Exploring Options for

Global Climate Policy

A New Analytical Framework

THE UNIQUE combination of features that characterize the climate change problem—diversity of temporal and spatial scales, complexities of the processes involved, and the multitude of social values and interests affected—requires novel frameworks of scientific inquiry

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and policy support. Efforts to mitigate climate change face scientific uncertainties: How do atmospheric physics and chemistry determine the concentrations of different greenhouse gases and the magnitude and rate of warming they cause? How do changes in regional climate affect different sectors of societies and the environment? What are the costs of implementing mitigation technologies, and when should they be implemented? An international research project has recently developed a new analytical framework that helps to address these questions.

economic losses from overzealous emission targets against an indispensable precaution: preserving the option to stabilize greenhouse gas concentrations at lower levels of the currently considered spectrum (450 parts per million carbon-dioxide equivalent or below), in case the resolution of uncertainties about the climate system or climate change impacts necessitates such low stabilization targets.

By 2005, when negotiators in the United Nations Framework Convention on Climate Change (UNFCCC) will begin discussing emission targets and

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Given all these complexities and uncertainties, the only reasonable way to manage the climate change problem is to implement a series of policy packages over time. Each package needs to contain a combination of mitigation and adaptation policies for the subsequent decade or two. The relative weights of these main components and the exact nature of the policies have to be revised regularly in light of new scientific information and changing social preferences. Setting an emission target for a period 10–15 years ahead is a key component of the policy package. The package should balance the costs of emission reductions and the risk of unnecessary

implementation strategies for the second commitment period, with an expected target year of 2020, the uncertainties are not likely to be significantly reduced. Thus, setting a reasonable medium-term emission target such as 2020 would require the consideration of numerous factors, among them the plausible range of the long-term climate stabilization target. In particular, higher medium-term emissions might exclude the possibility of arresting global warming at a low level; however, enforcing medium-term emission levels that are too strict might turn out to be unwarranted. Currently, the long-term possibilities are not being adequately

considered. The focus of the negotiations under UNFCCC on near-term emission reductions and their associated costs is in sharp contrast with its self-declared long-term objective to avoid "dangerous anthropogenic interference with the climate system," as stated in Article 2 of UNFCCC.[1]

The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has attempted to help: Working Group II provided a list of "reasons for concern" based on expected effects associated with incremental levels of global mean temperature increase, and Working Group III reviewed the cost estimates of stabilizing greenhouse gas concentrations at different levels.[2] However, these two sets of data are difficult to consolidate because of the widely differing assumptions of the studies and the models behind them as well as because of the different metrics applied by the working groups.

A New Analytical Approach

To bridge the gaps between short-term and long-term solutions and between science and policy, the authors developed a new analytical concept for the climate change problem, dubbed the tolerable windows approach (it is also called the inverse approach, as it takes the form of an inverse optimization problem) and operationalized it in the ICLIPS (Integrated Assessment of Climate Protection Strategies) modeling framework.[3]

The model determines the critical boundaries for long-term greenhouse gas emissions according to a predefined set of normative climate policy concerns (defined by the model user—such as an adviser to a negotiator, a national ministry official, an environmental nongovernmental organization, or a citizens group). These boundaries delineate an emission corridor, which encompasses the full set of permitted emission paths that will keep the climate system within specified impact constraints without exceeding specified mitigation costs. An emission path denotes the emissions of one or more greenhouse gases over a given period of time. The analysis described here focuses on emissions of carbon dioxide (CO_2)—the most important anthropogenic greenhouse gas—throughout the twenty-first century.

The tolerable windows approach facilitates a balanced consideration of the impacts and the mitigation costs associated with specific climate policy strategies. It has now been implemented as the ICLIPS integrated assessment model. This model steps beyond the span of all other integrated assessment models by allowing users to establish climate stabilization objectives on the more tangible basis of what they consider unacceptable impacts (such as reduced food production potential or ecosystem change) rather than on the more abstract basis of greenhouse gas concentrations—and by providing a whole range of suitable climate protection strategies instead of just one.

The ICLIPS model can help in exploring the tradeoffs between different combinations of targets and costs—either as a stand-alone modeling tool or embedded in a participatory assessment. In a participatory assessment, representatives of different regions or nations decide upon the impacts and costs that are acceptable to them and then find out whether a global emission corridor exists that can fulfill their specifications. The levels of acceptable impacts can be defined at different scales—from impacts on small regions (such as changes in agricultural yields in Kenya or Germany) to globally aggregated indicators (such as the overall transformation of ecosystems for all nonagricultural areas of the Earth's surface). Climate impact response functions provide the link between regionally acceptable impacts and the global climate change limit.

The global climate change limit corresponds to the impact limit of the region and impact sector that allows the smallest departure from the present-day climate. If the required emission reductions for the region or impact sector with the lowest tolerance for climate change turn out to be overly expensive, other countries could provide assistance ("side-payment"). Side-payment would reduce the region's vulnerability and increase the magnitude of climate change it could handle. In turn, it would enhance the global climate change limit by easing the most binding "acceptable impact" constraint and widening the corridor of permitted emission paths, which would now include less expensive long-term emission trajectories.

The emission corridor—representing "policy space"—allows some degree of flexibility in choosing the actual emission path. Negotiators can consider policy details that are not explicitly modeled and can set near-term targets within the corridor accordingly. For example, experience from the negotiations about national emission targets for the Kyoto Protocol indicates that many domestic considerations (such as energy, industry, transport, and agriculture) determine the mitigation commitments that are decided upon in international agreements. These are impossible to represent adequately in a highly aggregated long-term model. However, the emission corridor is helpful because it clearly indicates the range inside which aggregated global emissions need to be in a given year. Depending on the emission target being considered, the model can calculate a new subcorridor within the original emission corridor for the rest of the time horizon. This flexibility also allows mid-course corrections in light of new information and recalculation based on revised model parameters or normative targets.

The inverse framework separates normative choices about acceptable climate change targets and mitigation costs from the scientific analysis of their implications. This separation is important because political choices about acceptable climate change impacts and mitigation costs are socially determined. They reflect societies' extremely diverse perceptions of and attitudes toward risk as well as their abilities and willingness to pay for climate protection—all of which represent their concerns about future generations as motivated by their perceptions of fairness within and across generations. In contrast, the scientific analysis carried out by the model is based on systematic observations of natural processes (such as atmospheric chemistry and physics, climate, and ocean systems)

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sion path as well as the upper boundary of any emission corridor. In the ICLIPS economic model, the 11 world regions are linked via intertemporal trade, capital flows, and emission-permit trading, which is based on the concept of differentiated burden sharing. The share of each region in the allocation of the total emission budget can be specified externally by the model user, while the total amount of emissions is determined endogenously in the process of computing the emission corridor.

Stepping beyond traditional approaches to establishing cost curves for mitigation, the ICLIPS model incorporates results from a new technique of estimating dynamic regional carbon-mitigation cost functions.[9] The procedure combines processes of technological change in energy systems over the long term in the context of macroeconomic models and establishes relatively simple relationships between cumulative mitigation actions, technological changes, and their effects on economic development. A multitude of scenarios is processed statistically to derive dynamic carbon-mitigation cost curves. These cost curves are used to determine the costs of CO_2 emission reductions relative to emissions in the baseline scenario. They take into account the cost-diminishing effects of emission reductions undertaken previously (dubbed "learning by doing").

The potentially high costs of fast emission reductions stem from the early retirement of capital stock (before it reaches the end of its economic lifetime) that has been installed in the absence of a carbon constraint and needs to be replaced by low-carbon- or non-carbon-emitting capital stock to satisfy the emission limitation. Because capital stock dynamics in the energy sector are not explicitly modeled in the core model, an upper limit has been set to the rate of emission reduction to prevent unrealistic model behavior.

Greenhouse *gas emissions link the ICLIPS climate model to the highly aggregated model of the world economy.*

Climate Impact Response Functions

To foster an informed choice of possible unacceptable impacts of climate change, climate impact response functions (CIRFs) have been developed to describe how a particular climate-sensitive system or sector—such as an ecosystem or agricultural yield—responds to climatic changes. CIRFs are produced by driving multiple simulation runs of geographically explicit sectoral impact models with representative samples of future climate conditions. The resulting CIRF indicates the relationship between the relevant climatic variables and a sectoral impact indicator that describes the degree to which the sector is affected. It thus efficiently represents simulated impacts of climate change across a wide range of plausible future climate scenarios. A pilot set of CIRFs has been developed for agricultural crops, water availability, and natural vegetation.[10] CIRFs for natural vegetation are used below to illustrate the application of the ICLIPS integrated assessment model in inverse mode.

Climate and atmospheric composition are, among other factors such as land use, nutrient availability, and ultraviolet radiation, important determinants for the distribution of life on Earth. A rapidly growing body of evidence shows that recent climatic changes have affected the phenology of organisms, the range and distribution of species, and the composition and dynamics of ecological communities, and that they probably already have caused the extinction of species.[11] About 200 million years ago, the end-Triassic mass extinction event resulted in a turnover of more than 95 percent of megafloral species (including angiosperms and gingko). A threefold to fourfold increase in CO_2 (due to extensive basaltic volcanicity), associated with a rise in global mean temperature of 3–4 degrees Celsius, has been suggested as the main cause of this mass extinction.[12]

Various types of models are used to assess the likely effects of future changes in climatic factors on the distribution, productivity, and diversity of ecosystems. These models are distinguished into equilibrium and dynamic models, by their level of geographical and functional detail, and by whether they include nonclimatic factors.

The global scope of the analysis presented in this article and the need for an easily conceivable, aggregated indicator of climate impacts on natural ecosystems motivated the use of a suitably adapted version of the BIOME 1 global vegetation model. This model determines, for each 0.5°-by-0.5° grid cell of land surface, which one of the 14 distinguished biomes is compatible with local climate and soil conditions for a given concentration of atmospheric CO_2.[13] (Biomes, such as tundra, savanna, and tropical evergreen forest, are coarse categories of vegetation assemblages.)

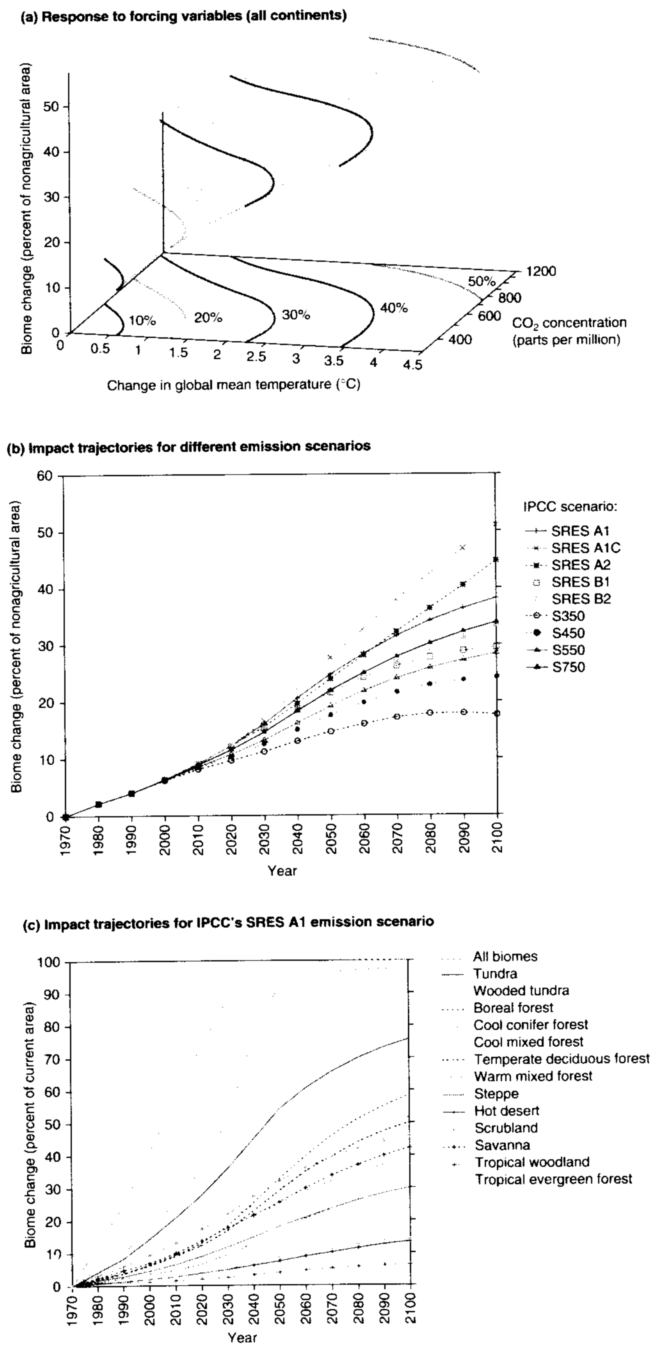
In contrast with dynamic vegetation models, equilibrium models such as BIOME 1 are not designed to determine the exact timing of changes in vegetation.[14] Depending on the migration abilities of competing species and the occurrence of weather-related disturbances such as fire, wind-throw, pests, and disease outbreaks, these changes may lag several decades behind the changes in average climate.[15]

The impact indicator chosen here denotes the global share of the ice-free land surface in nonagricultural areas (agricultural areas were masked out because their land cover is fully controlled by human activities) where the current biome becomes unsuitable under changed climate and atmospheric conditions. Although this indicator does not account for the full diversity of potential climate impacts on ecosystems, the fraction of the land area where ecosystems that have existed for millennia will no longer be feasible is a useful indicator with which to consider "dangerous anthropogenic interference with the climate system" and its implications. See Figure 1 on this page for examples of ecosystem transformation under different simulated scenarios.

Most ecosystems are sensitive to changes in climate as well as CO_2 concentration. Figure 1a shows the resulting response surface diagram as a dose-effect relationship between the two forcing variables in the horizontal plane and the impact indicator of biome change on the vertical axis. It is clear that constraints on both drivers of ecosystem change are necessary to avoid exceeding a specific impact level.

Figure 1b depicts simulated vegetation changes for five baseline emission scenarios (which begin with "SRES") and four stabilization scenarios ("S" followed

Figure 1. Simulation results for ecosystem transformation



NOTE: IPCC stands for the Intergovernmental Panel on Climate Change, which developed the five baseline emission scenarios (marked "SRES" for Special Report on Emission Scenarios) and four stabilization scenarios shown in Figure 1b.

SOURCE: F. L. Toth et al.

by a number) developed by IPCC. Baseline scenarios assume that no specific policy actions are introduced to mitigate climate change, whereas in stabilization scenarios, greenhouse gas concentrations are stabilized at a certain level. The simulated changes for 2100 vary between 34 and 51 percent globally for the baseline scenarios and between 17 and 35 percent for the stabilization scenarios.

Figure 1c shows more specific results for the SRES A1 baseline scenario. Biome changes in the year 2100 amount to almost 40 percent globally yet with distinct variability across biomes. Tropical woodland will be relatively unaffected (less than 10 percent of the current range), but wooded tundra is simulated to become unsuitable in all of its present locations. Given the simplicity of the applied model, the information in this figure should be interpreted as an indication of plausible future changes rather than an exact forecast. A comprehensive set of CIRFs developed in the ICLIPS project is now available as the ICLIPS Impacts Tool.[16]

The ICLIPS *model incorporates results from a new technique of estimating dynamic regional carbon-mitigation cost functions.*

Application of the ICLIPS Integrated Assessment Model

The ICLIPS integrated assessment model can be used in "forward mode" for policy simulations to determine how a given scenario of socioeconomic development and associated greenhouse gas emissions affects climate change and its impacts. The uniqueness of the ICLIPS integrated assessment model stems from its applicability in inverse mode to demarcate the emission policy space under exogenously specified environmental and social targets. An inverse application of the model starts with the "decision step," in which users define normative constraints to prevent climate change impacts and socioeconomic consequences of mitigation measures that they perceive to be unacceptable. In the second step, the "analysis step," the model is applied to derive a carbon emission corridor that comprises all admissible climate protection strategies that are compatible with the predefined constraints.

This procedure makes the inverse approach especially suitable for deriving carbon emission corridors for discontinuous climate impacts that exhibit a qualitative change beyond a certain threshold of climate forcing.[17] A typical example of such a discontinuous change is the potential collapse of the thermohaline ocean circulation that might be triggered by additional freshwater input in North Atlantic regions from increased precipitation and ice melting caused by a warming climate. An earlier application of the ICLIPS model involved a series of runs to establish emission corridors that preserve the thermohaline circulation.[18]

Illustrative Application of the ICLIPS Model

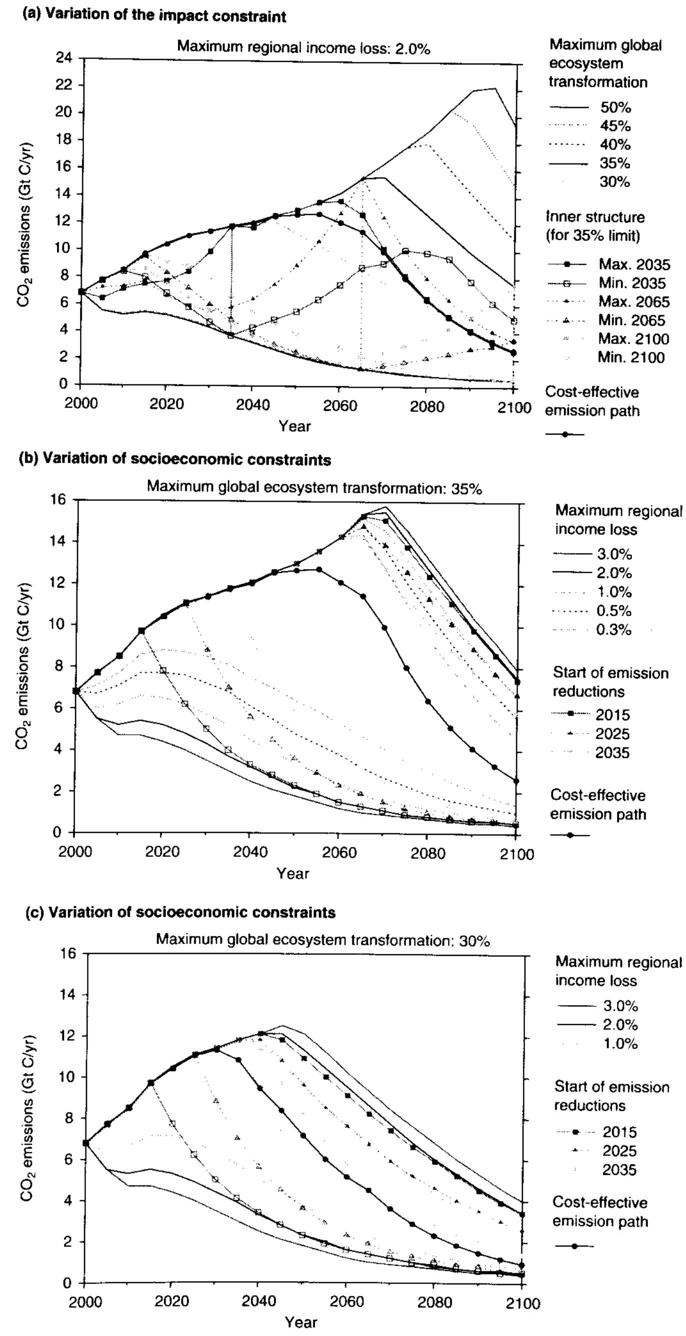
The authors completed an illustrative application of the ICLIPS model that considers climate change impacts on terrestrial ecosystems, the regional costs of mitigation measures, and the timing of emission reductions. Let us assume a global policy agreement that transforming more than 35 percent of the Earth's ecosystems would constitute a dangerous climate change impact, while mitigation costs exceeding 2 percent of the per-capita consumption (relative to the baseline) of any present or future generation in any region would be socially unacceptable. In a sensitivity analysis, deviations from this central case are investigated by varying the impact constraint (percent of ecosystem change), the mitigation cost limit (percent of per-capita consumption), and the starting year for emission reductions (between the present year and 2035).

For the purposes of this analysis, a compromise-based allocation of emission rights is assumed to begin with the status quo (emission rights allocated according to actual emissions in the initial year of the model run) and gradually transform into an equal per-capita entitlement by 2050. This means that the emission entitlement of any region after 2050 is determined by the region's population in the year 1990. In all of these experiments, energy-related CO_2 emissions are modeled endogenously. Emissions of other greenhouse gases are prescribed until 2100 according to the average of the four SRES marker scenarios and are kept constant thereafter.[19] Radiative forcing from halocarbons is taken from Version 2.3 of the MAGICC model.[20] SO_2 emissions are coupled with industrial CO_2 emissions, assuming a globally averaged desulfurization rate of 1.5 percent per year.

The carbon emission corridors that result from varying the different constraints are displayed in Figure 2 on this page. The area with the black borderline in Figure 2a shows the carbon emission corridor, selected paths to illustrate its internal structure, and the cost-effective path (the emission path that optimizes welfare for the given environmental and social targets). It follows from the conceptual foundations of the inverse approach that any point within the corridor can be reached by at least one permitted emission path, but an arbitrary path inside the corridor is not necessarily a permitted path. For example, the upper boundary of the corridor can be reached in 2065 only if emissions remain far inside the corridor (substantially below baseline emissions) for several decades in the first half of the twenty-first century (the path marked with orange triangles). The cost-effective path, in contrast, follows the baseline up to about 2040 and then switches to a path of accelerating reduction. This shift occurs as both autonomous and learning-by-doing types of technological development make mitigation efforts less expensive.

Figure 2a also shows the sensitivity cases when the acceptable ecosystem transformation varies between 30 and 50 percent. The 30-percent limit results in a drastically narrower emission corridor (the green line inside the 35-percent corridor). No corridor exists for the 25-percent limit. This suggests that, given the amount of greenhouse gases already in the atmosphere and the inertia of the climate system, it is not possible to limit ecosystem transformation to 25 percent of nonagricultural areas globally by controlling CO_2 emissions alone, with the given willingness to pay. (Future extensions of the model should explore how much flexibility would be provided by mitigating other greenhouse gases.) Conversely, if the global society were willing to allow half of the world's ecosystems to undergo biome changes, the corridor of acceptable carbon emission paths (red line) would be much wider, permitting higher annual and cumulative emissions.

Figure 2. Corridors for energy-related CO_2 emissions



NOTE: These three figures show the sensitivity of the corridors to variations of different normative constraints. In Figure 2a, the internal structure is illustrated by emission paths that hit the upper or lower boundaries of the corridor (the area inside the black borderlines) in selected years. Figure 2b varies cost constraints for a 35-percent ecosystem transformation limit, and Figure 2c applies a stricter ecosystem transformation limit of 30 percent. Gt C/yr = gigatons of carbon per year.

SOURCE: F. L. Toth et al.

In Figure 2b, another set of corridors indicates the sensitivity of the emission policy space to societies' willingness to pay for climate change mitigation. The limit to acceptable mitigation costs is varied between 0.3 and 3 percent consumption loss, for the central case of a 35-percent maximum ecosystem transformation. These variations mainly affect the lower boundary of the corridors.

The timing of mitigation action has been the subject of fierce debates in climate policy in recent years. The effects of delaying emission reductions are investigated in Figure 2b. If emissions proceed along the baseline path until 2015, 2025, and 2035 (marked with gray, orange, and light blue lines, respectively), while the impact and cost constraints remain those specified for the central case, the implications of delaying emission reductions are rather modest for the corridor.

Figure 2c shows that setting the limit of ecosystem transformation to 30 percent leads to much narrower corridors that also are much more sensitive to variations in socioeconomic constraints. At least about 1 percent consumption loss is required to have an open corridor. If emission reductions are postponed until 2015, 2025, and 2035, the resulting corridors (areas between the marked lines in Figure 2c) become increasingly narrower compared with a situation in which emission reductions are implemented without delay. The 2035 corridor (the light blue line) is a very tight lane of sustained emission reduction that approaches the maximum rate permitted by the declining-cost technologies and the emission reduction rate constraint.

Understanding the Implications of Climate Change

The tolerable windows approach and its implementation as an integrated assessment model allow long-term greenhouse gas–reduction options to be explored under a wide variety of normative concerns that shape the global climate policy debate.[21] The results of the model show the extreme importance of environmental targets in defining the climate policy space.

The model results also reveal, in particular, the strong nonlinearity and sensitivity of the climate policy space to impact constraints such as the transformation of ecosystems. They also disclose the intricate relationships among the numerous decision factors as they determine how near-term choices foreclose or preserve options for long-term climate policy.

The sensitivity analysis shows that the existence and the shape of the emission corridor are more sensitive to the maximum acceptable climate change impact than to the limits on mitigation costs or the timing of emission reductions. This confirms the fact that CO_2 is a stock pollutant—its detrimental effects are associated with its actual previous concentrations in the atmosphere and with the related climate forcing rather than with the amount of annual emissions. Therefore, its management requires long-term perspectives to secure both climate protection and sustainable development. The effectiveness of near-term emission reductions, even ambitious ones permitted by high willingness to pay, is limited.

The results highlight the importance of improving the understanding of the implications of climate change—as well as the options for and costs of reducing the vulnerability and increasing the adaptive capacity of the affected systems such as agriculture or water resources. It is clear that in the case of natural ecosystems considered here, human interventions may alleviate some negative effects of ecosystem changes, but they cannot prevent the changes altogether. Following the carbon-intensive baseline emission scenario for another few decades will progressively preclude potential climate stabilization (and impact) targets from being achievable at reasonable cost. The emission corridors show that over the long term, carbon emissions must decline significantly below their current levels for major transformations of the world's ecosystems and socioeconomic sectors that are influenced by climate to be avoided.

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16. The ICLIPS Impacts Tool is a graphical user interface that provides convenient access to about 100,000 impact diagrams. It is freely available on CD-ROM from one of the authors (fuessel@pik-potsdam.de). A more detailed description can be found in H.-M. Füssel, "The ICLIPS Impacts Tool: Presenting Climate Impact Response Functions for Integrated Assessments of Climate Change" (proceedings of the conference of the International Environmental Modelling and Software Society (iEMSs 2002), Lugano, Switzerland, June 2002, 24–27).

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