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Mitigation: Cross-Sectoral and Other Issues

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EXECUTIVE SUMMARY

Comprehensive evaluation of possible opportunities for mitigation of greenhouse gas (GHG) emissions requires consideration of a complex set of interlocking issues that together determine feasibility and implementability. Chapters 19 through 24 describe opportunities and challenges for GHG mitigation in six sectors of natural and socioeconomic systems, providing an encompassing summary of possible options. An important additional perspective comes from consideration of issues and opportunities that cut across the options presented for the individual sectors. These cross-cutting issues include whether energy end-use mitigation options can realistically reduce demands to levels that can be met by alternate supply systems at low emissions, whether the many competing pressures for the use of land can be reconciled, and whether nontraditional "geo-engineering" offers any plausible options that may be employed to intentionally counterbalance anthropogenic climatic forcings and change. This chapter summarizes the limited information that is available for addressing these questions.

Energy Implications for Low-Emissions GHG Scenarios

The energy supply and end-use sectors are collectively responsible for more than half of the world's total anthropogenic GHG emissions. For most situations, there are more candidate mitigation technologies and options than can be realistically adopted and implemented in a given national or regional setting. In addition to considering purely technological aspects of implementation, however, decisionmakers need to consider corollary benefits and potential side effects of individual mitigation measures. Additional factors to consider include how these options may complement or conflict with each other and with key national and subnational objectives, and which of the candidate options can be most readily implemented by the country's institutions and social and economic structure.

Many emissions-reduction estimates of individual mitigation measures draw from diverse studies based on limited data from specific countries or regions; they often use widely varying social and economic growth assumptions. It is not possible to predict future energy demand reductions in the aggregate with any certainty—as is indicated by the very large range of energy demands described in the end-use demand mitigation chapters in this assessment. However, studies indicate that it is feasible to reduce energy demand in individual end-uses and even in the aggregate—hence to reduce substantially fossil fuel-related emissions against baseline trends. The extent of actual reductions will depend on numerous factors, including energy prices, government policies, continued research and development of energy-efficient devices, and societal and behavioral trends, as well as other environmental concerns. Reductions in energy demand could be coupled with low-emissions energy supply systems to further reduce emissions. Current options in the energy supply arena that would be able realistically to meet energy demand at low emissions will be limited if energy demands are not constrained. Thus, a more flexible energy future is likely to be one where energy supply and end-use mitigation measures are used in conjunction to achieve low emissions.

Issues Related to Land Use and Land Cover

A wide range of future mitigation options and strategies involving various uses of land areas has been suggested. The primary issue in evaluating these options is whether the world can continue to support an increasing population with its growing needs for food and fiber and, at the same time, expand the amount of land used for production of biomass for energy. Analyses of land-use trends and patterns make clear that substantial land can be made available for biomass energy resources only if high rates of improvement in agricultural productivity continue throughout the world. Alternatively, moderate increases in agricultural productivity, reduced population growth rates, and reduced emphasis on meat consumption in the future could provide an adequate global food supply with reduced requirements for agricultural land. Even making optimistic assumptions, however, there will be regional dislocations and imbalances as demand for food, limitations in agricultural productivity, and increasing populations come into conflict. Important stresses on land availability for agriculture, biomass plantations, and other land uses will emerge if population growth continues unabated, high-meat dietary preferences remain stable or increase, the rate of increase in agricultural productivity slows or stops, land degradation continues, or the development and penetration of new technologies cannot be extended to developing countries.

A significant problem in more thoroughly documenting, understanding, and projecting the potential for demands on the world's land resources is that changes in the extent and patterns of land cover and land use are not well-documented. Different global databases indicate large differences for comparable classes of land use and/or land cover. To carry through a thorough assessment of global land resources and their (potential) uses and productivity, significant research is needed—beginning with the development of state-of-the-art land use and land-cover databases that span the world. With such information, assessments of possible mitigation options and strategies related to land use and cover could be carried out using a geo-referenced framework that would enable determination of competing land-use activities and efficiently account for the effects of land degradation and the consequences for other environmental concerns, especially biodiversity.

Concepts for Counterbalancing Climatic Change

A review of conceptual approaches for counterbalancing anthropogenic climate change through geoengineering indicates that many options entail important adverse environmental consequences. Thus, these approaches do not provide an alternative that would readily permit the continued and expanded use of carbon-based fuels. Proposed concepts for geoengineering that have been examined include, for example, the deployment of solar radiation reflectors in space and the injection of sulfate aerosols into the atmosphere to mimic the cooling influence of volcanic eruptions. Most of these approaches are likely to be expensive to sustain and/or to have serious, but poorly understood, side effects, making them unattractive as possible mitigation options. Projections of the chemical and climatic effects of implementing such approaches are, for most options, at least as uncertain as those for future development of technologies and agricultural productivity. Geoengineering options also generally impose added costs on society and become essentially permanent commitments. Although it is perhaps appropriate to keep geoengineering approaches in reserve in case of unexpectedly rapid climatic change, investments in nontraditional approaches would seem much more effective if directed toward developing fossil fuel-free energy sources rather than at efforts to counterbalance the consequences of fossil fuel use.

Integrated Assessment of Mitigation Potential

Comprehensive assessment of different combinations of mitigation options can only be carried out in an integrated manner, considering both the direct and coupled implications of various choices—including, for example, the resulting changes in the fluxes of all greenhouse gases at local, regional, and global scales. The development and testing of capabilities for quantitative analysis, including integrated assessment modeling, are still in early stages of development. As a consequence, there is, at present, no single "right approach" to integrating an analysis across the various issues and disciplines. Models and related analyses, for example, must make tradeoffs between the level of sectoral detail they can include and the level of complexity and data requirements that can be realistically handled. Further, Integrated Assessment Models (IAMs) are only as good as the underlying socioeconomic assumptions and the necessary information on sectoral impacts, adaptation, and mitigation strategies. Across these issues information is lacking in many regions, particularly in developing countries. Over the next few years, the development of adequate databases and the improvement of analysis and assessment capabilities are essential to providing the information needed for the difficult choices that are being faced by decisionmakers.

25.1. Introduction

Mitigation options are measures, methodologies, and technologies to reduce emissions and enhance sinks of greenhouse gases or to otherwise limit climatic change and consequences resulting from human activities. This broad definition encompasses a large diversity of mitigation options. Chapters 19–24 of this volume present and discuss the most important options for a number of individual sectors, including energy supply, industry, transportation, human settlements, agriculture, and forestry. Such a compilation of information on specific measures to abate GHG emissions is an important first step in the analysis of mitigation options. In itself, however, it does not address the important need to analyze the overall, cross-sectoral potential for reduction of emissions within a country or region, the ways in which specific mitigation options interact with other options and with national or regional goals, and the implications of different combinations of mitigation options for the national or regional economy and resource base.

To address these broad cross-sectoral issues, integrated analysis of mitigation options is required. This chapter presents some of the cross-cutting themes central to such an analysis. Chapter 27 and its related appendices provide detailed information and methodologies that will be of use to national decisionmakers in analyzing mitigation options and developing national strategies for GHG emissions reduction. Within each country these options need to be integrated with other key national objectives—including, for example, promotion of rural development, increasing economic growth, generation of new employment opportunities, or improvement of environmental conditions.

There are several conceptual issues related to a cross-sectoral analysis of mitigation options. This chapter addresses some of these issues by focusing on four major questions:

- *What important cross-sectoral issues arise in efforts to reduce GHG emissions from the energy sector?*

  The energy sector is likely to be the major focus of GHG emissions mitigation in most countries. While an evaluation of options in individual sectors indicates that there are many opportunities to reduce fossil-fuel carbon emissions substantially below those in 1990 for particular activities or processes, it is not possible to determine how much total emissions can be reduced without combining these individual options into a comprehensive strategy or scenario. In the aggregate, how much can energy demand be reduced? What supply-side options can be relied upon to meet these energy demands? Which combinations of demand management options and alternative energy supply systems have the greatest potential for reducing emissions and meeting other national/regional goals? Section 25.2 describes the major challenges and approaches to analyzing mitigation options in the energy sector.

- *What specific constraints on land use and availability may limit mitigation options focusing on land management?*

  A wide range of future mitigation options and strategies have been suggested that involve various uses of land. The main issue is whether the world can continue to support an increasing population, with its growing needs for food and fiber, and, at the same time, expand the amount of land used for production of biomass for energy—while preserving environmental resources for other purposes, such as the maintenance of ecosystems, conservation of biodiversity, regeneration and storage of freshwater, assimilation of wastes, and so forth. Section 25.3 summarizes the issues and problems confronting efforts to assess land-use options and scenarios, including the lack of reliable global information on current and projected patterns of land cover and land use.

- *What ideas for large-scale "cross-sectoral" options exist for attempting to deliberately counterbalance potential human-induced climate change?*

  Suggested approaches to counterbalance anthropogenic climate change through geoengineering include, for example, the deployment of solar radiation reflectors in space and the injection of sulfate aerosols into the atmosphere to mimic the cooling influence of volcanic eruptions. Section 25.4 reviews what is known about these concepts, pointing out that based on current information, they appear to be very costly, very uncertain, and/or have significant side effects relative to measures to reduce GHG emissions.

- *Can we assess the overall effectiveness of mitigation options and strategies?*

  Comparison and assessment of different sets of mitigation options is best carried out in an integrated manner, considering fluxes of all GHGs at local, regional, and global scales. Such an assessment also should include the effects of economic activities and trade and potential climate-change feedbacks. Section 25.5 provides an overview of the issues that need to be considered as part of such a comprehensive assessment and includes a brief discussion of integrated models that are currently being developed.

25.2. Energy Implications for Low-Emissions Greenhouse Gas Scenarios

Energy supply and end-use sectors are collectively responsible for more than half of the world's total anthropogenic greenhouse gas emissions. Therefore, mitigation policies for these sectors are critical to achieving any reasonable future stabilization of GHG concentrations in the atmosphere. In 1990, the carbon (C) content of fossil energy was about 6 Gt C. Energy supply and end-use demand sectors both contributed significantly: 2.4 Gt C were emitted during energy conversion and distribution, while about 3.6 Gt C were emitted at the point of end-use (see Chapter B).

Options for reducing energy-related emissions, therefore, fall under two broad categories: those that reduce GHG emissions while providing energy services at projected levels of demand and those aimed at reducing energy demand itself in key end-use sectors. Previous chapters of this report investigate many aspects of these measures in great detail: Chapters 20 through 22 examine options to reduce energy use and process-related GHG emissions in the industrial, transportation, and residential/commercial sectors, respectively, and Chapter 19 discusses technologies to enhance fossil fuel conversion efficiencies and describes Low Emissions Supply Systems (LESS) to meet future energy demands. Chapter 28 and its companion appendix contain a detailed inventory of more than one hundred GHG mitigation technologies for the energy supply and end-use sectors, providing information on key parameters such as performance and environmental characteristics, capital and operating costs, and infrastructure requirements. Also, while specific mitigation policy measures and implementation challenges are discussed in the individual sectoral mitigation chapters, a more generic assessment of decisionmaking under uncertainty, mitigation costs, and macroeconomic measures can be found in Chapters 2, *Decisionmaking Framework to Address Climate Change,* Chapter 9, *A Review of Mitigation Cost Studies,* and Chapter 11, *An Assessment of Economic Policy Instruments to Combat the Enhanced Greenhouse Effect,* of the Working Group III volume.

25.2.1. Cross-Sectoral Implications

While the energy-related mitigation discussion in this assessment is both exhaustive and reflective of the current "state-of-the-science," such a compartmentalized framework of analysis does not address three very important cross-cutting questions:

- How can national decisionmakers rank and choose among mitigation options?
- Can sets of end-use mitigation options taken together realistically reduce future energy demands to levels that are assumed in the construction of energy-supply scenarios that lead to low emissions?
- What are the implications of high-biomass energy futures on other land-use requirements, including the provision of food for the world's increasing population?

Sections 25.2.2 through 25.2.5 provide a roadmap of the kinds of cross-cutting issues and tradeoffs that need to be considered in attempting to answer these questions.

25.2.2. Selecting Mitigation Options

Mitigation agendas are typically laid out by national, regional, and project-level decisionmakers, often with limited resources. A detailed description of mitigation options is therefore of limited use without a proper set of guidelines on how to select the promising options in a particular setting.

The first step in such an assessment is to establish the scope and overall goal(s) of the mitigation strategy. Considerations include whether the strategy is to meet particular emission reduction targets; assess specific technologies or policies; or identify measures that best integrate with key national and subnational objectives, such as increasing economic growth and self-reliance, reducing unemployment and social inequalities, or promoting rural development. Decisionmakers also must determine if they wish to target carbon dioxide (CO_2) only or several GHGs; which of the candidate options can be feasibly implemented by the country's institutional structure; and whether the options being considered will be available and cost-effective in their country within the timeframe under consideration.

25.2.3. Constructing Energy Demand Mitigation Scenarios

In the context of energy demand, the screening criteria described above can be used to identify, rank, and combine promising demand-side options into one or more scenarios. These mitigation scenarios can then be evaluated against the backdrop of a "no-policy," baseline scenario. Such disaggregated descriptive frameworks have been used for energy mitigation scenario analysis at national and regional levels (Lazarus *et al*., 1995). The question thus emerges whether the range of technology options discussed in the energy end-use chapters of the present report can be used to construct energy demand scenarios in different sectors and regions that can then be aggregated to global levels. Such an analysis has not been attempted here, for the following reasons:

- **Consistency of assumptions**: The end-use chapters in this report review a diverse set of studies on the mitigation potentials of various technologies and policies. These studies often are based on limited data from specific countries or regions and use widely varying social and economic growth assumptions [including gross domestic product (GDP), population growth, prices, productivity, exchange rates, technology diffusion, and market regimes]. Aggregating them or extrapolating their projections to other regions could produce misleading results.
- **Accounting for corollary benefits, potential side effects, and offsetting trends**: Sectoral mitigation strategies operate in a complex societal fabric where they may influence, or be influenced by, other social and environmental constraints and, in many cases, even other mitigation policies. Cleaner and more efficient vehicles, for example, will reduce local pollution and have beneficial impacts on human health; many demand-side management measures may also lower consumer expenditures on energy services. Such corollary benefits would make these options more attractive than from a purely GHG mitigation

standpoint. On the other hand, mitigation options also may have potential side effects. For example, heat cascading systems that result in better waste-energy utilization might require establishing industries and human settlements in close proximity and therefore might stress local water resources and possibly aggravate concerns about air, noise, and water pollution. In addition, the emissions reduction potential of many mitigation options can be offset by societal and behavioral trends. Improved household and car efficiency measures, for example, may have some of their mitigation potential offset by decreasing household size and car occupancy. This is because while less energy may be consumed on a per house or per car basis, more houses and cars will be required for a given number of people. A technology-based aggregation of mitigation potentials is unlikely to incorporate many of these interactions, which may play important roles in determining the feasibility, competitiveness, and achievable mitigation potential of various options in a given setting.

25.2.4. Consistency of Energy Supply Mitigation Scenarios with Energy Demand Projections

Many projections of future energy supply—such as the Low Emissions Supply Systems (LESS) described in Chapter 19—suggest that GHG emissions can be reduced substantially relative to 1990 levels by using a number of fuel-mix choices in the long term. However, these emissions futures hinge critically on the validity of the assumed set of future energy demands.

Future demands depend not only on a number of demographic and socioeconomic factors but also on the extent to which successful reductions can be achieved from the implementation of energy conservation and other demand-side management schemes. Many energy supply projections already assume substantial reductions in demand from baseline trends as a result of these end-use mitigation measures. The demand projections for the LESS constructions, for example, are based on a high economic growth, accelerated policy variant (i.e., including GHG mitigation policies) of the SA90 scenarios developed by the IPCC in 1990 (Bernthal, 1990). The long-term energy demands in this scenario are significantly less than those projected by IS92a, the median in the "nonintervention" (i.e., assuming no explicit GHG mitigation policies) scenario-set developed by the IPCC in 1992 (Leggett *et al*., 1992). The SA90 scenarios did not consider the range of technological and societal options considered in the end-use chapters of the present report. The question thus emerges: Are the SA90 accelerated policy demands assumed in the construction of the LESS scenarios consistent with reductions achievable in various end-use sectors? If so, can these demand reductions be achieved through mitigation measures that have a net benefit to society, even in the absence of climate change, or are they likely to be realized only at significant cost to society?

To answer these questions adequately would require the development of energy demand scenarios based on the technological options discussed in the end-use mitigation chapters of this report. As explained earlier, such an analysis has not been attempted here. However, short of the development of such scenarios, some conclusions can still be drawn.

First, the end-use demand mitigation chapters indicate that the range of future sectoral demands is very wide indeed. In the transportation sector, for example, if small, energy-efficient cars become fashionable and desirable and if urban traffic congestion and other concerns drive policy leading to greater use of mass transit, then it might be possible to achieve energy demands for transport consistent with SA90 through mitigation options that benefit society even in the absence of climate change. The same, however, cannot be said in a world in which incomes rise, personal vehicles proliferate, car occupancies decline, fossil fuels remain inexpensive, and additional transportation networks are built to meet the growing numbers of vehicles. Similarly, end-use demands for residential and commercial buildings consistent with the SA90 accelerated policy case are conceivable if three conditions are met: (1) energy prices rise over time sufficiently to influence consumer behavior; (2) governments enact strong policies to promote energy efficiency; and (3) research and development of energy-efficient devices is supported and continues to yield viable new products. A number of reference energy scenarios with such variations have been constructed (Alcamo *et al*., 1995).

Second, unconstrained energy demands are likely to limit the suite of energy supply options that realistically would be available to meet these demands at low emissions. This would lower the flexibility and may increase the vulnerability of the energy supply system. For example, the LESS projections include a "high-demand" variant based on demands similar to those in the median "nonintervention" IS92a scenario (Edmonds *et al*., 1994). Conceivably, low-emissions supply systems still could be developed that meet IS92a demands for the year 2100 at annual emissions approximately half of the 1990 levels and one-fifth of the IS92a emissions projections for 2100. However, such low-emissions supply systems would need to rely on a substantial increase in coal production (e.g., coal production for LESS "high-demand" constructions for the year 2100 in Chapter 19 is almost five times the 1990 levels) and require extensive CO_2 sequestering in aquifers and natural gas fields—a situation that may not be sustainable as gas fields become filled to capacity. Besides, other energy sources, including biomass, are likely to be pushed close to the limits of their realizable potential to meet high demands. A more flexible and possibly lower-cost energy future is likely to be one where energy supply and end-use mitigation options are used in conjunction to achieve low emissions.

25.2.5. Low Emissions Energy Supply and Land Use

Many alternative energy supply futures require that a substantial portion of the world's future energy needs be met by "modern" biomass. The biomass-intensive variant of LESS, in fact, targets almost 550 Mha of land for energy cultivation by the year 2100. This raises a number of concerns, including whether biomass plantations would conflict with land needed to meet regional food requirements for increasing populations, whether biomass cultivation on degraded lands would really be achievable at productivity levels assumed in the LESS constructions, and whether intensive cultivation practices would be needed that in turn might stress local water resources. As Section 25.3 shows, these concerns further complicate the gamut of issues concerning planning for current and future uses of land and land cover.

25.3. Issues Related to Land Use and Land Cover

Many mitigation options depend upon changes in land management, increasing carbon sequestration potential, and the use of renewable energy such as biomass (e.g., Chapters 19, 22, and 24). Many mitigation policies in the transportation sector also require changes in land-use patterns to reduce the need for goods, transport and travel. All of these mitigation options involve land, land use, and land cover. In the present context, "land" refers to the Earth's surface, including the soil and its geology and hydrology; the biosphere; and the lowest layer of the atmosphere. "Land cover" includes only the upper-soil layers and vegetation, while "land use" refers to the explicit purpose for which humans exploit land and its vegetative cover and consists of a series of activities that alter ecological and physical properties of land (Turner *et al*., 1993). A clear distinction between land use and cover is important for assessing land-related mitigation options because the availability of land, water, and related commodities is limited, and different land uses compete with each other.

This section discusses issues related to competition for land. Although land required for human settlement, infrastructure, and other uses is important locally and regionally, the cumulative effect of these uses is of lesser importance globally. The following discussion focuses on land required for agriculture—the most important land use worldwide.

Land use and its changes are heterogeneous, both spatially and temporally. The global significance of land use arises as a result of the cumulative effects of local and regional changes in land cover. These changes are not necessarily land-cover conversions. An altered management could change the properties of land cover (e.g., enhance plant growth through fertilization) without changing the overall structure or vegetation category (Turner *et al*., 1990). The consequences of such modifications seldom appear in regional and global environmental assessments but are important in altering emissions from land use (Leemans and Zuidema, 1995). Coarse land-cover patterns have been used most often to analyze historic and current land-cover change. These assessments are strongly limited by the quality of the available land-cover data. Nonetheless, some insights have emerged.

25.3.1. Patterns of Land Cover

Potential usage of land is determined by the local climate, soil, and land cover. Climate is the major constraint and controls the global patterns of vegetation structure and (potential) species composition (Walter, 1985; Woodward, 1987). Temperature and precipitation define the major latitudinal zones (e.g., boreal, temperate, and tropical), whereas seasonality of these factors largely defines the biomes (e.g., deserts, rangelands, and forests) within these zones. Variation between years, deviations

Box 25-1. Land-Cover Classifications

Research into many aspects of global change requires reliable, geo-referenced information on global land cover for a well-defined time period (Townshend, 1992). Several classification schemes have been developed to describe land-cover patterns. Schemes have been based on structural (e.g., trees vs. shrubs), physiognomic (e.g., deciduous vs. evergreen), floristic (e.g., oak-hickory forest), or bioclimatic (e.g., boreal forest) classes, or mixtures thereof. Imprecise terminology, such as "woodlands," is often used to label classes. Many classification schemes also include indices that are not directly related to land cover but to other environmental variables, such as climate (e.g., tropical rainforest). Such deficiencies are not problematic when a unique classification is applied throughout an analysis, but many global data sets are mixtures from different sources, using similar terminology but largely different criteria (Leemans *et al*., 1995). One of the few globally comprehensive classifications is the hierarchical UNESCO classification (1973). This hybrid classification (physiognomic and structural characteristics at higher levels, species composition at lower levels) was specially developed for the description of natural vegetation at a climax stage; this is probably one of the reasons that it has never resulted in a global assessment of land cover. Despite their problems, UNESCO vegetation maps have been produced for several regions (e.g., White, 1983). Since the development of the UNESCO classification, no such generally accepted scheme for land cover has been developed, although several approaches are emerging, mainly based on technologies involving remote sensing (Running *et al*., 1994). These approaches have led already to more comprehensive regional estimates of deforestation patterns (e.g., Skole and Tucker, 1993) and land-cover classifications (Defries and Townshend, 1994). Several international organizations, including UNEP and FAO, have recently formulated requirements for adequate land-use and land-cover classifications (Mücher *et al*., 1993; UNEP/GEMS, 1993, 1994) and concluded that the implementation of such schemes should be prioritized in order to assure consistent land-use evaluations (Fresco *et al*., 1994).

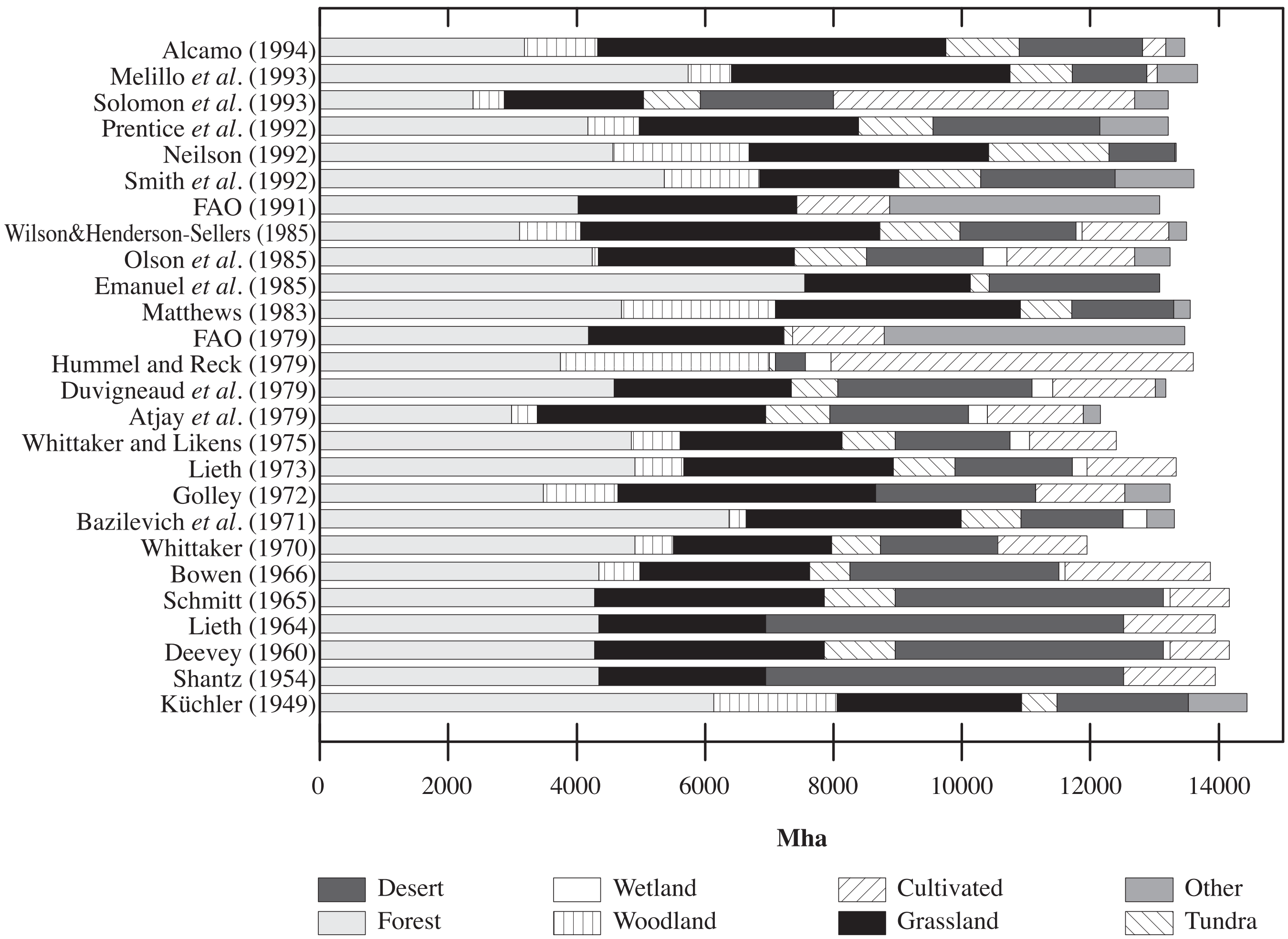

Figure 25-1: Global assessments for the extent of different land covers. The data are aggregated into coarse classes (i.e., Forest, Woodland, Grassland, Tundra, Desert, Wetland, Cultivated, and Other) from the original publications or data sets.

from climatic means, and extreme events (e.g., severe temperatures, storms, and droughts) influence plant growth and survival and lead to successional changes and further differentiate land cover locally. The history of natural events and human-induced changes determines the actual land cover in any region.

Several data sets of global land cover have been compiled. Most of these data banks are based on simple land-cover classification schemes, generally having between five and fifty classes worldwide (see Box 25-1). Despite their relative simplicity, significant differences exist among the different global land-cover databases. Figure 25-1 presents an aggregation of the different land-cover classes in each database into broad, but comparable, classes. These databases are derived from statistical sources, national maps, and/or other sources, such as climate atlases. This has led to the large variation in total extent of each class (Figure 25-1). The most apparent difference between these databases is for cultivated lands, for which estimates range from 0 to 55 x 10^6 km^2. Databases without cultivated land have focused primarily on natural (or potential) vegetation prior to human activities (e.g., Prentice *et al*., 1992; Neilson *et al*., 1992), while the largest values for this class (e.g., Solomon *et al*., 1993) stem from evaluations of land that could potentially be used for cultivation. The most authoritative estimate for cultivated land at present is likely that of FAO (1991), which gives 1450 Mha. Unfortunately, however, all of these estimates are only gross approximations. There are no accurate figures for many countries; much of the information is based on averages or ill-defined categories; and the global compilations are generated from a multitude of sources (Buringh and Dudal, 1987; Defries and Townshend, 1994; Leemans *et al*., 1995). One of the major limitations is that spatial patterns are often not well-depicted. Linkages between land-cover and other geo-referenced databases—such as climate, topography, and soils—could assist in removing some of the inconsistencies of the existing land-cover databases (Loveland *et al*., 1991; Running *et al*., 1994). Improvements in these linkages are a critical constraint in the use of land-cover data in mitigation assessments.

In spite of these shortcomings, many of these estimates are cited and used in different climate-change assessments. The differences in the estimates become important because the use of a different database can lead to significantly different results, and hence conclusions. Thus, global assessments always must be concerned with inconsistencies, limitations, and errors in these data sets. When used with care, these data sets can be used to determine possible impacts of climate change (e.g., Emanuel *et al*., 1985), simulate global carbon cycling (e.g., Melillo *et al*., 1993; Prentice *et al*., 1994), and parameterize land-surface properties in climate models (e.g., Hummel and Reck, 1979; Wilson and Henderson-Sellers, 1985). However, these data sets remain inadequate for describing local and regional properties of ecosystems fully, and consequently for assessing and evaluating mitigation potential accurately.

25.3.2. Societal Uses of Land

Land and land cover provide many resources—including food, fodder, fiber, and biomass—and functions, including biodiversity conservation, water regeneration, waste accumulation, and flood buffering. Human activities have led to significant changes in land cover, and such changes are expected to continue to change the land surface (Houghton, 1994; Table 25-1). On continental, regional, and local scales there are large differences in the rate and nature of changes in land cover (Turner *et al*., 1990; Meyer and Turner, 1994).

Approximately 11% of the land surface has been converted to cropland, and roughly 25% is occupied by pasture (FAO, 1991); 6% is legally protected in conservation areas and reserves (Morris, 1995). About half of the remaining forests and woodlands are managed secondary forests or plantations. In addition to the readily apparent changes in land cover, much of the land has been degraded or is at risk of degradation, including topsoil loss, nutrient depletion, acidification, and compaction. Recent estimates are 750 Mha for light degradation, 910 Mha for moderate degradation, and 310 Mha for severe degradation (World Resources Institute, 1992; Oldeman, 1993). Damaged and degraded lands can generally be rehabilitated to a productive state, but not always restored to their desired use (Barrow, 1991; Brown and Lugo, 1994). All of these transformations have had a large impact on natural processes, biodiversity, and the resilience of ecosystems, and directly affect the potential for carbon storage and other mitigation options involving land cover.

How much land and water is needed to provide adequate food, fodder, and fiber? What are the competing demands on those resource bases? At what rate is land degradation reducing their availability? Such questions have to be considered when land-focused mitigation options compete with existing land uses.

Table 25-1: *Changes in land cover and population from 1700 to 1980 (from Houghton et al., 1983).*

Year	Forests and Woodlands (Mha)	Grassland and Pastures (Mha)	Croplands (Mha)	Population (millions)
1700	6220	6860	270	680
1850	5970	6840	540	960
1920	5680	6750	910	1650
1950	5390	6780	1170	2500
1980	5050	6790	1480	4500

In general, mitigation options in the agriculture and forestry sectors focus on moving toward a more sustainable use of available resources by enhancing the sequestration potential of the ecosystems involved. Many of these options could well have other positive side effects, including pollution reduction, slowing the rate of land degradation, and biodiversity conservation. The proposed increase in biomass utilization to offset fossil fuel use illustrates the potential for competing demands for land. The suggested quantities of biomass can theoretically be provided by ecosystems globally—for example, through biomass plantations that can be established on many types of lands (Hall and Overend, 1987). However, minimizing costs and energy used in transportation would favor growing biomass close to urban areas; it is in such places where the greatest demands on land will occur, creating a possible conflict between land for biomass plantations and for other uses.

25.3.2.1. Global Food Production

Food security has long been a major concern, and several analyses have been conducted to evaluate whether the future food supply will be adequate to feed the growing population (e.g., FAO, 1993; Bongaarts, 1994; Dyson, 1994; Kendall and Pimentel, 1994; Smil, 1994; Waggoner, 1994). Many of these studies suggest that the land could provide food for the increasing population if current trends in agricultural productivity driven by improved management, use of high-yielding varieties, and changed cropping systems can be sustained. Other studies, however, suggest that increasing land degradation, limited water supply, and dependence on energy-intensive fertilizers, combined with a growing population, have already started to lead to a decline in per capita food production and land availability (e.g., Kendall and Pimentel, 1994). Continued downward trends would render the global food supply much less secure than appears from many analyses (Kendall and Pimentel, 1994).

The results of the above analyses are particularly sensitive to assumptions about dietary preferences. Different consumption patterns can lead to very different gross requirements. The amount of food consumed per capita differs significantly by country and region. Diets consisting mainly of grains and vegetables (e.g., China; Table 25-2) require different quantities and types of agricultural land compared to diets containing more meat and dairy products (e.g., United States, Table 25-2). A meat-based diet for the entire world population would clearly exceed current agricultural capabilities (Waggoner, 1994). A conceptually simple means to provide food for the increasing population would be to alter dietary habits. Although a slight shift from red meat toward poultry is occurring in the developed world (thereby reducing total feed grain requirements), red meat consumption is increasing in many other parts of the world (World Resources Institute, 1992). Bringing about dietary changes may be difficult to implement.

Land suitability for agriculture is dependent upon environmental factors, including climate, terrain, soil, water resources, and nutrient availability. These suitability patterns will shift under

Table 25-2: *Regional and global consumption of foods and grain (from Kendall and Pimental, 1994).*

Food/Feed[a]	**USA**	**China**	**World**
Food Grains	77	239	201
Vegetables	129	163	130
Fruits	46	17	53
Meat and Fish	88	36	47
Dairy Products	258	4	77
Eggs	14	7	6
Fats and Oils	29	6	13
Sugars and Sweeteners	70	7	25
Food Total	711	479	552
Feed Grains	663	126	144
Grand Total	1374	605	696
Calories[b]	3600	2662	2667

[a]In kg $capita^{-1}$ yr^{-1}.
[b]In $capita^{-1}$ day^{-1}.

climatic change. Although the consequences of climatic variability are not always adequately addressed (if at all), the potential global distribution of crops is well-understood and can be modeled for current and changed climate and atmospheric composition (e.g., Brinkman, 1987; Leemans and Solomon, 1993; Rosenzweig and Parry, 1994). Such studies indicate that 65% of the land area is suitable for agriculture (Leemans and Solomon, 1993; Solomon *et al*., 1993) but that the amount of land actually available is considerably lower because of unsuitable soils and terrain. As a result, the land potentially available for agricultural production is about 3000 Mha (approximately 20% of total land area, of which about 50% is already cultivated; see FAO, 1991).

Potential biomass productivity and, consequently, yield (which is only a fraction of total biomass production) can be estimated from growing-season characteristics and plant type (e.g., C_3 or C_4 plants). These parameters help determine photosynthetic, respiratory, and direct CO_2 responses for a given land area. When suboptimal water and nutrient availability (mainly nitrogen and phosphorus) are accounted for, the attainable yield of biomass ranges from 60–90% of the theoretical potential yield (Figure 25-2). The attainable yield is further reduced by competition for resources (including light); weeds; diseases; pests; and local air, water, and soil pollution. Proper land management, however, can help alleviate some of these reductions. In most cases, less-efficient agricultural practices can explain the large differences in yield and potential increases therein for different countries (see Plucknett, 1994).

Considering that agricultural productivity for many regions is still far below attainable yield levels, there is a large potential to enhance food production (e.g., FAO, 1993), but land degradation strongly affects attainable and actual productivities. The complex interactions among different environmental and management factors make it immensely difficult to project long-term sustainable agricultural productivities. Unfortunately, many future food and biomass assessments strongly focus on potential productivity (e.g., Hall and Overend, 1987; Waggoner, 1994), leading to overly optimistic conclusions.

25.3.2.2. Global Biomass Production for Energy

Biomass production competes with land required for food production and for other uses. Food production requires the most productive lands, whereas biomass crops can probably be grown on less-productive lands as well (Hall and Overend, 1987). However, growing these crops on less-productive land would lead (at least initially) to lower yields. It is often argued that biomass plantations can assist in the rehabilitation or improvement of degraded agricultural land and that these lands could be used in a profitable and sustainable manner (e.g., Bongaarts, 1994; Hall *et al*., 1994). Although this is probably true for regions with lightly and moderately degraded soils (about 16.5 x 10^6 km^2), plantations are unlikely to be useful in regions with severely degraded soils (about 3.1 x 10^6 km^2). Rehabilitation in such regions is a long-term and difficult process, especially if the original functions of the system (i.e., biological productivity) are to be restored (Barrow, 1991; Brown and Lugo, 1994).

Biomass crops have been demonstrated to be economically feasible in many different regions (e.g., Hall, 1991; Carpentieri *et al*., 1993). However, large increases in biomass requirements would require a significant quantity of additional land (Alcamo *et al*., 1994). In many regions this would pose no problem—due to, for example, the use of existing biomass sources, such as municipal waste, and crop and forestry residues. However, in regions where food supply already is stressed and will continue to be stressed in the near future (e.g., sub-Sahelian zone: FAO, 1993), biomass probably is not a viable option.

Whereas most emphasis in biomass energy has been directed toward terrestrial systems, proposed alternative sources include micro-algae, marine algae, and halophytes, which grow rapidly in saline lands. Micro-algae are single-celled, fast-growing plants that grow well over a wide range of environmental conditions. In regions with inexpensive flatlands, shallow ponds can be constructed where these algae can reproduce (Wyman, 1994), but this technique is currently quite expensive. Because their productivity is usually high, the potential use of marine algae for the conversion of solar energy is large (Orr and Sarmiento, 1992), but their natural extent is limited to regions of high nutrients (i.e., areas of upwelling). Currently, cultivation of marine algae is commercially viable only for specific purposes (pharmaceutical, chemical, and food products), because it is too expensive for large-scale biomass production (Bird, 1987). Saline lands in coastal zones and arid regions could produce biomass using halophytes (Glenn *et al*., 1993). Although halophytes could assist in slowing or rehabilitating degraded

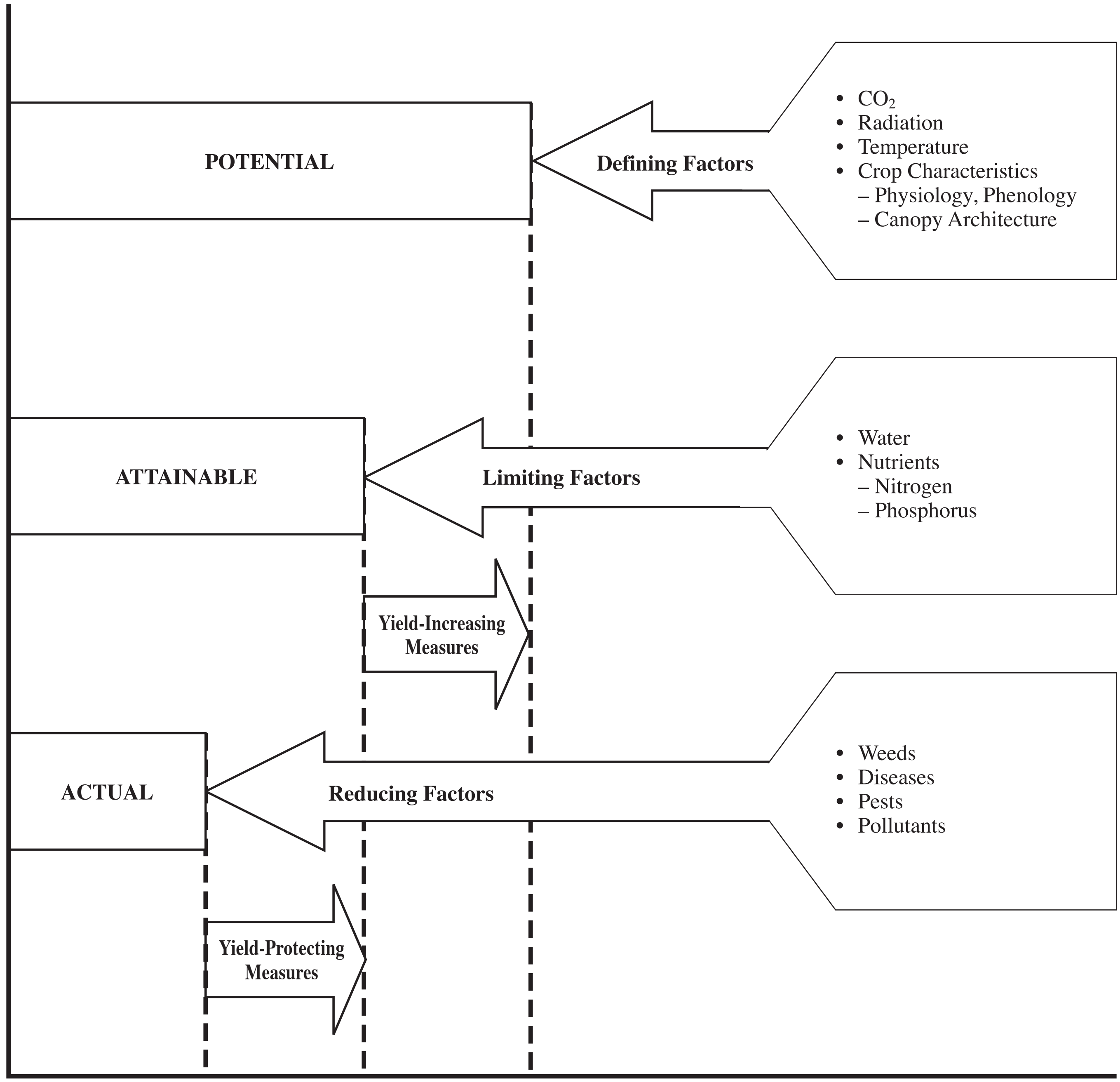

Figure 25-2: Different levels of agricultural productivity (after Rabbinge and van Ittersum, 1994).

arid lands, their productivity is too low for them to be a significant source of biomass in arid regions.

25.3.3. Land Use and Mitigation: An Assessment

Article 2 of the UN Framework Convention on Climate Change (FCCC) does not directly address the issue of mitigation. Mitigation options, however, are primary means for meeting the first part of the objective of the Article (i.e., stabilization of GHG atmospheric concentrations). Mitigation options also can help address the second part of the objective (i.e., ecosystem adaptive capabilities, food security, and sustainable economic development). The land-use and land-cover consequences of mitigation options also are linked strongly with UNCED's Agenda 21 and international treaties on desertification, forests, and biodiversity.

The low quality of available land-use and land-cover data and the lack of understanding of the complex human driving forces behind changes in these properties limit the validity of analyses of current land uses and make future projections speculative (Riebsame *et al*., 1994). Discussions on land availability for biomass production are therefore not yet compelling but are promising enough to support additional, more-comprehensive research. A preliminary conclusion is that if current trends in agricultural production can be continued, competition for land is not likely to be a significant problem globally but could generate serious problems locally and/or regionally. The biggest challenge is to increase agricultural productivity in the least-productive regions and simultaneously to provide room for additional uses and functions for that land.

Much of the scientific effort required to improve these assessments needs to be directed toward integrating important social, economic, and cultural driving forces of land use with physical and ecological (including agricultural) options for land use and land cover (Turner *et al*., 1993; Meyer and Turner, 1994). For example, large-scale development of biomass plantations could limit degradation of dry lands (e.g., by desertification) and enhance C sequestration, but also could have negative impacts on biodiversity in other regions as a result of increased deforestation or restrictions on the types of afforestation that are feasible (Ramakrishnan *et al*., 1994). Unfortunately, such an integrated approach is only in the early stages of development (e.g., Alcamo, 1994; Edmonds *et al*., 1994; Morita *et al*., 1994; Rotmans *et al*., 1994).

25.4. Concepts for Counterbalancing Climatic Change

Climate change induced by GHG emissions is an accidental result of human activities. The question, therefore, arises as to whether there are practical, large-scale, deliberate actions that might be taken to counterbalance these inadvertent changes. Such actions, sometimes referred to as "geoengineering" the climate, differ from traditional mitigative actions—which attempt to reduce the causes of the perturbing influences—in that the geoengineering approaches allow the emissions but seek to negate or reverse their influence or effects. While some geoengineering options have been suggested, in general they would require significant efforts relative to implementing alternative energy technologies or to moderating and avoiding the actions causing the greenhouse emissions.

There are four fundamental approaches to geoengineering that have been suggested to limit the perturbing effects and impacts of GHG emissions: (1) accelerating the removal of greenhouse gases from the atmosphere; (2) altering the Earth's radiation balance to compensate for the effects of the increase in concentrations of GHGs; (3) moderating the climatic response to increasing GHGs by counteracting the positive feedback processes in the atmosphere-ocean-land surface system; and (4) counteracting the harmful effects of the changes that do occur.

In reviewing these options, it should be recognized that analysis of these concepts is only schematic. For several of these ideas, effectiveness cannot yet be evaluated, leaving much for further exploration. Coupled to the rather significant costs and potential environmental side effects that are likely to be involved, starting down such a path is most appropriately considered a "last resort" option.

25.4.1. Accelerating the Removal of Greenhouse Gases from the Atmosphere

Direct removal of GHGs from the atmosphere is generally impractical—the concentrations being so dilute that it would be comparatively more practical, although still quite costly, to remove GHGs from the emissions stream at their sources. As an example of the impracticality of such direct efforts, Viggiano *et al*. (1995) analyzed a proposal to remove chlorofluorocarbons (CFCs) already released to the atmosphere using negative-ion chemistry techniques and found that the energy requirements brought the cost of the proposal well above the costs of approaches such as limiting the uses and emissions of CFCs.

Proposed approaches for accelerating the natural removal processes for CO_2 include enhancing the storage of carbon by the terrestrial biosphere and enhancing the pumping of carbon to the deep ocean by the oceanic biosphere. In these schemes, solar energy and photosynthesis would be used to power a removal process facilitated by human intervention. The advantages and disadvantages of possible approaches involving the enhancement of terrestrial carbon storage (e.g., in forests or soils), and the potential for deriving biomass fuels through these efforts, are covered in Chapters 23 and 24; approaches focusing on enhancing ocean removal are addressed here.

The oceans cover more than twice as much area as the land, are uninhabited by humans, and contain much more carbon than the terrestrial biosphere (~40,000 vs. ~2,200 Gt C, respectively)—making the potential for enhancing oceanic storage seemingly significant. In the oceans, the biosphere acts to slowly pump carbon into the deep ocean, while the net effect of the oceanic circulation is to bring carbon back to the surface to be released into the atmosphere. In preindustrial (but postglacial) times, these biological and circulation fluxes were apparently in quite close balance, keeping the atmospheric concentration nearly constant. With human activities releasing about 7 Gt C per year to the atmosphere, the net flux to the deep ocean is estimated to have increased by about 2 Gt C per year (primarily by increased downward transport of carbon). Enhancing this circulation-based removal process to accommodate a greater fraction of fossil-fuel carbon emissions would reduce the atmospheric burden, but such changes would be very difficult to achieve (although the natural downward flux will rise slowly as the CO_2 concentration increases).

Because of the chemical buffering of the atmospheric CO_2 concentration by the ocean, reduction of the atmospheric concentration would require extensive fertilization of the ocean to promote biological carbon uptake. Studies indicate that iron fertilization of the Southern Ocean would lead to only modest additional oceanic uptake of carbon. A recent iron-fertilization experiment on an 8 x 8 km oceanic plot sought to enhance biological carbon uptake but concluded that, although growth was initially enhanced, the net effect was negligible due to losses in the food chain (Martin *et al*., 1994). However, preliminary results from a more recent iron-fertilization study found a 30- to 40-fold increase in chlorophyll in the eastern equatorial Pacific (Monastersky, 1995a, 1995b); the extent of the potential long-term effects and the consequences for nutrient cycles are not yet known. Even a major fertilization effort might well be equivalent to only the increase in the CO_2 concentration occurring over about a 10-year period (Joos *et al*., 1991; Peng and Broecker, 1991). Such fertilization might also induce major side effects, further making this approach problematic.

Because carbon dissolved in the ocean also is present in inorganic form, a second conceivable means of increasing oceanic uptake would be by increasing oceanic alkalinity. However, this could be a practical possibility only if the weathering of rocks and river runoff were increased substantially (e.g., by a factor of 30: Flannery *et al*., 1995)—a solution that is unlikely to be feasible.

25.4.2. Altering the Earth's Radiation Balance

Several approaches have been suggested to counterbalance the additional trapping of infrared radiation of GHGs by reducing the available solar energy. A number of analyses (e.g., Manabe and Wetherald, 1980; Hansen and Lacis, 1990) have suggested an approximate equivalence in the influence of changes in radiative forcing by infrared and solar radiation; however, more-recent simulations that include the effects of the oceans show that the equivalence is less than perfect in terms of the latitudinal and seasonal patterns of the climatic response (Hansen *et al*., 1994). Nonetheless, at least some of the solar-reduction schemes could be latitudinally and perhaps seasonally tailored to achieve essential equivalence, so that the resulting radiative change would be nearly equal and opposite. Comparisons described below generally assume the need for a reduction in solar radiation of 1%, which would roughly counterbalance a 50% increase in CO_2 concentration. Note, however, that to be effective over time, the intensity of the counterbalancing effort would have to increase continuously to match the increasing GHG effect, requiring a continually increasing, and major, societal commitment.

Reducing solar radiation reaching the top of the atmosphere is conceptually possible by putting mirrors either in Sun-synchronous or near-Earth orbits. The first approach would involve placing a 2,000 km-diameter solar radiation deflector at the first Sun-Earth Lagrange point (1.5 million km from Earth), as suggested by Early (1989). Although this would require significant initial efforts—possibly including a construction base on the Moon—it would be relatively easy to sustain, would have few inadvertent consequences, and could be incrementally controlled or removed in the event of unexpected side effects. The National Academy of Sciences (1992) explored a near-Earth option involving orbiting mirrors. They estimated that counterbalancing the effects of a 50% increase in the CO_2 concentration would require placing about 55,000 mirrors, each measuring 10 x 10 km, into orbit; such objects—in addition to being difficult to control—would eclipse the Sun, the Moon, and the stars roughly 1% of the time from the view of a person looking upwards. Placing reflecting or absorbing aerosols in orbit also would be possible, but the amounts would need to be continuously replenished to make up for relatively rapid removal by the solar wind and atmospheric reentry.

In addition to other disadvantages, these extraterrestrial geoengineering options would require significant up-front funding that could be used alternatively to develop various renewable energy sources. For example, the funding could be used to develop extraterrestrial technologies such as solar-power satellites (NAS, 1981) or to locate solar collectors on the Moon that would beam energy to Earth to provide a substitute for fossil energy; the cost likely would be comparable to lofting satellites that would simply diminish incoming solar energy.

Within the atmosphere, several concepts have been suggested for reducing solar radiation by the requisite amount; each approach has its advantages and disadvantages (National Academy of Sciences, 1992; Flannery et al., 1995). About a trillion reflective balloons—each several meters in diameter and floating in the upper stratosphere—would neither create partial eclipses nor significantly affect stratospheric chemistry but likely would be hard to design and hard to keep near the equator. The multitude of injected aluminum particles from rocket exhaust and the burn-up of reentering spacecraft may already be having a very minor influence of this type; see Brady *et al*. (1994) and TRW (1994) for an evaluation of their effects on the ozone layer. Continuous injection of sulfate aerosols into the stratosphere could be carried out to create the equivalent of a very large volcanic eruption. While this could be achieved at low cost using large artillery pieces for injection (see National Academy of Sciences, 1992), volcanic aerosols have tended to deplete stratospheric ozone. The aerosols would also whiten the skies because they scatter radiation forward more effectively than they reflect it. Injection of sufficient amounts of sooty aerosols into the stratosphere would cause warming in the stratosphere while cooling the troposphere—much like a suggested "nuclear winter" (Turco *et al*., 1983; Pittock *et al*., 1989). Due to the infrared effects resulting from stratospheric warming, the amount of soot injected would need to be quite significant. In this case, the sky would dim rather than whiten. Even though direct effects on ozone chemistry might be avoided because pure soot particles can be made unreactive to stratospheric ozone, the increased temperatures in the stratosphere might tend to decrease ozone concentrations. Other inadvertent environmental consequences of such measures remain poorly researched.

As appears to be happening inadvertently as a result of sulfur dioxide emissions from fossil fuel combustion (Charlson *et al*., 1991; Kiehl and Briegleb, 1993; Taylor and Penner, 1994), injection of sulfate aerosols into the troposphere can lead to a counterbalancing effect to GHGs (National Academy of Sciences, 1992; IPCC, 1995; Flannery *et al*., 1995). Such aerosols act in the clear sky by reflecting and scattering radiation (creating the white haze so evident over industrial regions). They also may have an effect in cloudy regions by brightening the clouds or enhancing cloud extent or lifetime.

Due to the short lifetimes of tropospheric aerosols, this approach would require injection of sulfate aerosols in amounts much greater than those currently emitted by fossil fuel power plants—leading to acid deposition, visibility impairment, ecosystem damage, and structural damage.

Increases in the albedo of the surface could be used to increase reflection of solar radiation back to space. While this may be practical in cooling residences and urban areas (see Chapter 22), countering the effect of a 50% increase in CO_2 would require covering roughly 10% of the Earth's land area or 5% of the ocean with a substance as reflective as new snow; such a change would be virtually impossible and highly disruptive of the surface climate.

25.4.3. Altering Climatic Feedback Mechanisms

Much of the predicted climatic response to GHGs is due to the amplifying effects of positive climatic feedback mechanisms, particularly the increase in the atmospheric water-vapor concentration. If these feedback mechanisms could be countered, the extent of global warming could be greatly reduced.

Possible approaches have not been carefully considered, but might include reducing the rate of evaporation of water (e.g., by coating or covering water surfaces) to reduce the intensity of water vapor feedback; increasing the extent and reflectivity of clouds (e.g., adding sulfates to decrease cloud-droplet size); enhancing the intensity of the oceanic thermohaline circulation (which would cool low latitudes and might promote increased heat loss in high latitudes); or altering atmospheric chemistry (e.g., by reducing tropospheric ozone to reduce its positive greenhouse effect). These proposed ideas have not been studied in even a preliminary way; however, each of these concepts likely has important side effects (e.g., altering precipitation patterns) that are as significant as the inadvertent perturbation to be avoided. Moreover, the positive feedbacks that they are intended to counteract have been poorly quantified; therefore, it is not yet possible to assess the effectiveness of these approaches.

25.4.4. Countering Harmful Effects

Means to counter at least some of the harmful consequences of greenhouse warming also have been suggested. For example, the predicted sea-level rise could be reduced by coating the polar ice caps to reduce melting or by pumping sea-water up onto East Antarctica as part of a giant snow-making operation; however, such projects would create enormous energy demands. Alternatively, it might be possible (e.g., by manipulating sea ice cover) to redirect Southern Ocean storms to increase snowfall onto East Antarctica; in fact, such a snow build-up may happen naturally (see Chapter 7, *Changes in Sea Level*, in the Working Group I volume).

If warmer oceans increase typhoon intensity or frequency, it may be possible to alter their tracks or reduce their strength by cloud seeding or by limiting evaporation via releasing oil slicks on the ocean. Locally, increasing the reflectivity of the surface (urban whitening) can reduce warming influences. Overall, however, acting after nature has amplified the original direct forcing of the GHGs is a relatively difficult and very inefficient option, and one that could well lead to unintended side effects.

25.4.5. Assessment of Climate Adjustment Options

There are at least as many uncertainties and complications involved in pursuing geoengineering options as in projecting the inadvertent climatic change of GHGs. In addition to scientific uncertainties, the UN Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques, which entered into force 5 October 1978, may introduce complications if some countries may be negatively impacted while others benefit. Geoengineering, therefore, should be considered a viable response option only if imminent and especially rapid or threatening inadvertent change be found as a result of projected greenhouse warming (e.g., if collapse of the polar ice caps and concomitant sea-level rise are imminent). For this reason, exploring the advantages and shortcomings of the range of approaches and alternatives is a useful precaution but is not justified at the expense of the development of more practical and economical approaches.

If undertaken as a complement to reducing or slowing an unexpectedly rapid onset of inadvertent influences, geoengineering activities might be required only for a few decades. However, if undertaken as an alternative to actions to limit increasing emissions of greenhouse gases, geoengineering options would have to continue for many centuries—becoming a new, formidable, and quite possibly very costly societal responsibility. Assumption of this responsibility would need to be considered very carefully because suddenly halting such actions, even unintentionally, would, at least for most approaches, cause a rapid climatic readjustment toward the higher temperature state projected as a consequence of the inadvertent activities (i.e., the Earth would face the "climatic shock" of sudden greenhouse warming). Such a situation might well lead to more detrimental impacts than the slower warming projected if geoengineering options were not undertaken.

25.5. Integrated Assessment of Mitigation Potential

A number of evaluations of the effectiveness of various mitigation options and strategies have been published (e.g., Nakícenovíc *et al*., 1994). Many of these mitigation assessments are based on models with limited scope, often with a strong emphasis on the energy sector (e.g., Dowlatabadi, 1994). Although some of these models include rudimentary simulations of global biogeochemical and physical processes and are suited for the evaluation of specific sectoral mitigation options, they remain of little use for evaluating combinations of mitigation options and the relations with major cross-sectoral issues, such as land use and water availability.

Many of these assessments also focus only on CO_2, neglecting other GHGs. Such partial assessments can be misleading because—through well-established linkages with other biological, chemical, and physical processes—reduction of CO_2 emissions could lead to enhanced emissions of other trace gases such as CH_4 (e.g., Dacey *et al*., 1994). Furthermore, competing land uses often are neglected or poorly evaluated. Determination of the effectiveness of mitigation options and strategies should be based on an approach involving the simultaneous evaluation of several trace gases, in which the diverse aspects of land use are guaranteed, and in which important physical and biogeochemical processes, linkages, and feedbacks are included (Leemans, 1995). This requirement should result in the combined analysis of the Earth system (Ojima, 1993), including technological and socioeconomic models (Meyer and Turner, 1994).

Such integration can be successful only if the relevant properties and dimensions of each domain (e.g., geosphere, biosphere, anthroposphere) are addressed. For example, early carbon-cycle models aggregated all land covers into a few classes characterized by globally averaged parameters (e.g., Goudriaan and Ketner, 1984). Although such an approach is straightforward to implement, it does not allow assessment of local and regional consequences of global change (see Chapter 24) and is therefore unsuitable for evaluation of the efficacy of mitigation options. In current assessment models, continental-scale regions are assumed to be homogeneous. Thus, these models are not capable of representing the wealth of socioeconomic components and market forces that cause and react to change at the community, state, and national level. Similar arguments can be developed for all other domains. To address the heterogeneous response of biogeochemical processes, a georeferenced approach has to be adopted. More-recent models have taken such an approach (e.g., Melillo *et al*., 1993; Klein Goldewijk *et al*., 1994). The integrated models required to evaluate mitigation options and strategies should be robust and convey confidence in their simulation of local to regional processes, while simultaneously considering regional to global characteristics.

25.5.1. Components of Integrated Assessment Models

Integrated Assessment Models (IAMs) can in principle serve three purposes: (1) They can help assess potential responses to climate change, either by comparing the costs of response options to the benefits of avoided impacts or by comparing the relative effectiveness and costs of alternate response options; (2) they provide an overview of the cross-sectoral linkages and tradeoffs that can facilitate a more systematic evaluation of policy options; and (3) they can help evaluate the importance of climate change relative to other socioeconomic concerns.

As discussed in Chapter 10, *Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results*, of the Working Group III volume, a number of IAMs have been developed that are integrated over different dimensions and to different degrees. "Full-scale" IAMs seek to address the linkages and feedbacks among human activities, managed and unmanaged ecosystems, emissions and atmospheric composition, and climate change and sea level. The various models differ in the level of detail and complexity considered both within and between the modules, the underlying socioeconomic assumptions used, and the manner in which physical and socioeconomic uncertainties are addressed.

25.5.2. Illustrative Examples and Results

IAMs can be used to evaluate the implications of extensive biomass plantations on land use and availability. This section discusses simulation results using two very different IAMs as examples: IMAGE 2.0 (Alcamo *et al*., 1994) and MiniCAM 2.0 (Edmonds *et al*., 1995). The basic structures of the models are described in Boxes 25-2 and 25-3, respectively. IMAGE 2.0 is a targets-based IAM with considerable regional and sectoral detail of potential physical impacts. These impacts, however, are not given economic values. Also, the model does not include explicit representations of uncertainty. It does, however, account for land use and changes in land cover through physical and biogeochemical feedbacks, such as changes in albedo, terrestrial carbon storage, and enhanced plant growth. MiniCAM 2.0, on the other hand, is designed to balance the costs and benefits of climate-change policies. In this model, constraints on human activities are explicitly represented and costed out. However, the model has a more aggregated representation of climate-change impacts.

The IMAGE 2.0 baseline scenario uses the population and economic growth assumptions from the IPCC IS92a scenario (Leggett *et al*., 1992); other scenario input variables come from a variety of sources (Alcamo *et al*., 1994). As part of this baseline, it is assumed that biomass is used for the generation of 208 EJ energy worldwide in 2100 (and 74 EJ in 2050), thereby reducing the dependence on fossil fuels. The basic assumption for this baseline is that most of this biomass would be taken from readily available sources, such as agricultural and forestry residues, municipal waste, and so forth. A second scenario assumes that only 60% of this demand is readily available, while the remaining 40% has to come from specific biomass crops. This "biomass crop scenario" results globally in an increased demand for agricultural land. A third scenario assumes that no modern biomass is used and that an equivalent amount of the energy demand would be satisfied by oil instead. This "no biomass scenario" does not alter land-cover patterns. The three scenarios differ in their regional and global patterns of fluxes, sources, and sinks of greenhouse gases (Table 25-3).

The three scenarios illustrate different possibilities for increases in the emissions of individual GHGs to the atmosphere as a consequence of interactions of land-use and energy options (Table 25-3). The biomass crop scenario would lead to a large increase in agricultural land cover, although there would be large regional differences in area and timing

Box 25-2. The IMAGE 2.0 Model

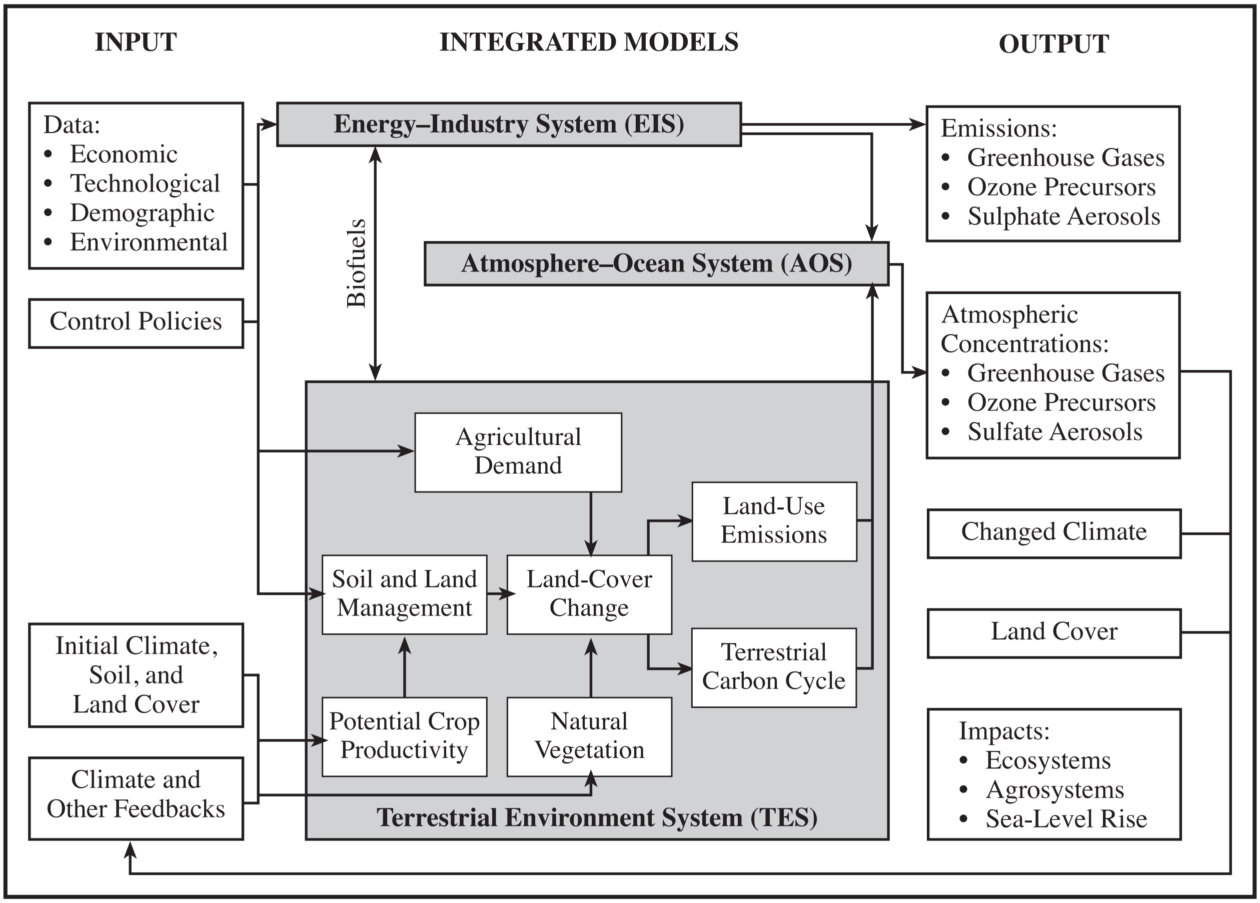

IMAGE 2.0 (Integrated Model to Assess the Greenhouse Effect) is a multidisciplinary, integrated model of climate change. The model is designed to provide support for comprehensive evaluations of national and international policies concerning the build-up of GHGs. The model consists of three fully linked components: Energy Industry System (EIS), Terrestrial Environment System (TES), and Atmosphere Ocean System (AOS). EIS divides the world into 13 regions and computes emissions in each as a function of energy consumption and industrial production. The EIS-models are designed to investigate the effectiveness of different fuel mixes and improved energy efficiencies. TES defines the role of the terrestrial biosphere using vegetation-climate-soil interactions and determining the impacts of land-use change. The dynamic simulation of land-use and land-cover change is an important component of TES. These changes are simulated on a 0.5-degree global grid. Each grid cell is characterized by its climate, topography, soil, and land cover. Changes in natural vegetation are simulated with the BIOME model (Prentice *et al*., 1992). Potential productivity for eight major crops is computed using the "agro-ecological zone" approach developed by UN-FAO (Brinkman, 1987; Leemans and Solomon, 1993). This approach provides the potential distribution and productivity of crops and natural vegetation over the grid. For each region, the demand for land-based commodities (crops, livestock, biomass, lumber, and fuelwood) is calculated. The per capita consumption is derived from an assumed elasticity between consumption and per capita income. Population, dietary preferences, and socioeconomic factors control changes in demand. Agricultural data for the period 1970–1990 from FAO were used to parameterize the demand functions and to calibrate the geo-referenced area of cultivated land from Olson *et al*. (1985) with observed regional productivities. TES then reconciles the demand for land with its potential through a set of heuristic rules that reflect key driving factors, including proximity to infrastructure, population, and productivity of land. This relatively simple model results in rich patterns of land use and cover change for each region. These changed patterns are used to calculate the GHG emissions and local responses of ecosystems with respect to the terrestrial carbon cycle. TES allows evaluation of the impact of environmental changes on ecosystems and agriculture and the effectiveness of mitigation policies. Such evaluation can be achieved comprehensively because of the systemic linkages with other components of IMAGE 2. TES is linked with EIS through the demand for fuelwood and biomass. TES and AOS are indirectly linked through changes in soil moisture and albedo, mediated by land-cover change. All emissions are combined in AOS to determine atmospheric concentrations of GHGs, while accounting for atmospheric chemistry and oceanic carbon uptake.

Box 25-3. The MiniCAM 2.0 Model

MiniCAM 2.0 is an integrated assessment model with four major components: Human Activities, Atmospheric Composition, Climate and Sea Level, and Ecological Systems. The model considers energy and land-use change both explicitly and interactively. The energy system model is the Edmonds-Reilly-Barns (ERB) model (Edmonds and Reilly, 1985), while the agriculture land-use model (ALM) was developed explicitly for MiniCAM 2.0. ALM partitions land into managed and less-managed systems. The managed lands are used intensively for human settlement and infrastructure and extensively for growing crops, raising livestock, managed forests, or biomass cultivation for energy use. Less-managed lands are partitioned into ecological categories. The allocation of lands to human settlement and infrastructure is determined by population and income, and this use of land takes precedence in the model over all other uses of managed land. Extensive land uses are determined by expected profitability—which in turn depends on plant productivities, product prices, technology, fertilization, atmospheric CO_2 concentrations, climate, population, income, taxes, tariffs, and subsidies. Less-managed lands include those that are "parked" (i.e., excluded from use for managed activities) and those that are potentially available for managed uses.

The boundary between the managed and less-managed systems is determined by the expected profitability of managed lands in general. Within ALM, global markets are established for each of the major traded commodities—crops, livestock, and forest products—and a world price is established that clears international markets. Biomass for energy use is determined interactively with the ERB. Because biomass is used as an energy resource, its demand and price are determined in the ERB while its supply is determined in the ALM. Changes in land allocations determine net trace-gas fluxes from the terrestrial biosphere, while the ERB determines energy-related emissions. Other emissions, such as those from cement manufacture and from CFCs and their substitutes, are handled exogenously.

(Alcamo *et al*., 1994). This increase would take up less carbon than the land cover the biomass crops replace. This would limit carbon sequestration in ecosystems and enhance emissions of CH_4 and other GHGs. The realized climate change does not necessarily differ significantly for these three scenarios.

The MiniCAM 2.0 model also has been used to address issues of conflicting land use in cases where low fossil fuel emissions objectives are pursued (Edmonds *et al*., 1995). The model was used to examine the implications for land-use competition resulting from the technologies described in the LESS constructions in Chapter 19. The principal finding of the analysis was that with biomass productivities as high as that considered in LESS, negative impacts from the competition for land use are minimal. That is, increases in emissions from land-use change are likely to be less than 10%, and per capita consumption of crops and livestock also are likely to be within 10% of their reference values. The results, however, are sensitive to several assumptions, such as the productivity of biomass energy plants, the rate of technological progress in agriculture, and the rates of population and income growth.

Table 25-3: *Globally averaged summary of IMAGE 2.0 results for the baseline, biomass crops, and no-biomass scenarios. The scenarios differ in the assumptions regarding the source of 74 or 208 EJ of energy in 2050 and 2100, respectively (after Alcamo et al., 1994).*

Year and Scenario	**Change in Atmospheric Concentration (%)**		**Change in Agricultural Productivity (% ha^{-1})**	**Change in Agricultural Area (%)**	**Change in Forest Area (%)**	**Change in Average Surface Temperature (°C)**	
	CO_2	CH_4				N. Hemisphere	S. Hemisphere
1990	358 ppm	1.7 ppm	100	2670 Mha	4720 Mha	14.2	13.0
2050							
Baseline	+46	+47	+72	+9	-26	+1.4	+1.0
Biomass Crops	+49	+53	+72	+30	-32	+1.5	+1.0
No Biomass	+57	+41	+72	+9	-26	+1.4	+1.0
2100							
Baseline	+117	+35	+108	+14	-27	+2.4	+1.8
Biomass Crops	+129	+41	+108	+65	-31	+2.7	+2.0
No Biomass	+139	0	+108	+15	-27	+2.4	+1.9

25.6. Concluding Remarks

A number of cross-sectoral linkages become evident only when an integrated analysis of climate and socioeconomic systems is used to complement sectoral analyses. The field of integrated assessment modeling is still under development, with various models being used to investigate different plausible ways to integrate across various disciplines. At present there is no single "right" approach to integrated assessment modeling, and models often have to make tradeoffs between the level of sectoral detail they can include and the level of complexity and data requirements that can be handled realistically. Further, Integrated Assessment Models are only as good as the underlying socioeconomic assumptions and information on sectoral impacts, adaptation, and mitigation strategies. As discussed throughout this report, there are key gaps in the understanding of the climate system, how climate change would impact the various sectors, and the feasibility and possible ancillary impacts of various adaptation and mitigation options. Across these issues, information from developing countries is particularly lacking.

The discussion in this chapter is, at best, a roadmap of the types of cross-sectoral issues and tradeoffs decisionmakers will need to consider in evaluating the various mitigation options. While the analysis has focused on energy and land use—which are two key arteries cutting across the various sectors—issues relating to society's demands for water and how water resources would be affected by different mitigation strategies have not yet been addressed in the same level of detail. Further, many cross-cutting impacts of mitigation policies also would be transmitted through trade and market forces. An analysis of these, however, falls beyond the mandate of this Working Group.

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References

Alcamo, J. (ed.), 1994: *IMAGE 2.0: Integrated Modeling of Global Climate Change*. Kluwer Academic Publishers, Dordrecht, The Netherlands, 318 pp.

Alcamo, J., G.J. van den Born, A.F. Bouwman, B. de Haan, K. Klein Goldewijk, O. Klepper, R. Leemans, J.A. Olivier, B. de Vries, H. van der Woerd, and R. van den Wijngaard, 1994: Modeling the global society-biosphere-climate system, part 2: Computed scenarios. *Water Air Soil Pollut.*, **76**, 37-78.

Alcamo, J., A.F. Bouwman, J. Edmonds, A. Grübler, T. Morita, and A. Sugandhy, 1995: An evaluation of the IPCC IS92 emission scenarios. In: *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios* [Houghton, J.T., L.G. Meira Filho, J. Bruce, H. Lee, B.A. Callander, N. Harris, and K. Maskel (eds.)]. Cambridge University Press, Cambridge, UK, pp. 247-304.

Atjay, G.L., P. Ketner, and P. Duvigneaud, 1979: Terrestrial primary production and phytomass. In: *The Global Carbon Cycle* [Bolin, B., E.T. Degens, S. Kempe, and P. Ketner (eds.)]. Wiley and Sons, New York, NY, pp. 129-187.

Barrow, C.J., 1991: *Land Degradation*. Cambridge University Press, Cambridge, UK, 295 pp.

Bazilevich, N.I., L.Y. Rodin, and N.N. Rozov, 1971. Geographical aspects of biological productivity. *Soc. Geogr. Rev. Transl.*, **12**, 293-317.

Bernthal, F.M. (ed.), 1990: *Climate Change: The IPCC Response Strategies*. World Meteorological Organization/United Nations Environment Program, Geneva, Switzerland, 270 pp.

Bird, K.T., 1987: Cost analysis of energy from marine biomass. In: *Seaweed Cultivation for Renewable Resources* [Bird, K.T. and P.H. Benson (eds.)]. Elsevier, Amsterdam, The Netherlands, pp. 327-350.

Bongaarts, J., 1994: Can the growing human population feed itself? *Sci. Am.*, **1994**, 18-24.

Bowen, H.J.M., 1966: *Trace Elements in Biochemistry*. Academic Press, London, UK, 268 pp.

Brady, B.B., E.W. Fournier, L.R. Martin, and R.B. Cohen, 1994: *Stratospheric Ozone Reactive Chemicals Generated by Space Launches Worldwide*. Aerospace Report No. TS-94(4231)-6, The Aerospace Corporation, El Segundo, CA, 25 pp.

Brinkman, R., 1987: Agro-ecological characterization, classification and mapping: Different approaches by the international agricultural research centres. In: *Agricultural Environments: Characterization, Classification and Mapping* [Bunting, A.H. (ed.)]. C.A.B. International, Wallingford, UK, pp. 31-42.

Brown, S. and A.E. Lugo, 1994: Rehabilitation of topical land: A key to sustaining development. *Restorat. Ecol.*, **2**, 97-111.

Buringh, P. and R. Dudal, 1987: Agricultural land use in space and time. In: *Land Transformation in Progress* [Wolman, M.G. and F.G.A. Fournier (eds.)]. John Wiley and Sons, New York, NY, pp. 9-43.

Carpentieri, A.E., E.D. Larson, and J. Woods, 1993: Future biomass-based electricity supply in Northeast Brazil. *Biomass and Bioenergy*, **4**, 149-173.

Charlson, R.J., J. Langer, H. Rodhe, C.B. Leovy, and S.G. Warren, 1991: Perturbation of the northern hemisphere radiative balance by backscattering of anthropogenic sulfate aerosols. *Tellus AB*, **43**, 152-163.

Dacey, J.W.H., B.G. Drake, and M.J. Klug, 1994: Stimulation of methane emission by carbon dioxide enrichment of marsh vegetation. *Nature*, **370**, 47-49.

Deevey, Jr., E.S., 1960: The human population. *Sci. Am.*, **203**, 195-204.

Defries, R.S. and J.R.G. Townshend, 1994: NDVI-Derived land cover classifications at a global scale. *Int. J. Remote Sens.*, **15**, 3567-3586.

Dowlatabadi, H., 1994: Integrated assessment of climate change: An incomplete overview. In: *Integrative Assessment of Mitigation, Impact, and Adaptation to Climate Change* [Nakícenovíc, N., W.D. Nordhaus, R. Richels, and F.L. Toth (eds.)]. International Institute for Applied System Analysis, Laxenburg, Austria, pp. 105-117.

Duvigneaud, P., B. Bolin, E.T. Degens, and S. Kempe, 1979: The global biogeochemical carbon cycle. In: *The Global Carbon Cycle* [Bolin, B., E.T. Degens, S. Kempe, and P. Ketner (eds.)]. Wiley and Sons, New York, NY, pp. 1-56.

Dyson, T., 1994: Population growth and food production: Recent global and regional trends. *Populat. Developm. Rev.*, **20**, 397-411.

Early, J.T., 1989: Space-based solar screen to offset the greenhouse effect. *J. Brit. Interplanet. Soc.*, **42**, 567-569.

Edmonds, J. and J. Reilly, 1985: *Global Energy: Assessing the Future*. Oxford University Press, New York, NY, 317 pp.

Edmonds, J., M. Wise, and C. MacCracken, 1994: *Advanced Energy Technologies and Climate Change: An Analysis Using the Global Change Assessment Model (GCAM)*. PNL-report PNL-9798, UC-402, Pacific Northwest Laboratory, Richland, WA, 41 pp.

Edmonds, J., M. Wise, R. Sands, C. MacCracken, and H. Pitcher, 1995: *Agriculture, Land-Use, and Energy: An Integrated Analysis of the Potential Role of Biomass Energy for Reducing Potential Future Greenhouse-Related Emissions*. Pacific Northwest Laboratory, Washington, DC, (in press).

Emanuel, W.R., H.H. Shugart, and M.P. Stevenson, 1985: Climatic change and the broad-scale distribution of terrestrial ecosystems complexes. *Climatic Change*, **7**, 29-43.

FAO, 1979: *FAO Production Year Book*. FAO Statistics Series 22, vol. 32, Food and Agricultural Organization of the United Nations, Rome, Italy, pp. 45-56.

FAO, 1991: *Agrostat PC. Land Use*. Computerized Information Series 1/3, Food and Agriculture Organization of the United Nations, Rome, Italy, October, 18 pp. (+Diskette: Version 2.0, April 1995).

FAO, 1993: *Agriculture: Towards 2010*. Conference C93/94, Food and Agriculture Organization of the United Nations, Rome, Italy, November, 362 pp.

Flannery, B.P., G. Marland, W. Broecker, H. Ishatani, H. Keshgi, H. Komiyama, M. MacCracken, N. Rosenberg, M. Steinberg, and T.M.L. Wigley, 1995: Geoengineering climate. In: *The Engineering Response to Climate Change* [Watts, R. (ed.)]. Lewis Publishers, Chelsea, MI (in press).

Fresco, L.O., L. Stroosnijder, J. Bouma, and H. van Keulen (eds.), 1994: *The Future of the Land: Mobilizing and Integrating Knowledge for Land Use Options*. John Wiley and Sons, Chichester, UK, 409 pp.

Glenn, E., V. Squires, M. Olsen, and R. Frye, 1993: Potential for carbon sequestration in the drylands. *Water Air Soil Pollut.*, **70**, 341-355.

Golley, F.B., 1972: Energy flux in ecosystems. In: *Ecosystem Structure and Function* [Wiens, J.A. (ed.)]. Oregon University Press, Corvallis, OR, pp. 69-90.

Goudriaan, J. and P. Ketner, 1984: A simulation study for the global carbon cycle, including man's impact on the biosphere. *Climatic Change*, **6**, 167-192.

Hall, D.O. and R.P. Overend (eds.), 1987: *Biomass: Regenerable Energy*. John Wiley and Sons, Chichester, UK, 594 pp.

Hall, D.O., 1991: Biomass energy. *Ener. Pol.*, **19**, 711-737.

Hall, D.O., F. Rosillo-Calle, and J. Woods, 1994: Biomass utilization in households and industry: Energy use and development. *Chemosphere*, **29**, 1099-1119.

Hansen, J.E. and A.A. Lacis, 1990: Sun and dust versus greenhouse gases: An assessment of their relative roles in global climate change. *Nature*, **346**, 713-719.

Hansen, J., M. Sato, A. Lacis, and R. Reudy, 1994: Climate impacts of ozone change. In *Proceedings of IPCC Hamburg Meeting*, May 1993.

Houghton, R.A., J.E. Hobbie, J.M. Melillo, B. Moore, B.J. Peterson, G.R. Shaver, and G.M. Woodwell, 1983: Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO_2 to the atmosphere. *Ecol. Monogr.*, **53**, 235-262.

Houghton, R.A., 1994: The worldwide extent of land-use change. *Bioscience*, **44**, 305-313.

Hummel, J.R. and R.A. Reck, 1979: A global surface albedo model. *J. Appl. Meteorol.*, **18**, 239-253.

Joos, F., J.L. Sarmiento, and U. Siegenthaler, 1991: Estimates of the effect of southern ocean iron fertilization on atmospheric CO_2 concentrations. *Nature*, **349**, 772-775.

Kendall, H.W. and D. Pimentel, 1994: Constraints on the expansion of the global food supply. *Ambio*, **23**, 198-205.

Kiehl, J.T. and B.P. Briegleb, 1993: The relative roles of sulfate aerosols and greenhouse gases in climate forcing. *Science*, **260**, 311-314.

Klein Goldewijk, K., J.G. van Minnen, G.J.J. Kreileman, M. Vloedbeld, and R. Leemans, 1994: Simulating the carbon flux between the terrestrial environment and the atmosphere. *Water Air Soil Pollut.*, **76**, 199-230.

Küchler, A.W., 1949: A physiognomic classification of vegetation. *Ann. Ass. Amer. Geog.*, **39**, 201-210.

Lazarus, M., C. Heaps, and P. Raskin, 1995*: LEAP—Long-Range Energy Alternatives Planning System: User Guide for Version 95.0*. Stockholm Environment Institute, Boston, MA, 220 pp.

Leemans, R., 1995: Incorporating land-use change in Earth system models. In: *Proceedings of the First IGBP-GCTE Science Conference* [Walker, B. (ed.)]. Cambridge University Press, Cambridge, UK (in press).

Leemans, R. and A.M. Solomon, 1993: The potential response and redistribution of crops under a doubled CO_2 climate. *Clim. Res.*, **3**, 79-96.

Leemans, R. and G. Zuidema, 1995: The importance of changing land use for global environmental change. *Trends Ecol. Evol.*, **10**, 76-81.

Leemans, R., W. Cramer, and J.G. van Minnen, 1995: Prediction of global biome distribution using bioclimatic equilibrium models. In: *Effects of Global Change on Coniferous Forests and Grassland* [Melillo, J.M. and A. Breymeyer (eds.)]. J. Wiley and Sons, New York, NY (in press).

Leggett, J., W.J. Pepper, and R.J. Swart, 1992: Emissions scenarios for the IPCC: An update. In: *Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment* [Houghton, J.T., B.A. Callander, and S.K. Varney (eds.)]. Cambridge University Press, Cambridge, UK, pp. 71-95.

Lieth, H., 1964: Versuch einer kartographischer darstellung der produktivität der pflanzandecke auf der erde. In *Geogr. Taschenbuch. Franz Steiner Verlag*. Wiesbaden, pp. 72-80.

Lieth, H., 1973: Primary production: Terrestrial ecosystems. *Human Ecol.*, **1**, 303-332.

Loveland, T.R., J.W. Merchant, D.O. Ohlen, and J.F. Brown, 1991: Development of a land-cover characteristics database for the conterminous U.S. *Photgram. Engin. Rem. Sens.*, **57**, 1453-1463.

Manabe, S. and R.T. Wetherald, 1980: On the distribution of climatic change resulting from an increase in CO_2 content of the atmosphere. *J. Atmos. Sci.*, **37**, 99-118.

Martin, J.H., K.H. Coale, K.S. Johnson, S.E. Fitzwater, R.M. Gordon, S.J. Tanner, C.N. Hunter, V.A. Elrod, J.L. Nowicki, T.L. Coley, R.T. Barber, S. Lindley, A.J. Watson, K. Vanscoy, C.S. Law, M.I. Liddicoat, R. Ling, T. Stanton, J. Stockel, C. Collins, A. Anderson, R. Bidigare, M. Ondrusek, M. Latasa, F.J. Millero, K. Lee, W. Yao, J.Z. Zhang, G. Friederich, C. Sakamoto, F. Chavez, K. Buck, Z. Kolber, R. Greene, P. Falkowski, S.W. Chisholm, F. Hoge, R. Swift, J. Yungel, S. Turner, P. Nightingale, A. Hatton, P. Liss, and N.W. Tindale, 1994: Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean. *Nature*, **371**, 123-129.

Matthews, E., 1983: Global vegetation and land use: New high-resolution data bases for climate studies. *J. Clim. App. Meteorol.*, **22**, 474-487.

Melillo, J.M., A.D. McGuire, D.W. Kicklighter, B. Moore III, C.J. Vorosmarty, and A.L. Schloss, 1993: Global climate change and terrestrial net primary production. *Nature*, **363**, 234-239.

Meyer, W.B. and B.L. Turner II (eds.), 1994: *Changes in Land Use and Land Cover: A Global Perspective*. Cambridge University Press, Cambridge, UK, 537 pp.

Monastersky, R., 1995a: Iron surprise: Algae absorb carbon dioxide. *Science News*, **148**, 53.

Monastersky, R., 1995b: Iron versus the greenhouse. *Science News*, **148**, 220-222.

Morita, T., Y. Matsuoka, M. Kainuma, K. Kai, H. Harasawa, and L. Dong-Kun, 1994: *Asian-Pacific Integrated Model to Assess Policy Options for Stabilizing Global Climate*. AIM report 1.0, National Institute for Environmental Studies, Tsukuba, Japan, July, 23 pp.

Morris, D.W., 1995: Earth's peeling veneer of life. *Nature*, **373**, 25.

Mücher, C.A., T.J. Stomph, and L.O. Fresco, 1993: *Proposal for a Global Land Use Classification*. Final Report LUIS, FAO, ITC and WAU, Rome, Enschede, and Wageningen, February, 37 pp.

Nakícenovíc, N., W.D. Nordhaus, R. Richels, and F.L. Toth (eds.), 1994: *Integrative Assessment of Mitigation, Impact, and Aadaptation to Climate Change*. International Institute for Applied System Analysis, Laxenburg, Austria, 669 pp.

National Academy of Sciences, 1981: *Electric Power from Orbit: A Critique of a Satellite Power System*. National Academy Press, Washington, D.C., 332 pp.

National Academy of Sciences, National Academy of Engineering and Institute of Medicine, 1992: *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base*. National Academy Press, Washington, DC, 918 pp.

Neilson, R.P., G.A. King, and G. Koerper, 1992: Toward a rule-based biome model. *Landscape Ecol.*, **7**, 27-43.

Ojima, D. (ed.), 1993: *Modeling the Earth System*. UCAR/Office for Interdisciplinary Earth Studies, Boulder, CO, 472 pp.

Oldeman, L.R., 1993: Global extent of soil degradation. In: *Soil Resilience and Sustainable Land Use* [Greenland, D.J. and I. Szabolcs (eds.)]. C.A.B. International, Wallingford, UK, pp. 99-118.

Olson, J., J.A. Watts, and L.J. Allison, 1985: *Major World Ecosystem Complexes Ranked by Carbon in Live Vegetation: A Database*. Report NDP-017, Oak Ridge National Laboratory, Oak Ridge, TN, September, 164 pp.

Orr, J.C. and J.L. Sarmiento, 1992: Potential of marine macroalgae as a sink for CO_2: Constraints from a 3-D general circulation model of the global ocean. *Water Air Soil Pollut.*, **64**, 405-422.

Peng, T.-H. and W.S. Broecker, 1991: Dynamical limitations on the Antarctic iron fertilization strategy. *Nature*, **349**, 227-229.

Pittock, A.B., T.P. Ackerman, P.J. Crutzen, M.C. MacCracken, C.S. Shapiro, and R.P. Turco, 1989: *Environmental Consequences of Nuclear War: Physical and Atmospheric Effects*. John Wiley and Sons, Chichester, UK, 350 pp.

Plucknett, D.L., 1994: *Science and Agricultural Transformation*. IFPRI Lecture Series, International Food Policy Research Institute, Washington, DC, September 1993, 34 pp.

Prentice, I.C., W. Cramer, S.P. Harrison, R. Leemans, R.A. Monserud, and A.M. Solomon, 1992: A global biome model based on plant physiology and dominance, soil properties and climate. *J. Biogeogr.*, **19**, 117-134.

Prentice, I.C., M.T. Sykes, M. Lautenschlager, S.P. Harrison, O. Denissenko, and P.J. Bartlein, 1994: Modelling global vegetation patterns and terrestrial carbon storage at the last glacial maximum. *Glob. Ecol. Biogeogr. Let.*, **3**, 67-76.

Rabbinge, R. and M.K. van Ittersum, 1994: Tension between aggregation levels. In*: The Future of the Land: Mobilizing and Integrating Knowledge for Land Use Options* [Fresco, L.O., L. Stroosnijder, J. Bouma, and H. van Keulen (eds.)]. John Wiley and Sons, Chichester, UK, pp. 31-40.

Ramakrishnan, P.S., J. Campbell, L. Demierre, A. Gyi, K.C. Malhotra, S. Mehndiratta, S.N. Rai, and E.M. Sashidharan, 1994: Ecosystem rehabilitation of the rural landscape in south and central Asia: An analysis of issues. In: *Special Publication UNESCO Regional Office of Science and Technology for South and Central Asia (ROSTCA)* [Hadley, M. (ed.)]. New Delhi, India, 29 pp.

Riebsame, W.E., W.B. Meyer, and B.L. Turner II, 1994: Modeling land use and cover as part of global environmental change. *Climatic Change*, **28**, 45-64.

Rosenzweig, C. and M.L. Parry, 1994: Potential impact of climate change on world food supply. *Nature*, **367**, 133-138.

Rotmans, J., M.B.A. van Asselt, A.J. de Bruin, M.G.J. den Elzen, J. de Greef, H. Hilderink, A.Y. Hoekstra, M.A. Janssen, H.W. Köster, W.J.M. Martens, L.W. Niessen, and H.J.M. de Vries, 1994: *Global Change and Sustainable Development: A Modelling Perspective for the Next Decade*. RIVM report no. 461502004, National Institute of Public Health and Environmental Protection, Bilthoven, June, 80 pp.

Running, S.W., T.R. Loveland, and L.L. Pierce, 1994: A vegetation classification logic based on remote sensing for use in global biogeochemical models. *Ambio*, **23**, 77-81.

Schmitt, W.R., 1965: The planetary food potential. *Ann. NY Acad. Sci.*, **118**, 645-718.

Shantz, H.L., 1954: The place of grasslands in the Earth's cover of vegetation. *Ecology*, **35**, 143-145.

Skole, D. and C. Tucker, 1993: Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988. *Science*, **260**, 1905-1910.

Smil, V., 1994: How many people can the Earth feed. *Populat. Developm. Rev.*, **20**, 255-292.

Smith, T.M., R. Leemans, and H.H. Shugart, 1992: Sensitivity of terrestrial carbon storage to CO_2 induced climate change: Comparison of four scenarios based on general circulation models. *Climatic Change*, **21**, 367-384.

Solomon, A.M., I.C. Prentice, R. Leemans, and W.P. Cramer, 1993: The interaction of climate and land use in future terrestrial carbon storage and release. *Water Air Soil Pollut.*, **70**, 595-614.

Taylor, K.E. and J.E. Penner, 1994: Response of the climate system to atmospheric aerosols and greenhouse gases. *Nature*, **369**, 734-737.

Townshend, J.R.G., 1992: *Improved Global Data for Land Application: A Proposal for a New High Resolution Data Set*. IGBP-Report No.20, International Geosphere-Biosphere Programme, Stockholm, Sweden, 87 pp.

TRW, 1994: *The Impact of Deorbiting Space Debris on Stratospheric Ozone*. TRW Space and Electronics Group, P.D. Lohn and E.Y. Wong, El Segundo, CA, 83 pp.

Turco, R.P., O.B. Toon, T.P. Ackerman, J.B. Pollack, and C. Sagan, 1983: Nuclear winter: Global consequences of multiple nuclear explosions. *Science*, **222**, 1283-1293.

Turner, B.L. II, W.C. Clark, R.W. Kates, J.F. Richards, J.T. Mathews, and W.B. Meyer (eds.), 1990: *The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 Years*. Cambridge University Press, Cambridge, UK, 713 pp.

Turner, B.L. II, R.E. Kasperson, W.B. Meyer, K.M. Dow, D. Golding, J.X. Kasperson, R.C. Mitchell, and S.J. Ratick, 1990: Two types of global environmental change: Definitional and spatial-scale issues in their human dimensions. *Global Environ. Change*, **1**, 14-22.

Turner, B.L., R.H. Moss, and D.L. Skole, 1993: *Relating Land Use and Global Change: A Proposal for an IGBP-HDP Core Project*. IGBP Report No. 24 and HDP Report No. 5, International Geosphere-Biosphere Programme and the Human Dimensions of Global Environmental Change Programme, Stockholm, Sweden, February, 65 pp.

UNEP/GEMS, 1993: *Vegetation Classification*. Report of the UNEP-HEM/WCMC/GCTE preparatory meeting, Charlottesville, Virginia, GEMS Report Series No. 19, United Nations Environment Programme, Nairobi, Kenya, 21 pp.

UNEP/GEMS, 1994: *Report of the UNEP/FAO Expert Meeting on Harmonizing Land Cover and Land Use Classifications*. GEMS Report Series No. 25, United Nations Environment Programme, Nairobi, Kenya, March, 43 pp.

UNESCO, 1973: *International Classification and Mapping of Vegetation*. Report, United Nations Educational, Scientific and Cultural Organization, Paris, France, 35 pp.

Viggiano, A.A., R.A. Morris, K. Gollinger, and F. Arnold, 1995: Ozone destruction by chlorine: The impracticality of mitigation through ion chemistry. *Science*, **267**, 82-84.

Waggoner, P.E., 1994: *How Much Land Can Ten Billion People Spare for Nature?* Task Force Report no. 121, Council for Agricultural Science and Technology, Ames, IA, February, 64 pp.

Walter, H., 1985: *Vegetation of the Earth and Ecological Systems of the Geo-Biosphere*. Springer-Verlag, Berlin, Germany, 318 pp.

White, F., 1983: *Vegetation Map of Africa*. UNESCO, Paris, France, 350 pp.

Whittaker, R.H., 1970: *Communities and Ecosystems*. MacMillian, New York, NY, 270 pp.

Whittaker, R.H. and G.E. Likens, 1975: The biosphere and man. In: *Primary Productivity of the Biosphere* [Lieth, H. and R.H. Whittaker (eds.)]. Springer-Verlag, Berlin, Germany, pp. 305-328.

Wilson, M.F. and A. Henderson-Sellers, 1985: A global archive of land cover and soils data for use in general circulation climate models. *J. Climatol.*, **5**, 119-143.

Woodward, F.I., 1987: *Climate and Plant Distribution*. Cambridge University Press, Cambridge, UK, 174 pp.

World Resources Institute, 1992: *World Resources 1992-93: A Guide to the Global Environment*. Oxford University Press, New York, NY, 385 pp.

Wyman, C.E., 1994: Alternative fuels from biomass and their impact on carbon dioxide accumulation. *Appl. Biochem. Biotechnol.*, **45-46**, 897-915.