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Climate Change and Economics: A Study

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ABSTRACT

This paper studies the current state of knowledge, climate change and economics also their effect on economy and society. This paper tries to elaborate briefly on multidimensional aspect of climate change, climate engineering economics and the differences as well as the uncertainties in Economics.

An important feature of the projections is the fact that the climate effects will occur on top of a water scarcity situation that currently prevails in many parts of the world. The impact of climate change on scarcity is generally small compared to the impact of the socioeconomic factors.

There are two alternative approaches to reducing risks from climate change besides abatement: adaptation and climate engineering. Adaptation reduces risk by making systems more resilient to climate change. Recognizing that climate impacts will be heterogeneous and often regressive, the international community has elevated adaptation on the agenda with the goal of helping poor nations code with existing and inevitable climate change. Climate engineering, also known as geo-engineering, is a more recent addition to academic and policy conversations about climate risk. The economics literature on climate engineering is nascent. Here, review that literature and discuss its implications for how this new set of instruments could help deal with climate change. The possibility of human activity influencing the climate through the operation of the greenhouse effect has been recognized for over a hundred years. But it is only relatively recently that its extent and implications have come to be accepted by the great majority of scientists. This consensus has been expressed in an intergovernmental Panel on Climate Change (IPCC) report produced in 1990, and a supplementary report in 1992, reflecting the view of a large number of scientists from many countries. It is now agreed that, in the absence of specific actions to prevent it, the temperature of the earth's surface will increase, changing agricultural constraints, increasing sea levels and affecting human living conditions. Even if action is taken, some temperature increase remains inescapable.

Keywords : Climate Change, Climate Engineering, Uncertainty, Greenhouse gases

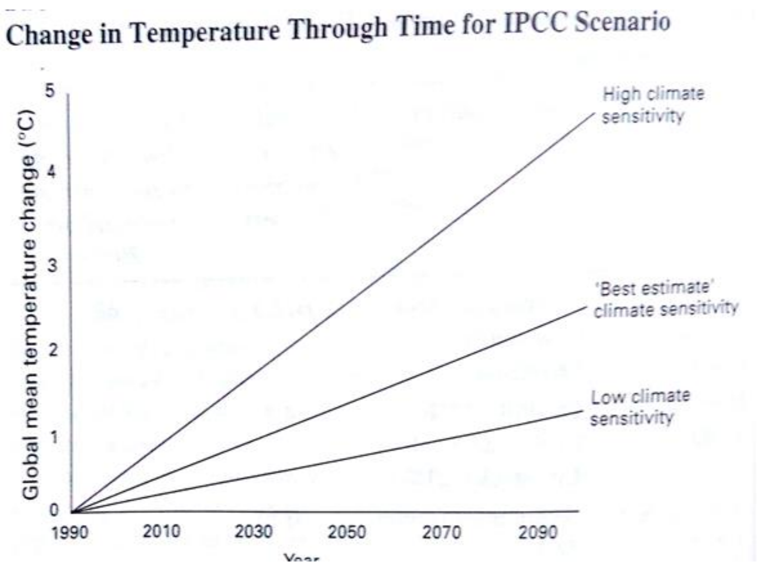
What is going on?

When radiation from the sun reaches the earth it is redistributed by the atmosphere, oceans and land. Some is re-rediated into space at longer wavelength than that of the incoming radiation. Water vapour, carbon dioxide (CO_2), methane and other 'greenhouse' gases are relatively transparent to the shorter wavelengths of the incoming solar radiation, but much more opaque to the longer wavelengths of the reflected radiation. As a consequence they allow about half of the incoming radiation to reach the earth's surface, but trap about 80-90 per cent of the radiation directed away from the earth's surface. This has the effect is a natural phenomenon, mainly caused by water vapour, raising the earth's temperature from an average of -18^0C to an average of $+15^0C$.

Climate change is a result of an enhanced greenhouose effect. Emissions of greenhouse gases as a consequence of human activity (anthropogenic emmissions) increase the concentration of these gases in the atmosphere so that a higher proportion of incoming radiation is trapped, warming up the earth's surface and lower atmosphere. There are however, very many uncertainties as to the impact which this effect will have over future years. One important variable relates to the earth's sensitivity to increases in greenhouse gas concentrations in the atmosphere. This sensitivity is measured in terms of the long-run effect of a doubling of greenhouse gas concentrations through the development of complex models of the global atmosphere. The IPCC 'best estimate' for this figure is 2.5^0C, with it being unlikely to lie outside the range 1.5 to 4.5^0C.

Greenhouse gases arise from many anthropogenic sources, CO_2 is primarily produced by the combustion of fossil fuels and land use changes, primarily deforestation, methane is produced from coil, oil and natural gas industries and from agriculture, particularly rice and animal production. Nitrous oxides arise from manufacturing processes, such as nylon and nitric acid production and from automobiles. CFCs, which are best known for their contribution to the damage of the ozone layer, are also greenhouse gases.

One estimate for the rise in annual global mean surface temperature (^0C) relative to 1990 is shown in below Figure. This indicates an increase of nearly 3^0C by the year 2100. The estimate is based on an IPCC scenario which projects CO_2 emissions in the middle of the range of scenarios considered. The range within below Figure represents the different estimates of the earth's sensitivity to increases in greenhouse gases as mentioned above.



Source : IPCC (1992).

Regional variations in the effect of climate change are expected and estimates have been generated, although there is even greater uncertainty associated with them. There are likely to be regional changes in rainfall; average rainfall is expected to increase by between 8 to 15 per cent, depending upon the type of model used as a result of the higher temperature. In the high latitudes and in the tropics this will occur throughout the year and in the middle latitudes in winter. There have been suggestions that warming could be associated with more variable and severe weather conditions, although there is little firm evidence in support of this.

Uncertainties

There are very many uncertainties facing any estimates of global temperature changes. These relate both to our ability to model atmospheric processes and to project the patterns of human activity which will feed into them. There are still significant gaps in the climate models which could have significant impacts on their outputs. For example, the role of clouds is not well modeled. One indication of this is the relatively poor performance of the models in comparison with observed data. Observed historic data indicate a lower rate of warming than those predicted in the models. It is becoming apparent that at least part of the explanation for this lies in the role of sulphur in the atmosphere. SO_2 emissions lead to the formation of sulphate aerosols, airborne particles which enhance the ability of the atmosphere to reflect radiation back into space before it reaches the earth's surface. To perverse implication of this is that reductions in acid rain may cause increases in global warming.

Perhaps the greatest uncertainty arises from the possible feedbacks associated with warming, some with potentially catastrophic consequences. These are generally excluded from the models used. One example relates to the role of the oceans. Massive amounts of carbon (roughly equivalent to all coal deposits) are stored in ocean sediments. Warming might disturb these, releasing huge volumes of methane making a very significant further contribution to global warming. Another possibility which has been suggested is that the West Antarctic ice sheet could disintegrate, raising the sea level by five to six metres. While this is not considered likely in a typical scenario, it could become more likely in the very long term. Another uncertainty relates to possible changes on ocean currents.

In order to generate potential global temperature changes, it is necessary first to develop specific scenarios which indicate levels of greenhouse gas emissions over the next hundred years or more. These in turn will depend upon many socio-economic variables, including population growth, economic growth, the technology and structure of economic activity and any policies which may be adopted in response to climate change. These inevitably involve some heroic assumptions. We might wonder what predictions would have been made in the 1890s for conditions in the 1990s, with transport in its infancy, electronics undreamed of and with the great majority of the population living in very basic circumstances. There is no reason to suppose that changes in the next hundred years will be any less fundamental.

The Consequences and Costs of Warming

The major impacts of global warming are expected to be on agriculture, land loss due to sea level rise, the need for air conditioning, water supply and air pollution. There will also be ecological changes which may not affect directly.

Agriculture

Obviously, changes in climate will affect agricultural production and profitability. A warmer climate effectively shifts agricultural zones away from the equator, north in the northern hemisphere. It has been estimated that thermal limits of agriculture would be shifted about 300 kms of latitude and 200 metres of altitude per ^{0}C.

Any actual changes in land use and farm profitability will depend on markets, prices and policy. For example, the area of land suitable for grain maize production may increase to such an extent that prices would fall, raising the relative profitability of other products. This would mean that maize may not be produced in all of the areas where it could be produced.

Sea Level Rise

Global warming will raise the levels of the seas through two processes: thermal expansion of sea water and the melting of land-based glaciers and ice sheets. However, some models suggest an accumulation of ice in the Antarctic ice sheet, reducing sea levels slightly, although the effect of warming on ice-melt is a further aspect over which there remains considerable uncertainty. The IPCC simulated a sea-level change, due to thermal expansion alone, of between 2 to 4 cm per decade. Because of natural geological movements, the south-east is currently sinking and the north-east is rising. As a result, sea-level rise will exacerbate the problems of coastal flooding, erosion and salination already being experienced in the south-east of the country. Given predictions of the sea levels relative to land levels, it is possible to estimate and value the areas of land which will be inundated and to estimate increased costs of coastal protection.

Ecological Impacts

As climate changes, the suitability of an area to particular species changes. This implies a movement of suitable habitats and a migration of species away from the equator. However, not all species or habitats can simply move with the appropriate temperature conditions. They may be obstructed by human settlement or the areas where temperatures become suitable may be unsuitable in other respects, such as in terms of soils or water availability. In consequence, warming will be associated with a loss of species. The valuation of such losses is obviously difficult. The box below mentions about modeling the Economic impact of climate change.

Box: Modeling the Economic Impacts of Climate Change

Estimates of the economic costs of climate change are generally conducted using integrated Assessment Models (IAMs) with long-term perspectives, to the end of this century and beyond[a]. Most of these studies have a stylized, aggregated representation of the economy focusing on projections of climate change impacts over time. They often include highly aggregated integrated structures, in which climate change impacts in different sectors are aggregated and used to re-evaluate welfare in the presence of climate change. An IAM projection is presented in detail in the section on the uncertainty of Cost Projections.

A smaller strand of literature uses computable general equilibrium (CGE) models to examine the economic implications of climate impacts in specific sectors, often using a comparative static approach[b]. Because CGE models have a more disaggregated structure, they need more information to determine annual equilibria, and to run them forward, linking annual changes for more than 40 to 50 years, becomes very difficult. On the other hand, they can track the impacts of climate in a more detailed way than IAMs, which rely on reduced form functions linking impacts to temperature Recent work at the Organisation for Economic Co-operation and Development (OECD 2015a) has attempted to address these issue by combining a CGE

Model to investigate the economic impacts of climate change to 2060 with an IAM model (AD-RICE) to look at impacts beyond that. Because their results are similar to a number of other models for the two periods, it is instructive to discuss them in some detail.

The OECD CGE model (ENV-Linkages) contains 35 economic sectors and 25 regions. It models trade flows as well as capital accumulation using capital vintages, in which technological advances trickle down only slowly over time to affect existing capital stocks. The model estimates the impacts of changes in different inputs (including water) as a result of climate change using a production function that represents the activity of a specific industry or group of industries in the basic structure of the model. Climate impacts have the potential to directly affect sectors' use of labor, intermediate inputs, and resources. They also affect the productivity of inputs to production Adverse climate-related shocks to the economy therefore increase the need for more inputs to generate a given level of output. Compared to Integrated Assessment Models in which climate damages are subtracted as a total from GDP, the production function approach can also explain how the composition of GDP is affected over time by climate change: what sectors are most affected and what changes in production factors contribute the most to overall changes in GDP.

a. See, for example, nordhaus (1994, 2007); Tol (2005); Stern (2007); Agrawala et al. (2011)
b. See, for example, Bosello, Roson, and Tol (2006); Bosello, Eboli, and Pierfederici (2012)

Causes and consequences of global warming

Nearly half of the solar energy that approaches the planet Earth is reflected or absorbed by gases and aerosols in the atmosphere, with the greatest amount, approximately 22 per cent, being intercepted by the white tops of clouds. The remaining solar radiation, most of which in the form of infrared or visible light waves, passes through the atmosphere to the surface of the planet. There it is either reflected off light surfaces such as snow and ice, or absorbed by land, water or vegetation. Much of this energy that is absorbed by the Earth is reradiated out from the planet toward outer space in the form of longer-wave infrared rays. A portion of this escaping energy is absorbed by certain gases found in the atmosphere, in particular CO_2, CH_4 and NO. in the process, heat is released that warms the lower atmosphere (Anthes 1992: 50-4). These substances that are so critical to the Earth's climate account for only about 0.03 per cent of atmospheric gases. Water vapor, which occurs in concentrations of from 0 to 4 per cent of the atmosphere, also intercepts outgoing infrared radiation. This process has become known as the 'greenhouse effect', because as with the glass walls of a greenhouse, the atmosphere allows solar energy t pass inwards while blocking its escape, thus keeping the space within it warm compared to outside conditions. Thus, it is the so-called greenhouse gases (GHGs) - CO_2, CH_4 and NO – along with water vapor, that account for the Earth's moderate climate Much larger amounts of CO_2

in the atmosphere of Venus explains its intensely hot climate, while the frigid conditions on Mars are attributable to lesser concentrations of GHGs (Fisher 1990: 18-20).

Human activities are adding significantly to the concentrations of the principal GHGs in the Earth's atmosphere. The burning of fossil flues, in particular coal and petroleum, releases CO_2, which can remain in the atmosphere for a century or longer. The clearing of forests not only releases the carbon stored in the trees, but also removes an important sink for CO_2, as trees absorb $CO_2$from the air through the process of photosynthesis. Concentrations of CO_2 in the atmosphere have risen from approximately 280 ppm prior to the industrial age to 371 ppm by 2001 (Keeling and Whorf, 2002). Level of CH_4, a gas that is shorter-lived in the atmosphere, have also been rising even more sharply due to a variety of human activities, such as wet rice cultivation, livestock raising and the production and transport of natural gas. Atmospheric scientists are concerned that human-generated pollutants are responsible for an 'enhanced greenhouse effect' that is reflected in a significant rise in global mean temperatures (Trenberth 2001).

Long ice cores extracted from deep in the glaciers of Greenland, Antarctica and the Andes mountains provide a record of the composition of the Earth's atmosphere and climate as far back as 400,000 years. By analyzing the chemical composition of gases trapped in air pocket in the ancient ice, scientists have been able to determine that there is now substantially more Co_2 in the atmosphere than at any other time during the era covered by the ice cores Their research also reveals that over this extended period there is a striking relationship between major shifts in climate and fluctuations in concentrations of Co_2 (Barnola et al. 1987).

There are already indications that human additions to CHG concentrations in the atmosphere are having an impact on global temperatures. The United Nations sponsored Intergovernmental panel on Climate Change concluded in its third report, released in 2001, that global mean temperatures had risen by 0.6^0C over the past century. Moreover, the 1990s appears to be the warmest decade since 1860 and 1998 was the warmest year for that period. The report concludes that most of the warming that had occurred during the last 50 years can be attributed to human activities. The same report projects an increased global mean temperature of 1.4 to 5.8^0C for the period 1990 to 2100 if concentrations of GHGs continue to rise at current rates (IPCC 2001: 10-13). To put this amount of change in perspective, global mean temperatures were about 1^0C lower during the Little Ice Age from approximately 1400 to 1850 and about 5^0C colder during the most recent major glacial era, which ended about 10,000 years ago (Oeschger and Mintzer 1992: 63).

A significant warming of the atmosphere is likely to trigger substantial climate changes. These impacts are expected to vary considerably by region. Some areas will experience warmer and drier climates, while others may become cooler and moister. Substantial changes in temperature and rainfall patterns would have significant implications for agriculture. Reductions in stream flows might trigger water shortages, jeopardize irrigation and limit the production of hydroelectric power. Unusually dry conditions in some areas might set the stage for immense, uncontrollable forest and range fires, which would generate large amounts of smoke and release additional Co_2into the atmosphere. At the other extreme, abnormal precipitation events are likely to become more frequent, causing increasingly destructive floods. As ocean waters warm, potentially destructive tropical storms, such as hurricanes, cyclones and typhoons, may become more frequent and intense (Stevens 1999).

Global warming is likely to trigger many other changes in the natural environment. If present trends continue, sea levels are projected to rise by between nine and 88 cm over the next century due to both thermal expansions of the ocean waters and the melting of polar and mountain glaciers (IPCC 2001: 16). Rising sea levels pose a threat to low-lying coastal zones, where many of the world's major cities are located. Small island states, many of which are located in the Caribbean Sea and western Pacific Ocean, are especially vulnerable to sea level rises as well as to tropical storms and associated storm surges. Shifts in climate zones may exceed the adjustment capacity of many species, while other adaptable species, including agricultural pests and disease vectors, may be able to spread more widely. Forests are especially vulnerable to climatic changes because trees migrate very slowly and are susceptible to infestations (Stevens 1999).

The greatest amount of warming is expected to take place in the polar regions. With the shrinking of glaciers and ice packs, less solar energy will be reflected while more is absorbed, thus contributing to further warming (McCarthy and McKenna 2000). Warmer conditions may also accelerate the melting of permafrost, which would release large amounts of the GHG CH_4 into the atmosphere. A lessening of the temperature gradients between the equator and the poles could strongly influence the prevailing weather patterns in the temperate mid-latitude regions. It could also weaken major ocean currents that distribute heat around the planet. If the warm, northward-flowing Gulf Stream were to weaken considerable, the climate of northern Europe might cool significantly (Calvin 1998).

While there is a general convergence of opinion among scientists that human additions to atmospheric concentrations of GHGs are likely to trigger significant climate and environmental changes, considerable uncertainties remain about how much change will take place and how these changes will play out in specific regions. Questions remain about key factors such as the amount of atmospheric Co_2that will ultimately be absorbed by the oceans and the impacts that clouds will have on future climates. Furthermore, it is difficult for scientists to isolate the causes of recent weather and environment anomalies that appear to bear out the global warming scenario, such as the spate of unusually warm years since 1990 and an increased incidence of floods resulting from unusually heavy precipitation. Let us focus on the basic of Climate Engineering Economics.

Climate Engineering Economics

Climate engineering, also known as geoengineering,[1] is a more recent addition to academic and policy conversations about climate risk. The economics literature on climate engineering is nascent. To start by briefly reviewing the relevant scientific concepts related to the two broad categories of climate engineering: carbon dioxide removal (CDR) and solar radiation management (SRM).[2] There are three characteristics that make SRM the focus of the majority of climate engineering economics literature: 1) SRM is inexpensive compared to abatement; 2) SRM allows rapid action which could circumvent some of the inertia of the Earth's carbon cycle; 3) SRM imperfectly (or ineffectively) compensates for carbon dioxide-driven warming, and it may introduce unintended consequences.[3]

Science and Engineering

Climate engineering is a term used to refer to technologies as disparate as sun-deflecting mirrors in space and orchestrated algal blooms, most approaches fall into two classes of technologies, which have little else in common than an unconventional approach to reducing climate change risks. The first class, solar radiation management (SRM), counteracts the warming effects of anthropogenic greenhouse gases by deflecting sunlight back into space before it can be absorbed by the Earth. The second class, carbon dioxide removal (CDR), reduces concentrations of the greenhouse gas carbon dioxide Co_2 in the atmosphere directly.

Carbon Dioxide Removal

One of the main challenges associated with reducing the risks of higher concentrations of Co_2 in the atmosphere is its long lifetime. While the ocean and biosphere are natural sinks that take up a portion of new Co_2 emissions, the rate at which they do so is limited and saturates as high atmospheric Co_2 concentrations persist. A significant fraction of emitted Co_2 remains in the atmosphere for thousands of years (Archer et al., 2009). CDR technologies are a way of artificially increasing the capacity and uptake rate of carbon sinks.

Brief description of different technologies

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[1] Although the term "geoengineering" is perhaps more commonly used and more recognizable, in this paper, use the term "Climate Engineering" to clarify that these technologies are specifically addressing climate change. "Geoengineering" is also occasionally used to refer to geological engineering or geotechnical engineering. Another proposed term for climate engineering is "climate intervention" (National Research Council, 2015a,b).

[2] CDR is also known as direct air capture (DAC); SRM is also known as albedo modification (AM) or solar geoengineering (SGE).

[3] The review complements recent reviews on the economics of climate engineering. Barrett (2014) focuses on governance issues and just studies SRM, not CDR. Klepper&Rickels (2012) and Klepper & Rickels (2014) provide overviews of both science and economics of CDR and SRM. To synthesize the science / engineering and economic/policy literatures on CDR and SRM, and to compare both CDR and SRM to abatement. Wagner & Weitzman (2015).

A number of approaches for CDR are potentially viable. They include bioenergy with carbon capture and sequestration (BECCS), which captures carbon in plant biomass and subsequently sequesters the Co_2 produced in using the biomass to produce energy; direct air capture, in which a chemical sorbent such as an alkaline liquid is exposed to ambient air, removing Co_2; enhanced weathering, in which the carbonate or silicate reactions that naturally sequester atmospheric Co_2 over millennial timescales could be accelerated or supplemented; and ocean fertilization, in which large amounts of nutrients, most notably iron, would be dispersed on the ocean surface to enhance phytoplanktonic growth that would sequester Co_2 in biomass. (National Research Council, 2015b).

The Basic Economics of Climate Engineering

Analytical Model

The economic model that can provide a framework for how to think about the economics of climate engineering. This model is very similar to the model of SRM presented in Heutel et al. (2015a), though here include both SRM and CDR.

To consider a representative agent model, in an economy where there are external damages from pollution that can be alleviated either by reducing pollution (abatement or CDR) or by reducing the harmful effect of pollution (through SRM). There is a fixed stock of capital k that can be allocated towards production (k_p), abatement (k_a), CDR (k_{CDR}), or SRM (k_{SRM}), so that $k_p + k_a + k_{CDR} + k_{SRM} = k$. Gross output is $f(k_p)$, but net output can be reduced because of damages from pollution x. This is a static model without saving, so all net production is consumed: $y = c = f(k_p)\ (1 - d(x;\ k_{SRM}))$. The function $d \in [0, 1]$ is the damage function, expressed as the fraction of gross output that is lost due to pollution damages. To assume that there is increasing and convex. SRM affects how pollution reduces gross output: $d_k < 0$ and $d_{xk} < 0$, so that SRM reduces total and marginal damages. [4]

Baseline or business-as-usual pollution is normalized to be equal to the capital stock k, but it can be reduced through abatement or CDR. Thus, pollution $(1 - \mu)k - \gamma$, where μ is the fraction of pollution abatend and γ is the pollution removed through CDR. Pollution abated μ is modeled as a fraction of total pollution k; while pollution removed from CDR is modeled as an absolute quality[5]. The fraction of pollution that is abated is a function of the capital stock devoted to abatement, and the pollution removed through CDR is a function of the capital stock devoted to CDR: $\mu = g(k_a)$ and $\gamma = h(k_{CDR})$. Assuming that both cost functions g and h are increasing and concave.

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[4] These assumption do not imply that there are no direct damages from implementing SRM, but they do assume that on net SRM is beneficial to society.

[5] This is to reflect that CDR is not limited to reduction of present-day emissions but can take on the emissions of others, past and present, even resulting in negative pollution.

The planner's problem is to maximize net output subject to the resource constraint:

$$\frac{max}{k_p; k_a; k_{SRM}; k_{CDR}} f(k_p)(1-d(x;\ k_{SRM})) \qquad (1)$$

Such that

$$k = k_p + k_a + k_{CDR} + k_{SRM} \qquad (2)$$

$$x = (1-g(k_a)k - h(k_{CDR}) \qquad (3)$$

The solution to this problem can be described by the following set of first-order conditions[6]:

$$f'(k^*_p)\ (1-d(x^*;\ k^*_{SRM})) = f(k^*_p)kg'(k^*_a)d_x(x^*;\ k^*_{SRM}) \qquad (4)$$

$$f'(k^*_p)\ (1-d(x^*;\ k^*_{SRM})) = f(k^*_p)\ h'(k^*_{CDR})d_x(x^*;\ k^*_{SRM}) \qquad (5)$$

$$f'(k^*_p)\ (1-d(x^*;\ k^*_{SRM}) = f(k^*_{SRM})) = -f(k^*_p)d_k(x^*;\ k^*_{SRM}) \qquad (6)$$

These three equations represent setting the marginal benefit equal to the marginal cost for abatement, CDR, and SRM, respectively. The left-hand-side of each equation is the marginal benefit of an additional unit of productive capital k_p, which is the ability to produce and consume more output. It equals the marginal benefit of an additional unit of either abatementk_a, CDR k_{CDR} or SRM k_{SRM}.

The first two equations are nearly identical to each other, and they imply that $kg'(k^*_a) = h'(k^*_{CDR})$. The marginal cost of reducing a unit of pollution through abatement the marginal cost of reducing it through CDR. Because abatement and CDR are (in this mode) perfect substitutes, this equimarginal condition must hold at the optimum. SRM, through, is not perfectly analogous to CDR or abatement. The first-order conditions imply that $-d_k(x^*\ k_{SRM}) = kg'(k^*_a)d_x(x^*;\ k^*_{SRM})$. The marginal benefit of an additional unit of SRm, in terms of reduced marginal damages, equals the marginal benefit of an additional unit of abatement, in terms of its reduced marginal damages times the cost of achieving those damages.

The model demonstrates how SRM and CDR both are alternative means of reducing climate change damages, and they should be employed at an efficient level directed by equating marginal benefits. Of course, this simple model omits many important relevant features of the real world. For example, the model is static, though climate change is a dynamic problem. Moreno-Cruz & Smulders (2007) develop

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[6] Assuming an interior solution and that the second-order conditions ensure a unique solution.

a model that incorporates climate dynamic and economic growth and show the main trade-offs presented in this simpler model remain true. But new insights are revealed. They find that for high levels of damages caused directly by atmospheric CO_2, climate engineering and abatement could act as strategic complements in the sense that climate engineering implementation would increase abatement efforts in the economy, and for lower CO_2concentrations, climate engineering is still used acting as a strategic substitute for traditional abatement with the final objective of boosting the productivity of the economy.

Conclusions:

Climate engineering has remained at the fringes of climate policy debate and academic economic research. The literature is growing, though, and much of it suggests that climate engineering technologies can have a substantial impact on climate policy and international climate negotiations. This may be especially true given the current difficulty that nations continue to face in coordinating a response to the climate change. CDR and SRM are two sets of technologies that offer climate risk mitigation alternatives. CDR offers a path towards decarbonization, with relatively low uncertainty and large benefits, but at very high costs. SRM is available at much lower direct costs, but comes with more uncertainty and does not address the root cause of climate change.

Alternative approaches of linking climate impacts to the economy work through their effects on growth, rather than output. There is some empirical evidence in support of this path, but the results are not firmly established and it is difficult to see the causal path-ways. Nevertheless, some attempts have been made to estimate damages through their impacts on the capital stock. They indicate an increase in damage relative to the computable general equilibrium (CGE) model approach, but not a large one Further work is needed in this area.

Adaption can make a major contribution to reducing damages from climate change for all mitigation scenarios, and more so when mitigation is absent or limited. Adaptation will require both private and public actions. Public action may need to be at least as large as private action initially, but by 2100 the main focus will be on private action. If undertaken optimally, at a cost of less than 0.5 precent of GDP, adaptation could remove up to around 70 percent of damages by the end of the century, at a cost that would leave net damages considerably reduced.

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