Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO_2 emissions

Mario Molina[a], Durwood Zaelke[b,1], K. Madhava Sarma[c], Stephen O. Andersen[d], Veerabhadran Ramanathan[e], and Donald Kaniaru[f]

[a]Department of Chemistry and Biochemistry, University of California, San Diego, 9500 Gilman Drive, MC 0356, La Jolla, CA 92093; [b]Institute for Governance and Sustainable Development, and International Network for Environmental Compliance and Enforcement, 2300 Wisconsin Ave., NW, Washington, DC 20007; [c]Montreal Protocol Technology and Economics Assessment Panel, AB 50, Anna Nagar, Chennai, India 600040; [d]Montreal Protocol Technology and Economic Assessment Panel, 2317 North Road, Barnard, VT 05031-0257; [e]Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla CA 92093-0221; and [f]National Environment Tribunal of Kenya, Woodvale Grove, Sarit Centre, Nairobi, Kenya

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Current emissions of anthropogenic greenhouse gases (GHGs) have already committed the planet to an increase in average surface temperature by the end of the century that may be above the critical threshold for tipping elements of the climate system into abrupt change with potentially irreversible and unmanageable consequences. This would mean that the climate system is close to entering if not already within the zone of "dangerous anthropogenic interference" (DAI). Scientific and policy literature refers to the need for "early," "urgent," "rapid," and "fast-action" mitigation to help avoid DAI and abrupt climate changes. We define "fast-action" to include regulatory measures that can begin within 2–3 years, be substantially implemented in 5–10 years, and produce a climate response within decades. We discuss strategies for short-lived non-CO_2 GHGs and particles, where existing agreements can be used to accomplish mitigation objectives. Policy makers can amend the Montreal Protocol to phase down the production and consumption of hydrofluorocarbons (HFCs) with high global warming potential. Other fast-action strategies can reduce emissions of black carbon particles and precursor gases that lead to ozone formation in the lower atmosphere, and increase biosequestration, including through biochar. These and other fast-action strategies may reduce the risk of abrupt climate change in the next few decades by complementing cuts in CO_2 emissions.

biosequestration | black carbon | hydrofluorocarbons | tipping points | tropospheric ozone

The stated goal of international climate policy is to avoid "dangerous anthropogenic interference" (DAI) with the climate system (1). Establishing a DAI threshold cannot be based on science alone. It involves social and political judgments about acceptable outcomes and risks, including considerations of the precautionary principle, interpersonal equity, and a sense of "carbon justice" to protect the most vulnerable. As illustrated by the *Stern Review* (2), considerations of economic costs and impacts and economic well-being also inform DAI threshold analyses.

Dangerous Anthropogenic Interference

Meinshausen et al. (3) report that >100 countries have set the threshold for DAI at a 2 °C increase above preindustrial temperatures and calculate probabilities of staying below this limit for various levels of greenhouse gas (GHG) emissions. They calculate a 75% chance of staying <2 °C if total emissions from 2000 to 2050 are <1,000 billion tonnes (Gt) CO_2 (3), increasing CO_2 by 128 parts per million (ppm). Hansen and Nazarenko (4) define DAI in terms of "melting ice and sea level rise," and Hansen et al. (5) recommend an initial maximum of 350 ppm CO_2 as the appropriate target, which Meinshausen et al. (6) calculate will have a >75% chance of staying <2 °C. The Alliance of Small Island States calls for the more aggressive goals of stabilizing temperatures below a 1.5 °C increase and maximum of 350 ppm CO_2-equivalent (CO_2-eq.) (7).

Tipping Points for Abrupt Climate Change. Paleoclimate records include steady linear changes as well as abrupt nonlinear changes, where small increases in average surface temperature produced qualitatively different modes of operation of the climate system that were irreversible on a timescale of millennia (5, 8). Lenton et al. (8) extend the concept of abrupt climate change to include "tipping points" that refer to a critical threshold at which a very small perturbation can switch the state of a system to a qualitatively different one, possibly on a long time scale. They define the corresponding "tipping elements" as large-scale components of the Earth's system that are at least subcontinental in scale.

There are large uncertainties associated with tipping points, which are often considered as examples of "surprises." Ramanathan and Feng (9) estimate the likelihood of reaching the predicted critical temperature threshold that triggers various tipping elements by considering the probability distribution for the temperature increase associated with the "committed" level of warming, which these authors report to be 2.4 °C (1.4–4.3 °C). This is the estimated average surface temperature increase above preindustrial values that would take place if the concentrations of GHGs were held constant at their 2005 values, but without aerosol forcing, land surface albedo changes, or any other anthropogenic forcing; that is, the 2.4 °C value is based on past emissions and is comprised of 0.76 °C observed surface warming plus 1.6 °C additional warming lagged in the oceans and "masked" by cooling aerosols (9). Fig. 1 presents their results for various policy-relevant tipping elements (9), most of which Lenton et al. (8) include in their analysis; for elimination of Arctic summer sea ice and melting of the Himalayan-Tibetan glaciers and the Greenland Ice Sheet, the probability that the committed warming exceeds the tipping point temperature is estimated to be larger than 50%, and it is estimated to be >10% for dieback of the Amazon Rainforest, more persistent and higher amplitude El Niño conditions, reorganization of the North Atlantic Thermohaline Circulation, and melting of the

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[1]To whom correspondence may be addressed. E-mail: dzaelke@igsd.org or zaelke@inece.org.

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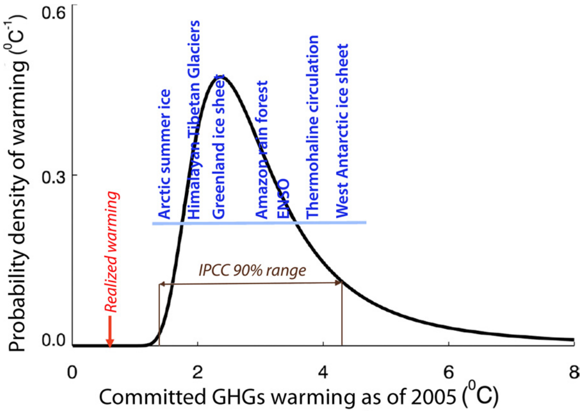

Fig. 1. "Probability distribution for the committed warming by GHGs between 1750 and 2005. … Shown are the tipping elements [large-scale components of the Earth's system] and the temperature threshold range that initiates the tipping…." Reproduced from Ramanathan and Feng (2008) (9).

West Antarctic Ice Sheet. The transition time scales estimated for these tipping elements vary from as little as 10 years for loss of summer sea ice in the Arctic to 50 years for Amazon and other forest die-off, to 300 years, at the low end, for melting of the Greenland Ice Sheet, and 300 years as the worst-case scenario for the collapse of the West Antarctic Ice Sheet (8, 9). Even if the actual warming is less severe than estimated by Ramanathan and Feng (9), the probability that threshold temperatures will be reached for several of the identified tipping points is very significant if emission of GHGs continues along the current path.

The potential consequences associated with these tipping points may be largely irreversible and unmanageable (10) and include widespread loss of biodiversity, meters of sea level rise, and famine, which could lead to political instability (9, 11). In a worst-case scenario, climate change could produce runaway feedbacks, such as methane release from permafrost (12).

Current Climate Policy. International climate policy has focused primarily on long-term reductions of CO_2 emissions, for example, through increased energy efficiency, renewable energy sources, and other low-carbon strategies. Despite the availability of mitigation strategies that are low-cost and even profitable (13), the United Nations Framework Convention on Climate Change (UNFCCC) reports that developed country Parties to the Kyoto Protocol—excluding former Soviet countries with economies in transition—had increased their emissions 9.9% above 1990 levels by 2006, and only economic slowdown by countries with economies in transition has produced real reductions (14). Non-Parties advocating a separate approach have not done better.

Even when CO_2 emissions stop, climate change is largely irreversible for 1,000 years (15, 16). Efforts to limit CO_2 emissions alone may not be sufficient to avoid or reduce the risk of DAI on a decadal time scale, including the risk of abrupt climate change from committed warming (8, 9).

Available Fast-Action Mitigation Strategies. In response to these challenges, there is growing demand among governments and commentators for fast-action mitigation to complement cuts in CO_2 emissions, including cuts in non-CO_2 climate forcing agents, which together are estimated to be as much as 40–50% of positive anthropogenic radiative forcing (17, 18).

Island countries are calling for "fast-action" mitigation strategies to avoid sea level rise, including strategies to cut hydrofluorocarbons (HFCs) and black carbon (BC) and to expand biosequestration (19–21). The 2008 *Major Economies Forum Declaration* calls for "urgent action" to strengthen the Montreal Protocol for climate protection (22). The 2009 *G8 Leaders Declaration* calls for "rapid action" on BC and pledges to ensure HFC reductions (23). The 2009 *North American Leaders Declaration* commits to phasing down HFCs under the Montreal Protocol (24). The 2009 Arctic Council *Tromsø Declaration* urges "early actions" on short-lived climate forcers (25) including tropospheric ozone. A *Nature* editorial in July 2009, *Time for early action*, calls for "early action" on BC and methane, and on HFCs under the Montreal Protocol (26), and another in April 2009, *Time to act*, notes "short-term opportunities" to cut BC and methane (27). Wallack and Ramanathan call for action on BC and tropospheric ozone in their 2009 policy paper in *Foreign Affairs* to produce "rapid results" (28).

We discuss four of the available fast-action regulatory strategies that can begin within 2–3 years and be substantially implemented within 5–10 years, with the goal of producing desired climate response within decades. The first is to phase down the production and consumption of HFCs with high global warming potential (GWP), accelerate the phase-out of hydrochlorofluorocarbons (HCFCs), and recover and destroy stratospheric ozone-depleting GHGs in discarded products and equipment. The second is to reduce emissions of BC, giving priority to emissions that affect regions of snow and ice, including the Arctic, Greenland, and the Himalayan-Tibetan glaciers. The third is to reduce pollutant gases that lead to formation of tropospheric (lower atmosphere) ozone, a significant GHG. The fourth is to expand biosequestration through improved forest protection and biochar production.

1. Strengthening the Montreal Protocol

Current Climate Mitigation from the Montreal Protocol. The Montreal Protocol is widely considered the most successful environmental treaty, phasing out almost 100 ozone-depleting chemicals by 97% and placing the ozone layer on the path to recovery by mid-century (18). It also is the most successful climate treaty to date, because chlorofluorocarbons (CFCs) and most other ozone-depleting substances (ODSs) that it has phased out are powerful GHGs with high GWPs that contribute 12% of the radiative forcing from long-lived GHGs and 20% of net anthropogenic forcing in 2005 (29).

From 1990 to 2010, the Montreal Protocol's controls on production and consumption of ODSs will have reduced GHG emissions by the equivalent of a net 135 Gt CO_2, which is equivalent to 11 Gt CO_2 per year (30). Considering only the direct warming effect, these actions of the Montreal Protocol delayed the increase in climate forcing from CO_2 by 7–12 years (30). The total delay in climate forcing is 31–45 years, when early voluntary and national actions to reduce ODSs are included, beginning with the early warning in 1974 (30, 31). Without early action, ODS emissions would have reached an estimated equivalent of 24–76 Gt CO_2 per year in 2010, and these emissions would have contributed nearly as much radiative forcing as anthropogenic emissions of CO_2 (30).

Key Features of Montreal Protocol Success. The Montreal Protocol's governance provides insights for other fast-action climate mitigation strategies and is consistent with a sectoral approach for controlling climate forcing. The Montreal Protocol's orderly chemical phase-outs allow markets to innovate and adjust, and its "critical use" exemptions provide a safety valve when environmentally acceptable options are not yet available. The Montreal Protocol started modestly, learned by doing, and was strengthened continuously by adding additional controlled substances through amendments and accelerating phase-outs of existing controlled substances through "adjustments" and other consensus-based decisions. Adjustments approved by the Meetings of the Parties take effect automatically without further ratification by each Party.

The Montreal Protocol's three Assessment Panels report to the Parties annually or more often as required. Through 2011, the dedicated Multilateral Fund (MLF) will have provided nearly US $3 billion in "agreed incremental costs" in 3-year cycles based on an independent calculation by the Protocol's Technology and Economic Assessment Panel (TEAP) of the funding needed to ensure that developing country Parties can meet their mandatory obligations for ODS control measures. The MLF allocates funds using "double majority" voting, with a majority of both developing and developed country Parties needed for approval.

The Montreal Protocol's vigorous implementation of the principle of common but differentiated responsibility for all 195 Parties includes a typical 10-year grace period for developing country Parties to phase out chemicals, as well as dedicated funding through the MLF. It is supported by national ozone units in 146 developing countries, continuous capacity building, nine worldwide networks of these units that learn from each other, and compliance assistance backed up with trade measures for noncompliance.

Additional Climate Mitigation from the Montreal Protocol: Phasing Down High-GWP HFCs. The accelerated phase-out of HCFCs agreed by Montreal Protocol Parties in 2007 is estimated to provide up to 16 Gt CO_2-eq. in climate mitigation by 2040 (32). At their annual meeting in 2008, the Parties provided a 3-year replenishment of US $490 million to assist developing country Parties meet their HCFC commitments. To realize the full climate mitigation potential from the accelerated phase-out of HCFCs, however, low-GWP alternatives must be used to satisfy the demand for products that would otherwise have used either high-GWP HFCs or HCFCs.

The Montreal Protocol Parties started a dialogue with the UNFCCC and other stakeholders in 2008 to "discuss technical and policy issues related to alternatives for ozone-depleting substances, with a particular focus on exchanging views of the best ways of how the experience from the Montreal Protocol can be used to address the impact of hydrofluorocarbons on climate, and also with a view to maximizing the stratospheric ozone and climate benefits of the hydrochlorofluorocarbon early phase-out under the Montreal Protocol" (33).

The European Council notes that the accelerated phase-out of HCFCs may lead to rapid increase in HFC emissions and suggests that "the Copenhagen agreement should include an international emission reduction arrangement for HFC emissions. This will encourage industry to step up intensified research into and development of chemicals with low global warming potentials and HFC-free alternatives" (34). The European Council wants any arrangement to "contribute toward meeting the EU's 30% commitment" under any climate treaty (35).

The Montreal Protocol can be applied to reduce HFCs because like ODSs, but unlike CO_2, HFCs are used in manufactured products, and are not simply unwanted by-products of industrial and agricultural processes. (The exception is the HFC-23 by-product from the production of HCFC-22.) Reducing HFC production and consumption, and hence the opportunity to reduce later emissions, can be done by regulating HFCs under the Montreal Protocol. It is indicative of the market forcing power of regulation that six low-GWP substitutes were announced by chemical companies just weeks after the European F-Gas Directive set the schedule for phasing out HFC-134a refrigerants in automobile air-conditioning (36). The refrigerant currently offering the highest reduction in total GHG emissions in automobile AC is HFO-1234yf, which has a GWP <4, and along with natural refrigerants such as hydrocarbons (GWP < 5) and CO_2 (GWP $= 1$) are likely suitable for most refrigeration and air-conditioning applications currently using HFC-134a, which has a GWP of 1,440. Natural refrigerants can also replace high-GWP HFCs in other applications. The Montreal Protocol TEAP estimates that global transition from HFC-134a to HFO-1234yf in vehicle air-conditioning can be accomplished in 7 years or less worldwide, eliminating $>30\%$ of current HFC emissions (37).

Velders et al. (38) estimated scenarios for HFC emissions derived from gross domestic product and population growth and incorporating information on demand for HCFC products in developing countries, patterns of replacements of HCFCs by HFCs, and increases in HFC-134a use in mobile air-conditioning. Global HFC emissions in 2050 are projected to be 5.5–8.8 Gt CO_2-eq. per year, which is equivalent to 9–19% of projected global CO_2 emissions in business-as-usual scenarios. Global HFC emission projections increase strongly after 2013 and significantly exceed previous estimates after 2025. Without regulatory action, global radiative forcing from projected HFC emissions in 2050 will be equivalent to that from 6 to 13 years of CO_2 emissions. The HFCs contribute a radiative forcing of 0.25–0.40 Wm^{-2} in 2050 compared to CO_2 values of 2.9–3.5 Wm^{-2} (38).

Relying on the Velders et al. estimates and facing the threat of sea level rise, a group of island nations led by the Federated States of Micronesia and Mauritius proposed an amendment to the Montreal Protocol that would provide jurisdiction over the production and consumption of HFCs and that would use the technical expertise and administrative structure of that treaty to start quickly phasing down HFCs with high GWPs (39). The United States, Canada, and Mexico followed with a similar joint proposal (77). In both cases, emissions of HFCs could be left in the Kyoto Protocol basket of gases.

Additional Climate Mitigation from the Montreal Protocol: Collecting and Destroying Banks. Up to 6 Gt CO_2-eq. by 2015 and an additional 14 Gt CO_2-eq. thereafter can be avoided by collecting and destroying "banks" of ODSs that would otherwise be emitted from unwanted stockpiles and discarded refrigeration and air-conditioning equipment and insulating foam (17, 40). An additional 5 Gt CO_2-eq. can be avoided by 2015 by recovering and destroying discarded HFCs in these sectors (17). The Montreal Parties agreed at their 2008 annual meeting to begin pilot projects to accomplish these goals (33). The European Council notes that within "the context of the Montreal Protocol possibilities are currently being assessed and explored of how to reduce emissions of high Global Warming Potential ozone depleting substances (e.g., CFCs, HCFCs) stored in products and equipment" (35).

In sum, the Montreal Protocol, with >20 years of success, is seen by a growing number of countries and commentators as a regulatory framework that can ensure significant additional climate mitigation on a decadal time scale to help reduce the threat of DAI and abrupt climate change.

2. Reducing Emissions of BC

BC (or soot) is an aerosol and is among the particle components emitted from the incomplete combustion of fossil fuels and biomass. BC causes warming in two ways. First, BC in the atmosphere absorbs solar radiation, which heats the surrounding air; second, deposition of airborne BC can darken snow and ice and accelerate melting (29). In addition, aerosols containing BC can alter cloud formation processes that can indirectly change climate: solar heating of cloudy air can burn off low-level stratus and cumulus clouds (41), which in turn will let more solar radiation penetrate to the surface and amplify the global warming effects of BC. However, when BC is mixed with other water soluble aerosols (e.g., sulfates), it can lead to more cloud drops and more persistent low-level clouds, which reflect more solar radiation and cool the surface (29). It is clear, though, that reducing BC emissions can provide fast climate response (42), because it has an atmospheric lifetime of only days to weeks.

BC is estimated to be the second or third largest warming agent, although there is uncertainty in determining its precise radiative forcing. There is also uncertainty in determining the relative warming effects of BC compared to cooling aerosols such as sulfates, as discussed by Myhre (43). Calculations of BC's direct climate forcing vary from the Intergovernmental Panel on Climate Change (IPCC) estimate of $+0.34\ Wm^{-2}$ ($\pm$ 0.25) (29) to the estimate by Jacobson (44) in the range of 0.5 to 0.75 Wm^{-2} and Ramanathan and Carmichael of $+0.9\ Wm^{-2}$ (with a range of 0.4 to 1.2 Wm^{-2}), which is 55% of CO_2 forcing and larger than CH_4, CFCs, N_2O, or tropospheric ozone (42). The IPCC estimates that BC's additional forcing from deposition on snow and ice is approximately $+0.1\ Wm^{-2}$ ($\pm$0.1) globally (29).

As a result of various feedbacks, Flanner et al. (45) estimate that BC on snow may produce warming that is approximately three times greater than would be caused by an equal forcing of CO_2. Shindell and Faluvegi (46) estimate that BC may be responsible for ~0.5–1.4 °C of the 1.9 °C warming observed in the Arctic from 1890 to 2007. Quinn et al. (47) suggest that BC from northern Eurasia, North America, and Asia may have the greatest absolute impact on the Arctic, and that reducing emissions from local source regions could mitigate Arctic warming on a more immediate time scale than CO_2 reductions. Hansen and Nazarenko (4) estimate that reducing BC emissions to restore snow albedo "would have the double benefit of reducing global warming and raising the global temperature level at which dangerous anthropogenic interference occurs."

In the Himalayan region, Ramanathan and Carmichael (42) estimate that solar heating from BC at high elevations may be as important as CO_2 for melting snow and ice, and their model simulations indicate that approximately 0.6 °C of the 1 °C warming in the Tibetan Himalayas since the 1950s may be due to atmospheric BC. Flanner et al. (48) estimate that BC and copollutants may be responsible for nearly as much total springtime snow melt in Eurasia as anthropogenic CO_2, and that eliminating these emissions could restore up to 25% of the ice cover lost since preindustrial times. This large warming trend is the proposed causal factor for the accelerating retreat of Himalayan-Tibetan glaciers, which threatens fresh water supplies and food security in China and India (9). The IPCC (49) projects that the surface area of Tibetan Plateau glaciers will shrink to 100,000 km^2 by 2030 from 500,000 km^2 in 1995. The Institute of Tibetan Plateau Research in China (50) estimates that under current trends, two-thirds of the plateau glaciers could disappear by 2050 and recommends reducing BC as a priority.

Globally, Cofala et al. (51) estimate that BC can be reduced by approximately 50% with full application of existing technologies by 2030, primarily from reducing diesel emissions and improving cook stoves. Wallack and Ramanathan (28) estimate that it may be possible to offset the warming effect from one to two decades of CO_2 emissions by reducing BC by 50% using existing technologies.

Replacing traditional cooking with efficient BC-free stoves may reduce BC warming by 70–80% over South Asia and by 20–40% over East Asia (42). According to a recent synthesis and assessment by the U.S. Climate Change Science Program (52), it appears that BC reductions from Asia domestic fuel use offers the greatest potential to substantially and simultaneously improve local air quality and reduce global warming. Reductions in BC from diesel emissions would also have a large impact (52). According to Quinn et al. (47), another strategy is to reduce "prescribed agricultural burns in eastern Europe so that black carbon emission and deposition does not occur in spring as radiation is increasing and the area of snow/ice pack is large." In addition to its potential climate benefits, reducing BC is justified for public health reasons. With approximately 50% of the world still using fossil fuels for cooking, indoor air pollution from BC is associated with respiratory illness, the fourth leading cause of excess mortality in developing countries (28).

Strategies to reduce BC could borrow existing management and institutions at the international and regional levels, including existing treaty systems regulating shipping (53) and regional air quality (54). International financial institutions could use climate and health funds to obtain the cobenefits of BC reductions. Regional and bilateral partnerships could accelerate BC reductions as well. These could include partnerships among Arctic countries, as well as partnerships within existing bilateral relationships between the European Union and India, between the United States and China, and between the United States and Mexico. BC reductions also could be accomplished by coordinating climate policy with local air pollution policies, including local policies reducing sulfates and other cooling aerosols. Schellnhuber (12) notes that reducing BC ahead of cooling aerosols can reduce the risk of DAI.

3. Reducing Tropospheric Ozone

Ozone in the lower atmosphere (tropospheric ozone) is a major pollutant and a significant GHG. Human activities do not emit ozone directly, but add pollutant gases such as carbon monoxide (CO), nitrogen oxides (NO_x), methane, and other nonmethane volatile organic compounds (VOCs). These "ozone precursor" gases undergo complex photochemical reactions and form ozone in the initial 10–15 km above the ground. Because of the large increase in methane, CO, VOCs, and NO_x since the preindustrial era, tropospheric ozone has increased by ≈30% (55), and its contribution to global warming is as much as 20% of that due to CO_2 (29). Tropospheric ozone is toxic to humans and plants including crops. The recent ozone report published by the Royal Society notes that in 2000 ozone damage to crops was estimated from $14–26 billion annually, threatening food security in developing and developed nations (56). Ozone may reduce the effectiveness of land-based carbon sinks (56).

The Royal Society (56) estimates that rigorous global implementation of air pollution regulations and available technologies, including for shipping and aviation, can reduce NO_x and CO emissions by >50%, which would reduce the anthropogenic tropospheric ozone forcing from 20 to 10% (29). That reduction in ozone forcing would delay by ≈10 years' time when the threshold for DAI would otherwise have been passed (28). Molina and Molina (57) show how cooperation between scientists and policy makers can help craft tropospheric regulation that will also protect the climate.

4. Expanding Sinks through Biosequestration

Biological sequestration (biosequestration) "includes direct removal of CO_2 from the atmosphere through land-use change, afforestation, reforestation, carbon storage in landfills, and practices that enhance soil carbon in agriculture" (58).

Forests. As reported by the IPCC, Sohngen and Sedjo (59) estimate that forests may be able to provide global climate mitigation of 278 Gt CO_2 >50 years. Canadell et al. (60) estimate current emissions from deforestation to be 1.5 Gt C, or 5.5 Gt CO_2 per year, the vast majority from deforestation in tropical regions. McKinsey & Company (13) estimate reducing emissions from deforestation and degradation can provide mitigation up to 5.1 Gt CO_2-eq. per year by 2030. The *Stern Review* (2) notes mitigation from reduced deforestation is "highly cost-effective." McKinsey & Company (13) calculate that afforestation can provide mitigation of 1.0 Gt CO_2-eq. per year by 2030, reforestation 1.4 Gt CO_2-eq. per year by 2030, and improved management another 0.3 Gt CO_2-eq. per year by 2030.

Biochar Production. Like other biosequestration strategies, biochar technology captures CO_2 through plant photosynthesis. The captured carbon is then converted into a stable charcoal-like substance called "biochar," with estimates of characteristic storage time varying from hundreds to thousands to tens of thousands of years (61). The process is pyrolysis, that is, high-temperature decomposition in an oxygen-deprived environment (61). In addition to its potential to replenish long-term carbon sinks, biochar can be a beneficial soil amendment, as noted by a recent review of published literature by Sohi et al. (61). These authors report that although biochar is increasingly being promoted by climate policy makers, relatively few studies provide a quantitative assessment of biochar soil management scenarios, and some of the fundamental mechanisms of the interaction of biochar with the soil require further research (61).

Pyrolysis also produces bio-gas and bio-oil that can displace fossil fuel use (62, 63), making it a potential "carbon negative" source of energy (64). Feedstocks for biochar production are widely available (61, 62), and the technology exists for rapid biochar deployment, including mobile or stationary units for use at local or regional levels (64). At household level, fuel-efficient cookstoves can produce biochar and reduce emissions of BC (65).

The International Biochar Initiative estimates that biochar production has the potential to provide 1 Gt carbon per year in climate mitigation by 2040, or 3.67 Gt CO_2 per year, using only waste biomass (66). Hansen et al. (5) estimate that if slash-and-char agriculture replaced slash-and-burn practices, and if agricultural and forestry wastes were used for biochar production, it would be possible to drawdown CO_2 concentrations by approximately 8 ppm or more within half a century, or $\approx$62.5 Gt CO_2. According to Sohi et al. (61), the global potential for annual sequestration of CO_2 may be "at the billion-ton scale" within 30 years, although they note that the published evidence is largely from small-scale studies and cannot be generalized to all locations and types of biochar. Under an aggressive scenario, where all projected demand for renewable biomass fuel is met through pyrolysis, Lehmann et al. (62) estimate that biochar may be able to sequester 5.5–9.5 Gt C per year, or $\approx$20–35 Gt CO_2, per year by 2100. Lenton and Vaughan (67) suggest that the capture of atmospheric CO_2 by plants to provide bio-energy followed by carbon capture and storage, combined with afforestation and biochar production, may have the potential to remove 100 ppm of CO_2 from the atmosphere under the most optimistic scenarios and reduce radiative forcing by 1.3 Wm^{-2}. However, this may conflict with food production and ecosystem protection (67).

Biosequestration through biochar production may be able to be deployed rapidly and relatively cheaply on a decadal time scale (68) using both regulatory and market-based approaches at national, regional, and global levels. The United Nations Convention to Combat Desertification has proposed including biochar in the UNFCCC climate negotiations (69). The island countries include biosequestration as a fast-action strategy in the work program proposed in the UNFCCC negotiations (70). Forests are being discussed in the negotiations for the post-2012 climate treaty (71). Given the size and relative speed of the potential mitigation available from the forestry sector, protecting and expanding forests appears to be an important fast-action climate mitigation strategy for reducing DAI, although the absence of a robust international or regional governance structure makes this challenging.

Conclusion

Faced with serious and largely irreversible changes to large components of the Earth's climate system, a comprehensive climate policy can benefit from considering all sources of warming and all mitigation options. Besides considering CO_2 emission reductions, it could emphasize strategies that can produce the fastest climate response. This selection process would be aided by a metric focusing on the importance of time required to produce actual mitigation and actual cooling. For example, Jacobson (72) takes into account the time to deliver energy technologies for mitigation, and Velders et al. (30, 38) use the metric of years-of-delay in climate forcing in their analysis as a measure of climate benefits from the Montreal Protocol.

The fast-action strategies discussed here could be implemented within the next 5–10 years and lead to climate response within decades or sooner. HFCs, BC, tropospheric ozone, and other short-lived forcers can be addressed in large part through existing treaties as well as through coordinated local air pollution policies, along with funding and technology transfer through existing institutions. As noted by Pachauri (73), there is an important role for regulation to advance climate mitigation, including mandatory standards and codes in various sectors. Regulatory standards, including phase-downs, provide policy certainty to drive investment and innovation needed to accelerate solutions as shown by the Montreal Protocol, although market-based approaches also will be needed to expand biosequestration. Strong compliance mechanisms are needed to ensure the integrity of all climate mitigation (74, 75).

Fast-action strategies to avoid DAI are supported by the precautionary principle embodied in the UNFCCC and the existing obligation on all Parties to implement national policies and measures to reduce GHG emissions and enhance sinks, with the extent of actions by developing country Parties dependent upon assistance from developed country Parties. Fast-action strategies also are called for by the commitment in the *Bali Action Plan* to take action "now, up to and beyond 2012" (76). They can complement strategies for adapting to the effects of climate change by delaying warming for several decades, reducing adaptation costs, and mitigating risks to ecosystems and economic prosperity.

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