic, environmental, and sociocultural impacts, both positive and negative. The following sweeping (therefore imperfect) generalizations summarize our findings: strategies based on energy conservation and efficiency have broadly beneficial impacts and offer major achievable mitigation, as do strategies involving non-fossil-fuel energy (though with significant environmental and sociocultural negative implications in certain cases). Land-based options offer significant mitigation but with some significant negative impacts mainly by competing with other land uses such as food production. Ocean biological sequestration has major collateral concerns. CO_2 disposal in ocean and geological repositories has significant mitigation potential, but its side effects are still poorly known.

A more detailed analysis of a specific case, land-based mitigation through bioenergy and sequestration, has explored the implications for the pressure on land for food and other essentials under six SRES scenarios. These options offer a sustainably achievable mitigation potential only under SRES scenarios A1T and B1.

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Notes

1. Equation (2) is similar to the "Kaya identity" (Nakicenovic, Chapter 11, this volume): $F_{Foss} = P \times (G/P) \times (E/G) \times (F_{Foss}/E)$. To focus on mitigation, we break (F_{Foss}/E) into the factors f and i defined above. Both equation (2) and the Kaya identity are examples of the "IPAT" model (Impact = Population × Affluence × Technology), where $g = G/P$ is affluence.

2. Primary energy E_{Pri} is the total power generated by humankind, inclusive of waste heat in generation and transmission. It is conventionally called an "energy" although it is actually a power (energy per unit time) with units exajoules per year (EJ y^{-1}) or terawatt (TW) (1 EJ = 10^{18} J; 1 TW = 10^{12} W = 31.536 EJ y^{-1}).

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