TRADEABLE PERMITS AND GREENHOUSE GAS REDUCTIONS: SOME ISSUES FOR U.S. NEGOTIATORS

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TABLE OF CONTENTS

FOREWORD iii

EXECUTIVE SUMMARY iv

0. INTRODUCTION 1

1. SOME GENERAL ISSUES 7
   1.1 Equity 7
   1.2 Verification and Enforcement 15

2. SOME SCIENTIFIC ISSUES 19
   2.1 Natural greenhouse gas sinks 20
   2.2 The Science of Greenhouse Gas Budgets 22
      2.2.1 The General Issue of Scientific Uncertainty 22
      2.2.2 Prospects for reducing uncertainty 24
      2.2.3 Global budgets for greenhouse gases 24
         2.2.3.1 Carbon Dioxide (CO_2) 24
         2.2.3.2 Nitrous Oxide (N_2O) 32
         2.2.3.3 Methane (CH_4) 34
         2.2.3.3 Tropospheric Ozone (O_3) 39

3. ARGUMENTS AGAINST A STEPWISE APPROACH 40

4. CONCLUSION 49

FIGURES AND TABLES 54

FOREWORD

This report is the first in a series of three papers on policy alternatives to reduce greenhouse gases. Two additional papers, one on a CO_2 offset policy, and another on carbon taxes, will be released by Harvard's Global Environmental Policy Project later this year.

Over the course of the last year, a number of response strategies have been suggested in the course of the process leading up to international negotiations on global climate change. Carbon taxes, offset policies and tradeable permits have been among the options which have been most actively discussed.

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EXECUTIVE SUMMARY

This paper explores the feasibility of implementing a comprehensive program of tradeable permits to control all greenhouse gases. It closely examines the sources and sinks of four gases that directly contribute to global warming (CO_2, N_2O, CH_4, and O_3) as well as those of an indirect contributor (CO).

In recent months, concern over an enhanced greenhouse effect has yielded interest in an international convention to control greenhouse gas concentrations. Although the question of whether such gases should be controlled remains unresolved, several proposals have already appeared for control mechanisms. One of these mechanisms is the utilization of a comprehensive market-based approach to greenhouse abatement. This approach is termed "comprehensive" because it would include all the main greenhouse gases -- carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and tropospheric ozone (O_3) -- and perhaps even carbon monoxide (CO) (which indirectly contributes to the greenhouse effect.) Most other proposed approaches have focussed only on CO_2 (e.g. a carbon tax). (CFCs are not considered in the discussion here because they are already controlled under the Montreal Protocol on Substances that Deplete the Ozone Layer.)

The approach is termed "market-based" because it would utilize a global system of tradeable greenhouse gas emissions permits. Under this system, each nation would be allocated a target level of greenhouse gas emissions, and the nation would then allocate permits to emitters that allow emissions up to the targets. Emitters could use those permits on their own, sell or lease them to other emitters, and/or augment their permits with

purchases of additional permits. National as well as international trading on "greenhouse markets" would be permitted. Emissions of greenhouse gases would be debited against the permits of the emitters. Conversely, absorption of greenhouse gases from the atmosphere -- e.g. by investments in afforestation, which removes atmospheric CO_2 -- would be credited to the emitters who made such investments.

Each year, the books must balance so that the total net emissions from an emitter do not exceed the number of permits held. One could imagine other features of the tradeable permits system such as requirements that excessive net emissions in one year be compensated for in subsequent years; or, there might be large fines or trade sanctions for excessive net emissions. Other structures for a global system of tradeable permits are also possible, but the basic principles would not change.

The main advantage of an international tradeable permits system is that it would provide opportunities for market forces to work on a global level. For example, U.S. auto manufacturers may find it cheaper to purchase extra emissions permits from industries in Brazil than to reduce CO_2 emissions by dramatically increasing the fuel efficiency of their cars. Additionally, because the proposed system would be comprehensive (includes all greenhouse gases) there would be opportunities to lower abatement costs by concentrating on reductions where the cost of abatement is lowest. For example, China may find it is less expensive to limit methane emissions from its rice paddies than to place stringent controls on CO_2 emissions from its coal-fired power plants. In general, the comprehensive market-based

approach could allow considerable flexibility which can help nations achieve a prescribed level of greenhouse abatement at lower costs. This is in contrast to existing "command-and-control" pollution strategies which are typically more rigid and expensive.

In addition to the advantages of using the market to reduce emissions, a tradeable permits system has certain advantages over other market approaches such as taxes. With tradeable permits, the total emissions of greenhouse gases would be limited by the number of permits issued. Assuming all nations abide by the agreement, the fixed number of permits would effectively cap the net emissions of greenhouse gases. In contrast, with a tax based system there is no inherent cap. Further, a tax-based system presents the sticky problem of what level the tax should be set at; if the tax is too low then emissions will be too high and vice-versa.

This paper argues that this proposed global system of comprehensive tradeable permits is flawed, because it ignores the details. These concerns fall into three categories: 1) ethical issues; 2) lack of scientific knowledge; and 3) difficulties in monitoring and verification.

1) Ethical Issues

Some nations will invariably raise moral objections against creating a tradeable "right to pollute." This objection will likely be coupled with legitimate fears of "eco-imperialism" since a system of tradeable permits might allow developed nations to "buy up the environment," effectively reducing economic growth by limiting the emissions of greenhouse gases in developing countries. However, transfers of technology and funds from North to

South might accompany international permit trading which could allay some of these economic fears. Still, developing countries -- even if they agree to the principles of marketable permits -- will likely want assurances that such technology and capital flows will occur.

2) Lack of Scientific Knowledge

It is difficult to bundle all greenhouse gases into a single, comprehensive tradeable permits system. The greenhouse effect is caused by a variety of different greenhouse gases, and each gas makes a different contribution to the problem. Presumably, sources (and sinks) of these gases could be weighted according to their global warming potential (GWP). However, any GWP index that claims to account for all of the relevant factors must also be based on a number of controversial and uncertain assumptions. This is most evident in the discussion of carbon monoxide (CO) emissions, but these problems of scientific uncertainty affect nearly all parameters used to compute GWPs for the gases considered in this paper.

3) Monitoring and Verification

Not enough is known about how much of each gas is emitted by each country to monitor and verify a comprehensive, global system of tradeable permits. The largest section of this paper consists of a detailed analysis of this problem, including a gas by gas description of the sources, sinks and uncertainties.

For CO_2 it is conceivable that sufficient data could be collected to adequately verify anthropogenic sources and sinks on a country by country basis. For the other gases the prospect of collecting sufficient country specific information on sources and sinks is dim at present. Because of this, any comprehensive approach -- especially a comprehensive system of tradeable permits -- may be unworkable.

Further, it may not be economically desireable to pursue a comprehensive system of tradeable permits. In the case of methane (a strong greenhouse gas) it is hypothesized here that the costs of developing a monitoring and verification apparatus for use with a global system of tradeable permits might be so large that these costs might consume much of the economic benefits of using tradeable permits.

In sum, the comprehensive approach appears premature given the present state of greenhouse science. More is known about the sources and sinks of CO_2 than for the other gases, so in place of a comprehensive approach, one option is to start with controls on CO_2 and to expand the regime stepwise to include the other gases later on (as the scientific knowledge about the sources and sinks of those gases improves). Controlling CO_2 will also, to some extent, control the emissions of other greenhouse gases since CO_2-emitting activities (fossil fuel combustion and deforestation) are also linked to the emissions of those gases.

In the final sections of the paper, this stepwise approach of starting with CO_2 is analyzed in more detail. If the tradeable permits mechanism is utilized, then starting with only CO_2 permits is technically feasible. However, once a CO_2 regime is in place it may be difficult to expand the market to other gases since permit holders in the "CO_2-only" market will

presumably object. Adding new permits to the market would devalue their existing permits. Also, the CO_2-only and stepwise approaches to tradeable permits do not resolve the moral arguments that a tradeable permits system will create an "eco-imperialistic regime."

Summation

Because the stakes in a greenhouse treaty are large, it makes sense to negotiate and sign an international agreement which minimizes the opportunities for cheating. This means that such a treaty must be verifiable and enforceable. At present, a comprehensive treaty which includes all sources and sinks of all gases does not satisfy this requirement because the sources and sinks are highly uncertain for all greenhouse gases except CO_2 (and, as just reviewed, the uncertainties are non-trivial even for CO_2). This suggests that while the comprehensive approach is an appealing goal for the greenhouse negotiations, at present the science probably only supports a CO_2 protocol. As the science improves, other protocols which control other gases might be included. It appears that the N_2O estimates are narrowing so it may be possible to include it in the near future. Possibilities for CH_4 are more distant. It is probably too difficult to include tropospheric O_3 (or, more precisely, emissions which form tropospheric O_3) at any point in the foreseeable future.

0. INTRODUCTION

Over the last two years, domestic and international attention has turned to the prospects for regulating global warming due to an enhanced greenhouse effect. At present, a general scientific consensus supports the theory of the greenhouse effect with its associated (generally negative) effects on public welfare due to shifts in sea level, agriculture, hydrology, and other integral components of modern society.[1] Although scientific dissent exists on the magnitude and timing of global warming,[2] the simple physics of the problem are relatively clear. That is, increased concentrations of so called "greenhouse gases" yields increased absorption of infrared radiation by the atmosphere which then forces changes in climate.[3] The most significant contributors to global warming are carbon dioxide (CO_2), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), methane (CH_4), and tropospheric ozone (O_3). The projected contributions of each of these gases to global warming is shown in Figure 1. CFCs are currently controlled by the Montreal Protocol to the Vienna Convention and are excluded from further discussion here because their inclusion would greatly complicate the practice and intentions of the ongoing Montreal protocol negotiations.[4] However, it is

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[1]J.B. Smith and D.A. Tirpak (eds.), 1989. The Potential Effects of Global Climate Change on the United States EPA Draft report to Congress. Also, S.H. Schneider, 1989. "The Greenhouse Effect: Science and Policy," Science 243:771-781.

[2]e.g. Marshall Institute, 1989. Scientific Perspectives on the Greenhouse Problem (Washington: Marshall Institute), 2 vols.

[3]Much (though not all) of the dissent focuses on the extent to which chemical, geological, or other feedback processes amplify or dampen the initial forcing due to increased concentrations of greenhouse gases.

[4]Most likely, the Montreal protocol will be expanded this year to include carbon tetrachloride (CCl_4), methyl chloroform (CH_3CCl_3) and several CFCs beyond the five CFCs currently controlled under the Protocol. This is important because in addition to the effects of these gases on ozone depletion, all of them are also greenhouse gases.

assumed that efforts to strengthen the Montreal control levels will continue since even small concentrations of CFCs can have a relatively large impact on climate.[5] It is currently expected that CFCs will be phased out in the next version of the protocol which is currently under negotiation.[6] If CFCs are not completely phased out then there may be opportunities to include CFC controls in a greenhouse treaty,[7] but that issue is not addressed here. In any case, the percentage contribution to global warming due to CFCs will probably be smaller than shown in figure 1 because of the binding CFC controls in the Montreal Protocol.[8]

For more on their role in the greenhouse effect see V. Ramanathan et al., 1987. "Climate-Chemical Interactions and Effects of Changing Atmospheric Trace Gases," Reviews of Geophysics 25(7):1441-1482.

[5]For a quantification of the impact it is typically stated that molecule-for-molecule at steady-state concentration in the atmosphere, CFCs are about 10,000 times more efficient than CO_2 as greenhouse gases. However, this figure is somewhat dependent upon the concentrations of the respective gases in the atmosphere.

[6]Not all nations have signed and ratified the protocol because they see CFC restrictions as contrary to their development plan. This may become an issue in the greenhouse discussions. If so, one option is to include CFCs in a greenhouse treaty. A second option is to exclude CFCs so that intransigence on the CFC issue does not preclude agreement on a greenhouse treaty. One compromise is to choose the second option but to require or urge nations which have not signed and ratified the Montreal protocol to do so. This may become a very sticky issue since large developing countries such as China and India which are important to having a broad international agreement on greenhouse gases have not, unfortunately, signed the Montreal Protocol.

[7]For example, a greenhouse treaty might mandate CFC controls which are more stringent than under the Montreal Protocol. Or, nations which pursue their own CFC cutbacks beyond the levels required under Montreal might receive greenhouse credits which they can use to relax controls on, for example, CO_2.

[8]Assuming that CFC alternatives (some of which are greenhouse gases) are added to the list of Montreal substances and/or atmospheric release of these CFC alternatives does not dramatically increase in the future. Also, some of the CFC alternatives are ozone-benign and, therefore, would not be controlled even in a strengthened Montreal Protocol. However, some of these ozone-benign alternatives are still greenhouse gases (e.g. CFC-134a) and, presumably, should be included in a greenhouse agreement if possible. This issue should be examined in the negotiation of a greenhouse treaty if it appears that these CFC alternatives are becoming (or will be) widely used. For a review of the ozone and global warming effects of the CFCs and their (presently known) substitutes see: World Meteorological Organization, 1990. Scientific Assessment of Stratospheric Ozone: 1989, Global Ozone Research and Monitoring Project report #20, especially volume 2 (available through NASA, Washington). Also see two papers based on the above report: D.A. Fisher et al., 1990. "Model calculations of the relative effects of CFCs and their replacements on global warming," Nature 344:513-516. And, D.A. Fisher et al., 1990. "Model calculations of the relative effects of CFCs and their replacements on stratospheric ozone," Nature 344:508-512.

Thus, the analysis presented here focuses on efforts to slow growth, stabilize, or even reduce the concentrations of the other four greenhouse gases: CO_2, N_2O, CH_4, and tropospheric O_3.[9]

It is widely agreed that both the sources and sinks for these gases are globally dispersed; the effects of climate change are also globally dispersed. Thus, a coordinated international response is required. However, some have suggested that a phase of unilateral activity to manage concentrations of greenhouse gases may or should precede an international phase.[10] In any case, it appears that a timely international agreement to control greenhouse gas concentrations would probably be a more efficient and effective approach to the problem than

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[9] Scientifically, this approach is appealing because it does not rely on the crude global circulation models (GCMs), but simply on the recognition that the greenhouse effect is a problem. Therefore, we should seek to control the concentrations or emissions of greenhouse gases and not worry about the details of the effects. Theoretically, it demands little from the greenhouse science except confidence that 1) these are the gases that cause the problem, and 2) that the problem is real.

However, it must be noted that the details of the science are very important for determining the control levels for greenhouse gas emissions or concentrations. Should we, for example, cut greenhouse gas emissions by 20%, or will the desired magnitude of climate change require a different cut, or no cut at all? This issue will pervade the bargaining process; in practice, it is expected that--as with the Montreal protocol--that the target levels will be set by the negotiating process and not simply some scientific projection for target levels. (The computer models clearly showed that a 95% cut in all CFCs would be required to achieve stabilized atmospheric chlorine levels; the 50% cut agreed to under the Montreal Protocol was a function of necessary compromise). These are serious and important issues, but the setting of target levels is not the focus of this paper.

[10] "Background Paper on Funding Mechanisms," Prepared by McKinsey and Company in October 1989 for the Ministerial Conference on Atmospheric Pollution and Climatic Change, with particular attention to global warming, 6th and 7th November 1989. The role of unilateral action is not insignificant. For example, in 1987, 21.7% of worldwide fossil fuel CO_2 emissions were from the United States (4.2% from natural gas; 9.6% from oil; 7.7% from coal; 0.2% from cement production and gas flaring). In terms of per-capita emissions, the U.S. is 4.5 times higher than the world average. For countries like the U.S. which are large emitters, even small unilateral cuts can make a big difference in the global CO_2 budget. Data from UN Energy Statistics processed at Oak Ridge National Laboratory at the Carbon Dioxide Information and Analysis Center. Procedures described in Oak Ridge Publication ORNL/CDIAC-25, Published May, 1989.

an erratic and expensive amalgam of uncoordinated individual state actions. (This argument assumes, of course, that some sort of mitigating policy response is warranted and that it is not better to wait and adapt to climate change.)

Among the proposals for controlling greenhouse gases is one which suggests that a greenhouse treaty should be comprehensive and should employ a system of tradeable permits. As described in the executive summary, the proposal is comprehensive in that it would include all sources and all sinks of all greenhouse gases. The tradeable permits feature allows nations and/or firms to internationally trade emission credits and sink debits and thus seek the lowest greenhouse abatement cost worldwide.[11] Although proposed together, the

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[11]See "U.S. Concept Paper: Comprehensive greenhouse gas approach to addressing climate change," filed with the IPCC on 29 December 1989 (Response strategies working group). See also "Discussion paper: A 'comprehensive' approach to addressing potential global climate change," presented at an informal seminar, 3 February 1990, U.S. Dept. of State. The intellectual background for this proposal is persuasively developed in B.A. Ackerman and R.B. Stewart, 1988. "Reforming environmental law: The democratic case for market incentives," Columbia Journal of Environmental Law 13:171-199. Also see the preceding article: R.B. Stewart, 1988. "Controlling environmental risks through economic incentives," Columbia Journal of Environmental Law 13:153-169. The idea of marketable permits has been explored in other fora as well. For example: Project 88: Harnessing market forces to protect our environment, A public policy study sponsored by Senators T.E. Wirth and J. Heinz. The Project 88 ideas are also described in R.N. Stavins, 1989. "Harnessing Market forces to protect the environment," Environment 31:4ff. For a review of past uses of marketable permits in the U.S. see "Using incentives for environmental protection: An overview," Congressional Research Service, 89-360 ENR. It is not irrelevant that the generally successful history of tradeable permits is based on cases where the pollutant sources are well understood and the scale was local or, at most, regional. This attitude--which broadly treats source regions as bubbles inside which users are free to trade permits--overlooks the critical importance of the spatial distribution of sources which, in turn, affects the spatial distribution of effects. Thus it does not acknowledge that some environments are more sensitive to the effects and deeper cuts while other environments are more tolerant. I do not specifically consider this problem in this document since the argument that you can't realistically do the "ideal" job of regulating pollution is persuasive. Nonetheless, there is much more to the problem of controlling acid rain in an effective, permit-based system than just issuing permits, devaluing them, and not worrying about where utilities actually locate power plants. For example, emissions from power plants which cause acid rain over sensitive lakes and forests should be weighed more heavily. For regional and global air pollution it is somewhat more complicated than Stewart supra p.168 has implied in the case of acid rain. Arguably, in this respect the greenhouse problem is simpler than acid rain since gases are globally mixed and thus the location of sources is less important. This is true for gases with long atmospheric lifetimes (i.e. CO_2 and N_2O) which are effectively well mixed in the global atmosphere, but this argument is less true for gases with shorter lifetimes (i.e. CH_4 and, especially, O_3 and CO) where the geographical position of the source vis a vis the natural sinks is an important factor in determining the relative greenhouse contribution from a certain pattern and magnitude of emissions. This issue will be raised again later in this memo.

ideas are somewhat distinct: a greenhouse treaty might have features of the comprehensive proposal and/or features of the marketable permit proposal. Thus the discussion below will, where possible, separate the two components and address the strengths and weaknesses independently. Throughout this discussion it is assumed that the scope of the comprehensive approach includes only anthropogenic sources and sinks; however, some issues related to natural sources and sinks will be discussed.

The appeal of the comprehensive market-based approach is based on three facts: 1) the cost of greenhouse abatement varies across national boundaries,[12] 2) the cost of greenhouse abatement varies across the different gases as well, and 3) different greenhouse gases have different magnitudes of climatic effects. The combination of a comprehensive approach and a market-based permit system allows maximum trading and, therefore, will probably help nations find lower marginal costs for greenhouse abatement. Furthermore, it is clear that technology, population, and development will dramatically change in the future, and a market-based approach to greenhouse gas reductions will accommodate the need for flexibility better than other proposals. Finally, a comprehensive approach prevents nations from switching emissions of greenhouse gases away from controlled and towards uncontrolled gases. Together, the arguments above form the main case in favor of a comprehensive and/or market-based approach.

[12]It is clear that the efficiency of energy technologies, for example, varies dramatically across national boundaries. See, for example, N. Nakicenovic, 1989. Technological progress, structural change and efficient energy use: Trends worldwide and in Austria: International part, Final report 700/76.716/9 Verbundgesellschaft.

Given these potential advantages for a tradeable permit system, this paper will explore the options for a tradeable permit system by examining, in depth, the scientific-technical details which pertain to the enforcement, verification, and management of a tradeable permit system. The problem will be evaluated by comparing and contrasting two options. The first option is the proposed comprehensive tradeable permit system. The second option is an alternative proposal which is a tradeable permit system for only CO_2.

The discussion presented here is divided into three parts. The first part raises several general issues which challenge any greenhouse framework (including the comprehensive and market-based proposals). This discussion will also raise several options for managing these general issues. The second part of this argument presents the technical problems which specifically affect the verification and management of a permit-based system. It will be evident from the discussion that, at present, there are serious technical problems with pursuing the comprehensive option. Thus, it is implied that the CO_2-only option may be a good first step; as the science improves, control measures might be expanded stepwise to include other greenhouse gases. Given this, a third section raises and answers several objections to this stepwise approach.

In an effort to appeal to a wide audience, many expanded technical discussions -- especially on a number of the extraordinarily complex scientific issues -- are confined to the footnotes. The main argument is presented entirely within the main text.

1. SOME GENERAL ISSUES

There are several central issues which affect any greenhouse treaty, including the comprehensive and tradeable permits proposals. These issues are raised in conjunction with this document for two reasons: 1) resolution of these issues is required for global acceptance of a greenhouse treaty without which greenhouse action would be at best expensive and at worst ineffective and expensive; 2) the legal and economic literature on which the comprehensive tradeable permit system is based inadequately addresses these questions.

1.1 Equity

There are two classes of equity considerations that affect any proposal. The first equity problem is the pervasive problem of pre-existing inequities. For example, the per capita national income of the United States is nearly 11 times that of Brazil;[13] additionally, U.S. per capita energy consumption is over 12 times that of Brazil.[14] In essence, it will be argued -- primarily by LDCs -- that a greenhouse treaty must also deal with these problems

[13]1985 data from U.S. Dept. of Commerce, 1989. Statistical Abstract of United States: 1989 (Washington: GPO), p.822.

[14]Per capita primary energy consumption. As reported by British Petroleum, 1989. BP Statistical Review of World Energy (London: BP), June.

of different levels of development. This is because it is widely believed that energy is required for development, and across-the-board cuts in CO_2 emissions, for example, will preclude the abundant availability of energy for LDC development.[15]

One approach to this problem is to negotiate longitudinal greenhouse gas controls with the intention of reducing or at least not exacerbating present inequities. An example of this is the European Community's Directive on Large Combustion Plants which requires EC nations to reduce the emission of acid rain-causing pollutants from large power plants. Based on their national wealth and willingness to pay for abatement, different countries were assigned different reduction levels. Richer countries (e.g. West Germany) were assigned stringent reductions while poorer countries (e.g. Portugal) were actually allowed small increases.[16] Applying this approach to greenhouse targets, presumably there would be an uneven set of control levels based on national income or some other measure such as a hybrid of national

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[15]There are some options here. For example, nations can, if they have the river resources, use hydroelectric power. However, in the example of Brazil, hydroelectric dam projects are increasingly scrutinized for their negative effects on the environment (due to flooding of forests) and on the local populations (due to displacement of native populations). In any case, while such zero-CO_2 energy projects are possible, they are not feasible in all countries and probably can not provide the vast amount of energy that countries project will be required for their development needs. However, assuming other environmental problems can be dealt with, these projects will presumably become more popular if a greenhouse treaty enters into force.

A related issue not raised here is the effect of greenhouse controls on natural resources. Presumably nations with rivers suitable for hydroelectric dams (even after the climate changes) would have resources of increased value. Conversely, nations well endowed with fossil fuel resources--like the U.S.--will see the value of those resources depleted due to the international desire to use less fossil fuels under a greenhouse regime. Similarly, the U.S. must be prepared to respond to Gabon's claim the U.S. has used fossil fuels for 100 years and emitted CO_2 into the atmosphere; now it is time to shift fossil fuel production to Gabon and give that country similar opportunities as those the U.S. and the rest of the industrialized world have enjoyed. The ramifications of these resource issues -- along with the general issue of higher energy prices -- may be the single-largest source of U.S. domestic opposition to a greenhouse treaty. I am indebted to J. Ausubel for this discussion of resource issues.

[16]For more on the E.C. directive, the Long Range Transboundary Air Pollution convention (LRTAP) and the thee LRTAP protocols (one on sulfur, one on nitrogen, and one on funding of monitoring activities) see A.A. Fraenkel, 1989. "The convention on Long-Range Transboundary Air Pollution: Meeting the Challenge of International Cooperation," Harvard International Law Journal 30(2):447-476. See, especially, note 146.

income, current greenhouse gas emissions, population, etc. Perhaps the factors used to set targets should change over time: initially, national target levels would be set based on per capita national income and current greenhouse gas emissions so that rich nations which are large net emitters of greenhouse gases would have to make the most stringent cutbacks. Over time, a population factor could be included so that there are also incentives for nations to reduce long term population growth which is also part of the problem.[17]

Thus, this approach might address the equity problem by allowing greenhouse gas emissions from poorer nations to grow while emissions from richer nations are more stringently controlled. A lesson from the negotiating history of the E.C. Large Combustion Plant Directive is that the exact distribution of control levels is a function of the negotiating process although generalized distinctions -- such as between rich and poor nations -- are broadly applied to such variable control schemes.[18] In the case of negotiating greenhouse gas controls the same will presumably hold: that is, rich nations will face more stringent

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[17]In the U.S., population increases by about 1% per year; three-fourths of that increase is natural (i.e. more births than deaths) and the balance is due to immigration. Population controls might give an incentive to limit immigration which might raise opposition to including a population constraint unless there was a threshold population growth (for example, 1% per year) below which there are no penalties for population growth. Data from U.S. Department of Commerce, 1989. Statistical Abstract of the United States: 1989 (Washington: GPO), tables 2 and 5.

[18]Another lesson is that good ideas are less useful when they are worked out after the negotiating process and not before it. Recent work on the economics and atmospheric science of European acid rain have shown that there are large financial benefits to sharing the costs of acid rain abatement among all nations rather than approaching the problem with more simple nation-by-nation targets. Of course there are political problems with this, but another reason it has not been broadly applied to the structure of European acid rain abatement is that these findings are relatively new and have been introduced only since the Sulfur Protocol, Nitrogen Protocol, and Plant Directive negotiations began (these two protocols are to the LRTAP convention discussed earlier, see footnote 16). This point is mentioned because it seems that the tradeable permit system may be a good idea and there should be attempts to work out the details and to explore its feasibility. Perhaps this could be done by a committee of technical experts in conjunction with the process of negotiating a greenhouse treaty.

controls than poor nations, but there will be many individual exceptions due to the nature of the negotiating process and the need for compromise.[19] Given that over 100 nations may participate, it could be very complicated.

Arguably, the proposed system of tradeable permits will reduce inequities since it may foster technology transfer to nations in greatest need of such technology. This is because firms which find their own costs of pollution abatement too high can invest in less costly pollution reductions elsewhere. For example, U.S. utilities might find it cost effective to pay for improving the energy efficiency of Brazilian power plants since the marginal cost of improving energy efficiency in Brazil is lower than in the U.S.[20] In exchange for this investment and/or technology transfer, the U.S. utility would receive greenhouse gas permits from Brazil which the U.S. utility could then apply towards its total permit allocation. It is expected that such transnational investments will disproportionately take place in LDCs

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[19]Here the focus has been on national income as an indicator of which countries should have which control levels. However, in the course of the negotiations an equally important indicator of the control levels which will emerge from the negotiation process is "willingness to pay." For example, the Netherlands has strong environmental attitudes and is highly committed to controlling the rise in greenhouse gas concentrations (indeed their energy plan through 2010 calls for CO_2 reductions even if there isn't an international greenhouse agreement). Thus the Netherlands has a high willingness to pay for greenhouse abatement. Although the per-capita GNP of the Netherlands is only about 54% that of the U.S., we may nonetheless see that the Netherlands will agree to spend as much or even more than the US (on a per capita basis) for greenhouse abatement because the U.S. is relatively less willing to pay. Thus the process of negotiating uneven control levels will help address the equity concerns, but in the process of negotiating control levels there will be lots of factors which will affect the negotiations. GNP statistics for 1985 in constant dollars from U.S. Department of Commerce, 1989. Statistical Abstract of the United States: 1989 (Washington: Government Printing Office), p. 822.

[20]This is primarily because the average energy efficiency of Brazilian power plants is probably lower than U.S. power plants for simple reasons of technology differences. This argument assumes that the costs of international transactions -- tariffs, import/export restrictions, etc. -- do not overwhelm the advantages of tech. transfer discussed here.

because it is in these countries that the marginal costs of, for example, increasing energy efficiency are probably lowest. In the process, efficient technologies are transferred to LDCs.[21]

However, there is also a persuasive argument for the opposite case: despite the economic efficiencies of investing transnationally, firms will not do that because they prefer to invest at home where the political, cultural, and economic environments are familiar and the infusion of capital will benefit the local economy. Thus while technology transfer might be an incentive for LDCs to sign and ratify a tradeable permits-based treaty, those countries will presumably want the U.S. and other developed nations to substantiate the claim that the proposed greenhouse framework will increase technology transfer to LDCs and that the technology transferred will be good for their development. Indeed, one can foresee that there may be a demand by LDCs to include special provisions on the legal, technical and economic issues of technology transfer precisely because there is apprehension about whether or not tradeable permits will actually increase the transfer of useful technologies.[22]

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[21]This assumes that the costs of international transfers of capital are not larger than the supposed benefits of transferring such capital.

[22]Specifically, there may be at least two issues related to technology transfer that LDCs will bring up and try to address through the structure and wording of a greenhouse convention. First, is the technology really "transferred" in the sense that technological investment builds indigenous technological "know how" and not just mysterious technological marvels such as modern power plants and smelters. Second, is the technology transferred useful in development and the quest for equality? Unfortunately, there are numerous examples in the history of development where modern, efficient facilities have not fulfilled their promise of helping the development process. It is not clear that these two conditions will be satisfied and that marketable tradeable permits will result in technology transfer on the scale sought by many LDCs. As mentioned in the text, these technology transfer issues are raised here only because it seems likely that LDCs will raise them at the bargaining table. Technically, it does not matter from a greenhouse perspective whether the technology is effectively transferred. All that is important is that the technology transfer achieve its primary goal of increasing energy efficiency and, thus, making available greenhouse gas emission permits for use elsewhere. However, it is presumed that if the LDCs bring up technology transfer--and they will--then they would like some guarantees that technology transfer will be done properly; otherwise they may not go along with a greenhouse treaty.

The second, virtually ignored equity problem is operational. Inequities will result when greenhouse control measures enter into force because different population groups, industries, and countries will feel the effects of pollution constraints differently. This is especially true for energy related constraints since energy taxes are usually highly regressive. A typical response to this problem is to include some sort of transfer mechanism which might be financed with permit fees. Transfers would be made to people, organizations or nations which are adversely affected by, for example, rising energy costs due to the greenhouse treaty. However, the United States and other countries are understandably concerned that such a transfer mechanism applied worldwide would be misused and that money would be wasted on inappropriate activities. Theoretically, it is possible to design a transfer mechanism which could only be used for certain activities such as energy conservation and forest preservation; in practice, however, ensuring that only approved activities would be quite difficult. An invasive transfer mechanism -- one which oversees and controls the proper use of every penny -- would be challenged by many nations as an undue threat to sovereignty.[23] Similarly, a transfer mechanism which seeks to correct inequities at levels below the state (e.g. transfers to adversely affected individuals, groups, or economic sectors) will also be challenged as an illegitimate circumvention of state sovereignty.

[23]There is technically a third equity problem, one of intergenerational inequities. That is, the current generations are paying for greenhouse gas controls which will only benefit future generations. Alternatively, the current generations are polluting but future generations will have to pay the consequences. This is a very complicated issue, and my impression is that it is not a large concern for the construction of a greenhouse treaty since entire economies and industrial structures change on the scale of generations. In essence, we can't effectively deal with this intergenerational equity problem.

Drawing, once again, on the European effort to reduce acid rain, one approach to the operational equity problem is to view it as a domestic problem and thus one which international policy should not address. Applied to the case of controls on greenhouse gas emissions, this approach would require nations to reach control levels as a nation, but the distributional equity problems due to the costs of such abatement would have to be addressed by the nation itself. This approach is appealing because it avoids the complicated, contentious and administratively expensive problem of managing a worldwide transfer system to deal with these operational equity problems.[24] It is not appealing because there will certainly exist major disruptions and inequities below the state level which the international greenhouse regime would like to rectify.

There is also concern that firms will "buy up the environment" and thus keep poor nations poor by depriving them of energy consumption required for development. This is a nontrivial problem, but there are possible solutions. One way to structure the permit system is to distinguish between primary and secondary energy.[25] A permit may be traded

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[24]However, pushing the question of operational inequities off as a domestic policy issue does not avoid the appeal among some LDCs of some sort of transfer mechanism. For example, India stated in a recent Commonwealth meeting that it would only accept a greenhouse treaty if it included a trust fund or some other transfer mechanism. It is unclear what shape this interest in a trust fund will take, but the LDCs may make it the central condition upon which their acceptance on a greenhouse treaty rests. They may argue that there should be a global per-capita greenhouse gas target, and nations above the target must pay into the trust fund while nations below the target can withdraw from the trust fund. Withdrawals would be used to increase energy efficiency and other activities which help environmental conservation. In an effort to reduce expensive payments, nations with high net greenhouse gas emissions would have an incentive to reduce emissions and/or increase sinks. However, there are two problems with this. First is that there is no way to practically ensure the proper use of the trust fund money since some nations will not have pure intentions. Second, there will be a major disagreement over how to structure the population term in the agreement (i.e. is per capita based on today's population or future population or some mix of the two). Third, for the fund to provide adequate incentives to comply it must be large, but that would also be perceived by some nations as a global "bribe." Thus, some nations will view such a structure as a threat to their sovereignty.

[25]Primary energy consists of fuel feed stocks (coal, oil, natural gas) while secondary energy consists of useful energy products (e.g. electricity, steel production, and usable heat).

internationally only if the trade itself does not decrease the amount of secondary energy (e.g. electricity, produced steel, etc.) available to the country. This allows the tradeable permit system to improve energy efficiencies internationally without decreasing the amount of usable energy available to the local population. This proposal might also be coupled to an agreement on permit durations (in essence, creating leases) of, for example, 10 years which will allow nations to recover permits if required for development. Shorter term leases -- instead of permanent trades -- will degrade the economic efficiency of the tradeable permit proposal because firms will not have long term guarantees of permit supply which are critical to business decision making. While this is a serious drawback, it seems unlikely that market-based approaches can gain widespread acceptance without some sort of compromise along these lines. Indeed, leasing rather than trading may be the most important step towards addressing the claim that a market-based approach is immoral precisely because some firms will "buy up the environment." However, many of these modifications to the permit system will be accounting nightmares which will presumably drive up the administrative costs of the system and degrade economic efficiency.

The varied equity problems are, of course, inseparable because they reinforce each other and their solutions must exist together. Furthermore, equity problems will change over time, so any approach to these issues must be flexible. It seems that the structure of a greenhouse treaty -- comprehensive, marketable permits or otherwise -- does not particularly affect the resolution of the equity issues. However, some may view the tradeable permit system as one which presents more serious equity problems than a system of national targets with no trading because the permit trading will allow rich nations to buy up the environment. As

mentioned before, this problem can be addressed. Indeed, assuming that technology transfer issues are resolved to the satisfaction of LDCs, the tradeable permit system might even be cast as an inequity-reducing measure. However, this is a large assumption.

In general, the basic equity issues will be about the same for any treaty. Regardless of the structure chosen for a treaty, it seems likely that the basic distinction between rich and poor nations and between large CO_2 emitters will remain a major issue during negotiations and the LDC demands for solutions to equity problems will be quite similar. With respect to the two options considered throughout this document -- the comprehensive approach and the CO_2-only approach -- the equity issues are, also, nearly identical.

1.2 Verification and Enforcement

Provided that an acceptable solution to the equity problem exists, the twin problems of verification and enforcement will remain. These issues will resurface in the later section on the scientific details of the sources and sinks, but the general points are raised here.

The problem of verification stems from the fact that the sources and sinks of these greenhouse gases are not directly verifiable. With present technologies, it is impossible to realistically monitor the annual worldwide distribution of sources and sinks for any of these gases.[26] Instead, gas budgets are constructed on the basis of conditions or behaviors which are "known" to produce certain greenhouse gas emissions. For example, the worldwide

[26]In passing it must be noted that it is typically assumed that control levels will be set using annual data. However, one way to reduce costs and to increase data accuracy is to use longer periods (e.g. two or three years) and to average data over those periods.

emission of CO_2 from deforestation is computed by observing the net flux of CO_2 from many "representative" deforestations and then applying that flux to the worldwide rate of deforestation. Thus the science of these sources and sinks is constructed on 1) knowledge of the intensity with which these conditions or behaviors generally emit or absorb greenhouse gases and 2) a global accounting of the location and duration of those conditions and behaviors. Uncertainties arise when one or both of these is not well known; for example, in the case of deforestation, uncertainties in both factors contribute about equally to the overall uncertainty. For adequate verification and permit management, both of these numbers must be known with sufficient certainty and the inventory must, at least, have a resolution on a per-country scale.[27] As discussed later, one way to manage the problem of uncertainty is to agree on a single methodology which is scientifically acceptable and minimizes uncertainties. This works only when the sources and sinks are relatively clear and scientific disputes are not that large. Furthermore, as will be evident, for some of the sources of some of the gases there are already industries and organizations which collect accurate, reliable data; this is not true for any of the sinks. Thus verification is more difficult when we expand the discussion to include activities which have, in the past, not been monitored and, therefore, have no reliable monitoring bodies or methodologies (such as CO_2 sinks).[28]

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[27]In practice, this is much more difficult than it appears since countries span a wide variety of terrains, soil nutrients, atmospheric conditions, etc. Thus, a country-level resolution requires a reasonably fine level of resolution. This problem is not so serious given that the proposed comprehensive approach only includes anthropogenic sources. But, this issue is still relevant if, for example, agricultural activities are included since greenhouse gas emissions from different agricultural activities vary with soil types and, especially, with nutrient levels (both natural nutrient levels and artificial nutrients applied as fertilizers).

[28]This does not mean that efforts to establish such bodies and methodologies will be hopeless but only that it will take time, money and commitment. Indeed, we should probably start creating such institutions now so that they are ready for use in conjunction with a greenhouse treaty at some point in the future.

Enforcement raises the complicated problem of jurisdiction since there is limited power to enforce decisions under international law. Perhaps the experience of the Montreal Protocol will provide guidance on the problem of enforcement, but more stringent control measures adopted under the Montreal Protocol will not enter into force until later in this decade and there will be a further 10 year delay for developing nations. Thus, the lessons from the Montreal process are not yet evident and will not be for some time. Specifically, it is not clear how effectively the trade sanctions built into the Protocol will work.[29]

We might turn to the European experience with acid rain controls to look for lessons on verification and enforcement, but the lessons are mixed. Regarding verification, the Long Range Transboundary Air Pollution (LRTAP) convention which is the framework for European acid rain reductions includes a protocol which sets up mandatory contributions for the monitoring network.[30] That monitoring network has been a primary source of reliable information for use in acid rain assessment and modelling. Thus, here is a good precedent for a member state-funded monitoring body whose lessons can be applicable to the verification and permit management questions surrounding a greenhouse treaty. Regarding

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[29]Violations of the Montreal protocol are also much easier to detect than would violations under a greenhouse treaty. This is because the CFCs controlled under the Montreal protocol are produced in relatively few CFC plants. Thus it is clear where verification and enforcement efforts should be directed.

[30]The network monitors both emissions of acid rain-causing gases <u>and</u> the effects of acid rain. This extensive monitoring work has been used to develop computer models of acid rain transport, and these models may be used in negotiating the next, more stringent set of acid rain controls. Provided they are trusted by all the participating nations, computer models can theoretically make the abatement process more efficient by showing where it is most efficient -- for the environment and the cost of abatement -- to reduce acid rain emissions. The models work reasonably well because the acid rain transport process is well understood given certain aggregate assumptions. However, the effects of acid rain are not well understood. To some extent, these problems of the distribution of sources are not relevant to the greenhouse effect if we assume that the atmosphere is well mixed (i.e. it does not matter where the source is because any pollution is mixed evenly worldwide). As discussed later, this assumption is adequate for some gases but not for others.

enforcement, the close-knit economic and legal structure of the EC is sufficiently different from the world system of nations that we can not apply the lessons of enforcement from the European experience to the global greenhouse problems. Enforcement consistently appears as, perhaps, among the most intractable problem greenhouse negotiators will face.

On balance, it appears that a well-administered system of tradeable permits neither helps nor hurts the basic greenhouse enforcement problem since permit sanctions or other permit-based enforcement mechanisms are relatively useless against a state which intends to violate the agreement. Thus enforcement issues are essentially distinct from the comprehensive and/or tradeable permits proposals.

Serious problems may arise if nations accuse each other of cheating or if nations use conflicting scientific evidence to their benefit. Most likely, both these situations will occur. This may be dealt with by a central, unbiased Judge or international greenhouse commission; but, there still remains the question of enforcement jurisdiction for the nation that decides not to abide by the decision of the central authority. It seems unlikely that states will give up much of their sovereignty to such a central authority; thus, this problem of jurisdiction will remain.[31]

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[31]Enforcement is easier if there is an incentive for all nations to abide. For example, transfer payments would presumably be made contingent upon abiding by the treaty; similarly, participation in the popular idea of a trust fund might be tied to abiding by the treaty constraints. Michael Grubb has suggested that one option is to tax all imports from recalcitrant nations. This is theoretically possible, but it seems unlikely that nations will simultaneously agree to controls on greenhouse gases and to the binding decision of some central authority to invoke broad taxes if it is decided the participating nation is not abiding by the treaty. I can imagine no plan which would invoke greater fears within LDCs than such a plan which might be perceived as a broad initiative by the developed world to control global trade. Furthermore, the domestic political consequences of this import tax plan are not insignificant since import taxes yield inflation and are seen by many as isolationist. In sum, for political reasons it does not seem that the import tax idea is particularly feasible at the present time although it may be useful to explore it further in conjunction with the LDCs. For expanded discussion see M.J. Grubb, 1989. The Greenhouse Effect: Negotiating Targets, Energy and Environmental Programme, The Royal Institute of International Affairs.

The next section addresses the problem of treaty design on a gas-by-gas basis and raises the issues of verification and enforcement as they affect the prospects for controlling the various gases. In general, the verification and enforcement problems are similarly problematic for all treaties. However, a marketable permit system may present a slightly larger set of problems than will other potential treaty structures since verification must be done on a per-permit basis rather than on a per-nation basis, and some authority must keep track of international permit trading. As evident in the next section, a comprehensive treaty will present intractable verification and permit management problems because 1) the sources and sinks are not well understood for gases other than CO_2, and 2) there are no international organizations which consistently produce reliable data on the activities which lead to emissions of greenhouse gases other than CO_2. Even for the case of CO_2 there are nontrivial monitoring and verification problems since the anthropogenic sources and sinks (especially those related to tropical forests) are not perfectly worked out.

2. SOME SCIENTIFIC ISSUES

The comprehensive proposal is comprehensive in that it encompasses all greenhouse gases as well as all anthropogenic sources and sinks of those gases. It assumes that we can issue, trade, and administer permits for all sources and all sinks for all these gases. This section will examine some of the scientific issues which may challenge this assumption. Specifically, there may be two problems: 1) the question of natural sinks might be inverted

to include interpretations which are not in the interests of the United States,[32] and 2) scientific understanding of the issues -- especially in the distribution of the sources and sinks -- is highly uncertain for some gases. Underlying the discussion on this second point is the assumption that a workable permit system requires good knowledge of the sources and sinks of the gases so that the permits can be verified and managed without excessive administrative costs.

2.1 Natural greenhouse gas sinks

The intention of the comprehensive approach is to allow maximum flexibility in the goal of reducing concentrations of greenhouse gases. Especially innovative is the attention given to greenhouse gas sinks. However, this issue of sinks might be inverted in such a manner that makes the entire proposal too costly for the U.S. and other higher latitude countries. This is because the major natural chemical and biological processes which remove most greenhouse gases from the atmosphere are sunlight-dependent. How, then, does the U.S. respond to the claim that tropical nations jointly own perhaps 70% or 80% of the global sink for most of these greenhouse gases and are, therefore, due large sink credits under the proposed comprehensive tradeable permit system?[33] Likewise, who owns areas of net CO_2 uptake in the oceans within the 200 mile exclusive economic zone (EEZ)? Are nations

[32]U.S. interests broadly defined to include the economic health of the U.S. and the world, U.S. foreign policy regarding certain states (especially adversaries), and the general U.S. interest in effectively managing the concentrations of greenhouse gases.

[33]However, it is not clear what fraction of this tropical sink is over international waters and, theoretically, not "owned" by any nation.

responsible for reducing net oceanic outgassing of CO_2 within the EEZ in their overall obligation to cut greenhouse gas emissions? As mentioned earlier, the comprehensive treaty is intended only to control anthropogenic sources and sinks, but this question of natural sinks is raised for two reasons: 1) some (primarily tropical) nations may raise it during the negotiations because it is to their benefit to include such sinks, and 2) for some gases it is not so clear what is natural and what is anthropogenic.[34,35] This is especially true since the global environment is a naturally variable system and it is difficult to identify the causes of natural variations in the sources, sinks and concentrations of the different greenhouse gases.[36]

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[34]Furthermore, is it an anthropogenic source of CO_2, for example, if a large forest stand burns down because the greenhouse effect (assumed to be anthropogenic) makes a warmer, drier climate in some areas which increases the likelihood of forest fires? Perhaps this is stretching the case too much, but nations will likely seek relief from correcting greenhouse gas emissions due to natural disasters. In a naturally variable system like the Earth's climate, it is difficult to distinguish natural variation from human-induced changes in the climate. Perhaps it is believed that a convention of the best scientists will resolve this problem; but that is unlikely because there are (and will continue to be) too many genuine uncertainties. Perhaps it is believed that a central tribunal can mediate disputes over such issues; but for reasons of jurisdiction and sovereignty raised earlier, it seems unlikely that such a tribunal would ultimately be effective.

[35]There is another reason to be sure that natural sources of greenhouse gases. A treaty which has provisions to include natural sources may give incentives to plunder CH_4 emitting anaerobic wetlands or certain N_2O emitting soils and forests. Clearly this is nobody's intention, but even if the wording of the treaty is anthropogenic, there may be loopholes or interpretations which can expand the scope over the fuzzy line to include some natural sources.) For more on N_2O emissions from natural forest soils see M. Keller, W.A. Kaplan, and S.C. Wofsy, 1986. "Emissions of N_2O, CH_4 and CO_2 from tropical forest soils," Journal of Geophysical Research 91:11791-11802. The incentives to deforest may not exist if deforested land has the same or higher N_2O emissions; see F. Luizao, P. Matson, G. Livingston, R. Luizao, and P. Vitousek, 1989. "Nitrous oxide flux following tropical land clearing," Global Biogeochemical Cycles 3:281-285. For more on CH_4 emissions from natural wetlands see E. Matthews and I. Fung, 1987. "Methane Emission from Natural Wetlands: Global Distribution, area and environmental characteristics of sources.," Global Biogeochemical Cycles 1:61-86.

[36]I am indebted to J. Ausubel for this point.

2.2 The Science of Greenhouse Gas Budgets

2.2.1 The General Issue of Scientific Uncertainty

It is widely believed that the main uncertainty which plagues the comprehensive approach is the problem of establishing a weighting system for the various greenhouse gases. This problem, it is argued, could be solved by convening the best scientists who would agree on the appropriate emission factors for greenhouse gases.[37,38] These values would then be used to weigh permits for different greenhouse gases which the market would then value based on their abundance and utility. This is simple enough and the science is reasonably well understood and can be adjusted periodically if needed.[39]

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[37]Some of the supposed uncertainty is artificial, derived from conflicting translations of the scientific literature on infrared absorption by non-experts. This problem is readily solvable by experts.

[38]There are two uncertainty issues here: 1) the question of the marginal effect of an additional unit of concentration of a given gas on the heat trapping ability of the atmosphere, and 2) the lifetime of the various gases in the atmosphere. Uncertainty on the first issue is essentially nonexistent while there remains considerable debate on the second issue. Still, a convention of good, knowledgeable scientists could yield consensus values as was done for the CFC emission factors (known as the ozone depletion potentials, ODPs) in the Montreal protocol negotiations. For more on the marginal effects of greenhouse gas emissions see V. Ramanathan et al., 1987. "Climate-Chemical Interactions and effects of changing atmospheric trace gases," Reviews of Geophysics 25(7):1441-1482. For more on the lifetimes of gases in the atmosphere see the review papers cited for the source and sink budgets of the various greenhouse gases (tables 1, 2, and 3 and footnote 65 in this paper). See also D.A. Lashof and D.R. Ahuja, 1989. "Relative contributions of greenhouse gas emissions to global warming," Nature 344:529-531.

[39]However, even here there are some serious disputes since it is unclear how CO_2 source (or sinks) should be compared with sources (or sinks) of other gases. This is because the chemical and biological processes which remove anthropogenic CO_2 from the atmosphere are dramatically different from those which remove other gases. Thus inter-gas comparisons are quite difficult.

Although nontrivial, the concern on weighting uncertainty is misdirected; virtually nonexistent in the tradeable permit literature is a discussion of the more important uncertainty question on the sources and sinks of greenhouse gases. This is not surprising since the case for tradeable permits is based on the positive experience with tradeable permits in local pollution where the intensity and distribution of sources is reasonably well understood. Thus it is assumed that the scientists can work out the source and sink patterns and that the only serious problem is in weighing the effects and in the setting of target levels. The next few sections will show that for the case of the greenhouse effect, there are major scientific uncertainties regarding the sources and sinks for some of these gases. These uncertainties are large and real and can't adequately be resolved by simply convening a group of the best scientists. Furthermore, it will be argued that without better resolution of these uncertainties we can not expect to adequately issue and manage the trading of permits. Thus, at present, we should focus on those gases where uncertainty is reasonably low.[40]

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[40]It may be useful to examine the problems of uncertainty that affected the Montreal Protocol. When the Protocol was negotiated, the only scientific uncertainty that directly affected the Protocol was the question of ODPs. However, the uncertainty was quite small (e.g. about 10% or so) and could be resolved relatively quickly by agreeing on certain chemical modelling methodologies and rate constants. By the time the ODP question affected the Montreal Protocol negotiating process the science of the relevant chemical reactions was quite advanced. For the one halocarbon which could not be assessed, Halon 2402 ($C_2F_4Br_2$), the decision of the appropriate ODP was postponed. Since Halon 2402 is relatively obscure, this did not seriously affect the signing of the Protocol. It is indicative of the advanced state of the ODP science that an elegant paper which sets out all the relevant chemical and dynamical processes was published in a prestigious peer-reviewed journal the same year the Protocol ODPs were negotiated. See J.K. Hammitt, F. Camm, P.S. Connell, W.E. Mooz, K.A. Wolf, D.J. Wuebbles, and A. Bamezai, 1987. "Future emission scenarios for chemicals that may deplete stratospheric ozone," Nature 330:711-716. For applications of this chemistry to projected chlorine and bromine concentrations in the stratosphere see J.S. Hoffman and M.J. Gibbs, 1988. Future concentrations of stratospheric chlorine and bromine, U.S. Environmental Protection Agency, EPA 400/1-88/005.

2.2.2 Prospects for reducing uncertainty

Very briefly it is noted here that a typical response to the problem of uncertainty is to recommend further research and to proceed with the negotiations with the assumption that the scientists will eventually work out the technical issues. This is an appealing approach because it removes many of the technical problems from what will clearly be a complicated negotiating process. Unfortunately, the promise of future research may fail, especially if the research is intended to iron out the uncertainties on all greenhouse gases and to do so in the very near future (the target date for a greenhouse convention is 1992). As evident in the next few sections, it will take some time to work out these extraordinarily complex issues of sources and sinks for some of the gases.

2.2.3 Global budgets for greenhouse gases

2.2.3.1 Carbon Dioxide (CO_2)

Anthropogenic sources and sinks of CO_2 are better understood than most other greenhouse gases except that there are major uncertainties on the natural processes -- especially in the oceans -- which remove excess CO_2 from the atmosphere. CO_2 is also the most significant contributor to the greenhouse effect and thus the greatest anthropogenic leverage point on

climate.[41] Table 1 shows the net sources and sinks for CO_2; as currently understood, there are no large net natural sources of CO_2, and about 1/2 or more of the anthropogenic CO_2 source is taken up by natural processes in the ocean.[42] As mentioned before, this balance between anthropogenic sources and natural sinks is an important factor for setting global anthropogenic CO_2 controls. The fraction of anthropogenic CO_2 consumed by the oceans may vary in the future; furthermore, the rate of oceanic uptake is somewhat dependent upon the amount of CO_2 added to the atmosphere.[43]

By far, the largest anthropogenic source is the combustion of fossil fuels. The CO_2 emission factors are fairly well worked out for the different fossil fuels,[44] and there is good agreement on fossil fuel consumption data. There is already a United Nations (U.N.) system in place which collects and disseminates data on fossil fuel production and trade;

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[41]This is technically not true although widely stated. Water vapor is actually the most serious greenhouse gas, but the global concentration of atmospheric water vapor is naturally regulated and thus not under consideration. Of course, water vapor content will be affected, but the point remains that direct anthropogenic water vapor changes are not believed to be a primary cause of climatic change. Changes in water vapor are treated by the climate modelers as a "feedback mechanism" and not an anthropogenic forcing of climate change.

[42]B.Bolin, 1986. "How much CO_2 will remain in the atmosphere?" in B.Bolin, B.R. Doos, J. Jaeger, and R.A. Warrick (eds.) The greenhouse effect, climatic change, and ecosystems: A synthesis of present knowledge (Chichester: Wiley), pp. 157-203.

[43]The dependence is not linear and is subject to a number of lags in the ocean-atmosphere system. See, for example, L.D.D. Harvey, 1989. "Managing Atmospheric CO_2," Climatic Change 15:343-381.

[44]According to respected sources, the emission factors are as follows: Coal, 0.683; Oil, 0.52; and Gas, 0.411. Units are in tons of carbon emitted per ton of coal-equivalents burned. The figures are computed based on the carbon content of the fuels and on different assumptions about the % oxidation of the fuels (99% for coal, 91.8% for crude petroleum, and 98% for gas). Lack of 100% oxidation is due in part to incomplete burning, in part to fuel leaks, and in part to uses of fuel for non-combustion purposes (e.g. petrochemicals). This assumed level of oxidation is easily adjusted to account for CO emissions, discussed later in a different memorandum. Computations in J.H. Ausubel, A. Grubler, and N. Nakicenovic, 1988. "Carbon Dioxide Emissions in a Methane Economy," Climatic Change 12:245-263. Data based primarily on R.M. Rotty and C.D. Masters, 1985. "Carbon Dioxide from fossil fuel combustion: Trends, resources, and technological implications," in J.R. Trabalka (ed.) Atmospheric Carbon Dioxide and the Global Carbon Cycle, DOE/ER-0239.

furthermore, individual governments and independent organizations also collect such data and can provide important verification of the U.N. system.[45] However, the U.N. fossil fuel data are regarded by many as quite poor, so improvements would probably be required to increase the data quality to acceptable levels. Still, there are relatively few complications related to CO_2 emissions from fossil fuels and thus it would be reasonable to expect that administrative costs for a permit-based greenhouse treaty would be relatively low (especially since the organizations and methodologies are already largely in place).

Regarding enforcement, there is considerable trade in fossil fuels which may allow an especially effective systems of trade sanctions for greenhouse treaty violations. However, jurisdictional and sovereignty issues still remain, and these could plague the creation of an enforceable treaty (and they will plague any treaty). Also, in some fossil fuel-endowed countries there are opportunities for covert fossil fuel production and consumption; this could

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[45]The U.N. and other data sources also include trade in fossil fuels. It is assumed that debits for CO_2 emissions are attached to the fossil fuels themselves and not to the country where they are recovered from the ground. The question of how to manage CO_2 credits due to trade in fossil fuels is probably easy to solve. We can model the system after the Montreal Protocol, for example, which controls "calculated consumption" defined in Articles 1 & 3 as Production plus imports minus exports (and accounting with ozone depletion factors for the relative ozone-depleting effect of the different halocarbons). The Montreal Protocol also controls production of halocarbons (i.e. not adjusted for international trade) at slightly less stringent levels than for consumption. This allows exporting nations to slightly expand production to service the halocarbon needs of nations which have little or no domestic CFC production facilities. However, such exports have certain constraints regarding the Montreal Protocol participation of countries to which the exports are made; most notably, the increased exports are only allowed for satisfying the needs of developing countries operating under article 5 of the protocol.

A combination of consumption <u>and</u> production restraints might be a good way to structure a greenhouse treaty. However, we should be prepared for the argument made by countries with large fossil fuel reserves that such a treaty will lower the value of reserves already in the ground (the U.S. might argue this, for example). Presumably, resolution of this operational equity problem would be a function of the bargaining process and would be reflected in different control levels for consumption or production such as was done the Montreal Protocol.

challenge enforcement efforts as well as verification and permit management. However, it is likely that covert production and consumption will be very small compared with world consumption of fossil fuels.

The second largest anthropogenic contribution to atmospheric CO_2 is deforestation. The problem of deforestation is more difficult to include in a tradeable permit system. There is considerable controversy over both the rate of deforestation (i.e. hectares per year) and emission intensity (i.e. CO_2 released per hectare); however, the overall estimate of CO_2 flux from deforestation has narrowed considerably in the last eight years.[46] In practice, the uncertainty in deforestation sources of CO_2 can be reduced for inclusion in a treaty by agreeing on a single data set and setting overall greenhouse targets based on the assumptions derived from that agreed data set. Methodological uncertainties can be reduced with a scientific agreement on a single methodology, but it is not clear how likely it is that acceptable agreement on methodologies and data sets can be reached at the present time. At present, the best candidate is probably the 1980 data set because it has been used for many studies in this area and is generally well-known by scientists working on the deforestation issue.[47] Certainly it is technically feasible to establish nation-by-nation estimates of deforestation CO_2 emissions since that has already been done with the 1980 data set.[48]

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[46]This does not necessarily mean that the estimates are narrowing on the "right" number but just that there is greater agreement among scientists.

[47]There is emerging international agreement that there would have to be an agreed data set and methodology for rates of deforestation. Deforestation rates could be measured with in situ observations or through remote sensing using a Landsat-type system. However, there still exists an expensive, sticky but probably solvable problem of funding and flying an international array of satellites or other remote sensing devices.

[48]R.A. Houghton et al., 1987. "The flux of carbon from terrestrial ecosystems to the atmosphere in 1980 due to changes in land use: geographic distribution of the global flux," Tellus 39B:122-139. See, especially, figure 2 and pages 128-129 for tabulation of the net carbon fluxes by nation.

Administrative costs for such an endeavor will be very high since forests must be surveyed every year or so (however, some of this would be done anyway as part of international scientific research on deforestation).[49]

The deforestation issue will be a major point of debate in the course of negotiating a greenhouse convention and its protocols. Given the sensitivity and importance of the issue, I will consider two options for approaching this problem during the negotiations.

One option is to remain firm on the question of deforestation and to demand inclusion of deforestation greenhouse gas emissions in any convention or protocol. The argument in favor of this option is that a treaty which does not include deforestation -- a major CO_2 source and important for other reasons such as biodiversity -- simply institutionalizes an inadequate approach to managing the greenhouse effect. Indeed, some have argued that such a treaty may be worse than no treaty at all because it gives the illusion of addressing the greenhouse problem when, in fact, it is not. Further, the argument maintains, that by not including forests we are missing a great opportunity to preserve them since there may not be much forest left in a few decades when (or if) we finally get around to doing something about the problem. Also, including deforestation in a tradeable permit treaty would allow the greatest flexibility in finding the most cost-effective means of controlling CO_2 (some nations will find it more cost effective to slow deforestation rather than slow fossil fuel use). Thus, we should be sure to include forests in the greenhouse treaty.

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[49]Perhaps the greatest benefit of post cold war thaw is that nations will be more willing to release high resolution satellite technologies for use in deforestation monitoring. This could help reduce costs since the research and development costs for such satellites have already been incurred.

The second option is to compromise on the forest question if it appears that intransigence on deforestation will sacrifice agreement on a more limited treaty which, for example, might control only fossil fuel use. The argument in favor of this option maintains that a limited treaty is better than none because fossil fuels are the largest source of CO_2 and the largest single contributor to theorized global warming. Choosing this option does not mean that the deforestation problem is ignored; instead, it simply means that it is not worth sacrificing a treaty over the deforestation issue. Indeed, there is a persuasive case for dealing with the deforestation issue through smaller bilateral and multilateral agreements. This is because the primary deforestation concerns are currently related to the practices of a few countries -- Brazil, Colombia, Ivory Coast, Thailand, Indonesia and Laos -- thus it may be easier to negotiate directly with those states rather than to tie the deforestation issue into a broader, more complicated treaty with many other nations.[50] The argument in favor of this option maintains that the greenhouse negotiations will be so complex that it does not make sense to make them even more complex. This argument is especially compelling since any resolution of the forest issue will also raise many other issues regarding trade of timber products, debt relief, etc. All of these issues will involve even more organizations (e.g. GATT, IBRD, etc.) than currently involved in the IPCC process, and that will exponentially increase the complexity of the negotiations. Of course, the deforestation issue is high on the

[50]These six nations are responsible for 53% of deforestation CO_2 emissions. Data from Houghton et al., 1987 supra note 48. If we expand this list to include another ten nations or so we can do a good job of addressing not only current CO_2 emissions from deforestation but also future emissions from countries which have, until now, not had extensive deforestation.

agenda of the IPCC discussions. Most likely, any series of forest-related bilateral or multilateral arrangements outside a greenhouse treaty would, nonetheless, be negotiated with reference to a greenhouse treaty.

From the perspective of forest-endowed countries, there may be advantages to including deforestation in a treaty if it allows such countries higher greenhouse control levels. This would allow countries to stop deforestation -- a policy which is advantageous for international political reasons given new interest in preserving the forests -- and also receive CO_2 credits.[51] In passing, it may be noted that if so called "debt-for-nature swaps" increase then some nations may actually receive greenhouse credits for reducing deforestation rates as well as debt relief.

Related to the problem of deforestation is the general question of whether CO_2 sink credits will work. As with deforestation, there are problems of verification and enforcement. Furthermore, a sink credit creates a fundamentally new set of constraints on land ownership and land use when the biomass on a particular plot of land has been used for such a credit. There also remains a question of liability for biomass lost from land used for a CO_2 credit. This problem becomes especially difficult when the loss is due, for example, to an

[51]Countries would not technically receive CO_2 credits for stopping deforestation; rather, if they reduce deforestation sources of CO_2 then there is greater room for expanding fossil fuel sources of CO_2. There are, however, some accounting games here which are easily solved through agreed methodologies on CO_2 accounting as implied earlier (note 50). For example, some think that stopping deforestation will both 1) stop the emission of deforestation CO_2 and 2) increase the sink of CO_2. This is not true because stopping deforestation merely keeps the carbon content of the forest and soils constant; it does not increase the carbon content. Thus, stopping deforestation only stops the deforestation CO_2 source. However, reversing deforestation (i.e. stopping deforestation and then reforesting some areas) both stops the deforestation CO_2 source and then increases the CO_2 sink for the area which is reforested.

unforeseeable natural disaster which, itself, may have been due to global warming.[52] These problems aside, the greenhouse sink credit for CO_2 is technically feasible to implement: a piece of land would be nominated for sink credit, surveyed for carbon content by the treaty's monitoring body and then monitored for carbon content changes during the reforestation or other carbon-increasing operation.

Since such a monitoring body is not in existence today, the marginal administrative costs of including these CO_2 sinks will be high. However, any treaty which includes reforestation as a CO_2 sink will have this administrative problem, so it is not peculiar to the tradeable permits proposal. It seems likely that a greenhouse treaty will include reforestation CO_2 sinks given the current popularity of CO_2 offset plans and the general realization that reforestation can be an inexpensive way to control atmospheric CO_2.

Less discussed are the options for extracting CO_2 from the atmosphere or from smoke stacks which are technically feasible but far from cost effective at present. As currently understood, these systems would present no major verification problems, but most likely there will be some debate on their efficacy in removing CO_2 from the atmosphere. Do proposed systems which pump CO_2 into the deep ocean get a 100% credit, or does some of the CO_2 resurface and/or reduce the capacity of the oceans to absorb excess CO_2 elsewhere?

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[52]For example, is a nation responsible for reforesting an area after a big forest fire if the fire happened during a dry season which might have been caused by climatic change or by natural variations in climate? Are the CO_2 emissions from the fire included in the Nation's total permit allocation; if so, are they included immediately or phased in over time? What if the fire was due to dryness of the forests but the nation could have taken measures such as increased patrols of the forest which would have prevented or limited the scope of the fire? Is it irrelevant that after such a fire the clear land may be useful for crops or pastures? How can one distinguish between accidental fires and ones which only appear as accidents?

Most of these questions can be answered when they appear although there may be some large uncertainties. Research on many of these options is currently underway, but at present none of the greenhouse gas removal options are economically viable.[53]

In sum, a treaty which controls anthropogenic sources and sinks of CO_2 has no insurmountable technical problems in either verification or the issuance and administration of permits. However, as suggested before, there are serious technical problems in the setting of overall target emission levels (i.e. the number of permits to issue, over what period they should be reduced, etc.). This does not mean that we should not attempt to control the sources or sinks of CO_2, but it does mean that using the scientific evidence for precise decision on the appropriate target levels will be difficult.[54]

2.2.3.2 Nitrous Oxide (N_2O)

Global budgets for nitrous oxide are less well understood than for CO_2. Table 2 shows the sources and sinks of nitrous oxide.

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[53]There are also other technical approaches not mentioned here. A hybrid approach is to "reform" fossil fuels by chemical reaction with water at high temperatures (e.g. in a nuclear reactor or a solar station) thus creating hydrogen and some CO_2. CO_2 could then be separated out and disposed while the hydrogen is burned for energy (hydrogen combustion doesn't release any CO_2). Even if the CO_2 from the "reforming" process is vented to the atmosphere the net effect is much lower CO_2 emissions than if the fossil fuels were burned directly. One of the problems, of course, is that you need a nuclear reactor or a solar station to make the process work. This is just one example of the many exotic processes which might appear on the future energy agenda. None of the processes under consideration present serious challenges for monitoring under a greenhouse treaty. The biggest problem is that none of them are currently even close to being cost effective.

[54]For example, recent work on the role of the oceans in consuming excess CO_2 from the atmosphere could be highly variable in the future. Thus, if we decide we want to stabilize CO_2 concentrations in the atmosphere (i.e. cut sources so they equal sinks) then it is not clear what the target level should be. This may be of secondary importance, however, since the primary problem is agreeing to some sort of controls on CO_2.

Over the last 10 years the magnitude of the global N_2O budget and, especially, the distribution of sources have changed dramatically in the light of new scientific evidence. However, the budget in table 2 is presented with a fairly high degree of confidence although attention should be paid to the differences between the budget in the table and the new IPCC figures discussed in the note. The overall budget is probably known within about 20% although uncertainties on individual sources can be much wider. Those anthropogenic sources which are known seem to be very small or highly uncertain (probably only 10% of the total budget).[55]

There is some opportunity to control N_2O emissions through limiting nitrogen fertilizer use, but the evidence clearly shows that the rate of N_2O emissions is dependent upon fertilizer application rates which thus presents a substantial field-by-field verification problem.[56] Likewise, there are opportunities to control N_2O emissions through fossil fuels (which would, nonetheless, be controlled if only CO_2 were included in a greenhouse treaty). The direct emissions of N_2O from fossil fuel combustion are probably very small, but N_2O emissions due to acid deposition (see the note to table 2) may be large and, therefore, controls on acid-causing emissions might help (although such emissions, also, would be controlled to some degree under a CO_2-only greenhouse treaty). At present, however, the uncertainties on acid deposition-related N_2O emissions are quite large (they vary by a factor of 40).

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[55]Once again, please pay special attention to the uncertainties raised in the footnote, especially the uncertainties in the IPCC update.

[56]However, there is a more complicated second-order relationship between runoff of nitrogen fertilizers into the oceans (e.g. Chesapeake bay) which then raises the N_2O flux from the oceans (i.e. the accounting which allocates 2 Tg to the "natural" oceans may not be entirely correct).

At present, the sinks for N_2O are unchangeable because they are stratospheric reactions dependent primarily upon the abundance of sunlight and oxygen (i.e. the prospects for human intervention are essentially nil).[57]

In sum, there are some opportunities for reducing anthropogenic N_2O emissions. Further, while large uncertainties remain they have decreased considerably in the last decade; after CO_2, nitrous oxide would probably be the next gas for which there is sufficient certainty to include in a tradeable permit system. However, the anthropogenic sources of N_2O are relatively small, so their inclusion in a treaty will not make a dramatic difference in the attempt to control greenhouse gases.

2.2.3.3 Methane (CH_4)

As shown in table 3, the prospects for methane reductions appear greater than those for N_2O. Over half of the annual methane source is anthropogenic. It appears that here is a case where there may be great flexibility and opportunities to trade permits in different gases.

Under close scrutiny, the prospects for methane reductions within a system of tradeable permits are not so promising. In part, this is because the scientific uncertainties are so large. Biomass burning, rice paddies, and landfills have uncertainties up to 50% or more; the uncertainty for domestic animals is approximately 25%. Thus, it will be very difficult (and expensive) to monitor CH_4 emissions on a permit-by-permit basis.

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[57] In theory, however, technological changes may enable a cost effective device that removes N_2O from the atmosphere.

Even if the uncertainty problems are solved, there are still many other problems. Notably, controlling methane production from rice paddies is politically unwise given the staple role of rice in some cultures. There may, however, be opportunities to reduce methane emissions by using new varieties of rice, but the point remains that this is politically and culturally difficult for a staple food. The same is true for livestock emissions which might be even more problematic than rice since countries raise cattle for local consumption and for lucrative export contracts. Thus controls will be difficult because they affect both local diets and the current account.

If these anthropogenic sources of methane are included in a tradeable permits system, complicating factors which affect methane emission rates will likely drive up permit administration costs. Work at EPA and elsewhere has convincingly shown that there are significant opportunities to reduce methane emitted from livestock.[58] However, it appears that the most cost effective manner is to improve the quality and quantity of feeds which will increase the productivity per cow and decrease both the overall methane emissions and the emissions per cow for a given level of beef and/or milk production. But this requires monitoring the diets of individual herds. With the current cattle population at 1.3 billion worldwide, the task seems large. The same conclusions apply to sheep, buffalo, and other ruminants. Clearly the approach to verification and permit management would not be on a

[58]M.J. Gibbs, L. Lewis, and J.S. Hoffman, 1989. "Reducing methane emissions from livestock: Opportunities and issues," EPA 400/1-89/002.

per-animal basis but rather on crude estimates of herd size, diet, emission factors, but there would be many legitimate objections to the estimates given the highly uncertain state of the science.[59]

Likewise, preliminary work has shown that relatively inexpensive measures to reduce methane emissions may exist for landfills, rice paddies, and coal mines.[60] But as with livestock, the scientific evidence shows that CH_4 emissions can be reduced through a variety of add-on technologies (e.g. CH_4 traps on cola mines or on landfills) or through changes in agricultural methods (e.g. altering the rice growing cycle, using different rice strains, or using different fertilizers). While encouraging, this work challenges a permit-based system because the administrative body must account not only for the overall level of activity (tons of coal, landfill garbage, or rice produced) but also the distribution and efficiency of all these complicating factors (e.g. which landfills have traps or which rice farmers use which strains). Given this, it is effectively impossible to implement a permit system which adequately accounts for these greenhouse gas controls since administrative costs of such a

[59]There may also emerge an equity issue here since the solution to lower methane emissions is better feed. Thus poor nations will see this as a tactic by rich nations which can feed their cows better food. The EPA work has shown that better food might pay for itself in higher production, but the issues are not always seen that way by poor subsistence herders. This long term economic perspective on production is not evident in the way cattle herds are maintained in some countries. The point here is simply that the feasibility of doing this internationally--especially through a binding greenhouse treaty--may be quite low at present.

[60]e.g. see EPA internal briefing, "Controlling Methane: A major opportunity," EPA global change division, Office of Atmospheric and Indoor Air Programs, Office of Air and Radiation, Nov. 11, 1989.

permit system will be quite large. This may become especially problematic as landfill methane sources increase in the developing world where a data-collecting infrastructure is not adequately in place for monitoring and verification.[61]

Roughly one-fifth of the annual methane source is from coal (35 $\pm$ 10 Tg) and natural gas operations (45 +5, -20 Tg).[62] It may be possible to include these methane sources in a treaty at the present time, but there are substantial uncertainties. Research currently underway should help reduce these uncertainties somewhat, but there are still large uncertainties regarding, for example, the size of leaks from natural gas pipelines in Eastern Europe and the U.S.S.R.; also, there are uncertainties regarding the exact level of methane emissions from coal mining operations in some countries, but there are some good estimates.[63,64] However, methane emissions from fossil fuels will be limited by a treaty even if methane is not explicitly included simply because these methane releases are associated with the same activities which release CO_2.

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[61]For the assumptions used in a current methodology of CH_4 emissions from landfills and solid waste see H.G. Bingemer and P.J. Crutzen, 1987. "The Production of Methane from Solid Wastes," Journal of Geophysical Research 92: 2181-2187, esp. pp. 2183-2186.

[62]Perhaps these numbers are much higher than presented here. See D.C. Lowe, C.A.M. Brenninkmeijer, M.R. Manning, R. Sparks and G. Wallace, 1988. "Radiocarbon determination of atmospheric methane at Baring Head, New Zealand," Nature 332:522-525.

[63]e.g. EPA Internal Briefing, 1989. "Controlling Methane: A Major Opportunity," Office of Atmospheric and Indoor Air Programs, November 11.

[64]These uncertainties will likely persist for some time for two reasons. First, it will take a while to collect data on mine-by-mine emissions of methane for coal and pipeline-by-pipeline emissions of natural gas. Furthermore, natural gas leaks are not just from pipelines but also from wellheads (probably very small) and from end-users from natural gas (potentially very large). Thus it is a big job to tabulate and monitor these methane sources, but work is underway. Second, the isotopic method of analyzing atmospheric methane does not precisely reveal the sources of methane. There are other sources of methane which have the same isotopic signature as fossil fuel methane, thus using the atmospheric record does not give ideal resolution on the sources of methane.

Although verification problems may preclude exploring these methane-reducing options under an international greenhouse treaty, some of these options are worth exploring anyway. Perhaps methane reductions are an area where unilateral action would make sense since the U.S. is a major emitter (although the numbers are quite uncertain). There are also compelling reasons to follow the prescriptions for lower methane emissions from these sources since they would also yield certain economic benefits such as higher livestock productivity and marketable natural gas recovered from coal mines and landfills.

The question of methane controls may be the most important with respect to choosing between the comprehensive and/or the market-based approaches and some other system of greenhouse gas controls. This is because there already exists great pressure to include methane in a greenhouse treaty because it is a strong greenhouse gas and the anthropogenic sources are large. This pressure may ultimately undermine support for a comprehensive and/or market-based approach because they demand more from the science of the greenhouse effect than is currently available. The comprehensive approach demands that sources and sinks of CH_4 be comparable to sources and sinks of other gases, notably CO_2; but with present scientific understanding, such inter-gas comparisons are quite difficult and attempts to formulate a global warming potential (GWP) for all greenhouse gases yield different results, depending on the (controversial and quite uncertain) assumptions used to formulate the GWP.[65] The market-based approach demands very good knowledge of the sources and

[65]See D.A. Lashof and D.R. Ahuja, 1990. "Relative contributions of greenhouse gas emissions to global warming," Nature 344:529-531. Also see H. Rodhe, 1990. "A comparison of the contribution of various gases to the greenhouse effect," Science 248:1217-1220. For a response to Lashof and Ahuja and an analysis of the sensitivity of the assumptions used (especially the assumptions for the atmospheric lifetime of CO_2) see D.G. Victor, 1990. "Sensitivity of global warming potentials to feedback and carbon cycle assumptions: implications for policy," Nature (submitted).

sinks of these gases so that permits can be issued. That means that the activities and synergies which result in sources and sinks must be monitored on a per-permit basis. For CO_2, it has been argued, the task is difficult but manageable. For CH_4, the task is presently unmanageable. If anything, the administrative costs from monitoring the complex series of factors which affect CH_4 emissions will likely consume the supposed economic benefits of pursuing a comprehensive or market-based treaty.

2.2.3.3 Tropospheric Ozone (O_3)

At present, it is impossible to establish the global budget of tropospheric ozone with any degree of certainty. It is clear that tropospheric ozone is formed with the concurrence of three factors: reduced carbon (e.g. some hydrocarbons and carbon monoxide), oxides of nitrogen (NO_x), and sunlight. The relative concentrations of the gases as well as diurnal and seasonal shifts in sunlight dramatically affect ozone formation. Furthermore, the world hydrocarbon source is poorly understood and includes both natural and anthropogenic sources. Even if all the sources and sinks of these ozone precursors were known, we would still have to know the ambient concentrations around the world to predict areas of ozone formation and, thus, where to assess greenhouse debits. In sum, while the schematic processes of ozone formation and destruction are reasonably well known, the state of the science does not support any attempt to include tropospheric ozone in a treaty.[66] As argued

[66]The effects of ozone on the climate are somewhat complicated. At low altitudes (e.g. the urban ozone problem) the net effect of ozone is as a greenhouse gas: increasing ozone leads to warming of the Earth's surface. In the upper troposphere and in the stratosphere, increasing ozone will decrease temperatures at the Earth's surface. The difference is because the role of ozone in the stratospheric heat budget is quite different

before, however, a CO_2-only treaty would presumably also lower associated production of carbon monoxide (CO) and NOx by controlling demand for fossil fuels; this will help control tropospheric ozone concentrations.

3. ARGUMENTS AGAINST A STEPWISE APPROACH

Throughout the above discussion it has been implied that given the current scientific evidence, a tradeable permit system could only include CO_2. Quite simply, the sources and sinks of the other gases are not well enough understood to make their inclusion technically feasible. Even for CO_2 it will be sufficiently difficult to overcome the existing uncertainties in the anthropogenic sources and sinks. Given this, it has been suggested that on technical grounds a global warming treaty can include only CO_2. This might be done as a first step and made with the understanding that as the scientific evidence improves, additional protocols which cover other gases would be added (or, it is conceivable that protocols might only address certain emissions such as from coal mining or from livestock rather than all emissions of a certain greenhouse gas). If the tradeable permits mechanism is utilized, this stepwise approach would entail issuing permits for CO_2 emissions initially and then expanding the scope of controlled gases later on.

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from the role of ozone in the lower troposphere. The ozone issues raised in this memo primarily affect ozone concentrations in the lower troposphere and, thus, increases contribute to the greenhouse effect. See generally: J.A. Logan, 1985. "Tropospheric Ozone: Seasonal behavior, trends, and anthropogenic influence," Journal of Geophysical Research 90:10463-10482.

This section considers the feasibility of such a stepwise approach to installing a tradeable permits system by challenging five possible counter-arguments. On technical grounds it is argued that a stepwise approach is feasible and preferable to a tradeable permits system that includes all greenhouse gases since, as argued above, the present scientific understanding of the greenhouse gas budgets is insufficient for monitoring and verifying the permit system. However, in the conclusion it is suggested that several intractable problems still remain, and these remaining problems are sufficiently serious that a global system of tradeable permits is probably not realistic, whether or not the system is comprehensive.

The first counter-argument is that the stepwise approach is not as appealing as a comprehensive one because it will be less economically efficient, thus forcing a more expensive approach to greenhouse gas abatement. At present, there is little evidence to support this claim considering that the demands for verification of a comprehensive treaty may well consume all of the advantages in efficiency. This is because verification activities are expensive and the bureaucracies required to verify a comprehensive permit system also contribute to overall inefficiency.[67] Agreed methodologies may help make verification easier (e.g. agreement that activity X which we can verify easily will lead to Y emissions of Z greenhouse gas), but it is difficult to achieve agreed methodologies for greenhouse gases when the sources and sinks are highly uncertain. Furthermore, it might not be wise to force such an agreement since it institutionalizes certain numbers for sources and sinks, and those numbers may change dramatically if the scientific evidence changes. Repeated changes in the numbers may undermine support for a greenhouse treaty.

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[67]However, more research on these questions of economic efficiency over the next two or three years can help answer the objection raised here.

Second, and related, is the argument that by not approaching the greenhouse problem comprehensively and including all anthropogenic sources and sinks, the greenhouse treaty will fail to effectively control greenhouse gas concentrations. This argument maintains that emitters will simply switch from emitting CO_2 to other greenhouse gases. It is highly unlikely that this will happen. With one exception, none of the CO_2-emitting activities discussed here can be tailored to emit significant quantities of other greenhouse gases in place of CO_2. The exception is the case of natural gas (primarily methane) which will likely become a more popular fuel source in the greenhouse era since it has a lower CO_2 emission factor than coal or oil. The concern is that in the rush to use natural gas consumers will construct leaky systems which will offset some or all of the CO_2 benefits of switching to natural gas.[68] There are two options for dealing with this problem. The first option is to include methane leaks from natural gas in a CO_2 protocol or as a separate protocol. The second option is to wait and see if this becomes a problem. The first option is appealing because it will give natural gas users incentives to make the natural gas system as tight as possible, and that will help control global warming. The problem with the first option is that

[68]To some extent, the popularity of natural gas as a fuel in the greenhouse era will offset the possibility of large leaks. This is because prices for natural gas will presumably rise and that will give incentives to reduce leaks. Although this is true, it seems unlikely that sufficient incentives will exist to reduce leaks down to nearly 0%. This is especially true in countries which are natural gas resource-rich and capital-poor. For those countries it will make sense to install locally-produced pipeline and mining equipment which is somewhat leaky rather than spend valuable foreign exchange on imported state-of-the-art equipment.

verification and management of the permits will be very difficult since it is currently not possible to discern exactly what the leak rates are. The second option is appealing because it is both less complicated and less expensive.[69]

A third argument is that focusing only on CO_2 hides behind scientific uncertainty and therefore lacks boldness. This is true, but even a treaty on the relatively well understood (and most studied) problem of CO_2 sources and sinks will provide ample opportunity for scientific disputes, distrust, economic crisis, verification battles, and enforcement dilemmas. We should not needlessly contribute to the chaos of an already sensitive bargaining process.

A fourth argument is that this approach does not seriously address the question of carbon monoxide (CO) emissions and their role in future global warming. CO is not a greenhouse gas but it may extend the lifetime of methane (CH_4), in essence increasing the abundance of CH_4 in the atmosphere and thus the greenhouse heat trapping. This is because the removal mechanism for CO in the atmosphere is:

$$CO + OH^{\cdot} + O_2 \text{ ----> } CO_2 + HO_2^{\cdot} \quad (1)$$

So-called $OH^{\cdot}$ "radicals" are also responsible for the removal of methane in the atmosphere:

$$CH_4 + OH^{\cdot} + O_2 \text{ ----> } CH_3O_2^{\cdot} + H_2O \quad (2)$$

Thus, CO emissions can deplete $OH^{\cdot}$ concentrations and create an "OH-feedback" which affects methane concentrations. Of interest is a recent paper by Lashof and Ahuja which

[69]However, small leaks can make a big difference. Using a zero-dimensional longitudinal model of CO_2 and CH_4, I have estimated that the break even point (i.e. where CH_4 leaks exactly offset the advantages of lower CO_2 emissions of natural gas) is between 2% and 4%. See D.G. Victor, 1989. "Leaking methane from natural gas vehicles: Implications for US greenhouse gas reductions from the automobile sector," IIASA working paper WP-89-055. More accurate and detailed treatment of atmospheric feedbacks and a short review of the literature on the existing natural gas leak rates is found in D.G. Victor, 1990. "Leaking methane and natural gas vehicles: Implications for U.S. transportation policy in the greenhouse era," Climatic Change (submitted in revised form).

uses this argument to make the claim that emissions of CO have a significant greenhouse warming potential due to their effect on CH_4.[70] It is quite possible that this view is incorrect. At least, there are large uncertainties which make inclusion of CO emissions in a system of tradeable permits nearly impossible.

The scientific evidence clearly shows that there is a complex relationship between CO, $OH^{\cdot}$, and other gases. Attempts to reconstruct the history of $OH^{\cdot}$ and CO concentrations have made the reasonable assumption that CO and $OH^{\cdot}$ are inversely related but nonetheless find that current understanding of the atmosphere predicts a large role for NO_x concentrations. Thus the abundance of OH depends not only on CO but also on NO_x.[71] Furthermore, as mentioned before (section 2.2.3.3), the right combination of CO and NO_x is a prerequisite for tropospheric ozone formation which also affects $OH^{\cdot}$.

It is in this complex relationship between CO, NO_x, sunlight, hydrocarbons, meteorology and tropospheric ozone formation that the problem lies. $OH^{\cdot}$ is formed by a two step reaction:

$$O_3 + \text{sunlight} \longrightarrow O_2 + O('D) \quad (3)$$

$$O('D) + H_2O \longrightarrow OH^{\cdot} + OH^{\cdot} \quad (4)$$

Thus a scientific analysis of this problem must critically consider not only CO and CH_4 emissions but also the ambient concentrations of other gases which affect O_3 abundance and the nature of their atmospheric chemistries. A greenhouse emissions index that would be

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[70]Also, there is a greenhouse warming factor since all CO emissions are oxidized to CO_2. See D.A. Lashof and D.R. Ahuja, 1989. "Relative contributions of greenhouse gas emissions to global warming," Nature 344:529-531.

[71]A.M. Thompson and R.J. Cicerone, 1986. "Possible perturbations to atmospheric CO, CH_4, and OH," Journal of Geophysical Research 91: 10853-10864.

used to weight emissions of CO against other emissions in a system of tradeable permits cannot adequately account for the synergies which relate CO emissions to $OH^{\cdot}$ concentrations and CH_4 lifetime. Indeed, the scientific literature shows that it could go either way: depending on NO_x concentrations, $OH^{\cdot}$ may go up or may go down in the future at various latitudes and altitudes.[72] The most reasonable assertion is that $OH^{\cdot}$ will go down with rising CO, but the general conclusion is very important: the extent of $OH^{\cdot}$ depletion depends on other factors which are not included in a simple greenhouse gas index.[73] Furthermore, this paper has not seriously addressed the problem of the spatial distribution of sources which clearly adds another complication to an average, worldwide greenhouse gas index. The lifetime of methane, for example, varies by a factor of about two from the equator to high latitudes. Should the greenhouse gas emission index be source dependent? If so, CH_4 emissions at the equator are roughly one half as important as CH_4 emissions from Appalachian coal mines (assuming a 0% discount rate).[74] Since CO emissions are linked to global warming through their effect on methane, should emissions of CO be weighted by latitude? How can we adequately account for all of these important but highly variable (and uncertain) factors in a scheme to include CO emissions in a global system of tradeable permits?

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[72]S. Hameed, J.P. Pinto, and R.W. Stewart, 1979. "Sensitivity of the predicted CO-OH-CH_4 perturbation to tropospheric NOx concentrations," Journal of Geophysical Research 84:763-768. Also see A.M. Thompson, R.W. Stewart, M.A. Owens, J.A. Herwhe, 1989. "Sensitivity of tropospheric oxidants to global chemical and climate change," Atmospheric Environment 23, 519-532.

[73]For more on the factors which affect OH variability see A.M. Thompson and R.J. Cicerone, 1986. "Possible perturbations to atmospheric CO, CH_4, and OH." Journal of Geophysical Research 91:10853-10864.

[74]Even this rough estimate is somewhat complicated by the general circulation of the atmosphere which probably mixes the atmospheric on a global basis on the scale of a few years.

Even if these technical problems are resolved and a greenhouse index is validated for use with CO, there still remains the question of whether the arduous task of incorporating CO into a treaty will make the treaty a better one. A budget presented in table 4 indicates, as with the other non-CO_2 greenhouse gases, that a CO_2-only treaty will do a substantial job of also controlling CO emissions since the anthropogenic sources of CO are closely related to activities that also emit CO_2. Furthermore, efforts to control local air pollution problems will hopefully keep CO emissions down; in the US, for example, the ambient air quality requirements have helped force lower emissions of CO over the last fifteen years.[75] At present, it appears that the technical problems overwhelm any prospect of including CO emissions in a greenhouse treaty, especially if the treaty includes tradeable permits since permits must be issued on the basis of good knowledge of the sources and sinks of the relevant gases.[76]

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[75]Council on Environmental Quality, 1989. Environmental Quality (Washington: US GPO); see, especially, p. 49. The main reductions in CO are from the requirement that new cars be equipped with catalytic converters.

[76]Lashof and Ahuja correctly make the point that CO emissions have a global warming potential (GWP) at least equal to that of CO_2 (the GWP of CO_2 is defined as 1). This is because CO is rapidly oxidized to CO_2 in the atmosphere. However, this view does not necessarily mean that we should make a major effort to include CO in a greenhouse treaty. If the treaty includes CO_2 then the system used for verifying and managing permits would be one which monitored, for example, the consumption of fossil fuels. Since different fossil fuels emit different amounts of carbon when burned, a standard approach is to measure the carbon content of the fuel and assume that the carbon is completely oxidized to CO_2. With this assumption of complete oxidation we arrive at the CO_2 emission factors for each fuel. Combined with total consumption of the fuel the overall CO_2 emissions are calculated for the purpose of the greenhouse treaty. Note that by accounting for fossil fuel combustion and deforestation according to carbon content, CO emissions are already counted equally with CO_2 (i.e. they both have one carbon atom). Thus, we probably do not need to include CO from fossil fuels because it is double-counting the emissions.

If the GWP of CO is slightly larger than 1 because of the OH-feedback then there is a stronger case for including CO. Lashof and Ahuja have persuasively estimated the CO GWP to be about 1.4. However, given that the increase to 1.4 is only a 40% increase in the GWP and worldwide anthropogenic CO emissions are less than 10% of anthropogenic CO_2 emissions, there is not that much to be gained by expanding the scope to include CO, even if the sources were well enough understood and verifiable to do so. Still, if the science on the distribution of CO sources improves presumably a CO protocol should be added to a greenhouse convention.

A fifth, and final argument that may be raised is that the inclusion of market principles which force us to focus only on CO_2 is the wrong way to approach greenhouse gas reductions. Instead, the argument maintains, we should assume that certain agricultural, industrial, and other practices are loosely connected to emissions of greenhouse gases and thus we should agree on certain targets for such activities. This argument may be problematic for three reasons. 1) It suggests creating a needlessly complex regulatory mechanism for the agreement and control of target levels; if, for example, technological shifts reduce the greenhouse gas emission intensity of some activity[77] we may have to go through the arduous process of re-negotiating targets to account for that technological shift. On this point, the market incentives literature (see footnote 11) demonstrates that for the relatively simple problem of domestic pollution control the approach of regulation rather than markets is needlessly inefficient.[78] However, this problem of re-negotiation exists for all proposals; the only claim made here is that a system of negotiated targets for a wide variety of activities is more difficult to renegotiate. 2) The regulatory approach that seeks targets for a wide variety of activities does not adequately acknowledge the problem of scientific uncertainty. What if the science "changes" during or after the negotiations on target levels? This is not so unlikely with error bars of 50% on the sources. Most recently, for example, the N_2O source from fossil fuels has been revised downward due to unforseen experimental

[77]For example, it may be found that rice farming on some soils with certain strains of rice and X kilograms per hectare of fertilizer can reduce the emission intensity of methane.

[78]Furthermore, I have not considered the problem of costing the targets which, the market literature argues, is not well done in a regulatory environment. Is it, for example, cost-effective to control agricultural practices which use nitrogen fertilizers if such fertilizers are only responsible for about 10% of the annual N_2O source, if that.

errors in previous estimates. 3) This argument does not acknowledge that a permit system will give long term economic incentives to develop technologies and agricultural practices which are less greenhouse gas-intensive. A more rigid system of individually negotiated targets does not give such strong incentives to innovate.

Still, this argument is quite powerful, especially if there is interest in including gases beyond only CO_2. If the analysis in the paper is correct, it is probably administratively too difficult and too expensive to install a system of international permit trading for gases other than CO_2. However, the case has been made without any real cost numbers or with any proposed research methodology, so clearly there is much more work to be done. This argument does suggest that the case in favor of marketable permits for gases beyond CO_2 would greatly benefit from some serious scholarship on the balance between supposed economic efficiency and potentially very expensive administrative costs of pursuing that economically efficient solution.[79] Generally, however, the argument is that the cost-effective options for reducing sources of greenhouse gases other than CO_2 appear to present serious challenges to the verifiability of a comprehensive treaty and the management of permits. This may change in the future as the science of the greenhouse gas budgets (most notably of CH_4) improves.

[79]It must be mentioned that some of what needs to be done to account for emissions of these greenhouse gases will be done for scientific reasons, whether or not there is a tradeable permit system. So, if marketable permits are introduced, the marginal administrative costs might not be as high as implied here. Still, the data collected for scientific reasons will probably not have the resolution in time and in space as would be required to manage permits.

Going down the path of tradeable permits seems to foreclose the near term option of addressing greenhouse gases comprehensively. Under a strict regime of tradeable permits, the pace at which other gases are included will be set by the pace of scientific understanding and the capacity to lower administrative costs. That pace may be quite slow, so a near-term treaty which includes more than only CO_2 will probably have to look beyond tradeable permits for a workable structure (or, tradeable permits might not be used except for the CO_2 controls).

4. CONCLUSION

In sum, the argument in favor of tradeable permits is based on the abstract assumption that a market-based approach to pollution abatement is, economically, the most efficient mechanism. This requires, however, that the sources and sinks of the gases are well enough understood to effectively issue and manage the permits. Given the nature of the science, CO_2 is the only gas which is currently well enough understood to support such a market mechanism. However, there are still large uncertainties in the deforestation estimates and the monitoring of forest CO_2 sinks will be difficult. Even the best known CO_2 source -- fossil fuel combustion -- is complicated by uncertainties in the fossil fuel databases.

Because the stakes in a greenhouse treaty are large, it makes sense to negotiate and sign an international agreement which minimizes the opportunities for cheating. This means that such a treaty must be verifiable and enforceable. At present, a comprehensive treaty which includes all sources and all sinks of all gases does not satisfy this requirement because the

sources and sinks are highly uncertain for all greenhouse gases except CO_2 (and, as just reviewed, the uncertainties are nontrivial even for CO_2). This suggests that while the comprehensive approach which includes all anthropogenic sources and sinks of all greenhouse gases is an appealing goal for the greenhouse negotiations, at present the science probably only supports a CO_2 protocol. As the science improves, other protocols which control other gases might be included. It appears that the N_2O estimates are narrowing so it may be possible to include N_2O in the near future. Possibilities for a CH_4 are more distant. It is probably too difficult to include tropospheric O_3 (or, more precisely, emissions which form tropospheric O_3) at any point in the foreseeable future.[80]

Still, it is tempting to try and include gases beyond just CO_2 in a greenhouse treaty simply because the other gases are such strong greenhouse absorbers. But it is precisely this reason why we must not rush the scientific understanding in this area. For strong greenhouse gases it is critically important that the sources, sinks, and residence times be well understood before they are included because small shifts in the scientific understanding will make a big difference in where we concentrate our greenhouse abatement efforts. For example, if nations are allowed to use abatement of CH_4 emissions from rice paddies towards their overall control levels then we should be certain that we know what the CH_4 emissions from rice production actually are. A treaty which allows nations to offset rising CO_2 emissions by curtailing CH_4 emissions from rice paddies will backfire if it turns out that estimates of rice

[80]Nothing in this argument should be interpreted to suggest that the prospects for including gases beyond CO_2 are hopeless and, therefore, the scientific enterprise should not bother trying to reduce uncertainty. Indeed, the situation is quite the opposite. A vigorous series of research programs can and will reduce these uncertainties. The main argument in favor of proceeding stepwise is that the uncertainties for gases other than CO_2 may not be reduced in a timely manner consistent with the schedule for a greenhouse treaty (a greenhouse convention is supposed to be ready for signature as early as 1992).

CH_4 have been too high. If this is the case, the supposed greenhouse savings from lower CH_4 emissions will have been an illusion although CO_2 will have grown relatively unabated. A series of failures like this will undermine a treaty for two reasons: 1) overall greenhouse gas concentrations will rise higher than they would have been if we had controlled only CO_2 because abatement will have been misdirected, and 2) risk averse nations will not ratify a treaty whose control measures will change in unpredictable ways as the scientific understanding of the issue evolves. Further, in the effort to lower abatement costs and find the most effective and least disruptive greenhouse treaty, long term predictability of control levels may be the most important factor. That means controlling right now what is well known and waiting until later to attempt controls on what is currently less well known.[81]

This is not a "wait and see" approach but rather one which recognizes that good knowledge of the sources and sinks of greenhouse gases will affect where we focus our efforts. Similarly, good knowledge of the sources and sinks of greenhouse gases is a critical first step to evaluating the cost effectiveness of various greenhouse gas controls. The analysis here does not necessarily suggest that we should be complacent while the scientists work out the greenhouse gas budgets. It is clear that the anthropogenic sources and sinks of CO_2, the most important greenhouse gas, are relatively well known and thus it may be timely to start the process of controlling the greenhouse effect with a series of controls which will manage CO_2 into the future.

[81] "Later" may be only a few years off if scientists successfully resolve the most serious puzzles. A great deal of effort is directed towards these problems right now and the results are promising.

Controlling CO_2 de facto controls more than just CO_2. Emissions of CH_4 and CO as well as production of tropospheric O_3 are all somewhat linked to fossil fuel consumption; emissions of N_2O, CH_4 and CO are all somewhat linked to deforestation. Thus in addition to the greatest certainty on the anthropogenic sources and sinks, CO_2 controls also yield the greatest leverage on the greenhouse effect. If it is decided that global warming is worth limiting then starting with CO_2 may be a good first step.

Given this, it may be interesting to consider a CO_2-only system of tradeable permits. By avoiding the other gases and focussing only on CO_2 (at least now), many of the technical objections raised above can be avoided. However, the moral objections to a global system of tradeable permits still remain. Regardless of which gases it includes, some nations will still argue that the tradeable permits system Given this, it might be possible to create an international system of tradeable permits which is not fully global. All nations could sign an agreement to control greenhouse gases on their own, and then only those nations that favor a tradeable permits system could create a tradeable permits system on their own. However, doing this would probably require the approval of all parties in the greenhouse agreement which may be impossible to negotiate to all nations' satisfaction. Even if the technical obstacles raised in this paper are overcome (which may be a Herculean task), the political obstacles will remain (which may be equally formidable).

Finally, starting with CO_2 in a system of tradeable permits may create obstacles if/when it is decided that the permits system should be extended to include other greenhouse gases. Notably, holders of permits will be reluctant to have their holdings devalued by newly issued permits when the CO_2-only trading system is expanded to include gases beyond CO_2. Thus

permit holders under a CO_2-only emissions trading system may constitute an interest group firmly committed to not extending the permits system to other gases, even if at some point in the future the science is sufficiently advanced that those other gases can be adequately monitored and verified. This suggests that a global system of tradeable permits for greenhouse gases should start by being comprehensive rather than attempting to proceed stepwise. Since a comprehensive tradeable permits system is probably not feasible, perhaps we should turn elsewhere for a workable mechanism to employ in the international control of greenhouse gases.[82]

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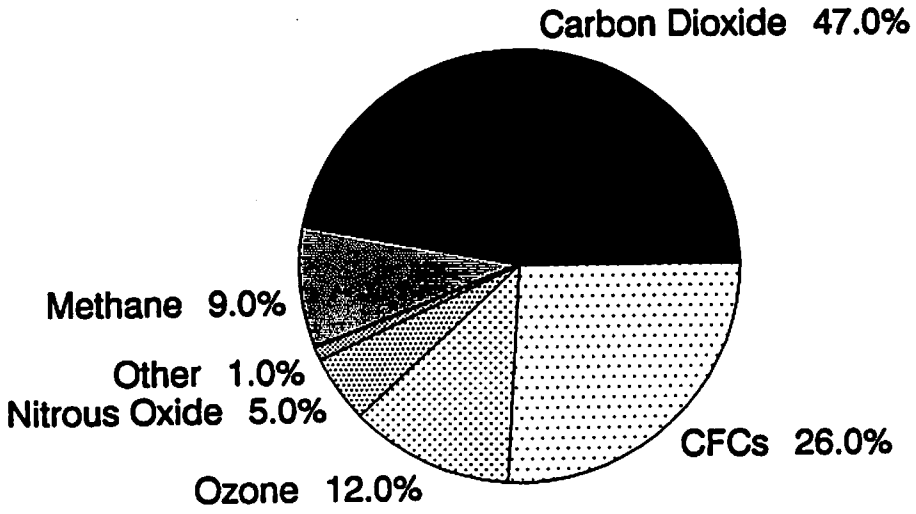
FIGURES AND TABLES

Figure 1: Percentage global warming for projected changes in major greenhouse gases (ozone is tropospheric and stratospheric).



Notes on figure 1:

Adapted from figure 3 in V. Ramanathan, R.J. Cicerone, H.B. Singh, and J.T. Kiehl, 1985. "Trace Gas Trends and their potential role in climate change," Journal of Geophysical Research 90:5547-5566. Estimates based on assumed growth in concentrations of the various gases as described by Ramanathan et al., 1985 (above). Because of the entry-into-force of the Montreal Protocol the CFC percentages will likely be lower. There are two issues which may require elaboration.

First, these are not percentage contributions to the total "greenhouse effect" but rather increases in the greenhouse effect (i.e. global warming) due to anthropogenic additions of these gases. The total effect of various greenhouse gases on the greenhouse effect is not a very instructive number for the public policy process since it does not indicate the relative contributions of anthropogenic and natural sources and sinks. Similarly, such numbers do not indicate which gases are changing in concentration due to anthropogenic influences; thus we do not know where to focus our efforts. Thus, the approach adopted here is to show the increases in greenhouse "forcing" due to increased concentrations of these gases. This approach directly measures the relative contribution of the gases to greenhouse warming.

The second issue relates to the projections for ozone (O_3). This is extraordinarily complicated because some of these greenhouse gases -- CH_4 and the CFCs in particular -- affect the concentration of stratospheric ozone; similarly, CH_4 contributes to stratospheric water vapor which affects both the chemistry and the radiative balance of the stratosphere. Since ozone is a greenhouse gas, modelling these effects is very important for understanding the overall changes in greenhouse "forcing." Currently, it is projected that the total abundance of ozone will decrease and that may lead to cooling. However, increases in ozone at low altitudes (below about 12 kilometers) will lead to increases in greenhouse forcing (assuming all other factors are held constant). It is expected that such low altitude ozone will, in fact, increase due to urban air pollution and rising CH_4 and CO concentrations (both CH_4 and CO are oxidized in the atmosphere and, under some conditions, produce O_3 in the process). These are only some of the complicated stratosphere/troposphere issues since this is a typical case where everything affects everything else. For more see V. Ramanathan et al., 1987. "Climate-Chemical Interactions and effects of changing atmospheric trace gases," Reviews of Geophysics 25:1441-1482. Also see V. Ramanathan et al., 1985. "Trace gas trends and their potential role in climate change," Journal of Geophysical Research 90:5547-5566; especially pages 5550-5551, 5552-5553, and 5561-5563 for a discussion of the CFC/O_3 chemical and radiative properties.

Table 1
Net sources and sinks of carbon dioxide

	Tg (10^{12}g) C yr^{-1}
Anthropogenic Sources	
Fossil FuelCombustion:	
Coal	2400
Oil	2400
Natural Gas	930
Cement production	136
Gas flaring	45
Deforestation	1300 +2900,-800
TOTAL SOURCES:	7211
Natural Sinks	
Net uptake by oceans	3600 $\pm$ 1000
Another biospheric sink	? (assumed 0)
TOTAL SINKS:	3600 $\pm$ 1000

Notes on Table 1:

Data from a variety of sources. Fossil fuel data from W.C. Clark (ed.), 1982. Carbon Dioxide Review: 1982 (New York: Oxford), pp. 458-460 (data scaled to 1988 using fossil fuel consumption figures in BP Statistical review of world energy, June 1989 (London: BP). See also G. Marland et al., 1989. Estimates of CO_2 Emissions from fossil fuel burning and cement manufacturing, based on the United Nations Energy Statistics and the U.S. Bureau of Mines Cement Manufacturing Data, ORNL/CDIAC-25, NDP-030, available from DOE/Oak Ridge National laboratory. Oceanic uptake data based on an estimated airborne fraction of 50% as discussed in B. Bolin, 1986. "How much CO_2 will remain in the atmosphere," in B. Bolin, B.R. Doos, J. Jager, and R.A. Warrick (eds.). The greenhouse effect, climatic change, and ecosystems: A synthesis of present knowledge (Chichester: Wiley), pp. 157-203. The deforestation number is an estimate based on a review of the literature; however, it is about 30% lower than the number given by Houghton et al., 1987 (see note 48). The numbers shown in this table are net sources and sinks and do not include the entire carbon cycle.

Table 2
Sources and sinks of nitrous oxide

	Tg (10^{12}g) N yr^{-1}
Natural sources	
Oceans	2 $\pm$ 1
Grasslands	<.1
Forests:	
boreal and temperate	0.1 - 0.5
tropical and subtropical	7.4 $\pm$ 4
Anthropogenic sources	
Combustion:*	
Coal and oil (prim. coal)	<0.5?, +5*
biomass	0.7 $\pm$ .2
Agricultural fertilizers (artif. + manure)	0.8 $\pm$ .4
TOTAL SOURCES:	15.3 $\pm$ 6.7*
Natural Sinks	
Reactions in the stratosphere:	
N_2O + hv --> N_2 + O	
N_2O + O('D) --> 2NO	10.5 $\pm$ 3

*Coal/oil combustion source is probably less than 0.5. See note for more on the combustion sources.

Notes on table 2:

Data from WMO, 1986. Atmospheric Ozone (Washington: NASA), Vol. 1, p. 81. The overall magnitude of the budget is generally consistent with the N_2O budget in J.W. Elkins, 1989. "State of the research for atmospheric nitrous oxide (N_2O) in 1989," contribution to IPCC. Except that recent work (published in 1988) has shown that the N_2O source from fossil fuel combustion is most likely much too high; this is because of it is now known that there were serious errors methods of analyzing N_2O emissions from power plants; these errors systematically overestimated N_2O emissions by perhaps a factor of 10. Thus, Elkins' very recent survey of the literature shows a lower source for combustion (less than 0.5 Tg N yr^{-1}). For other reasons, his work shows a lower source for natural tropical forests (3.7 Tg N yr^{-1}). Elkins also claims a large source (0.13 to 5.0 Tg N yr^{-1}) from dry and wet deposition (in part due to acid "rain"). Note that the uncertainty in this last number is over a factor of 10.

Table 3
Sources and sinks of methane

	Tg (10^{12}g) CH_4 yr^{-1}
Natural sources	
Animal fermentation	4±2
Natural wetlands	115 +85, -15
Termites	40 +60, -30
Oceans	10 +10, -5
Freshwaters	5 +20, -4
Methane hydrates	5?
Anthropogenic sources	
Domestic animals	74 ±11
Coal mining	35 ±10
Natural gas operations	45 +5, -20
Rice paddies	110 ±50
Biomass burning	55 +45, -5
Landfills	40 +30, -10
TOTAL SOURCES:	533 +100, -140
Natural Sinks	
Tropospheric reaction:	
$CH_4 + OH^{\cdot} \rightarrow CH3^{\cdot} + H_2O$	425
Stratospheric reactions:	
$CH_4 + OH^{\cdot} \rightarrow CH3^{\cdot} + H_2O$	
$CH_4 + Cl \rightarrow CH3^{\cdot} + HCl$	
$CH_4 + O('D) \rightarrow CH3^{\cdot} + OH^{\cdot}$	75
TOTAL SINKS:	500

Notes on table 3:

Data primarily from R.J. Cicerone and R.S. Oremland, 1988. "Biogeochemical aspects of atmospheric methane," Global Biogeochemical Cycles 2: 299-327. Further data resolution on livestock from P.J. Crutzen, I. Aselmann, and W. Seiler, 1986. "Methane production by domestic animals, wild ruminants, other herbivorous fauna, and humans," Tellus 38B:271-284. Wetlands data from E. Matthews and I. Fung, 1987. "Methane emission from natural wetlands: global distribution, area, and environmental characteristics of sources," Global Biogeochemical Cycles 1:61-86.

Table 4
Sources and sinks of carbon monoxide

	Tg (10^{12}g) C yr^{-1}
Natural Sources	
Oceans	20
Oxidation of CH_4	80
Forest wild fires (temperate)	10
Oxidation of nat'l hydrocarbons (temperate)	100
Oxidation of natural hydrocarbons	150
Anthropogenic Sources	
Fossil fuel combustion	190
Anthropogenic hydrocarbons (oxidation)	40
Wood used as fuel	20
Agricultural burning (temperate)	10
Burning of savanna and trop. agricult. land	100
Forest clearing (tropics)	160
Oxidation of CH_4	180
TOTAL SOURCES:	1060
Natural Sinks	
Tropospheric reactions:	
$CO + OH^{\cdot} \dashrightarrow CO_2 + H$	820 $\pm$300
uptake by soils	110
TOTAL SINKS:	930

Notes for table 4:

Data primarily from WMO, 1986. Atmospheric Ozone: 1985, p.106. CH_4 oxidation prorated based on the distribution of natural and anthropogenic sources as listed in table 3.

THE GLOBAL ENVIRONMENTAL POLICY PROJECT

The Global Environmental Policy Project (GEPP) began in 1989 as a joint effort of the Kennedy School of Government's Energy and Environmental Policy Center (EEPC) and its Science, Technology and Public Policy Program (STPP), and the Harvard Business School Negotiations Project. The Global Environmental Policy Project focuses on four subjects:

- *Options for Negotiations*

  In recent history, regional agreements have emerged bringing together countries who share a common resource. There are lessons to be learned from the formulation and implementation of these environmental negotiations. The Project explores various global negotiations issues, including technology transfer from developed to developing countries, funding mechanisms to cover the cost of reforestation, and CO_2 emissions and reductions.

- *Analytic Tools*

  The analytical tools that we use to evaluate environmental impact and mitigation options were developed to combat problems with local impact and short time frames. These tools are not adequate for the examination of issues, such as global climate change, which are characterized by long-time horizons, tremendous factors of uncertainty, and a broad spectrum of perceptions among nations. The Project is developing a range of analytical techniques for the evaluation of policy options to provide governments with decision rules to assist in their selection among these options.

- *Social Learning*

  GEPP researchers are looking at how nations have responded to issues of global environmental change over the past forty years. What lessons can we draw from these experiences? Are societies improving their responses to issues of environmental change? What impedes more rapid progress? Given that different countries react differently, what can we learn from these different responses and how can we use these lessons in developing future programs and policies?

- *Training*

  Global environmental issues will require nations to look at energy, environment, security and economic policy in a more integrated fashion. Furthermore, they will force countries to absorb more scientific and technical information than they can currently evaluate. Many nations do not have the internal capability independently to assess information being generated on global environmental problems.

  The Project is attempting to develop an executive program to teach senior government officials how to assess and manage global and regional environmental problems.