

# The New Palgrave Dictionary of Economics Online

## climate change, economics of

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### Abstract

Climate-change economics attends to the various threats posed by global climate change by offering theoretical and empirical insights relevant to the design of policies to reduce, avoid, or adapt to such change. This economic analysis has yielded new estimates of mitigation benefits, improved assessments of policy costs in the presence of various market distortions or imperfections, better tools for making policy choices under uncertainty, and alternative mechanisms for allowing flexibility in policy responses. These contributions have influenced the formulation and implementation of a range of climate-change policies at domestic and international levels.

### Keywords

carbon emissions tax; climate change, economics of; computable general equilibrium (CGE) models; contingent valuation; discount rate; global warming; hedonic approach; integrated assessment models; intergenerational equity; learning-by-doing; Monte Carlo methods; price-based vs. quantity-based policies; production function approach; technology policy; time preference; tradable emission permits; uncertainty

### Article

The prospect of global climate change has emerged as a major scientific and public policy issue. Scientific studies indicate that human-caused increases in atmospheric concentrations of carbon dioxide (largely from fossil-fuel burning) and of other greenhouse gases are leading to warmer global surface temperatures. Possible current-century consequences of this temperature increase include increased frequency of extreme temperature events (such as heat waves), heightened storm intensity, altered precipitation patterns, sea-level rise, and reversal of ocean currents. These changes, in turn, can have significant impacts on the functioning of ecosystems, the viability of wildlife and the well-being of humans.

There is considerable disagreement within and among nations as to what policies, if any, should be introduced to mitigate and perhaps prevent climate change and its various impacts. Despite the disagreements, in recent years we have witnessed the gradual emergence of a range of international and domestic climate-change policies, including emission-trading programmes, emission taxes, performance standards, and technology-promoting programmes.

Beginning with William Nordhaus's 'How fast should we graze the global commons?' (1982), climate-change economics has focused on diagnosing the economic underpinnings of climate change and offering positive and normative analyses of policies to confront the problem. While overlapping with other areas of environmental economics, it has a unique focus because of distinctive features of the climate problem – including the long time-scale, the extent and nature of uncertainties, the international scope of the issue, and the uneven distribution of policy benefits and costs across space and time.

In our discussion of the economics of climate change, we begin with a brief account of alternative economic approaches to measuring the benefits and costs associated with reducing greenhouse gas emissions, followed by a discussion of uncertainties and their consequences. We then present issues related to policy design, including instrument choice, flexibility, and international coordination. The final section offers general conclusions.

### Assessing the benefits and costs of climate change mitigation

#### Climate change damages and mitigation benefits

As noted, the potential consequences of climate change include increased average temperatures, greater frequency of extreme temperature events, altered precipitation patterns, and sea-level rise. These biophysical changes affect human welfare. While the distinction is imperfect, economists divide the (often negative) welfare impacts into two main categories: *market* and *non-market* damages.

*Market damages.* As the name suggests, market damages are the welfare impacts stemming from changes in prices or quantities of marketed goods. Changes in productivity typically underlie these impacts. Often researchers have employed climate-dependent production functions to model these changes, specifying wheat production, for example, as a function of climate variables such as temperature and precipitation. In addition to agriculture, this approach has been applied in other industries including forestry, energy services, water utilities and coastal flooding from sea-level rise (see, for example, Smith and Tirpak, 1989; Yohe et al., 1996; Mansur, Mendelsohn and Morrison, 2005).

The production function approach tends to ignore possibilities for substitution across products, which motivates an alternative, hedonic approach (see, for example, Mendelsohn, Nordhaus and Shaw, 1994; Schlenker, Fisher and Hanemann, 2005). Applied to agriculture, the hedonic approach aims to embrace a wider range of substitution options, employing cross-section data to examine how geographical, physical, and climate variables are related to the prices of agricultural land. On the assumption that crops are chosen to maximize rents, that rents reflect the productivity of a given plot of land relative to that of marginal land, and that land prices are the present value of land rents, the impact of climate variables on land prices is an indicator of their impact on productivity after crop-substitution is allowed for.

*Non-market damages.* Non-market damages include the direct utility loss stemming from a less hospitable climate, as well as welfare costs attributable to lost ecosystem services or lost biodiversity. For these damages, revealed-preference methods face major challenges because non-market impacts may not leave a 'behavioural trail' of induced changes in prices or quantities that can be used to determine welfare changes. The loss of biodiversity, for example, does not have any obvious connection with price changes or observable demands. Partly because of the difficulties of revealed-preference approaches in this context, researchers often employ stated-preference or interview techniques – most notably the contingent valuation method – to assess the willingness to pay to avoid non-market damages (see, for example, Smith, 2004).

#### Cost assessment

The costs of avoiding emissions of carbon dioxide, the principal greenhouse gas, depend on substitution possibilities on several margins: the ability to substitute across different fuels (which release different amounts of carbon dioxide per unit of energy), to substitute away from energy in general in production, and to shift away from energy-intensive goods. The greater the potential for substitution, the lower are the costs of meeting a given emission-reduction target.

Applied models have taken two main approaches to assessing substitution options and costs. One approach employs 'bottom-up' energy technology models with considerable detail on the technologies of specific energy processes or products (for example, Barretto and Kypreos, 2004). The models tend to concentrate on one sector or a small group of sectors, and offer less information on abilities to substitute from energy in general or on how changes in the prices of energy-intensive goods affect intermediate and final demands for those goods.

The other approach employs 'top down' economy-wide models, which include, but are not limited to, computable general equilibrium (CGE) models (see, for example, Jorgenson and Wilcoxon, 1996; Conrad, 2002). An attraction of these models is their ability to trace relationships between fuel costs, production methods, and consumer choices throughout the economy in an internally consistent way. However, they tend to include much less detail on specific energy processes or products. Substitution across fuels is generally captured through smooth production functions rather than through explicit attention to alternative discrete processes. In recent years, attempts have been made to reduce the gap between the two types of models. Bottom-up models have gained scope, and top-down models have incorporated greater detail (see, for example, McFarland, Reilly and Herzog, 2004).

Because climate depends on the atmospheric stock of greenhouse gases, and because for most gases the residence times in the atmosphere are hundreds (and in some cases, thousands) of years, climate change is an inherently long-term problem and assumptions about technological change are particularly important. The modelling of technological change has advanced significantly beyond the early tradition that treated technological change as exogenous. Several recent models allow the rate or direction of technological progress to respond endogenously to policy interventions. Some models focus on *R&D-based* technological change, incorporating connections between policy interventions, incentives to research and development, and advances in knowledge (see, for example, Goulder and Schneider, 1999; Nordhaus, 2002; Buonanno, Carraro and Galeotti, 2003; Popp, 2004). Others emphasize *learning-by-doing-based* technological change where production cost falls with cumulative output, in keeping with the idea that cumulative output is associated with learning (for example, Manne and Richels, 2004). Allowing for policy-induced technological change tends to yield lower (and sometimes significantly lower) assessments of the costs of reaching given emission-reduction targets than do models in which technological change is exogenous.

#### Integrated assessment

While the cost models described above are useful for evaluating the cost-effectiveness of alternative policies to achieve a given emissions target, the desire to relate costs to mitigation benefits (avoided damages) has spawned the development of *integrated assessment models*. These models link greenhouse gas emissions, greenhouse gas concentrations, and changes in temperature or precipitation, and they consider how these changes feed back on production and utility. Many of the integrated assessment models are optimization models that solve for the emissions time-path that maximizes net benefits, in some cases under constraints on temperature or concentration (see, for example, Nordhaus, 1994).

#### Dealing with uncertainty

The uncertainties about both the costs and the benefits from reduced climate change are vast. In a recent meta-analysis examining 28 studies' estimated benefits from reduced climate change (Tol, 2005), the 90 per cent confidence interval for the benefit estimates ranged from – \$10 to +\$350 per ton of carbon, with a mode of \$1.50 per ton. On the cost side, a separate study found marginal costs of between \$10 and \$212 per ton of carbon for a ten per cent reduction in 2010 (Weyant and Hill, 1999).

#### Uncertainty and the stringency of climate policy

Increasingly sophisticated numerical models have attempted to deal explicitly with these substantial uncertainties regarding costs and benefits. Some provide an uncertainty analysis using Monte Carlo simulation, in which the model is solved repeatedly, each time using a different set of parameter values that are randomly drawn from pre-assigned probability distributions. This approach produces a probability distribution for policy outcomes that sheds light on appropriate policy design in the face of uncertainty. Other models incorporate uncertainty more directly by explicitly optimizing over uncertain outcomes. These models typically call for a more aggressive climate policy than would emerge from a deterministic analysis. Nordhaus (1994) employs an integrated climate-economy model to compare the optimal carbon tax in a framework with uncertain parameter values with the optimal tax when parameters are set at their central values. In this application, an uncertainty premium arises: the optimal tax is more than twice as high in the former case as in the latter, and the optimal amount of abatement is correspondingly much greater. The higher optimal tax could in principle be due to uncertainty about any parameter whose relationship with damages is convex, thus yielding large downside risks relative to upside risks. In the Nordhaus model, the higher optimal tax stems primarily from uncertainty about the discount rate (Pizer, 1999).

#### The choice of discount rate under uncertainty

The importance of the discount rate arises because greenhouse gases persist in the atmosphere for a century or more, and therefore mitigation benefits must be measured on dramatically different timescales from those of ordinary environmental problems. A prescriptive approach links the discount rate to subjective judgements about intergenerational equity as indicated by a pure social rate of time preference (see, for example, Arrow et al., 1996). A descriptive approach relates the discount rate to future market interest rates. Under both approaches, significant uncertainties surround the discount rates. Recent work by Weitzman (1998) points out that a rate lower than the expected value should be employed in the presence of such uncertainty, a reflection of the relationships among the discount *factor*, the discount *rate*, and the time interval over which discounting applies. Put simply, the discount factor  $e^{-rt}$  is an increasingly convex function of the interest rate  $r$  as the period of discounting  $t$  increases. This implies that in the presence of uncertainty the certainty-equivalent discount rate is lower than the expected value of the discount rate: that is,  $\partial \pi(E[e^{-rt}]) / t < E[r]$ . The difference between the appropriate, certainty-equivalent rate and the expected value of the discount rate widens the longer the time horizon is. While Weitzman focuses on a single uncertain rate, Newell and Pizer (2003a) show that, under reasonable specifications of uncertainty about the evolution of future market rates, this approach doubles the expected marginal benefits from future climate change mitigation compared with the estimated benefits from an analysis that uses only the current rate.

#### Act today or wait for better information?

In addition to concerns about convexity and valuation, uncertainty raises important questions about whether and how much to embark on mitigation activities now as opposed to waiting until at least some uncertainty is resolved. Economic theory suggests that, in the absence of fixed costs and

irreversibilities, society should mitigate (today) to the point where expected marginal costs and benefits are equal. Yet climate change inherently involves fixed costs and irreversible decisions both on the cost side, in terms of investments in carbon-free technologies, and on the benefit side, in terms of accumulated emissions. These features can lead to more intensive action or to inaction, depending on the magnitude of their respective sunk values (Pindyck, 2000). Despite the ambiguous theory, empirically calibrated analytical and numerical models tend to recommend initiating reductions in emissions in the present, reflecting initially negligible marginal cost and non-negligible environmental benefits (Manne and Richels, 2004; Kolstad, 1996).

### The choice of instrument for climate-change policy

Policymakers can consider a range of potential instruments for promoting reductions in emissions of greenhouse gases. Alternatives include emissions taxes, abatement subsidies, emission quotas, tradable emission allowances, and performance standards. Policymakers also can choose whether to apply a given instrument to emissions directly (as with an emission-trading programme) or instead to pollution-related goods or services (as with a fuel tax or technology subsidy).

Initial economic analyses of climate-change policy tended to focus on a carbon tax because it was relatively easy to model and implement. This is a tax on fossil fuels – oil, coal, and natural gas – in proportion to their carbon content. Because combustion of fossil fuels or their refined fuel products leads to carbon dioxide (CO<sub>2</sub>) emissions proportional to carbon content, a carbon tax is effectively a tax on CO<sub>2</sub> emissions. In the simplest analysis, a carbon tax set equal to the marginal climate-related damage from carbon combustion would be efficiency-maximizing. However, in more complex analyses – where additional dimensions such as uncertainty, other market failures, and distributional impacts are taken into account – the superiority of such a carbon tax is no longer assured. We now consider these other dimensions and their implications for instrument choice.

#### Prices (taxes) vs. quantities (tradable allowances) in the presence of uncertainty

Theoretical and empirical work by Kolstad (1996) and Newell and Pizer (2003b) suggests that the marginal benefit (avoided damage) schedule for emissions reductions is relatively flat. Weitzman's (1974) seminal analysis indicates that under these circumstances expected welfare losses are smaller from a price-based instrument like a carbon tax than from a quantity-based instrument like emission quotas or a system of tradable emission allowances. That is, it is preferable to let levels of emissions remain uncertain (which is the result under a tax) than to let the marginal price of emission reductions remain uncertain (which is the result under a quota). Despite these economic welfare arguments, and recent work on hybrid approaches (Pizer, 2002), many environmental advocates prefer the quantity-based approach precisely because it removes uncertainty about the level of emissions.

#### Fiscal impacts and instrument choice

A second issue stems from the potential for policies such as carbon taxes and auctioned permits to generate revenues. A number of studies show that using such revenues to finance reductions in pre-existing distortionary taxes on income, sales, or payroll can achieve given environmental targets at lower cost – perhaps substantially lower cost – than other policies (see, for example, Goulder et al., 1999; Parry, Williams and Goulder, 1999; Parry and Oates, 2000). Therefore, carbon taxes and auctioned permit programmes that employ their revenues this way will lower the excess burden from prior taxes, giving them a significant cost-advantage. Correspondingly, subsidies to emission reductions or to new, 'clean' technologies will have a cost disadvantage associated with the need to raise distortionary taxes to finance these policies.

#### Distributional considerations

Despite these attractions of revenue-raising policies such as carbon taxes and auctioned tradable allowance systems, trading programmes with freely distributed permits have achieved greater popularity among policymakers. In New Zealand, for example, industry opposition led the government to drop its proposed carbon tax in 2005. At the same time, the European Union has, and Canada is planning, trading programmes where tradable permits are freely distributed, in line with virtually all conventional pollution trading programmes in the United States. The politics may reflect differences between systems of freely allocated allowances and systems with auctioned allowances (or carbon taxes) in terms of the distribution of the regulatory burden. Under both types of emission-permit system, profit-maximizing firms will find it in their interest to raise output prices based on the new, non-zero cost associated with carbon emissions. If the allowances are given out free, firms can retain rents associated with the higher output prices, and this offsets other compliance costs. In contrast, if the allowances are auctioned, firms do not capture these rents. Thus, firms bear a considerably smaller share of the regulatory burden in the case of freely allocated permits. Indeed, Bovenberg and Goulder (2001) show that freely allocating all carbon permits to US fossil fuel suppliers generally will cause those firms to enjoy *higher* profits than in the absence of a permit system; and freely allocating less than a fifth of the permits may be sufficient to keep profits from falling. These considerations reveal a potential trade-off between efficiency and political feasibility: the revenue-raising policies (taxes and auctioned permits) are the most cost-effective, while the non-revenue-raising policies (freely distributed permits) have distributional consequences that may reduce political resistance.

#### Emissions instruments vs. technology instruments

As noted in the cost discussion, the long-term nature of the climate-change problem makes technological change a central issue in policy considerations. Economic analysis suggests that both 'direct emissions policies' and 'technology-push policies' are justified on efficiency grounds to correct two distinct market failures. Direct emissions policies (emission trading or taxes) gain support from the fact that combustion of fossil fuels and other greenhouse-gas-producing activities generate negative externalities in the form of climate change-related damages. Technology-push policies (technology and R&D incentives) gain support from the fact that not all of the social benefits from the invention of a new technology can be appropriated by the inventor. The latter argument applies to research and development more generally, and is especially salient if the first market failure is not fully corrected (Fischer, 2004a). Numerical assessments reveal substantial cost-savings from combining the two types of policy (Fischer and Newell, 2005; Schneider and Goulder, 1997).

#### Policy designs to enhance flexibility

The previous discussion indicates that no single instrument is best along all important policy dimensions, including cost uncertainty, fiscal interactions, distribution and technology development. A further issue in policy choice is how to give regulated firms or nations the flexibility to seek out mitigation opportunities wherever and whenever they are cheapest. For both price- and quantity-based policies, flexibility is enhanced through broad coverage: specifically, by including in the programme as many emissions sources as possible and by providing opportunities for regulated sources to offset their obligations through relevant activities outside the programme. For quantity-based programmes, flexibility can also be

promoted through provisions allowing trading of allowances across gases, time, and national boundaries. Such flexibility is automatically provided by price-based programmes simply because they involve no quantitative emissions limits. Importantly, as quantity-based programmes provide these additional dimensions of flexibility, they reduce the efficiency arguments for price-based policies in the face of uncertainty voiced in the preceding section by providing opportunities to adjust to idiosyncratic cost shocks across time, space and industry (Jacoby and Ellerman, 2004).

#### Flexibility over gases and sequestration

So far we have focused almost exclusively on emissions of carbon dioxide from the burning of fossil fuels as both the cause of human-induced climate change and the object of any mitigation policy. Yet emissions of a number of other gases (as well as non-energy-related emissions of carbon dioxide) contribute to the problem and possibly the solution, particularly in the short run. Models suggest that half of the reductions achievable at costs of \$5–\$10 per ton of carbon dioxide equivalent arise from gases other than carbon dioxide. In addition, carbon sequestration can be part of the solution. Biological sequestration (for example, through afforestation) has been cited as a particularly inexpensive response to climate change (Sedjo, 1995; Richards and Stavins, 2005). Geological sequestration (for example, injection into depleted oil or gas reservoirs) represents a very expensive proposition now, but could be an important component of a long-term policy solution if costs decline (Newell and Anderson, 2004). Four issues can complicate the inclusion of these activities: monitoring, baselines, comparability and, in some cases, liability. First, some of these sources are fugitive emissions that are difficult to monitor at any point in the product cycle. Second, some activities, especially those involving fugitive emissions, are often left unregulated but allowed to enter as ‘offsets’, requiring a counterfactual baseline against which actual emissions levels can be measured. Fischer (2004b) evaluates various approaches to defining project baselines. Third, a problem of comparability arises with non-CO<sub>2</sub> gases because it is necessary to determine relative prices among greenhouse gases in a market-based programme. As a theoretical matter, the ratio of prices of a ton of current emissions of two different gases should be the ratio of the present value of damages from these emissions (Schmalensee, 1993). In practice it is difficult to apply this formula because it requires a great deal of information about the damages and because it calls for time-varying trading ratios (Reilly, Babiker and Mayer, 2001), which implies significant administrative burdens. Under the Kyoto Protocol and the EU Emissions Trading Scheme, one set of trading ratios is used at all times, and the ratios are calculated by determining the ratio of warming impacts over a 100-year horizon beginning with the present time. Finally, a liability issue arises with regard to sequestration. For both biologically and geologically sequestered carbon, a key question is who should be held liable for carbon dioxide that is released accidentally or otherwise.

#### Flexibility over time

While price policies naturally allow emissions to rise and fall in response to shocks over time, quantity-based policies must explicitly address the question of whether regulated sources can bank unused allowances for future use or, in some cases, borrow them from future allocations. In the climate change context, merely shifting emissions across time, as opposed to allowing accumulated emissions to vary, holds the environment harmless because climate consequences are generally due to accumulated concentrations, not annual emissions (Roughgarden and Schneider, 1999, discuss the possibility of dependence on both accumulated concentrations and the rate of accumulation.) Such shifts across time might reflect either a more efficient choice of timing in response to capital turnover and technological progress (Wigley, Richels and Edmonds, 1996), or an attempt to ameliorate cost shocks (Williams, 2002; Jacoby and Ellerman, 2004). The rate of exchange between present and future emissions allowances need not be unity: Kling and Rubin (1997) show that the optimal rate at which banked allowances translate across periods should reflect the expected trend in marginal mitigation benefits, the interest rate, and decay rate of the accumulated gas.

#### Flexibility over location

The defining feature of the climate-change problem may be its intrinsically global nature. Greenhouse gases tend to disperse themselves uniformly around the globe. As a result, the climate consequences of a ton of emissions of a given greenhouse gas do not depend on the location of the source, either within or across national borders, and shifts in emissions across locations do not change global climate impacts. Under these circumstances, economic efficiency calls for making market-based systems as geographically broad as possible. It supports federal over regional policies, and international coordination over idiosyncratic domestic responses.

#### International policy initiatives and coordination

International coordination is both crucial and exceptionally difficult to achieve. Studies indicate that the economic and social impacts of climate change would be distributed very unevenly across the globe, with the prospect of large damages to several nations in the tropics coupled with the potential for *benefits* to some countries in the temperate zones (see, for example, Tol, 2005; Mendelsohn, 2003). This uneven distribution makes achieving international coordination especially difficult.

The Kyoto Protocol is the first significant international effort to reduce greenhouse gas emissions. It assigns emission limits to participating industrialized countries for 2008–12, but offers flexibility in allowing these countries to alter their limits by buying or selling emission allowances from other industrialized countries or by investing in projects that lead to emission reductions in developing countries. The importance of these flexibility mechanisms for dramatically lowering compliance costs in this international setting is well documented (Weyant and Hill, 1999). The Protocol has been criticized on the grounds that it imposes overly stringent emission-reduction targets and lacks a longer-term vision for action. In addition, a core feature of the Protocol – legally-binding emission limits – has been challenged on the grounds that such limits are not self-enforcing, an arguably necessary attribute in a world of sovereign nations (Barrett, 2003). Some argue that the Protocol’s project-based mechanisms for encouraging (but not requiring) emission reductions in developing countries are highly bureaucratic and cumbersome, consistent with our earlier comments about project-based programmes more generally. These criticisms have led to considerable research considering the Kyoto structure and comparing it with various alternative international approaches. Aldy, Barrett and Stavins (2003) summarize more than a dozen alternatives, which include an international carbon tax and international technology standards.

A further major criticism is that the Protocol imposes no mandatory emissions limits on developing countries, which collectively are expected to match industrialized countries in emissions of greenhouse gases by 2035. The desire to promote greater participation by developing countries, as well as to involve the United States in the international effort, has motivated considerable research examining, within a game-theoretic framework, the requirements for broader participation and for stable international coalitions (see, for example, Carraro, 2003; Hoel and Schneider, 1997; Tulkens, 1998).

#### Conclusions

Climate-change economics has produced new methods for evaluating environmental benefits, for determining costs in the presence of various market

distortions or imperfections, for making policy choices under uncertainty, and for allowing flexibility in policy responses. Although major uncertainties remain, it has helped generate important guidelines for policy choice that remain valid under a wide range of potential empirical conditions. It has also helped focus empirical work by making clear where better information about key parameters would be most valuable. Clearly, many theoretical and empirical questions remain unanswered. We suggest (with some subjectivity) that there is a particularly strong need for advances in the integration of emissions policy and technology policy, in defining baselines that determine the extent of offset activities outside a regulated system, and in fostering international cooperation.

From 2003 until 2030 the world is poised to invest an estimated \$16 trillion in energy infrastructure, with annual carbon dioxide emissions estimated to rise by 60 per cent. How well economists answer important remaining questions about climate change could have a profound impact on the nature and consequences of that investment.

### See Also

- coalitions
- computation of general equilibria
- contingent valuation
- diffusion of technology
- environmental economics
- energy economics
- hedonic prices
- learning-by-doing
- options
- Pigouvian taxes
- second best
- social discount rate
- uncertainty

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