A variety of actions are under discussion to manage the challenge posed by climate change: Cutting emissions, reforestation, and geoengineering are a few. Current research suggests that some of the possible actions are not only important but necessary for any chance of success—but no single action is sufficient on its own.

Systems Management

As discussed in Earth Systems (Chapter One) at the beginning of this Compendium, scientists are becoming more and more concerned about the long-term trajectory of climate change effects. They realize that we are committed to centuries of climate impacts even with a solid management plan for cutting greenhouse gas emissions and returning concentrations to a reasonable level (Ramanathan and Feng 2008, Lenton et al. 2008, Smith et al. 2009, Solomon et al. 2009). Without an internationally accepted management strategy, how can we avoid counter-productive initiatives and maladaptations, ranging from legal impediments to wasted resources, possibly leading to famine, migration and conflict?

Combinations of management actions at scales ranging from local to global and from ecosystem adaptation to rebuilding infrastructure are needed to deal with climate change and its impacts. The necessary actions include a switch to environmentally sound energy sources; a halt to rampant deforestation in the tropics; sustainable management of fisheries, forests, agriculture, and other ecosystem services; and the development of innovative approaches to sequester carbon from the atmosphere over decades to millennia.

In 2007, the United Nations Foundation and Sigma Xi, the Scientific Research Society, prepared a report for the 15th session of the Commission on Sustainable Development with the intriguing title ‘Confronting Climate Change: Avoiding the Unmanageable and Managing the Unavoidable’ (SEG 2007). Adopting this conceptual approach to systems management for climate change is attracting attention from the policy-research community.

MANAGING THE UNAVOIDABLE

Through the use of innovative approaches in modelling and interdisciplinary analytical teams, scientists are beginning to design management systems that may enable the use of possible mitigation and adaptation actions at various scales in response to the changing climate.

Ecosystem adaptations

Current research suggests that business-as-usual will not work. For instance, until very recently, technology transfer to address climate change has dwelled on mitigation issues. Given that the overwhelming majority of global greenhouse gas emissions are from the energy sector, energy alternatives became the dominant focus for technology transfer. Since energy technologies have been promoted as centralized and infrastructure dependent, it has been a priority on the part of developing country decision-makers to emulate developed country models by promoting infrastructure development, modernizing energy delivery, and stimulating private sector investment in large-scale installations. So technology transfer in the climate context has come to focus squarely on flows of experience, know-how, and equipment installation arrangements between countries, especially from developed to developing countries, and less on deployment and dissemination within countries and communities. Now that the question of technology for adaptation has moved into focus, some of the ideas about technology transfer for mitigation have been carried forward into the adaptation domain. However, this approach is not likely to work (Klein et al. 2006).

Adaptation requires responses at multiple scales. Building local resiliency in designated sectors and with acceptable socio-economic constraints on possible options offers many opportunities for stakeholder involvement and other community benefits. However, the rapid onset of climate change effects may forestall the gradual adaptation recommended (Klein et al. 2006). While many decision-makers think of mitigation and adaptation as two independent paths in responding to climate change, recent work shows that adaptation and mitigation are closely linked. For example, on the one hand reforestation can be an effective net sink of carbon and therefore qualify as a mitigation measure. On the other hand, forests are also under threat from changing climate, and must therefore also adapt to climate change (Jackson et al. 2008).

Threats to forests can take many forms, including increases in temperature and growing seasons that encourage potentially threatening pests (Parkins and McKendrick 2007). In the northwestern region of North America, the
mountain pine beetle, *Dendroctonus ponderosae*, has been ravaging US and Canadian forest stands for nearly a decade. Their active populations have persisted because of warmer winters in which few beetle larvae are killed off by freezing temperatures. In addition, longer warm summers support more reproduction every year so larger populations of pine bark beetles are surviving to produce more offspring and to weaken the trees. Not only are the forests losing their ecosystem capacities to sustain water tables and avert soil erosion, but they are also turning from carbon sinks to carbon sources as more trees succumb to pests and begin to decompose (Kurz et al. 2008).

**Box 5.1: Adaptation of natural systems**

Our growing appreciation of ecosystem services and recognition of their economic as well as intrinsic value requires that we protect what we need and preserve as much as possible in the face of changing climate. In June of 2009, Resources for the Future published a broad review of challenges to terrestrial ecosystem adaptation to climate change. The authors presented a list of possible interventions that could be used to facilitate ecosystem adaptation with the intention to provoke discussion and stimulate innovative approaches. They focused on options realistic for the US where most semi-natural lands are managed by state and federal government agencies. Possible interventions could include:

**Water management**

The decline in the duration and extent of mountain seasonal snow will have progressively detrimental effects. One option for adaptation for stream systems may be to develop a large number of small high mountain water storage reservoirs in the upper cirques of the mountains just below the snowline. This activity was common before the advent of electrical grids and large dam complexes, when small dams, often only one to two metres high, were built to retain snowmelt for summer stream flow. A modern equivalent of small dams impounding areas of only a few hectares may be worth considering. Slow release of the impounded water from these dams would mimic the glacier and snow melt that has extended into the midsummer, providing stream flow all summer long. The ecological cost of this approach would be the loss of many high mountain meadows and timberline ecosystems, many of which would scarcely benefit from the increased water availability and could be damaged by construction activity.

**Vegetation management**

Adaptations for natural forest and range management involve planting and cutting. In the US, the Department of Agriculture’s Forest Service is planting more southern ecotypes of trees on the lands that are being manually replanted. Although there is some risk of getting “ahead” of the climate, much of the genetic variation in these trees revolves around cold hardiness dormancy timing and frost tolerance. Low daily temperatures are increasing faster than high temperatures. However, autumn temperatures are not increasing as fast as springtime temperatures. Therefore, this approach runs some risk for frost damage from early autumn freezes. Large-scale insect epidemics and large-scale wildfires are increasing dramatically in natural ecosystems. The primary proactive adaptation to these problems is more active forest thinning and vegetation harvesting. The approach is to have significantly less stressed forests of lower density, mimicking pre-fire suppression ecosystems.

**Manage for resilience**

More than a century of ecological research on ecosystem responses to biotic and abiotic conditions has clarified that the effects of climate change can only be understood in synergy with other human-caused stressors, including habitat fragmentation, roads, urbanization, and disease. Managing for resilience will require a focal species approach because species responses to climate change are and will be largely idiosyncratic. Some categories of focal species that might make the most appropriate targets for managed reduction of anthropogenic interference would include: (a) highly vulnerable species, (b) species with a high public profile, (c) data rich species, and (d) strongly interacting species.

**Facilitate connectivity**

Many species are unable to migrate due to habitat fragmentation or infrastructural barriers. Managing land to facilitate the movement of focal species beyond their current occupied range will preserve options for the species to adjust their geographic ranges and movement patterns under climate change. Large, contiguous, intact wildland regions provide large gradients of elevation and bioclimatic niches for species movement. However, even in human-dominated ecosystems, natural regions of parkland and riparian ecosystems may be critical for facilitating connectivity.

**Directed evolution of native animals**

Given the likelihood that those animals which will prosper in a changed climate are likely to be species humans consider to be invasive, pests, or overabundant, managers may need to consider a role for directed evolution. In essence, directed evolution would involve human mediated facilitation or acceleration of evolutionary adaptation to climate change. Livestock breeders, farmers, and gardeners always select their propagating stocks from individuals that manifest desired characteristics the cultivator wants to reproduce—directed evolution applies the same approach to undomesticated species.

*Source: Running and Mills 2009*
Figure 5.1: Decision framework for assessing possible species translocation

Assessing the feasibility of whether to attempt the movement of a species to prevent its extinction or ecosystem collapse. Source: Hoegh-Guldberg et al. 2008

Box 5.2: Gene bank for a warming world

In February of 2008, the Norwegian Government officially opened an international seed depository near the town of Longyearbyen on Spitsbergen Island, in the Svalbard archipelago. The facility will provide secure long-term cold storage for preserving plant resources. Once completed, the Svalbard depository could maintain up to 4.5 million different seed varieties: ideally, samples of every variety of almost every important food crop in the world.

The vast collection is intended as insurance against disaster so food production can be restarted anywhere should it be threatened by a regional or global catastrophe. When the depository was originally conceived in the early 1980s, the perceived threats came from nuclear war and geopolitical uncertainty. When the idea resurfaced in 2002, following the adoption by the UN of the International Treaty on Plant Genetic Resources for Food and Agriculture, concerns about genetic resource loss from climate change brought new urgency and motivation to the concept.

The Svalbard facility will depend on seeds acquired according to strict protocols from sources around the world. If dried and packaged with the proper moisture content and stored at the right temperature, seeds from most major food crops will remain viable for hundreds to thousands of years. The seed collection will be maintained at optimal conditions for their long-term storage, maintained at a temperature of -18 degrees Celsius through the use of the naturally cold temperatures deep within Spitsbergen’s permafrost and an artificial cooling system. The vault has been excavated out of sandstone—120 metres inside a mountain and lined with a metre of reinforced concrete. The facility is among the most energy-efficient and reliable structures in the world, with low operating costs and virtually no maintenance.

While no location can possibly provide 100 per cent insurance against the threat of natural and human dangers, Svalbard offers a level of protection that is difficult to match. At 78 degrees latitude—roughly 1,000 kilometres north of the northernmost tip of continental Norway—the location is suitably cold and isolated. The absence of volcanic or significant seismic activity in the region and the site’s elevation above projected potential sea-level rise also contribute to the ideal longterm storage conditions.

The area also offers excellent infrastructure, including a dependable power supply and a nearby airport. Depositors retain ultimate ownership of the materials held in storage. However, the facility is owned by the Government of Norway and will be managed by the Nordic Gene Bank, which has been conserving seeds since 1984 in a facility located within an abandoned coal mine in Sweden.

Source: Fowler 2007, Skovmand 2007, UNEP 2008c

Assisted colonization

Rapid climatic change has already forced changes to the distributions of many plants and animals, leading to severe range contractions and the potential extinction of some species (see Earth’s Ecosystems, Chapter Four). The geographic ranges of many species are moving to higher latitudes and altitudes in response to shifts in the habitats to which these species have adapted over long periods. Some species already appear to be unable to disperse or adapt fast enough to keep up with the rates of climate change—currently happening at unprecedented rates for many living species. These organisms face increased extinction risk and whole ecosystems, such as cloud forests and coral reefs, may cease to function in their current form (Hoegh-Guldberg et al. 2007).

Previous discussions of conservation responses to climate change have considered assisted colonization as an option (McLachlan et al. 2007). Researchers have recently proposed the adoption of a risk assessment and management framework that could assist in identifying circumstances that require moderate action, such as enhancement of conventional conservation measures, or those that require more extreme action, such as assisted colonization.

One of the most serious risks associated with assisted colonization is the potential for creating new pest problems at the target site. Introduced organisms can also carry diseases and parasites or can alter the genetic structure and breeding systems of local populations (Hoegh-Guldberg et al. 2007, Running and Mills 2009).

In addition to the ecological risks, socio-economic concerns must be considered in decisions to move threatened species. Financial or human safety constraints, for example, may make a species’ introduction undesirable. Current disputes already demonstrate that it is unacceptable to move threatened large carnivores into regions that are important for grazing livestock. Introduced plants that may affect the quantity or quality of grazing livestock output may also not be welcome. Using gene banks may be the only practical option for these and other species until more suitable habitat can be found or developed in the future. Currently, gene banks for agriculturally significant seeds have been established with consideration of conservation in a warming world. This approach needs to be applied to many more plants and animals that may not be of economic significance presently but that may prove invaluable in an uncertain future (Hoegh-Guldberg et al. 2007, Swaminathan 2009).

The reality of a rapidly changing climate has caught many natural-resource managers and policy-makers unprepared. Large-scale translocations might now be needed. Consequently, the conservation community needs to move beyond the preservation or restoration of species and ecosystems in place as the correct approach (Hoegh-Guldberg et al. 2007, Running and Mills 2009).

Assisted colonization will always carry some risk, but these must be weighed against those of extinction and ecosystem loss. Already some regions of the Earth such as the Arctic are experiencing high levels of warming. Many others will experience unprecedented heat within the next 100 years, as well as altered precipitation and ocean acidity. The future for some species and ecosystems is so uncertain that assisted colonization might be their best chance. These management decisions will require careful thought and will need to be backed up by detailed scientific understanding if they are to succeed (Hoegh-Guldberg et al. 2007, Running and Mills 2009).

Managed agricultural adaptation

Climate change threatens the sustainability of world agriculture. Its effects are likely to be unpredictable, making it particularly difficult for plant breeders, agronomists, and farmers to respond. As well as direct effects of changing climate on crops themselves, there will be indirect but potentially devastating pressures from weeds, pests, and diseases.
It is essential that everyone involved in sustaining food production be ready to meet this challenge. How mankind emerges from the coming century or more of predicted major shifts in climate will depend on how well agricultural production can be maintained (Sanghi and Mendelsohn 2008, Hafldad 2009).

Of the Earth’s 130 million square kilometres of land, 12–15 million square kilometres are under crops, with another 35 million being grazed. Agriculture is a major economic, social, and cultural activity for billions of people, and it provides a wide range of ecosystem services. To meet projected growth in human population and per capita food demand, historical increases in agricultural production will have to continue, eventually doubling current production—a significant challenge even without the complexities introduced by the changing climate. Agriculture is highly sensitive to climate variations: Climate variability is the dominant source of production unreliabilities from year to year in many regions, and persists as a source of disruption to ecosystem services (Howen et al. 2007).

However, that climate variability has led to the development of an immense diversity of agricultural practices along with cultural, institutional, and economic factors. This means there is a correspondingly large array of possible adaptation options to meet the challenges of climate change.

Over the next four decades, the amount of available cropland per person is projected to drop to less than 1,000 square metres, due to biological limits, requiring an increase in agricultural production that is unattainable through conventional means (Montgomery 2008). A sense of urgency has been growing, in response to the universal decline of soil quality that results from various systems of intensive agriculture. The problem of soil degradation, which has affected 84 per cent of the world’s croplands, presents serious implications for agricultural productivity and broader ecosystem services (Hazell and Wood 2008).

An emerging body of scientific research focuses on spatially integrated management approaches to agriculture. This would involve a move away from the conventional model of land-use segregation, in which some areas are dedicated wholesale to food production, while others are set aside for conservation or other uses (Scherr and McNeeley 2008, Holden et al. 2009). For decades, biodiversity conservation and agricultural productivity were thought to be incompatible and mutually exclusive pursuits. But practitioners of eco-agriculture challenge these notions. Their approach transforms large-scale, high-input monoculture plantations at the farm level to a more diverse, low-input, and integrated system at the landscape level. Given the necessary management, policy, and governance structures, these new eco-agricultural land-use mosaics could support biodiversity while meeting increasing demands for wider ecosystem services and achieving critical goals of agricultural sustainability (Scherr and McNeeley 2008). By treating food production as just one of many possible ecosystem services, eco-agriculture in a sense encourages landholders to cultivate clean air and water, rich soil, and biological diversity, as well as food. The local and regional resilience this produces is also the basis of well-managed adaptation to climate change.

Forms of eco-agriculture have been practised in the past and at impressive scales: Terra Preta soils of central Amazonia could provide tremendous opportunities for multiple benefits (UNEP 2009). Large-scale generation and utilization of nutrient-rich Terra Preta soils would decrease the necessity for clearing new agricultural lands that require deforestation. Less deforestation for agricultural lands would maintain biodiversity while mitigating both land degradation and climate change and, if done properly, can alleviate waste and sanitation problems in some communities (Glaser 2007).

Multiple challenges for agriculture

In spring 2008, precipitous increases in staple food prices, which threatened the lives of tens of millions, provoked demonstrations and food riots in 37 countries and were attributed by some to projections for biofuel demand created by a response to climate change. These events may signal the arrival of an era in which longstanding relative inequalities have reached a breaking point for the global poor. It has become clear that ecosystem management and food security are intimately linked. The surplus living resources and ecological margin of error in many regions are gone. As societies struggle over diminishing tracts of fertile and irrigable land—and over traditional fishing grounds—the accelerating threats of changing climate, ecosystem collapse, and population stress have converged in a way that calls the very future of food availability into question. The debates are vigorous and highly contentious. The issue of food security created global political panic in 2008 and will no doubt continue to occupy much of the international agenda for years to come (UNEP 2009).

There is no denying the achievements of past agricultural intensification in the mid to late 20th century. The economic and social advances that characterize India, China, and much of Latin America today are, to a significant degree, due to that agricultural intensification. The problem is that while the global agricultural system that emerged is undeniably more productive, in a mid 20th century sense, its practice has accelerated soil erosion, soil salination, nitrification of water bodies, and overuse of synthetic pesticides with subsequent loss of natural pest control and other ecosystem services affecting agricultural sustainability. At the same time,
Box 5.3: IPCC suggests cropping system adaptations

» Altering inputs such as varieties/species to those with more appropriate thermal time and vernalization requirements and/or with increased resistance to heat shock and drought, altering fertilizer rates to maintain grain or fruit quality consistent with the prevailing climate, altering amounts and timing of irrigation and other water management.

» Wider use of technologies to “harvest” water, conserve soil moisture (e.g., crop residue retention), and use and transport water more effectively where rainfall decreases.

» Managing water to prevent water logging, erosion, and nutrient leaching where rainfall increases.

» Altering the timing or location of cropping activities.

» Diversifying income through altering integration with other farming activities such as livestock raising.

» Improving the effectiveness of pest, disease, and weed management practices through wider use of integrated pest and pathogen management, development, and use of varieties and species resistant to pests and diseases and maintaining or improving quarantine capabilities and monitoring programs.

» Using climate forecasting to reduce production risk.

Source: Parry et al. 2007

these intense agricultural practices have contributed to the burden of GHG concentrations in the atmosphere—producing the changing climate now threatening those socio-economic achievements.

Our agricultural systems’ distribution flaws—based on fossil-fuelled cheap transportation—make whole populations vulnerable to supply shocks as witnessed in 2008 (Surowiecki 2008). Despite higher crop yields in many countries, there are vast, persistent, and widening gaps in the ability of societies to feed themselves, much less to protect future resources and ecosystem services (Hazell and Wood 2008). For most developing countries, entrenched and deepening poverty stems from the fact that millions of small-scale farmers, many of whom are women, are simply unable to grow enough food to sustain their families, their communities, or their countries (AGRA 2008, Ngongi 2008). The efficiencies derived from the economy of scale in intensified agricultural systems do not apply at the scale of these families and communities (Dossani 2008).

As the human population continues to grow, the pool of land available for agricultural production shrinks, and climate change disrupts expected precipitation patterns, the costs and efforts required to avert a worst-case global food crisis will inevitably increase for developing countries. A number of institutions and research bodies are pressing for a complete rethink of the role of agriculture in achieving equitable development and sustainability. Increasingly, they are advocating approaches to agriculture that recognize the importance of multiple ecosystem services and that build resilience in the face of the changing climate.

The extensive 2008 International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) report advocates a radical move away from technologically-based production enhancements to a focus on the needs of small farmers in diverse ecosystems, particularly in areas of high vulnerability to climate change and other threats to ecosystems. Recognizing that the poor have benefited the least from increased productivity, the study argues for improving rural livelihoods, empowering marginalized stakeholders, enhancing ecosystem services, integrating diverse knowledge, providing more equitable market access for the poor, and building climate resilience (IAASTD 2008). In November 2008, the UN’s Food and Agricultural Organization (FAO) called for an immediate plan of action on a new ‘World Agricultural Order’ to ensure that production meets rising demand in the face of climate change, while safeguarding the goals of sustainable ecosystem management (FAO 2008). It proposed a new governance system for world food security and agricultural trade that offers farmers, in developed and developing countries alike, the means of earning a decent living (Diouf 2008).

While increased chemical and technological inputs may keep the agricultural production system going over the short-term, it becomes progressively more difficult to sustain (Montgomery 2008, Pretty 2008). In the context of climate change and how it is affecting Earth’s Systems now as demonstrated by physical and ecosystem shifts, the evolving reality will compel those responsible for the new agricultural paradigm to reach a balance between production and ecosystem integrity. If we can establish the balance sooner, we will avoid the inevitable shocks and panics that result from business-as-usual practices—and we will avoid famine, migration, and conflict that could result from agricultural incapacity (Montgomery 2008).

Management of terrestrial biomass

Maintaining ecosystem integrity is gaining new importance as a basis for sustainable agriculture. At the same time, agricultural principles can be applied to forestry and soil ecosystem services, when they are regarded as potential carbon sinks that can be enhanced through conscientious management practices. Such sustainable management practices aim for long-term sequestration capacities while maintaining ecosystem service cycles on the shorter term for supporting local communities and their interactions in a globalized economy. As noted by some researchers, sustainable forest management practices can maximize carbon sequestration rates and then provide harvests as carbon accumulation dwindles for exploitation as...
low GHG fuel through advanced combustion or as long-term construction products that replace high carbon intensity concrete and steel materials (Fahey et al. 2009, Liu and Han 2009). Innovative soil sequestration approaches can keep carbon out of the atmosphere for millennia while locally mitigating soil degradation problems that affect 84 per cent of the world’s arable land (Montgomery 2008, UNEP 2009, Bruun et al. 2009).

Carbon sequestration in forests
Carbon is stored in forest ecosystems in the form of living tree biomass and dead organic matter. In most forests, the largest carbon pools are above-ground live biomass and mineral soil organic matter, with smaller amounts in roots and surface detritus.

Currently, forests are major contributors to the terrestrial ecosystems that remove about 3 billion tonnes of anthropogenic carbon from the atmosphere every year through net growth, absorbing about 30 per cent of all CO$_2$ emissions from fossil fuel burning and net deforestation (IPCC 2007c, Karsenty et al. 2008, Ceccon and Miramontes 2008). The 40 million square kilometres of forest ecosystems, almost a third of the Earth’s total land area, store reservoirs of carbon holding more than twice the amount of carbon in the atmosphere.

Scientists and policy makers agree there are a number of major strategies available to mitigate carbon emissions through forestry management activities (Canadell and Raupach 2008). First, reforestation and afforestation increase total forested land area. China has cultivated 240,000 square kilometres of new and regrown forest during the 20th century, transforming net carbon emissions to net gains of nearly 180 million tonnes of carbon per year and offsetting 21 per cent of Chinese fossil fuel emissions in 2000 (Wang et al. 2007, Gregg et al. 2008).

Second, increasing the carbon density of existing forests at both stand and landscape scales enhances the effectiveness of forested area. Fire suppression and harvest exclusion in US forests during the 20th century led to a 15 per cent increase in forest biomass between 1927 and 1990, although the policy was not implemented for the purpose of carbon sequestration (Canadell and Raupach 2008).

Third, optimizing the use of forest products to substitute for other fossil-fuel CO$_2$ emissions: At a larger scale, this may mean using lumber instead of concrete for some building purposes. But it can also affect fire reduction policies that require the removal of undergrowth and occasional thinning by local communities to contribute to fuel needs among those who harvest the “windfall” (UNEP 2008c).

Finally, reducing deforestation has high potential for cost-effective contributions to climate protection. The continued destruction of Earth’s tropical forests alone accounts for an estimated 17 per cent of all GHG emissions. Under the reducing emissions from deforestation and forest degradation (REDD) scheme, developing countries with tropical forests would participate in a new international carbon market to receive compensation for reducing and stabilizing national deforestation rates (Canadell and Raupach 2008, UNEP 2009).

Significant uncertainty defines the future size and stability of the terrestrial carbon stock in the context of climate change and possible feedbacks (Bonan 2008, Jackson et al. 2008, Rethultz et al. 2009). Most global climate-carbon coupled models for the 21st century indicate some carbon accumulation in biomass, largely from a CO$_2$ fertilization effect on certain types of plants. However, there are uncertainties about the outcome from interacting variables (Canadell et al. 2007, Canadell and Raupach 2008). Regions with large carbon stores that are vulnerable to climate change have been identified that could lead to the release of billions of tonnes of carbon by the end of this century: Not only the possible releases from northern landscapes and continental shelves, but also from peat swamp forests in Southeast Asia where climate models agree on a future drying trend (Li et al. 2007).

Forest management practices affect net carbon exchange with the atmosphere, both by changing the amount of carbon stored in various pools and by altering the trajectory of net ecosystem productivity at a location. Sustainable forest management can increase total carbon sequestration because much of the carbon in wood products removed during forest harvest is not returned immediately to the atmosphere, but is stored in durable products and more trees can be grown to sequester more carbon (Liu and Han 2009). Theoretically, maintaining the landscape in the optimal stages of net ecosystem productivity can maximize carbon sequestration. This is accomplished by managing for maximum tree stocking and by using the harvested wood for durable products or as a substitute for fossil fuels. The overall effect of forest management on GHG emissions depends on the type of forest, the type of wood products, and the efficiency of biomass conversion. Assumptions about how the wood and wood residues will substitute for other products that embody greater carbon intensity in their manufacture or their consumption as fuel must also be considered (Eriksson et al. 2007, Fahey et al. 2009).

Box 5.4: Reducing emissions from deforestation and forest degradation
Since the close of the IPCC’s Fourth Assessment Report, a growing amount of world-wide research has been devoted to the mitigative and adaptive capacities of forests. Experts suggest that the active protection of tropical forests is not only a crucial ecosystem management priority, but also a cost-effective means of reducing overall emissions (UNEP 2009). This has given rise to the concept of “reducing emissions from deforestation and forest degradation” (REDD). For instance, reducing deforestation by 50 per cent by 2050, and stopping deforestation when countries reach 50 per cent of their current forested area, would avoid emissions equivalent to 50 billion tonnes of carbon (Gullison et al. 2007, UNEP 2009). As pressures build for a global policy for mitigating GHG emissions, an international mechanism for REDD implementation is likely to emerge as a central component of an optimal climate change treaty (Dietzreicher et al. 2009, UNEP 2009).

However, including REDD in a new climate treaty raises many difficult institutional, methodological, and scientific issues (Strassburg et al. 2009, Preskett et al. 2008). For example, robust, reliable and regular estimation of forest emissions from deforestation and degradation is a crucial requirement of REDD policy, which has not yet been realized (Howes 2009). To verify the uptake of carbon by a particular forest, it will be necessary to develop new tools that are both inexpensive and accurate, but not easily dissembled or manipulated. Another difficult issue concerns the question of governance of forests and the need to find equitable models of land tenure and land use rights under a REDD policy (IUFRIO 2009, UNEP 2009).

There are other aspects of REDD policy that will be less difficult to implement. For example, it will be fairly easy from a technical standpoint to verify the quantity of wood used from a particular forest as a substitute for carbon-intensive building materials or fossil fuels. However, some technical issues remain, for instance, regarding the permanence of the forest, and about spinoff effects of using wood as a substitute material (Fahey et al. 2009).

Many questions remain about national capacities and institutional preparedness to carry out REDD policies. It is wrong to assume, for example, that all developing countries are willing or able to implement REDD policies (Schope 2009).

Finally, in the rush to introduce REDD policies, it is important not to sidetrack the beneficial trend towards sustainable forest management which calls for multiple benefits from using forests including social, intrinsic, and non-market values. Sustainable forest management also puts high value on the ecosystem services provided by forests and on incorporating indigenous knowledge into forest management. REDD policies should reinforce rather than undermine sustainable forest management practices. (Howes 2009).
Long-term sequestration in soils
An innovative approach to soil carbon sequestration has emerged that may offer a low-risk and very efficient way to mitigate climate change and replenish soil fertility. The concept involves producing biologically derived charcoal, or biochar, and incorporating it into soils. Biochar is essentially the product of cooking biomass at low temperature and in the absence of oxygen, so it turns into charcoal.

Early research suggests that biochar sequestration may not only keep CO$_2$ from reaching the atmosphere, but could also extract CO$_2$ from the atmosphere (McHenry 2009, Gaunt and Lehmann 2008, Bruun et al. 2009). In addition, the prolonged decomposition of biochar—centuries to millennia—enhances soil fertility and other properties of soil quality including increased water retention and cation exchange capacities (Bruun et al. 2009).

The idea for using biochar as a response to today’s climate change challenge originates from traditional ecological knowledge. Pre-Columbian inhabitants of the central Amazon basin made Terra Preta—Portuguese for dark earth. These dark, nutrient-rich soils were manufactured by mixing large amounts of charred residue, organic wastes, manure, and bone into relatively infertile soil. By controlling low-temperature, low-oxygen smoldering fires at the surface of the soils, the prehistoric soil managers were able to carbonize the majority of the accumulated biomass and produce a rich Terra Preta.

Terra Preta soils are three times more concentrated in their organic matter, nitrogen, and phosphorous content, and 70 times more rich in mineralized carbon than the surrounding nutrient-depleted soils. The half-life of the charcoal in Terra Preta soils is estimated at thousands of years (Kleiner 2009, UNEP 2009). Today, research scientists are refining the techniques of this early tradition with the aim of developing biochar production technologies as a tool that could lock carbon for similar millennial time-periods.

To better understand the optimal benefits of biochar sequestration, it is important to distinguish between how CO$_2$ is released and captured through the lifecycle of plant growth, a process that is considered carbon for dark earth.
Carbon dioxide removal (CDR) techniques are designed to extract CO₂ from the atmosphere through photosynthesis by comparison, is carbon negative, as it results in a long-term withdrawal of CO₂ from the atmosphere by diverting a portion of the carbon out of the photosynthesis cycle and into a much slower, stable, and resistant state of mineralized carbon.

Recent studies have improved our understanding of the biochar mechanisms for mineralizing carbon. However, most scientists concede that the rates of subsequent demineralization through chemical breakdown are not thoroughly understood (Gaunt and Lehmann 2008, Bruun et al. 2009). However, farmers are moving ahead with the use of biochar because of its ability to revitalize degraded soils. A biochar product with the brand name ‘Agrichar’ has been marketed as a product from a patented pyrolysis process.

According to a study which examined the viability of 17 carbon management and geoengineering options, biochar has the potential to sequester nearly 400 billion tonnes of carbon over the 21st century, reducing atmospheric CO₂ concentrations by 37 parts per million (Lenton and Vaughan 2009). Although some researchers caution that these numbers are likely high, even the most conservative estimates of 20 billion tonnes of carbon sequestered by 2030 could have a significant impact on atmospheric GHG concentrations. Biochar could be a central component of systems management necessary for meeting the climate change challenge (Kleiner 2009, Lehmann 2007).

AVOIDING THE UNMANAGEABLE

Society has very important decisions to make. Even if GHG emissions ceased immediately, the warming of the Earth and associated changes—as well as those of ocean acidification—would continue beyond this century and perhaps this millennium (SEG 2007, Ramanathan and Feng 2008, Smith et al. 2009, Solomon et al. 2009). Management practice decisions for addressing such monumental issues must be effective, efficient, and equitable, within the realization that there are no instantaneous solutions.

We know the necessary components of any comprehensive management strategy: A switch to environmentally sound energy sources; a halt to rampant deforestation in the tropics; sustainable management of fisheries, forests, agriculture, and other ecosystem services; and development of innovative approaches to carbon sequestration from the atmosphere over decades to millennia. These are necessary components but may not be sufficient to prevent dangerous anthropogenic climate change. Additional, not alternative, schemes are under discussion that need very serious and considered decisions to be made—by society.

Geoengineering

Large-scale physical interventions, or technological fixes on a planetary scale, are proposed actions addressing climate change grouped under the term geoengineering. Proposals to manipulate the global climate system to correct the Earth’s radiative imbalance through catalyzing carbon out of the atmosphere or through reducing the amount of incoming shortwave solar radiation (Lenton and Vaughan 2009, Victor et al. 2009).

Carbon dioxide removal (CDR) techniques are designed to extract CO₂ from the atmosphere while solar radiation management (SRM) techniques reflect a small percentage of the Sun’s light back into space to offset the effects of increased GHG concentrations (Royal Society 2009). CDR concepts are based on the carbon sequestration accomplished by nature through photosynthesizing plants and other organisms. SRM concepts are based on the natural effects observed in the atmosphere after powerful volcanic eruptions.

One method for the removal of CO₂ from the atmosphere is ‘iron fertilization’. This exploits the CO₂ sequestration potential in parts of the ocean that are nutrient rich but do not support plankton growth due to a lack of iron. Supplying large amounts of iron to these areas of the ocean could stimulate plankton blooms that theoretically will bind carbon molecules and eventually sequester them on the deep sea-floor. Many small-scale experiments have been conducted over the last two decades that show some success at producing plankton blooms. These experiments have invoked strong reactions, both for and against the concept. The most serious concern, voiced by scientists, is the possible disruption in nutrient cycles that feed ocean life. This would constitute a serious challenge to marine ecosystems already overexploited and endangered by human activities. In November 2007, the Convention on the Prevention of Marine Pollution stated that “…planned operations for large-scale fertilization operations using micronutrients—for example, iron—to sequester carbon dioxide are currently not justified” (IMO 2007, UNEP 2008).

Another potential ocean-based approach to CO₂ removal is the manipulation of the overturning circulation of the oceans to increase the rate of sequestration of atmospheric carbon into the deep sea. Vertical pipes would pump nutrient-rich deep water to the surface, enhancing upwelling rates and promoting the downwelling of dense water in the subpolar oceans (Loglione and Rapley 2007). A potential drawback is that the manner in which altering natural circulation patterns locally will affect the overall carbon balance is unknown and could lead to release, rather than sequestration, through upwelling of carbon from the deep ocean (Royal Society 2009, Yool et al. 2009).

A land-based approach involves completely artificial CO₂ collectors that emulate the sequestration capability of photosynthesizing plants. Based on a technology used in fish tank filters and developed by scientists from Columbia University’s Earth Institute, a method called ‘air capture’ would remove CO₂ directly from the atmosphere at the location of the ideal geological deposits for storage. In a project in Iceland, CO₂ is collected from a local industrial process and injected into the underlying basalt formations, rich in magnesium and calcium, with the goal of reproducing the natural processes that form calcite and dolomite deposits and binding carbon molecules for millions of years. These formation types are common on every continent (Gislason et al. 2007). Whether this scheme
Carbon Capture and Storage (CCS) is a method for the geological sequestration of carbon dioxide (CO$_2$). CCS systems are designed to capture CO$_2$ emissions where they are most concentrated at industrial point sources such as coal power generation plants and to transport it to storage reservoirs.

In theory, the captured CO$_2$ would be compressed into a liquid, then pumped through a pipeline or transported on a ship to a site where it would be injected into the target reservoir. The injection technology already exists and is used in an oil field optimization technique. When an oil or gas field has become depleted and the remaining fossil hydrocarbon lacks pressure to reach the wellhead, CO$_2$ is injected into the far side of the reservoir to put pressure on the remaining fossil hydrocarbon, pushing it towards the wellhead where it is brought to the surface. This technique is called enhanced oil recovery and has been used by the oil and gas industry for decades. These depleted oil and gas reservoirs have been suggested as suitable CO$_2$ destinations, as have deep saline formations and unexploited coal seams (Lenton and Vaughan 2009).

Other storage methods under investigation include the direct injection of CO$_2$ into the deep oceans where it is assumed the high pressure will keep any CO$_2$ from leaking to the surface—or into the ocean itself and contributing to ocean acidification and resulting marine ecosystem crises. Another suggested destination involves mineral carbonation, which would combine minerals with concentrated CO$_2$ to form carbonate crystals. All these methods are still regarded as experimental in terms of storing large amounts of CO$_2$, and their effectiveness is unknown. Also their possible environmental impacts are not yet known (Blackford et al. 2008).

CCS will require significant expenditures on equipment and infrastructure to capture, transport, and store the compressed CO$_2$. Large pipeline networks are expensive but even without such considerations the main problems involve the size, location, accessibility, and reliability of suitable geological reservoirs. The risks of subsequent carbon leakage and the potential for interactions with groundwater are another unknown and could be prohibitive.

Recent modelling results from the International Energy Agency suggest that CCS could provide 20 per cent of total GHG emission reductions in 2050 under advantageous economic conditions (IEA 2008a, IEA 2008b). However, a 2009 analysis of CCS start-up costs determine the price of avoided CO$_2$ would be US$120 to 180 per tonne (Al-Juaied and Whitmore 2009).
Although implementing any of the SRM proposals could take decades, the cooling effect they are designed to achieve would be relatively rapid, with atmospheric temperatures responding within a few years once the apparatus was in place (Matthews and Caldeira 2007). The SRM methods may therefore provide a useful tool for reducing global temperatures rapidly should catastrophic climate changes begin. However, such systems would require a huge commitment of resources given the need for constant upkeep over the period of their implementation, since any failure or ‘switching off’ of an SRM scheme could result in rapid warming (Rebock 2008a).

Without a reduction of GHG concentrations in the atmosphere, other direct effects of increased CO₂—particularly ocean acidification and the collapse of marine ecosystems—remain unmitigated. The logistical and technical considerations of space-based geoengineering, plus the uncertainties in costs, effectiveness, risks and timescales of implementation make these measures unfeasible as solutions to dangerous climate change in the short-term (Royal Society 2009).

Another consideration that geoengineering approaches must address is liability: Who or what company, agency, government, or institution is responsible for unfortunate side effects that may result from deliberate interference with Earth Systems? The legal issues behind geoengineering are likely to pose more of a problem than the technical challenges of implementing such an endeavour (Royal Society 2009).

Carbon dioxide removal methods may be preferable to solar radiation management methods because they involve fewer risks and uncertainties. Although CDR methods have the advantage of returning the climate system closer to its natural state, none of the methods has yet proved effective at an affordable cost and with acceptable side effects (Royal Society 2009).

Given these wide ranging implications that must be kept under consideration of geoengineering schemes—as well as the potential to overshoot the effects on Earth Systems by underestimating climate sensitivity—experimentation must be strictly controlled and liabilities must be delineated. Deploying a well-planned and closely controlled solar radiation management scheme could be an option for a worst case climate scenario. However, some kind of carbon dioxide removal methods must be explored as well, including aggressive afforestation programmes, use of soil amendments such as biochar, and construction of carbon extraction towers over geological sinks. Considering how difficult it has been to reach agreement on the obvious climate change solutions based on common but differentiated responsibilities, the uncertainties involved in geoengineering schemes may prohibit any global agreement on deliberately interfering with Earth’s Systems (Boyd 2008, Royal Society 2009, Jackson 2009).

Among the research findings and the analysis that scientists have been discussing over the past few years, a significant proportion is now addressing issues of irreversibility and commitment to climate effects that will last for centuries if not a millennium. Abrupt change, tipping elements, and cumulative effects concern the analysis more and more. In this Compendium, we see evidence of thousands of marine and terrestrial species already stressed by climate change effects. Discussion has opened on decision frameworks for assisted colonization, gene banks for storing material from species which cannot be relocated, and launching what experimentation must be strictly controlled and liabilities must be delineated. Deploying a well-planned and closely controlled solar radiation management scheme could be an option for a worst case climate scenario. However, some kind of carbon dioxide removal methods must be explored as well, including aggressive afforestation programmes, use of soil amendments such as biochar, and construction of carbon extraction towers over geological sinks. Considering how difficult it has been to reach agreement on the obvious climate change solutions based on common but differentiated responsibilities, the uncertainties involved in geoengineering schemes may prohibit any global agreement on deliberately interfering with Earth’s Systems (Boyd 2008, Royal Society 2009, Jackson 2009).

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Among the research findings and the analysis that scientists have been discussing over the past few years, a significant proportion is now addressing issues of irreversibility and commitment to climate effects that will last for centuries if not a millennium. Abrupt change, tipping elements, and cumulative effects concern the analysis more and more. In this Compendium, we see evidence of thousands of marine and terrestrial species already stressed by climate change effects. Discussion has opened on decision frameworks for assisted colonization, gene banks for storing material from species which cannot be relocated, and launching what would normally be considered pollutants into the atmosphere. These trends communicate a sense of alarm among the scientists and practitioners who are most familiar with the science of climate change.

CONTINUING SCIENTIFIC ROLE

The necessary management practices to respond to climate change include a switch to environmentally sound energy sources; a halt to rampant deforestation in the tropics; sustainable management of fisheries, forests, agriculture, and other ecosystem services; and the development of innovative approaches to sequester carbon from the atmosphere over decades to millennia. While none of these options is sufficient to address the challenge, each must be part of the strategy. Another necessary component in any effective response to climate change must be to continue supporting, and even expanding, the admirable efforts that our scientists have been exerting in attempts to comprehend Earth System Science.

In 2008, authors of the IPCC Fourth Assessment Report (AR4) met with representatives from the Global Climate Observing System (GCOS), the World Climate Research Programme (WCRP), and the International Geosphere-Biosphere Programme (IGBP) to discuss needs for future climate change research and observations in the context of what was learned from the IPCC AR4 process. Participants agreed to 11 key priorities for science and climate change that, if fulfilled, would advance us well on our way to further understanding of how climate is changing and how we can respond. As scientists continue to ask themselves how to fill gaps and to better examine the complexities of natural systems, they will continue to lead us in what has been termed the greatest challenge of the 21st century: Addressing climate change.

**Box 5.7: Key priorities for science of climate change**

1. Improve process-level understanding, climate models, observations of climate-relevant parameters and climate monitoring systems in specific areas.
2. Make climate information more relevant to decisions concerning impacts, adaptation and mitigation.
3. In addition to global, decadal predictions, increase focus on regional-scale climate information, accounting for land surface processes and biosphere–atmosphere interactions.
4. Climate and impact relevant observational data records should be reprocessed to reflect new knowledge and to improve the flagging of errors and estimation of biases; and incorporated into reanalysis efforts.
5. Datasets must be expanded to include observations of the impacts of climate change and to account for autonomous or planned adaptation, especially highly vulnerable regions.
6. A systematic approach must be established specifically to monitor and assess vulnerability.
7. Develop and apply a consistent, harmonized set of scenarios of land use, land cover, and emissions databases to support both the climate and integrated assessment communities, with consistency across spatial and temporal scales, and considering both historic and future timescales.
8. Observations and innovative technology should be utilized to better understand variations in the hydrologic cycle, both in the very short-term and sustained over decades, particularly with respect to extremes.
9. Establish a community initiative that uses physical process studies, observations, and syntheses to obtain a consensus on the possible nonlinear responses of ice sheets to climate change, including their influences on rates of sea-level rise.
10. Improve process modelling and understanding of feedbacks in the carbon cycle across the Earth Systems.
11. Improve understanding of the processes involved in aerosol indirect forcing (e.g., aerosol transport, convective processes, cloud formation and dissipation) to represent them reliably in climate models.

Source: Doherty et al. 2009