Technical Summary: Impacts, Adaptations, and Mitigation Options

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1. Scope of the Assessment

The Intergovernmental Panel on Climate Change (IPCC) charged Working Group II with reviewing current knowledge about the impacts of climate change on physical and ecological systems, human health, and socioeconomic sectors. IPCC also asked Working Group II to review available data on the technical and economic feasibility of a range of potential adaptation and mitigation strategies. In producing this report, Working Group II has coordinated its activities with those of Working Groups I and III, and built on the 1990 and 1992 IPCC assessments.

This assessment provides scientific, technical, and economic information that can be used, *inter alia*, in evaluating whether the projected range of plausible impacts constitutes "dangerous anthropogenic interference with the climate system" at the local, regional, or global scales as referred to in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC), and in evaluating adaptation and mitigation options that could be used in progressing toward the ultimate objective of the UNFCCC (see Box 1). However, the assessment makes no attempt to quantify "dangerous anthropogenic interference with the climate system." Interpreting what is "dangerous" involves political judgment—a role reserved to governments and the Conference of Parties to the UNFCCC.

The UNFCCC's Article 2 explicitly acknowledges the importance of natural ecosystems, food security, and sustainable economic development. This report directly addresses these and other issues important to society, including water resources and human health. It assesses what is known about the impact of climate change on terrestrial and aquatic ecosystems, human health, and socioeconomic systems at varying time and geographic scales, as well as what is known about their vulnerability to climate change. A system's vulnerability to climate change depends on its sensitivity to changes in climate and its ability to adapt. The vulnerability assessment takes into account the different economic and institutional circumstances among developed and developing countries. It also recognizes the strong influence on most of these systems of other human-induced stresses (e.g., population demographics, land-use practices, industrialization, consumption patterns, air and water pollution, and soil degradation). Where possible, this assessment attempts to evaluate the sensitivity of systems and their potential for adaptation to: (i) changes in mean climate; (ii) changes in extreme weather events; (iii) changes in variability; (iv) the rate of climate change; and (v) the effects of elevated CO_2 concentrations on vegetation (via enhanced photosynthesis and water-use efficiency). The report also describes technical guidelines for assessing climate change impacts and adaptations.

This assessment also reviews and analyzes practices and technologies that (i) reduce anthropogenic emissions of greenhouse gases arising from the production and use of energy (industry, transportation, human settlements) and (ii) increase carbon storage (in what are generally called sinks) and reduce greenhouse gas emissions from agricultural, forestry, and rangeland systems. It also describes methodologies for assessing mitigation options and an inventory of technology characterizations.

Box 1. Ultimate Objective of the UNFCCC (Article 2)

> "...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner."

2. The Nature of the Issue: Projected Changes in Climate

Earth's climate has remained relatively stable (global temperature changes of less than 1°C over a century) during the last 10,000 years (the present interglacial period). Over this period, modern society has evolved and, in many cases, successfully adapted to the prevailing local climate and its natural variability. Now, however, society faces potentially rapid changes in future climate because of human activities that alter the atmosphere's composition and change the Earth's radiation balance.

Atmospheric concentrations of greenhouse gases (which tend to warm the atmosphere) and aerosols (which in some regions partially offset the greenhouse effect) have increased since the industrial era began around 1750. Carbon dioxide (CO_2) has risen by about 30%, methane (CH_4) by more than 100%, and nitrous oxide (N_2O) by about 15%. These gases now are at greater concentrations than at any time in the past 160,000 years (the period for which scientists can reconstruct historical climates and atmospheric compositions by analyzing ice-core data). The combustion of fossil fuels and, to a lesser extent, changes in land use account for anthropogenic CO_2 emissions. Agriculture is responsible for nearly 50% of human-generated CH_4 emissions and about 70% of anthropogenic N_2O emissions. Although CO_2 emissions far exceed those of CH_4 and N_2O, the global warming potentials of these latter two gases are relatively high. Hence, they represent significant contributors to the anthropogenic greenhouse effect. CO_2 has contributed about 65% of the combined radiative effects of the long-lived gases over the past 100 years; CH_4 and N_2O have contributed about 20 and 5%, respectively.

Most projections suggest that without policies specifically designed to address climate change greenhouse gas concentrations will increase significantly during the next century. Emissions of greenhouse gases and the sulfate aerosol precursor sulfur dioxide (SO_2) are sensitive to growth in population and gross domestic product (GDP), the rate of diffusion of new technologies into the market place, production and consumption patterns, land-use practices, energy intensity, the price and availability of energy, and other policy and institutional developments

Table 1: *Summary of assumptions in the six IPCC 1992 alternative scenarios.*

Scenario	**Population**	**Economic Growth**	**Energy Supplies**
IS92a,b	World Bank 1991 11.3 billion by 2100	1990–2025: 2.9% 1990–2100: 2.3%	12,000 EJ conventional oil 13,000 EJ natural gas Solar costs fall to \$0.075/kWh 191 EJ of biofuels available at \$70/barrel[a]
IS92c	UN Medium-Low Case 6.4 billion by 2100	1990–2025: 2.0% 1990–2100: 1.2%	8,000 EJ conventional oil 7,300 EJ natural gas Nuclear costs decline by 0.4% annually
IS92d	UN Medium-Low Case 6.4 billion by 2100	1990–2025: 2.7% 1990–2100: 2.0%	Oil and gas same as IS92c Solar costs fall to \$0.065/kWh 272 EJ of biofuels available at \$50/barrel
IS92e	World Bank 1991 11.3 billion by 2100	1990–2025: 3.5% 1990–2100: 3.0%	18,400 EJ conventional oil Gas same as IS92a,b Phase out nuclear by 2075
IS92f	UN Medium-High Case 17.6 billion by 2100	1990–2025: 2.9% 1990–2100: 2.3%	Oil and gas same as IS92e Solar costs fall to \$0.083/kWh Nuclear costs increase to \$0.09/kWh

[a] Approximate conversion factor: 1 barrel = 6 GJ.
Source: IPCC, 1992: Emissions scenarios for IPCC: an update. In: *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment* [J.T. Houghton, B.A. Callander, and S.K. Varney (eds.)]. Section A3, prepared by J. Leggett, W.J. Pepper, and R.J. Swart, and WMO/UNEP. Cambridge University Press, Cambridge, UK, 200 pp.

(see Table 1 for a summary of assumptions used in the six IPCC 1992 emissions scenarios). Figure 1 shows plausible ranges of CO_2 emissions, in the absence of emissions abatement policies, projected over the next 100 years in the IPCC IS92 emissions scenarios, which are reevaluated in the Working Group III volume of this 1995 assessment.

Climate models, taking into account greenhouse gases and aerosols, calculate that the global mean surface temperature could rise by about 1 to 3.5°C by 2100. This range of projections is based on the range of sensitivities of climate[1] to increases in greenhouse gas concentrations reported by IPCC Working Group I and plausible ranges of greenhouse gas emissions projected by IPCC in 1992. These projected global-average temperature changes would be greater than recent natural fluctuations and would occur at a rate significantly faster than any since the last ice age more than 10,000 years ago. High latitudes are projected to warm more than the global average. The reliability of regional projections remains low.

Model calculations, however, suggest the following:

- Climate warming will enhance evaporation, and global mean precipitation will increase, as will the frequency of intense rainfall. However, some land regions will not experience an increase in precipitation, and even those that do may experience decreases in soil moisture because of enhanced evaporation. Climate models also project seasonal shifts in precipitation. In general, models project that precipitation will increase at high latitudes in winter, and soil moisture will decrease in some mid-latitude continental regions during the summer.
- Variability associated with the enhanced hydrological cycle translates into prospects for more severe droughts and floods in some places, and less severe droughts and/or floods in other places. As a consequence, the incidence of fires and pest outbreaks may increase in some regions. It remains unclear whether the frequency and intensity of extreme weather events such as tropical storms, cyclones, and tornadoes will change.
- Regional and global climate changes are expected to have wide-ranging and potentially adverse effects on physical and ecological systems, human health, and socioeconomic sectors. These will affect the economy and the quality of life for this and future generations.
- Models project that sea level will increase by about 15 to 95 cm by 2100, allowing for average ice melt, but could be either higher or lower than this range.

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[1] Climate sensitivity is the equilibrium change in global annual mean surface temperature due to a doubling of atmospheric concentration of CO_2 (or equivalent doubling of other greenhouse gases).

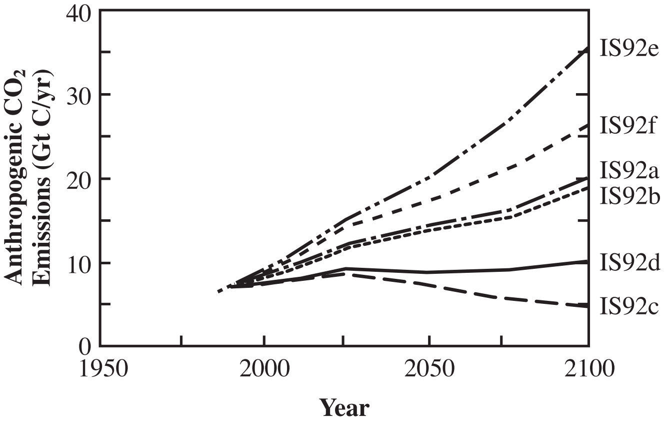

Figure 1: Projected anthropogenic CO_2 emissions from fossil fuel use, deforestation, and cement production for the six IPCC 1992 scenarios (IS92a-f)—from *Climate Change 1994: Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios* (IPCC, 1995).

Policymakers are faced with responding to the risks posed by anthropogenic emissions of greenhouse gases in the face of significant scientific uncertainties. It is appropriate to consider these uncertainties in the context of information indicating that climate-induced environmental changes cannot be reversed quickly, if at all, due to the long time scales associated with the climate system (see Box 2). Decisions taken during the next few years may limit the range of possible policy options in the future, because high near-term emissions would require deeper reductions in the future to meet any given target concentrations. Delaying action might reduce the overall costs of mitigation because of potential technological advances but could increase both the rate and eventual magnitude of climate change, hence the adaptation and damage costs.

Box 2. Time Scales of Processes Influencing the Climate System

- Turnover of the capital stock responsible for emissions of greenhouse gases: ***Years to decades*** (without premature retirement)
- Stabilization of atmospheric concentrations of long-lived greenhouse gases given a stable level of greenhouse gas emissions: ***Decades to millennia***
- Equilibration of the climate system given a stable level of greenhouse gas concentrations: ***Decades to centuries***
- Equilibration of sea level given a stable climate: ***Centuries***
- Restoration/rehabilitation of damaged or disturbed ecological systems: ***Decades to centuries*** (some changes, such as species extinction, are irreversible, and it may be impossible to reconstruct and reestablish some disturbed ecosystems)

Policymakers will have to decide to what degree they want to take precautionary measures by mitigating greenhouse gas emissions and enhancing the resilience of vulnerable systems by means of adaptation. Uncertainty does not mean that a nation or the world community cannot position itself better to cope with the broad range of possible climate changes or protect against potentially costly future outcomes. Delaying such measures may leave a nation or the world poorly prepared to deal with adverse changes and may increase the possibility of irreversible or very costly consequences. Options for adapting to change or mitigating change that can be justified for other reasons today (e.g., abatement of air and water pollution) and make society more flexible or resilient to anticipated adverse effects of climate change appear particularly desirable.

3. Vulnerability to Climate Change: Impacts and Adaptation

This section discusses the sensitivity, adaptability, and vulnerability (see Box 3) of physical and ecological systems, human health, and socioeconomic sectors to changes in climate. It begins with a number of common conclusions, then describes to the extent possible (i) the functions and current status of each system; (ii) the sensitivity of each system to climate change and to other environmental and human-induced factors; and (iii) the vulnerability of each system to climate change, taking into account adaptation options and impediments to adaptation.

Although we have made much progress in understanding the climate system and the consequences of climate change, large uncertainties cloud our view of the 21st century. In particular,

Box 3. Sensitivity, Adaptability, and Vulnerability

Sensitivity is the degree to which a system will respond to a change in climatic conditions (e.g., the extent of change in ecosystem composition, structure, and functioning, including primary productivity, resulting from a given change in temperature or precipitation).

Adaptability refers to the degree to which adjustments are possible in practices, processes, or structures of systems to projected or actual changes of climate. Adaptation can be spontaneous or planned, and can be carried out in response to or in anticipation of changes in conditions.

Vulnerability defines the extent to which climate change may damage or harm a system. It depends not only on a system's sensitivity but also on its ability to adapt to new climatic conditions.

Both the magnitude and the rate of climate change are important in determining the sensitivity, adaptability, and vulnerability of a system.

our understanding of some key ecological processes remains limited. So does our current ability to predict regional climate changes, future conditions in the absence of climate change, or to what degree climate will become more variable. Changes in average conditions, climate variability, and the frequency and intensity of extreme weather events all would have important implications for both ecological and social systems.

3.1. Common Themes and Conclusions

Human health, terrestrial and aquatic ecological systems, and socioeconomic systems (e.g., agriculture, forestry, fisheries, and water resources) are all vital to human development and well-being, and are all sensitive to changes in climate. Whereas many regions are likely to experience the adverse effects of climate change—some of which are potentially irreversible—some effects of climate change are likely to be beneficial. Hence, different segments of society can expect to confront a variety of changes and the need to adapt to them. The following conclusions apply to many ecological and socioeconomic systems:

- **Human-induced climate change adds an important new stress**. Human-induced climate change represents an important additional stress, particularly to the many ecological and socioeconomic systems already affected by pollution, increasing resource demands, and nonsustainable management practices. The most vulnerable systems are those with the greatest sensitivity to climate changes and the least adaptability.
- **Most systems are sensitive to climate change**. Natural ecological systems, socioeconomic systems, and human health are all sensitive to both the magnitude and the rate of climate change.
    - *Natural ecosystems*. The composition and geographic distribution of many ecosystems will shift as individual species respond to changes in climate; there will likely be reductions in biological diversity and in the goods and services that ecosystems provide society—for example, sources of food, fiber, medicines, recreation and tourism, and ecological services such as nutrient cycling, waste assimilation, and controlling water runoff and soil erosion. Large amounts of carbon could be released into the atmosphere during periods of high forest mortality in the transition from one forest type to another.
    - *Food security*. Some regions, especially in the tropics and subtropics, may suffer significant adverse consequences for food security, even though the effect of climate change on global food production may prove small to moderate.
    - *Sustainable economic development*. Some countries will face threats to sustainable development from losses of human habitat due to sea-level rise, reductions in water quality and quantity, disruptions from extreme events, and an increase in human diseases (particularly vector-borne diseases such as malaria).
- **Impacts are difficult to quantify, and existing studies are limited in scope**. While our knowledge has increased significantly during the last decade and qualitative estimates can be developed, quantitative projections of the impacts of climate change on any particular system at any particular location are difficult because regional scale climate change projections are uncertain; our current understanding of many critical processes is limited; and systems are subject to multiple climatic and non-climatic stresses, the interactions of which are not always linear or additive. Most impact studies have assessed how systems would respond to climate change resulting from an arbitrary doubling of equivalent atmospheric CO_2 concentrations. Furthermore, very few studies have considered dynamic responses to steadily increasing greenhouse gas concentrations; fewer still have examined the consequences of increases beyond a doubling of equivalent atmospheric CO_2 concentrations or assessed the implications of multiple stress factors.
- **Successful adaptation depends upon technological advances, institutional arrangements, availability of financing, and information exchange**. Technological advances generally have increased adaptation options for managed systems such as agriculture and water supply. However, many regions of the world currently have limited access to these technologies and appropriate information. The efficacy and cost-effective use of adaptation strategies will depend upon the availability of financial resources, technology transfer, and cultural, educational, managerial, institutional, legal, and regulatory practices, both domestic and international in scope. Incorporating climate-change concerns into resource-use and development decisions and plans for regularly scheduled investments in infrastructure will facilitate adaptation.
- **Vulnerability increases as adaptive capacity decreases**. The vulnerability of human health and socioeconomic systems—and to a lesser extent ecological systems—depends upon economic circumstances and institutional infrastructure. This implies that systems typically are more vulnerable in developing countries where economic and institutional circumstances are less favorable. People who live on arid or semi-arid lands, in low-lying coastal areas, in water-limited or flood-prone areas, or on small islands are particularly vulnerable to climate change. Some regions have become more vulnerable to hazards such as storms, floods, and droughts as a result of increasing population density in sensitive areas such as river basins and coastal plains. Human activities, which fragment many landscapes, have increased the vulnerability of lightly managed and unmanaged ecosystems. Fragmentation limits natural adaptation potential and the potential effectiveness of measures to assist adaptation in these systems, such as the provision of migration corridors. A changing climate's near-term effects on ecological and socioeconomic

systems most likely will result from changes in the intensity and seasonal and geographic distribution of common weather hazards such as storms, floods, and droughts. In most of these examples, vulnerability can be reduced by strengthening adaptive capacity.

- **Detection will be difficult and unexpected changes cannot be ruled out**. Unambiguous detection of climate-induced changes in most ecological and social systems will prove extremely difficult in the coming decades. This is because of the complexity of these systems, their many non-linear feedbacks, and their sensitivity to a large number of climatic and non-climatic factors, all of which are expected to continue to change simultaneously. The development of a baseline projecting future conditions without climate change is crucial, for it is this baseline against which all projected impacts are measured. The more that future climate extends beyond the boundaries of empirical knowledge (i.e., the documented impacts of climate variation in the past), the more likely that actual outcomes will include surprises and unanticipated rapid changes.
- **Further research and monitoring are essential**. Enhanced support for research and monitoring, including cooperative efforts from national, international, and multilateral institutions, is essential in order to improve significantly regional-scale climate projections; to understand the responses of human health, ecological, and socioeconomic systems to changes in climate and other stress factors; and to improve our understanding of the efficacy and cost-effectiveness of adaptation strategies.

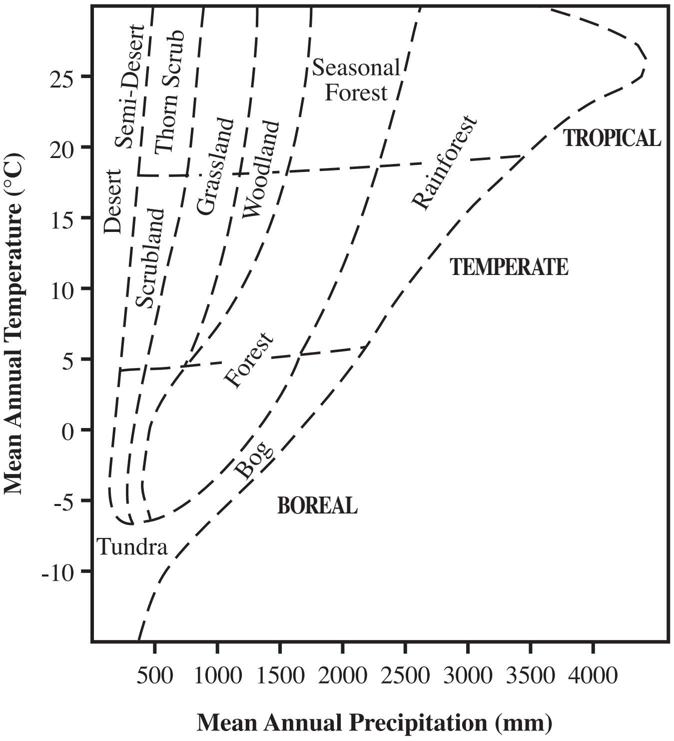

Figure 2: This figure illustrates that mean annual temperature and mean annual precipitation can be correlated with the distribution of the world's major biomes. While the role of these annual means in affecting this distribution is important, it should be noted that the distribution of biomes may also strongly depend on seasonal factors such as the length of the dry season or the lowest absolute minimum temperature, on soil properties such as water-holding capacity, on land-use history such as agriculture or grazing, and on disturbance regimes such as the frequency of fire.

3.2. Terrestrial Ecosystems

Ecosystems contain the Earth's entire reservoir of genetic and species diversity, and provide goods and services critical to individuals and societies. These services include (i) providing food, fiber, medicines, and energy; (ii) processing and storing carbon and other nutrients, which affect the atmospheric concentrations of greenhouse gases; (iii) regulating water runoff, thus controlling floods and soil erosion; (iv) assimilating wastes and purifying water; and (v) providing opportunities for recreation and tourism. These systems and the functions they provide are sensitive to the rate and extent of changes in climate. Figure 2 illustrates that mean annual temperature and mean annual precipitation can be correlated with the distribution of the world's major biomes. While the role of these annual means in affecting this distribution appears to be important, it should be noted that the distribution of biomes also strongly depends on seasonal factors and other non-climate conditions, such as soil properties and disturbance regimes.

Changes in climate and associated changes in the frequency of fires and the prevalence of pests could alter various properties of terrestrial ecosystems. These include structure (physical arrangement, density of populations, species composition), function (movement of energy and material within ecosystems), and productivity (rates and magnitudes of carbon fixation and respiration).

Most terrestrial ecosystems are under major pressures from population increases and human decisions about land use, which probably will continue to cause the largest adverse effects for the foreseeable future. However, continuing climate change would induce a disassembly of existing ecosystems and an ongoing assembly of plants and animals into new ecosystems—a process that may not reach a new equilibrium for several centuries after the climate achieves a new balance.

In analyzing the potential impacts of climate change, researchers must consider how species and ecosystems respond to elevated concentrations of atmospheric CO_2. Higher CO_2 concentrations may increase the net primary productivity (NPP) of plants, which would alter species composition by changing the competitive balance among different plants. Although biologists have quantified these effects at the leaf to plant level in controlled settings, such effects are only now being quantified at the ecosystem level. This is because of the complex interactions among plants in their natural environments, which depend

Box 4. Regional Implications of Climate Change for Forests

Tropical forests. It is likely that temperature increases will have a smaller impact on tropical forests than on temperate or boreal forests, because models project that temperatures will increase less in the tropics than at other latitudes. However, tropical forests are very sensitive to the amount and seasonality of rainfall. In general, human activities causing conversion to other land-cover types will likely affect tropical forests more than climate change. If CO_2 fertilization is important, it may lead to a gain in net carbon storage because of the slow rate at which the associated soil respiration increases in this zone.

Temperate forests. In some temperate forests, NPP may increase due to warming and increased atmospheric CO_2. However, in other regions warming-induced water shortages, pest activity, and fires may cause decreased NPP and possible changes in temperate forest distribution. Most temperate forests are located primarily in developed countries that have the resources to reduce the impacts of climate change on their forests through integrated fire, pest, and disease management, and/or encouraging reforestation.

Boreal forests. As warming is expected to be particularly large at high latitudes, and as boreal forests are more strongly affected by temperature than forests in other latitudinal zones, climatic change is likely to have its greatest impact on boreal forests. Increased fire frequency and pest outbreaks are likely to decrease the average age, biomass and carbon store, with greatest impact at the southern boundary, where the boreal coniferous forest is likely to give way to temperate zone pioneer species or grasslands. Northern treelines are likely to advance slowly into regions currently occupied by tundra. The NPP of forests that are not limited by water availability is likely to increase in response to warming, partly mediated by increased nitrogen mineralization. However, there may be a net loss of carbon from the ecosystem because of associated increases in soil organic matter decomposition.

upon changes in factors such as temperature, soil moisture, and the availability of nutrients. To date, the magnitude and persistence of the CO_2 fertilization effect remains unquantified. Despite increases in plant growth anticipated from CO_2 fertilization, the total amount of carbon stored in an ecosystem may still decrease because increased temperature also stimulates the decomposition of dead leaves and soil organic matter.

In addition to the changes within ecosystems, temperature changes and increased CO_2 could result in significant alterations in the overall distribution of the world's biomes. Figure 3 shows the potential distribution of the major world biomes under current climate conditions and a doubled CO_2-equivalent climate-change scenario. The possible effects of climate change on the boundaries of forests and rangelands are discussed further in Boxes 4 and 5. The consequences for some terrestrial ecosystems depend critically on how fast climate zones shift. The rates of these shifts are important in part because different plant species migrate at different rates, depending on their growth and reproductive cycles.

3.2.1. Forests

Forests contain a wide range of species with complex life cycles. These ecosystems contain 80% of all aboveground carbon in vegetation and about 40% of all soil carbon. Forests and forest soils also play a major role in the carbon cycle as sources (e.g., forest degradation and deforestation) and sinks (reforestation, afforestation, and possibly enhanced growth resulting from carbon dioxide fertilization). Forests, particularly in the tropics, harbor as much as two-thirds of the world's biodiversity. They directly affect climate up to the continental scale by influencing ground temperatures, evapotranspiration, surface roughness, albedo, cloud formation, and precipitation.

A variety of biological, chemical, and physical factors affect forest ecosystems. Forest productivity and the number of species generally increase with increasing temperature, precipitation, and nutrient availability. Forests are particularly vulnerable to and may decline rapidly under extreme changes in water availability (either drought or waterlogging). Models project that a sustained increase of 1°C in global mean temperature is sufficient to cause changes in regional climates that will affect the growth and regeneration capacity of forests in many regions. In several instances, this will alter the function and composition of forests significantly. As a consequence of possible changes in temperature and water availability under doubled equivalent-CO_2 equilibrium conditions, a substantial fraction (a global average of one-third, varying by region from one-seventh to two-thirds) of the existing forested area of the world will undergo major changes in broad vegetation types—with the greatest changes occurring in high latitudes.

Climate change is expected to occur rapidly relative to the speed at which forest species grow, reproduce, and reestablish themselves. For mid-latitude regions, an average global warming of 1–3.5°C over the next 100 years would be equivalent to shifting isotherms poleward approximately 150–550 km or an altitude shift of 150–550 m; in low latitudes, temperatures would generally be increased to higher levels than now exist. This compares to past tree species migration rates on the order of 4–200 km per century. Entire forest types may disappear, and new ecosystems may take their places.

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Box 5. Regional Implications of Climate Change for Rangelands

Tropical rangelands. Temperature increases *per se* should not lead to major alterations in tropical rangelands, except where infrequent frosts currently limit some species. The most severe consequences could result from altered rainfall (seasonality and amount). Increasing carbon-to-nitrogen ratios could also result in reduced forage quality and palatability. The influence of increasing concentrations of CO_2 on photosynthesis and greater growth would have a major impact on the productivity of these rangelands.

Temperate rangelands. Climate change clearly will alter temperate rangelands and associated savannas and shrublands. Because of the high correlation between rangeland types and climate belts, any shifts in temperature and precipitation will bring corresponding shifts in rangeland boundaries. Continental areas that experience drier conditions during the growing season may see a shift from grasslands to shrublands.

Tundra. Tundra systems should exhibit high sensitivity to climatic warming. Indirect temperature effects, especially those associated with decreases in the amount of frozen soil and with changes in nutrient availability, will result in shifts in species composition. Changes in precipitation and temperature could decrease soil moisture in high-latitude tundra systems, changing some tundra systems from net sinks to net sources of carbon dioxide to the atmosphere while also increasing surface oxidation and decreasing methane flux.

Mature forests are a large terrestrial store of carbon. In general, temperate and tropical forests contain as much carbon aboveground as belowground, but boreal forests contain most of their carbon belowground. It remains unclear whether forests will continue to sequester carbon through growth under less suitable conditions than exist today. Although NPP could increase, the standing biomass of forests may not because of more frequent outbreaks and extended ranges of pests and pathogens, and increasing frequency and intensity of fires. Large amounts of carbon could be released into the atmosphere during transitions from one forest type to another, because the rate at which carbon can be lost during times of high forest mortality is greater than the rate at which it can be gained through growth to maturity.

3.2.2. Rangelands

Rangelands (i.e., unimproved grasslands, shrublands, savannas, deserts, and tundra) occupy 51% of the Earth's land surface. They contain about 36% of its total carbon in living and dead biomass, include a large number of economically important species and ecotypes, and sustain millions of people. Rangelands support 50% of the world's livestock and provide forage for domesticated animals and wildlife.

The amounts and seasonal distribution of precipitation are the primary controls on rangeland carbon cycling and productivity. Water availability and balance play vital roles in controlling the productivity and geographic distribution of rangeland ecosystems; thus, small changes in extreme temperatures and precipitation may have disproportionate effects.

Increases in CO_2 likely will result in reductions of forage quality and palatability because of increasing carbon-to-nitrogen ratios and shrub encroachment. These effects will become more evident in low-latitude rangelands, where the low nutritional value of forage already creates a chronic problem.

Boundaries between rangelands and other ecosystems appear likely to change as a result of direct climate effects on species composition as well as indirect factors such as changes in wildfire frequency and land use. Temperate rangelands will experience these effects the most. Migration rates of rangeland vegetation appear to be faster than for forests.

Precipitation and temperature variations associated with climate change may alter the role of high-latitude tundra systems in the carbon cycle. During the past decade, some tundra systems have shifted from a net sink to a net source of atmospheric CO_2, perhaps due to decreased soil moisture associated with warmer summers (a positive climate feedback). The tundra and taiga (subarctic evergreen forests) also provide 10% of the global atmospheric input of CH_4. Warming-related changes may dry soils and increase surface oxidation, thus decreasing CH_4 releases (a negative climate feedback).

Devising adaptation strategies for rangeland systems may prove difficult in marginal food-producing areas where production is very sensitive to climate change, changing of technology is risky, and the rate of adoption of new techniques and practices is slow. Decreases in rangeland productivity would result in a decline in the overall contribution of the livestock industries to national economies, with serious implications for food production in many developing areas with pastoral economies. Adaptation options in more highly managed pastures include management of forage, animal breeding, pasture renewal, and irrigation.

3.2.3. Deserts and Land Degradation

If the Earth's climate does change as projected in current scenarios, conditions in most deserts are likely to become more extreme—in that, with few exceptions, they are projected to become hotter but not significantly wetter. Temperature increases, in particular, could be a threat to organisms that now exist near their heat-tolerance limits. The impacts of climate change on water balance, hydrology, and vegetation remain uncertain and would probably vary significantly among regions.

Land degradation—which reduces the physical, chemical, or biological quality of land and lowers its productive capacity—already poses a major problem in many countries. Current general circulation models (GCMs) project that in some regions, climate change will increase drought and result in rainfall of higher intensity and more irregular distribution. This could increase the potential for land degradation, including loss of organic matter and nutrients, weakening of soil structure, decline in soil stability, and an increase in soil erosion and salinization. Areas that experience increased rainfall and soil moisture will benefit from the opportunities for more flexible use. However, they may experience stronger leaching, leading to increased acidification and loss of nutrients. In appropriate situations, additions of lime and fertilizers or conservation management policies could correct these deficiencies.

Desertification, as defined by the United Nations Convention to Combat Desertification, is land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities. Droughts may trigger or accelerate desertification by reducing the growth of important plant species. Grazing can strip the land of its cover under these conditions. However, the amount of precipitation needed to sustain growth varies with the temperature, soil moisture capacity, and species. Desertification is more likely to become irreversible if the environment becomes drier and the soil becomes further degraded through erosion and compaction. Adaptation to drought and desertification may rely on the development of diversified production systems, such as agroforestry techniques and ranching of animals better adapted to local conditions. However, adaptation also needs political, social, extension service, and educational inputs.

3.2.4. Cryosphere

Many components of the cryosphere (i.e., snow, ice, and permafrost) are particularly sensitive to changes in atmospheric temperature. The last century has witnessed a massive loss and retreat of mountain glaciers, a reduction in the areal distribution of permafrost, and evidence of later freeze-up and earlier break-up of river and lake ice in many northern countries. These observations are consistent with a 0.5°C increase in the annual global mean temperature during the last century.

Projected changes in climate will substantially reduce the extent and volume of the cryosphere over the next century, causing pronounced reductions in mountain glaciers, permafrost, and seasonal snow cover. By the year 2100, between one-third and one-half of all mountain glaciers could disappear. The reduced extent of glaciers and depth of snow cover would affect the seasonal distribution of river flow, with potential implications for water resources (e.g., hydroelectric generation, agriculture). Data on iceberg calving from ice sheets and expected changes in calving as a result of projected temperature increases are inconclusive, although some scientists suggest that certain ice shelves currently are breaking up systematically. Little change in the extent of the Greenland and Antarctic ice sheets is expected over the next 50–100 years. An increase in temperature would extend the duration of the navigation season on rivers and lakes affected by seasonal ice cover. Projected reductions in the extent and thickness of the sea-ice cover in the Arctic Ocean and its peripheral seas could substantially benefit shipping, perhaps opening the Arctic Ocean as a major trade route. A reduction in the areal extent and depth of permafrost would have serious consequences for a number of human activities. Thawing of permafrost releases CH_4 hydrates.

3.2.5. Mountain Regions

Mountains cover about 20% of continental surfaces and serve as an important water source for most of the world's major river systems. Mountain ecosystems are under considerable stress from humans, and climate change will exacerbate existing conflicts between environmental and socioeconomic concerns.

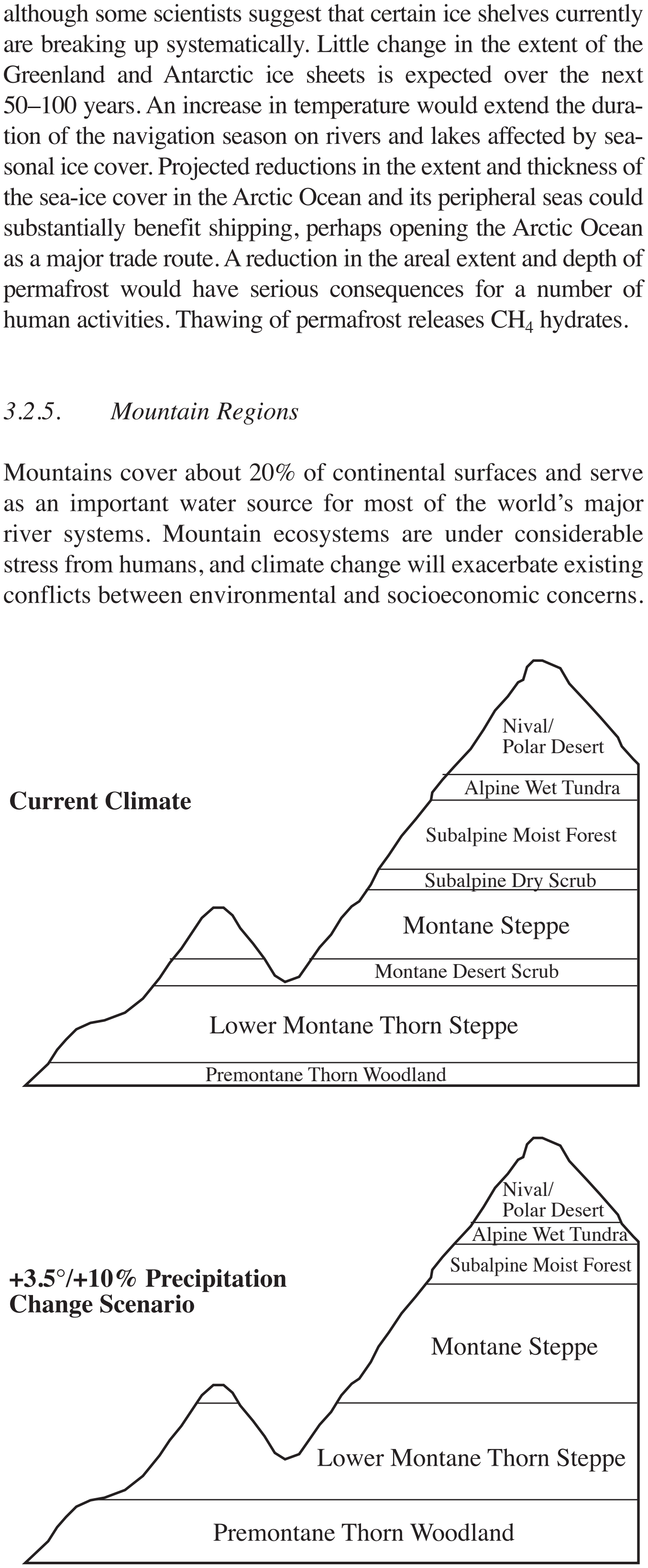


Figure 4: Comparison of current vegetation zones at a hypothetical dry temperate mountain site with simulated vegetation zones under a climate-warming scenario. Source: Beniston, 1994 (see Chapter 5 for complete citation).

Paleologic records indicate that past warming of the climate has caused the distribution of vegetation to shift to higher elevations, resulting in the loss of some species and ecosystems. Simulated scenarios for temperate-climate mountain sites suggest that continued warming could have similar consequences (see Figure 4), thus species and ecosystems with limited climatic ranges could disappear because of disappearance of habitat or reduced migration potential.

In most mountain regions, a warmer climate will reduce the extent and volume of glaciers and the extent of permafrost and seasonal snow cover. Along with possible precipitation changes, this would affect soil stability and a range of socioeconomic activities (e.g., agriculture, tourism, hydropower, and logging). Climate change may disrupt mountain resources for indigenous populations (e.g., fuel and subsistence and cash crops) in many developing countries. Recreational activities, which are increasingly important economically to many regions, also face likely disruptions. People living outside mountain regions who use water originating in them also would experience significant consequences.

Because of their climatic and habitat diversity, mountains provide excellent locations for maintaining biological diversity. In particular, large north-south mountain chains such as the Andes can facilitate migration under changing climate if appropriately managed.

3.3. Aquatic Ecosystems

Aquatic ecosystems encompass lakes and streams, non-tidal wetlands, coastal environs, and oceans. These systems are sensitive to changes in temperature, precipitation, and sea level and in turn exert important feedbacks on climate by influencing carbon fluxes. They provide a range of socioeconomic values and benefits—including food, energy, transportation, timber, flood mitigation, erosion control, water supply, and recreation.

3.3.1. Lakes and Streams

Climate change will influence lakes and streams through altered water temperatures, flow regimes, and water levels. These will directly affect the survival, reproduction, and growth of organisms; the productivity of ecosystems; the persistence and diversity of species; and the regional distribution of biota. Climatic warming would tend to shift geographic ranges of many species poleward by approximately 150 km for every 1°C increase in air temperature. Changes in the heat balance of lakes would alter their mixing properties, which would have large effects on their primary productivity. Changes in runoff and groundwater flows to lakes and streams would alter the input of nutrients and dissolved organic carbon, which in turn would alter the productivity and clarity of the waters. Changes in hydrologic variability are expected to have greater ecological effects than changes in mean values. For example, increased frequency or duration of flash floods and droughts would reduce the biological diversity and productivity of stream ecosystems.

Although the effects on lake and stream ecosystems will vary with the distribution of climate changes, some general conclusions emerge. Warming would have the greatest biological effects at high latitudes, where biological productivity would increase, and at the low-latitude boundaries of cold- and cool-water species ranges, where appropriate thermal habitat would become more fragmented and extinctions would be greatest. The rate of climatic warming may exceed the rate of shifts in species ranges. Warming of the larger and deeper temperate lakes will increase their productivity and thermal habitat favorable for native fishes, whereas warming of shallow lakes and streams could lead to increased anoxia and reduction in suitable habitat. Deep tropical lakes may become less productive as thermal stratification intensifies and nutrients become trapped below the mixed layer. Lakes and streams in dry, evaporative drainages and in basins with small catchments are most sensitive to changes in precipitation and would experience the most severe water-level declines if precipitation were to decrease. For many lakes and streams, the most severe effects of climate change may be the exacerbation of current stresses resulting from human activities, including increasing demands for consumptive uses, increasing waste effluent loadings and runoff of agricultural and urban pollutants, and altered water balance and chemical input rates from landscape disturbance and atmospheric deposition.

3.3.2. Non-Tidal Wetlands

Wetlands are areas of low-lying land where the water table lies at or near the surface for some defined period of time, producing extensive shallow, open water and waterlogged areas. Wetlands exist on every continent (except Antarctica), in both inland and coastal areas, and cover approximately 4–6% of the Earth's land surface. Human activities such as agricultural development, construction of dams and embankments, and peat mining already threaten these ecosystems and have contributed to the disappearance of more than half of the world's wetlands during the last century. Non-tidal (primarily inland) wetlands provide refuge and breeding grounds for many species, including a large number with commercial value; are an important repository of biodiversity; control floods and droughts; and improve water quality. They also serve as a carbon sink. Boreal and subarctic peatlands store an estimated 412 Gt C, or about 20% of the global organic carbon stored in soils.

Climate change will most greatly influence wetlands by altering their hydrologic regimes (increasing or decreasing water availability; changing the depth, duration, frequency, and season of flooding). These changes will affect the biological, biogeochemical, and hydrological functions of wetlands and alter their value to societies for such functions as aquifer recharge, sediment retention, waste processing, and carbon storage. There will be an impact of climate change on greenhouse gas release from non-tidal wetlands, but there is uncertainty regarding the exact effects from site to site; some arctic areas already have shifted from weak carbon sinks to weak CO_2 sources due to drying.

The geographical distribution of wetlands is likely to shift with changes in temperature and precipitation. Warming would severely affect wetlands in arctic and subarctic regions by thawing permafrost, which is key to maintaining high water tables in these ecosystems.

Possibilities for adaptation, conservation, and restoration in response to climate change vary among wetland types and their various functions. For regional and global functions (e.g., trace-gas fluxes and carbon storage), no responses exist that humans can apply at the necessary scale. For wetland functions at the local scale (habitat value, pollution trapping, and, to some degree, flood control), possibilities do exist. However, interest in wetland creation and restoration has outpaced the science and technology needed to successfully create wetlands for many specific purposes.

3.3.3. Coastal Ecosystems

Many commercially important marine species depend on coastal ecosystems for some part of their life cycle, and some coastal ecosystems (e.g., coral reefs, mangrove communities, and beaches) provide an important buffer against storms and surges. Sea-level rise, altered rainfall patterns, and changes in ocean temperature likely will result in additional adverse impacts on coastal ecosystems, particularly where human activities already affect environmental conditions.

Coastal systems are ecologically and economically important, and are expected to vary widely in their response to changes in climate and sea level. Climate change and a rise in sea level or changes in storms or storm surges could result in the displacement of wetlands and lowlands, erosion of shores and associated habitat, increased salinity of estuaries and freshwater aquifers, altered tidal ranges in rivers and bays, changes in sediment and nutrient transport, a change in the pattern of chemical and microbiological contamination in coastal areas, and increased coastal flooding. In many areas, intensive human alteration and use of coastal environments already have reduced the capacity of natural systems to respond dynamically. Other regions, however, may prove far less sensitive and may keep pace with climate and sea-level change. This suggests that future impact analyses must be carried out region by region.

Nonetheless, research findings strongly indicate that some coastal ecosystems face particular risks from changes in climate and sea level. A number of regional studies show the disappearance of saltwater marshes, mangrove ecosystems, and coastal wetlands at a rate of 0.5–1.5% per year over the last few decades. The interaction of climate change, sea-level rise, and human development will further threaten these particularly sensitive ecosystems. Climate-change impacts on coastal ecosystems will vary widely. The sea level may rise faster than sediment accretion rates in many coastal areas; thus, existing wetlands will disappear faster than new ones appear. Ecosystems on coral atolls and in river deltas show special sensitivity to climate and sea-level change. Changes in these ecosystems almost certainly would have major negative effects on tourism, freshwater supplies, fisheries, and biodiversity. Such impacts would further modify the functioning of coastal oceans and inland waters already stressed by pollution, physical modification, and material inputs due to human activities.

Coral reefs are the most biologically diverse marine ecosystems; they also are very sensitive to climate change. Short-term increases in water temperatures on the order of only 1–2°C can cause "bleaching," leading to reef destruction. Sustained increases of 3–4°C above long-term average seasonal maxima over a 6-month period can cause significant coral mortality. Biologists suggest that fully restoring these coral communities could require several centuries. A rising sea level also may harm coral reefs. Although available studies indicate that even slow-growing corals can keep pace with the "central estimate" of sea-level rise (approximately 0.5 cm per year), these studies do not take account of other pressures on coral populations, such as pollution or enhanced sedimentation.

3.3.4. Oceans

Oceans occupy 71% of the Earth's surface. They provide an important component of the climate system, due to their role in controlling the distribution and transfer of heat and CO_2 (internally and with the atmosphere) and in the transfer of water back to the continents as precipitation. They provide vital mineral resources, an environment for living resources ranging from phytoplankton to whales, and support for socioeconomic activities such as transportation, fishing, and recreation.

Oceans are sensitive to changes in temperature, freshwater inputs from continents and atmospheric circulation, and the interaction of these factors with other environmental factors such as ultraviolet-B (UV-B) radiation and pollution (which is especially important in inland seas, bays, and other coastal areas). Climate change may alter sea level, increasing it on average, and could also lead to altered ocean circulation, vertical mixing, wave climate, and reductions in sea-ice cover. As a result, nutrient availability, biological productivity, the structure and functions of marine ecosystems, the ocean's heat- and carbon-storage capacity, and important feedbacks to the climate system will change as well. These changes would have implications for coastal regions, fisheries, tourism and recreation, transport, off-shore structures, and communication. Paleoclimatic data and model experiments suggest that abrupt climatic changes can occur if freshwater influx from the movement and melting of sea ice or ice sheets significantly weakens global thermohaline circulation (the sinking of dense surface waters in polar seas that moves bottom water toward the equator).

3.4. Water

Water availability is essential to national welfare and productivity. The world's agriculture, hydropower production, municipal and industrial water supply, instream ecosystems, water-based recreation, and inland navigation depend on surface and groundwater resources. The quantity and quality of water supplies pose a serious problem today in many regions, including some low-lying coastal areas, deltas, and small islands. Water availability already falls below 1,000 m^3 per person per year—a common benchmark for water scarcity—in a number of countries (e.g., Kuwait, Jordan, Israel, Rwanda, Somalia, Algeria, Kenya). Other nations likely to fall below this benchmark in the next 2 to 3 decades include Libya, Egypt, South Africa, Iran, and Ethiopia. In addition, a number of countries in conflict-prone areas depend on water originating outside their borders (e.g., Cambodia, Syria, Sudan, Egypt, Iraq). This makes them quite vulnerable to any additional reduction in indigenous water supplies. The depletion of aquifers, urbanization, land-cover changes, and contamination exacerbate the problem of water availability.

A changing climate will lead to an intensification of the global hydrological cycle, which determines how precipitation is partitioned between ground and surface water storage (including snow cover), fluxes to the atmosphere, and flows to the oceans. Changes in the total amount of precipitation and in its frequency and intensity directly affect the magnitude and timing of runoff and the intensity of floods and droughts; however, at present, specific regional effects are uncertain. In addition, changes in the hydrological cycle affect land cover and the surface energy balance, thus altering important feedbacks on the climate system.

Relatively small changes in temperature and precipitation, together with the non-linear effects on evapotranspiration and soil moisture, can result in relatively large changes in runoff, especially in arid and semi-arid lands. High-latitude regions may experience increased runoff due to increased precipitation, whereas runoff may decrease at lower latitudes due to the combined effects of increased evapotranspiration and decreased precipitation. Even in areas where models project a precipitation increase, higher evaporation rates may lead to reduced runoff. More intense rainfall would tend to increase runoff and the risk of flooding, although the magnitude of the effect would depend on both an area's rainfall change and its catchment characteristics. This effect could be exacerbated in regions where extensive reductions occur in vegetation (e.g., deforestation, overgrazing, logging). Winter snowfall and spring snowmelt determine the flow rates of rivers and streams in many continental and mountain areas. Should the climate change and the proportion of precipitation falling as snow decrease, widespread reductions in spring runoff and increases in winter runoff seem likely. These changes would have consequences for water storage and delivery systems, irrigation, and hydroelectricity production.

Many factors, including changes in vegetation, population growth, and industrial and agricultural demands complicate an assessment of the potential effects of climate change on water resources. Current understanding suggests that climate change can have major impacts on regional water supplies. At present, general circulation models only provide projections on a large geographic scale. They do not agree on a likely range of changes in average annual precipitation for any given basin or watershed, hence fail to provide sufficient information to assist water managers in making decisions.

A change in the volume and distribution of water would affect all of a region's water uses. The impacts, however, will depend also on the actions of water users and managers, who will respond not only to climate change but also to population growth and changes in demands, technology, and economic, social, and legislative conditions. In some cases—particularly in wealthier countries with integrated water-management systems—these actions may protect water users from climate change at minimal cost. In many others however—particularly those regions that already are water-limited—substantial economic, social, and environmental costs could occur. Water resources in arid and semi-arid zones are particularly sensitive to climate variations because of low-volume total runoff and infiltration and because relatively small changes in temperature and precipitation can have large effects on runoff. Irrigation—the largest use of water in many countries—will be the first activity affected in regions where precipitation decreases. This is because in some regions water used for agriculture costs less than water for domestic and industrial activities. During water shortages, allocations to agriculture will most likely decline before allocations to those other uses.

The increased uncertainty in the future supply and demand of water resources raises a key issue for water management. Countries with high population growth rates are likely to experience significant decreases in per capita water availability even without climate change. The issue is complicated further when projected climate change is taken into account. Based on outputs from transient climate models, hydrological models indicate that per capita water availability would vary widely, from slight increases in percentage of water available per capita to large percentage decreases, for the countries considered. Significant differences in the regional distribution of water deficits and surpluses also may occur within each country.

Options for dealing with the possible impacts of a changed climate and increased uncertainty about future supply and demand for freshwater include:

- More efficient management of existing supplies and infrastructure
- Institutional arrangements (e.g., market and regulatory measures) to limit future demands on scarce water supplies
- Improved hydrological monitoring and forecasting systems and establishment of early warning systems for floods/drought
- Rehabilitation of presently denuded tracts of upland watersheds, especially in the tropics

- Construction of new reservoir capacity to capture and store excess flows produced by altered patterns of snowmelt and storms (although this often would be difficult to plan in the absence of improved watershed climate information).

Water managers, in a continuously adaptive enterprise, respond to changing demographic and economic demands, information, and technologies. Experts disagree about whether water supply systems will evolve substantially enough in the future to compensate for the anticipated negative impacts of climate change and the anticipated increases in demand.

3.5. *Food and Fiber*

Two broad classes of climate-induced effects influence the quality and quantity of agricultural and forestry yields: (i) direct effects from changes in temperature, water balance, atmospheric composition, and extreme events; and (ii) indirect effects through changes in the distribution, frequency, and severity of pest and disease outbreaks, incidence of fire, weed infestations, or through changes in soil properties. Fisheries respond to direct climate-change effects such as increases in water temperature and sea level and changes in precipitation, freshwater flows, climate variability, and currents. They respond also to indirect effects such as shifts in food supply and the expansion in ranges of red tides and other biotoxins, which could lead to increased contamination of fisheries. The vulnerability of food and fiber production to climate change depends not only on the physiological response of plants and animals but also on the ability of the affected production and distribution systems to cope with fluctuations in yield.

3.5.1. *Agriculture*

Recent studies support evidence in the 1990 assessment that, on the whole, global agricultural production could be maintained relative to baseline production in the face of climate change modeled by GCMs at doubled-equivalent CO_2 equilibrium conditions. However, more important than global food production—in terms of the potential for hunger, malnutrition, and famine—is the access to and availability of food for specific local and regional populations. Many new crop studies conducted since the 1990 assessment report results that vary widely by crop, climate scenario, study methodology, and site (results are aggregated and summarized in Table 2). Limited ranges for some countries reflect the small number of studies available. At broader regional scales, subtropical and tropical areas—home to many of the world's poorest people—show negative consequences more often than temperate areas. People dependent on isolated agricultural systems in semi-arid and arid regions face the greatest risk of increased hunger due to climate change. Many of these at-risk populations live in sub-Saharan Africa; South, East, and Southeast Asia; and tropical areas of Latin America, as well as some Pacific island nations.

These conclusions emerge from studies that model the effects on agricultural yields induced by climate change and elevated CO_2. These studies presently do not include changes in insects, weeds, and diseases; direct effects of climate change on livestock; changes in soils and soil-management practices; and changes in water supply caused by alterations in river flows and irrigation. Moreover, the studies have considered only a limited set of adaptation measures and are based on yield analyses at a limited number of sites. Failure to integrate many key factors into agronomic and economic models limits their ability to consider transient climate scenarios and to fully address the costs and potential of adaptation. However, increased productivity of crops due to elevated concentrations of CO_2 is an important assumption in most crop modeling studies. Although the mean value response under experimental conditions is a 30% increase in productivity for C_3 crops (e.g., rice and wheat) under doubled-CO_2 conditions, the range is -10 to +80%. The response depends on the availability of plant nutrients, plant species, temperature, precipitation, and other factors, as well as variations in experimental technique.

A wide range of views exists on the potential of agricultural systems to adapt to climate change. Historically, farming systems have adapted to changing economic conditions, technology and resource availability, and population pressures. Uncertainty remains regarding whether the rate of climate change and required adaptation would add significantly to the disruptions resulting from other socioeconomic or environmental changes. Adaptation to climate change via new crops and crop varieties, improved water-management and irrigation systems, and information (e.g., optimal planting times) will prove important in limiting negative effects and taking advantage of beneficial changes in climate. The extent of adaptation depends in part on the cost of the measures used, particularly in developing countries; access to technology and skills; the rate of climate change; and constraints such as water availability, soil characteristics, topography, and the genetic diversity bred into crops. The incremental costs of these adaptation strategies could create a serious burden for some developing countries; some adaptation strategies may result in cost savings for some countries. There are significant uncertainties about the capacity of different regions to adapt successfully to projected climate change. Many current agricultural and resource policies—already a source of land degradation and resource misuse—likely will discourage effective adaptation measures.

Changes in grain prices, in the prevalence and distribution of livestock pests, and in grazing land and pasture productivity all will affect livestock production and quality. In general, analyses indicate that intensively managed livestock systems have more potential for adaptation than crop systems. In contrast, adaptation presents greater problems in pastoral systems where production is very sensitive to climate change, technology changes incur risks, and the rate of technology adoption is slow.

3.5.2. *Forestry*

Global wood supplies during the next century may become increasingly inadequate to meet projected consumption due to

Table 2: *Selected crop study results for 2 x CO_2-equivalent equilibrium GCM scenarios.*

Region	Crop	Yield Impact (%)	Comments
Latin America	Maize	-61 to increase	Data are from Argentina, Brazil, Chile, and Mexico; range is across GCM scenarios, with and without CO_2 effect.
	Wheat	-50 to -5	Data are from Argentina, Uruguay, and Brazil; range is across GCM scenarios, with and without CO_2 effect.
	Soybean	-10 to +40	Data are from Brazil; range is across GCM scenarios, with CO_2 effect.
Former Soviet Union	Wheat Grain	-19 to +41 -14 to +13	Range is across GCM scenarios and region, with CO_2 effect.
Europe	Maize	-30 to increase	Data are from France, Spain, and northern Europe; with adaptation and CO_2 effect; assumes longer season, irrigation efficiency loss, and northward shift.
	Wheat	increase or decrease	Data are from France, UK, and northern Europe; with adaptation and CO_2 effect; assumes longer season, northward shift, increased pest damage, and lower risk of crop failure.
	Vegetables	increase	Data are from UK and northern Europe; assumes pest damage increased and lower risk of crop failure.
North America	Maize Wheat	-55 to +62 -100 to +234	Data are from USA and Canada; range is across GCM scenarios and sites, with/without adaptation and with/without CO_2 effect.
	Soybean	-96 to +58	Data are from USA; less severe or increase with CO_2 and adaptation.
Africa	Maize	-65 to +6	Data are from Egypt, Kenya, South Africa, and Zimbabwe; range is over studies and climate scenarios, with CO_2 effect.
	Millet	-79 to -63	Data are from Senegal; carrying capacity fell 11–38%.
	Biomass	decrease	Data are from South Africa; agrozone shifts.
South Asia	Rice Maize Wheat	-22 to +28 -65 to -10 -61 to +67	Data are from Bangladesh, India, Philippines, Thailand, Indonesia, Malaysia, and Myanmar; range is over GCM scenarios, with CO_2 effect; some studies also consider adaptation.
China	Rice	-78 to +28	Includes rainfed and irrigated rice; range is across sites and GCM scenarios; genetic variation provides scope for adaptation.
Other Asia and Pacific Rim	Rice	-45 to +30	Data are from Japan and South Korea; range is across GCM scenarios; generally positive in north Japan, and negative in south.
	Pasture	-1 to +35	Data are from Australia and New Zealand; regional variation.
	Wheat	-41 to +65	Data are from Australia and Japan; wide variation, depending on cultivar.

Note: For most regions, studies have focused on one or two principal grains. These studies strongly demonstrate the variability in estimated yield impacts among countries, scenarios, methods of analysis, and crops, making it difficult to generalize results across areas or for different climate scenarios.

both climatic and non-climatic factors. Assuming constant per capita wood use, analysis of changing human populations suggests that the annual need for timber will exceed the current annual growth increment of 2% by the year 2050. However, growth could increase slightly from warming and enhanced atmospheric CO_2 concentrations, or decrease greatly from declines and mortality of forest ecosystems brought on by climate change.

Tropical forest product availability appears limited more by changes in land use than by climate change, at least through the middle of the next century. By then, projections indicate that growing stock will have declined by about half due to non-climatic reasons related to human activities. This projected decline holds up even after calculating changes in climate and atmospheric composition during this period, which could increase forest productivity and the areas where tropical forests can potentially grow. Communities that depend on tropical forests for fuelwood, nutrition, medicines, and livelihood will most feel the effects of declines in forested area, standing stock, and biodiversity.

Temperate-zone requirements for forest products should be met for at least the next century. This conclusion emerges from projected climate and land-use changes that leave temperate forest covering about as much land in 2050 as today. It further assumes that current harvests increase only slightly, that the annual growth increment remains constant, and that imports from outside increasingly meet the temperate zone's need for forest products—although it is not clear if this assumption can be met given production projections in other zones.

Boreal forests are likely to undergo irregular and large-scale losses of living trees because of the impacts of projected rapid climate change. Such losses could initially generate additional wood supply from salvage harvests, but could severely reduce standing stocks and wood-product availability over the long term. The exact timing and extent of this pattern is uncertain. Current and future needs for boreal forest products are largely determined outside the zone by importers; future requirements for forest products may exceed the availability of boreal industrial roundwood during the 21st century, given the projections for temperate- and tropical-zone forest standing stocks and requirements.

Effective options for adapting to and ameliorating potential global wood supply shortages include the following:

- In the tropics, the greatest progress may result from developing practices and policies that reduce social pressures driving land conversion (e.g., by increasing crop and livestock productivity) and by developing large plantations.
- In temperate areas, application of modern forestry practices to reduce harvest damage to ecosystems, combined with the substitution of nontimber products, could reduce significantly the effect of climate on wood availability.
- In boreal regions, adaptation to potential climate-induced, large-scale disturbances—such as by rapid reforestation with warmth-adapted seeds—appears to be most useful. Increased prices for forestry products seem certain to lead to adaptation measures that will reduce demand, increase harvest intensity, and make tree plantations more economically feasible.

3.5.3. *Fisheries*

Climate-change effects will interact with other stresses on fisheries, including pervasive overfishing, diminishing nursery areas, and extensive inshore and coastal pollution. Overfishing stresses fisheries more than climate change today, but if fisheries management improves and climate changes develop according to IPCC scenarios, climate change may become the dominant factor by the last half of the next century.

Although marine fisheries production will remain about the same globally, projections indicate that higher latitude freshwater and aquaculture production will increase. This assumes, however, that natural climate variability and the structure and strength of ocean currents remains unchanged. Alterations in either would have significant impacts on the distribution of major fish stocks, rather than on global production. Positive effects (e.g., longer growing seasons, lower natural winter mortality, and faster growth rates in higher latitudes) may be offset by negative factors such as changes in established reproductive patterns, migration routes, and ecosystem relationships. Climate change can be expected to have the greatest impact on the following (in decreasing order): (i) freshwater fisheries in small rivers and lakes in regions with larger temperature and precipitation change; (ii) fisheries within exclusive economic zones, particularly where access regulations artificially reduce the mobility of fisher groups and fishing fleets, thus their capacity to adjust to fluctuations in stock distribution and abundance; (iii) fisheries in large rivers and lakes; (iv) fisheries in estuaries, particularly where there are species without migration or spawn dispersal paths, or estuaries affected by sea-level rise or decreased river flow; and (v) high-seas fisheries. Where rapid change occurs due to physical forcing (e.g., changes in currents and natural variability), production will usually favor smaller, low-priced, opportunistic species that discharge large numbers of eggs over long periods. Loss of coastal wetlands could cause a loss of nurseries and have significant adverse effects on fisheries.

If institutional mechanisms do not enable fishers to move across national boundaries, some national fish industries may suffer negative effects. Subsistence and other small-scale fishers, often the most dependent on specific fisheries, will suffer disproportionately from changes. Several adaptation options exist. These include improved management systems, ecological and institutional research, and expansion of aquaculture.

3.6. ***Human Infrastructure***

Human infrastructure, a key determinant of a region's productivity and development, includes all varieties of human-made capital and assets—residential and commercial properties, transportation facilities, industries and manufactured goods, coastal embankments, and equipment for energy production and distribution. Human infrastructure and socioeconomic systems—including industry, energy, and transportation—may be affected *directly* through changes in temperature, precipitation, sea level, or increased frequency or intensity of extreme events that can damage exposed infrastructure or affect outputs. Due to the interconnectedness of economic activity, many of the influences of climate change on industry, energy, and transportation are expected to be *indirect* and transmitted by changes in markets sensitive to climate (e.g., energy demand for space heating and cooling) or changes in resources sensitive to climate (e.g., agroindustries and biomass production). Human migration in response to chronic crop failures, regional flooding, or drought may create additional pressure on human infrastructures. These indirect impacts are difficult to quantify or value in monetary terms.

In many sectors, the effects of climate change will amount to less than those resulting from changes in demography, technology, and markets. Yet unexpected changes in climate could occur and much capital is invested in locations that could be affected by such changes. Relocating or defending this infrastructure could require costly actions and a high degree of foresight and coordination.

3.6.1. Industry, Energy, and Transportation

In general, the climate sensitivity of most activities in these sectors is relatively low compared to that of agriculture or natural ecosystems. Certain activities, however, display a greater degree of climate sensitivity than do industry, energy, and transportation as a whole. Subsectors and activities most sensitive to climate change include agroindustry, production of renewable energy such as hydroelectricity and biomass, energy demand, construction, some transportation activities, existing flood mitigation structures, and transportation infrastructure located in many areas, including vulnerable coastal zones and permafrost regions.

In the energy sector, the consequences for hydroelectric power generation will depend upon changes in the balance between the amount and timing of precipitation and evaporation. Increased scarcity of fuelwood in dry and densely populated regions could exacerbate problems caused by deforestation. Peak winter demand for primary energy is projected to decrease due to a reduction in space-heating needs; peak summer demand for electricity may increase with greater cooling requirements in some regions. ‘The net effects of these changes in energy demand will be regionally dependent. There is low confidence in estimates of these net effects.

In contrast to research on mitigation options, relatively few studies exist on climate change impacts on and adaptation options for the industry, energy, and transportation sectors. This situation reflects a perception of low vulnerability to climate change for these sectors.

3.6.2. Coastal Zones/Small Islands

Many coastal zones and small islands are particularly vulnerable to direct effects of climate change and sea-level rise. Present estimates of global sea-level rise represent a rate two to five times that experienced during the last 100 years. Recent scientific findings indicate that sea-level rise may deviate from the global average by a factor of two or more due to regional differences in ocean salinity and temperature change.

Sea-level rise can have negative impacts on tourism, freshwater supplies, fisheries, exposed infrastructure, agricultural and dry lands, and wetlands. Impacts may vary across regions; societal costs will greatly depend upon the vulnerability of the coastal system and a country’s economic situation.

Climate change clearly will increase the vulnerability of some coastal populations to flooding and erosional land loss. Estimates put about 46 million people per year currently at risk of flooding due to storm surges. This estimate results from multiplying the total number of people currently living in areas potentially affected by ocean flooding by the probability of flooding at these locations in any year, given the present protection levels and population density. In the absence of adaptation measures, a 50-cm sea-level rise would increase this number to about 92 million; a 1-m sea-level rise would raise it to 118 million. If one incorporates anticipated population growth, the estimates increase substantially. Some small island nations and other countries will confront greater vulnerability because their existing sea and coastal defense systems are less well-established. Countries with higher population densities would be more vulnerable. For these countries, sea-level rise could force internal or international migration of populations.

A number of studies have evaluated sensitivity to a 1-m sea-level rise. This increase is at the top of the range of IPCC Working Group I estimates for 2100; it should be noted, however, that sea level is actually projected to continue to rise in future centuries beyond 2100. Studies using this 1-m projection show a particular risk for small islands and deltas. Given the present state of protection systems, estimated land losses range from 0.05% for Uruguay, 1% for Egypt, 6% for the Netherlands, and 17.5% for Bangladesh up to about 80% for the Majuro Atoll in the Marshall Islands. Large numbers of people are also affected—for example, about 70 million each in China and Bangladesh. Many nations face lost capital value in excess of 10% of GDP. Although annual adaptation/protection costs for many nations are relatively modest (about 0.1% of GDP), the average annual costs to many small island states total several percent of GDP. For some island nations, the high cost of providing storm-surge protection would make it essentially infeasible, especially given the limited availability of capital for investment.

3.6.3. Human Settlements

Projected climate change will affect human settlements in the context of changes such as population growth, migration, and industrialization. Settlements where these forces already stress the infrastructure are most vulnerable. Besides coastal communities and those dependent on subsistence, rain-fed agriculture, or commercial fishing, vulnerable settlements include large primary coastal cities and squatter settlements located in flood plains and steep hillsides. Many of the expected impacts in the developing world could occur because climate change may reduce natural resource productivity in rural areas, thus may generally accelerate rural-to-urban migration. Direct impacts on infrastructure would most likely occur as a result of changes in the frequency and intensity of extreme events. These include coastal storm surges, floods and landslides induced by local downpours, windstorms, rapid snowmelt, tropical cyclones and hurricanes, and forest and brush fires made possible in part by more intense or lengthier droughts.

3.6.4. Insurance and Financial Services

Within the financial services sector, property insurance stands most vulnerable to direct climatic influence. A higher risk of extreme events due to climate change could lead to higher insurance premiums or the withdrawal of coverage for property in some vulnerable areas. Changes in climate variability and the risk for extreme events may be difficult to detect or predict, thus making it difficult for insurance companies to adjust premiums appropriately. If such difficulty leads to insolvency, companies may not be able to honor insurance contracts, which could economically weaken other sectors such as banking. The insurance industry currently is under stress from a series of "billion dollar" storms since 1987 (see Table 3), resulting in dramatic increases in losses, reduced availability of insurance, and higher premiums. Some in the insurance industry perceive a current trend toward increased frequency and severity of extreme climate events. Examination of the meteorological data fails to support this perception in the context of a long-term change, although a shift within the limits of natural variability may have occurred. Higher losses strongly reflect increases in infrastructure and economic worth in vulnerable areas, as well as a possible shift in the intensity and frequency of extreme weather events.

Table 3: *"Billion dollar" storms.*

Year	Event	Insured Cost ($B)
1987	"Hurricane" in SE England/NW France	2.5
1988	Hurricane Gilbert in Jamaica/Mexico	0.8
1989	Hurricane Hugo in Puerto Rico/S. Carolina	5.8
1990	European Storms—Four	10.4
1991	Typhoon Mireille in Japan	4.8
1992	Hurricane Andrew in Florida	16.5
1993	"Storm of the Century" in Eastern USA	1.7
1995	Hailstorms in Texas	1.1
1995	Hurricane Opal in Southern USA	2.1

Sources: Munich Re, 1990; Leggett, 1994; PCS, 1995 (see Chapter 17 for complete citations).

Withdrawal of insurance would increase direct financial losses to property owners and businesses unable to obtain insurance, with serious long-term implications for societies and governments. The implications of climate change for financial services outside of property insurance appear less clear; these sectors generally have not acknowledged the potential for such impacts. Adaptation may prove difficult, given the long-term nature of many investors' financial commitments.

3.6.5. Adaptation Options for Human Infrastructure

Because the life cycles of planning and investment for much human infrastructure are shorter than those associated with climate change, adaptation could occur through management and the normal replacement of capital in many sectors, as long as climate change happens gradually. This, however, depends on people and organizations becoming adequately informed about potential impacts and having the financial, technical, and institutional capacity to respond. In the more sensitive sectors, adaptation may need the support of policy measures. Incorporating potential climate and sea-level changes in planning would reduce future risks to human infrastructure. Climate changes, however, could occur suddenly. Uncertainty about the rate and effects of climate change makes some investment decisions difficult. This holds particularly true for planning and investments for infrastructure such as channels, water supply systems, and coastal or river-flooding defenses, which can have lifetimes as long as 100 years.

Many developing countries currently depend on a limited number of crops or on fishing—hence are economically vulnerable to climate change that harms agroindustry. For these countries in particular, diversifying economic activity—coupled with improved management practices such as integrated coastal-zone management and land-use regulation—could constitute an important precautionary response and facilitate successful adaptation to climate change (e.g., by directing populations away from vulnerable locations).

Implementing adaptation measures and integrated management practices requires overcoming constraints that include (but are not limited to) technology and human resource capability; financial limitations; cultural and social acceptability; and political, legal, and other institutional bottlenecks. The literature remains scarce on adaptation; dealing effectively with the issue requires additional research and new methods of risk and probability assessment.

3.7. Human Health

Climate changes and their effects on food security, water supply and quality, and the distribution of ecological systems may have wide-ranging and potentially adverse effects on human health, via both direct and indirect pathways (see Figure 5); it is likely that the indirect impacts would, in the longer term, predominate. Quantifying the potential health impacts of climate change remains difficult. For many effects, forecasting techniques—especially modeling—are just being developed. Furthermore, the extent of climate-induced health disorders depends on numerous coexistent and interacting factors that characterize the vulnerability of the particular population. These include environmental circumstances (such as water purity) and socioeconomic factors (such as nutritional and immune status, population density, and access to health care).

Direct health effects include increases in heat-related (predominantly cardiorespiratory) mortality and illness resulting from an anticipated increase in the intensity and duration of heat waves. Studies in selected cities in North America, North Africa, and East Asia indicate that the annual numbers of heat-related deaths would increase several-fold in response to climate-change projections. Temperature increases in colder regions should result in fewer cold-related deaths.

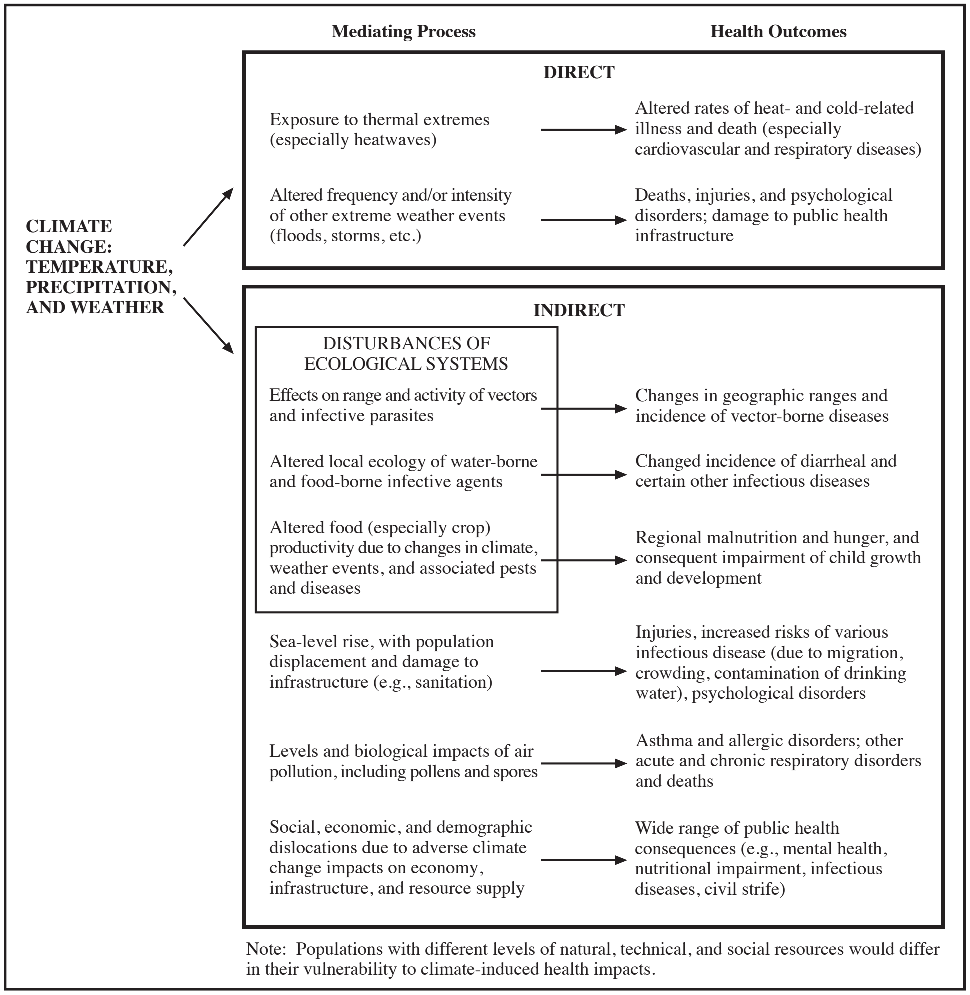
The incidence of deaths, injuries, psychological disorders, and exposure to chemical pollutants in water supplies would increase if extreme weather events (e.g., droughts and floods) were to become more frequent.

Indirect effects include increases in the potential transmission of vector-borne infectious diseases (e.g., malaria, dengue, Chagas' disease, yellow fever, and some viral encephalitis) caused by extensions of the ranges and seasons of vector organisms. Climate change also would accelerate the maturation of certain infectious parasites (e.g., the malaria organism). Currently, approximately 350 million cases of malaria occur annually, resulting in 2 million deaths. Using first-generation mathematical models, scientists recently forecast the impact of changes in basic climate variables on the global/regional pattern of potential malaria transmission. Approximately 45% of the world's population presently lives in the climate zone where mosquitoes transmit malaria. Projections by models (that entail necessary simplifying assumptions) indicate that the geographical zone of potential malaria transmission in response to world temperature increases at the upper part of the IPCC-projected range (3–5°C by 2100) would increase to approximately 60% by the latter half of the next century. This possible extension in potential transmission area would encroach most on temperate regions. However, actual climate-related increases in malaria incidence (50 to 80 million additional annual cases) would occur primarily in tropical, subtropical, and less well-protected temperate-zone populations currently at the margins of endemically infected areas.

Some increases in non-vector-borne infectious diseases—such as salmonellosis, cholera, and other food- and water-related infections could occur—particularly in tropical and subtropical regions because of climatic impacts on water distribution, temperature, and microorganism proliferation.

Other likely indirect effects include increases in asthma, allergic disorders, cardiorespiratory diseases, and associated deaths. These might result from climate-induced changes in pollens and spores, and from temperature increases that enhance the formation, persistence, and respiratory impact of certain air pollutants. Exposure to air pollution and stressful weather events combine to increase the likelihood of morbidity and mortality.

Though still uncertain, the regional effects of climate change upon agricultural, animal, and fisheries productivity could increase the local prevalence of hunger, malnutrition,



Note: Populations with different levels of natural, technical, and social resources would differ in their vulnerability to climate-induced health impacts.

Figure 5: Ways in which climate change can affect human health.

and their long-term health impairments, especially in children. Limitations on freshwater supplies also will have human health consequences. A range of adverse public health effects would result from physical and demographic disruptions due to sea-level rise.

Various technological, organizational, and behavioral adaptations would lessen these adverse effects. These include protective technology (e.g., housing, air conditioning, water purification, and vaccination), disaster preparedness, and appropriate health care. However, the tropical and subtropical countries at highest risk from many of these impacts may still lack adequate resources for adaptation.

4. Options to Reduce Emissions and Enhance Sinks of Greenhouse Gases: Mitigation

4.1. Common Themes and Conclusions

Significant reductions in net greenhouse gas emissions are technically possible and can be economically feasible. These reductions can be achieved by employing an extensive array of technologies and policy measures that accelerate technology development, diffusion, and transfer in all sectors, including the energy, industry, transportation, residential/commercial, and agricultural/forestry sectors. By the year 2100, the world's commercial energy system in effect will be replaced at least twice, offering opportunities to change the energy system without premature retirement of capital stock; significant amounts of capital stock in the industrial, commercial, residential, and agricultural/forestry sectors also will be replaced. These cycles of capital replacement provide opportunities to use new, better performing technologies. It should be noted that the analyses of Working Group II do not attempt to quantify potential macroeconomic consequences that may be associated with mitigation measures. Discussion of macroeconomic analyses is found in the contribution of IPCC Working Group III to the Second Assessment Report. The degree to which technical potential and cost-effectiveness are realized is dependent on initiatives to counter lack of information and overcome cultural, institutional, legal, financial, and economic barriers that can hinder diffusion of technology or behavioral changes. The pursuit of mitigation options can be carried out within the limits of sustainable development criteria. Social and environmental criteria not related to greenhouse gas emissions abatement could, however, restrict the ultimate potential of each of the options.

- **Numerous technology options are available for reducing emissions and enhancing sinks**. Promising technologies and measures follow:
  - *Energy demand*. The technical potential for best practice energy technologies to improve energy efficiency relative to present average practice is large; 10–30% efficiency gains at little or no cost in many parts of the world, through conservation measures and improved management practices, and 50–60% is possible, provided that relevant technologies and financing are available.
  - *Industry*. Short-term emissions reductions of about 25% can be obtained in industrialized nations by improving efficiency, recycling materials, and implementing "industrial ecology" practices that use less energy and fewer materials.
  - *Transportation*. Emissions reductions of up to 40% by 2025 could be achieved by changing vehicle engineering to use more efficient drive trains and materials; reducing the size of vehicles; switching to alternative fuels; reducing the level of passenger and freight transport activity by altering land-use patterns, transport systems, mobility patterns, and lifestyles; and shifting to less energy-intensive transportation modes.
  - *Commercial/residential sector*. Cuts of 50% in the projected growth in emissions over the next 35 years—and deeper cuts in the longer term—could be achieved by more efficient lighting, appliances, and space-conditioning systems; reduced heat transfers through walls, ceilings, and windows; and modern control systems such as automatic sensors.
  - *Energy supply*. Options include more efficient conversion of fossil fuels (from the present world average for electric power generation of about 30% to more than 60% in the longer term); switching from high- to low-carbon fossil fuels (coal to oil to gas); decarbonization of flue gases and fuels, coupled with CO_2 storage; increasing the use of nuclear energy; and increased use of modern renewable sources of energy (e.g., biomass for production of electricity and liquid/gaseous fuels, wind, and solar). In the longer term, renewable sources of energy could meet the major part of the world's demand for energy as technological advances offer new opportunities and declining costs.
  - *Land management*. A number of measures could conserve and sequester substantial amounts of carbon (approximately 60–90 Gt C in the forestry sector alone) over the next 50 years, including slowing deforestation, enhancing natural forest generation, establishing tree plantations, and promoting agroforestry. Significant additional amounts could be sequestered by altering management of agricultural soils and rangelands, and by restoring degraded agricultural lands and rangelands. Other practices, such as improving efficiency of fertilizer use or the diet of domesticated ruminants, could reduce emissions of other greenhouse gases such as CH_4 and N_2O.
- **Policies can accelerate reductions in greenhouse gas emissions**. Governments can choose policies that facilitate the penetration of less carbon-intensive technologies and modified consumption patterns. Indeed, many countries have extensive experience with a variety of policies that can accelerate the adoption of such technologies. This experience comes from efforts over the past 20 to 30 years to achieve improved energy

efficiency, reduce the environmental impacts of agricultural policies, and meet conservation and environmental goals unrelated to climate change. Many of these policies appear potentially useful for reducing greenhouse gas emissions. They include energy pricing strategies; changes in agricultural subsidies; provisions for accelerated depreciation and reduced costs for the consumer; tradable emissions permits; negotiated agreements with industry; utility demand-side management programs; regulatory programs, including minimum energy-efficiency standards; market pull and demonstration programs that stimulate the development and application of advanced technologies; and product labeling. The optimum mix of policies will vary from country to country; each nation needs to tailor its policies for local situations and develop them through consultation with those affected. Analysis of the historical experience of different countries with various policy instruments can provide guidance on their strengths and weaknesses.

- **Success is most likely if there are multiple benefits**. Actions to reduce greenhouse gas emissions appear more easily implemented when they are designed to address other concerns that impede sustainable development (e.g., air pollution, traffic congestion, soil erosion).
- **Commitment to further research is essential**. Developing technologies that will reduce greenhouse gas emissions and enhance greenhouse gas sinks—as well as understanding the barriers that inhibit their diffusion into the marketplace—requires a continuing commitment to research.

4.2. Energy, Industrial Process, and Human Settlement Emissions

The production, conversion, and end-use of fossil fuel energy results in significant atmospheric releases of greenhouse gases—in particular, CO_2 and CH_4. In the published literature, different methods and conventions are used to characterize energy consumption. These conventions differ, for example, according to their definition of sectors and their treatment of energy forms. Based on aggregated national energy balances, 385 EJ of primary energy was consumed in the world in 1990, resulting in the release of 6 Gt C as CO_2. Of this, 279 EJ was delivered to end users, accounting for 3.7 Gt of carbon emissions as CO_2 at the point of consumption. The remaining 106 EJ was used in energy conversion and distribution, accounting for 2.3 Gt C emissions as CO_2. In 1990, the three largest sectors of energy consumption were industry (45% of total CO_2 releases), residential/commercial (29%), and transport (21%). Of these, transport sector energy use and related CO_2 emissions have been the most rapidly growing over the past 2 decades. The combustion of fossil fuels ranks as the primary human-generated source of SO_2 (the sulfate aerosol precursor), as well as other air pollutants.

Global energy demand has grown at an average annual rate of approximately 2% for almost 2 centuries, although energy demand growth varies considerably over time and between different regions. During that time, the mix of fuels has changed dramatically (see Figure 6). Figure 7 depicts total energy-related emissions by major world region. The Organisation for Economic Cooperation and Development (OECD) nations have been and remain major energy users and fossil fuel CO_2 emitters, although their share of global fossil fuel carbon emissions has been declining. The contribution to global fossil fuel carbon emissions by the former Soviet Union and Eastern Europe (FSU/EE) has grown, although recent economic restructuring has reduced emissions. The diverse developing nations, taken as a group, still account for a smaller fraction of total global CO_2 emissions than industrialized nations (OECD and FSU/EE) due to their lower per capita emission rates (see Figure 8). Most projections indicate that with forecast rates of population and economic growth, the developing world will increase its share of CO_2 emissions as its standard of living increases and as population grows.

Oil and gas reserves worldwide contain approximately 200 Gt C and coal reserves about 600 Gt C. Estimates place remaining, ultimately recoverable, fossil fuel resources at some 4,000 Gt C, roughly three-quarters of it in coal and the rest in conventional and unconventional oil and gas. Atmospheric content totaled about 750 Gt C in 1990. Exhaustion of fossil resources therefore offers no near-term physical-barrier solution to the emissions of energy-related CO_2. The carbon-to-energy intensity ratio of different fossil fuels varies by a factor of almost two: Coal contains 25 Mt C/EJ; oil, 20 Mt C/EJ; and natural gas, 15 Mt C/EJ.Renewable energy sources are sufficiently abundant that they potentially could provide all of the world's energy needs foreseen over the next century. However, economics, technology development, and other practical constraints limit the rate at which the use of renewable energy can expand.

The prices of fuels and electricity influence energy use and fuel choice in all sectors. In many instances, prices do not reflect the full social costs of providing energy; subsidies and other

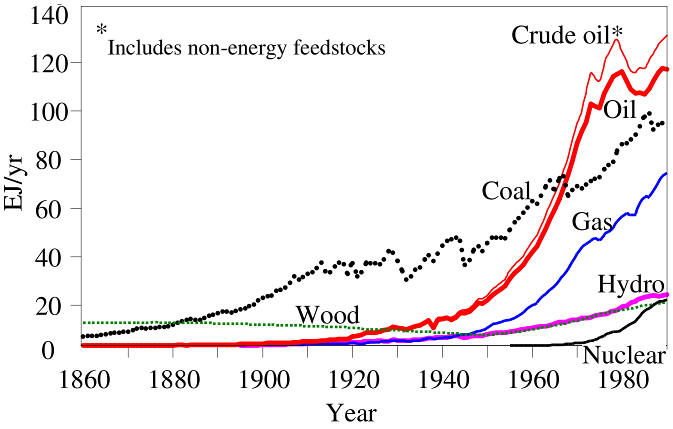


Figure 6: Global primary energy consumption by source, and total in EJ/yr (data for crude oil include non-energy feedstocks). Sources: BP, various volumes; IEA, 1993; Marchetti and Nakicenovic, 1979 (see the Energy Primer for complete citations).

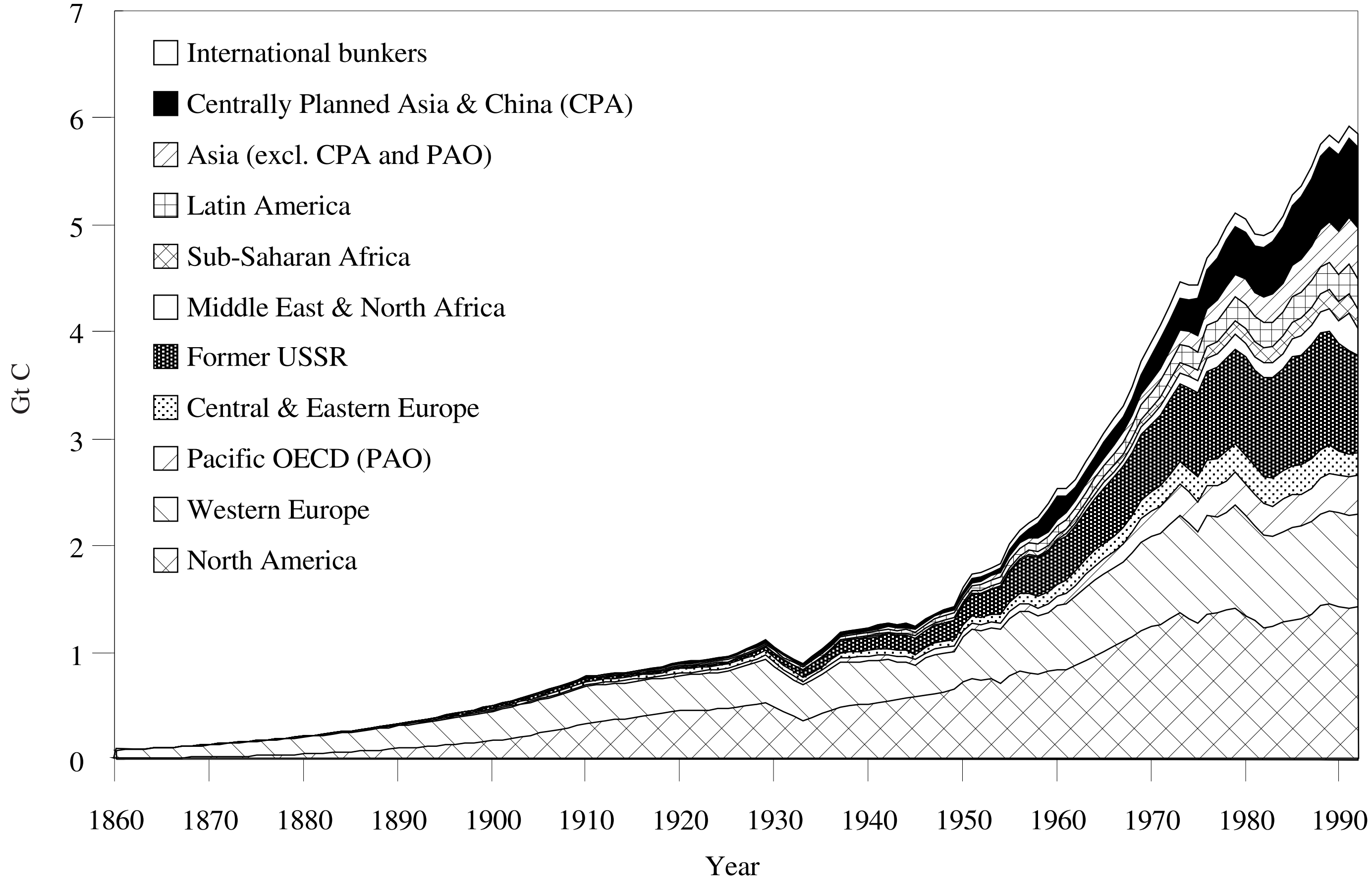


Figure 7: Global energy-related CO_2 emissions by major world region in Gt C/yr. Sources: Keeling, 1994; Marland *et al*., 1994; Grübler and Nakicenovic, 1992; Etemad and Luciani, 1991; Fujii, 1990; UN, 1952 (see the Energy Primer for complete citations).

interventions restrict the choices made by energy suppliers and users.Price rationalization, voluntary agreements, regulations, and information programs have successfully helped to accelerate the use of more energy-efficient technologies and practices in various areas of end-use, especially in the residential and transport sectors. These measures—when implemented as part of the normal replacement cycles of the world's energy supply infrastructure and energy-use equipment—offer the greatest potential to change the technology and systems now used.

4.2.1. Energy Demand

Numerous studies have indicated that 10–30% energy efficiency gains above present levels are feasible at little or no net cost in many parts of the world through technical conservation measures and improved management practices over the next 2 to 3 decades. Using technologies that presently yield the highest output of energy services for a given input of energy, efficiency gains of 50–60% would be technically feasible in many countries over the same time period. Achieving these potentials will depend on future cost reductions, financing, and technology transfer, as well as measures to overcome a variety of non-technical barriers. The potential for greenhouse gas emission reductions exceeds the potential for energy use efficiency because of the possibility of switching fuels and energy sources. Because energy use is growing world-wide, even replacing current technology with more-efficient technology could still lead to an absolute increase in CO_2 emissions in the future.

In 1992, the IPCC produced six scenarios (IS92a-f) of future energy use and associated greenhouse gas emissions. These scenarios provide a wide range of possible future greenhouse gas emission levels, without mitigation measures. In the Second Assessment Report, future energy use has been reexamined on a more detailed sectoral basis, both with and without new mitigation measures, based on existing studies. Despite different assessment approaches, the resulting ranges of energy consumption increases to 2025 without new measures are broadly consistent with those of IS92. If past trends continue, greenhouse gas emissions will grow more slowly than energy use, except in the transport sector.

The following paragraphs summarize energy efficiency improvement potentials estimated in the IPCC Second Assessment Report. Strong policy measures would be required to achieve these potentials. Energy-related greenhouse gas emission reductions depend on the source of the energy, but

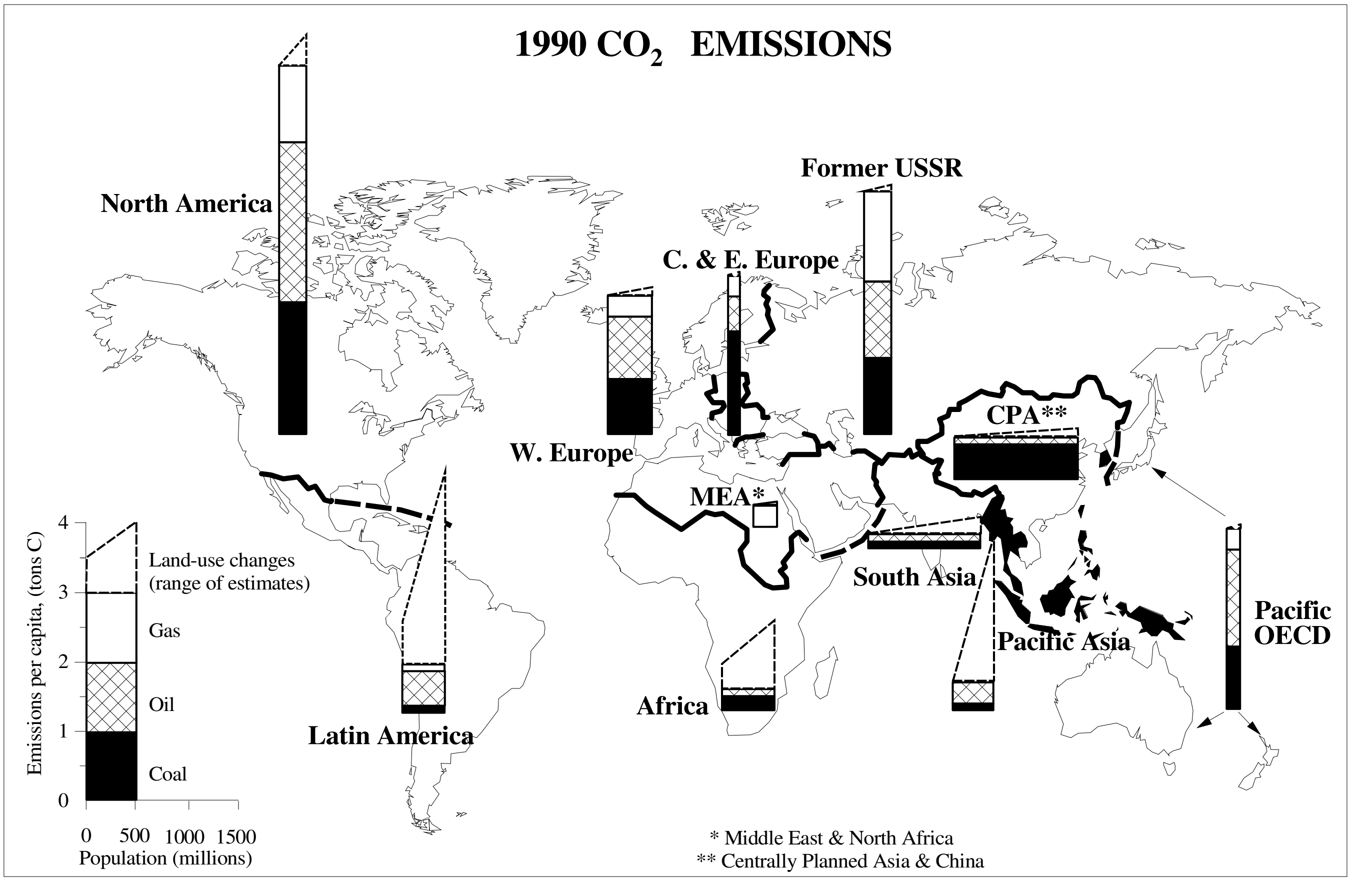


Figure 8: 1990 per capita CO_2 emissions by region and source, fossil fuels, and range for biota sources (includes sustainable use of biomass that does not contribute to atmospheric concentration increase). Sources: IEA, 1993; Marland *et al.*, 1994; Nakicenovic *et al.*, 1993; Subak *et al.*, 1993; IPCC, 1990, 1992; Bos *et al.*, 1992; Houghton *et al.*, 1987 (see the Energy Primer for complete citations).

reductions in energy use will, in general, lead to reduced greenhouse gas emissions.

4.2.1.1. Emissions mitigation in industry

Energy use in 1990 is estimated to be 98–117 EJ, and is projected to grow to 140–242 EJ in 2025 without new measures. Developing countries now account for only about one-quarter of global industrial final energy use, but projections put their share of industrial energy demand growth over the next century at more than 90%.

A few basic processes, including the production of iron and steel, chemicals, building materials, and food, account for more than half of all energy use in the industrial sector. Industry has reduced energy intensity impressively over the past 2 decades. In some countries, improvements in energy efficiency have permitted major increases in production with little or no increase in energy use. In contrast to the industrial emissions of developing countries, which continue to increase as their economies grow, developed countries' industrial-sector emissions have stabilized or declined during the past 2 decades. Even the former Soviet Union's industrial emissions have remained stable for a decade. These changes have occurred without any climate policies in place and essentially have arisen from a combination of economic restructuring, shedding of some energy-intensive industries, and gains in the energy efficiency of industrial processes. These developments have combined to decrease overall primary energy intensity (see Figure 9), resulting in stabilized or decreased CO_2 emissions in many industrialized countries (see Figure 10). Because each nation has a unique set of resources, labor, and capital that will influence its development path, this historical perspective does not suggest a particular outcome for developing countries. It does imply that the relationship between CO_2 emissions and GDP is unlikely to retain its present course, given the technological opportunities currently available.

Opportunities now exist to use advanced technologies to reduce emissions significantly in each of the major energy-consuming industries. The short-term potential for energy-efficiency improvements in the manufacturing sector of major industrial nations is around 25%. The potential for greenhouse gas emission reductions is larger. The application of available, highly efficient technologies and practices could significantly reduce industrial energy demand growth.

Efficient use of materials can lower industrial greenhouse gas emissions, and recycling materials can reduce energy

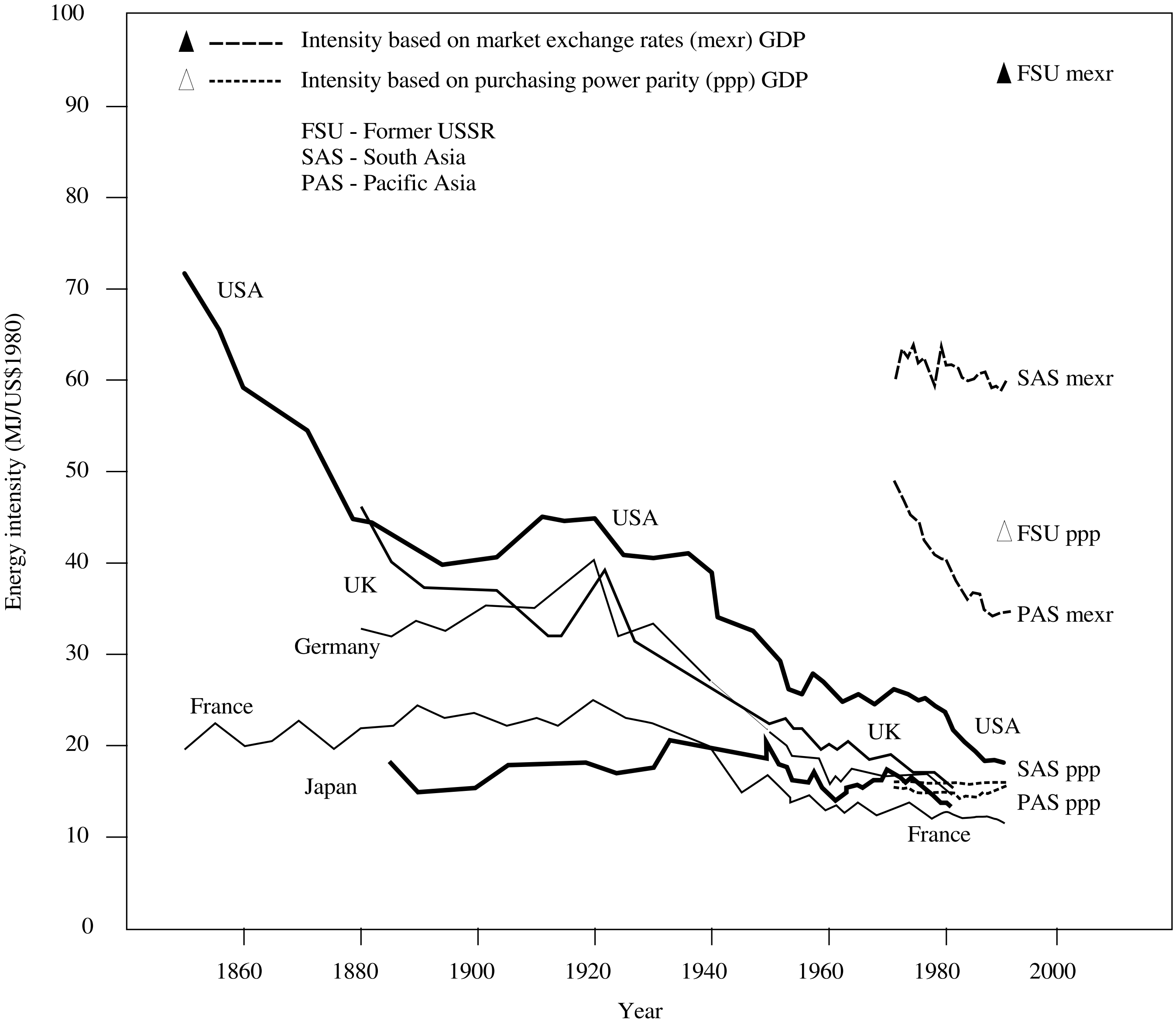


Figure 9: Primary energy intensity (including wood and biomass) of value added in MJ per constant GDP in 1980 dollars [at market exchange rates (mexr) and purchasing power parities (ppp)]. The countries shown account for approximately 80% of energy-related CO_2 emissions. Source: Grübler, 1991 (see the Energy Primer for a complete citation).

requirements and energy-related emissions substantially (see Figure 11). Recycling iron and steel scrap, for example, could cut the energy required per ton of steel produced to half the current level even in Japan, the world's most efficient steel-producing nation. Not all steel scrap is recyclable, however, so recycling provides no panacea. Using less energy-intensive materials offers another option—for example, substituting wood for concrete and other materials as possible.

Some technologies—such as electric motor drives, heating, and evaporation—are used across many industries, thus offering large opportunities for energy savings. Electric motor drives, for example, use more than half of all electricity in the industrial sector in many developing countries, including China and Brazil. Investments in motor-speed controls and more efficient motor components can reduce electricity use in industrial motor applications, with an internal rate of return on investment of 30 to 50%.

Integrating industrial and residential-commercial energy use by establishing energy-management systems that utilize an "energy cascade" presents promising opportunities for increased efficiency—especially in newly industrialized nations, where a systematic approach to efficiency improvements is particularly important. An energy cascade uses successively lower temperature industrial waste heat in a variety of other industrial, residential, and commercial district heating and cooling applications.

Limiting industrial emissions of CO_2 and other greenhouse gases, such as halocarbons, CH_4, and N_2O associated with industrial processes, can also play an important role.

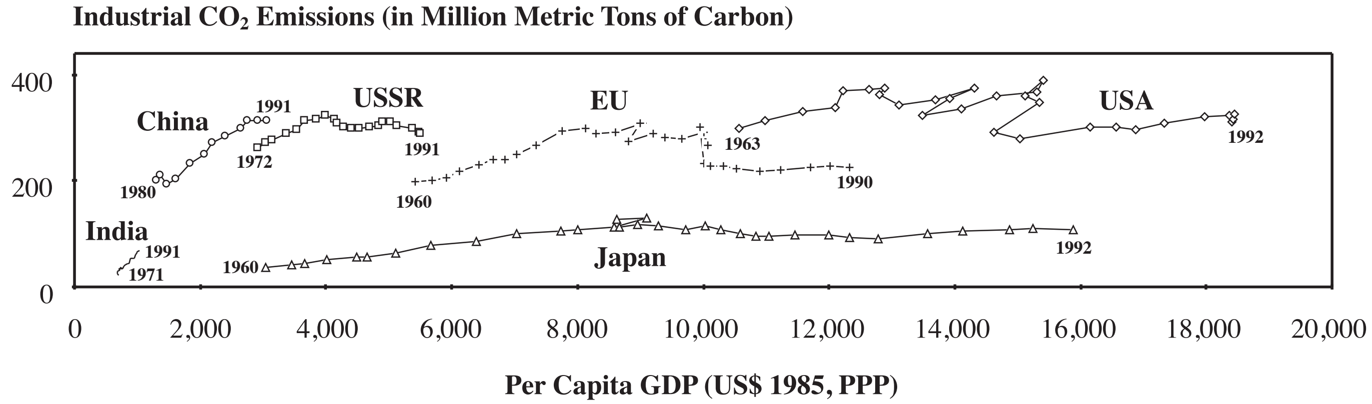


Figure 10: Fossil fuel CO_2 development path for the industrial sectors of the United States, the 15 nations that now comprise the European Union (less the former East Germany), Japan, China, India, and the former Soviet Union. The industrial sector is as defined by OECD, plus CO_2 associated with refineries and the fraction of electricity that is used by industry. The CO_2 values are from OECD (1994), and the ppp values are from Sommers and Heston (1991, 1994); see Chapter 20 for complete citations.

Identifying all the benefits, costs, and potentials for reducing both process and energy greenhouse gases in the industrial sector requires an examination of all aspects of resource use. Developing the capability to carry out full “industrial ecology” analyses represents a major research need.

Implementing more energy-efficient industrial technologies will depend on many factors. Chief among them are financing, energy and materials pricing, market imperfections, research and development, and the extent to which technology transfer occurs from developed countries to developing nations and those with economies in transition.

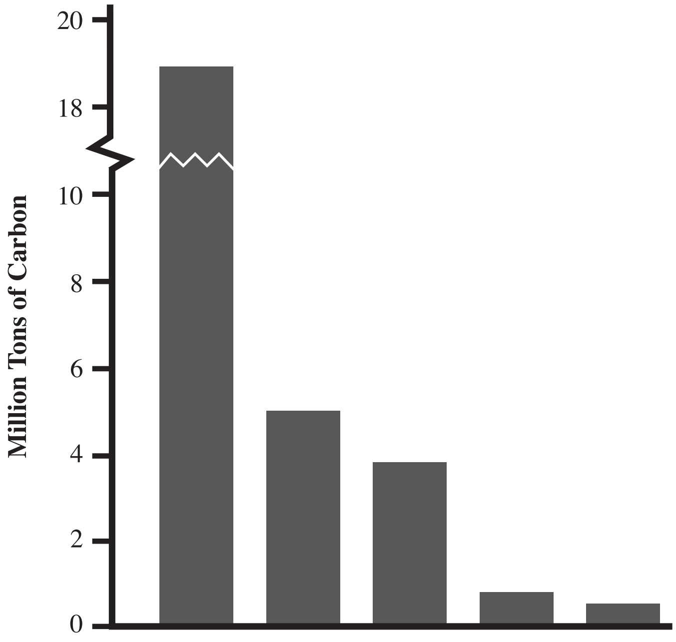


Figure 11: Tons of carbon avoided by OECD countries by increasing recycling by 10%—from *Long-Term Strategies for Mitigating Global Warming* (IIASA, 1993).

4.2.1.2. Emissions mitigation in transportation

Transport energy use in 1990 is estimated to be 61–65 EJ, and is projected to grow to 90–140 EJ in 2025 without new measures (see Figure 12). Energy use by cars, aircraft, and heavy trucks is growing particularly rapidly. Although industrialized countries account for about 75% of current energy use and greenhouse gas emissions from this sector, the greatest growth is expected in developing countries and transition economies. By 2025, these countries could generate the majority of transport-related emissions.

Transportation energy demand historically has been linked closely to GDP growth, although there is also a strong negative correlation with fuel prices (see Figures 13 and 14). However, projected energy use in 2025 could be reduced by about a third to 60–100 EJ through vehicles using very efficient drive-trains, light-weight construction and low-air-resistance design, without compromising comfort and performance. Further energy-use reductions are possible through the use of smaller vehicles; altered land-use patterns, transport systems, mobility patterns, and lifestyles; and shifting to less energy-intensive transport modes. Greenhouse gas emissions per unit of energy used could be reduced through the use of alternative fuels and electricity from renewable sources. These measures, taken together, provide the opportunity for reducing global transport emissions by as much as 40% of projected emissions by 2025. Actions to reduce greenhouse gas emissions from transport can simultaneously address other problems, such as local air pollution.

Realizing these opportunities seems unlikely, however, without new policies and measures in many countries. We have learned much already about the effective use of policies, such as fuel and vehicle taxes and fuel-economy standards, to encourage energy-efficiency improvements. Yet developing cheap, light-weight, recyclable materials and advanced propulsion and vehicle-control systems will require continued research. Policies that affect traffic volume also play an important role. These include road tolls, restriction of car access and parking

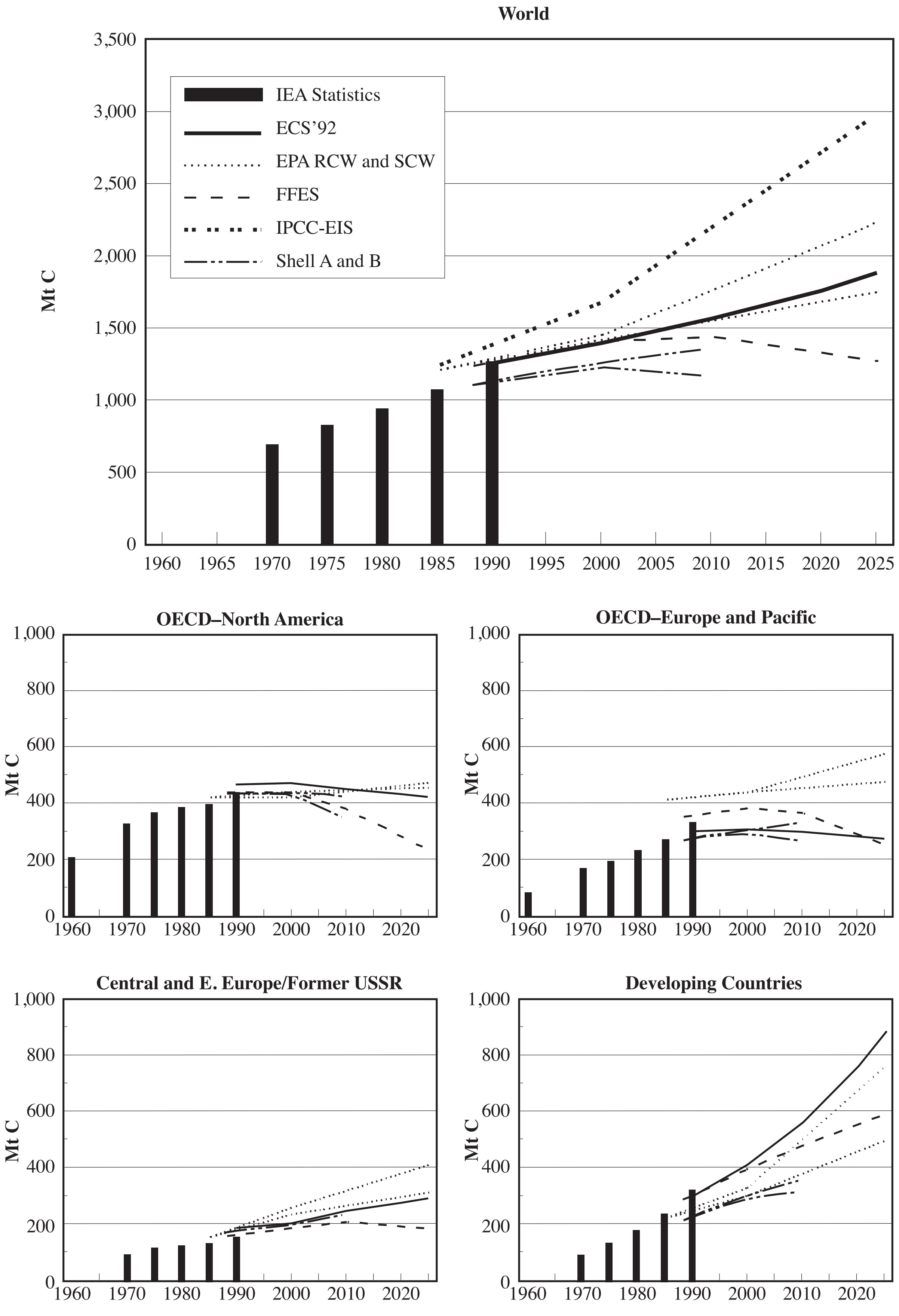


Figure 12: Comparison of transport CO_2 emission scenarios to 2025 (Grübler, 1993). Note: IEA = International Energy Agency; ECS = Environmentally Compatible Energy Strategies; RCW = Rapidly Changing World and SCW = Slowly Changing World; FFES = Fossil-Free Energy System; and EIS = Energy Industry System.

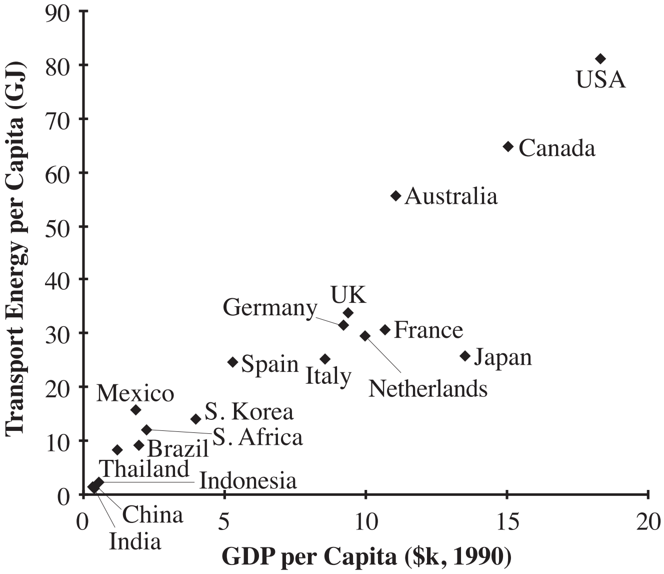


Figure 13: Total transport energy use vs. gross domestic product in 1990, for 18 of the world's largest transport energy users. Excludes Russia, Ukraine, Iran, Saudi Arabia, and Kazakhstan; former West and East Germany data have been combined. Sources: IEA, 1993c, 1993d (see Chapter 21 for complete citations).

in town centers, and the provision of infrastructure for nonmotorized transport in town centers. Several cities in Latin America, Southeast Asia, and Europe have succeeded in stemming growth in car use by employing combined strategies.

Transport plays an increasingly important social and economic role, and measures to reduce emissions may fail if people perceive them as compromising this role. Success in reducing carbon emissions will require integrated approaches and probably will depend on simultaneously addressing other problems such as congestion and air pollution [including emissions of particulates, and of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) that are precursors to tropospheric ozone].

4.2.1.3. *Emissions mitigation in the commercial/residential sector*

Activities in this sector currently account for just over 40% of energy use. Figure 15 shows historical carbon emissions from the developing world, industrialized countries, and the FSU/EE resulting from energy use in the residential and commercial sectors in 1973, 1983, and 1990. Energy use in 1990 is estimated to be 100 EJ, and is projected to grow to 165–205 EJ in 2025 without new measures. Although industrialized countries currently release about 60% of associated emissions, developing countries and the FSU/EE could account for 80% of all growth in building emissions during the next century.

Projected energy use could be reduced by about a quarter to 126–170 EJ by 2025 without diminishing services through the use of energy efficient technology. The potential for greenhouse gas emission reductions is larger. Technical changes might include more efficient space-conditioning and water-supply systems; reducing heat losses through building structures; more efficient lighting; more efficient appliances; and more efficient computers and supporting equipment. In addition, measures to counter trends toward higher ambient temperatures in urban areas (through increased vegetation, greater reflectivity of roofing and siding materials, and better architectural design) can yield significant reductions in the energy required for heating and air conditioning.

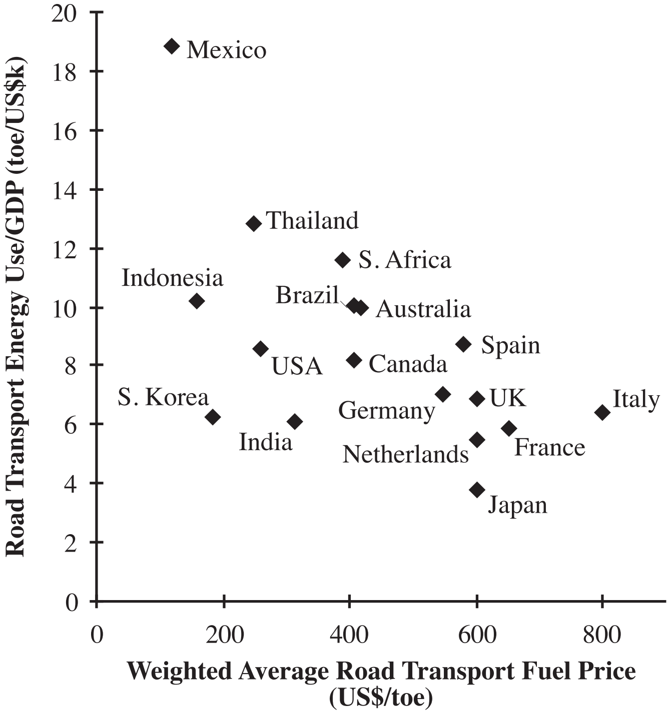


Figure 14: Road transport energy per unit of GDP vs. average fuel price in 1990, for 17 of the world's 20 largest transport energy users. Excludes China, Russia, and Ukraine; former West and East Germany data have been combined. Sources: IEA, 1993c, 1993d, 1994a; ADB, 1994 (see Chapter 21 for complete citations).

This assessment suggests that three types of activities could significantly reduce the growth of building-related emissions:

- Support for energy-efficiency policies, including pricing strategies; individual, meter-based billing for energy use in multiple-family dwellings; regulatory programs including minimum energy-efficiency standards for buildings and appliances; utility demand-side management programs; and market pull and demonstration programs that stimulate the development and application of advanced technologies
- Enhanced research and development in energy efficiency
- Enhanced training and added support for financing efficiency programs in all countries, but especially in developing countries and transition economies.

Many energy-efficiency policies, information/education measures, and research and development programs—carried out primarily in industrialized countries—have achieved significant reductions in energy use. Although the technical and economic potential for further efficiency improvements is high, effective implementation requires well-designed combinations of financial incentives and other government policies. Strategies to reduce emissions likely will prove more effective if they use well-integrated mixes of policies, tailored for local situations and developed through consultation with and participation by those most affected.

4.2.2. Mitigating Industrial Process and Human Settlement Emissions

Process-related greenhouse gases—including CO_2, CH_4, N_2O, halocarbons, and SF_6—are released during manufacturing and industrial processes, such as the production of iron, steel, aluminium, ammonia, cement, and other materials. Large reductions are possible in some cases. Measures include modifying production processes, eliminating solvents, replacing feedstocks or materials substitution, increased recycling, and reduced consumption of greenhouse gas-intensive materials. Capturing and utilizing CH_4 from landfills and sewage treatment facilities, and lowering the leakage rate of halocarbon refrigerants from mobile and stationary sources can also lead to significant greenhouse gas emission reductions.

4.2.3. Energy Supply

This assessment focuses on new technologies for capital investment and not on potential retrofitting of existing capital stock to use less carbon-intensive forms of primary energy. It is technically possible to realize deep emissions reductions in the energy supply sector in step with the normal timing of investments to replace infrastructure and equipment as it wears out or becomes obsolete. Many options for achieving deep reductions will also decrease the emissions of SO_2, NO_x, and VOCs. Promising approaches, not ordered according to priority, include the following:

- **Greenhouse gas reductions in the use of fossil fuels**
  - *More-efficient conversion of fossil fuels*. New technology offers considerably increased conversion efficiencies. For example, the efficiency of power production can be increased from the present world average of about 30% to more than 60% in the longer term. Also, the use of combined heat and power production replacing separate production of power and heat—whether for process heat or space heating—offers a significant rise in fuel conversion efficiency.
  - *Switching to low-carbon fossil fuels and suppressing emissions*. Switching from coal to oil or natural gas, and from oil to natural gas, can reduce emissions. Natural gas has the lowest CO_2 emissions per unit of energy of all fossil fuels at about 14 kg C/GJ, compared to oil with about 20 kg C/GJ, and coal with about 25 kg C/GJ. The lower carbon-containing fuels can, in general, be converted with higher efficiency than coal. Large resources of natural gas exist in many areas. New, low-capital-cost, highly efficient, combined-cycle

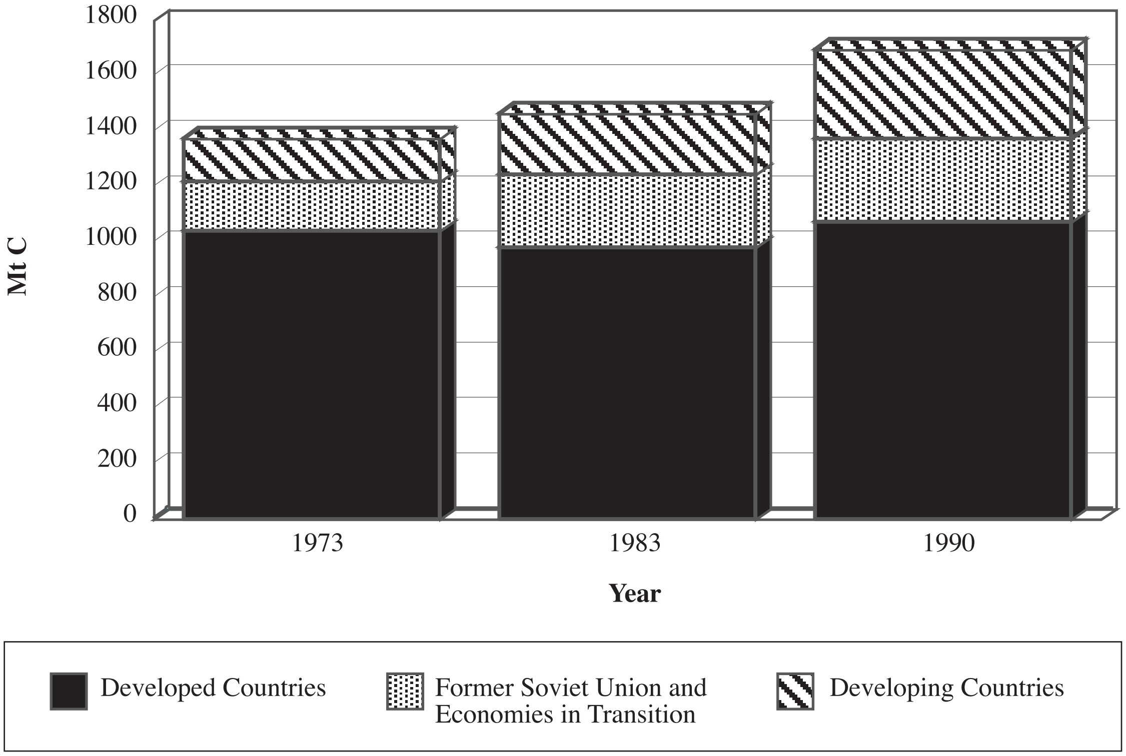


Figure 15: Historical carbon emissions resulting from energy use in the residential and commercial sectors.

  technology has reduced electricity costs considerably in some areas. Natural gas could potentially replace oil in the transportation sector. Approaches exist to reduce emissions of CH_4 from natural gas pipelines and emissions of CH_4 and/or CO_2 from oil and gas wells and coal mines.
  - *Decarbonization of flue gases and fuels and CO_2 storage*. The removal and storage of CO_2 from fossil fuel power-station stack gases is feasible, but reduces the conversion efficiency and significantly increases the production cost of electricity. Another approach to decarbonization uses fossil fuel feedstocks to make hydrogen-rich fuels. Both approaches generate a byproduct stream of CO_2 that could be stored, for example, in depleted natural gas fields. The future availability of conversion technologies such as fuel cells that can efficiently use hydrogen would increase the relative attractiveness of the latter approach. For some longer term CO_2 storage options, cost, environmental effects, and efficacy remain largely unknown.
- **Switching to non-fossil fuel sources of energy**
  - *Switching to nuclear energy*. Nuclear energy could replace baseload fossil fuel electricity generation in many parts of the world if generally acceptable responses can be found to concerns such as reactor safety, radioactive-waste transport and disposal, and nuclear proliferation.
  - *Switching to renewable sources of energy*. Solar, biomass, wind, hydro, and geothermal technologies already are widely used. In 1990, renewable sources of energy contributed about 20% of the world's primary energy consumption, most of it fuelwood and hydropower. Technological advances offer new opportunities and declining costs for energy from these sources. In the longer term, renewable sources of energy could meet a major part of the world's demand for energy. Power systems can easily accommodate limited fractions of intermittent generation and, with the addition of fast-responding backup and storage units, also higher fractions. Where biomass is sustainably regrown and used to displace fossil fuels in energy production, net carbon emissions are avoided as the CO_2 released in converting the biomass to energy is again fixed in biomass through photosynthesis. If the development of biomass energy can be carried out in ways that effectively address concerns about other environmental issues and competition with other land uses, biomass could make major contributions in both the electricity and fuels markets, as well as offering prospects of increased rural employment and income.

Future emissions will depend on the nature of the technologies nations choose as they expand and replace existing energy systems.

4.2.4. *Integration of Energy System Mitigation Options*

To assess the potential impact of combinations of individual measures at the energy system level, in contrast to the level of individual technologies, variants of a low CO_2-emitting energy supply system (LESS) are described. The LESS constructions are "thought experiments," exploring possible global energy systems.

The following assumptions were made: World population grows from 5.3 billion in 1990 to 9.5 billion by 2050 and 10.5 billion by 2100. GDP grows 7-fold by 2050 (5-fold and 14-fold in industrialized and developing countries, respectively) and 25-fold by 2100 (13-fold and 70-fold in industrialized and developing countries, respectively), relative to 1990. Because of emphasis on energy efficiency, primary energy consumption rises much more slowly than GDP. The energy supply constructions were made to meet energy demand in (i) projections developed for the IPCC's First Assessment Report in a low energy demand variant, where global primary commercial energy use approximately doubles, with no net change for industrialized countries but a 4.4-fold increase for developing countries from 1990 to 2100; and (ii) a higher energy demand variant, developed in the IPCC IS92a scenario where energy demand quadruples from 1990 to 2100. The energy demand levels of the LESS constructions are consistent with the energy demand mitigation chapters of this Second Assessment Report.

Figure 16 shows combinations of different energy sources to meet changing levels of demand over the next century. The analysis of these variants leads to the following conclusions:

- Deep reductions of CO_2 emissions from energy supply systems are technically possible within 50 to 100 years, using alternative strategies.
- Many combinations of the options identified in this assessment could reduce global CO_2 emissions from fossil fuels from about 6 Gt C in 1990 to about 4 Gt C per year by 2050, and to about 2 Gt C per year by 2100 (see Figure 17). Cumulative CO_2 emissions, from 1990 to 2100, would range from about 450 to about 470 Gt C in the alternative LESS constructions.
- Higher energy efficiency is underscored for achieving deep reductions in CO_2 emissions, for increasing the flexibility of supply-side combinations, and for reducing overall energy system costs.
- Interregional trade in energy grows in the LESS constructions compared to today's levels, expanding sustainable development options for Africa, Latin America, and the Middle East during the next century.

Costs for energy services in each LESS variant relative to costs for conventional energy depend on relative future energy prices, which are uncertain within a wide range, and on the performance and cost characteristics assumed for alternative technologies. However, within the wide range of future energy prices, one or more of the variants would plausibly be capable of providing the demanded energy services at estimated costs

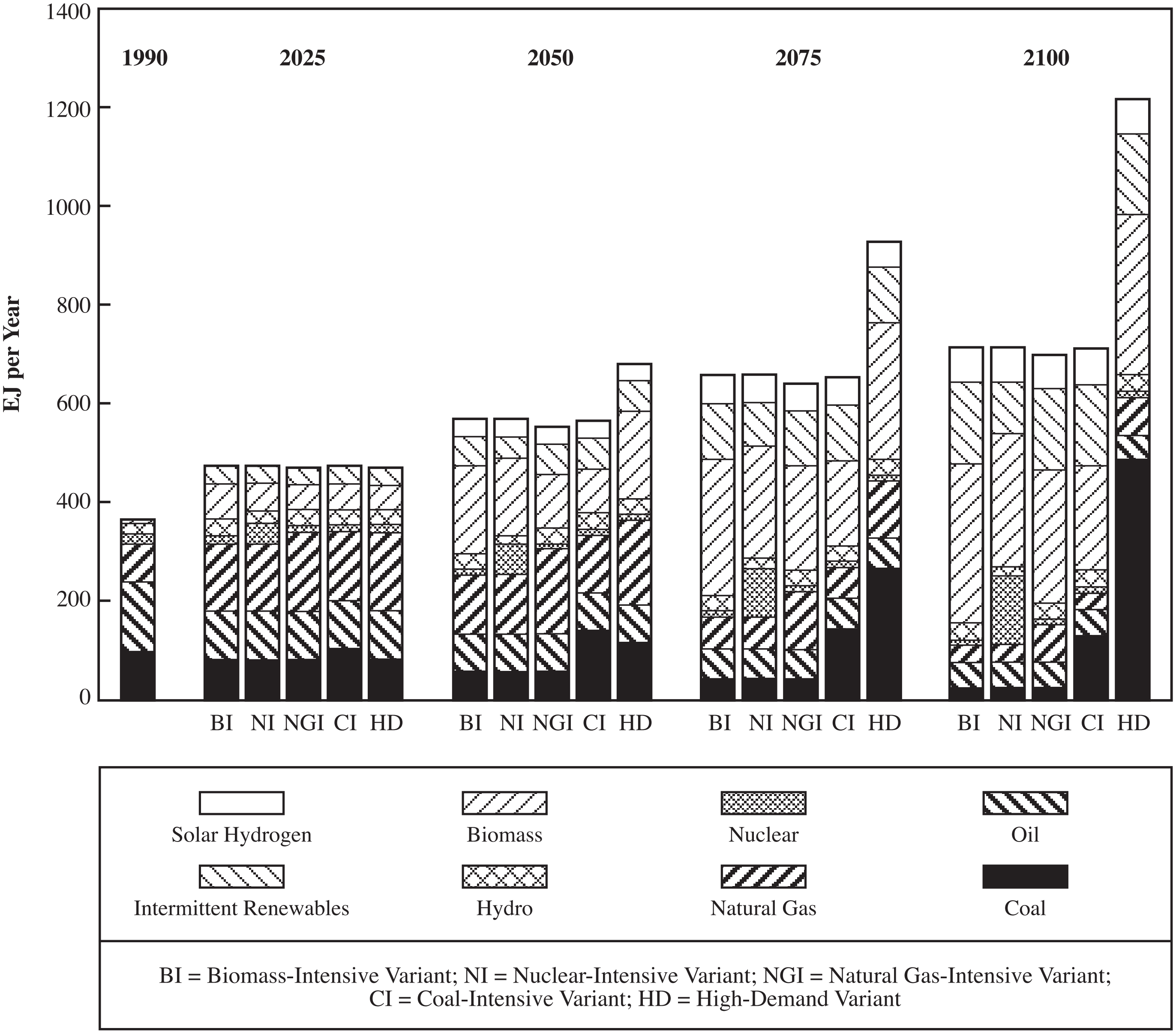


Figure 16: Global primary energy use for alternative Low CO_2-Emitting Energy Supply System (LESS) constructions: Alternatives for meeting different energy demand levels over time, using various fuel mixes.

that are approximately the same as estimated future costs for current conventional energy. It is not possible to identify a least-cost future energy system for the longer term, as the relative costs of options depend on resource constraints and technological opportunities that are imperfectly known, and on actions by governments and the private sector.

The literature provides strong support for the feasibility of achieving the performance and cost characteristics assumed for energy technologies in the LESS constructions, within the next 2 decades, though it is impossible to be certain until the research and development is complete, and the technologies have been tested in the market. Moreover, these performance and cost characteristics cannot be achieved without a strong and sustained investment in research, development, and demonstration. Many of the technologies being developed would need initial support to enter the market, and to reach sufficient volume to lower costs to become competitive.

Market penetration and continued acceptability of different energy technologies ultimately depends on their relative cost, performance (including environmental performance), institutional arrangements, and regulations and policies. Because costs vary by location and application, the wide variety of circumstances creates initial opportunities for new technologies to enter the market. Deeper understanding of the opportunities for emissions reductions would require more detailed analysis of options, taking into account local conditions.

Because of the large number of options, there is flexibility as to how the energy supply system could evolve, and paths of energy system development could be influenced by considerations

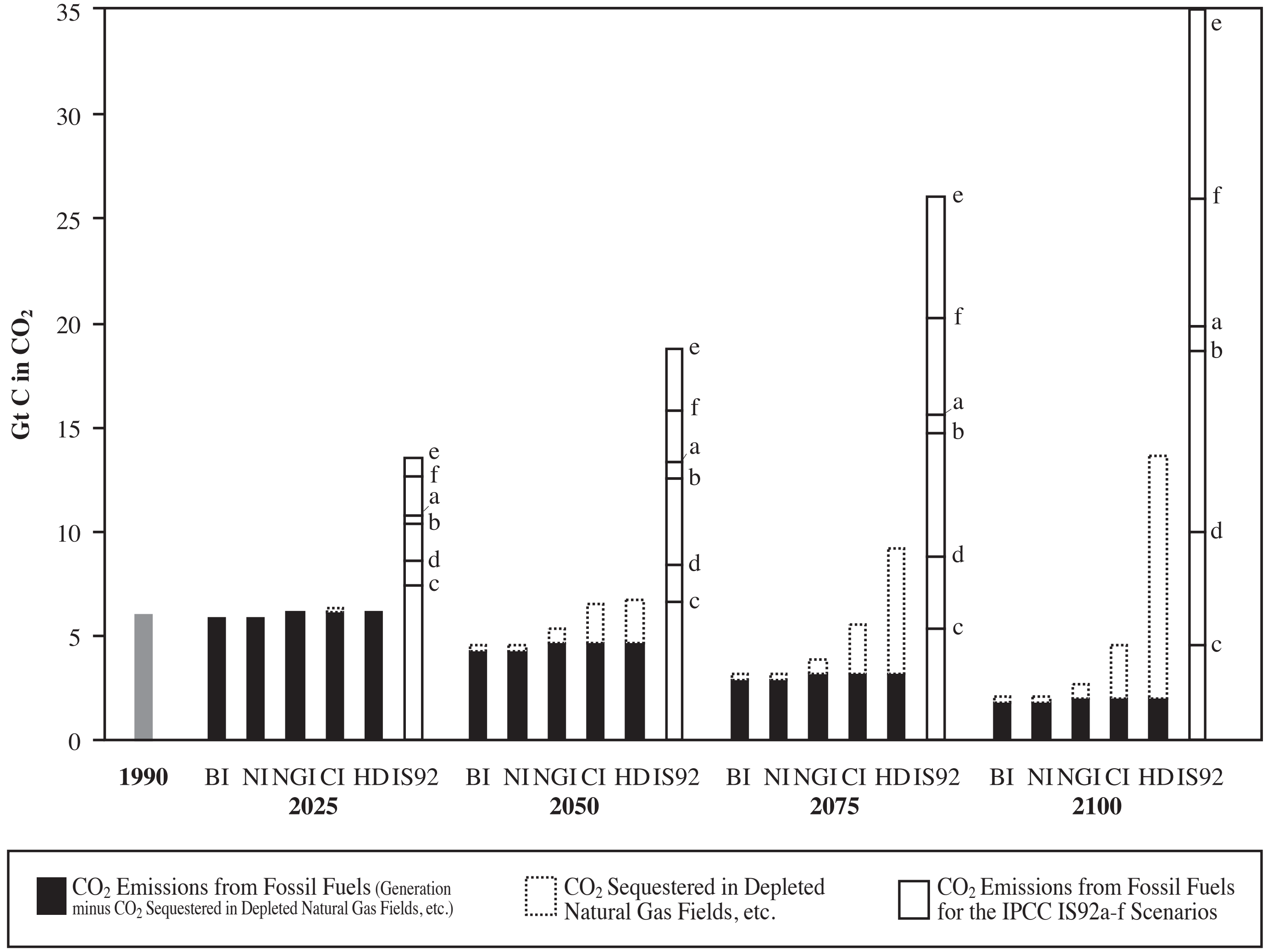


Figure 17: Annual CO_2 emissions from fossil fuels for alternative LESS constructions, with comparison to the IPCC IS92a-f scenarios (see Figure 16 for acronym definitions).

other than climate change, including political, environmental (especially indoor and urban air pollution, acidification, and land restoration) and socioeconomic circumstances.

4.3. Agriculture, Rangelands, and Forestry

Management of agricultural lands, rangelands, and forests can play an important role in reducing current emissions and/or enhancing the sinks of CO_2, CH_4, and N_2O. Measures to reduce emissions and sequester atmospheric carbon include slowing deforestation, enhancing natural forest generation, establishing tree plantations, promoting agroforestry, altering management of agricultural soils and rangelands, restoring degraded agricultural lands and rangelands, and improving the diet of ruminants. Although these are demonstrated, effective measures, a number of important uncertainties linger regarding their global potential to reduce emissions or sequester carbon. The net amount of carbon per unit area conserved or sequestered in living biomass under a particular forest-management practice and present climate is relatively well-understood. The most important uncertainties associated with estimating a global value are (i) the amount of land suitable and available for forestation, regeneration, and/or restoration programs; (ii) the rate at which tropical deforestation can actually be reduced; (iii) the long-term use (security) of these lands; and (iv) the continued suitability of some practices for particular locations given the possibility of changes in temperature, water availability, and so forth under climate change. Management options vary by country, social system, and ecosystem type.

Proposed options for conserving and sequestering carbon and reducing other greenhouse gas emissions in the forestry and agriculture sectors are consistent with other objectives of land management—such as sustainable development, industrial wood and fuelwood production, traditional forest uses, protection of other natural resources (e.g., biodiversity, soil, water), recreation, and increasing agricultural productivity.

4.3.1. Carbon Dioxide

Since the 1990 IPCC assessment, significant new information has emerged concerning the potential of forests to conserve and sequester carbon, as well as the costs of forestry programs to promote this carbon storage. Biomass for the production of electricity or liquid fuels, continuously harvested and regrown in a sustainable manner, would avoid the release of fossil carbon. In the long run, this would offer a more efficient strategy than one based on carbon storage in vegetation and soils, which would saturate with time. The development of this mitigation option will depend critically upon the competitiveness of biomass. However, managing forests to conserve and increase carbon storage offers an effective mitigation option during the transition period of many decades necessary to stabilize atmospheric concentrations of carbon.

In the forestry sector, assuming the present climate and no change in the estimated area of available lands, the cumulative amount of carbon that could feasibly be conserved and sequestered through establishment of plantations and agroforestry, forest regeneration, sustaining existing forest cover, and slowing deforestation over the period 1995–2050 ranges between 60 and 90 Gt C. The literature indicates that the tropics have the potential to conserve and sequester the largest quantity of carbon (80% of the global total in the forestry sector), with more than half due to promoting forest regeneration and slowing deforestation. Tropical America has the largest potential for carbon conservation and sequestration (46% of tropical total), followed by tropical Asia (34%) and tropical Africa (20%). The temperate and boreal zones could sequester about 20% of the global total, mainly in the United States, temperate Asia, the former Soviet Union, China, and New Zealand. Altering the climate and land-use assumptions—for example, by increasing demand for agricultural land in the tropics or accounting for potential consequences of climate change—would reduce these estimates significantly.

Estimates of the full costs of conserving or sequestering carbon in forests should include land values as well as capital, infrastructure, and other costs. However, many of these costs are particularly difficult to generalize given the amenity value of forests, their importance in traditional economies, and their significance in maintaining regional environments and biodiversity. Costs for conserving and sequestering carbon in biomass and soil are estimated to range widely, but can be competitive with other mitigation options. Factors affecting costs include opportunity costs of land, initial costs of planting and establisment, costs of nurseries, the cost of annual maintenance and monitoring, and transaction costs. Direct and indirect benefits will vary with national circumstances and could offset the costs. Additional amounts of carbon could be sequestered in agricultural and rangeland soils over a 50-year period by improved management practices, although less is currently known about the global potential in this sector.

4.3.2. Methane and Nitrous Oxide

Nations can achieve significant decreases in CH_4 emissions from agriculture through improved nutrition of ruminant animals and better management of rice paddies (e.g., irrigation, nutrients, new cultivars). Altering the treatment and management of animal wastes and reducing agricultural biomass burning also will decrease CH_4 releases. Combining these practices could reduce CH_4 emissions from agriculture by 25 to 100 Mt/yr. Agricultural sources of N_2O include mineral fertilizers, legume cropping, animal waste, and biomass burning. Using presently available techniques to improve the efficiency of fertilizer and manure could reduce agricultural emissions by 0.3 to 0.9 Mt of nitrogen per year.

4.4. Cross-Sectoral Issues

Cross-sectoral assessment of different combinations of mitigation options focuses on the interactions of the full range of technologies and practices that are potentially capable of reducing emissions of greenhouse gases or sequestering carbon. Current analysis suggests the following:

- *Competing uses of land, water, and other natural resources*. A growing population and expanding economy will increase the demand for land and other natural resources needed to provide, *inter alia*, food, fiber, forest products, and recreation services. Climate change will interact with the resulting intensified patterns of resource use. Land and other resources could also be required for mitigation of greenhouse gas emissions. Agricultural productivity improvements throughout the world and especially in developing countries would increase availability of land for production of biomass energy.
- *Geoengineering options*. Some geoengineering approaches to counterbalance greenhouse-induced climate change have been suggested (e.g., putting solar radiation reflectors in space, or injecting sulfate aerosols into the atmosphere to mimic the cooling influence of volcanic eruptions). Such approaches generally are likely to be ineffective, expensive to sustain, and/or to have serious environmental and other effects which are in many cases poorly understood.

4.5. Policy Instruments

Mitigation depends on reducing barriers to the diffusion and transfer of technology, mobilizing financial resources, supporting capacity building in developing countries, and other approaches to assist in the implementation of behavioral changes and technological opportunities in all regions of the globe. The optimum mix of policies will vary from country to country, depending upon political structure and societal receptiveness. The leadership of national governments in applying these policies will contribute to responding to adverse consequences of climate change. Governments can choose policies that facilitate the penetration of less greenhouse gas-intensive technologies and modified consumption patterns. Indeed, many countries have extensive experience with a variety of policies that can accelerate the adoption of such technologies.

This experience comes from efforts over the past 20 to 30 years to achieve improved energy efficiency, to reduce the environmental impacts of agricultural policies, and to meet conservation and environmental goals unrelated to climate change. Policies to reduce net greenhouse gas emissions appear more easily implemented when they are designed to address other concerns that impede sustainable development (e.g., air pollution and soil erosion). A number of policies, some of which may need regional or international agreement, can facilitate the penetration of less greenhouse gas-intensive technologies and modified consumption patterns, including:

- Putting in place appropriate institutional and structural frameworks
- Energy pricing strategies (e.g., carbon or energy taxes, and reduced energy subsidies)
- Reducing or removing other subsidies (e.g., agricultural and transport subsidies that increase greenhouse gas emissions)
- Tradable emissions permits
- Voluntary programs and negotiated agreements with industry
- Utility demand-side management programs
- Regulatory programs including minimum energy-efficiency standards, such as for appliances and fuel economy
- Stimulating research, development, and demonstration to make new technologies available
- Market pull and demonstration programs that stimulate the development and application of advanced technologies
- Renewable energy incentives during market build-up
- Incentives such as provisions for accelerated depreciation and reduced costs for consumers
- Education and training; information and advisory measures
- Options that also support other economic and environmental goals.

Accelerated development of technologies that will reduce greenhouse gas emissions and enhance greenhouse gas sinks—as well as understanding the barriers that inhibit their diffusion into the marketplace—requires intensified research and development by governments and the private sector.

5. Technical Guidelines for Assessing Climate Change Impacts and Adaptations

Working Group II has prepared guidelines to assess the impacts of potential climate change and to evaluate appropriate adaptations. They reflect current knowledge and will be updated as improved methodologies are developed. The guidelines outline a study framework that will allow comparable assessments to be made of impacts and adaptations in different regions/geographical areas, economic sectors, and countries. They are intended to help contracting parties meet, in part, their commitments under Article 4 of the UNFCCC.

Impact and adaptation assessments involve several steps:

- Definition of the problem
- Selection of the methods
- Testing the method
- Selection of scenarios
- Assessment of biophysical and socioeconomic impacts
- Assessment of autonomous adjustments
- Evaluation of adaptation strategies.

Definition of the problem includes identifying the specific goals of the assessment, the ecosystem(s), economic sector(s), and geographical area(s) of interest, the time horizon(s) of the study, the data needs, and the wider context of the work.

The selection of analytical methods(s) depends upon the availability of resources, models, and data. Impact assessment analyses can range from the qualitative and descriptive to the quantitative and prognostic.

Testing the method(s), including model validation and sensitivity studies, before undertaking the full assessment is necessary to ensure credibility.

Development of the scenarios requires, firstly, the projection of conditions expected to exist over the study period in the absence of climate change and, secondly, the projection of conditions associated with possible future changes in climate.

Assessment of potential impacts on the sector(s) or area(s) of interest involves estimating the differences in environmental and socioeconomic conditions projected to occur with and without climate change.

Assessment of autonomous adjustments implies the analysis of responses to climate change that generally occur in an automatic or unconscious manner.

Evaluation of adaptation strategies involves the analysis of different means of reducing damage costs. The methodologies outlined in the guidelines for analyzing adaptation strategies are meant as a tool only to compare alternative adaptation strategies, thereby identifying the most suitable strategies for minimizing the effects of climate change were they to occur.

6. Methods for Assessing Mitigation Options and Inventory of Mitigation Technologies

Working Group II also has prepared guidelines to assess mitigation of options. Recognizing that there are many viable approaches for mitigating greenhouse gas emissions and that countries need to identify those approaches best suited to their needs and conditions, these guidelines provide a range of analytical methods and approaches for assessing mitigation options and developing national mitigation plans and strategies. The types of methods covered include macroeconomic models, decision analysis tools, forecasting methods, costing models, market research methods, and monitoring and evaluation methods.

In addition to descriptions of methods, the guidelines describe several broader aspects of the mitigation options assessment process, including the strategic, analytical, and informational challenges; organizational issues; and important cross-cutting issues such as top-down versus bottom-up modeling, accounting for uncertainty, and incorporating externalities.

The guidelines place a special emphasis on the needs of developing countries and countries with economies in transition. The methods and models addressed are therefore intended to match a range of analytical capabilities and resource constraints.

Research in the preparation of these guidelines has demonstrated that methods to assess mitigation options are available to all countries for use in developing strategies and evaluating programs and projects that (i) support national economic, social, and institutional development goals, and (ii) slow the rate of growth in greenhouse gas emissions. Although involving analytical challenges, these methods have been widely applied in both industrialized and developing countries. Moreover, the Global Environment Facility, other international organizations, and bilateral programs provide resources to assist developing countries and those with economies in transition in obtaining information on, testing, and using these methods. The IPCC recommends that all countries evaluate and use, as appropriate, these draft methods in preparing country studies and their national communications.

In the future, development and application of mitigation assessment methods will result in further improvements in the methods and the capabilities of countries to assess mitigation options. The IPCC, in coordination with other multilateral institutions, could accelerate the dissemination of selected information on assessment methods through seminars, workshops, and educational materials.